OCEANOGRAPHY 1988

JOA MEXICO 88

Edited by

Agustín Ayala-Castañares
Warren Wooster
Alejandro Yáñez-Arancibia

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
CONSEJO NACIONAL DE CIENCIA Y TECNOLOGÍA

WITH SUPPORT OF UNESCO

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

COORDINACIÓN DE LA INVESTIGACIÓN CIENTÍFICA

CONSEJO NACIONAL DE CIENCIA Y TECNOLOGÍA

WITH SUPPORT OF THE
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND
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Foreword

The Joint Oceanographic Assemblies were conceived as scientific meetings with global participation and with an interdisciplinary scope programme involving all aspects of marine sciences.

Earlier meetings of similar scope to JOA were the International Oceanographic Congresses: 1959 (New York) and 1966 (Moscow). The JOA have traditionally been held every six years; previous JOA's were: Tokyo (1970), Edinburg (1976) and Halifax (1982).

The program of JOA Mexico 1988 was developed by the **International Programme Committee**, apointed by SCOR included: four General Symposia on topics of broad interdisciplinary interest; twelve Special Symposia on designated interdisciplinary subjects and Association Sessions (CMG, IABO, IAMAP and IAPSO) of contributed papers and posters.

JOA Mexico 1988 was attended by 479 participants from 51 countries; it was particularly interesting the active presence of 274 scientists from 28 developing countries, by far more than in any previous JOAs. The attendence to JOA Mexico 1988 had full international coverage, in accordance with the purpose of the meeting.

The book *Oceanography 1988* includes the Proceedings of JOA Mexico 1988 and a collection of the scientific papers presented in the Four General Symposia. The papers cover a wide renge of topics of broad interdisciplinary interest. All together they represent a valuable account of the present state, problems and future of marine research. We consider *Oceanography 1988* a clear indication of trends in modern oceanography.

We thank the authors of the papers in particular to the four authors who accepted to present lectures in the Session "State of the Art", giving lectures summarizing the work, in their own fields, who was reported at the Assembly.

The Editors

AGUSTÍN AYALA-CASTAÑARES

WARREN W. WOOSTER

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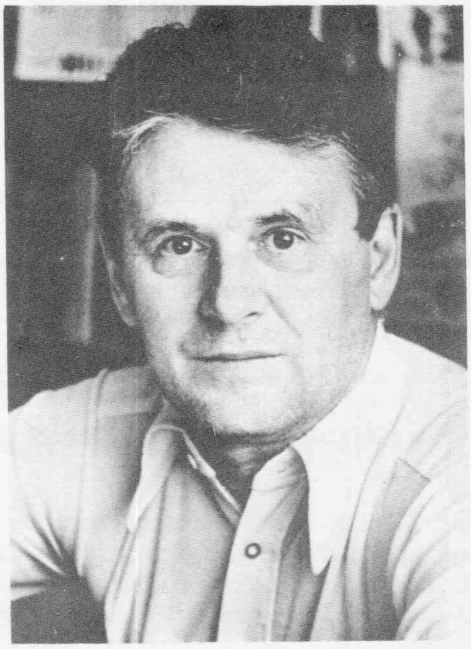

Konstantin Nikolaevich Fedorov
1927-1988

None of us present at the Joint Oceanographic Assembly in Acapulco in late August, 1988, could have believed that it would be the last time we would be fortunate enough to meet Konstantin Fedorov. He died suddenly and unexpectedly on September 21, 1988.

At the Assembly he was energetic and active as usual and in the plenary session at the end of this event he summarized his impressions on the state of physical oceanography as reflected in the contributions presented there. That he was chosen for this task was most natural considering his knowledge of the field, both from the past and at the present frontiers.

Konstantin Fedorov had a warm personality, and although we mostly talked science, the subject easily shifted to family where his pride in his own young family was obvious. It is a tragedy both for his family and for the scientific community that he died so soon.

He was born in Leningrad on December 17, 1927. At twenty he received a diploma in meteorology and six years later an oceanography diploma at the university of his home town. He finished his Ph.D. in physical oceanography in 1955 at the Institute of Oceanology in Moscow. The foundation of his excellent knowledge of English was perhaps laid during a Unesco fellowships period in the United Kingdom in 1958-1959 when he studied at universities both in Liverpool and London.

Konstantin Fedorov played an important role on the international oceanographic scene, in both intergovernmental and nongovernmental bodies. He served as Secretary of the Intergovernmental Oceanographic Commission of Unesco between 1963 and 1969. Later, having returned to his scientific work in Moscow, he was elected President of the Scientific Committee on Oceanic Research (SCOR) of the International Council of Scientific Unions, serving from 1976 to 1980, followed by a term as Past President until 1988. In Acapulco his last appearance as a member of the SCOR Executive Committee was honored at a special gathering. In these positions, he helped to promote cooperation in science between intergovernmental and non-governmental organizations as well as between east and west.

Most of his scientific work related to fine-scale thermohaline structure and mixing in the ocean. His research expanded considerably our knowledge of such processes. Much of this work was based on direct observations at sea, and his experience in work on research vessels was considerable. His long list of publications presented in journals and books, in many of which his wife, Ann Ginsburg collaborated, is a solid documentation of his important scientific contributions.

As a final word, I can't do better than my predecessor, Professor Gerold Siedler, in the SCOR Proceedings following the 19th General Meeting in Acapulco: "The international oceanographic community has lost one of its prominent scientists, SCOR has lost one of its most committed members, and many of us have lost a friend. Konstantin will be missed".

Jarl-Ove Stromberg

President of SCOR

Organizers

- Scientific Committee on Oceanic Reasearch (SCOR)
- Mexican Organizing Committee

Co-Sponsored by

- International Association for Biological Oceanography (IABO)
- International Association of Meteorology and Atmospheric Physics (IAMAP)
- International Association for Physical Sciences of the Ocean (IAPSO)
- Commission for Marine Geology (CMG)
- International Council for the Exploration of the Sea (ICES)

With support from

- Intergovernmental Oceanographic Commission (IOC)
- United Nations Educational and Cultural Organization (UNESCO)
- and other United Nations cooperating Institutions

Acknowledgements

The Joint Oceanographic Assembly Mexico 1988 was hosted by Mexico, organized by the Scientific Committee on Oceanic Research (SCOR) and the Mexican Organizing Committee. This Committee extends its appreciation to all those who were concerned with the Assembly on a national or international basis, particularly the sponsoring and supporting organizations. Special appreciation is given to Lic. José Francisco Ruíz Massieu, Constitutional Governor of the State of Guerrero for his enthusiastic and decisive support.

The Assembly success was the result of the efforts of many people who were involved in the preparation of the scientific program and the administrative arrangements. Although it would be difficult to single all of those who made substantial contributions, special recognition is extended to Prof. Warren S. Wooster, Chairman of the International Programme Committee, Julio Arreguín, Executive Secretary of JOA 1988 and to all members of the National Organizing Committee for their important contribution to the meeting.

I take the opportunity to thank to all symposia lectures and conveners as well as those who participated in the Association Sessions and in the Poster Sessions.

The book Oceanography 1988 is published jointly by the Universidad Nacional Autónoma de México (UNAM) and the Consejo Nacional de Ciencia y Tecnología (CONACyT) with support of Unesco. I thank this three institutions for their valious cooperation.

AGUSTÍN AYALA-CASTAÑARES

President of JOA Mexico 1988

OPENING ADDRESSES

Welcome Address

Agustín Ayala-Castañares

Instituto de Ciencias del Mar y Limnología, UNAM, A.P. 70-157, México 04510, D.F.

It is a pleasure and an honor for me to welcome you on behalf of the Mexican Organizing Committees of the Joint Oceanographic Assembly. It is very stimulating to realize that such an important group of scientists -representatives of many disciplines and numerous countries from all over the world- came to México to discuss marine sciences and ocean research within a purely scientific atmosphere.

The economic, political and social importance of the ocean for mankind is obvious; it was fully recognized in 1982 when, a few months after the previous JOA, the UN Convention on Law of the Sea was signed by 120 nations. This historical event marked, indeed, the begining of a new era of relations between mankind and the oceans. It represents to some extent the culmination of a long process of universal negotiation among states.

We are in a period where the nations, impulsed by a series of pressures, are rediscovering the oceans, reevaluating their importance and redefining their role in vital aspects for mankind.

Recent technological advances have produced great changes in oceanography, particularly in methods of observation, data collection and sampling, as well as the capacity of massive data processing. Today the seas are used in ways never dreamed of a century ago. We have reached the point in which managing the ocean at global scale is a necessity and the interaction between man and the environment cannot be ignored. The limited existence of marine resources is also recognized as well as the need of a solid scientific basis for their proper management. Also, the capacity to predict in the ocean depends upon our knowledge of the sea and its processes.

The Joint Oceanographic Assembly provides a unique opportunity for high level inter-, multi- and cross-disciplinary exchange of ideas and experiences between the oceanographic community of the world in a way which is not accomplished in any other meeting. The value of these assemblies lies primarily in their ability to allows scientists from many disciplines and many countries to meet and to learn one from each other. Not only the individual papers are important, but also the free communication and overall exchange of ideas, including cultural aspects, particularly between individuals from developed and developing nations. Developing countries had a very low participation in previous JOA; although we are convinced that if we want to have a truly world-wide meeting it is necessary to increase such participation. In JOA México 88 we are interested in promoting this dialogue maintaining the high academic quality of this event. I hope JOA México 88 really allows us to gain a better view of the structure of global oceanography.

We expect to be able to evaluate advances in marine research, identifying outstanding new developments, and assessments for research. When doing so, we contribute to promote mankind's understanding and in this manner improve the positive relations among nations of the world.

In the program of JOA México 88 we are dealing with 509 abstracts; the number of authors is 930 representing 58 countries, twenty countries more than in JOA Halifax.

As you know the Assembly belongs to a series of meetings established long time ago. They include, first, the International Oceanographic Congresses held in

New York (1959) and Moscow (1966); and later the Joint Oceanographic Assembly, with sessions in Tokyo (1970), Edinburg (1976) and Halifax (1982). It is a privilege to host this important meeting in México and it is a great satisfaction that our nation was the first developing country selected by SCOR to do so.

The level of the scientists attending this meeting and the program are, by themselves, demostrations of the universality of science and particularly oceanography. It also reinforces the concept that the ocean requires cooperation between states and that no nation can do all by itself.

We are glad to note the significant contribution made by scientists from developing countries to our meeting. It is, without a doubt, a clear indication of the advances made in such countries in recent years, regardless of the serious problems they are facing with the economic crisis. It proves their potential, even recognizing their limitations, reflected in the topics involved; mostly related to coastal and resource problems.

I hope that their participation in the JOA contributes to world oceanography, to consolidate their experience and to reaffirm their convictions. We should be prepared to incorporate their scientific results, as much as possible, in international regional and global projects; with the idea that cooperation in marine sciences is not only desirable but indispensable. The workshop organized by IAPSO on physical oceanography in developing countries is a step along this line.

Therefore, the spirit that we want to convey is that we are convinced of the immense potential of marine sciences and technologies for the benefit of mankind, but also that they offer the oportunity, if we are imaginative enough, to strengthen cooperation between industrialized and developing countries. This should happen in a spirit of partnership, using all available possibilities, both governmental and non-governmental. The presence of our friends professors Federico Mayor, Director General of Unesco, Gerold Siedler, President of SCOR and Ulf Lie, Chairman of IOC is stimulating.

I hope that in the future this situation will continue and that the marine scientific community of the world, with a generous attitude and with solid cooperation links, advocates the study of the complex and exciting problems of modern oceanography making good use of recent technological advances.

I would like to make some reflections concerning my country; the oceanographic problems which México faces largely reflect those of the rest of the world; they may look national but their solution requires global action.

México has large marine areas and an enormous oceanic potential. The petroleum industry, supported with vast amounts of oil coming from the submarine shelf is one of the pillars of our economy and is considered one of the largest in the world. Fishery production plays an important role in our economy. Our harbors are fundamental to consolidate our marine transport system and require strong support with solid technical basis. There are strategic submarine mineral deposits in the Mexican Pacific. Our coastal areas are well recognized for their extension, variety, resources and beauty.

We can say that we live in a country in which destiny and future are linked with the ocean and where development will largely depend on the proper application of marine scientific and technological knowledge.

The Mexican Government has demonstrated a deep interest in the ocean. As a consequence, we participated actively in the 3rd. UN Conference on the Law of the Sea; México signed and ratified the Convention and later adopted the Federal Law of the Sea, adjusting the Mexican legislation to the Convention.

México has limited tradition in science and technology; although it has increased particularly in the last 20 years. The main efforts have been oriented towards building the scientific structure and the preparation of highly qualified human resources. This has been attained through long-term scholarship programs, supporting young scientists to study their doctoral degrees in different institutions, national and abroad, and by strengthening our universities and higher education centres. After 1970, due to joint efforts between C-ONACyT, the UNAM and other institutions, marine specialized units, were created, like the Instituto de Ciencias del Mar y Limnologia-UNAM, the CICESE, the CIB and the Unidad Merida of CINVESTAV.

In addition, large investments in facilities, vessels and equipment have been made with great effort. As a consequence, now we have a young, small but vigorous, marine scientific community properly prepared to contribute towards the understanding and preservation of the ocean, making good use of the Mexican marine resources. It is ready to participate in the major marine sciences international programs, if proper support and opportunities are available.

It is interesting to remember that it was here, in the state of Guerrero, where we held, in 1963, 25 years ago, the First Mexican Oceanographic Congress, with great enthusiasm. Such event contributed heavily to further advance our marine sciences. We are now in an important stage where strong support is necessary and even more efforts to consolidate Science. Unfortunately, in recent years support has been reduced, creating serious problems. This is an enormous mistake; as science and technology in developing countries should be considered as a major long-term investment if they want to pass over this *status*. I hope this situation will be reconsidered soon.

Before finishing I would like to express my sincere gratitude to all those institutions and persons which made possible the organization of JOA México 88 . In particular I wish to thank Lic. Jose Francisco Ruiz Massieu, Governor of Guerrero for his strong and generous support and to all members of the Mexican Organizing Committee for their dedication and efforts.

Finally, I hope our meeting will be a success and you all have a pleasant stay in México. I also hope that you will gain a better understanding of my country and my people. We will do our best to help whenever it is necessary. Thank you.

Address at the Opening Session

Federico Mayor
Director General of the United Nations Educational, Scientific and Cultural Organization (UNESCO)

Mister Chairman, the Minister of Education, and representative of the President of the Republic

Mr. Governor of the State of Guerrero

Mr. Minister of Fisheries

Mr. Chairman of the Scientific Committee

Mr. Chairman of the Local Organizing Committee

Mr. President of the SCOR and other officials of non-governmental scientific bodies associated with the organization of JOA

Mr. Chairman of IOC

Mr. Ambassador, Permanent Delegate of Mexico to Unesco

Distinguished participants and Dear Colleagues

It is for me a great pleasure to be in Mexico at the kind invitation of your Government, Mr. Minister and to have the honour of addressing this Joint Oceanographic Assembly. This Session of JOA in Mexico, the sixth of its kind is, as previous speakers have pointed out, the first, since such Assemblies were initiated in 1959, to be convened in a so called developing country, a country traditionally open to dialogue among nations, in the respect of their national identities and cultures, and which has contributed significantly to the development of international cooperation among States and the role of the United Nations System. In this context, I wish to recall the leading role of Mexico first in the successful negotiation of the UN Convention on the Law of the Sea and now in the effective implementation of its major provisions through legislation. This is indeed a significant contribution to a new ocean regime, of which marine scientific research and related aspects of technology transfer are major components.

The importance Mexico attaches to science and education in general, a key factor in development and self-reliance, is well known, as is your constant readiness to share your experience with others. This is exemplified by your long-standing, active collaboration with Unesco, particularly in the field of marine science. Your efforts in the specific domain of the oceans are often singled out as an excellent example of how the required capabilities in marine sciences and their applications can be built up so as to achieve national goals in ocean affairs. Such efforts, which include the essential aspects of research and education, have helped in the formation of the required specialized human resources as well as in the adequate assimilation of knowledge in development and management. In this context, allow me, Mr. Minister, to pay tribute to the enlightened approach adopted by your Government. Special mention should be made of one of the originators of this approach, Dr. Agustín Ayala-Castañares, founder of the Institute of Marine Sciences and Limnology of the National Autonomous University of Mexico, who has also played a leading role in incorporating this national effort into the broader process of international cooperation, for the mutual benefit of Member States and their scientific communities. We are most grateful to Dr. Ayala-Castañares for this outstanding contribution to, and long association with, Unesco and its Intergovernmental Oceanographic Commission, particularly when he was its Chairman.

As reflected in the UN Convention on the Law of the Sea, the ocean has to be managed as an integrated space, since sectoral uses interact in many ways. This calls for advanced forms of management based on adequate scientific findings generated by multidisciplinary research involving not only the natural sciences but also economic and sociological aspects. Such an integrated and multidisciplinary approach is needed in order to respond to the growing complexity of the ocean phenomena and processes, including those affected by human activities, through a variety of scales and time-frames. And, of course, we must also take into account the fact that the marine environment and its resources are, in some cases, shared by many nations or linked to global concerns.

The relations between human societies and the ocean have evolved to take into account the *protection of nature* and the concept of *sustainable development*. As we talk of the protection of the sea, of its resources, of the plankton, we cannot but think of the oil that is discharged into these waters, or of the fishing methods that use suction and other such procedures, or again of the thousands of tons of pesticides and fertilizers -often used unnecessarily or excessively- that finish up in the oceans. We the scientific community and Unesco, must not remain silent; we must provide decision-makers with solutions, even when these imply radical, costly changes in present habits and behavior. It is our common duty not to cause damage now that will compromise the ecological conditions in which forthcoming generations will live.

I attach great importance personally to this concern. We can and do, indeed, pay attention to the born, but we *must* also think of the as yet unborn -those who will inherit this planet in five, ten or twenty decades' time. If for example some irreversible damage is done to the biosphere, thus limiting the full exercise of those rights, then future generations will look back and say we were irresponsible. *We*, those of us who know what the consequences of present global behaviour are likely to be, cannot remain in our ivory towers; we must speak out in a simple, concise and concerted manner, to provide governements with significally-based solutions and alternatives for the important problems we are facing. The concept of *intergenerations responsibilities* thus implies anticipation as a requisite for the effectiveness of all long-term strategies.

Putting such ethical concepts into practice will rely more and more on the role and devotion of scientists and technologists, enlightened decision-makers and all concerned men and women. This is decisive for the full mobilization of talent for the political will and for the means to achieve such goals on a community as well as on a planetary level. We should not forget that the maritime areas under national jurisdiction must also be seen within the broader context of international issues and the needs of humankind as a whole. An important aspect of this process is the ability of governmental and non-governmental organizations concerned with marine sciences to adapt to the trends emerging from the new ocean regime, so as to serve more effectively their respective national constituencies and, by so doing, the world community. As we enter the Age of the Oceans, we enter the Age of Science in the Service of Mankind, which means, in fact, an era guided by human values and rights and a new global ethical approach involving both individuals and societies.

I am sharing my views with you, both as a scientist and also in my capacity as Director-General of Unesco, as I wish to take full advantage of the special nature of this Joint Oceanographic Assembly, which I see as a forum particularly suited to this kind of reflection, as far as the marine scientific community is concerned. In fact, JOA is the major interdisciplinary gathering of marine scientists meeting in their personal capacities. In this regard, it is worth recalling the origin and purpose of JOA and its predecessor the International Oceanographic Congresses, whose history and that of Unesco and its IOC are intimately related . We in Unesco have continued this tradition by contributing within the means available to us to securing the participation of scientists to this Assembly, especially those from developing countries. I wish to pay tribute to the scientific efforts of the ICSU bodies which have organized this Assembly; the Scientific Committee on Oceanic Research, the International Association of Biological Oceanography, the International Association of Meteorology and Atmospheric Physics, the International Association for Physical Sciences of the Ocean, and the Commission for Marine Geology. In the field of Marine Sciences, Unesco has always considered cooperation with those non-governmental scientific organizations as vital to maintaining the scientific quality of its own programme. In Unesco, the marine sciences programmes and those of IOC originated from the enlightened views and foresight of a group of marine scientists from industrialized and developing countries who felt, in the immediate post-war period, the need for programmes aimed at acquiring a better knowledge of the ocean and its resources through international scientific cooperation and the concerted action of Member States. Anticipating coming trends in marine research and related needs for ocean services, as well as of the required support and commitment of governments, these scientists took advantage of the International Congresses of Oceanography to promote such an idea, thus influencing the scientific programmes of Unesco and leading to the creation of IOC.

Throughout the 30 years since the first Congress, major changes have occured as a result of trends in science and in evolving perceptions on both national and international levels. Despite the growing gap between industrialized and developing countries, the number of scientists, including those in developing countries, has increased manyfold in the last few decades. Many countries -as this meeting demonstrates- have strengthened their capabilities in ocean research and a better understanding of common interest has led to improved cooperation in research and to the establishment of ocean services and monitoring systems for modelling and forecasting, as well as a much closer relation between scientific knowledge, technological development and social welfare.

Unesco is proud of its role in creating IOC, and in supporting the efforts of the international marine scientific community for almost a half century. In so doing, we have contributed to the progress of oceanography and its applications and we have facilitated the involvement of developing countries through relevant training, education and mutual assistance. A special effort is also required in the mobilization of the required means through the formulation and implementation of technical assistance projects under the Unesco-IOC Comprehensive Plan for a Major Assistance Programme to Enhance the Marine Science Capabilities of Developing Countries.

We hope, by these measures, to respond better to the increasing needs of the scientific communities of the Member States and thus to prepare ourselves to assist with the new generation of programmes aimed at responding to global changes -- of which the effect of the ocean on climate is a most notable example. These research efforts depend on long-term commitment. They can only be achieved through the joint efforts of the relevant non-governmental bodies, such as SCOR, the Scientific Committee on Oceanic Research, operating in the framework of ICSU, and intergovernmental organizations, especially those part of the UN Systems, including -- Unesco and its IOC, which is responsible for coordination of the Long-term and Expanded Programme of Oceanic Exploration and Research (LEPOR).

Exciting challenges are therefore facing human societies with regard to the multiple use of the oceans and the need to protect the human environment as a whole, while ensuring sustainable development. As far as the oceans are concerned I note in passing that the communique issued after the Oslo meeting of the UN Agency heads and the Prime Minister Brundtland last July gave its rightful place to the oceans! In all of this, as I have said earlier, scientists will play an increasing, vital role. Your assessment and your aspirations would be a valuable input as we proceed with the drafting of the next Medium-Term Plan of Unesco, which will cover the period 1980-85, but those effects will continue to be felt well into the new millenium.

Science is for the scientists to conduct. Its results and conclusion, if they are to be relevant, must be incorporated into the policies and strategies of the nations, Unesco can play a very effective role here, as it is an intergovernmental organization. I am thus determined to give the floor to the scientific comminity to provide it with every possible support. It is indeed quite clear to me from my own experience as a scientist, and now seen from the Unesco viewpoint, that the complex tasks and ambitious objectives before us can only be achieved through a spirit of full and open cooperation.

Scientists with the requisite intellectual freedom and independence and a deep sense of social responsability, working together with Governments and international organizations imbued with the same ideals to achieve universally acceptable socio-economic goals for the common benefit of humankind, will I am sure, bring our expectations to realization.

Acapulco, this wondeful city, is a symbol. It is a symbol because of its history, but also as a result of its present dynamism, as exemplified by the meeting held here last November, after which eight prominent Latin American countries, represented at the highest level, issued such a clear-sighted Declaration on how humankind should proceed in its common endeavours. The key is openness to all kinds, boldness, knowledge, and above all. trust in what is the human race's distinctive capacity: imagination, creativity and will.

Opening JOA MEXICO 88

Gerold Siedler
President of Scientific Committee on Oceanic Research

Honorable Presidium, Ladies and Gentlemen, dear colleagues and friends:

It is a pleasure for me to welcome the participants of the Joint Oceanographic Assembly on behalf of the Scientific Committee on Oceanic Research. We were certainly glad to receive and accept the invitation from the Mexican SCOR Committee, arranged with the help of CONACYT, to hold the assembly in this country. We realize how much hard work was necessary by the local organizers, and particularly by Dr. Ayala-Castañares, to bring us together today. We also much appreciate the valuable support provided by the Federal Government of Mexico, the Government of Guerrero, and the City of Acapulco.

As most of you know, SCOR was established within the International Council of Scientific Unions for the purpose of bringing together all the disciplines of marine science. Usually the work of SCOR is performed in working groups and committees, and not through the organization of major congresses. We considered it appropriate, however, in a time when interaction between different disciplines is becoming increasingly important to environmental science, to continue the series of the Joint Oceanographic Assemblies. We were fortunate in being able to convince Prof. Wooster that he should chair the Scientific Program Committee, and I want to acknowledge the excellent work done by him and the members of his committee.

The word "joint" in JOA not only symbolizes the joint nature of discussions held by different disciplines in marine science, but also indicates that the assembly is a joint endeavor of non-governmental and inter-governmental organizations. On the non-governmental side, the four associations of ICSU (IAPSO, IAMAP, IABO and CMG) cosponsored the assembly and took an active role in the design of scientific programs. On the inter-governmental side, the International Council for the Exploration of the Sea and the ICSPRO bodies of the United Nations cooperated in the planning and funding of the assembly.

I particularly want to note the valuable assistance of UNESCO and the Intergovernmental Oceanographic Commission. It is a great pleasure to have the Director General of UNESCO, Dr. Mayor, here at our assembly. We take this as a firm sign that SCOR scientists can expect continued support from UNESCO for the further development of a close, well-balanced and productive cooperation in marine science.

Finally, I wish to acknowledge the supplementary financial support provided for the travel of participants by the World Meteorological Organization, the Third World Academy of Sciences, and the U.S. National Science Foundation.

In the planning of the scientific program for the assembly, an attempt was made to achieve an appropriate balance between lectures related to major international programs and papers concerning individual research projects. The major international programs which determine to a large extent the course of oceanography now, or will do so in the foreseeable future, are:

-TOGA and WOCE, which are subprograms of the World Climate Research Program concentrating on studies of air-sea interaction and global oceanic circulation,

-the Joint Global Ocean Flux Study, JGOFS, which for the first time will bring biologists, chemists and physicists together in a global investigation of the fluxes of particles and diluted substances, particularly the carbon fluxes, in the ocean,

- and the International Geosphere-Biosphere Program which is just starting to take shape and will be aimed at the interactive processes between terrestrial, atmospheric and oceanic systems with an emphasis placed on anthropogenic factors influencing the global environment.

Of course these programs do not stand apart from one another, but are interrelated in many ways. With this in mind, it is particular value that the chairman of the ICSU Special Committee for the Geosphere-Biosphere Program, Dr. McCarthy, has agreed to give a lecture on the Global Change Program in the second part of the opening session.

The present Joint Oceanographic Assembly is special in the respect that it is being held for the first time in a country that is at the cross-roads between the industrialized and developing worlds. When you look at the list of participants in this assembly, you will note that we have a larger number of scientists from developing countries than we have had in earlier JOAs. We had expected this would happen, and hope that as a result it will be easier to build bridges, not only between scientists from research institutions with often limited access to up-to-date information and modern tools and investigators from the more highly developed and specialized laboratories, but also between young scientists who only have recently joined the field of marine science and experts with long-standing experience in oceanography.

We hope the assembly will provide an opportunity to look across disciplinary boundaries and to identify common research interests. The assembly will be a success if the discussions in the sessions and outside the lecture rooms can become starting points for future joint projects and experiments in oceanography.

Opening Address

Ulf Lie
Chairman, Intergovernmental Oceanographic Commission, Unesco

Distinguished guests, Honorable Presidium, Fellow scientists, Ladies and Gentlemen:

It is a pleasure and an honour for me, on behalf of the Intergovernmental Oceanographic Commission to address the Joint Oceanographic Assembly. Before us we have eight days of interesting and challenging scientific contributions in the beautiful setting of the city of Acapulco.

The choice of Mexico as the site for the first JOA in a developing country is by no means coincidental. Not only has this country considerable experience with the organization of large international meetings, but Mexico is also a country which has had a spectacular development of its marine sciences during the recent two decades.

The Joint Oceanography Assembly is the olympiad of the marine sciences with emphasis on communication instead of competition. It might be argued, that the large scientific confereces are anachronisms in our day of data networks, marine information databases and advanced information technology. Still, scientific cooperation often starts as a result of direct contacts between scientists at conferences, and the importance of the critique and encouragement of peers at such conferences cannot be overrated.

I therefore feel that the Joint Oceanography Assembly defends its important position for the development of marine sciences and I hope that scientists also in the future will recognize the value of direct scientist to scientist communication. Although I believe that governments have a decisive role to play in the advancement of science; the major functional unit is the individual scientist.

The increasing complexity at all levels of society calls for utilization of science and technology, and national development has therefore to some extent become synonymous with the ability to apply science in mastering society's affairs. Therefore, at the United Nations Conference on Science and Technology for Development in Vienna in 1979, developing countries stressed that an enhanced level of science and technology is a prerequisite for development.

The realization of the importance of science in society has resulted in interesting developments in science itself. The scientist has been invited out of his ivory tower in order to participate fully in the development of society, and as a result we now see that the former distinct boundaries between basic science and applied science are breaking down; major contributions to basic science take place in laboratories of industry or government, whereas university scientists seek participation in scientific projects leading to practical applications. On the national scene this development has led to organizations representing the full scope of marine science and technology and on the international scene we see close cooperation between organizations representing the academic sciences, such as SCOR, and intergovernmental scientific organizations such as the IOC.

Since the 1960'ies we have witnessed a spectacular increase in the development of marine sciences. The total number of marine scientists in the world increased from about 2500 in 1964 to about 18000 in 1983, and the increase is to a considerable extent linked to utilization of marine resources and the related applied sciences. Perhaps even more significant than the increase in total number of marine scientists is the realization of the importance of marine sciences in developing countries. This was stimulated by the new ocean regime emerging from the Third United Nations Conference on the Law of the Sea, which gave coastal nations jurisdiction and thereby the right and duty to make scientific studies of about 40% of the surface of the oceans.

An indication of the increasing awareness in developing countries for strengthening marine science and technology can be seen in the increased membership of my own organization, the Intergovernmental Oceanographic Commission. When the organization as founded in 1961 the total membership was 40 mostly developed countries, whereas the 117 Member states today are dominated by developing countries.

In keeping with this general trend I find it highly pertinent that we now also for the first time have the Joint Oceanographic Assembly in a developing country, and the programme before us demonstrates a very considerable contribution from scientists from developing countries.

A characteristic feature of our time is the realization that man contributes to the destruction of our environment at a scale which may have serious socio-economic consequences affecting the entire world population. The solution to these large scale problems must be sought in global international political cooperation, based on solid scientific know-how. To provide this scientific platform is not a task for the few but for all of us, and the World Commission on the Environmet and Development has therefore in their report pointed to the close relationship between protection of the environment and national development. The World Commission has stressed that the existing inequality in the distribution of wealth and exploitation of resources must be diminished, and that a balance between economic growth and ecological capacity must be sought under the concept of "sustainable development". The ability to determine the ecological capacity is in the realm of the natural sciences.

Sustainable development depends upon a rational and closely managed utilization of both renewable and non-renewable resources. As pointed out by the World Commission on the Environment and Development, the terrestrial resources are to a large extent already overexploited, and the marine resources may indeed be the world's last resources. Sustainable development on a global scale therefore depends on our ability to manage the marine resources rationally, and that calls for a full mobilization of the marine sciences and for cooperation among governments to take full advantage of the scientific results regarding exploitation of resources and protection of the environment.

The marine sciences are particularly well prepared to contribute to these tasks. The marine sciences are naturally interdisciplinary. One can hardly conceive of a large-scale marine research project which does not have components of both physical, chemical, biological and geological oceanography, and all these components rest on a solid foundation on fundamental sciences such as mathematics, physics, chemistry, biology and geology.

The marine sciences are therefore also in their application both multidisciplinary and interdisciplinary. Furthermore, as our research environment is more or less the same and even has the ability to flow among countries, marine scientists have traditionally been concentrating on large scale and even global processes in international research programme. Therefore, in our time when mankind is facing problems on a global scale the marine scientific community is well prepared and organized to tackle the problems at their proper scale. The excellent programme drawn up by the organizers of this Joint Oceanographic Assembly will give all of us a view of the state of the art in our science and provide intellectual stimulating for further advancement.

I want to congratulate SCOR and the Mexican Organizing Committee for their thorough preparation of the Mexico Joint Oceanographic Assembly in Acapulco and I look forward to an exciting scientific meeting.

Scientific Programme

GENERAL SYMPOSIA

G1. New Developments (current topics of special interest)

G2. Ocean and climate

G3. Hydrothermal processes

G4. State of the art

SPECIAL SYMPOSIA

S1. Oceanography in México

S2. Physical and ecosystem models

S3. New observation methods

S4. Large scale changes from human activity

S5. Life strategies in extreme environmental conditions

S6. Small scale ocean processes in the surface layer

S7. Tropical coastal systems

S8. Global ocean storage and fluxes

S9. Pollution in the marine environment

S10. Ocean variability and biological change

S11. Global sea level change

S12. Scientific basis for ocean resource use

ASSOCIATION SESSIONS

A1. International Association for Biological Oceanography (IABO)

A2. International Association of Meteorology and Atmospheric Physics (IAMAP)

A3. International Association for Physical Sciences of the Ocean (IAPSO)

A4. Commission for Marine Geology (CMG) Scientific Committee on Oceanic Research (SCOR)

ALLIED MEETINGS

SCOR General Meeting

IABO General Assembly

IAPSO Workshop on Physical Oceanography in Developing Countries

SCOR Working Group 82

JPOTS Subpanel on CO_2 Standards

POSTER SESSIONS

S1. Oceanography in México

S9. Pollution in the marine environment

A1. International Association for Biological Oceanography (IABO)

A2. International Association of Meteorology and Atmospheric Physics (IAMAP)

A3. International Association for Physical Sciences of the Ocean (IAPSO)

A4. Commission for Marine Geology (CMG)

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CHAPTER 1

NEW DEVELOPMENTS

Cheney, R.E., B.C. Douglas and L. Miller. 1989. The NOAA Geosat Altimeter Project: Monitoring Sea Level from Space, p. 1-10. In: A. Ayala-Castañares, W. Wooster and A. Yáñez-Arancibia, eds. *Oceanography 1988*. UNAM Press, México D F, 208 p.

The NOAA Geosat Altimeter Project : Monitoring Sea Level from Space

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ABSTRACT

In March 1985, the U.S. Navy altimeter satellite GEOSAT began generating a new data set with unprecedented spatial and temporal coverage of the global oceans. Designed and built at the Johns Hopkins University Applied Physics Laboratory (APL), GEOSAT carries a radar altimeter that provides a profile of sea level, wind speed, and significant wave height along the ground track. The primary mission of GEOSAT was improvement of the marine gravity field. Because of the military value of this information, the first 18 months of sea level observations are classified. However, at the end of GEOSAT's geodetic mission its orbit was changed to closely match the Seasat orbit, and data collected after November 1986 are not classified. These data are routinely processed by the National Geodetic Survey and distributed to the public 2-3 months after acquisition. In order to work with the entire GEOSAT data set, we maintain a secure computing facility and have analyzed the first 3.5 years of these data to derive time series of sea level throughout the tropical Pacific Ocean. A clear relationship is seen between changes in sea level and fluctuations in the large-scale wind field on time scales of weeks to months. This 3-year period is particularly valuable because it includes the recently completed 1986-87 El Niño. The GEOSAT data have provided the first complete picture of sea level variability during an El Niño event. Sea level anomaly maps of the Indian Ocean have also been produced, and both oceans are monitored in near-real time.

1. INTRODUCTION

After its initial 18 months in orbit, we described the GEOSAT altimeter mission as a "milestone in satellite oceanography" (Cheney *et al.* 1986). During this time GEOSAT gathered 270 million observations of sea level along 200 million km of the world ocean with a precision approaching 2 cm. In a field historically limited by a lack of observations, it was already the most extensive oceanographic data set ever collected.

Two years later, GEOSAT continues to observe the global oceans, and the NOAA data sets (Cheney *et al.* 1987) are the focus of oceanographic and geophysical research at over 40 institutions around the world. It is anticipated that the mission will last through the next decade, hopefully linking up with the ERS-1 altimeter mission in 1990.

As suggested by its name (GEOSAT stands for Geodetic Satellite), the satellite's primary purpose was improvement of our knowledge of the marine gravity field. Because of the value of this information to the U.S. military, the first 18 months of observations are classified. In October 1986, however, the satellite was maneuvered into a new orbit with a repeat period of 17 days (Born *et al.* 1987). The ground track for this Exact Repeat Mission (ERM) is close enough to previously released Seasat altimeter data tracks that the new data are unclassified.

Even though raw altimeter heights from the initial geodetic mission are classified, records of sea level as a function of time determined from these data are releasable because they contain no geodetic information. Thus GEOSAT is unusual in that releasable products are not watered-down versions of classified ones. In this report we present GEOSAT sea level time series derived from both the geodetic mission and the ERM. Our principal interest concerns sea level variability in the equatorial regions as it relates to long-term changes in weather and climate.

2. COMPUTATION OF SEA LEVEL TIME SERIES

The Crossover Difference Method

During the GEOSAT geodetic mission the ground tracks seldom repeated but instead formed a dense network with an average cross-track spacing of approximately 5 km. This generated an equally dense network of crossovers (intersections of the satellite ground track with itself). In 18 months, approximately 35 million crossovers were obtained over the global oceans. At each of these locations, the two crossing passes provide independent sea level measurements at the same place but at different times. Differences of the sea surface heights at the two times, or "crossover differences", form the basis for sea level variability and time series studies from the geodetic mission.

Various authors have described the general technique used to process crossover differences into records of sea level change as a function of time (Fu and Chelton 1985, Cheney *et al.* 1986, Miller *et al.* 1986). The method that we employ is best documented by Milbert et al. (1989). Routine corrections are first made for tides, troposphere, and ionosphere. Least squares crossover difference adjustments are then performed to eliminate time-dependent orbit error from long (approx. 10,000 km) arcs of data. Finally, the fully corrected crossover differences are aggregated into relatively small cells for which sea level time series can be computed. Size and shape of these cells are determined by the physics of the particular ocean region.

To study low-frequency, long-wavelength sea level variability in the equatorial Pacific, Miller *et al.* (1988) chose cells having dimensions of 8° longitude by 2° latitude. Hexagonal regions (truncated diamond-shapes) were chosen because they produce a more uniform sampling of crossover differences than rectangles. Here we present similar analyses, but reprocessed in 8x1 and 2x1 degree polygons to improve the spatial resolution. The smaller, 2x1 degree sample area is needed in mid-latitude regions where mesoscale eddies are generally more common. Figures 1 and 2 shows examples of two such polygons at the equator using 18 months of GEOSAT GM data. The 2x1 degree region is located at the center of the 8x1 degree area. In the larger polygon (Fig. 1) there are 2509 crossovers formed by 326 intersecting passes. The elongated shape of the 8x1 degree regions gives a dense temporal sample of variability (two passes every three days) and adequately resolves the zonally banded structure of the equatorial ocean. The 2x1 degree example (Fig. 2) contains 558 crossovers and 81 passes. Increased resolution in space is gained only at the expense of resolution in time. A typical 2x1 degree area is sampled by the altimeter only 3 times in approximately 3 weeks.

After assuming an arbitrary height (say zero) for the mean sea surface height of the polygon, the relative height of each pass in the polygon can be estimated based on the differences of height at the crossovers. Of course these are not absolute sea surface heights, since there is only relative information in crossover data. Shown in the lower half of figures 1 and 2 are the sea level time series computed from the networks of crossover differences. The least-squares solution yields one observation of sea level for each pass traversing the sample polygon. The individual measurements are then smoothed by objective analysis to form a continuous record with evenly-spaced, daily values (a 15-day decorrelation time is used for the 8x1 degree areas; 30-day for the 2x1 degree sample regions). The differing frequency content and temporal resolution can be easily seen in the two sample time series. In general the 8x1 degree record shows evidence of the 30-day fluctuations typical of the equatorial ocean, but sampling in the 2x1 degree region is inadequate to resolve these features. A specific example is the upward pulse of sea level centered on June 1, 1986 in the 8x1 degree record, which is absent from the 2x1 degree record because of the sparse temporal sampling. This pulse is the well-documented downwelling Kelvin wave generated by a cyclone pair in the western Pacific (Miller *et al.* 1988, McPhaden *et al.* 1988). For determination of low-frequency sea level changes, however, the two records give similar results; when averaged at monthly intervals the rms agreement is 1.8 cm.

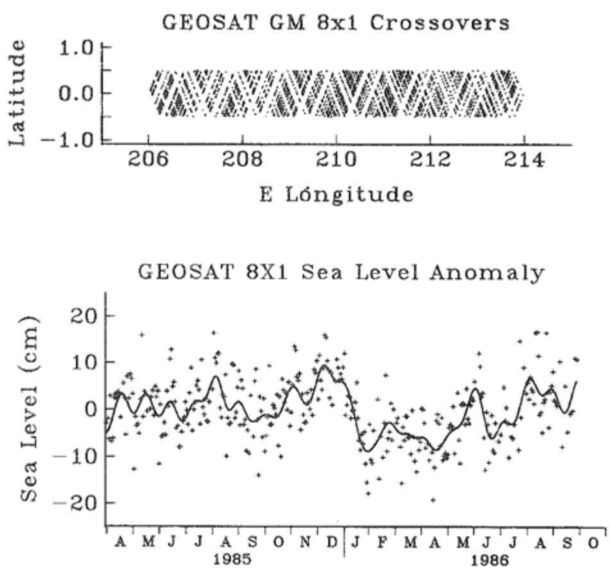

Figure 1. (upper) GEOSAT crossover difference locations during the 18-month Geodetic Mission for an arbitrary 8x1 degree polygon on the equator. Nearly daily sampling is obtained in these regions: 2 passes cross the box every 3 days. In this case, 326 passes create 2509 crossover differences. These are used to solve for a sea level as a function of time (lower). Average height along each pass segment is indicated by pluses. The smooth curve is computed using objective analysis where a 15-day decorrelation is assumed. Most of the sea level undulations shown here are responses of sea level to changing wind stress, either locally forced or propagating waves generated by wind anomalies in other parts of the Pacific ocean. For example, the upward pulse centered on June 1, 1986 is a downwelling Kelvin wave produced 5,000 km away in the western Pacific by a pair of tropical cyclones.

The Collinear Difference Method

Generation of sea level variability and time series from GEOSAT ERM data using the method of collinear differences is similar in concept to the crossover method., but is simpler in term of computations (Cheney *et al.* 1983). During the ERM, the satellite obtains profiles of sea height along a fixed, global grid at 17-day intervals. Along a given ground track, the geoid is always the same from one pass to the next. A sequence of GEOSAT profiles can therefore simply be subtracted

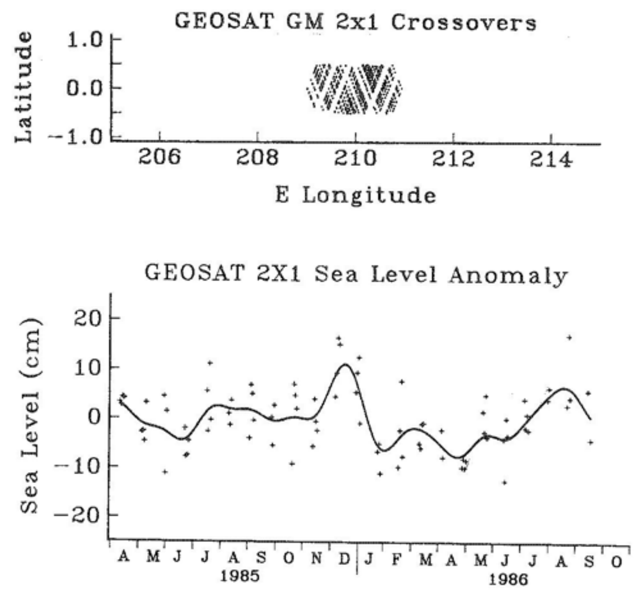

Figure 2. Same as Figure 1, but for a 2x1 degree polygon at the center of the 8x1 region. The smaller region improves the spatial resolution, but only at the expense of sampling in time. The 2x1 region is sampled approximately 3 times every 23 days. In this 18-month example 81 passes form 558 crossover locations. After computation of the sea level time series, individual observations are smoothed assuming a 30-decorrelation. Note the absence of the June 1, 1986 pulse in the smooth curve, although several of the individual passes show a peak at this time. For determination of low-frequency changes (1 month or longer), however, the 2x1 and 8x1 time series are nearly equivalent (1.8 cm rms agreement for monthly averages).

from the first pass to obtain a time series of sea level change along the ground track. (Orbit error, as always, must first be removed from each pass as a linear or quadratic trend over an arc length of several thousand kilometers. We use one pass along each ground track as a reference profile and adjust all others so that they agree with this pass in a least squares sense.) Altimeter profiles corrected for orbit error, tides, and environmental effects are then used to generate sea level time series on a regular grid over the ocean. For our analyses of the ERM data we have computed time series in cells having dimensions of 2 degrees longitude by 1 degree latitude. On average, each of these cells is sampled by GEOSAT 3 times every 17 days. A smooth time series is computed at each location using objective analysis, where 5-cm noise and 30-day decorrelation are assumed.

Combining Crossover and Collinear Time Series

To construct continuous, multi-year time series spanning both the geodetic mission and the ERM, we have taken the approach illustrated in figure 3. First, a 2.5-

year crossover difference time series is computed from April 1985 to November 1987. This record extends through the first year of the ERM. Note that in such a solution the ERM passes are analyzed strictly in terms of their crossover differences. Next a 2-year collinear difference time series is computed from November 1986 to October 1988 at the same location. The 1-year overlap between these two solutions (November 1986-87) is used to adjust the collinear solution relative to the crossover solution, resulting in a continuous record beginning in 1985. As more ERM data are collected, the time series is simply extended. The example in figure 3 is for a 2x1 degree cell in the central equatorial Pacific. The agreement between the two solutions in the 1-year overlap is almost perfect. Construction of long time series such as these over entire ocean basins is enabling us to look at large-scale, interannual changes in total water volume, something never before possible.

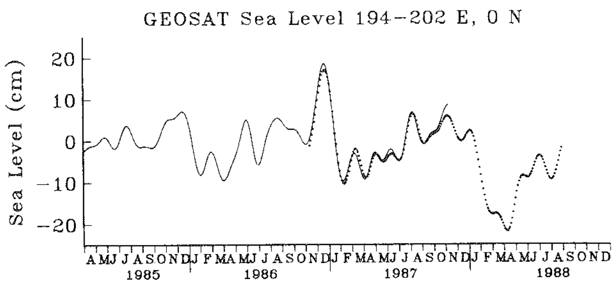

Figure 3. GEOSAT time series for an 8x1 degree region in the central equatorial Pacific. A continuous 3.5-year record has been constructed by combining crossover and collinear time series. The first 2.5-year record (solid line) is a crossover difference solution. The last 2 years is sea level determined from collinear differences (dotted line). The 1-year overlap has enabled the two separate records to be combined into a single time series dating back to 1985. The record can be extended into the future with additional altimeter data.

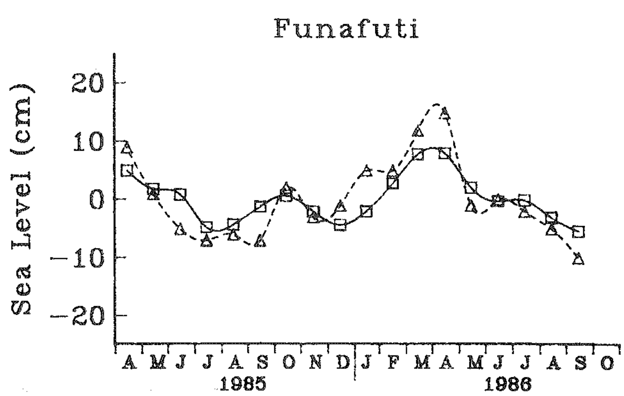

Figure 4. Comparison of GEOSAT sea level time series with island tide gauge data from Funafuti (8.5°S, 179.2°E). RMS difference is 3.8 cm with 0.87 correlation. Calculations are based on monthly means: squares/solid lines for the altimeter and triangles/dashed lines for the gauge. Tide gauge values were obtained from Wyrtki *et al.* 1988.

Accuracy of the Geosat Time Series

Sea level records computed this way from GEOSAT can be compared with *in situ* measurements to obtain a measure of their accuracy. Island tide gauges are one obvious source of surface data for such comparisons, as they are the only instruments capable of measuring sea level directly. Dynamic height computed from moored thermistor arrays are also valuable because they can provide surface truth in the open ocean where island data are not available. In a previous paper (Cheney *et al.* 1989) we compared GEOSAT geodetic mission time series with 14 tide gauge records and 2 moorings in the tropical Pacific. Average agreement of GEOSAT with the surface measurements was 3.7 cm rms with a correlation of 0.68. A typical tide gauge comparison is shown in figure 4 and a scatter plot based on all 16 sites in shown in figure 5. The scatter plot illustrates the very small sea height anomalies present in the tropical Pacific; two-thirds of the observations are less than 5 cm (relative to the mean for the 18-month period). From these comparisons we conclude that the GEOSAT time series are sufficiently accurate to enable study of tropical ocean phenomena.

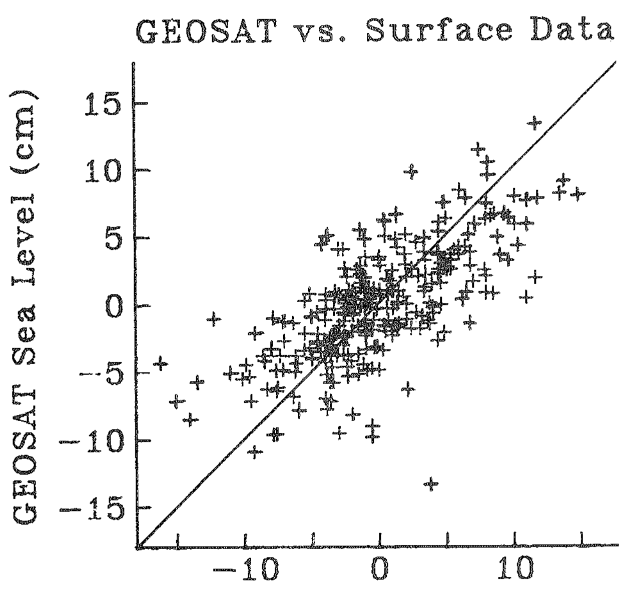

Figure 5. Scatter plot of all 282 monthly mean GEOSAT comparisons from 16 surface data sites presented by Cheney *et al.* (1989). The ensemble rms is 3.7 cm and correlation is 0.68. Solid line indicates perfect agreement. Two-thirds of the surface measurements have a dynamic range of 5 cm or less (relative to the 18-month mean sea level).

3. PACIFIC SEA LEVEL ANOMALY

The purpose of our work with the GEOSAT sea level data is to obtain improved descriptions of the tropical oceans, specifically the Pacific Ocean and the El Niño phenomenon. Sea level changes in the tropics are largely driven by changes in the large-scale wind field. An example of this relationship is shown in figure 6 where we have superimposed a GEOSAT sea level record from the central equatorial Pacific and a wind record showing the average zonal component at 850 mbar in the far western Pacific (5°S to 5° N, 120°E to 160°E. The sea level record has been lagged by 20 days (implying eastward propagation) to highlight the correlation between these two independent records. In general bursts of westerly (positive) winds correspond to increasing sea level while periods of pronounced easterly wind result in decreasing sea level. Miller *et al.* (1988) and Cheney and Miller (1988) showed that most of these sea level anomalies were equatorially-trapped Kelvin waves. They had sea level signatures of 10-15 cm, propagation speeds in mid-ocean of approximately 2.5 m/sec, and coherent zonal structure extending almost all the way across the Pacific Ocean. The period of most intense Kelvin wave activity is late 1986 and early 1987 during initiation of the El Niño which occurred at that time. This is consistent with the notion that short, intense, bursts of westerly winds in the western Pacific trigger the onset of El Niño through the generation of Kelvin waves.

We have generated sea level time series from GEOSAT data on a uniform 8x1 grid throughout the tropical Pacific. Sea level maps can be constructed by expressing each independent time series in terms of the anomaly with respect to the mean over a common period of time. We have chosen as our reference the 1-year period April 1985-86, the first year of the GEOSAT mission. Shown in figure 7 are three sea level anomaly maps at 6-month intervals beginning in May 1985. These maps display several features which are characteristic of the tropics. One is the distinct, zonally-banded structure, often extending across the entire Pacific. There is a strong tendency for these bands to be symmetrical about the equator. The maps also show a clear annual signal. In May 1985 sea level reaches a minimum in the region within 10 degrees of the equator while positive sea level anomaly dominates the off-equatorial bands between 10-20 degrees latitude in both hemispheres. In November 1985 we again see the zonally-banded, symmetrical structure, but with the opposite sign compared to 6 months earlier. By the following May the annual cycle has been completed with structure generally similar to May 1985. These patterns reflect the Ekman-layer response to changes in the trade winds, which parallel the zonal sea level anomaly bands. Positive sea level anomalies in general indicate regions of surface convergence while negative bands are associated with divergence.

We have compared our GEOSAT maps with those derived by A. Leetmaa and M. Ji (personal communication) using the ocean general circulation model of Philander and Seigel (1985). The model is forced with the observed monthly average surface wind stress and also includes any available XBT and surface thermal information. Dynamic height was computed relative to the bottom, and anomalies were expressed with respect

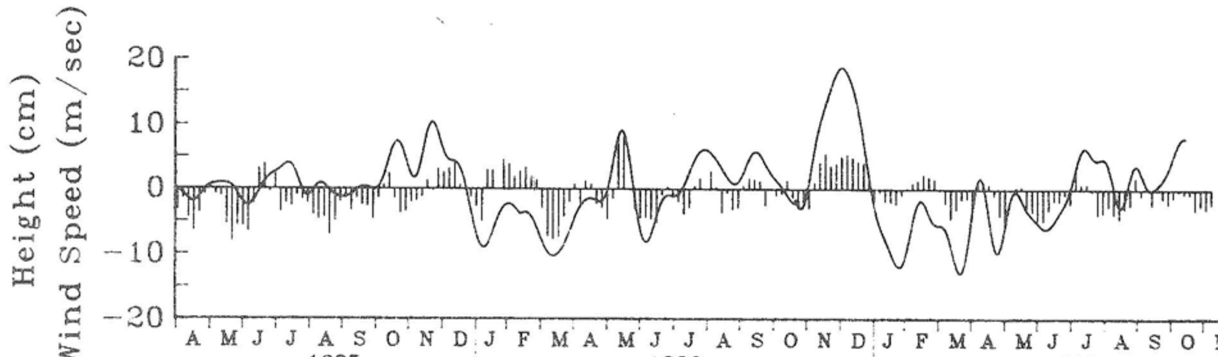

Figure 6. GEOSAT sea level time series in the central equatorial Pacific compared to wind in the western Pacific. Sea level was computed from crossover differences in an 8x1 region centered at 198°E, 0°N. Zonal wind record is at 850 mbar averaged between 5°S - 5°N, 120°E - 160°E. The sea level record has been lagged by 20 days. The good correlation indicates that many of the sea level features are eastward-propagating Kelvin waves as discussed by Miller *et al.* (1988) and Cheney and Miller (1988). Sustained westerlies in November-December 1986 resulted in large-scale redistribution of water and marked the onset of the 1986-87 El Niño.

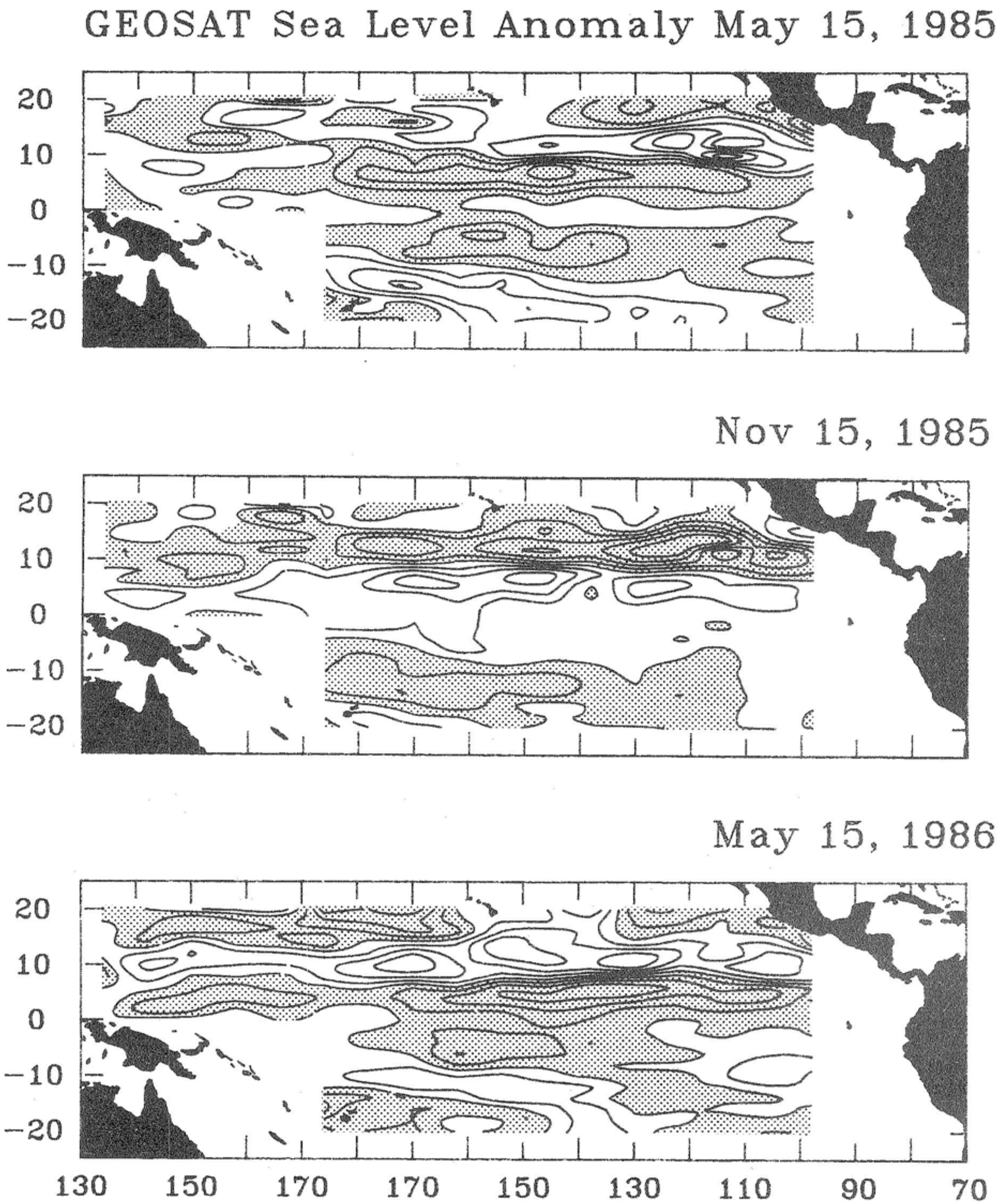

Figure 7. Sea level anomaly based on GEOSAT altimetry. Three maps are shown at 6-month intervals to illustrate the dominant annual signal seen by the altimeter; May and November represent the peak signal along the equator. Maps are constructed from independent time series, each determined using all altimeter data in an 8x1 degree area. Anomalies represent departures from a 1-year mean, April 1985-86. Contours are at 4-cm intervals with negative shaded.

to the same annual mean used in the GEOSAT maps. In addition, the model output was subsampled on the same grid used in the GEOSAT map to facilitate comparison. Statistically, the model/altimeter comparisons were found to be equivalent to the tide gauge/altimeter results; for the 1-year period, April 1985 to March 1986, the rms difference was approximately 4 cm (Cheney *et al.* 1989). More importantly, the model and altimeter maps revealed the same basic large-scale, zonally-banded structure providing confidence in both analyses.

It is interesting to look at maps constructed prepared using the higher-resolution 2x1 degree GEOSAT times series. Figure 8 is such a map for the same May 1985 time period shown in figure 7. The same large-scale trends are common to both, but the high-resolution maps contain more mesoscale features, especially at the higher latitudes. It is difficult to know how much of the high-resolution information is real and how much is noise, but one test is to look for the expected westward propagation at mid-latitudes. Figure 9 shows a sequence of maps at 1-month intervals for a 10-degree area southwest of Hawaii. The scale of the maps has been enlarged and the contour interval reduced to 1-cm to show more detail. The distinct 8-cm low located at 16° N in May gradually drifts westward during the following 3 months and is replaced by an 11-cm high in August. Westward propagation is also suggested along 13° N where the double-peaked high is replaced by a negative anomaly moving in from the east. Further south near 10° N westward propagation is less evident. The eddy-resolving maps therefore appear to be realistic, although much more analysis obviously remains to be done.

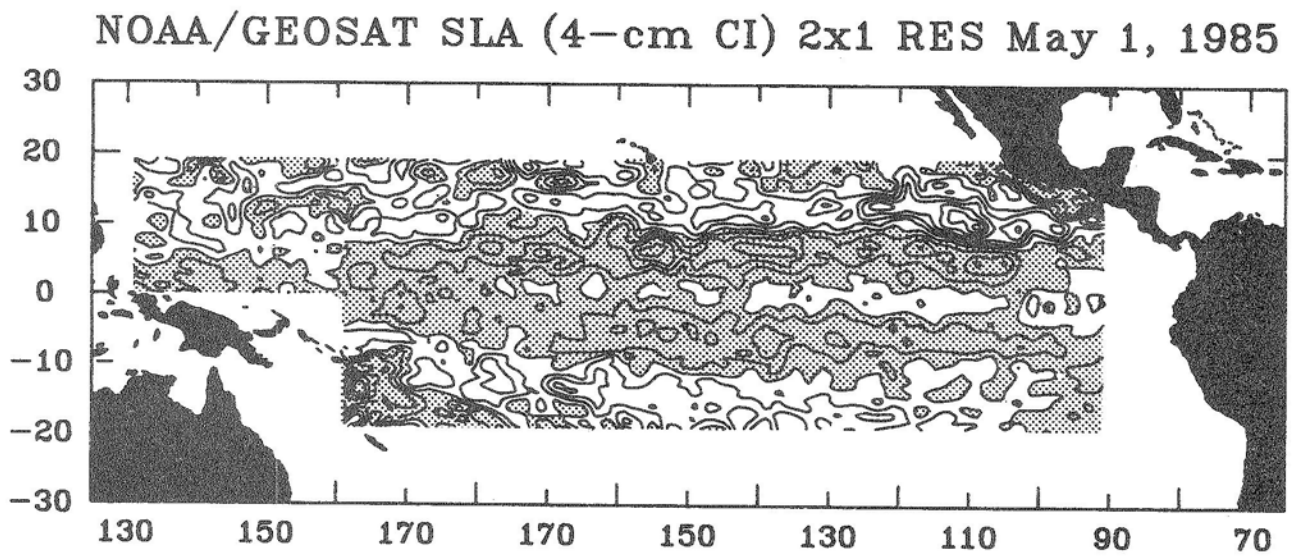

Figure 8. Same as Figure 7 (top), but constructed from higher-resolution, 2x1 degree GEOSAT time series. Large-scale patterns are the same as in the 8x1 map, but mesoscale features are now resolved.

4. INDIAN OCEAN SEA LEVEL ANOMALY

Recently we have begun processing the GEOSAT data in the tropical Indian Ocean using the same combination of crossover and collinear processing applied to the Pacific. Shown in figure 10 is the sea level anomaly for September 1988. In this case we have referenced the time series to the 1-year mean August 1987-88. The map shown here is based on 2x1 degree cells, but we have smoothed the sea heights in space using a Gaussian filter with half-widths of 5 degrees in the zonal direction and 2.5 degrees in the meridional. Contoured values range from -12 to +16 cm. The most pronounced feature is the tongue of positive anomaly extending WNW from Australia to 80 E. This is an area of strong annual sea level signal as shown by the 3.5-year GEOSAT time series in figure 11. Peak-to-peak variations are 40 cm with minimum in May-July and maxi-

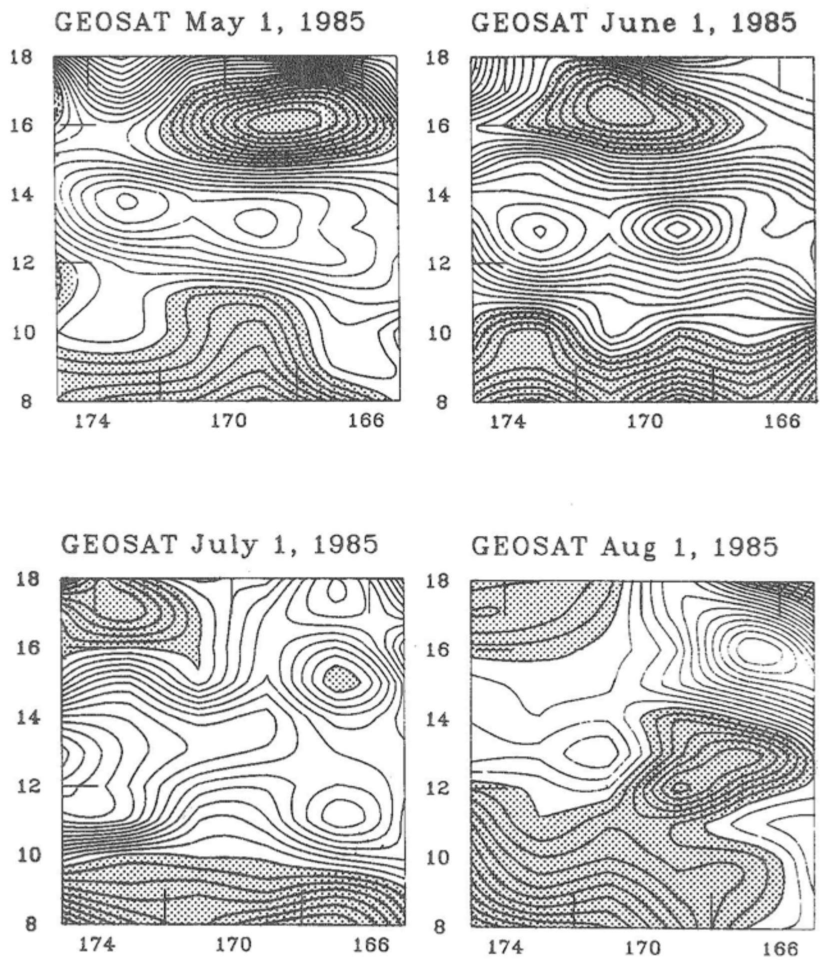

Figure 9. Enlargement of a 10-degree square area from Figure 8. Contour interval is 1 cm. This sequence of monthly maps shows feature propagating westward along 16°N and 13°N.

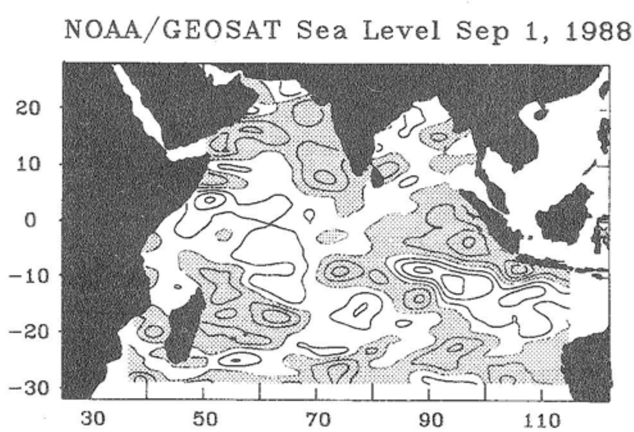

Figure 10. Sea level anomaly based on GEOSAT altimetry using the method of collinear differences. The map is constructed from time series in 2x1 degree areas, but additional smoothing was performed spatially. Anomalies represent departures from a 1-year mean, August

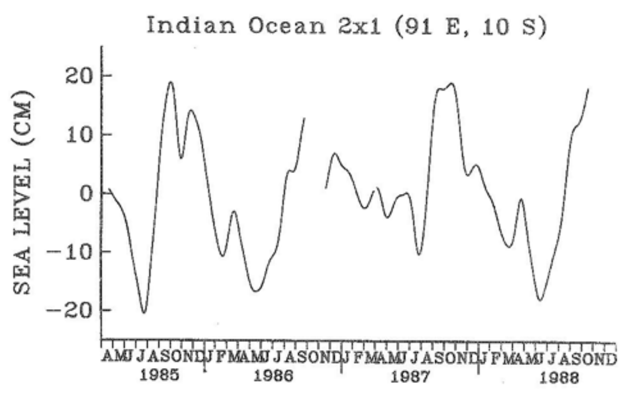

Figure 11. GEOSAT sea level time series in the Indian Ocean at 90°E, 10°S. This 3.5-year record is for a 2x1 degree cell. It shows a strong, 40-cm annual signal.

mum around September-November. In general, spatial patterns in the Southern Hemisphere parallel the trade winds. Off the Somali coast the small positive gyre with 16 cm amplitude may be the sea level signal of the Great Whirl, although the smoothing employed in this map is not optimum for detection of small-scale features such as this. In order to study narrow currents such as the Somali jet, collinear differences should be constructed along individual ground tracks to obtain maximum resolution in space.

5. CONCLUSIONS

The application of altimeter data to tropical ocean dynamics is one of the most challenging problems in satellite oceanography because of the small amplitude and large spatial scale of the sea level signatures. However, we have shown that accurate (better than 4 cm rms), altimetric determination of sea level change as a function of time is possible with appropriate processing. For example, comparison of GEOSAT time series with 18-month records from 16 island tide gauges and moorings in the tropical Pacific yielded 3.7 rms agreement. In addition, comparisons of our Pacific sea level anomaly maps with a wind-driven ocean circulation model have also yielded similarly good agreement. Such models represent the only means of obtaining spatial resolution comparable to that of the altimeter over entire ocean basins. In addition to providing confidence in each of the two products, it suggests that incorporation of altimeter data in wind-driven models of the tropical oceans will yield a powerful research tool that should lead to improved understanding of the combined ocean/atmosphere system.

GEOSAT marks the beginning of a series of satellite altimeter missions that should yield a decade or more of continuous global coverage. Such records are essential in order to obtain more complete descriptions of climate phenomena such as El Niño. The GEOSAT mission has also enabled the first near-real time monitoring of sea level over entire ocean basins. When it became evident in early 1987 that an El Niño was underway, we began processing and analyzing the GEOSAT data within 2 weeks of acquisition from the satellite. We were therefore able to observe the El Niño as it evolved during 1987. This monitoring effort continues today and has become an operational product, with GEOSAT maps published monthly by NOAA in the Climate Diagnostics Bulletin (Kousky 1988). In September 1988 we initiated a similar sea level product for the Indian Ocean. In the next decade, with the possibility of several altimeter satellites operating simultaneously, global sea level may be monitored in near-real time as routinely as the weather is today.

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We thank Russell Agreen, who developed many of the programs employed in these analyses, and Nancy Doyle, who assisted in GEOSAT data processing. We gratefully acknowledge cooperation of the U.S. Navy and the Johns Hopkins University Applied Physics Laboratory, who together conceived and carried out the GEOSAT altimeter mission. In particular, we thank GEOSAT Project Managers Cdr. Frank Wooldridge (U.S. Navy) and Dr. Charles Kilgus (JHU/APL).

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Towards a Joint Global Ocean Flux Study: Rationale and Objectives

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ABSTRACT

Past and present variations of the global carbon cycle are dominated by the oceans. At present the oceans act as moderator for the atmospheric CO_2 increase from combustion of fossil fuels. Current understanding of ocean-atmosphere exchange and fluxes into the ocean interior is, however, modest, and considerably more insight is required into how the ocean controls the global carbon cycle. The global scale of the problem and the complex interactions between physical, biological, and chemical forces warrant both an international and a truly multidisciplinary approach which is to be taken in the ICSU/SCOR Joint Global Ocean Flux Study, JGOFS. The objective of that study is:'To determine and understand on a global scale the time varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, the sea floor and continental boundaries'. Special attention will be paid to the important role that marine biota play in the carbon cycle as well as to interactions with many (trace) elements. For proper global quantification of the cycle large scale observation of the ocean surface from satellite is the only available tool. Implementation of JGOFS is now well underway with the 1989-1990 North Atlantic Pilot Study where ships from six countries participate in a study of temporal and spatial shifts of carbon fluxes related to spring and autumn plankton blooms. For the 1989-1999 period, the merits of selected study areas in the (i) Pacific basin, (ii) Southern Ocean, (iii) northwest Indian Ocean, and (iv) North Atlantic Ocean are being explored.

1. INTRODUCTION

International discussions during the last several years have led to the decision to develop a long-term international research effort to study marine biogeochemical fluxes. The program has been named the Joint Global Ocean Flux Study, JGOFS. In the discussion that follows, the rationale and objectives of JGOFS are set forth.

The Global Ocean

The ocean covers most of the surface of the globe. Its metabolism, i.e. the internal cycling and boundary exchanges of chemical constituents of the ocean, has a major impact on the atmosphere and the terrestrial biosphere. One example is the cycle of carbon, the prime building block of all biomass (Fig. 1). The seawater reservoir contains about 40,000 x 10^{15} grams or 40,000 gigaton carbon (largely as the bicarbonate ion: HCO_3^-),

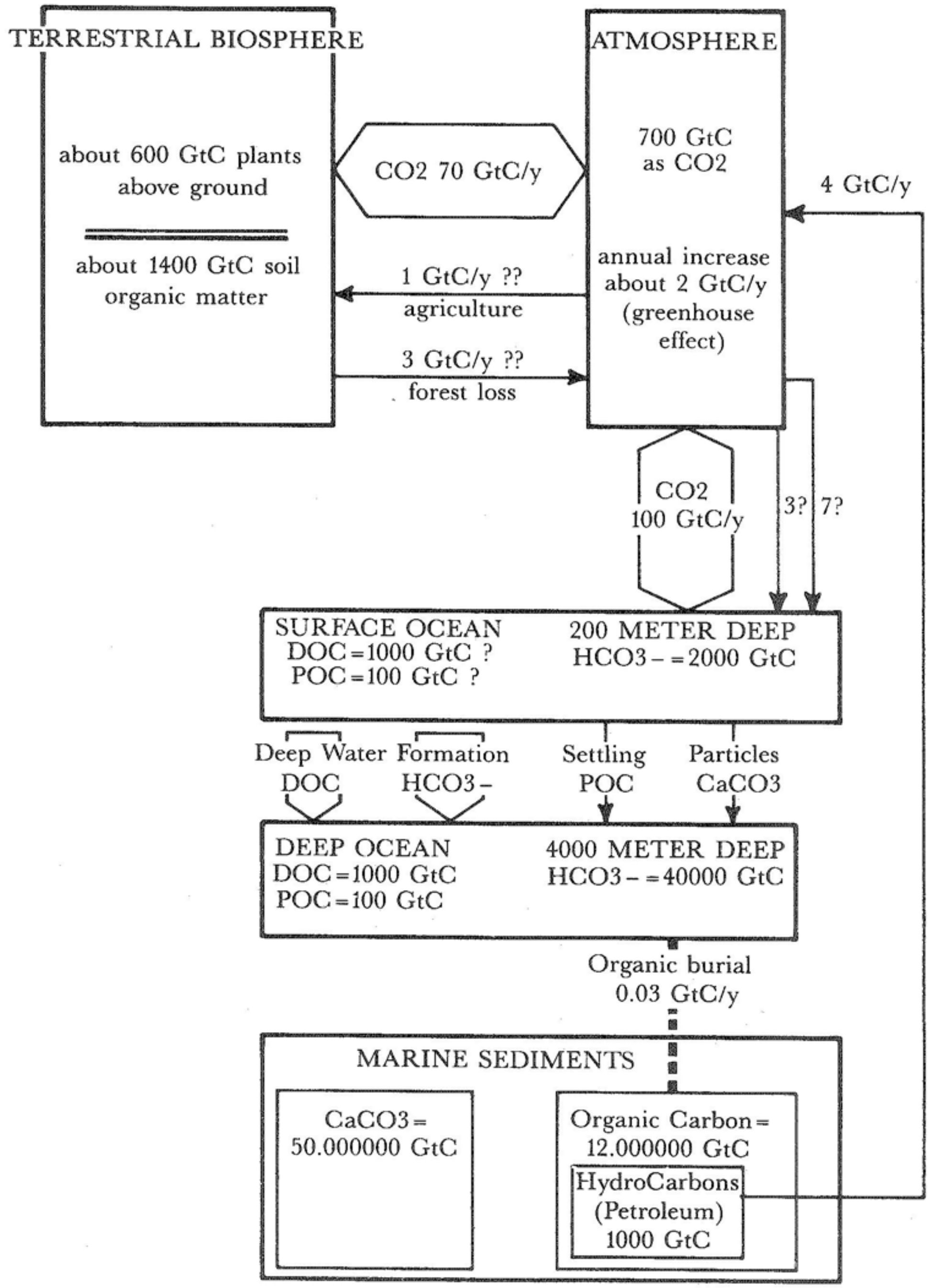

Figure 1. The global Carbon budget, after Moore and Bolin 1986, and others. Inventories [1 Gigaton = 10^{15} grm C] and Fluxes [GtC/year] are large relative to atmospheric CO_2 content and its annual increase. Large arrows for natural fluxes, small arrow fluxes arise from human activity.

and its annual exchange rate with the atmosphere is on the order of 100 GtC per year. The atmospheric reservoir itself contains only about 700 GtC as carbon dioxide (CO_2) and exchanges at a rate of about 70 GtC/yr with the terrestrial biosphere. The latter contains about 2000 GtC, of which some 70 percent, say 1400 GtC, is in the soil (humus) with the remaining 600 GtC above ground as plants.

Throughout geological time there have been variations in the geosphere/biosphere system, including shifts in the above inventories and fluxes of the C-system. For example, records over the past 160,000 years derived from Antarctic ice cores (Fig. 2) show atmospheric CO_2 variations between about 120×10^{-6} atm and 270×10^{-6} atm, the latter correlating with variations in surface temperature (Barnola *et al.* 1987). The apparent cause/effect relationship of this glacial / interglacial CO_2 shift (Neftel *et al.* 1988) is the subject of considerable debate (Knox and McElroy 1984, Broecker 1982, 1987, Sarmiento and Toggweiler 1984, Mix and Fairbanks 1985, Boyle 1986, 1988). Yet there is no doubt that the

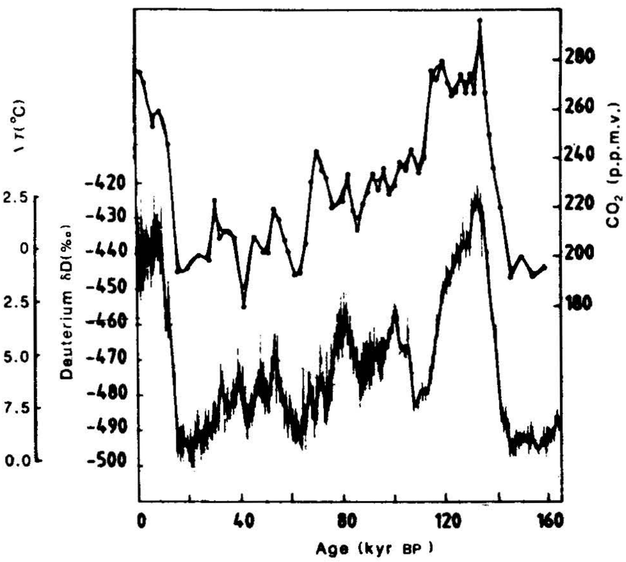

Figure 2. CO_2 concentrations ("best estimates") and smoothed values (spline function) in parts per million (volumetrically) plotted againts age in the Vostok record (upper curve). The deuterium scale corresponds to values after correction for deuterium changes of ocean water. Taken from Barnola *et al.* 1987.

oceans, through variations in circulation, biological productivity, nutrient regime, etc., play a crucial role (Sundquist and Broecker 1985, Moore and Bolin 1986, Bolin *et al.* 1986, Broecker and Peng 1987; Sarnthein *et al.* 1988, Berger *et al.*, 1989).

CO_2 and Global Warming

During the past century mankind has begun to influence the geochemical system on a global scale. With respect to the C cycle there is the well documented emission of CO_2, exponentially increasing in time until about 1973, to an annual rate which is currently more or less stable at about 5-6 GtC/yr (Fig. 1). Time series observations (Keeling *et al.* 1976a,b) have shown an increase in atmospheric CO_2 levels from about 270×10^{-6} atm in the nineteenth century through about 315×10^{-6}atm in 1958 to about 350×10^{-6} atm in 1988 (Fig. 3). This level is still increasing, and is already much higher than ever before in the past 160,000 years (Fig. 2). Mankind has truly ventured into its 'greatest' experiment ever (Revelle as cited by Bryan 1986). The growing envelope of atmospheric CO_2 may, through enhanced heat absorption, lead to a global warming trend, the so-called 'greenhouse effect', possibly accompanied by melting of ice caps and a general sea level rise (Tyndall 1863, Callendar 1938; National Academy of Sciences 1983; Schlesinger, Gates and Han 1985, Trabalka and Reichle 1986, Ferguson 1988). The likelihood of such CO_2 induced global warming is high (also judging from aforementioned ice core records), but accurate prediction of the timing and magnitude of this event is not yet possible. Keen observers have reported an increase in global surface air temperature of about 0.5 °C over the past century (Jones *et al.* 1988). Yet the underlying database as well as the statistical (long vs. short term, signal vs. noise) significance is debatable (Hare 1988). More importantly the suggested trend may also be ascribed to the fact that the deep ocean (with a response time of centuries) and atmosphere are probably still adjusting (Bryan 1986) from the 'Little Ice Age' (Grove 1988). That event was most severe in the early 17th century (Fig. 4), a period also known for the unusually high number of 'ice-scapes' with skating figures, created by Flemish and Dutch masters (Fig. 5).

Comparison of emission rates derived from fossil fuel (coal, oil, gas) statistics (National Academy of Sciences 1983) with the observed CO_2 increase has showed that only about half (estimates vary between 25-60 percent) of the fossil fuel derived CO_2 is retained in the atmosphere. The other half (range 40-75 percent) is presumably taken up by the oceans. The uncertainty derives from the fact that net CO_2 emissions due to changes in terrestrial biomass (deforestation, agriculture) are very difficult to assess. Estimates vary between extremes of -1 and +4 GtC/yr, corresponding to a small increase or larger decrease of terrestrial biomass respectively. Nevertheless it is obvious that the oceans serve as major sink for atmospheric CO_2. Through dissolution of CO_2 in the upper mixed layer (about 75m depth) of the ocean as well as biological C-fixation (photosynthesis) the surface ocean can take up about 2-3 GtC/yr, with an upper extreme estimate of 7 GtC/yr (Fig. 1). Biological activity may well be the most crucial factor controlling the actual rate of CO_2 uptake. The net amount is only a fraction of the gross annual atmosphere/upper ocean exchange of 100 GtC/yr. The physico-chemical uptake of CO_2 in surface waters is further predicted to actually decrease with increasing CO_2 levels (Revelle factor, see Takahashi *et al* 1980). The actual effectiveness of the net ocean sink is other-

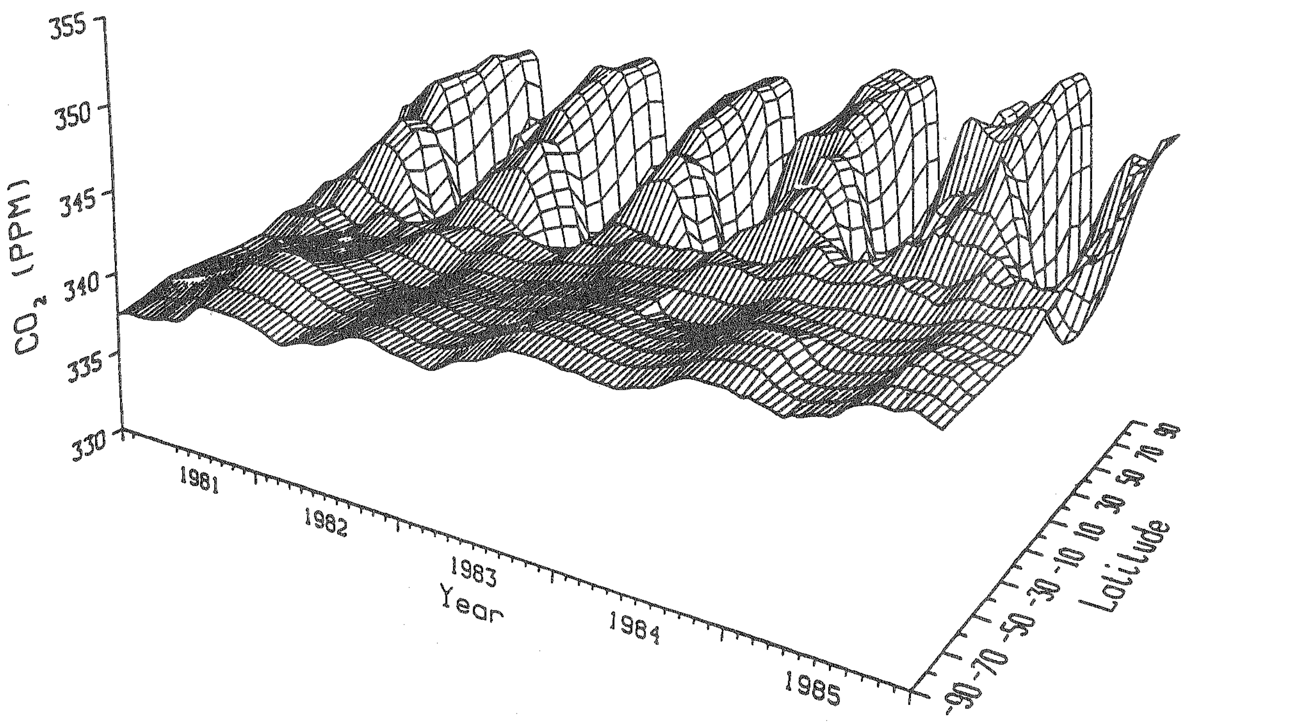

Figure 3. The increasing level of atmospheric CO_2 as a function of latitude over the 1980-1986 period. The pronounced seasonal oscillation in the Northern Hemisphere reflects the growth season of terrestrial plants, the latter being more abundant due to the predominance of landmasses in the Northern Hemisphere.

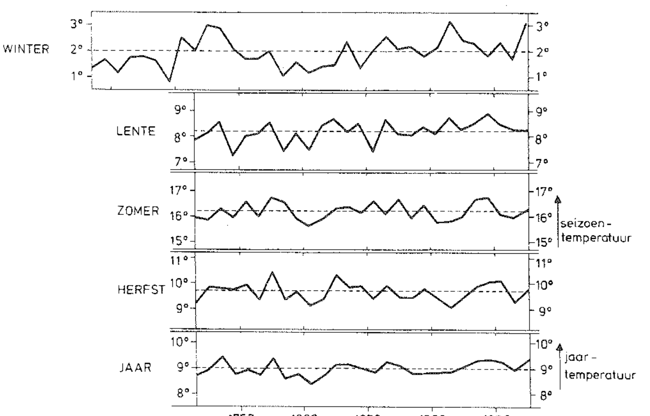

Figure 4. Trends in seasonal and annual mean temperature as measured from 1735 onwards, data from the Royal Netherlands Meteorological Institute (KNMI). Values shown represent means over ten year time intervals. The accuracy is 0.5° C. The winter series is extended by inclusion of (indirect) data on frozen conditions of canals used by tow barges, taken from diaries of inland shipping companies. Calibration of the latter versus the first record over the 1735-1839 period yields an accuracy of 0.7° C for the canal record. The overall winter and spring records suggest a weak warming trend, not observed in the annual mean.

wise not well known anyway and also varies from year to year. For example, significant changes in atmospheric CO_2 were noted during El Niño - Southern Oscillation events in the South Pacific Ocean (Bacastow 1976, 1977, Keeling and Revelle 1985). The exchange of CO_2 between atmosphere and ocean is clearly not in steady state but subject to dynamic variability throughout the frequency domain, further enhanced by the recent changes generated by industrial CO_2 emissions and dramatic clearing of tropical forests.

The excess CO_2, say 2-3 GtC/yr, taken up in the surface ocean is eventually carried downward both by water circulation (sinking of CO_2-saturated water at the poles) and biogeochemical processes. We are now however not able to quantify whether the physical and chemical processes alone (ocean heating, cooling, mixing, CO_2 dissolution) or the biological processes (photosynthesis and respiration) dominate the contemporary oceanic sink, both with respect to capacity as well as actual uptake rate of CO_2 (Brewer 1986). Clearly a better understanding and quantification of latter processes is crucial for modeling the atmospheric CO_2 content and ensuing 'greenhouse' effect. Scenarios for the latter

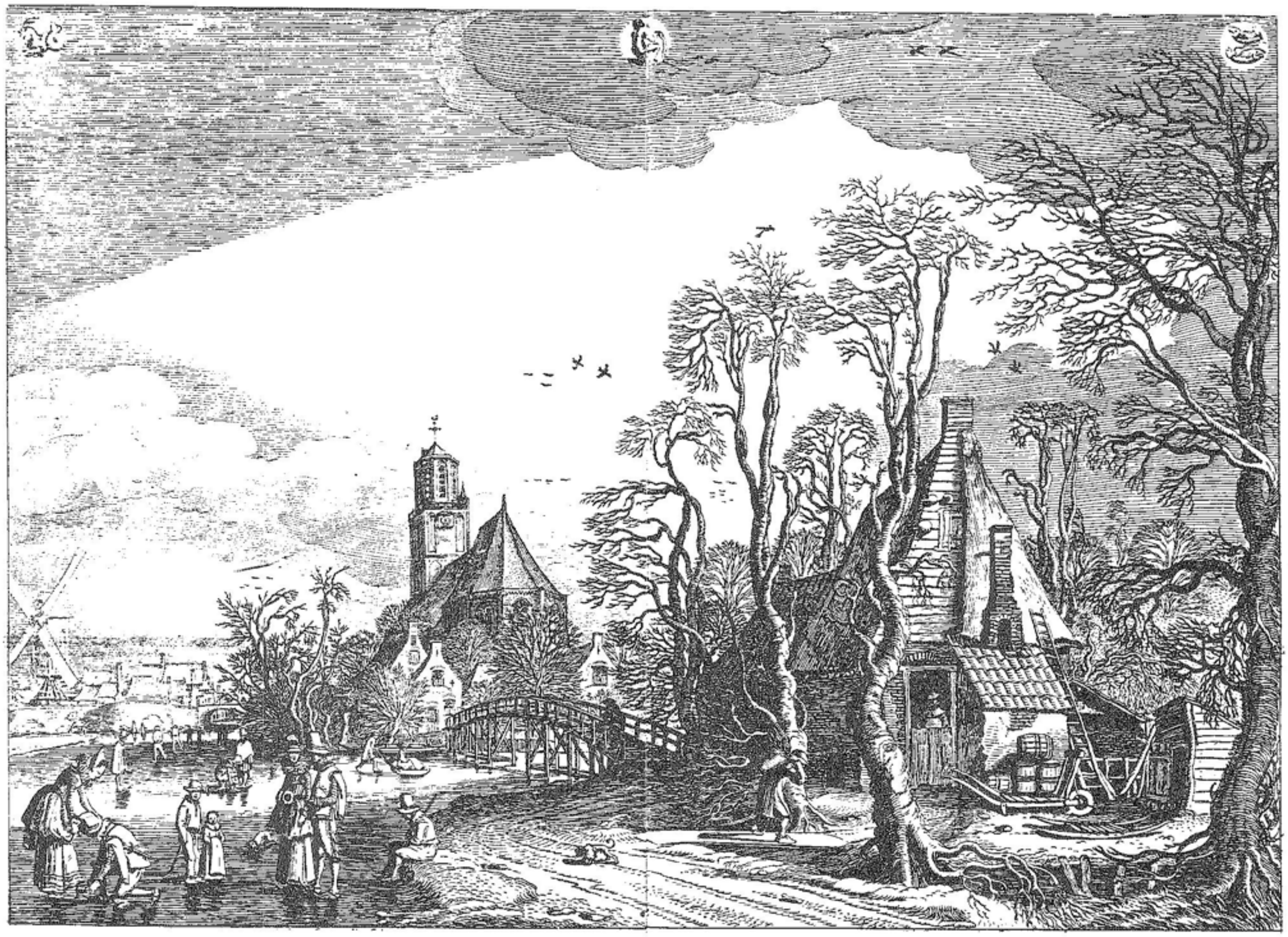

Figure 5. One of the many 'ice-scapes' produced in the seventeenth century, at the peak of the Little Ice Age. For the purpose of reproduction we selected an etch rather than one of the many color paintings. "HYEMS" or Winter, one of a series representing the four seasons by Jan van de Velde, approx. 1617. The Latin text translates: 'The cold does not slow one down and deserves no resentment. Ovidius, you were wrong: look at our young lads; See how they step on frozen rivers, with skate-irons under their feet, and in long rows they swing through the pastures'. Taken from De Groot (1979). Todays skaters within The Netherlands definitely resent the prospect of global warming.

(Hansen *et al.* 1984, Washington and Meehl 1984, Wetherald and Manabe 1986, 1988, Schlesinger 1986, Wilson and Mitchell 1987, Schlesinger and Mitchell 1987, Schlesinger and Zhao 1988) are in great need of proper oceanographic constraints (Schlesinger 1988) before they can serve as reliable tools for policy decisions on such matters as deforestation, curtailing CO_2 emissions and anticipation of a possible sea level rise (Ferguson 1988).

Other 'Greenhouse' Gases

Mankind also introduces other 'greenhouse' gases into the atmosphere, notably ammonia (NH_3), nitrous oxide (N_2O), ozone (O_3), methane (CH_4) and chlorofluorocarbons (CFC's or freons). Their combined effect on the global temperature is not well understood, but may well be comparable to the CO_2 effect alone. For methane, another component in the C cycle, recent work has shown an appreciable annual increase of the atmospheric CH4 burden (Fraser *et al.* 1981; Rasmussen and Khalil 1981a,b, 1984) in both hemispheres. This is consistent with an increasing trend, dating as far back as about 1580 A.D. as observed in ice cores (Craig and Chou 1982). In some respects the methane story is similar to that of CO_2, and in the various greenhouse scenarios possibly 30 % of the predicted warming rate may be ascribed to the methane increase alone (Senum and Gaffney 1985).

All these gases, except the CFCs (chlorofluorocarbons, or freons), have always existed in natural cycles, and complicated feedback mechanisms are conceivable or known to exist. For example, anthropogenic atmospheric emissions (NH_3; NO_x) as well as agricultural inputs of fertilizers (containing nitrogen and phosphorus) into rivers may yield higher rates for biological C-fixation in the upper ocean. In other words, eutrophication may enhance the removal of CO_2 from the atmosphere. For CFCs (Rasmussen and Khalil 1986, Wigley 1988) we know that they are also taken up by the oceans (and in fact employed as water mass tracers by oceanographers; Bullister and Weiss 1983, Weiss *et al.* 1985, Wallace and Lazier 1988), i.e. the ocean may again act as a moderator with respect to both global warming and the interaction between freons and ozone.

Strictly natural components cannot be overlooked (Andreae 1986). Biological activity in the upper ocean yields dimethylsulfide (DMS) which is partially emitted into the atmosphere. Atmospheric oxidation leads to sulfate aerosols which serve as nuclei for cloud formation, thus influencing climate both through albedo (reflection of incoming sunlight) and heat insulation. Other natural gaseous compounds like carbonylsulfide and various methylhalides are also released from the ocean into the atmosphere, where they affect the heat budget and the ozone layer.

Notwithstanding their importance in the JGOFS study we will in this paper refrain from further discussion of these 'other' greenhouse gases, limiting ourselves instead to a case-study of just CO_2. For this purpose we will focus on the relation of the oceanic C cycle to CO_2 and highlight some current issues of relevance to the marine carbon system.

2. CARBON POOLS AND PATHWAYS IN THE OCEANS

Throughout most of the world ocean there exist both a seasonal and a permanent thermocline at depth intervals typically near 50-150m and 200-800m respectively, which are characterized by strong temperature gradients. The corresponding density gradients largely prevent vertical mixing of water and its dissolved constituents between the surface ocean and the deep ocean interior.

Only in the surface mixed layer, the upper 25-250m driven by wind mixing, are gases like CO_2 exchanged with the atmosphere. The direction of CO_2 gas exchange is dictated by relatively straightforward equilibrium considerations (under- or over-saturation); the actual rate of exchange is determined by interaction of complex processes and concepts such as wind induced mixing, bubble injection, and surface film thickness (O'Brien *et al.* 1986).

The same surface layer also approximates the euphotic zone, the depth interval (down to about 1 % light penetration) where photosynthetic C-fixation (primary production) by algae is responsible for the massive conversion of dissolved inorganic bicarbonate into plant organic matter. This leads to lower values of DIC (Dissolved Inorganic Carbon) in the surface ocean (Fig. 6), so that further physicochemical dissolution of atmospheric CO_2 is possible. Much (typically 80-95 %) of this Gross Primary Production (GPP) is converted through grazing by zooplankton, microbial degradation and other processes within the complex food web of the upper ocean. The net results are the build-up of a pool of Dissolved Organic Carbon (DOC) and replenishment of the Dissolved Inorganic Carbon pool through complete recycling (mineralization, respiration) (Fig. 7).

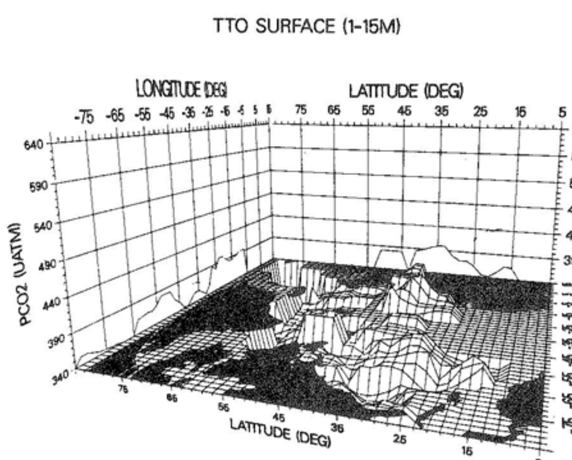

Figure 6. The partial pressure of CO_2 in surface seawater (1-15m) of the North Atlantic Ocean as measured during the TTO expeditions. A correction term for the surface excess of O_2 has been applied. This map does not represent synoptic sampling but a clear trend of over- (under-) saturation in equatorial (subpolar) waters is suggested. Taken from Brewer (1986).

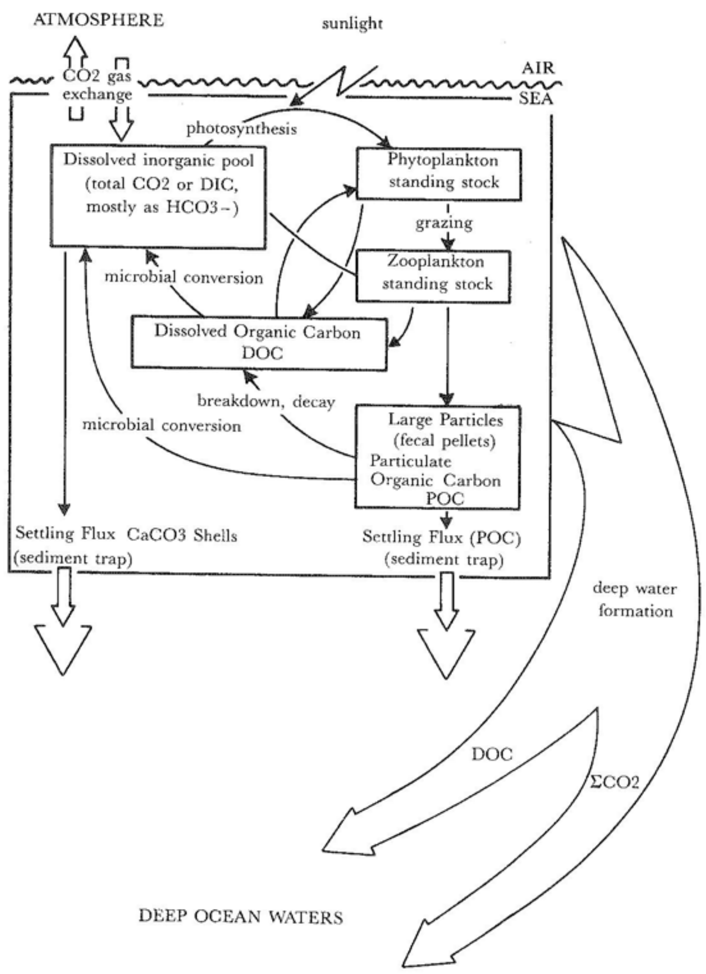

Figure 7. Simplified scheme of compartments and fluxes for C in the upper ocean. The large arrows depict the four pathways for 'pumping' carbon into the ocean interior.

However, plant and animal material or Particulate Organic Carbon (POC as well as DOC), also escapes mineralization and is exported to deeper waters. This 'New Production' term (Dugdale and Goering 1967, Eppley and Peterson 1979, Eppley 1989) represents the biologically mediated net flow of C from the atmosphere into the deep ocean. New production is typically one order of magnitude less than the Gross Primary Productivity. The larger size fractions in the particle spectrum settle down out of the euphotic zone into the deep ocean. This vertical flux of organic particles is one major pathway for transfer of atmospheric C into the deep ocean; the so-called 'biological pump' for removal of atmospheric CO_2. Concurrently, biologically essential elements (N, P, Si) are also being removed to such extent that very little remains available for plant growth. At 'near-zero' levels of nitrate, ammonia, phosphate or silicate, the surface ocean productivity is typically limited by N availability. Only through replenishment of N by physical mixing from deeper waters (or possibly from atmospheric input) can the new production flux be sustained.

Another pathway is the sinking of surface water by means of intense winter cooling. The latter process occurs seasonally in the northern North Atlantic (Norwegian and Greenland Seas, Labrador Sea) and the Weddell Sea off Antarctica. Through its tendency to equilibration with the atmosphere, the very cold water acts as a sink for inorganic CO_2; moreover it also carries down DOC.

Sluggish circulation within the dark abyss slowly fills the deep basins of the oceans; the mean 'age' of the deep water is about 500-1500 years (Stuiver *et al.* 1982, Broecker and Peng 1982). During this time period, most of the DOC is converted to DIC and also the settling large particles are remineralized to DIC (while settling but also at the seafloor). From the vertical and interoceanic distribution of various dissolved tracers (nitrate, phosphate, CO_2, ^{13}C, etc.) in the world ocean, we know that the net flux of organic matter originating from the surface ocean is remineralized within the deep sea and at the seafloor. We are not certain whether this organic matter is brought into the deep sea largely as particles settling from the euphotic zone, or mostly as DOC carried along with the general water circulation.

The water balance of the surface ocean is restored by a mean upward advective flow or upwelling in the order of 4 m per year. In certain regions, e.g. in the equatorial Atlantic, more intense upwelling is evidenced by excess CO_2 content of the water as compared with the atmosphere (Broecker and Peng, 1982, see also figure 5). Some of this excess is fixed by photosynthesis, and some escapes into the atmosphere, as was concluded from $^{13}C/^{12}C$ analyses of atmospheric CO_2 (Keeling *et al.* 1984). The short mixing time of the atmosphere makes each hemisphere fairly homogeneous with respect to CO_2; the ocean 'breathes' CO_2 by inhaling at the poles and exhaling at the equator. This ocean/atmosphere CO_2 exchange is massive (about 100 GtC/a) compared with the modern fossil fuel CO_2 additions (about 4 GtC/a) (Fig. 1).

3. BIOLOGICAL PRODUCTION

Within the context of a global study of the marine carbon cycle the marine ecosystem receives much attention (e.g. U.S.GOFS Report 7 1988, NERC 1987, Netherlands SSG 1988, Mills *et al.* 1987). In this paper we ignore the important intricacies of the marine foodweb, limiting ourselves instead to a simplified black box approach.

The biological fixation of C within the euphotic zone is regulated by physical forcing: light regime, temperature as well as the physical mixing (e.g. tides, wind, internal waves) required to replenish the limited supply of essential (typically N) nutrients (Dickey and Siegel 1988, Glover and Brewer 1988). In different areas of the world ocean (e.g. the euphotic zone of the North Atlantic, the North Pacific and the Antarctic Circumpolar waters) very different ecosystems exist with their own dynamics (diel to seasonal to interannual variability). The ensuing export or New Production term varies accordingly, as does the 'efficiency' or

f-ratio = New Production/Gross Primary Production

In other words, the fluctuating or outright episodic nature of the physical forcing and biological response yield considerable patchiness of the overall marine ecosystem. This patchiness largely prevents adequate *in situ* sampling on a global scale. However, biochemical tracers (e.g. nutrients, dissolved O_2) in the deep ocean provide a 'time-and-space' averaged record of the deep mineralization driven by new production imported from above. By combining Apparent Oxygen Utilization (AOU) derived from dissolved O_2 distributions with time scales derived from transient tracers ^3H and ^3He, Jenkins and co-workers arrived at estimates of New Production about an order of magnitude higher than assessed by other methods, roughly equalling rates commonly reported for Gross Primary Production (Jenkins 1982, Jenkins and Goldman 1985; Jenkins 1988). Reconciliation between this and various other approaches is of course being sought (e.g. Platt and Harrison 1985, 1986, Key 1987). If nothing else, these contradictory results have led us to a fresh look at the concepts of Gross Primary and New Production and the methods to measure these entities. Between the tracer approach and other methods (for GPP and NP) there is definitely a difference with respect to sampling of the ocean. Possible artefacts of the incubation methods have been described by Steeman-Nielsen 1952, Venrick *et al.* 1977, Gieskes *et al.* 1979, Fitzwater *et al.* 1982, Alldredge and Cox 1982, Ward 1984. In the PRPOOS experiment various incubation methods, including the novel $H_2{}^{18}O$ method (Bender and Grande 1987), were in good agreement, provided that state-of-the-art techniques (e.g. ultraclean to avoid trace metal interferences) are employed (Grande *et al.* 1989). Further intercalibration studies, refinements of existing methods and new methods for shipboard assessment of GPP and NP are currently under examination. The problem of inadequate *in-situ* sampling remains. Both the tracer approach and long term time series (moorings, free drifting buoys, weather ships) would somewhat fill the gaps by providing time-averaged information. Otherwise, only satellite observations (see below) would provide some synoptical sampling, at least of the sea surface (Platt and Satyendranath 1988).

In many open ocean areas the surface waters are extremely oligotrophic most of the year. The nanomolar levels of limiting N species (nitrate, nitrite) can now be measured with special techniques (Garside 1982, 1985). This has revolutionized our thinking about the oligotrophic euphotic zone (Platt and Sathyendranath 1988). Biological growth, in terms of New Production is virtually nil, except when during storm events new nitrate is mixed up along with richer deep waters (Eppley and Renger 1988, Jenkins 1988). New Production may further be considerable and continously high at the depth of the deep chlorophyll maximum, near the bottom of the euphotic zone (Gieskes and Kraay 1986). As a first (steady state) approximation, the annual mean upward diffusive N flux would be balanced by the export through POM and DOM. The key role of ultralow N levels for new production within the oligotrophic system deserves special attention, both directly in the field as well as in (laboratory or shipboard) incubation studies.

4. VERTICAL TRANSPORT OF PARTICULATE ORGANIC MATTER

The settling particles hypothesis (McCave 1975) has been predominant in the past decade, and is supported by extensive evidence from sediment traps (Honjo 1978, 1980, Wakeham *et al.* 1980, Fowler and Knauer 1986, Martin *et al.* 1987, Tambiev 1987). Thus far there has been a great deal of attention for the fecal pellet component, emphasizing the important role of the larger zooplankton in the export of particulate organic matter. However, fractions other than fecal pellets should not be overlooked either (Pilskaln and Honjo 1987). Compilations of VERTEX data suggest that more than 75 % of the particle flux is recycled within the upper 500m (Martin *et al.* 1987; Pace *et al.* 1987). In the deep ocean vertical gradients of the fluxes of organic matter (C/N/P, organic compound classes, etc.) indicate significant microbial mineralization and transformation during settling (De Baar *et al.* 1983b, Lee and Cronin 1984, Wakeham *et al.* 1984, Watson and Whitfield 1985). From the observed seasonality of long term records (Deuser and Ross 1980; Bacon *et al.* 1985, Deuser 1986) we now also know that the settling velocity can be very rapid indeed, effectively bringing the C down to the seafloor within about one month after a plankton bloom. The rate of interactions between the larger rapidly settling particles (e.g. fecal pellets) and the fine suspended matter can be estimated from U-Th series disequilibrium studies, focusing either on the deep ocean or the upper ocean box (Bacon and Anderson 1982, Bacon *et al.* 1985, Coale and Bruland 1987). The gap between the finest suspended particles and those that are larger and settle rapidly is bridged by the formation, alteration and destruction of larger aggregates (Alldredge 1986) and the flux and sinking speed of such 'marine snow' can now also be measured (Asper 1987). Here it should be emphasized that insight gained from fluxes driven by one ecosystem (e.g. North Pacific) do not necessarily apply to another (e.g. North Atlantic). For particle flux studies in JGOFS one would wish to perform both field experiments (process studies) and long term time series deployments in a limited number of judiciously selected ecosystems, for example the Sargasso Sea (Deuser 1986), central North Pacific, Weddell Sea (Fischer *et al.* 1988) or Northwest Indian Ocean.

5. DISSOLVED ORGANIC MATTER

The alternative DOC regeneration model in its ultimate form envisions a parcel of water as a closed system: while travelling laterally and aging in the deep abyss, DOC is slowly converted to DIC by microbial decay, at the expense of dissolved O_2. Recently published results, based on a careful modern rejuvenation of the High Temperature Combustion (HTCO) technique (Sugimura and Suzuki 1988) would appear to support exactly this hypothesis. The Apparent Oxygen Utilization (AOU) in the deep ocean would be largely accounted for by mineralization of DOC. These results are further supported by an inverse relation between Dissolved Organic and Inorganic Nitrogen (DON, DIN), where DON results are also based on a HTCO method (Suzuki, Sugimuri and Itoh 1985). The suggested oceanographically consistent relations (AOU/DOC and DON/DIN) are attractive. Once corroborated by additional measurements, they appear to make the notion of settling particles superfluous. Also the elevated DOC levels in surface waters would help explain observed discrepancies in the precise determination of alkalinity (Bradshaw and Brewer 1988). Another implication would be the significance of free ranging bacteria, rather than those attached on settling particles (Karl *et al.*, 1988, Cho and Azam 1988). These relations and the underlying HTCO methodology are currently the subject of considerable debate (Williams and Druffel 1988, Toggweiler 1989) and investigations (Fitzwater and Martin, Brewer and Peltzer, Mantoura and Preston, all in progress).

One should bear in mind that various sampling methods of particle size fractionations, settling particles, DOC, POC, (microbial) biomass, productivity measurements, etc., more often than not are fundamentally different, providing an outlook through very different windows into the deep ocean. An appreciable portion of all the perceived discrepancies stems from the observer.

6. THE MICROBIAL LOOP

The omnipresence and abundance of bacteria and small protozoans in the marine ecosystem, including the voracious predation on bacteria by protozoa (Williams 1981, 1984, Azam *et al.* 1983, Hobbie and Williams 1984), has received considerable attention in the past decade. Relationships between bacterial biomass and chlorophyll (Bird and Kalff 1984) or primary productivity have been established within a range of marine systems. Most of the bacteria appear to be free living (rather than attached), utilizing Dissolved Organic Carbon (DOC) rather than particles as a food source (Hodson and Azam 1977, Williams 1981). Through such studies the concept of a substantial microbial foodweb has been advanced, where the bacteria are sustained by a flow of dissolved organic matter derived from phytoplankton and herbivores. The dissipation of C through this pathway has now also been demonstrated in a large scale field study (Ducklow *et al.* 1986). Within the euphotic zone the overall effect of the bacteria may be net remineralization (Platt 1985), enhancing efficiency by retaining essential nutrients within the surface ocean (Frost 1984, Fasham 1985). The ensuing wax and wane of the the phytoplankton blooms (Fransz and Verhagen 1985) would be closely followed by changes in the flux-rate of CO_2. The conventional description of flows of energy and matter through trophic levels (phytoplankton, herbivores, carnivores, settling flux of fecal pellets) is now augmented by microbial pathways. For the deep ocean Cho and Azam (1988) and Karl *et al.* (1988) have provided evidence that free ranging bacteria play a major role in mineralization in the ocean interior as well.

These insights somewhat parallel the shift in thinking towards the cycling of Dissolved Organic Matter as a means of describing C fluxes in the sea, at the expense of the particle flux concept. Earlier we found substantial evidence for both the DOM paradigm and the (settling) POM concept. When taking into account the variety of pelagic ecosystems in different oceans as well as the current extreme undersampling of such ecosystems, one can predict that both mechanisms will finally prove to be significant for the marine carbon cycle.

7. TRACE ELEMENTS

The cycling of C by the oceanic biota is accompanied by the intentional or incidental entrainment of many trace elements (Bruland 1983, Wong *et al.* 1983). Vertical profiles of dissolved Cd, Zn, Ni, Cu (Boyle *et al.* 1976, 1977, Sclater *et al.* 1976, Bruland 1980), Pd (Lee 1983), Ba (Chan *et al.* 1977), the Rare Earths (Elderfield and Greaves 1982, De Baar *et al.* 1983a, 1985), Al (Hydes *et al.* 1988) as well as lateral sections (Kremling and Pohl 1988) show significant correlations with the nutrients. It is unlikely though that all these metals would also act as biolimiting nutrients. More complex mechanisms (e.g. adsorptive scavenging) for entrainment with particle fluxes have been proposed (Balistrieri *et al.* 1981, Honeyman *et al.* 1988). For example, for many metals the settling flux is proportional to the overall mass flux (Jickells *et al.* 1984). The scavenging agent on the settling particles may well be some ferromanganese oxide coating (Cowen and Bruland 1985). Entrained metals are indeed released (e.g. Rare Earths, De Baar *et al.* 1988, German *et al.*

1987; Schijf and De Baar 1989) when the FeMn phase dissolves under suboxic or anoxic conditions. In another instance (Ba) micro-environments are invoked (Bishop 1988).

Many transition metals like V, Cr, Mn, Fe, Co, Ni, Cu, Zn and Mo are indeed essential nutrients in, e.g., enzyme systems. However the oceanic distribution of most of these elements is not nutrient-like but apparently is dominated by other processes such as overriding input functions (atmospheric, riverine, hydrothermal) or oxidation-reduction (photo)chemistry (Landing and Bruland 1987, Saager and De Baar 1989, Sunda and Huntsman 1988). In some instances their availability may act as a significant limitation on rates of C-fixation, with Fe and Mn as examples (Anderson and Morel 1982, Brand *et al.* 1983, Martin and Fitzwater 1988, Martin and Gordon 1988, Coale and Bruland 1988, Harrison and Morel 1986, Buma *et al.* 1989). In the case of Cu the cupric ion activity primarily acts as toxicant, inhibiting rather than stimulating photosynthetic C-fixation (Sunda and Guillard 1976; Anderson and Morel 1978, Brand *et al.* 1986), also through competition with Mn (Sunda and Huntsman 1983). Likewise one finds Cd to act solely as a toxicant (Brand *et al.* 1986), an apparent paradox when contemplating its highly significant correlation with oceanic phosphate. The unraveling of the interaction of these trace elements with the biota has only just begun - a crucial step when assessing fluxes in the C cycle. At the level of methodology these metals may also, through shipboard contamination, affect the determination of primary productivity (Fitzwater *et al.* 1982). Several of these trace elements (Cd, Cu, Ni, Pb, Zn) are also discharged as human wastes into the ocean and feedback loops will undoubtedly be found to affect the oceanic carbon cycle, hence the atmospheric CO_2 level and the global heat budget.

8. GLOBAL SURVEY BY REMOTE SENSING

Remote sensing of the surface ocean with color scanners mounted on satellites allows worldwide survey of pigment (chlorophyll) abundance at the sea surface (Esaias 1981, Brown *et al.* 1985; Esaias *et al.* 1986). Corrections for atmospheric interferences have been developed now for resolving the signals from the past overflights (1979-1986) of the Coastal Zone Color Scanner (Gordon and Morel 1983). The resulting data describes the surface abundance of chlorophyll pigments, the biochemical site for C-fixation. From the chlorophyll distribution we have already gained considerable insight into the dynamics of the pelagic ecosystem (Banse and McClain 1986, Abbott and Zion 1987, Yoder *et al.* 1987, Walsh *et al.* 1987). In order to pursue further the desired global quantification of marine photosynthetic C-fixation (primary productivity), the satellite images need to be interpreted with proper algorithms. Development of such algorithms depends on simultaneous shipboard observations of pigment abundance (chlorophyll a) and primary productivity as ground truth data for calibrating the numerical models (Platt and Sathyendranath 1988, Lohrenz *et al.* 1988).

For more sophisticated assessment of various pigments, one should utilize HPLC methodology. Apart from the remote sensing application this technique of course also provides insight into composition and physical state of the plankton community, notably with respect to the important pico- and nanoplankton component (Gieskes and Kraay 1986; Gieskes *et al.* 1988). There is obviously room for further improvements in both precision and accuracy for conversion of satellite imagery into production estimates. Quantification of these production estimates with small overall error is one of the major objectives of the JGOFS program.

In 1991 new data will become available from the SeaWifs ocean color sensor scheduled to be flown on the Landsat-6 spacecraft (Putnam 1987). Application of atmospheric corrections and algorithms for productivity would rely strongly on the expertise available from the past CZCS experiment. Through coordination with carefully planned shipboard work (both local process studies as well as global survey lines) one should be able to produce in virtual real-time large scale maps of ocean color as well as productivity.

9. PUMPING CARBON INTO THE OCEANS

So far we dealt with the dissolution of CO_2 in seawater and its uptake into particulate and dissolved organic matter. Coccolithophorideae, planktonic foraminifera and planktonic ostracods also extract CO_2 (about 3 GtC per year) from surface seawater in the form of $CaCO_3$ shells. Much of this material eventually settles to the seafloor and thus constitutes another flux of C into the deep sea (Honjo 1980, Deuser *et al.* 1981). Some of this $CaCO_3$ is replenished by river input (Keir and Berger 1985), but most has to be regenerated within the oceans (Sundquist 1985) to maintain the existing steady state (the net flux of Ca from hydrothermal systems is here ignored; Thompson 1983). Both the $CaCO_3$ preservation record in marine sediments (lysocline depth, CCD, etc.; Kennett 1982) and physicochemical studies (Broecker and Peng 1982) suggest that such dissolution of calcite shells takes place only at great depth, where the lower carbonate ion concentration allows undersaturation of the ambient seawater. However, recent results indicate that an appreciable portion (as much as 50 %) of the calcite is in fact remineralized in the upper water column. From comparison of size fractions of living and dead (settling) foraminifera, it appears that some 80 % of the individuals (mostly juveniles, Brummer *et al.* 1986) or about 30 % of the foraminiferal calcite never reaches the deep sea (Brummer and Kroon 1988; see also Berger 1976, his Figure 29.6). Dissolution in the upper ocean is presumably achieved within the shell, where microbial oxidation of organic matter lowers the pH and the carbonate ion concentration to levels below those in ambient seawater (Alldredge and Cohen 1987). More insight in this latter scenario as compared to the classical settling and thermodynamical dissolution model needs to be gained for a realistic assessment of $CaCO_3$ fluxes out of the euphotic zone.

In summary we now have four, rather than three (Volk and Hoffert 1985) different routes for 'pumping' C into the deep ocean:

1. *Dissolved bicarbonate carried down during deep water formation.*
2. *Dissolved organic carbon carried down during deep water formation.*
3. *Vertical flux of organic matter in large settling particles.*
4. *Vertical flux (sedimentation) of calcite shells.*

For proper study of these four mechanisms it is also crucial to gain considerable insight into the interaction with other chemical elements (N, S, P, Mn and Fe were mentioned above), notably with respect to ocean/atmosphere exchange, primary productivity and new production.

10. MODELING

Modeling has become an essential tool for both setting up hypotheses before, as well as interpreting the gathered data after, experiments. In a rather extreme stance we might call the whole JGOFS exercise an effort towards developing a dynamic global model of the flow of C through the marine system. More modestly and realistically one may think of: models describing the nutrient field in the euphotic zone as a function of physical forcing (Glover and Brewer 1988); foodweb models (Fasham 1985); U-Th decay series modeling as to provide time clocks for oceanic processes (e.g. Bacon *et al.* 1985). Within the context of this short paper we cannot dwell extensively on the many aspects of marine modeling; excellent reviews are available (Fasham 1984, Fransz *et al.* 1989); U.S. GOFS 4 1987).

Field data of the North Atlantic Pilot Study (see below) will be used to implement and calibrate carbon flux models. Adequate models should describe quantitatively the rates of change of carbon content in biotic and abiotic ecosystem components, and transport processes in vertical and horizontal directions. Numerical integration may be applied to simulate seasonal variations, and to demonstrate the fate of assimilated carbon. This will also provide quantitative insight into annual budgets and balances.

11. TOWARDS AN INTERNATIONAL JOINT GLOBAL OCEAN FLUX STUDY

Planning for a long-term, international study of marine biogeochemical fluxes has been underway since 1984 and has led to agreement on a Joint Global Ocean Flux Study for the 1989-1999 decade, with the following main goal.

"To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, the sea floor and continental boundaries."

The Scientific Committee on Oceanic Research, SCOR, of the International Council for Scientific Unions, ICSU has taken the lead in organizing JGOFS, and supporting national programs are being developed in a number of countries (SCOR 1987a; SCOR/JGOFS 1988a, b). A North Atlantic Pilot Study has been planned for 1989-1990 and is now well underway (SCOR 1987b, 1988b).

Major aspects of JGOFS include:

1. *The need for fundamental field data:*

Climate and the oceanic carbon cycle are linked; quantitative insight into the cycle of the modern ocean is required as a benchmark for climate studies, with an emphasis on modern variability in time (from day to decade) and space.

The marine C budget is intimately related with that of other common (N, S, P) and trace (Fe, Mn, Cd, Cu, Th) chemical elements. Cycles of these biogenic elements deserve better understanding, also with respect to ocean/atmosphere exchange.

The existing archive database for marine primary productivity is biased in time and space and also suffers from artefacts of methods that were used. Significant global coverage suitable for global budget modeling can never be realized from shipboard measurements.

Process studies, based on state of the art methodology, in a number of judiciously chosen areas are now feasible and provide the basis for worldwide extrapolation based on satellite observation.

The important concept of new production and the ensuing F-ratio (new / total primary production) needs to be defined more precisely through innovative experimental approaches in the field. Quantification in various oceanic areas is required so as to assess the 'biological pump' that forces carbon from the euphotic zone to depth.

Process studies of fluxes (primary productivity, new production) should be complemented by species level studies of bacterio/phyto/zooplankton, their physiology, biochemistry (notably pigments) and their interactions within the overall marine foodweb.

Similarly the structure of the benthic community as related to regenerative fluxes from the seafloor deserves attention.

Organic chemical cycles in the ocean are relatively well understood and shown to be fascinating in themselves for several compound classes (Farrington 1987), but are largely obscure for other compounds or the total organic pools (notably DOC, DON, DOP). Development of improved analytical methodology (e.g. Mopper 1986; Sugimura and Suzuki 1988) is crucial.

Internally consistent datasets encompassing physical, biological and chemical variables are needed for well defined areas, also for those parameters which can already be measured satisfactorily (e.g. salt, nutrients), in order to constrain local, basinwide or global (mass balance) models.

2. *The need for time series observations over several decades, to allow observation on global change.*

Time series of vertical fluxes collected with sediment traps, as already in place near Bermuda, at various key oceanic stations.

Time series of chemical and biological parameters, with data being collected from ships or buoys.

Time series of plankton species abundance and provenance, such as the UK Continuous Plankton Recorder Survey.

Time series of phytoplankton pigment abundance, sea surface temperature and other parameters now available from satellite sensors.

3. *Opportunities from new technology.*

Satellite observation (NOAA/AVHRR) already provides data in the Infrared (Sea Surface Temperature) and Visible (Total Particulate Matter) region. Assessments of wind stress, sea state and ocean currents will become available from ERS-1 and TOPEX/POSEIDON. Most essential will be the ocean color data from the compact wide field sensor (Sea-WIFS) which will be launched aboard U.S. LANDSAT-6 in late 1991. The selected wavelengths of Sea-WIFS are compatible with those of CZCS (1979-1986) so that the algorithms for processing CZCS data can be utilized.

Modern computers have allowed development of sophisticated models of the ocean, models quite suitable for biogeochemical purposes. Validation requires collection of field data.

New or currently developed methodology is suitable for the necessary application at a larger scale: realistic measurements of nanomolar levels of nitrate, nitrite, ammonia in oligotrophic waters; accurate CO_2 determination by coulometry; clean techniques for assessing primary productivity; plankton characterization by flow cytometry; *in situ* sensors (pH, CO_2); photosynthetic pigments by HPLC; organic biomarkers and their transformations; DOC/DON; sediment traps and benthic instrument packages.

Large scale physical programmes like WOCE (1986, 1988) and TOGA are also oriented towards assessing the role of the ocean in climate; the physical insights (circulation, heat and salt exchange, predictive models, etc) to be gained with state of the art physical tools will complement the JGOFS focus on marine biological and chemical driving forces of climate.

12. PLANNING AND IMPLEMENTATION

The planning being undertaken through the SCOR Committee for JGOFS is beyond the scope of this paper. Briefly, JGOFS will pivot around three themes:

1. *Process studies in judiciously chosen locales.*
2. *Time series studies (e.g., sediment trap moorings).*
3. *Global survey through satellite observations.*

With respect to the process studies, the merits of selected sites in four regions -- Pacific basin, Southern Ocean, northwest Indian Ocean, North Atlantic Ocean -- are currently being explored (SCOR/JGOFS 1989). The ongoing North Atlantic Pilot Study serves to illustrate this approach (SCOR 1987b, 1988b). The Pilot Study is focusing on three areas (33°N, 48°N, 60°N) along the 20°W transect (Fig. 8) with special emphasis on mesoscale variability. Throughout the seasons, a wide range of mixing regimes will be encountered, driving the spring and autumn plankton blooms (Fig. 9). On each participating ship, a standard suite of key variables is being measured, following accepted protocols and including proper intercalibration (Table 1). The experience gained in this pilot bloom study will be useful when setting up other process studies later on in the 1990's.

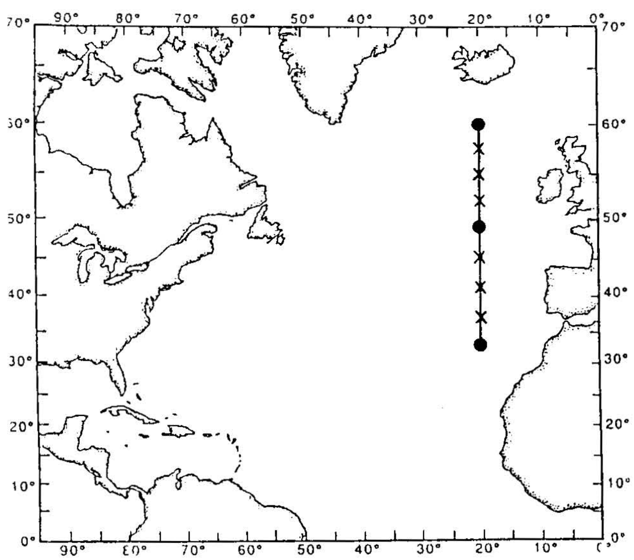

Figure 8. The 20°W transect as studied in the North Atlantic Pilot Study. The emphasis will be on the assessment of temporal and spatial scales at the three indicated stations: 30°N, 48°N and 60°N

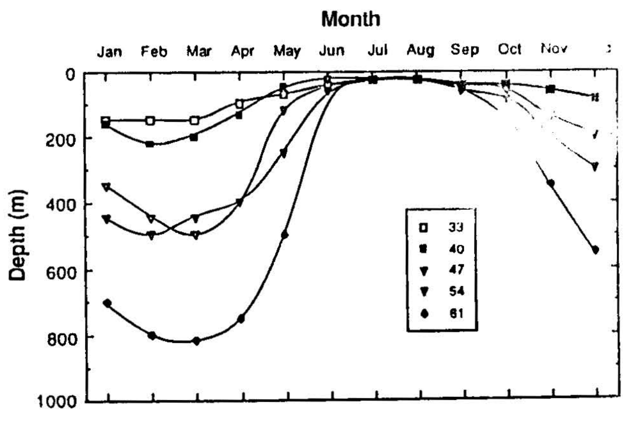

Figure 9. Mixed layer depth versus month at 30, 40, 47, 54, and 61°N latitude along the 20 W Pilot Study transect. Original data taken from Robinson *et al.* (1979).

TABLE 1.
Core measurements during the North Atlantic Pilot Study. In principle all measurements are executed by all participating ships/countries. Protocols are standardized with recommended precision and adequate intercalibration. Taken from Van den Dool *et al.* 1978

1. Meteorology and positioning.	11. Biomass - mesoplankton.
2. CTD, probe for dissolved O_2, fluorometry probe.	12. Biomass - microplankton.
3. Dissolved O_2 by titration.	13. Primary production by ^{14}C.
4. Dissolved nutrients.	14. Primary production by O_2.
5. Optics.	15. New production by ^{15}N.
6. Dissolved CO_2 chemistry.	16. Bacterial production.
7. Particulate organic carbon and nitrogen.	17. Grazing - mesoplankton.
8. Dissolved organic carbon.	18. Grazing - microplankton.
9. Pigments, chlorophyll.	19. Sediment traps - drifting.
10. Biomass - bacteria, cyanobacteria	20. Sediment traps - deep, moored.

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Radionuclides and Particle Associated Processes in Ocean Water Column

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ABSTRACT

The role of oceanic particles in controlling the distribution and cycling of elements in the water column is well recognised. Recent years have witnessed major advances in studies relating to the dynamics and sedimentation of particles in the water column and in particle/solute interactions. Many of these studies rely on the application of radionuclides, particularly those belonging to the natural radioactive series. As particles descend through water they adsorb onto them radionuclides dissolved in water, and remove them from solution, thereby creating radioactive disequilibrium within the decay series. The extent of radioactive disequilibrium provides data on the kinetics of the adsorption/desorption processes and particle transformation rates. Thorium isotopes, Pb-210 and Pa-231 are the commonly used nuclides for these studies. This paper focuses on the application of Th isotopes to study particle-associated processes in the oceans.

Environmental radioactive isotopes have proved to be powerful tools to understand the dynamics and transformation rates of particles and kinetics of elemental scavenging in the oceans. In addition, the measurement of their fluxes in sediment traps, employed to determine elemental fluxes through the water column, allows one to place constraints on their trapping efficiencies. In this paper the use of radionuclides as tracers to determine rates of particle settling and transformation and kinetics of elemental scavenging in the sea is discussed. The prerequisites for a radioactive isotope to be useful as a particle process tracer are (i) it should be 'particle-reactive' i.e. it should attach itself to particles in the water column, and (ii) the processes and rates of its supply should be known. This would enable quantitative modeling of its distribution to derive parameters of interest. In addition, from a practical point of view, its concentration in dissolved and different particulate pools should be measurable to a reasonable precision. Many isotopes belonging to the U-Th natural series and those released to the environment through nuclear weapon tests and from nuclear reactors satisfy some of these requirements. The naturally occurring isotopes are more commonly used to probe into particle associated processes as their supply rates to the oceans can be determined reasonably well. In contrast, the supply rates of artificially injected isotopes are difficult to ascertain and hence they serve more as markers to place limits on the time elapsed since the particles left the upper layers of the ocean. In this paper, the focus is on the three isotopes of thorium, ^{234}Th, ^{228}Th and ^{230}Th. All these isotopes are produced in the water column by the radioactive decay of their parents; ^{238}U(^{234}Th) ^{228}Ra(^{228}Th) and ^{234}U(^{230}Th).

Since the uranium concentration in sea water is nearly uniform, the production rates of ^{234}Th and ^{230}Th are also uniform through the ocean.

The basic approach to derive kinetics of particle associated processes is to set up material balance equations for the soluble and particulate pools of Th (e.g., Bacon and Anderson 1982).

$$\partial C/\partial t = P + k_2\bar{C} - k_1 C - \lambda C \quad (1)$$

$$\partial \bar{C}/\partial t = k_1 C - k_2\bar{C} - \lambda\bar{C} - S\, \partial\bar{C}/\partial z \quad (2)$$

where P is the production rate of the isotope from the dissolved parent, C and $\bar{C}$ are the Th isotope concentrations in the soluble and particulate phases, k_1 and k_2 are the adsorption and desorption rate constants for Th, λ is the radioactive decay constant and S is the settling velocity of the particles containing adsorbed Th. In setting up these balance equations, the changes resulting from diffusion and advection are neglected, as they are small compared to production and removal terms (Bhat *et al.*, 1969, Nozaki *et al.* 1981, Bacon and Anderson 1982, Coale and Bruland 1985). Solution of the above equations using the measured Th isotope profiles provides values for adsorption, desorption rates and particle settling velocities. However, further approximations can be made in these equations depending on the oceanic region under study and the Th isotope being used. For example, in surface waters the adsorption of ^{234}Th can be treated as irreversible. The short half-life of ^{234}Th and the short residence time of particles in surface water make the desorption processes insignificant (Coale and Bruland 1985). Hence for ^{234}Th the scavenging processes in these layers can be treated as irreversible. The use of Th isotopes to study particle associated processes in surface waters began with the work of Bhat *et al.* (1969), and was later expanded on by others (e.g. Broecker *et al.* 1973, Matsumoto 1975, Knauss *et al.* 1978, Coale and Bruland 1985).

All these studies show that the dissolved concentrations of ^{234}Th and ^{228}Th in surface waters were significantly lower than that of their radioactive parents. A typical data set for ^{234}Th is shown in figure 1. These data have been modeled to determine rates of thorium scavenging. The residence time of dissolved Th, τ_d, in surface waters with respect to irreversible adsorption onto particles is

$$\tau_d = (1/k_1) = \tau\lambda / [(P/\lambda C) - 1] \quad (3)$$

where $\tau\lambda$ is its radioactive mean life and other terms are as defined in equations 1 and 2. Similarly, the residence time of particulate Th (and hence that of particles themselves), τ_p, relative to its removal from surface waters (by settling, grazing etc) is given by the ratio of the standing crop of its activity (A^P, dpm/cm^2) to its flux out of surface layer (F, dpm/cm^2 yr)

$$\tau_p = A^P/F \quad (4)$$

Both A^P and F can be measured and hence particle residence times can be determined with a fair degree of precision (Coale and Bruland, 1985).

The ^{234}Th: ^{238}U and ^{228}Th: ^{228}Ra data suggest that in surface waters Th is removed from the dissolved phase by particle scavenging, on time scales of a few days to a few months. In addition, Th isotope data on particles yield a residence time in the range of a few days to a few weeks for particles in surface waters (Coale and Bruland 1985). The lower residence time of Th is typical of regions of high particle concentration, such as coastal water and zones of high biological productivity (Bhat *et al.* 1969, Coale and Bruland 1985). These studies suggest that any contaminant introduced in the surface waters which has properties similar to that of Th, would be removed to the ocean interior in a span of about a month.

^{234}Th and ^{228}Th are among the best available tracers today to determine scavenging rates and particle residence times in surface waters. However, there are some lingering doubts about the assumption that scavenging is irreversible. Considering that Th is adsorbed on phytoplankton (Fisher *et al.* 1987) and that a major fraction of biological productivity is recycled in surface waters, it is likely that a part of adsorbed Th is also returned to the water. Though limited data on ^{234}Th: ^{238}U and ^{228}Th: ^{228}Ra isotope pairs in the same water samples seem to support the assumption that the adsorption can be treated as irreversible (Kaufman *et al.* 1981), more work on these pairs from regions of different trophic status is needed for a proper check on the validity of the assumption.

Studies on the nature of solute particle interactions occurring in the ocean interior (a region of relatively low particle concentration and high residence times) rely mainly on the use of Th distribution in particulate and soluble pools. These studies began with the work of Krishnaswami *et al.* (1976, 1981) who measured profiles of particulate ^{230}Th with depth (Fig. 2). These results show a steady increase of particulate ^{230}Th with depth (Fig. 2), resulting from the uptake of ^{230}Th from solution by particles as they sink (eqn. 2). This increase provides a measure of settling velocity for the filtered particles, which average about a meter per day.

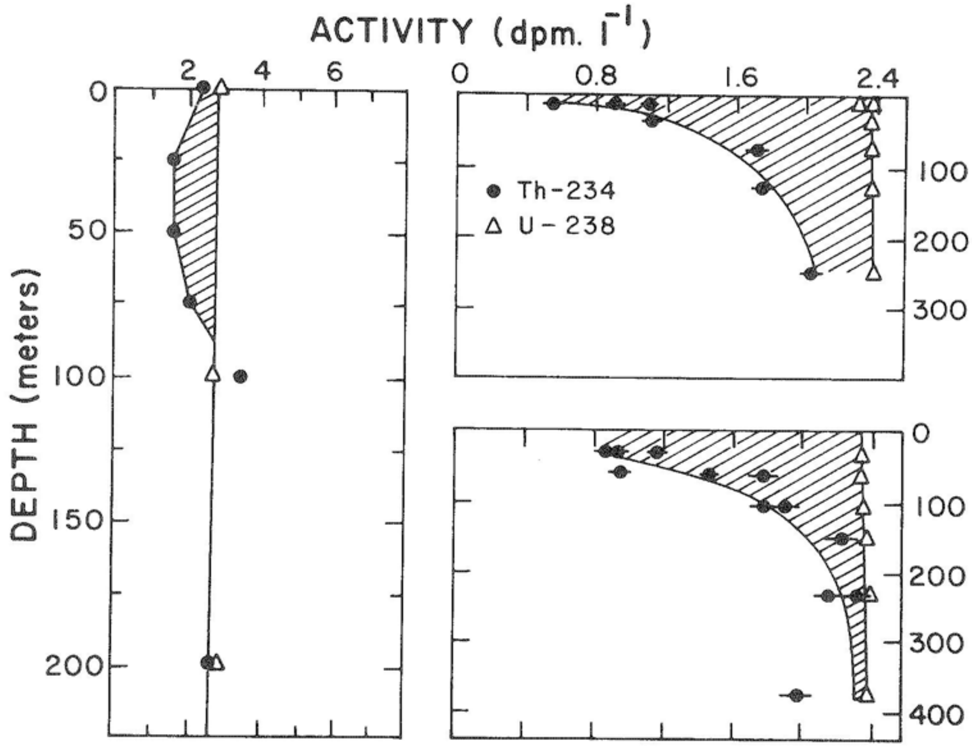

Figure 1. Typical profiles of ^{234}Th: ^{238}U in the oceanic surface waters. Data from Bhat *et al.* (1969) and Coale and Bruland (1985).

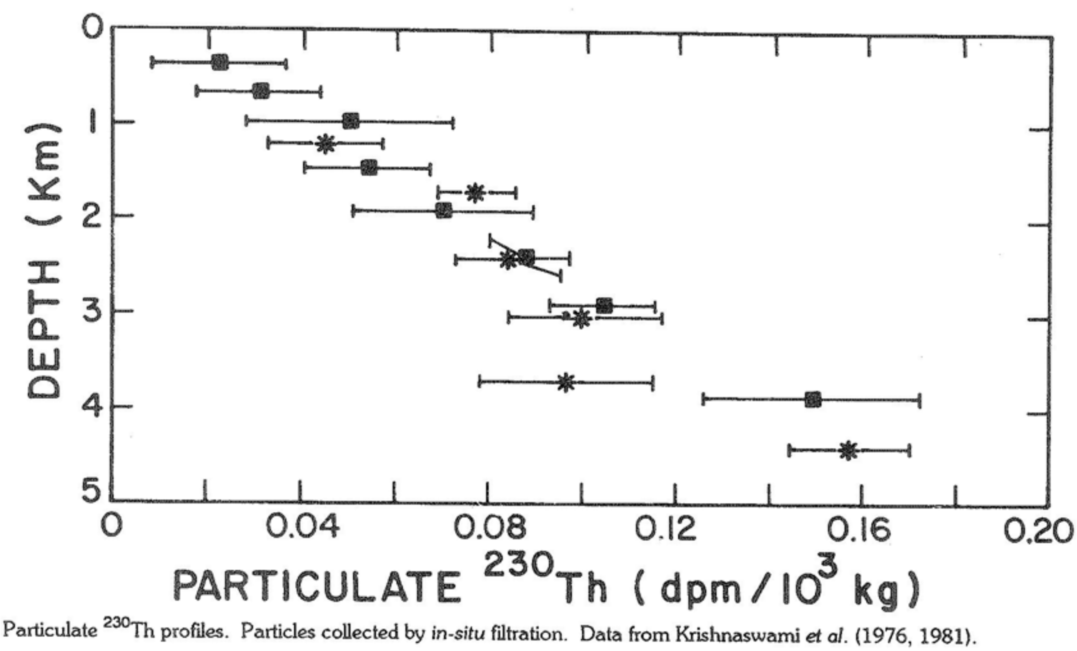

Figure 2. Particulate ^{230}Th profiles. Particles collected by *in-situ* filtration. Data from Krishnaswami *et al.* (1976, 1981).

Measurements of both dissolved (or total) and particulate ^{230}Th profiles provide a better insight into the nature of chemical scavenging processes in the ocean interior (Nozaki *et al.* 1981, Bacon and Anderson 1982) ^{230}Th is produced in the ocean from the radioactive decay of its parent, ^{234}U; its production rate is nearly uniform through the ocean. The concentrations of both total and particulate ^{230}Th increase with depth (Fig. 3), a result which can be explained in terms of continuous exchange of Th between sea water and particle surfaces, ie, reversible adsorption (eqn. 1). The rate constants for adsorption (k_1) and desorption (k_2) have been determined based on the measurements of ^{234}Th and ^{230}Th in different phases (Nozaki *et al.* 1981, Bacon and Anderson 1982, Nozaki *et al.* 1987). These studies yield a residence time of ~1 yr for dissolved Th with respect to adsorption and ~2 months for Th on particles relative to desorption. As these residence times are significantly lower than the transit time of particles through the water column (several years at a settling velocity of 1m/day), it follows that Th atoms would get transferred from one particle to another many times before their deposition on the sediments.

In addition to providing insight into details of scavenging processes in the ocean interior, Th isotope studies also lend support to the use of chemical equilibrium models to describe elemental scavenging in the

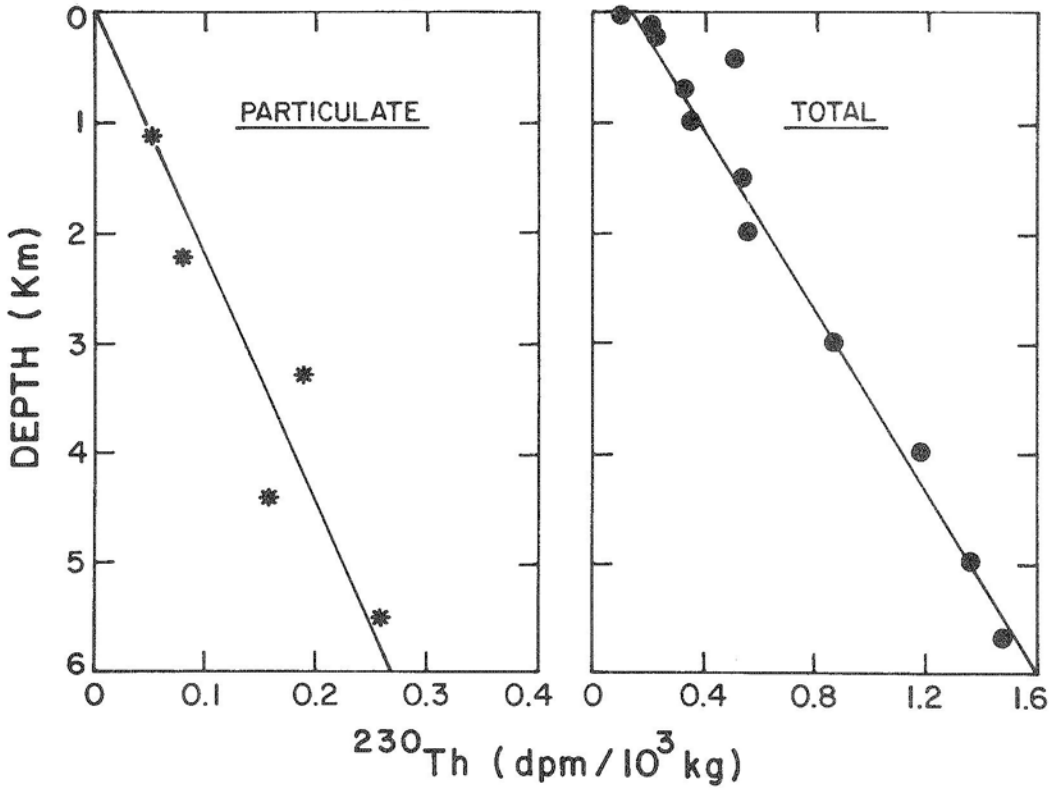

Figure 3. Particulate and total ^{230}Th profiles in western north Pacific waters. Data from Nozaki *et al.* (1981).

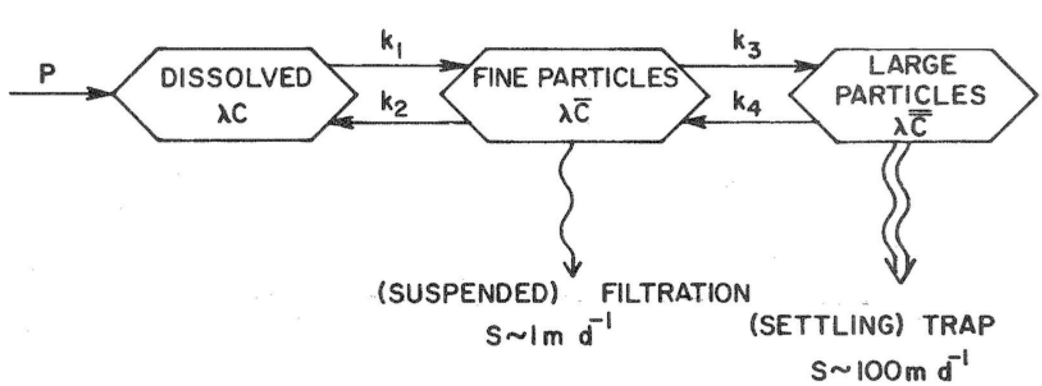

Figure 4 Schematic of particle transformation model (from Bacon and Anderson 1982 and Nozaki *et al.* 1987)

oceans (Bacon and Anderson 1982, Bacon 1988). These studies show that it is possible to estimate elemental residence times in deep sea if data on the particle residence times and on the distribution of elements between soluble and suspended phases are available. As discussed earlier, particle residence times can be determined from Th isotope data.

The advent of sediment traps and direct measurement of radionuclide fluxes have provided more information about particle transformation process (i.e., aggregation/breakup) in the ocean interior. Traps collect settling particles which are dominated by larger particle size and have velocities in the range of 100 m/day. Further there is evidence suggesting that these large particles are responsible for the majority of downward flux of materials in the sea (Fowler and Knauer 1986). One such evidence is the near equality of ^{230}Th flux measured in the traps to that expected from its deficiency in the overlying water column (Bacon 1988). These results, in a way, contradict those obtained from ^{230}Th profiles in filtered particles (Fig. 2) which suggest that particles in the ocean settle with a mean velocity of 1m/day. This apparent contradiction can be resolved by hypothesising two classes of particles and continuous exchange of materials between them (Fig. 4). These two classes of particles are the relatively rare, larger settling particles collected by the trap and the fine suspended matter recovered by filtration and which make up the bulk of the standing crop of particles. The exchange of materials between these two classes of particles takes place through aggregation-disaggregation processes occuring throughout the water column. The dissolved and particulate ^{230}Th profiles have helped place constraints on the time scales of particle aggregation-disaggration processes (Nozaki *et al.* 1987). Model-derived time scales for aggregation of fine particles into rapidly sinking large particles are a few months whereas the break up occurs much faster, on time scales of a few days. Thus materials are exchanged several times between fine particles and larger aggregates, resulting in a net downward drift of 1m/day.

In the foregoing discussions, I have shown that Th isotopes serve as *in-situ* probes to study particle scavenging and transformation processes in the ocean. The models used to interpret the Th isotope data and to derive the kinetics of various particle associated processes have been reasonably successful, though they are quite simple. It now remains to be ascertained how the Th isotope-based rates of scavenging and particle transformation compare with those determined from other tracers, particularly those elements which are actively taken up by biological organisms. It is also necessary to improve the available scavenging models by incorporating other parameters, such as particle concentration and size spectra which affect adsorption - desorption and biological processes which would consider the role of active uptake of elements. Future research on particle dynamics and transformation in the ocean interior should focus on some of these aspects.

TABLE 1
EXAMPLES OF PARTICLE-REACTIVE RADIONUCLIDE TRACERS

	Nuclide	Half life
NATURAL		
U-Th decay chain	Th-234	24.1 d
	Th-228	1.91 y
	Th-230	75,200 y
	Pb-210	20.3 y
	Po-210	138 d
Cosmic ray produced	Be-7	53 d
	Be-10	1.6 M y
	C-14	5730 y
ARTIFICIAL		
	Zr-95	65 d
	Ce-144	285 d
	Fe-55	2.6 y
	C-14	5730 y
	Pu-239	24,400 y

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Arctic Deep-Sea Drilling: Scientific and Technical Challenge of the Next Decade

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ABSTRACT

Why is it important to go to the major expense and long-term effort of organizing, preparing and executing drilling in the permanently ice-covered, deep-sea regions of the Arctic? Because of its unique characteristics, the Arctic Ocean has a climatic and oceanographic influence far beyond its limited geographic extent. For example, deep water formed in the polar and subpolar seas fills the basins of the rest of the world's ocean. The modern Arctic sea ice cover, although apparently thermodynamically unstable, has existed for several million years, affecting global heat budgets and therefore the global climate system. Yet we do not know when deep waters of the Arctic Ocean were first linked with those of the Norwegian-Greenland Sea, nor when sea ice first covered the Arctic Basin. Likewise the geologic composition and history of major morphologic features, ridges, plateaus and margins are practically unknown. This knowledge is missing because of a lack of appropriate samples of sediment and bedrock. With a coordinated effort of site surveying and drilling in the Arctic it would be feasible to obtain the required material. This report presents a scientific rationale and an organizational scheme together with various technological options for drilling in this hostile environment.

The Arctic Ocean is one of the last remaining frontiers in marine geosciences. It is covered by sea ice impenetrable to most research vessels (Fig. 1). With the exception of Nansen's FRAM expedition in the late 19th century (Nansen 1900-1906) and 20th century aeromagnetic surveys (Vogt *et al.*, 1979; Taylor *et al.*, 1981), most information on its geologic development comes from the labors of small groups of investigators deployed on ice stations by airplanes. Data collected during such expeditions are limited to regions where the combination of currents and wind happened to carry the ice floe with its scientific party.

Thus our knowledge about the paleoenvironmental development of the Arctic Ocean is extremely poor. For example, we do not know when the basin first became ice-covered nor why and how the ice cover fluctuated over time. We do not know what kind of glacial ice cover developed in the vicinity of the Arctic Ocean during the ice age, nor how the glacial events of the Northern Hemisphere corresponded to Antarctic glacial fluctuations. However, it is certain that the glacial events had worldwide influence on oceanic circulation and sedimentation.

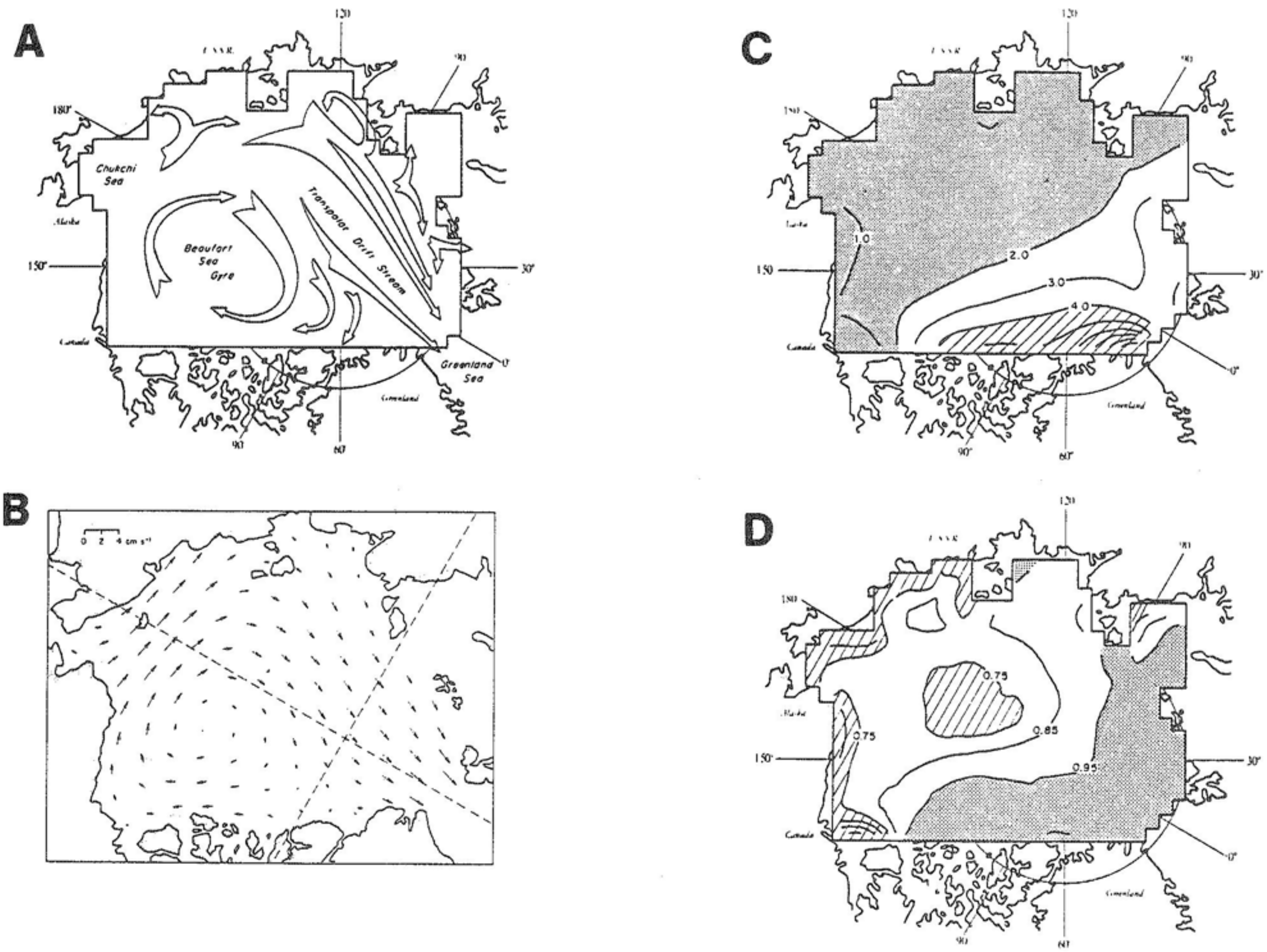

Figure 1. Sea ice characteristics: A) The pattern of mean drift in the Arctic Ocean (adapted by Hibler (1979) from Gordienko (1958)). B) Field of interpolated mean ice motion (Colony and Thorndike 1984). C) Average August thickness (in meters) taken from a standard model simulation (Hibler 1979). D) Average August compactness taken from a standard model simulation (Hibler 1979).

Similarly, knowledge of the tectonic development of the Arctic Basin is important for more than just solving regional problems in that it is linked to the evolution of the adjacent oceanic basins and continents. An understanding of past and present plate movements in the Arctic will be required before a complete model of late Mesozoic and Cenozoic Northern Hemisphere plate motions can be achieved. These motions and the composition, paleontology, and paleoenvironment of the sedimentary rock sequences of the circum-polar regions and its continental shelves are also highly relevant to the exploration for hydrocarbons.

Except in the Arctic Ocean, many paleoenvironmental and geologic questions related to the world ocean have been resolved by deep-sea drilling, obtaining and dating basement rocks and sediment cores hundreds of meters long which record the history of basin development. The longest Arctic deep-sea cores are less than 10m long. Only 4 samples exist of Arctic deep-sea sediment older than 40 million years (Fig. 2). The remainder of the more than 600 sediment cores are less than 5 million years old and most are less than 3m long, leaving us with a spotty and poorly documented record. Sediment characteristics of the older cores indicate an early restricted, oxygen-poor environment in a temperate regime. As recorded by accumulations of nearly pure siliceous biogenic material, an upwelling regime existed which apparently would rival the productivity of the present-day Gulf of California. All other cores are solidly within the later (less than 5 million years old) cold, glaciomarine environment (Fig.2).

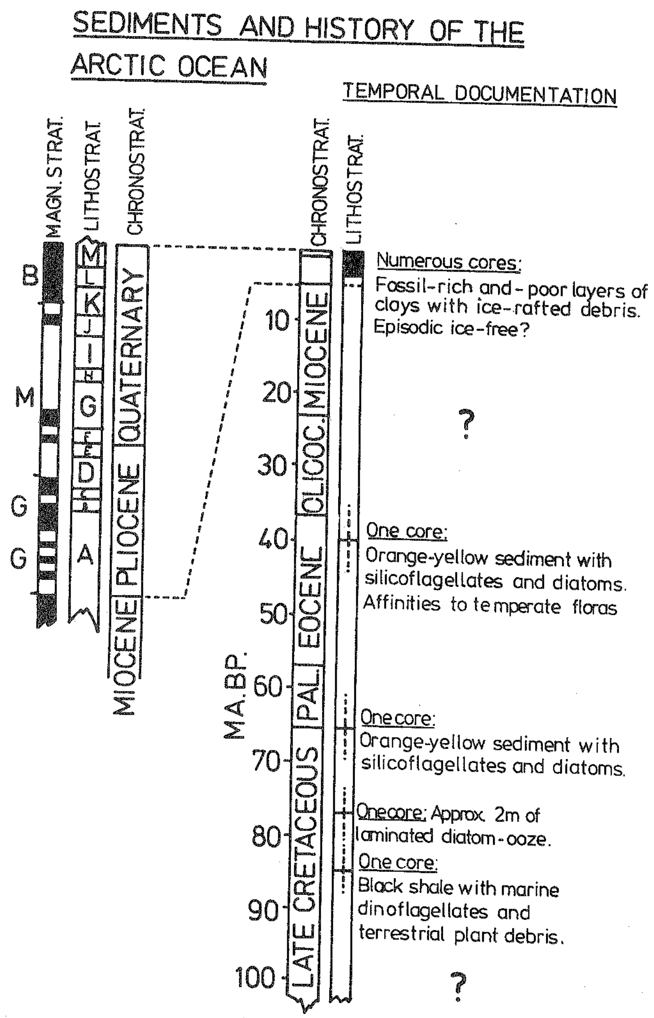

Figure 2. Ages and composition of Arctic deep-sea sediment cores (from Thiede *et al.* 1988b).

We can begin to answer questions about the tectonic and paleoenvironmental evolution of the Arctic only if we obtain long, continuous and undisturbed cores of Arctic deep-sea sediment in carefully chosen and well-surveyed locations. Arctic drilling, although difficult, is not impossible if tackled by the international scientific community. Various technological solutions to drilling in this ice-covered ocean are in preparation. Our challenge is to design a drilling program which will achieve the maximum in scientific results, while minimizing cost. A working concept for organization of this program, including scientific goals and a suite of technological approaches is outlined in this paper.

Nansen Arctic Drilling Program

The meeting on Arctic drilling in Ottawa, Canada, 23-24 June 1988 (Table 1), brought into focus the major outlines of the international arctic drilling program. To commemorate the pioneering work of Fridtjof Nansen with the FRAM expedition in 1893-1896, nearly 100 years ago, the program will be called the Nansen Arctic Ocean Drilling Program (NAD).

The primary goals of NAD are to understand:

A) the climate and paleoceanographic evolution of the Arctic region and its effects on global climate, biosphere and the dynamics of the world's ocean and atmosphere; and

B) the nature and evolution of the major structural features of the Arctic Ocean Basin and circum-Arctic continental margins.

TABLE 1
ARTIC DRILLING PROGRAM: STATUS AND FUTURE PLANS

July–Oct.	1985	ODP legs 104, 105. Linked high latitude subarctic biostratigraphy with North Atlantic standard biochronology, established ages of some endemic Arctic biota and major regional reflectors. Sampled 1 km of volcanics on a marginal plateau.
Aug.	1986	Meeting of the ICL Arctic Subcommittee, Kiel. Workshop was proposed on technological feasibility of Arctic drilling.
Sept.	1986	Canadian ODP Workshop, Montreal. 11 proposals were submitted, mostly for drilling in the western Arctic and Canadian polar margin.
Nov.	1986	IUGG Arctic drilling workshop, Halifax. Sites were submitted as follows: 8 on Yermak Plateau (Norway and USA), 6 on Alpha Ridge (USA and Canada), and 2 on Chukchi Plateau (USGS).
Dec.	1986	Workshop on "Feasibility of Deep–Sea Drilling in the Arctic", Dartmouth. Supported by IUGS–CMG, IUGG–ICL Subcommittee on Arctic, and SCOR WG 82. Arctic drilling was determined to be feasible (Blasco et. al, 1987).
Mar.	1987	ECOD Workshop at Gwatt, Switzerland.
July	1987	Second Conference of Scientific Ocean Drilling (COSOD II), Strasbourg. Arctic drilling was defined as a "Major Opportunity" (p. 40, Munsch, 1987) and labelled "Priority One" (p. 42, Munsch, 1987).
July	1987	Interagency Arctic Research Policy Committee publication of the United States Arctic Research Plan. Deep sea drilling in the Arctic was called "a paramount scientific need" (p. 140).
Apr.	1987	"Science and Politics of Drilling and Site Surveying in Arctic Deep Basins", a special session at the workshop on "Late Cenozoic Paleoenvironments and Geology of the Arctic" at the Spidsbergseter Fjellstue, Norway.
Jan.	1988	Nordic Workshop, Copenhagen.
Jan.	1988	ODP Regional Panels and SOHP urged submittal of Arctic drilling proposal and specific sites.
Mar.	1988	"Drilling in High Latitudes" Workshop at the "Kolloquium des DFG–Schwerpunkt–programms ODP/DSDP", Kiel.
May	1988	Meeting on European interests in and commitments to Arctic drilling, Copenhagen.
May	1988	"Drilling in the Atlantic", ECOD Workshop, Helsinki. Sites were proposed on Yermak Plateau, Hovgaard Fracture Zone, north and south of Jan Mayen Fracture Zone, Norway Basin, and Iceland Plateau.

June	1988	Arctic drilling proposal by Mudie et al. (1988) submitted to JOIDES PCOM.
June	1988	"Scientific Drilling in the Arctic Ocean: Planning for the 1990's", Ottawa. Announcement of the future committee structure of the Nansen Arctic Drilling Program. Presentation of drill site proposals.
July	1988	Meeting of SOHP and preparation of a White Paper on future drilling priorities.
Oct.	1988	"Geologic History of the Polar Oceans: Arctic versus Antarctic", Workshop in Bremen.
Oct.	1988	"Northern High Latitude Drilling Workshop", Bremen. Identified locations of paleoenvironmental and tectonic interest in high latitude Arctic regions which could be drilled with the JOIDES RESOLUTION. It was decided to submit a series of proposals to JOIDES PCOM by March 1.
Dec.	1988	Conference of Arctic and Nordic Countries on Coordination of Research in the Arctic, Leningrad.
	1989	Workshop to be convened on technological solutions to site–surveying in ice–covered waters.

	Acronyms
CMG	IUGS Commission for Marine Geology
DSDP	Deep Sea Drilling Project
ECOD	European Science Foundation Committee on Ocean Drilling
ICL	Inter–Union Commission on the Lithosphere (IUGG–IUGS)
IUGG	International Union of Geology and Geophysics
IUGS	International Union of Geological Sciences
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
ODP	Ocean Drilling Program
PCOM	JOIDES Planning Committee
SCOR WG 82	Scientific Committee on Ocean Research 82: Polar Deep Sea Paleoenvironments
SOHP	JOIDES Sediment and Ocean History Panel
USGS	United States Geological Survey

In the spirit of the FRAM expedition, NAD will be designed also to provide a platform for multidisciplinary research in the Arctic. Polar research disciplines other than geoscience will be able to make use of the logistic framework established for the drilling effort. In particular, close collaboration will be sought with physical and chemical oceanography, meteorology and marine biology. NAD will be led by an Executive Committee. Under the Executive Committee will be a Science Committee and a Technology Committee. At this point, it appears that NAD will employ a suite of drilling technologies (Table 2), designed to achieve specific goals in various regions. For example, JOIDES RESOLUTION may be selected for ice-edge Beaufort and Greenland Sea sites (the subject of a workshop in October 1988, see Table 1), while the bottom-mounted core approach may be used from Canadian, Swedish and German icebreakers on deep penetration expeditions to the central Arctic. A 5-year plan will be defined in the near future when membership in the various committees has been established.

Available Data

Because of the dependence of scientific understanding on observations and the limited accessibility of the Arctic Ocean, this remote region actually has not lost much of its mystery since Nansen's expedition with FRAM nearly 100 years ago. Nansen based his expedition on knowledge of sea ice drift patterns and distribution. Modern high technology investigations using satel-lite imagery and tracking of buoys deployed on the ice have confirmed these observations. Similarly, water mass circulation patterns described in Nansen's early work (Nansen 1902; Helland-Hansen and Nansen 1909) are widely used today, with only minor adjustments in view of higher resolution hydrographic information and sophisticated modelling of tracers.

Modern technology has provided significant new insight through aeromagnetic surveying (Vogt *et al.* 1979; Taylor *et al.* 1981). The Arctic Basin survey showed linear magnetic anomalies clearly indicative of sea-floor spreading in the Eurasian Basin (Fig. 3) and

TABLE 2
PROPOSED ARCTIC DRILLING PLATFORMS
WATER DEPTHS: 10-4000 m. PENETRATION BELOW SEA FLOOR: 50-1000 m

	Platform	Coring Capability	Comments	Approx. Cost*	Limitations
A.	bottom coupled	continuous if ODP technology used	deep holes possible, limited to one hole	1 m / day	very high cost 60 m max water depth
B.	ice (thickened)	"	deep holes possible	21–23 m / core	limited mobility, very high air logistic and support cost, ? summer
C.	drill ship	"	reas. cost limited mobility	30–60 m / year	requires icebreaker support, rounded hull
D.	frozen in barge	"	deep holes possible	40 m / year without icebreaker	lack of mobility, unless round hull is used, subject to ice crushing, ice breaker escort required
E.	shallow drilling	continuous	ship ice or land mounted	.0085 / day	depth limited (60 m) 120 m core length
F.	ODP	continuous with well logging		32.5 m / year	cannot work in even loose ice
G.	Canadian Class 8	continuous	maximum penetration ~ 150 m	?	will be capable of steaming to any region in the Arctic
H.	bottom–mounted	continuous	maximum penetration 50 m	0.3–2.5 m / corer	can be deployed from icebreakers anywhere in the Arctic

* Cost in millions $ U.S.

more complicated signatures in the Amerasian Basin, permitting interpretation of the gross tectonic scenario. Also, compilation of the growing number of bathymetric profiles (unfortunately not always made available from submarine surveys) show the gross geomorphologic features in ever increasing detail, especially along the basin margins (e.g. Perry *et al.* 1986). Within the context of these data, local seismic profiling and heat flow and gravity measurements have been carried out on the following which have also added to our knowledge of sediment and bedrock characteristics (Fig. 4):

A) FRAM I-IV: 1979-1982 (Hunkins *et al.* 1979, Baggeroer and Dyer 1982, Kristoffersen 1982, Kristoffersen *et al.* 1982, Manley *et al.* 1982, Kristoffersen and Husebye 1985),

B) LOREX: 1979 (Lomonosov Ridge Experiment: Sweeney *et al.*, 1982),

C) YMER: 1980 (Boström and Thiede 1984),

D) CESAR: 1983 (Canadian Expedition to Study the Alpha Ridge: Jackson *et al.* 1985), and

E) ARK IV/3: 1987 (Eastern Arctic Basin expedition with POLARSTERN: Polarstern Shipboard Scientific Party 1988, Spielhagen and Pfirman 1988, Thiede 1988).

Sea floor sediment sampling, although extensive in the uppermost sediments of the Amerasian Basin, has been of restricted use because of controversies in dating (e.g. Sejrup *et al.* 1984, Aksu and Mudie 1985, Mudie

Figure 3. Polar projection of the Arctic with major magnetic lineations compiled by Taylor *et al.* (1981)

1985, Mudie and Blasco 1985; Zahn *et al.* 1985, Lövlie *et al.* 1986; Clark *et al.* 1986a; Bleil 1987, Jones and Keigwin 1988), sediment penetration limitations, and the narrow diameter of the coring device used from the ice islands. Although 4 cores sampled sediments deposited before 40 Ma, all the other more than 600 cores now obtained from the Arctic Basin are believed to have penetrated less than the past 5 Ma of the sediment record (Figs. 2 and 4). This leaves gaps several tens of million years in duration in our understanding and documentation of the depositional environment of the Arctic region.

Only two samples of bedrock have ever been obtained from the Arctic Basin. One was a fragmented, highly altered alkaline basalt from the Alpha Ridge (Van Wagoner and Robinson 1985) and the other was a

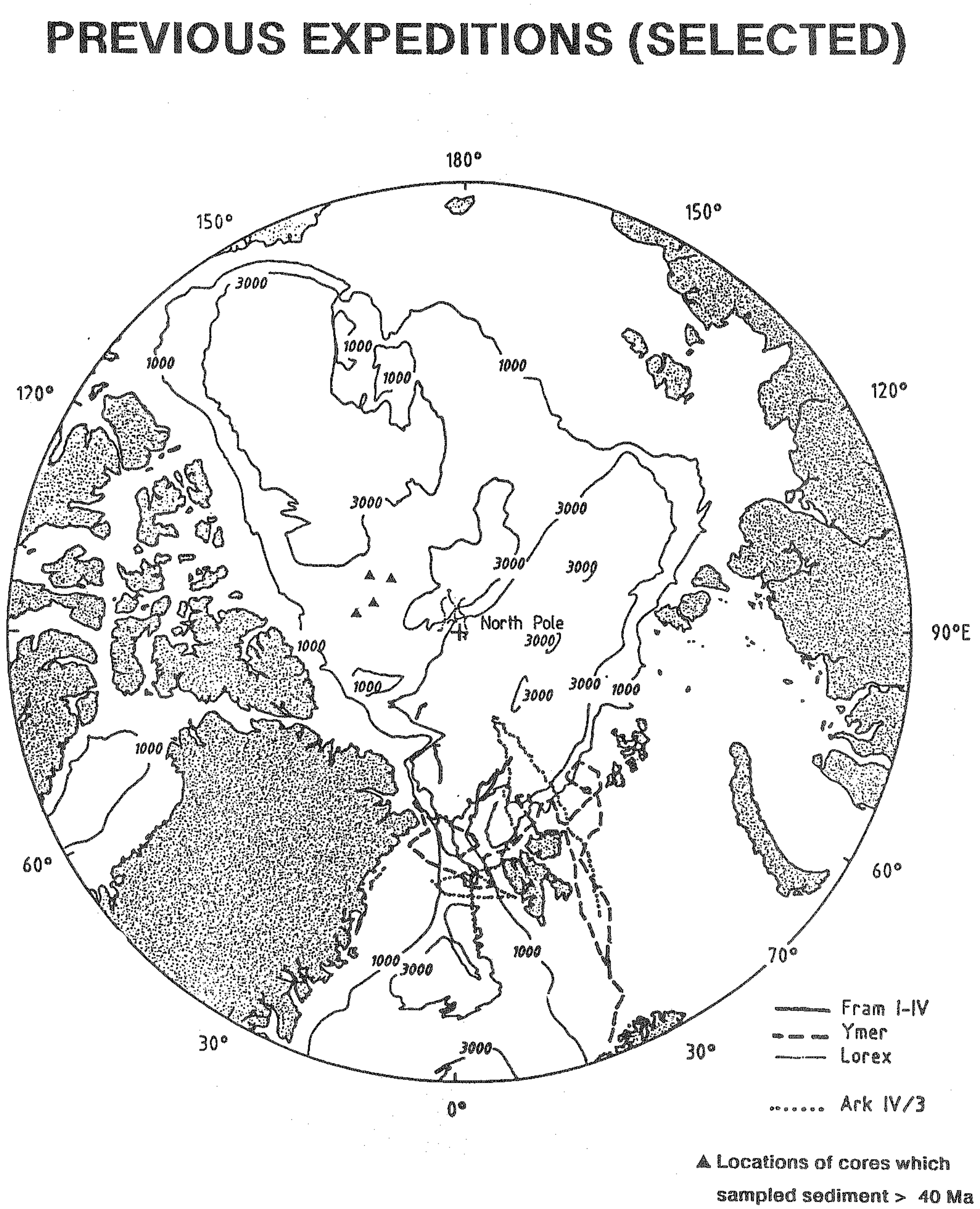

Figure 4. Some of the Arctic expeditions which have obtained data useful for drill site selection. Location of cores which sampled sediment 40 Ma from Clark *et al.* (1986b)

tectonized and hydrothermally altered basalt from the rift valley of the Nansen-Gakkel Ridge (Thiede 1988).

Scientific Goals

The Arctic remains the final frontier in geosciences because investigations in this hostile environment require large logistical and financial commitments, and therefore occur infrequently. Although studies specific for drilling will be designed within the new NAD committees, by incorporating the future goal of drilling in already planned research activities in the Arctic, many aspects of site-surveying and logistic reconnaissance can be carried out with on-going programs, paving the way for future drilling activity.

The two major scientific goals in the Arctic as defined by NAD, understanding the paleoenvironmental and the paleotectonic evolution of the Arctic Basin, are briefly reviewed below.

Paleoenvironmental Evolution

Today's polar oceans represent unique environments because of their cold hydrospheres and the ice caps on adjacent land masses. These environments are the result of a long-term climate change since the end of the Mesozoic and short-term, recurring climate shifts between late Cenozoic glacials and interglacials. On the basis of four cores which penetrated pre-Neogene sediments (Figs. 2 and 4), the Mesozoic and early Cenozoic (approximately 70-40 Ma) Arctic Ocean is interpreted to be ice free, relatively warm, with deep sea basins influenced by rhythmical faunal and floral changes. This paleoclimatic scenario seems to be in accordance with analyses of deposits on adjacent land areas, although evidence for ice rafting may indicate the local occurrence of nearshore ice (Dalland 1977, Thiede *et al.* 1988d). The Arctic Ocean sediments sampled were Campanian black muds and uppermost Cretaceous and Paleogene siliceous oozes, apparently indicative of upwelling, high surface water productivity, and probably oxygen-deficient bottom waters. It is not clear if the entire Arctic Ocean was so productive, or only the region over the western Alpha Ridge.

Since at least 3 to 5 Ma, numerous Arctic cores document that the Arctic Ocean has been cold, more or less ice-covered (Fig. 2). Sedimentation in the Eurasian Basin appears to differ markedly from the Amerasian Basin. For example, periodically the Amerasian Basin has received large amounts of coarse, ice-rafted sediment from adjacent continents (Clark *et al.* 1980) while preliminary investigation of recently obtained samples (Thiede 1988) from the Eurasian Basin sediments appear to contain only rare coarse material. Quaternary sedimentation rates in the Eurasian Basin may be as much as an order of magnitude more rapid (Thiede 1988) than the approximately 1-3 mm/Ky documented in the Amerasian Basin and central Arctic. These differences point toward different sediment sources and depositional regimes in the basins on either side of the Lomonosov Ridge.

Virtually nothing is known of the transition period, when the Arctic shifted from warm, upwelling to cold and glacial conditions because core material is lacking from the intervening stratigraphic section (Fig. 2). We do not know how and when the Arctic Ocean ice cover developed, nor how it behaved in response to late Cenozoic glacial-interglacial climatic fluctuation. Despite the apparent similarity of Quaternary high latitude paleoclimates, the development of glacial-type paleoceanographies of the northern and southern polar ocean appear to have important differences (the subject of a workshop in October 1988, see Table 1). Although Northern Hemisphere ice cover is only well documented for the past 2.6 Ma (based on subpolar drillsites, e.g. Leg 104 Scientific Party 1986), evidence from the Southern Hemisphere indicates that ice has been grounded on the continental shelf of East Antarctica since 35 Ma, and possibly since 42.5 Ma (Leg 119 Shipboard Scientific Party 1988), suggesting cooling occurred at least 20 My earlier than on its northern counterpart.

The NAD Program intends to select sites where drilling results will enhance understanding of the paleoenvironmental, paleogeographical, and paleobathymetrical evolution of the Arctic Basin. Specific aims are to determine:

A) characteristics of pre-glacial Arctic deep-sea paleoenvironments,

B) timing and characteristics of initial climatic cooling and glaciation,

C) timing, magnitude and periodicity of high amplitude late Cenozoic climatic oscillations and resultant ice sheets,

D) paleoceanographic and paleontologic (both flora and fauna) response to climatic change, warm-cold oscillations and changes in the depth and width of corridors linking Arctic and global oceans, and

E) comparison of Arctic with Antarctic cooling and development of glacial regimes.

Tectonic Evolution

The Cenozoic tectonic history of the Eurasian Basin is well understood because it involves the Eurasian and North American plates and is therefore constrained by data from more southerly regions. Also the active mid-oceanic Nansen-Gakkel Ridge contains a readily decipherable magnetic pattern (Vogt *et al.* 1979, Taylor *et al.* 1981). Understanding of the development of the older portion of the Arctic Ocean is less well-constrained (Jackson 1988). During the Cretaceous, the Amerasian Basin is reconstructed to have closed by rotation of the Arctic-Alaska plate against North America. This scenario, its timing and motion are consistent with the geology of the Canadian Arctic Islands and Alaska.

Questions still abound, however, about the age and nature of nearly every other major structural feature in the Arctic. The Alpha Ridge is perhaps the best-studied Arctic geomorphological feature. The CESAR expedition obtained highly altered alkaline volcanic rocks from the ridge, and refraction data indicated a crustal thickness of nearly 40 km with a high velocity lower crust (Jackson *et al.* 1985). In view of this data and magnetic information, the ridge is interpreted as an upper Cretaceous oceanic plateau, similar to the more recent Iceland-Faroe Ridge. However, we do not know if this one sample of alkali basalt is typical.

The Mendeleyev Ridge has a much weaker magnetic signature but appears to be related morphologically to the Alpha Ridge. Its composition and whether it developed together, or separately from the Alpha Ridge is unknown. The Lomonosov Ridge is assumed to be a rifted sliver from the Barents/Kara sea margin, but again, there is no direct proof. The Chukchi Plateau and borderland highs, and the Morris Jesup Rise and Yermak Plateau have never been sampled and have unknown continental/oceanic affinities. The Lincoln Sea is totally unknown and yet is a key region where the Lomonosov and Alpha Ridges meet the continents and where the Nares Strait joins the Arctic Ocean. Whether the Nares Strait acted as a transform fault while Baffin Bay opened is the subject of controversy (Jackson 1988).

Resolving the age and nature of major structural features is the second major goal of the NAD Program. This information, together with paleoenvironmental data provided from drilled sediment sections will permit reconstruction of the paleogeography and paleobathymetry of the Mesozoic and Cenozoic Arctic. Such results would have an impact far beyond the regional boundaries of the Arctic deep-sea basins.

Drilling Operations

Ultimately, in order to address successfully the scientific questions outlined above several drilling requirements must be met. First, detailed site surveys are necessary. Second, coring must be of high quality and should meet the following specifications: sediment penetration at least to 500m below sea floor, with the capability of coring 100m of rock; continuous, HPC type-coring with high-resolution well logging; drilling should be possible in water depths ranging from less 1000m to 4000m; environmental protection must be ensured.

Operational considerations which may limit attainment of these scientific goals are the perennial sea ice cover and constant ice movement, and the restricted possibilities for detailed pre-site surveys because of general inaccessibility of many regions of interest and disputed territorial jurisdictions.

Imaginative technical approaches have been suggested to deal with some of these problems. To a limited degree, and especially in the first drilling phase, sites may be selected based on information obtained from previous expeditions: e.g the ice islands FRAM I-IV, CESAR, and LOREX, and the YMER-80 and 1987 RV POLARSTERN expeditions to the eastern Arctic Basin (Fig. 4). In addition, the CEAREX (1988-9) and future RV POLARSTERN expedi-tions may provide new data in crucial regions in the near future. The CEAREX expedition is to the Arctic Basin margin north of the Barents Sea and Svalbard. A bilateral or multilaterial investigation using RV POLARSTERN from the Arctic shelf to the central Arctic and returning through Fram Strait has been proposed for 1991 (TRAPOLEX - the TRAns POLar EXpedition: Polarstern Shipboard Scientific Party 1988, Thiede 1988, Thiede *et al.* 1988a). However, surveys must also be carried out with regard to specific sites in order to satisfy both scientific and environmental considerations. Supplementing conventional surveying from icebreakers and submarines, innovative approaches to site surveys may include sledges deployed on the ice to conduct seismic profiling and drones sent out from icebreakers, submarines and/or the drill rig itself.

A workshop in 1986 hosted by the Bedford Institute of Oceanography and entitled "Feasibility of Deep-Sea Drilling in the Arctic" (Table 1) documented that drilling in the central Arctic regions was feasible (Blasco *et al.* 1987) either with existing or with new technologies (Table 2). Existing possibilities include: a bottom coupled rig to be used only in shallow depths (less than 45m), deployment of a rig on an ice island or artificially thickened stable ice, or operation of a drill ship such as JOIDES RESOLUTION during light ice years or with attendent icebreaker(s).

New technologies include: a frozen-in barge towed by an icebreaker or a barge modified to be mobile in sea ice, refitting JOIDES RESOLUTION with an ice-going capability (still to be used together with icebreaker support), or use of the newly developed bottom-mounted corer which can obtain samples up to 50m below the sea floor. It could be deployed to the sea bed from icebreakers such as POLARSTERN or the Canadian and Swedish new class 8s.

Using ice or frozen-in barges as the drilling platform has the disadvantage that drilling is subject to the ice drift, affecting both selection of drilling locations and limiting the amount of time available to drill at one site. The combination of a drill platform and icebreaker support provides maximum mobility and the highest probability of being able to move to pre-selected locations and maintaining position while drilling.

Proposed Drilling Locations: Rationale and Technology

A number of sites has been proposed for drilling in the Arctic Ocean (Fig. 5; Blasco *et al.* 1987 and Mudie *et al.* 1988). These sites are presented below together with additional sites in the seasonally ice-covered Norwegian-Greenland Sea.

Greenland and Hovgård Fracture Zones

The Greenland Fracture Zone (Fig. 5, site A) is a linear aseismic ridge, with water depths less than 1500m, extending southeastward from the continental slope of Greenland. No samples of basement have been obtained from this ridge. The fracture zone appears to be essentially non-magnetic and has an elongated gravity high (Vogt 1986). It apparently had a left-lateral offset of about 100 km before anomaly 13 time and the north side may be 15 to 20 million years younger than the southern part (Vogt 1986).

The so-called Hovgård Fracture Zone (Fig. 5, site B) is formed by two linear ridges, less than 1500m deep, arranged in an *en echelon* pattern with a 2600m deep trough in between (Perry 1986). The two segments have high gravity and magnetic anomalies (Vogt 1986), and Gronlie and Talwani (1982) have shown that dense, possibly gabbroic bodies underlie the ridge (Vogt 1986). To date, no samples of bedrock exist. Vogt (1986) proposes that the Hovgård Fracture Zone may not be a true fracture zone, but may be a band of high rift-mountain topography associated with and produced by the Knipovich Ridge. Myhre and Eldholm (1988) interpret the ridge to be a slice of the Svalbard continent which was rafted from the margin 36 Ma bp. If bedrock could be sampled by drilling, the origin and development of this important geomorphologic structure could be resolved.

Although the depth of these features has probably increased with age, even today the Greenland and Hovgård Fracture Zones play decisive roles in water circulation which ultimately determines the properties of deep water formed in the Greenland Basin. Morphologic and paleobathymetric evolution of these features is important to document especially during early phases of opening of Fram Strait, when water exchange with the Arctic is thought to have had large-scale climatic, floral, faunal, as well as sedimentological consequences. Drilling several sites along each ridge crest would indicate if there are age or paleodepth variations. In addition, these drill locations would provide a framework for mapping paleocirculation and ice-rafting influence by sampling from the western margin of the Norwegian-Greenland Sea, presently under the influence of the sea-ice-bearing East Greenland Current, on into the central basin region which is influenced by Atlantic water.

The Greenland and Hovgård Fracture Zones are seasonally free of ice and could be drilled with the JOIDES RESOLUTION with no icebreaker support.

Yermak Plateau and Morris Jesup Rise

Based on superficial geomorphological considerations, the Yermak Plateau (Fig. 5, sites 1-6, 53 & 54,66) and the Morris Jesup Rise (Fig. 5 sites 7 & 8, 68) are thought to be paired plateaus composed of excess oceanic crust. These plateaus are located in the vicinity of Fram Strait, presently the only deep water connection between the Arctic and the rest of the world ocean. Knowledge of their tectonic and physiographic evolution is crucial to reconstruction of the timing of establishment of the deep-water connection. Drilling these features is expected to provide data on the nature and age of the basement and its depth-age relationship; Atlantic vs. Arctic water inflow and outflow; onset of ice rafting and variations in glacial-interglacial sediment input; and ages of unconformities.

The Yermak Plateau is periodically free of sea ice and in a light ice year could be drilled with the JOIDES RESOLUTION, perhaps with emergency icebreaker support. Drill locations are in less than 1000m water depth. The plateau comes under the territorial jurisdiction of Norway. The Morris Jesup Rise is located in a region with perennial, generally thick ice (Fig. 1) which would be difficult to penetrate even with icebreaker support. Sea ice in this region moves at relatively low speed (Fig. 1), and therefore the best drilling approach might be a rig deployed on the ice, especially in view of the logistic support available near-by in Greenland. Water depths are about 1000m and the rise comes under the territorial jurisdiction of Greenland.

Lomonosov Ridge

Based on geomorphologic considerations and magnetic lineations in the Eurasian Basin, the Lomonsosov

Figure 5. Proposed sites for scientific drilling in the Arctic (from Blasco *et al.* 1987 with modifications added after the workshop on "Scientific Drilling in the Arctic Ocean: Planning for the 1990's", 23-24 June 1988, Ottawa).

Ridge (Fig. 5, sites 8, 17, 22 & 23, 59, 70-72) is believed to be a sliver of crust split off by sea-floor spreading from the Barents-Siberian Shelf. Basement has not yet been sampled on the ridge to confirm this hypothesis although large concentrations of Devonian palynomorphs have been found in some of the LOREX cores (Blasco *et al.* 1979). Basement drilling in this region, together with geophysical studies, is a high priority of NAD. In addition to providing crustal information important in understanding the tectonic development of the Arctic Basin, drilling several locations along the Lomonosov Ridge is also necessary for reconstruction of the paleoceanographic and paleoclimatic changes of the central Arctic Ocean for the Quaternary to the Paleogene. Although superficially similar, the ice cover, circulation and sedimentation patterns of the Amerasian and Eurasian Basins, separated by the Lomonosov Ridge, show marked differences. Of particular interest in drilling basement and the sediment cover along the ridge is to determine: 1) nature of the crust and timing of initial rifting, 2) paleotopography and subsidence of the ridge, 3) initiation and history of Arctic sea ice cover and Northern Hemisphere glaciation, 4) distribution of water masses and circulation patterns, particularly with respect to the history of Atlantic Water inflow, and 5) changes in biologic productivity associated with these paleoclimatic and paleoceanographic variations.

Sites of interest along the Lomonosov Ridge crest vary in depth from 500-2000 m, and sediment thickness is unknown. Except for locations just north of Greenland, ice drift can be expected to be fairly rapid (Fig. 1). The site north of Greenland could be drilled in the same manner as the near-by Morris Jesup Rise, and perhaps with the same logistical support. Sites on the central and Siberian sides of the ridge would most likely require icebreaker support for attaining and maintaining positions. The TRAPOLEX expedition would provide an opportunity for obtaining site survey data and can act as a "dry-run" for logistical requirements. If the bottom-mounted corer is available by this time, shallow drilling could also be carried out during the expedition.

Nares Strait Lineament

The Lincoln Sea (Fig. 5, sites 8 & 9, 17, 71) is totally unknown, and yet is a key region where the Lomonosov and Alpha ridges meet the continents and where the Nares Strait joins the Arctic Ocean. Greenland may have slid along the Nares Strait as Baffin Bay opened (Jackson 1988). Drilling will provide understanding of paleogeography of a possibly important link between the Arctic and the rest of the world ocean.

One reason why this near shore region remains a mystery is the difficult working conditions. Although the region is periodically free of sea ice, ice conditions are not predictable from year to year. However, water depths are shallow and Nares Strait is close to logistical support on Greenland. Perhaps drilling could be carried out opportunistically, during periods of unusually open ice.

Alpha-Mendeleyev Ridge

Although some geophysical information is available for the Alpha Ridge (Fig. 5, sites 14-21, 50-52, 75 & 76) and basement has been sampled, the nature and age of the ridge and the surrounding geomorphologic structures must be confirmed by basement drilling. This region is key to understanding how the Arctic Ocean began to open in mid-Mesozoic time and how it has developed since then. Basement age and depth relationships, which can be derived from ocean drilling, will aid in reconstruction of changes in the geometry of the sea floor and its influence on the oceanic environment. These southerly sites are in a region where late summer reversals in ice movement may cause lower ice concentration (McLaren *et al.* 1987) permitting easier icebreaker access.

Water depth of locations of interest range from 1000 m to nearly 2000 m. Ice thickness is high and velocity relatively low along the southern margin of the Alpha Ridge. Drilling in this region could be associated with the logistical support for the Lomonosov Ridge and Morris Jesup Rise sites. The northerly Alpha-Mendeleyev Ridge sites (62-66, 74) are in regions with more active ice movement, and the ice is thinner with more open regions. Drilling would most likely require support of icebreakers to maintain position. The Mendeleyev Ridge sites close to the Siberian continental margin may be approached from the seasonally ice-free shelf and could be drilled by JOIDES RESOLUTION with icebreaker support.

Chukchi Plateau

The Chukchi Plateau (Fig. 5, sites 31 & 32, 42-48, 78), another major geomorphologic feature in the Amerasian Basin has an ambiguous relationship to the Alpha-Mendeleyev Ridge and unknown continental/oceanic affinities. Drilling on this shallow plateau would provide information on its nature and depth evolution which is necessary for reconstructing the paleo-geography of the Arctic Ocean. Paleoenvironmental interpretations are also limited for the Amerasian Basin because turbidites blanket much of the surrounding sea floor rendering samples unsuitable for stratigraphic analyses. Sediments from the shallow crest of this plateau will provide a valuable record.

Drill sites can be approached with icebreaker support from the seasonally ice-free shelf regions in conjunction with Mendeleyev Ridge sites.

Makarov, Amundsen, and Nansen Basins

The Makarov, Amundsen and Nansen Basin all contain records of the sedimentary development of the interior Arctic Basin. Preliminary analysis of sediment cores recently obtained in the Nansen Basin (Thiede 1988) appear to show markedly different sedimentation rates and sediment sources during Pleistocene to Recent times than do central Arctic cores (Clark *et al.* 1980, Aksu and Mudie 1985; Clark *et al.* 1986a). It is not known if these characteristics gradually shift toward the basin interior, or if sea ice and water circulation patterns, together with varying sediment sources, create distinct sedimentological provinces. Drilling in the deep basins will provide a basis for comparison of the sedimentary record and oceanic environment, and will aid in reconstruction of paleogeography, paleobathymetry and paleoceanography.

Drilling in these central Arctic regions (Fig. 5, sites 1, 24, 60 & 61, 55, 69, 73, 77) with rapid ice movement, relatively thin ice and seasonally open leads (Fig. 1) would require icebreaker support for maintaining position. Penetration as far north as the Makarov Basin has been proposed for the TRAPOLEX expedition (Polarstern Shipboard Scientific Party 1988; Thiede *et al.* 1988a). This expedition could provide data on possible drilling locations as well as information on logistical requirements.

Laptev Sea - Nansen-Gakkel Ridge

The active midocean spreading center forming the Nansen-Gakkel Ridge intersects the Siberian continental margin in the Laptev Sea (Fig. 5, site 36). Not much is known of this intersection, although some bathymetric maps show the region to be draped by a large deep-sea fan. If surveys can be carried out to a sufficient degree to map the structural features, drilling could provide insight on their age and nature, thus advancing our understanding of this unusual plate junction.

Sea ice movement tends to be rapid in this region and drilling would therefore require icebreaker support. The proposed TRAPOLEX expedition would provide an opportunity for obtaining some site survey data and could provide information on logistic requirements.

2. SUMMARY AND CONCLUSIONS

One of the greatest challenges for the scientific community is the understanding of past environmental changes in order to predict possible effects of future alterations in global climate.

Analysis of sea floor sediment cores provides paleoenvironmental information on:

A. the geographical extent of sea ice and glaciation,

B. variations in oceanic and atmospheric circulation and material flux from the continents, and

C. changes in surface and deep water temperature, chemistry and productivity.

When coupled with global models, these data will aid in determination of interactions within the atmosphere, cryosphere, biosphere, and ocean systems.

The Arctic Ocean is a region crucial to today's climate. The paleoenvironmental development of this region is, however, only poorly known. Therefore the exact role of the Arctic in climatic developments remains a mystery to both local specialists and global modellers. In a background workshop (Blasco *et al.* 1987), it was shown that it is feasible to obtain the material required to document the evolution of the Arctic Basin, e.g. long, undisturbed sediment cores and samples of bedrock, with a coordinated effort of site surveying and drilling in the Arctic. Drilling in the Arctic has been given "Priority One" in the COSOD II report (Munsch 1987) and was called a "paramount scientific need" by the United States Interagency Arctic Research Policy Committee (1987).

This paper has outlined the scientific rationale and presented an organizational scheme, together with a discussion of the various technological options for drilling in this hostile environment. The Nansen Arctic Drilling Program will be formalized in the near future to provide coordination for this international and multidisciplinary effort. Expected results are:

A) determination of the paleoenvironmental evolution of the Arctic Ocean,

B) increased understanding of the influence of the Arctic on the global ocean circulation and climate systems, and

C) documentation of the tectonic development of the Arctic Ocean basin and its relationship to late Mesozoic and Cenozoic Northern Hemisphere plate motions.

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This paper is based largely on two documents which contain supplementary information (Johnson *et al.* 1988 and Thiede *et al.* 1988c). A summary of the ECOD workshop in Helsinki, Finland, on "Drilling in the Atlantic" which took place on 5-7 May 1988 may be obtained from the ESCO-secretariat, Department of Geology, University of Oslo, P.O. Box 1047, Blindern, N-0316 Oslo 3, Norway. The workshop on "Scientific Drilling in the Arctic Ocean: Planning for the 1990's", which took place in Ottawa on 23-24 June 1988, has been summarized by the Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2, Canada.

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Shoreline Evolution During the Twentieth Century

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ABSTRACT

One of the most significant worldwide tendencies of shoreline evolution in recent decades is active erosion nearly everywhere and the consequent shoreline retreat, even in areas of its previous advance. More than 70% of the accumulative coasts are retreating 10 m/yr or more, 20% 1 m/yr or more, and only 10% are stable or advancing. Recent shoreline erosion is caused by several factors whose relative significance varies with time and location. These causes are both natural and anthropogenic, the latter including intense economic activity in the coastal zone. The principal natural causes are rise in level of the world ocean at a rate of 1.5 mm/yr, formation of equilibrium coastal slope profiles, and inundation and barrier formation in river mouths. The last two factors lead to deficiency of sedimentary material in the coastal zone and release of wave energy for shoreline erosion. Economic activity also results in removal of sedimentary material from the coastal zone as well as deformation of the natural coastal system by hydrotechnical structures (ports, jetties, breakwaters) and decrease in river sediment flow by construction of hydroelectric power stations and river control activities. Thus the sedimentary balance of the coastal zone is changed in favor of erosion. In the next few decades, global shore destruction will continue. First, economic development of the coastal zone is increasing, affecting coasts not previously involved in the process, e.g., in the Arctic and in developing countries, now important areas of industrial and agricultural activity. Second, according to some predictions, level of the world ocean will increase by 3 m by the year 2000, submerging vast areas including some cities. Climate change resulting from accumulation of CO_2 and other greenhouse gases in the atmosphere will strengthen cyclone and typhoon activity, thereby intensifying shore destruction. At present, preventive measures involve mainly the construction of expensive structures (breakwaters, groins, sea walls) which both theory and practice have shown to be of little value. The solution lies in management of natural coastal zone processes based on the theory of shore development. For example, on many USSR coasts where sediments are deficient, sedimentary balance is being artificially restored. Other methods appropriate for different geographic and geological conditions of the world coastline need to be worked out and applied.

Being located between land and sea, coasts are especially dynamic natural features. Continuous transformations of relief and sediment take place there; the shoreline can move forward relatively quickly (in several years) to the ocean or withdraw to the land. It is not uncommon for many hectares of land, dwelling houses, factories, roads, etc. to be eroded and swept away.

In recent times, there has been a major global tendency for shores to erode actively and for shorelines then to retreat, even where they have previously advanced. In recent decades, shore erosion has gained strength and spread to many coastal areas of the world ocean. As early as 1972, the Coastal Environment Commission of the International Geographical Union drew attention to this tendency and carried out special investigations of shoreline erosion (Bird 1985). During 15 years, the Commission collected extensive information confirming that erosion was strengthening and shorelines retreating, especially at depositional, i.e., previously advancing, coasts. According to Commission data, more than 70% of the depositional coasts withdrew landward 10 cm or more per year; nearly 20% of sand and gravel coasts retreated more than 1 m per year.

The U.S. Atlantic coast, fringed by vast sand and gravel barrier islands, is receding at a mean speed of 80 cm/year, the Gulf coasts, 1.2 m/year, and Pacific coasts, where in many places rocky slopes border the ocean, 0.5 cm/year. In some places, shoreline erosion can reach catastrophic scales. At Shoalwater Cape (U.S. Pacific coast), more than 30 m of land is swept away to the sea each year. The Louisiana coastal zone decreased by 300 square miles since 1970. In Miami, 80 m of coast was eroded in several hours during the typhoon in 1926. Total losses from erosion on the Atlantic coast of the US reach 3 billion dollars per year (Bird 1985, Barth and Titus 1984).

Intensive coastal degradation is going on in Argentina (0.5 to 5 m/year), and almost everywhere in Holland and Poland. Erosion prevails in Australia and many other countries.

Of course, all the continents have areas of shoreline advance or stability. But they are not numerous and are associated with the mouths of rivers with great sedimentary load or with coasts formed of very strong rocks.

Substantial erosion occurs on many of the U.S.S.R. coasts which total more than 50,000 km in length. This process is most striking on the highly developed coasts of the Baltic and Black Seas, the Sea of Azov and the Caspian Sea. Of 155 km of the Baltic coast on the borders of Kaliningrad Region, 80 km are subject to intensive destruction with the rate of shoreline degradation reaching 1.5 m/year. The Kurshu Spit -a state reserve with unique landscapes, fauna and flora- causes special concern, being subject to erosion at a speed of 2 to 6 m per year.

There is significant shore destruction at the Black Sea and the Sea of Azov. Of 705 km of Crimean shorelines, 570 km are in a state of active erosion, 71 km of them being depositional shores that were relatively stable in the past. For the Azov coasts of the Ukraine with a total shoreline length of 824 km, , 484 km including 155 km of depositional forms are in an active state of destruction. On the northern Azov coast, 15 to 20 hectares of rich fertile land are being swept to the sea every year.

Many areas of the Black Sea coast in northern Caucasus are subject to destruction. In the last 10 years, the shoreline there retreated by 15-20 m.

In recent decades, shoreline erosion has become a global disaster which leads to enormous material losses and sometimes to human victims.

There are several reasons for the global extent of erosion of coastal depositional forms. General shoreline retreat is, on the one hand, a regular stage of natural coastal zone evolution and, on the other, a consequence of the intensive economic development there.

The world ocean level 17,000 to 15,000 BP rose by more than 100 m as a result of melting of the northern Eurasian and northern American continental glaciers. This was of primary importance for the formation of recent coastal zone relief and sediments. Glacial melting was quite rapid, and the ocean level rose at a speed of 9 m per thousand years. But 6,000-5,000 BP, the transgression slowed down to 1 m per thousand years, and sea level fluctuations occurred in the borders of the recent coastal zone, i.e., from -6 to +3 m from the modern baseline.

As the transgression slowed, coastal plains with rich supplies of loose sediments were exposed to wave attack. Waves intensively deformed the relief and sediments of coastal plains, thus generating bottom coastal profiles. A significant part of the loose material (sand, pebbles) was cast ashore, forming coastal depositional forms near sea level. It was in this period that such enormous depositional forms as the spits and coastal barriers of the U.S. Atlantic coast, Sakhalin Island, Chukchi Peninsula, Mexico, the complex depositional forms and terraces of the Argentine coast, West Africa, the coastal dunes of Eastern Australia, and the North and Baltic seas were formed. Absolute dating of these forms has confirmed that they were formed 5,000 to 2,000 B P, i.e., at the beginning of slowing down of the transgression (Kaplin 1973).

What factor determined the development of depositional forms over long coastal reaches? The principal process unique to the coastal zone is the transformation and dissipation of mechanical wave energy when waves interact with land. Submarine slopes of the coast (which are subject to change during the coastal development) and the quantity of sediments moved by the waves in the coastal zone play an important role in this interaction. Wave action, bottom slopes, and quantity and quality of sediments determine whether coastal zone development is erosional or depositional.

In many areas 5,000-2,000 BP, waves began to interact with gently sloping land and rich supplies of loose sediments. Then coasts advanced as sand and pebble were cast ashore from shallow waters. But in the last century, the speed of sea level rise has distinctly slowed and supplies of loose sediments on the bottom have been exhausted.

The recent deficiency of sediments on the bottom coastal slope in front of the depositional forms is a widespread phenomenon. During the prolonged nourishment of sediments from the bottom, the surface mother rock has become impoverished by those sedimentary fractions which were cast ashore by waves, making up the coastal depositional forms. The residual sediment reaches a dynamic equilibrium with the wave climate at a given bottom coastal slope and no longer supplies coastal accumulation.

If when sediments are deficient, sea level rises slowly (tide-gauge data show that on many coasts this process now has a speed of 1.5 mm/year), the ocean slope of depositional forms, which is steeper than the bottom coastal slope, becomes subject to wave action. Steep slopes assure that large, high-energy waves reach the shoreline. As a result of this process, the frontal parts of the depositional zones are eroded. Some portion of the material washes over the ridge to the back of the forms and the rest is lost to the bottom coastal slope where its accumulation compensates for the depth increase from sea level rise. Because of material redistribution and its washing over the ridge to the back, depositional forms migrate landward, crawling over the coastal plains or lagoons behind them (Zenkovich 1967).

In view of of the reshaping of the coastal zone profile, and land erosion during the rise in world ocean level, the mechanisms of these processes are being actively discussed. The scheme by Per Bruun (1962) is generally accepted. According to this, in the course of sea level rise, the upper part of the coastal slope and the above-water part of depositional forms are eroded. At the same time as this erosion and horizontal retreat of the shoreline, sediments accumulate and the bottom surface is elevated in the lower part of the underwater coastal slope (Fig. 1e). It is assumed that the volume of material eroded from the upper part of the coastal slope and that deposited on its lower part are equal.

In general, the Bruun scheme is supported by both natural and experimental data. But this scheme does not consider that during erosion of the frontal slope of depositional forms, some portion of the material would be washed over by waves and the body of the form would migrate in the direction of land (Fig. 1d). Such a migration process was carefully studied in the Chukchi Peninsula, Western Kamchatka, Sakhalin Island, etc.

In addition, the Bruun scheme is not universal. Both theoretical investigations of Soviet researchers and direct observations on the Caspian Sea coasts which were exposed to a sea level rise of 1.2 m in the last decade (i.e., 12 cm/year), allow identification of various types of coastal zone development under conditions of sea level rise. These types vary primarily with differences in inclination of the submarine coastal slope.

On the most gentle coasts (inclination approx. 0.0005), passive land flooding occurs without coastal zone reformation. These coasts are not subject to wave attack because waves lose their energy at the gentle submarine coastal slope long before reaching the shoreline (Fig. 1a).

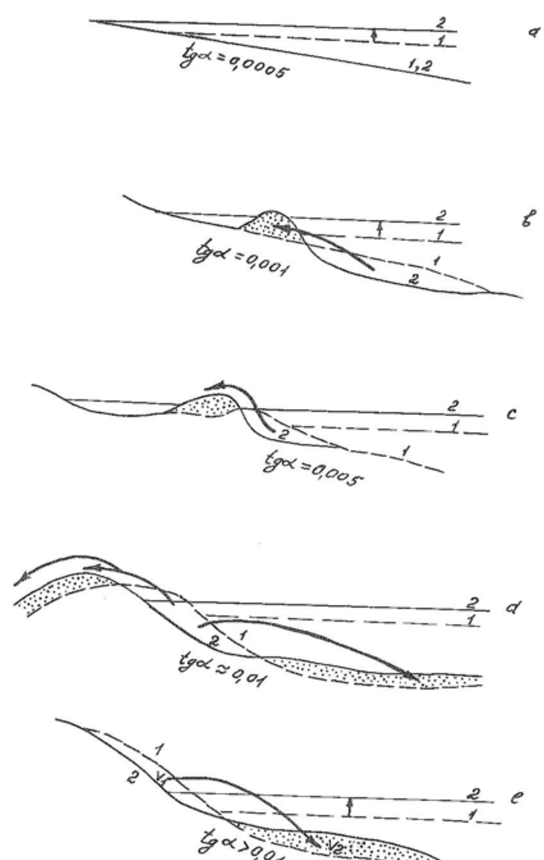

Figure 1. Different types of natural coastal zone development during sea level rise. Differences in schemes (a-e) are caused mainly by inclination tg α of the primary submarine coastal slope. Dotted lines show profiles before sea level rise; solid lines, profiles after sea level rise.

Where the inclination of submarine coastal slope is slightly more (approx. 0.001), increasing sea level results in formation of a coastal ridge in the wave-breaking zone at some distance from the shoreline. This ridge separates some part of the water regime, forming a lagoon (Fig. 1e). The ridge turns into a barrier and is made of bottom material (mainly shell material in the Caspian Sea).

Steeper slopes (approx. 0.005) cause waves to break near the shoreline. Sediments on the submarine coastal slope undergo differentiation, and a significant portion is cast ashore, raising the beach ridge. Simultaneously sea water infiltrates across the ridge, while the lagoon as it forms receives freshwater from land. During the following sea level rise, the beach ridge changes to the bar/barrier form, with a shallow lagoon behind it (Fig. 1c). But where land behind the bar/barrier is not low-lying, a lagoon does not form. Instead, the beach ridge is raised and migrates in the direction of land. In effect, it is the next type of coastal zone development shown in figure 1d.

Coastal development, according to Per Bruun, occurs where the bottom inclination is high, 0.01. There is much uncertainty, of course in using inclination figures alone, because coastal development according to one or another scheme also depends upon other variables, specifically sediment quantity and particle size.

So the experience of studies on the Caspian coasts is very useful for the general analysis of coastal zone development during sea level rise. The Caspian Sea serves as a natural laboratory which can be used for investigations of coastal processes during the projected world ocean level rise. In general, the rapid rise in level has strongly activated erosion processes on the Caspian coasts.

Depositional forms are nourished not only by bottom sediments. Many depositional forms, e.g., wide beaches, are made of disintegrated rock material which migrates along coasts from river mouths and areas of bedrock outcrops. At the beginning of the post-glacial transgression, the decrease of river discharges and the abundance of disintegrated rock material thus favored growth of depositional forms. In front of the abrasion areas, equilibrium underwater slope profiles were gradually formed by waves, so sediment supply from these areas was exhausted.

In recent centuries, sediment nourishment from river mouths, previously the main suppliers of disintegrated material for the coastal zone, has decreased sharply. In connection with the last stage of post-glacial transgression, the mouths of many rivers were flooded, thus resulting in weakening erosion and decreasing supply of loose material from river basins. In addition, numerous small bays and estuaries formed in which river sedimentary load was deposited. On many coasts, depositional forms separated bays and bights from the sea, thus changing them into lagoons. Sediments from rivers and slopes of these water bodies do not reach the ocean coastal zone and are lost irrevocably in these enclosed and semi-enclosed water areas.

But in the natural conditions found up to the present in the coastal zone of the world ocean, depositional coasts would probably exist in some sort of unstable equilibrium, even with the deficiency of sediments, being locally affected by erosion or accumulation. The coastal zone as a natural system is usually protected from degradational processes by some reserve of self-regulation and self-defense. However, the widespread technological interference in nature by man has apparently given rise to disruption of the natural equilibrium and has caused a progressively irreversible intensification of erosion processes.

Since the late nineteenth century, there has been rapid economic development and use of coastal resources: ports have been built, coastal areas strengthened by various engineering constructions, embankments and water collectors intensively built, etc. In most cases, technological interference did not take natural conditions into account and thus upset the existing equilibrium.

The most common type of interference by man into the natural coastal system is the withdrawal of sand and gravel for building. On many coasts, these withdrawals have been massive. This is not surprising in view of the relative simplicity of obtaining construction material from the beach rather than from special quarries. For example, in the 1940's to 1970's, some 30 million cubic meters of sand and pebble were withdrawn from the Georgian Black Sea beaches and delta areas for the construction of towns, resorts, roads, etc. It is not surprizing that this withdrawal has intensified a negative trend in the sedimentary budget of the coastal zone.

Construction of jetties out into the sea and other port facilities often greatly damages coastal zones. These engineering constructions make the alongshore migration of sedimentary material more difficult, break the integrity of natural coastal systems, and result in local but intensive erosion episodes. After the port construction in Poti (Georgia), a land strip 900 m wide was eroded relatively rapidly south of the port.

Anthropogenic activity has a great influence upon solids carried in river flow. According to some estimates, the total of such solids carried into the world ocean coastal zone is equal to 19.3 billion tonnes per year. A significant part of this material remains in river mouths or passes irretrievably to the great depths. Some 3 billion tonnes per year are pebble, gravel and sand, which accumulate in the coastal zone. At the same time, use of river runoff for irrigation and hydroenergy has sharply increased during the last several decades. As a result of dam construction for hydroelectric power, sedimentary material flow into the coastal zone from rivers is abruptly decreased. For example, after the construction of Aswan Dam, the Nile delta began to suffer from erosion at a speed of 40 m per year because of sedimentary deficiency. In general, river runoff under technological activity has a steady decline. According to predictions, continuation of this tendency will result in the reduction of river runoff by 50 percent by the year 2000; the solids carried in river flow will be reduced by approximately the same percent. Thus, because of the decrease of alluvial supply to the coastal zone, the erosion of depositional features nourished by rivers, which has intensified in the last century, will increase further.

In the near future, as the sedimentary deficiency in the coastal zone increases, the global tendency for shore destruction will be intensified. Firstly, occupation of coasts, especially those not previously touched by technological activity, for example of developing countries and the Arctic Ocean, will increase. Secondly, the rise of the world ocean level will continue and, according to predictions, may sharply accelerate in the near future. This rise of sea level is connected with the increase of CO_2 and some other gases in the atmosphere resulting in the so-called "greenhouse effect." CO_2 accumulates in the atmosphere as a result of industrial burning of different fuels. According to data of the U.S. National Academy of Sciences, doubling or even trebling of carbon dioxide, methane and some other gas concentrations in the atmosphere is expected by 2100. This might result in the warming of the earth's surface by 1.5-4.5°C. Such warming will cause glacier melting and, as a consequence, a rise of the world ocean level by 1.5-3.5 m (Barth and Titus 1984).

Even in the absence of greenhouse warming, shore erosion will continue to intensify in the near future because of continuing sea level rise, amplified by technological activity.

In view of these facts, shore protection is clearly a pressing need and suitable engineering constructions should have high priority in the rational use and protection of coasts. These actions should cover the whole coastal zone within the limits of integral natural systems, should minimize the breaches of natural connections, and should use natural conditions to the maximum to aid coastal self-defense.

There is now an urgent necessity to create and implement coastal management models. As one of these, we can consider a model of the sedimentary budget with artificial regulation of additions and subtractions to it.

The best way to defend a coast from storm waves is to construct a beach in front of it to exclude wave energy. Thus more and more specialists conclude that the basis of coastal protection activity should be the restoration of eroding beaches and the creation of new artificial ones. Depending on the specific conditions, different methods can be used to bring sedimentary material into the coastal zone: material can be unloaded from lorries at a definite point on the beach and then allowed independently to migrate alongshore to be distributed in the natural system; material can be unloaded from barges onto the bottom, being brought ashore by wave action, thus forming the beach; material can be transported from river mouths to the eroding coastal area by a pipeline; etc. These activities are carried out on a wide scale on the eastern Black Sea coast. On a regular basis, taking natural conditions into account, they pour out on the coastal zone considerable quantities of beach-forming material (sand, pebbles) from land quarries. For example, 510,000 cubic meters of sedimentary material were brought to the beach in the Gagra-Pitsunda area in 1982. The wide beach formed by now not only protects dangerous areas but also sharply improves the state of the whole 22 km long coast (Zenkovich and Schwartz 1987).

Until the beginning of the 1980s, 220 km of the total 312 km length of Georgian coasts underwent destruction. The rate of erosion reached 16 m per year in some places. During the last 5 years, the Georgian coastal zone condition has been significantly improved, and at present there are no heavily eroding coastal areas in the republic.

It is natural that in different geographical and geological conditions specific approaches to the shore protection would be needed. With coastal economic development, by carrying out a policy of coastal management based on self-regulation and self-defense of coastal systems, we should be able to stop the destruction of exceptionally valuable coastal territories and even to create conditions for their normal natural development.

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CHAPTER 2

OCEAN AND CLIMATE

Stewart, R.W. 1989. Causes and Estimates of Sea-Level Rise with Changing Climate, p. 65-68. In: A. Ayala-Castañares, W. Wooster and A. Yáñez-Arancibia, eds. *Oceanography 1988*. UNAM Press, México D F, 208 p.

Causes and Estimates of Sea-Level Rise with Changing Climate

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ABSTRACT

It is widely believed that rising temperatures associated with the anthropogenic increase in radiatively-active gases will result in some large rise of sea level. However, estimates consistent with the results given by models for future atmospheric temperatures are appreciably lower than those generally accepted. The reasons for the discrepancy are discussed.

1. THE RECENT PAST

Analysis of the sea-level records which have been obtained over the last century have been undertaken by a number of authors. Virtually all of the data used by these authors are held by IAPSO's Permanent Service for Mean Sea Level in IOS Bidston, United Kingdom. Typically, the conclusion is drawn from these data that over the last century the general (or eustatic) sea-level rise has been in the neighborhood of 10-15 cm. However, relative sea-level -- that is, the change in local mean sea level relative to local geodetic benchmarks -- has been observed to vary over a much wider range. In areas formerly heavily glaciated, such as Scandinavia, Alaska, and northern Canada, relative sea level is observed to be sinking at rates of the order of one meter per century. On the average, relative sea level on the east coast of North America has been rising at about 30 cm per century. The difference between these numbers and any eustatic rise is mostly the result of crustal movements of the earth at coastlines.

It is important to recognize that there may have been **no** significant eustatic rises of sea level over the last century, and that nearly **all** of the relative changes may be the result of crustal movements. Such crustal movements can be expected to continue into the next century regardless of the evolution of climate. However, in many areas the reasons for the crustal movements are not well-understood and rates of movement may change in the future. Indeed, these rates are so large from a geological standpoint that they must change, although perhaps not on the timescale of a human life-span. (For example, the geological state of the east coast of North America, a passive margin well removed from the mid-Atlantic spreading center, has hardly changed in the last 10 million years). Ten centimeters per century, or 10 km in 10 million years, is about 100 times the rate which would be inferred from the depth of shelf sediments which have accumulated over that time.

2. CAUSES OF RELATIVE SEA-LEVEL CHANGE

Climate-related sea-level change can have four causes:

1. Melting of land-supported ice *
(a) Small glaciers and ice-caps.
(b) Major ice-sheets on Greenland and Antarctica.

2. Heating of parts of the ocean, with associated expansion and surface rise.

3. Changes in wind fields and ocean currents, leading to the redistribution of surface water.

1. (a) It is common experience that mountain glaciers in Europe and in North America have lost mass during the last century, and there is little reason to doubt that there has been some rise in sea level from this cause. Meier has made a careful study of the ablation of mountain glaciers and small ice-sheets. He concluded that over the period he examined, 1900 to 1961, these small bodies of ice had lost mass equivalent to a rise in sea level of about 2.6 cm, with an uncertainty of about 50%.

Much of the ice in small glaciers and ice-fields resides in remote areas such as the Canadian Arctic islands, Patagonia, and mid-Asia. Many of these have not been subject to detailed survey. There is thus considerable uncertainty to how much ice remains. Studies which have been made by Flint and by Hollin and Barry indicate that mass of ice of this kind is sufficient to raise sea level by about half a meter should it all be melted. Again the uncertainty is about 50%.

A large proportion of this ice is at very high latitude, and/or altitude, and it is not likely that a doubling of carbon dioxide content in the atmosphere would lead to its complete elimination. A rise of sea level of some 10cm, with considerable uncertainty, is a reasonable figure to use for this effect.

1. (b) The great ice-caps in Antarctica and Greenland contain very much more mass. If all this ice should melt, sea level would rise about 75m. Thus the loss of a relatively small proportion of these ice-caps, say 2 %, would be very significant. The resulting 1.5 m rise in sea level would substantially exceed anything that has happened globally in historical times. There has been a great deal of discussion and speculation about the fate of the west Antarctic ice-sheet. This mass of ice is grounded below sea level and is therefore particularly vulnerable to the effects of rising temperature. There is considerable evidence that this area was deglaciated during a warm portion of interglacial immediately preceding the present one, and that there was a resultant 5m rise in sea level. However, present specialist views seem to be consolidating around an opinion that a massive reduction in the volume of the west Antarctic ice-sheet would be a rather slow process on a human time-scale. This contrasts with the rate of disintegration of the great Eurasian and North American ice-sheets at the end of the last glacial stage. Then sea level rose at about 1m per century. However, with the retreat of ice to about its present limits, which was completed about 4000 years ago, there has been little evidence of further melting. Indeed, according to Duplessy, all the remaining major ice-sheets are well "buttressed" by resistant rock, and are not particularly vulnerable to rapid disintegration.

Speculation about the future of the great ice-caps is greatly complicated by uncertainty over the amount of precipitation they will receive. Over the whole range of ocean temperature, an increase of one degree in surface temperature corresponds to an increase of 6% in vapor pressure. To a first approximation, the amount of evaporation will be expected to increase similarly. Over the whole earth, evaporation must equal precipitation. The distribution, however, is very different. On the average, the evaporation-precipitation regime acts to transport water from low latitudes to high.

Dealing with precipitation is one of the most difficult problems faced by atmospheric modelers. While there is little doubt that a general rise in temperature will increase both evaporation and precipitation, how much of this additional precipitation will fall on the high-latitude ice-caps is very uncertain. One can get some feel for the possible magnitudes by noting that the annual additions to and subtractions from in these ice-caps amount to the equivalent in sea level of rather less than one centimeter per year in each direction. Within the uncertainty, they are in balance. If a climate change tilted this balance by 20%, the resulting change in sea level would be at a rate of about 20 cm per century. That figure is a reasonable estimate for the uncertainty in sea-level evolution from changes in the mass of ice on ice-caps. There is no special reason to believe that it will go one way rather than the other.

2. The great majority of ocean water is cold, with temperature less than 4 degrees. In each ocean, a lens of warmer water floats on this cold water. The warmer

* It is worth noting that melting of floating ice, such as that covering the Arctic Ocean, would have no effect on sea level, since by Archimedes' Principle, floating ice already displaces its mass of water.

and thicker this lens, the higher it floats. Much of the anticipated rise in sea level is due to the expected warming and accompanying expansion of these warm lenses.

Sea-level rise for this cause is determined by three factors:

(a) Temperature rise.

(b) Depth over which this temperature rise occurs.

(c) Coefficient of expansion of the water.

All three vary significantly.

(a) The warmest surface water in the ocean has a temperature of 30°C, and only a very small proportion of tropical water gets this warm. The reason is the very rapid increase in evaporation with temperature, alluded to above. At 30°C nearly all the incoming solar radiation is used to provide latent heat of vaporization. It is very difficult for the temperature to rise higher, and this will continue to be the case with an increase in the concentration of radiatively-active gases since there is no expected increase in the amount of incoming solar radiation. Further, the long-wave radiation field over high temperature water is dominated by the presence of water vapor, so the addition of more greenhouse gases has comparatively little effect.

At higher latitudes the water is cooler, and more heat loss occurs by other mechanisms, including radiation. An increase in greenhouse gases, resisting radiation loss, leads to an increase in surface temperature. At high latitudes various feed-back mechanisms, such as the retreat of sea ice with increasing temperature, accentuate the effect. Thus it is a common feature of models comparing present climate with that anticipated in the next century to predict rather little temperature increase over the ocean in the tropics, and a very much larger increase at high latitudes.

(b) Because of the nature of ocean circulation, particularly wind-driven, the depth of the warm water lens varies a great deal. It tends to be rather shallow in equatorial regions and thicker at higher latitudes. It also gets cooler at higher latitudes. There is a good deal of difference of opinion about what will happen with global warming. Taking it as given that the surface water will warm, what will happen at depth? For example, if surface water now at 18°C warms to 20°C, will all the water now at 18°C become 20°C water, or will the deep 18°C water simply lie under the new 20°C water and become connected to 18°C water at higher latitude? The answer is important. If the effect of warming is to raise the temperature of most of the upper water significantly, the resulting sea-level rise could be a large fraction of a meter in some places. If the effect is mostly to move the surface outcrop of isotherms somewhat poleward, without deepening them much, the effect on sea level is a great deal less.

My own view is that the depth of the upper layer is determined largely by the dynamics of the ocean, and in particular by the wind-driven circulation. I therefore lean to the view that warming will lead to poleward movement of the outcrops of isotherms. With this prejudice, I expect something like the changes in sea level shown in Table 1.

3. Changes in Ocean Currents: Because of the effects of the earth's rotation, surface currents in the ocean are accompanied by slopes of the sea surface. Changes in ocean currents will therefore be accompanied by sea-level changes.

Sea-level variations associated with these currents amount to a total just over a meter. There is a good possibility that the result of climate change will be to reduce the temperature contrast between low latitudes and high, and therefore the strength of wind-driven ocean currents. If the reduction of wind strength is 10%, the average wind stress will be reduced by about 20 %. We might, therefore, expect a reduction of something like 25 cm in the variation of sea-surface elevation associated with currents.

The nature of the oceanic circulation is such that at mid-latitudes, where we have the great subtropical

TABLE 1

Present Temperature	Increase	Expansion Coefficient	Depth (m)	Sea-Level Rise (cm)
30 °C	1°C	3.4×10^{-4}	100	3.4
20 °C	2°C	2.6×10^{-4}	200	10.0
10 °C	3°C	1.7×10^{-4}	400	20.0
0 °C	4°C	0.8×10^{-4}	1000	30.0
ice	0°C		seasonal	5.0

gyres, the highest areas are relatively concentrated in the interior of the ocean, and the low areas are spread widely along the coast. A reduction in contrast, which represents a redistribution of warm water from the high areas toward the low areas, will take the form of a more substantial drop of the localized high areas than rise of the extensive low areas. It is therefore very unlikely that, of a possible 25cm in change of contrast, more than 5 or 6cm would appear as sea-level rise at the coastlines. It should be noted that this statement applies to continental coasts. Changes in ocean circulation could produce considerably larger effects at mid-ocean islands. Even for them, however, it is very unlikely that changes from this cause would exceed about 20cm.

What does this amount to altogether? My personal view is that ocean sea-level rise over the next century will not be particularly dramatic.

The contribution of the great ice-sheets in Greenland and the Antarctic could be 20cm either way, but my own guess is a much smaller value, not greatly different from zero. We might well see 10cm more water from the melting of small glaciers and ice-caps. I expect that the expansion of the ocean will produce sea-level rise of a few centimeters in the tropics to perhaps 30cm in a restricted range of high latitudes. Changes in ocean currents may cause sea-level changes of a few centimeters. Overall, I estimate a rise of some 20cm in tropical regions, mostly associated with the melting of glaciers and small ice-sheets, rising to something like 40cm at high latitudes, with a large contribution from the expansion of the ocean. It is worth noting that these high latitudes are where the land is rising because of post-glacial rebound, so that the relative change in sea level may be considerably reduced. There is much uncertainty in these numbers and they may be wrong by as much as a factor of two (either way).

A considerable fraction of the earth's coastlines have experienced relative sea-level changes larger than this over the last century, mostly because of crustal movements. Of course that does not mean that there will be no effect. Where crustal movements are producing relative sea-level rise, such as along the east coast of North America, a general rise of ocean levels will aggravate existing problems. Perhaps more important will be the fact that we must expect the areal extent of very warm water to expand appreciably. This will be accompanied by the expansion of the region of the earth subject to intense tropical storms. The resulting storm surges cause temporary local sea-level rise, which may be more intense in regions already subject to them, and occur in regions where they are now very rare. Such storm surges may be the most important sea-level aspect of the forthcoming climate warming.

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On the Synoptic Variability of the World Ocean

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ABSTRACT

My lecture is planned as a survey of the topic. First, I shall discuss the observations; second, define synoptic motions; third, outline possible generation mechanisms; fourth, consider the dynamics of synoptic motions; fifth, discuss the influence of synoptic motions on the earth's climate. The history and bibliography of the subject can be found in monographs (Robinson 1983; Kamenkovich *et al.*, 1986a). Here only selected references will be given to illustrate the basic ideas.

Observations

Synoptic motions have been described and studied only recently. The following well-pronounced structures are noteworthy.

1. Strong Current Eddies, or Rings

Consider the Gulf Stream region for which such eddies are most comprehensively described. Figure 1 shows the topography of the 15° isothermal surface for the period from March 16 to July 9, 1975. It is easy to see the Gulf Stream separating warm Sargasso waters from cold slope waters, well pronounced Gulf Stream meanders after Cape Hatteras, and Gulf Stream eddies (or rings) located to the south (cold core rings) and to the north (warm core rings) of the Stream. These eddies are formed as a result of the evolution of strong meanders leading to splitting off the meanders from the Stream with the trapped warm water (anticyclones) or cold water (cyclones).

In figure 2, as a typical example, the trajectory of the cold-core ring Bob is shown with the topography of the 15° isothermal surface at selected times of its life. We can see very clearly the birth of the eddy (during a year, from 5 to 8 such rings and approximately the same number of warm-core rings appear), the motion of the ring to the west, and the coalescence with the Stream (the evolution of warm-core rings differs somewhat from that of the cold-core rings). Figure 3 shows the detailed structure of the ring Bob. The typical horizontal scale of the ring is approximately 50 km (the total diameter is approximately 200 km) and the vertical scale is one kilometer; the velocity scale is 1 m s^{-1}; the speed of translation is 1-3 km day^{-1}; the time scale is 50 days.

The described ring is typical not only for the Gulf Stream region. Similar structures are observed near other strong, narrow currents including the Kuroshio, Brazil, East Australian, Agulhas, and Antarctic Circumpolar Currents.

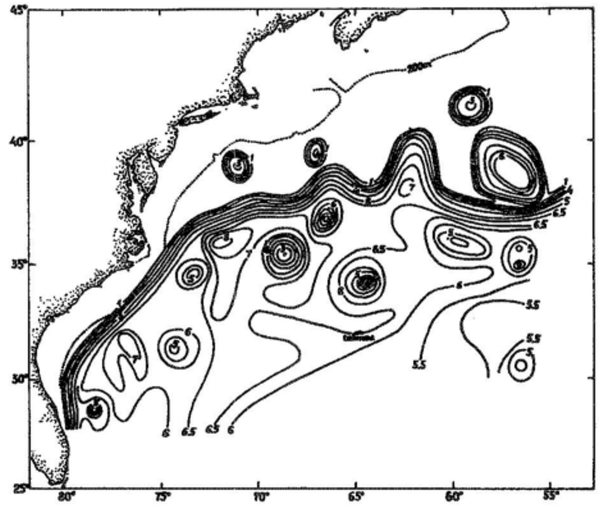


Figure 1. Topography (in hectometers) of the 15° isothermal surface showing the Gulf Stream and cold-core and warm-core rings for the period 16 March to 9 July 1973 (Richardson *et al.*, 1978).

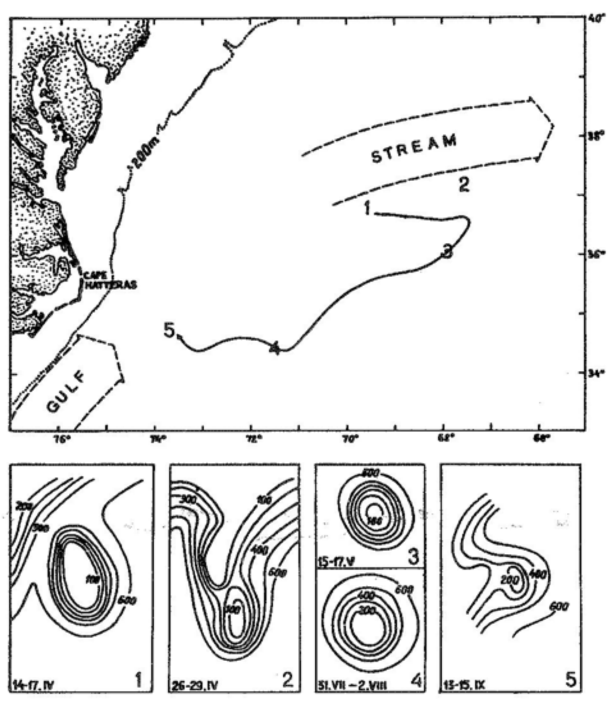


Figure 2. Trajectory of Ring **Bob** in 1977 (top) and the topography of the 15° isothermal surface in BOB at several times during its life (bottom). **Bob** moved eastward while interacting with the Gulf Stream, split off from the Stream, drifted southwestward through the Sargasso Sea, and then coalesced with the Stream near Cape Hatteras after a lifetime of 7 months (from Ring Group 1981, with some details omitted).

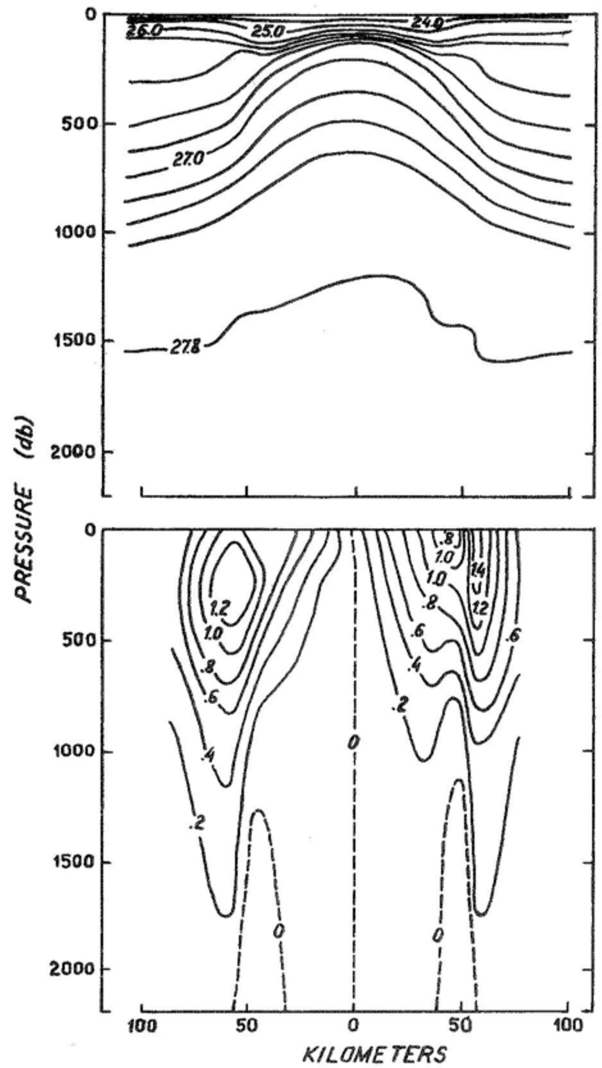


Figure 3. Isolines of the potential density, $\sigma\theta$ (kg m^{-3}) in a section of Ring **Bob** (top) and isotachs of the geostrophic velocity perpendicular to the section (m s^{-1}) relative to the 2500 db reference level (bottom) (Olson 1980).

2. Mid-Ocean Eddies

Mid-ocean eddies which are local maxima or minima in pressure distribution (i.e., structures with closed isobars or streamlines) in a horizontal plane. As a typical example, figure 4 gives a sequence of maps showing the evolution of such eddies during a two and a half month period in the region of the Soviet POLYMODE Expedition. Figure 5 reflects the vertical structure of these eddies.

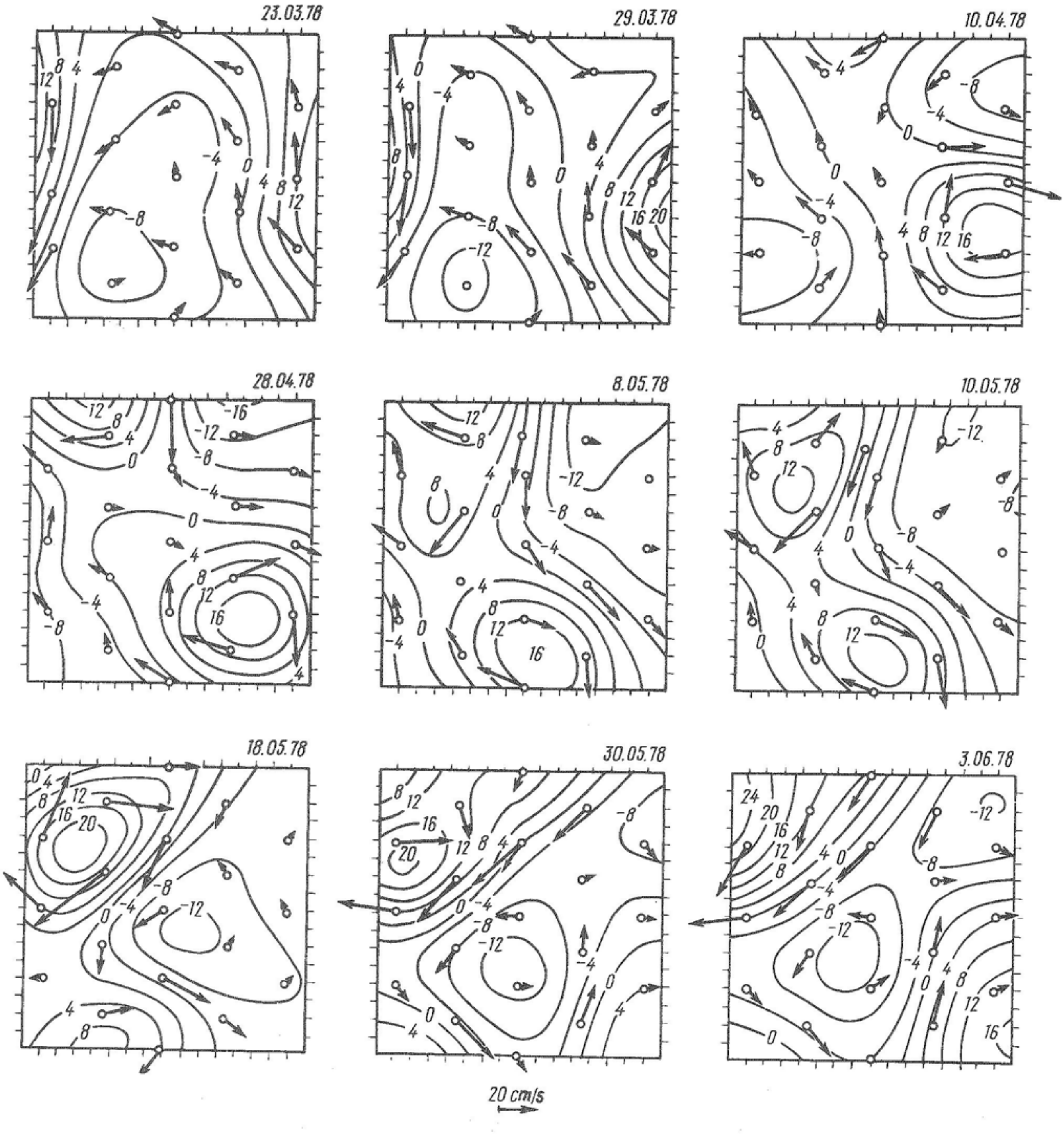


Figure 4. Streamfunction isolines (streamlines) and measured velocity vectors at the level 700 m in the Soviet POLYMODE region in March-July 1978 (Koshlyakov *et al.* 1980). The coordinates of the centre of the region are 29°N, 70°W; the side of the square is 288 km.

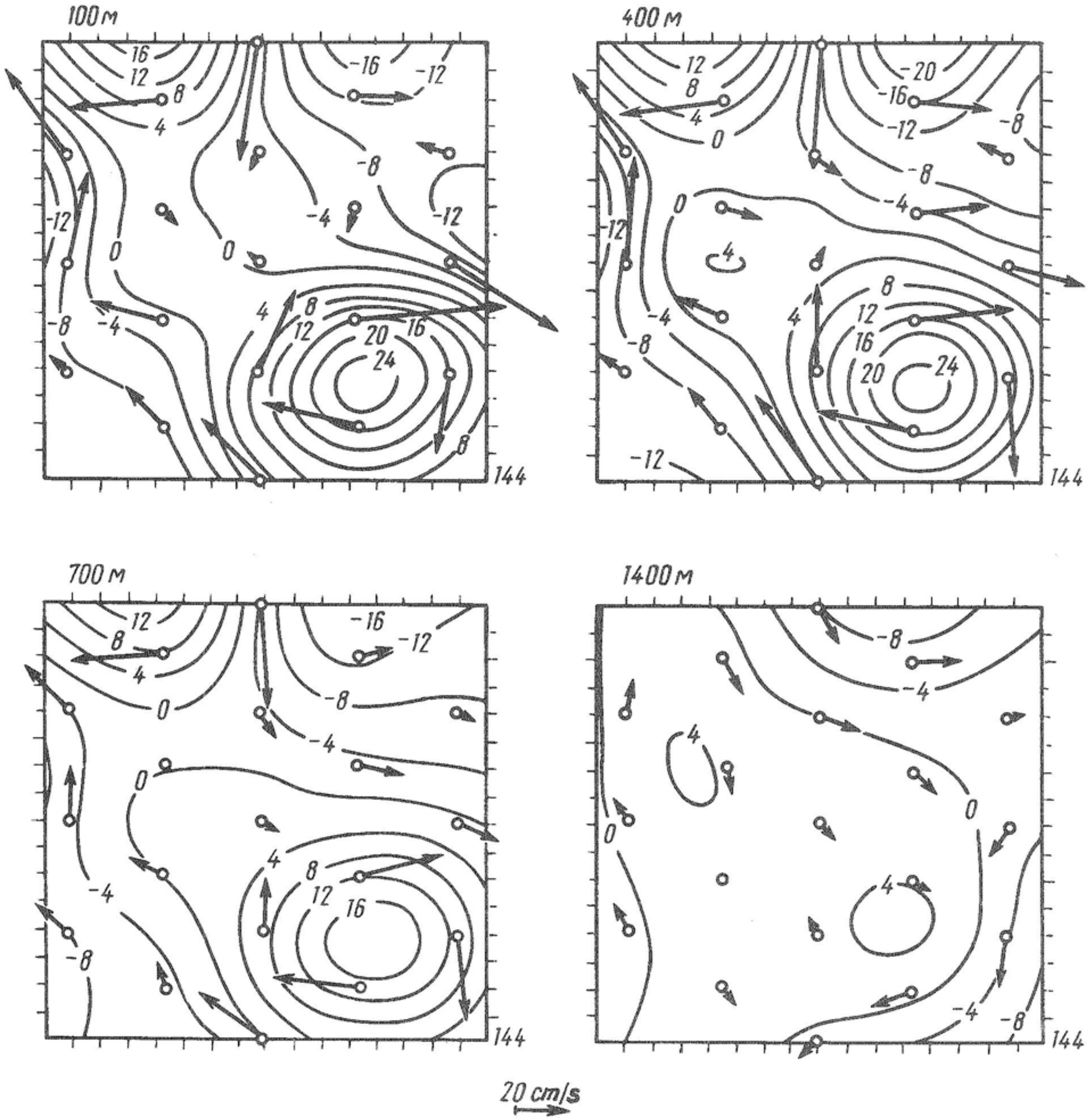


Figure 5. Stream function isolines (streamlines) and measured velocity vectors at levels 100 m, 400 m, 700 m, 1400 m in the Soviet POLYMODE region on 28 April 1978 (Koshlyakov *et al.*, 1980). The coordinates of the center of the region are 29°N, 70°W; the side of the square is 288 km.

The great amount of data collected up to now (both direct measurements made in different regions of the World Ocean and indirect data based on analysis of historical data, e.g., ship drift or hydrological data) demonstrates the ubiquity of mid-ocean eddies in the world ocean. The typical horizontal scale of such eddies is approximately 50-70 km; the vertical scale is 1 km; the velocity scale is 10 cm s^{-1}; the velocity of propagation is 1-3 km day^{-1}; the time scale is 50-100 days. Mid-ocean eddies usually consist of water of local origin.

It is important to note that as a rule water particle velocities in the eddies are greater than the velocities of mean global scale currents at the same place. That is why instantaneous measurements in the ocean by no means characterize the mean global scale currents.

3. Solitary Lens Eddies

Solitary lens eddies (intrathermocline) with typical thickness of several hundred meters and diameters of a few tens of kilometers, i.e. substantially smaller than mid-ocean eddies. These eddies are characterized by the existence of a well mixed core with anomalous T-S relationship and hydrochemical characteristics and stand out sharply from local conditions. This important feature points out that the region of formation of such eddies is located far away from the place of observation, sometimes 1000 km and more. The maximum azimuthal velocity of these eddies, of the order of 10 cm s^{-1}, is located within the thermocline (hence intrathermocline eddies). Their life time is of the order of a year or more. As a well pronounced example of such eddies, figures 6 and 7 show the lens observed by the Soviet Expedition MESOPOLYGON in 1985 in the tropical Atlantic (20° N, 37° W). The lens was oval in plane with axes of 70 km and 55 km (i.e., the characteristic horizontal scale is approximately 30 km, less than that of mid-ocean eddies). It was located in the 780 - 1400 m layer, and had record large anomalies of potential temperature (4.5° C) and salinity (0.87 ‰) in the well mixed core.

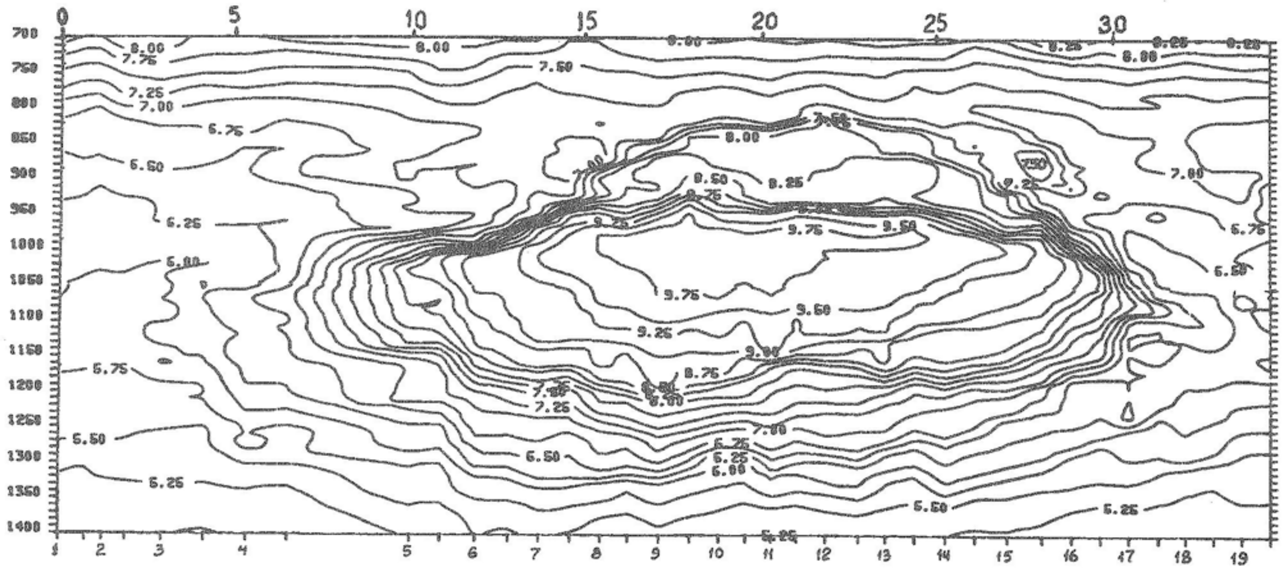


Figure 6. Isolines of temperature (°C) at a zonal section through the center of a lens of Mediterranean water along 20° 12'N on 21-22 June 1985 (Berestov *et al.* 1986 with some details omitted). At the top, distances are given in miles from 38° 35'W.

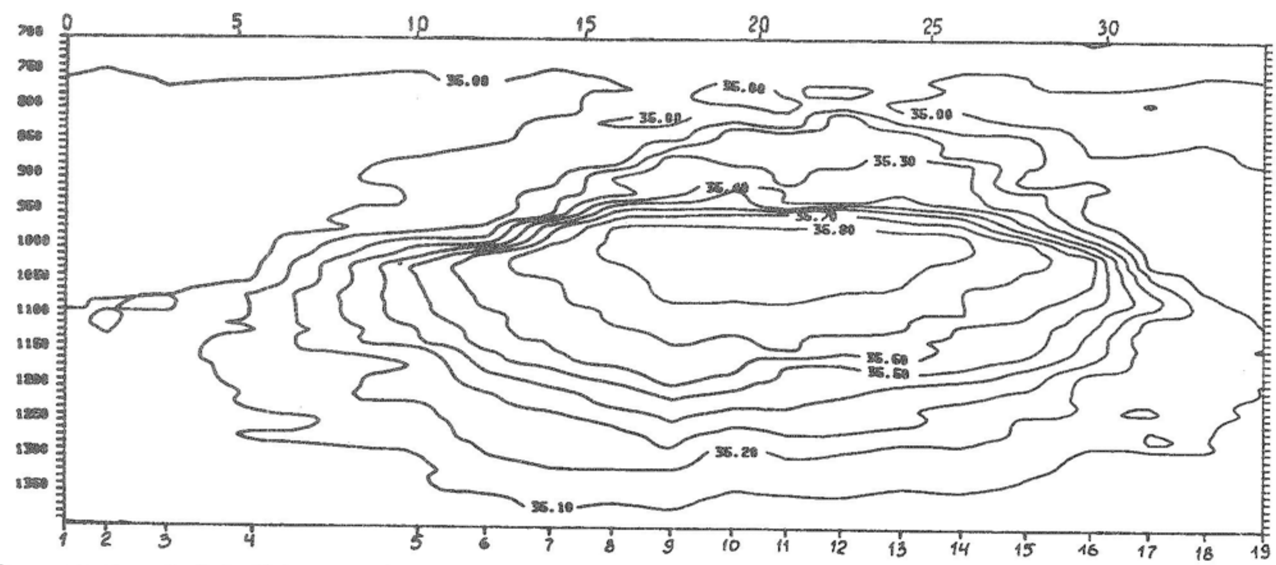


Figure 7. Isolines of salinity (‰) at a zonal section through the center of a lens of Mediterranean water along 20° 12'N on 21-22 June 1985 (Berestov *et al.* 1986 with some details omitted). At the top, distances are given in miles from 38° 35'W.

Intrathermocline eddies have been observed recently in many regions of the World Ocean, especially in the Atlantic (lenses with cores of Mediterranean water) and the Arctic (lenses with cores of Pacific water). Up to now, several hundred examples of such eddies have been described (Belkin *et al.*, 1986).

Definition of Synoptic Motions

After the above description, it is worthwhile to single out as a special class the motions with horizontal scales from tens of kilometers to a few hundreds of kilometers, vertical scales from hundreds of meters to a kilometer, time scales from weeks to months, and characteristic velocities from tens of cm s^{-1} to several m s^{-1}. The types of motions described above belong to this class which I shall call *synoptic motions*.

This name requires some explanation. In their physical nature, the described eddies are analogous in many ways to atmospheric mid-latitude cyclones and anticyclones which are represented on synoptic charts and for this reason are called synoptic motions. To stress this analogy, oceanic eddies are also called synoptic.

I would like to point out that the described oceanic eddies have the Rossby radius of deformation L_R as a characteristic scale, i.e. two important physical effects determining the vorticity distribution in the eddy field, the advection of relative vorticity and the stretching of vorticity lines, are of the same order for these motions.

Let us remember the formal definition of L_R:

$$L_R = H\overline{N}/f_o$$

where $\overline{N}$ is the characteristic value of the Väisäla frequency for the layer occupied by the motion, H is the vertical scale of the layer, and f_o is the characteristic value of the Coriolis parameter. For the region of the Soviet POLYMODE expedition, $L_R = 50$ km. It is now possible to reformulate this feature in the following manner: for the types of motion considered, the ratio of the vertical and horizontal characteristic scales H/L is of the order $f_o/\overline{N}$.

In English-language scientific literature, the term *mesoscale motion* is widely used instead of *synoptic motion* to stress the difference between the scales of eddies and of main oceanic gyres.

The eddies under consideration (rings, mid-ocean and lens eddies) do not exhaust all the possible types of synoptic motions in the ocean. There are also some intermediate types of motion, e.g., solitary eddies of smaller dimensions as compared to mid-ocean eddies observed during the POLYMODE expeditions (Kamenkovich *et al.*, 1986a, p. 305, 315-318). Further, there are Rossby waves in the ocean, both ordinary and topographic, which manifest themselves, for example, as wave-like disturbances which are imposed on smooth variations of the global scale ocean characteristics and which do not necessarily result in formation of closed isobars in a horizontal plane. The proof of the existence of Rossby waves in the ocean is given, for example, in Thompson 1977; Konyaev and Sabinin 1981. The meanders of strong currents like the Gulf Stream; Kuroshio, etc., also belong to the class of synoptic motions, but they have, of course, a more local character.

The stated definition is suitable for the separation of the synoptic motions in the statistical processing of data. For example, it is possible to single out the synoptic motions by considering their time scales (usually the motions obtained by such a method have "synoptic" horizontal, vertical, and velocity scales as well). Using such an approach, figure 8 was constructed by processing the data of all available moored stations in the northern Atlantic. Two features of the global distribution of synoptic motions should be stated: first, synoptic motion appears to be a universal feature of the North Atlantic; second, the energy of synoptic motions decreases when moving away from the Gulf Stream to the central part of the subtropical gyre.

Generation of Synoptic Motions

What physical mechanisms are responsible for the generation of synoptic motions in the ocean? I exclude from this discussion the rings and lens eddies which have very peculiar but more definite mechanisms and confine myself to discussing the generation of mid-ocean synoptic motions. The following physical mechanisms are possible:

1. Baroclinic and Barotropic Instability

Baroclinic and barotropic instability of the global scale motion in the ocean. The former transfers the available potential energy of global scale motions into the energy of synoptic scale motions and the latter transfers the kinetic energy of global scale motions into the energy of synoptic scale motions. In the ocean there is a large amount of stored available potential energy in the global scale motion. Simple estimates show that 10% of this energy is enough to support the observed eddy

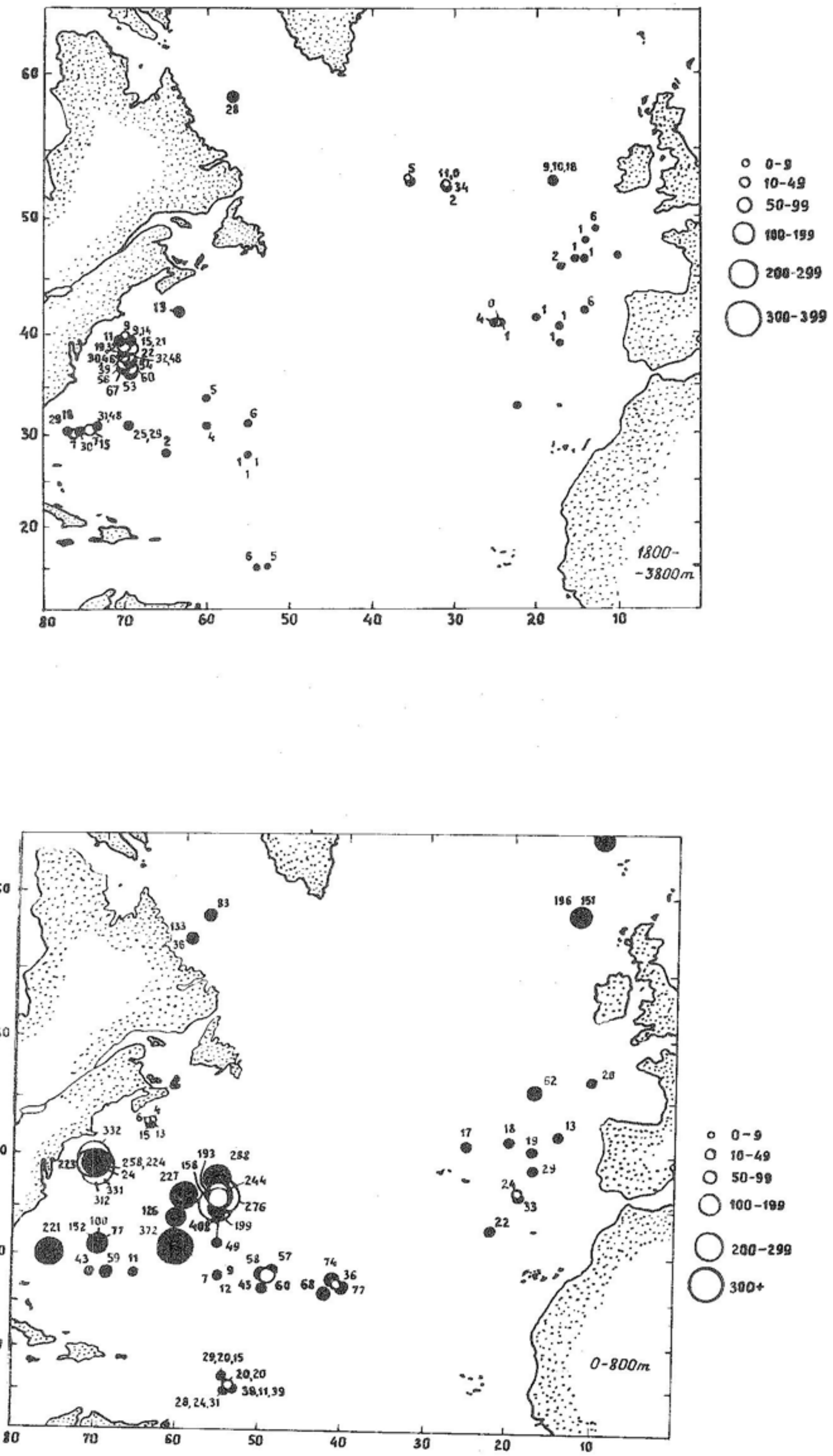


Figure 8. Distribution of mean specific kinetic energy (cm^2 s^{-2}) of synoptic motions in the upper (a) and abyssal (b) layers of the northern Atlantic (Dickson 1983 with some details omitted).

activity in the ocean. That is why the mechanism of baroclinic instability is very important. The results of recent work confirm this idea. First, figure 9 shows the importance of transfer of the available potential energy from mean currents to synoptic motions during the POLYMODE expeditions. Second, Holland has shown in his numerical model that in the most important eddy generation regions (the Gulf Stream and its recirculation zone and the southern flank of the subtropical gyre) the baroclinic instability plays a significant role, while the barotropic instability is important in the vicinity of the strong narrow currents (Holland 1983, 1986).

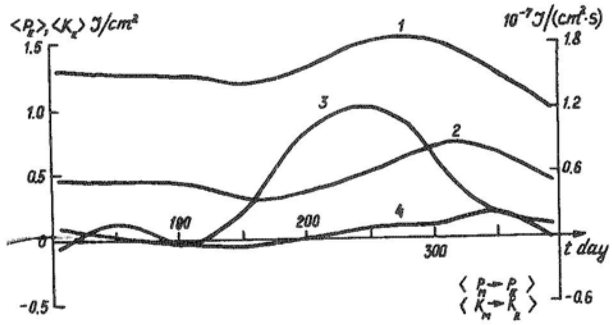


Figure 9. Time variations of densities of available potential energy P_E and kinetic energy K_E of synoptic motions (curves 1 and 2) and the densities of energy fluxes $P_M \rightarrow P_E$ and $K_M \rightarrow K_E$ (curves 3 and 4) for the period of the Soviet POLYMODE Expedition (Koshlyakov *et al.*, 1984 with some details omitted). All the curves are calculated from direct current measurements. The indices E and M are related to synoptic and mean currents, respectively; ... means smoothing over 170 days time period, area averaging of the moorings array, and integration over depth of the layer 500-1100 m.

2. The Radiation of Energy

The radiation of energy of synoptic motions by the meandering strong currents such as the Gulf Stream. In favor of the importance of this mechanism is the fact that the energy of synoptic eddies decreases when moving away from the Gulf Stream region. However, the physics of this mechanism is still not very clear although recently some new promising results have been obtained (e.g., see Reznik and Filyushkin 1988).

3. Direct Atmospheric Forcing

This mechanism implies the resonant generation of wave components in the ocean. It has been shown recently that in the spectrum of atmospheric fluctuations there is sufficient energy at wave numbers and frequencies corresponding to dispersion relations of oceanic Rossby waves. This mechanism appears to play a noticeable role in the central and eastern parts of oceanic gyres (Muller 1983; Holland 1983, 1986).

4. The Phenomenon of Self-organization

The phenomenon of self-organization in two-dimensional turbulent geostrophic motion. Model experiments demonstrated the possibility of forming isolated intensive eddies against the low-amplitude background. But these eddies are destroyed after some time, and flow returns to the turbulent regime, after which the process is repeated. This phenomenon is an internal feature of the motion not connected with the existence of special energy sources (McWilliams 1984; Larichev 1989).

5. The Influence of Bottom Relief

The Influence of Bottom Relief. Due to this effect, specific topographic eddies appear over underwater hills (e.g., Kamenkovich *et al.*, 1986a, Ch. 3.2).

6. The Specific Inertial-Viscous Mechanism

The specific inertial-viscous mechanism generating eddies within western boundary currents. In principle, such eddies can produce disturbances in the open ocean (Kamenkovich *et al.*, 1985).

In concluding this section, I would like to stress that the effectiveness and relative importance in the real ocean of all the enumerated mechanisms is not yet fully understood.

Dynamics

The study of the dynamics of synoptic eddies is based on the nonlinear equation of transport of quasi-geostrophic potential vorticity. It is impossible to review the papers devoted to the analysis of this equation in such a short lecture, and I shall give only some examples of simple exact solutions to this equation which describe disturbances localized in space and propagating with constant velocities without changing their form (soliton solutions). The construction and analysis of such solutions is of interest in connection with the search for an explanation of the long lifetimes of eddies as coherent structures in the ocean.

First, I shall point out the Larichev-Reznik barotropic soliton localized in the x,y plane (Fig. 10).

$$\psi_{LR} = [A J_1(\kappa r) - \frac{\beta + c\kappa^2}{\kappa^2} r] \sin\theta \quad \text{at } r<a \qquad 1$$

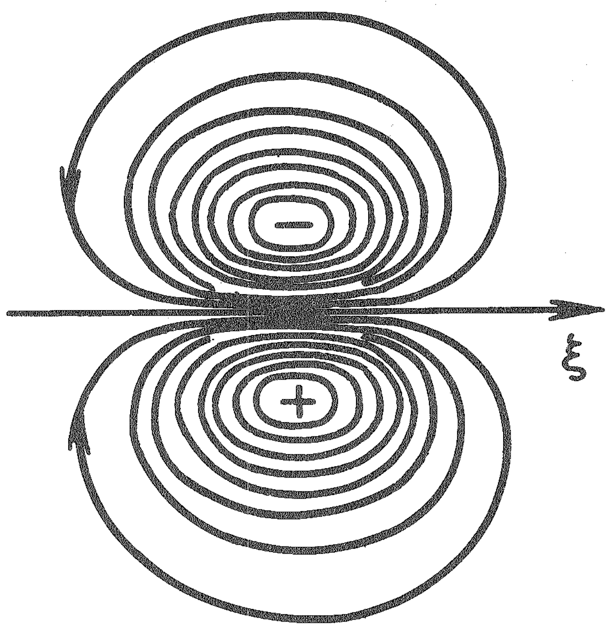


Figure 10. Streamlines for a fixed time t for the Larichev-Reznik barotropic soliton (Larichev and Reznik 1976). $\xi = x - ct$

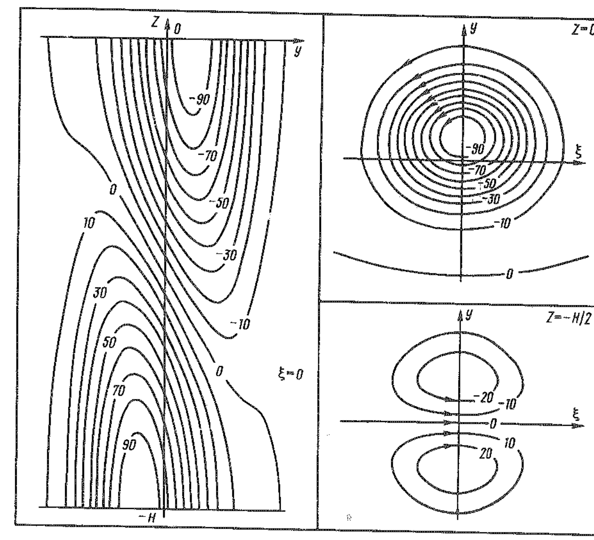


Figure 11. Isolines of stream function ψ (in percent of maximum value) for a fixed time t for the Kizner baroclinic soliton in the vertical plane $\xi = 0$ and the horizontal planes $z = 0$; $z = -H/2$ (Kizner 1984 with some details omitted). The pattern at $z = -H$ differs from the pattern at $z = 0$ in the directions of the arrows only.

$$\psi_{LR} = BK_1 (\sqrt{\beta/c}\, r) \sin\theta \qquad \text{at } r > a \qquad 2$$

where ψ is the stream function, r, θ are polar coordinates in the x,y plane, J_n is the Bessel function of order n; K_n is the Macdonald function of order n; β is the latitudinal variation of the Coriolis parameter; $c>0$ is the propagation velocity; A, B, a and k are constants (among the constants A, B, a, k, c, only two are independent).

Second, I shall point out the Kizner baroclinic soliton localized in the x,y direction (Fig. 11).

$$\psi_K = \psi_{LR} (r, \theta) + \phi(r)\, F_1 (z) \qquad 3$$

$$\phi = AJ_0 (\sqrt{K^2 - \lambda_1}\, r) + C \qquad \text{at } r < a \qquad 4$$

$$\phi = BK_0 (\sqrt{\beta/c + \lambda_1}\, r) \qquad \text{at } r > a \qquad 5$$

where $F_1(z)$ is the first baroclinic eigenmode for Rossby waves, λ_1 is the corresponding eigenvalue, z is the vertical coordinate, and A. B, C, a are constants.

Finally, I shall point out the Berestov baroclinic soliton which is localized in the space x, y, z (Fig.12).

$$\psi_B = [(A/\sqrt{r}) J_{3/2}(Kr) - (\beta + ck^2/K^2) r] \sin\theta \sin\varphi \qquad 6$$
$$\text{at } r < a$$

$$\psi_B = (B/\sqrt{r}) K_{3/2}(\sqrt{\beta/c}\, r) \sin\theta \sin\varphi \qquad \text{at } r > a \qquad 7$$

where r, θ, φ are spherical coordinates and A, B, k, a are constants.

There are various generalizations of these solutions and many investigations of the collision of the constructed solitons and their stability (Kamenkovich *et al.*, 1986a, Ch. 2, 4).

To conclude this section, I mention the forecast problem for synoptic motions in an open local oceanic area where studies have shown the possibility of forecasting such motions for a period of approximately one month (Kamenkovich *et al.*, 1986b, Pinardi and Robinson 1987).

Synoptic motions and climate

Unfortunately, there are very few data for an analysis of this problem; I have in mind both observations and simulated data obtained in numerical models of ocean

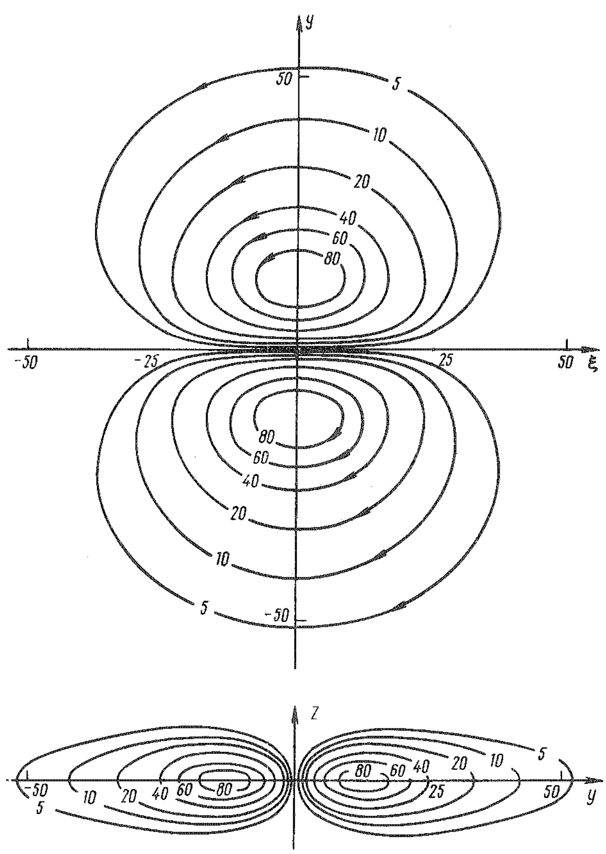
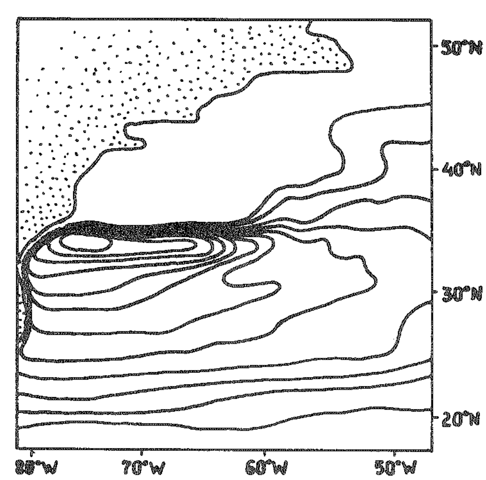


Figure 12. Isolines of streamfunction ψ (in percent of maximum value) for a fixed time t for the Berestov baroclinic soliton in the horizontal plane z = 0 and the vertical plane $\xi = 0$ (Kamenkovich *et al.* 1986a, Ch. 2.4, with some details omitted).

circulation. That is why in the literature we find various opinions on the role of eddies in climate formation, including the opinion that the role of eddies in general ocean circulation and integral heat transport is insignificant (Korotaev 1988, Introduction; Cox 1985, Bryan 1986, also the discussion in Harrison 1983). I present here certain reasons which, in my opinion, favor a substantial role for synoptic eddies in formation of the earth's climate.

First I consider the role of synoptic motions in formation of the mean general ocean circulation. First, consider the question of how the general ocean circulation can be defined. Monin (Kamenkovich *et al.*, 1986b, Ch. 1.1) suggested defining the general ocean circulation as a statistical ensemble of synoptic and global scale motions. Following this definition, to determine the mean general ocean circulation it is necessary to perform averaging over the entire ensemble. Usually this is replaced by time averaging of one realization. I refer to results of the numerical model of Holland who used a five-year averaging period for calculating mean currents.

Figure 13 shows calculation results for mean currents from the Holland eddy resolving general circulation



a

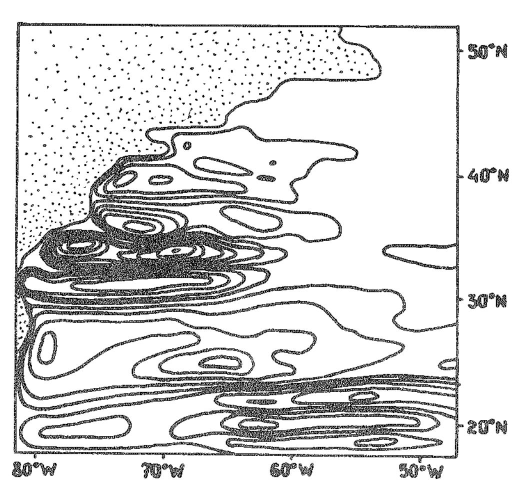


Figure 13. Streamlines of mean currents at levels 150 m (a) and 3000 m (b) in the North Atlantic calculated in the eddy-resolving general circulation model of Holland (1986). Only the western half of the domain is shown; some details are omitted.

model. It is evident that the model describes all the important features of the subtropical ocean gyre:

a. a strong western boundary current (Gulf Stream);

b. a strong eastward jet with a recirculation zone;

c. deep flow gyres (co-rotating and counter-rotating) underlying the upper layer recirculation;

d. a weak broad flow in the interior of the ocean.

Additionally, I point out that the total transports of the Gulf Stream and its extension have realistic values in the model and that the homogenization of potential vorticity in the central part of the gyre was also confirmed.

The hydrodynamical models which ignored the existence of synoptic eddies by postulating large turbulent viscosity in the model failed to describe all these features. Such models explained well only the formation of strong western boundary currents and a broad weak flow in the interior (the so-called westward intensification of wind-driven currents) and underestimated the total transport of the Gulf Stream north of the maximum of the mean wind-stress curl.

Thus one concludes that the above-mentioned realistic features (the strong eastward jet with a recirculation zone, deep flow gyres, and the homogenization of potential vorticity in a central part of a gyre) are affected by synoptic motions in the ocean. It seems plausible that the structure of the Gulf Stream region determines the structure of the whole subtropical gyre. Therefore I believe that the influence of synoptic eddies on the mean general circulation must manifest itself not only in specific regions but throughout the World Ocean.

The mean currents in the ocean form the mean sea surface temperature - the most important oceanic element of the climate system. This is one of the ways synoptic motions can influence the earth's climate.

Second, there is, of course, the direct influence of eddies on the earth's climate. Eddies, especially rings, can transport heat, (warm-core rings give up heat to colder waters and cold-core rings take up heat from warmer waters). Analysis of observations has shown that at least in two regions in the ocean (the Gulf Stream and its recirculation zone and the Antarctic Circumpolar Current) the heat flux due to the eddies is important (Bryden 1983, Hogg 1983, McWilliams 1983, Nowlin *et al.* 1985).

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Global Ocean Circulation During the Last Ice Age: Enhanced Intermediate Water Formation and Reduced Deep Water Circulation

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ABSTRACT

Oxygen and carbon isotope analyses of the benthic foraminifera genus *Cibicides* from the major oceanic basins have been used to reconstruct the major trends of the global deep and intermediate water circulation during the last glacial maximum. The major characteristic of the deep water circulation was the strong decrease in production of North Atlantic Deep Water, whereas the Antarctic Bottom Water invaded all deep oceanic basins. This water was cooler than now with a temperature close to the freezing point and was also very depleted in carbon-13 (and thus with a low-oxygen and high-CO_2 content). Carbon-14 analysis of planktonic and benthic foraminifera performed by Accelerator Mass Spectrometry indicates that the residence time of the carbon in this water was 500 years greater than today. Above the deep water, well-identified intermediate water masses were present in the Atlantic, Indian and Pacific oceans. These three water masses had a carbon-13 content higher than that of the deep water and thus were better oxygenated. Consequently, a major contrast between the glacial and modern oceanic circulation is the shift of the low-oxygen/high-CO_2 layer from a deeper level during the last ice age to intermediate depth under modern conditions.

1. INTRODUCTION

Deep water is formed at high latitudes, where the atmosphere extracts heat from the sea surface and where salinity increases from sea ice formation during winter conditions. Both processes make the surface water sufficiently dense to sink to great depth and flow toward the equator. Above the deep and bottom water masses of the ocean lie the intermediate water masses, which originate in the subpolar convergence zones of both hemispheres.

The global deep water circulation has changed dramatically during the last 150,000 years (the last climatic cycle), because conditions prevailing in the high latitude surface water of the northern hemisphere have varied considerably. For example, the Norwegian Sea was permanently ice-covered during most of the last glaciation (isotope stages 2-4). This sea was thus strongly stratified and did not form any bottom water until the last deglaciation (Duplessy *et al.* 1988b).

Similarly, the location of intermediate water formation experienced large climate-related changes. Although they are less documented than those of deep water, several modifications of the intermediate water circulation have been reported (Zahn *et al.* 1987; Oppo and Fairbanks 1987; Kallel *et al.* 1988). In this paper, we shall review the major characteristics of the deep and intermediate water masses during the last glacial maximum (isotope stage 2, about 18,000 years ago). The geochemical basis for paleoceanographic reconstructions have been described by Labeyrie *et al.* (1987) and Duplessy and Shackleton (1985).

2. THE ATLANTIC OCEAN

Data from 30 cores have been used by Duplessy *et al.* (1988a) to reconstruct a north-south section between 60° N and 45° S for the last glacial maximum, 18 K years ago. In the very high latitude of the North Atlantic, a Glacial North Atlantic Deep Water mass, with high $\delta\,^{13}C$ values is found. This water mass has a quite limited extent toward the south and disappears south of 45° N. This boundary coincides with the location of the ice age polar front (CLIMAP, 1976). South of this front, intermediate waters rich in ^{13}C are found. Carbon isotope records from the eastern Atlantic close to Gibraltar (Zahn *et al.* 1986, 1987) and from the Mediterranean Sea (Oppo and Fairbanks, 1987) suggest that the influence of Glacial Mediterranean Outflow Water (GMOW) was more important in the intermediate-deep Atlantic than it is today. An additional component for Glacial North Atlantic Intermediate Water (GNAIW) may derive from sinking of surface water to intermediate depths south of the polar front. Boyle and Keigwin (1987) have shown that GNAIW was more nutrient depleted, whereas deeper waters were more nutrient enriched. This suggests that the Glacial North Atlantic was an active source of intermediate water production during winter. We do not have enough data to resolve the various components of GNAIW and therefore consider it as a single water mass, which may be traced southward to 15° S.

Below 3000 m, most of the deep eastern Atlantic was filled with bottom water originating from the Southern Ocean so that the relative contribution of water from the southern hemisphere as compared to that from the northern hemisphere in the deep Atlantic was much greater than today. The comparison of the north Atlantic oxygen isotope records of benthic foraminifera with those of the Norwegian Sea, where the bottom water temperature was permanently close to -1° C, indicates that the deep and bottom water of the Atlantic Ocean was was cooler than today during the whole glaciation (Labeyrie *et al.* 1987)

3. THE INDIAN OCEAN

In order to determine the impact of the last glaciation on the Indian Ocean's circulation pattern, Kallel *et al.* (1988) have measured the foraminiferal $\delta\,^{13}C$ and $\delta^{18}O$ values in seventeen sediment cores from the two major basins of the Northern Indian Ocean, in the depth range from 1250 m to 3420 m. At 18 K years B.P., a very strong and sharp discontinuity separated the high $\delta\,^{13}C$ values of Intermediate Water to a depth of about 2000 m from negative $\delta\,^{13}C$ values deeper than 2300 m. This gradient of 0.5 to 1.0 per mil is in sharp contrast with the modern situation where the vertical $\delta\,^{13}C$ gradient in the North Indian Ocean is less than 0.1 per mil in this depth range. This change in the vertical profile originates from a decrease of the $\delta\,^{13}C$ values of Deep Water, which was as large as 1 ‰ during the last glacial maximum. At this time, the mean carbon isotopic composition of the total dissolved CO_2 in the global ocean was 0.32 ‰ smaller than the modern value (Duplessy *et al.* 1988a) as a result of the reduced mass of the continental biosphere associated with glacial climatic conditions (Shackleton 1977). The smaller glacial to interglacial $\delta\,^{13}C$ change for Intermediate Water, compared with this global $\delta\,^{13}C$ signal, indicates an enhanced glacial ventilation of this water mass, while the larger $\delta\,^{13}C$ change for Deep Indian Water indicates a very weak ventilation of the deep Indian Ocean during the last glacial maximum.

The profile obtained by plotting the $\delta\,^{18}O$ values of benthic foraminifera against depth also shows a sharp discontinuity at the same level as the $\delta\,^{13}C$ profile in both the Bay of Bengal and Arabian Sea (Kallel *et al.* 1988). This discontinuity is much larger than that observed under modern conditions and indicates that intermediate and deep waters had much more distinct characteristics in glacial times.

Because of a lowering of sea level during glacial conditions, Red Sea and Arabo-Persian Gulf contributions to Intermediate Water were probably very reduced or absent. Three sources are possible for the glacial Intermediate Water in the Northern Indian Ocean:

(i) dense water formed in the Northern Arabian Sea by the increased evaporation/precipitation ratio and the possible decreased temperatures of the surface water described by CLIMAP (1976) and Duplessy (1982),

(ii) expansion to the north of 10° S of the Antarctic Intermediate Water (AAIW) in the absence of a northern local source and

(iii) increased flow of intermediate water from the Pacific Ocean through the Indonesian Archipelago. A more complete coverage is required to determine unambiguously the origin of the glacial North Indian Intermediate Water. Kallel *et al.* (1988) argued that the vertical salinity/ $\delta^{18}O$ gradient in the northern Indian Ocean during 18 K years B.P. was not significantly different from the modern one. The sharp deep front between Intermediate and Deep Water is thus best explained by a decrease in deep water temperature in the Indian Ocean and the development of a deep thermocline. This would result in a strong density gradient, which prevented noticeable mixing between intermediate and deep waters.

4. THE PACIFIC OCEAN

Under present conditions, most areas of the Pacific Ocean lie below the carbonate compensation depth, and foraminifera are absent in the sediment. However, it has long been observed that, in contrast with the deep north Atlantic Ocean, dissolution was less intense in most of the Pacific Ocean during isotope stage 2, with a deepening by a few hundred meters of the carbonate compensation depth (Broecker 1982). This indicates a significant change in the chemistry of the deep waters, with a drop in the water total CO_2 content which may possibly be related to an increase in ventilation at intermediate depth. In contrast with modern conditions where benthic forams are not found deeper than 3500 m, at the last glacial maximum, they are often present in north Pacific sediments as deep as 4000 m. Duplessy *et al.* (1988a) have therefore generated a one-dimensional profile reconstructing the mean variations with depth of the $\delta^{13}C$ of the total dissolved CO_2 in the north and equatorial Pacific by measuring $\delta^{13}C$ values of *Cibicides* in 23 Pacific sediment cores. A similar profile was generated for the present conditions by interpolating from the GEOSECS data (Kroopnick 1974,1985). The shape of the two profiles is markedly different, as the $\delta^{13}C$ minimum that is present today between 1 and 2.6 km water depth is absent during the last glacial maximum. The glacial profile for the Pacific Ocean exhibits $\delta^{13}C$ values which are identical to the modern values for the 1000-2600 m depth range. Deeper than 3000 m, $\delta^{13}C$ values are lower than modern ones by 0.3 ‰ in agreement with the data of Keigwin (1987).

All the $\delta^{13}C$ values from water depths greater than 2600 m show a $\delta^{13}C$ shift indistinguishable from the global mean shift of 0.32 ‰. By contrast, the mean $\delta^{13}C$ shift for the 1000-2600m depth range is significantly smaller than the global signal. This implies a relatively larger contribution of ventilated water to this water mass during the last glaciation than in the modern ocean. The origin of the ventilated water is difficult to trace with the present data set. Core CH 84-27, located at 712 m depth on the northern slope of East China Sea has significantly lower $\delta^{13}C$ values for 18 K years B.P. than the other shallow cores. This indicates that there was no winter convection and hence no formation of ventilated deep water in this part of the east China Sea. High $\delta^{13}C$ values are observed in open water of the Pacific down to the equator in a depth range of 712-2600 m. As the sills of the Bering Sea and the Sea of Okhotsk are much deeper than 2000 m, the high $\delta^{13}C$ values cannot be due to deepwater formation by convective mixing in the whole water column during winter in these marginal basins. Duplessy *et al.* (1988a) therefore believe that the high oxygenation of the water mass in the range 712-2600 m is due to an enhancement of the mechanism which produces intermediate waters in the modern Pacific Ocean, i.e., vertical mixing through the pycnocline in high latitudes and lateral mixing along density surfaces (Reid 1965).

Kallel (1988) showed that in the equatorial Pacific ocean, the $\delta^{13}C$ deep front coincides with a sharp variation of the $\delta^{18}O$ value of benthic calcite. This result suggests that, as in the northern Indian Ocean, intermediate and deep waters were strongly separated by a well-developed thermocline and therefore a large density gradient.

5. VENTILATION AGE OF PACIFIC DEEP WATERS

Shackleton *et al.* (1988) estimated the variations of the ventilation age of the Pacific deep water at a depth of 3,210 m during the end of the last glaciation (from 14 to 30 K years B.P.) by comparing the C-14 age of the planktonic and benthic foraminifera from core TR 163-31 B from the Panama Basin. Their results show that the ventilation age of the Pacific deep water was about 500 years greater in last glacial times than it is today. However, during the beginning of the glacial to interglacial transition (i.e. from 17 to 14 K years B.P.), this situation was apparently reversed and the ventilation rate dropped to about 500 years. The turnover of the ocean was therefore rather rapid at that time, just when, on intuitive grounds, one would expect the opposite on the basis that the ocean should have begun to stabilize as a result of meltwater influx.

6. CONCLUSION

On the time scale of 10^4 years, the circulation of intermediate and deep waters is at least as variable as that of the surface water. It has apparently responded strongly to the climatic changes of the last 150,000 years. This is largely because much of the circulation at 18 K years B.P. and earlier was driven by processes occurring at high latitudes (as today), i.e. in regions where climatic changes have been largest.

During the last glacial maximum, the northern hemisphere source of deep water was relatively inactive in the North Atlantic and most of the ocean's bottom and deep water originated from poorly-oxygenated surface water sinking in the high latitudes of the Southern Ocean. By contrast, intermediate waters extended somewhat deeper than under modern conditions and were much more oxygenated than today in the Atlantic, Indian and Pacific oceans. In the Indian and Pacific oceans, intermediate waters were separated from the deep water by a well-developed deep thermocline.

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Experiments with an OGCM on the Cause of the Younger Dryas

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ABSTRACT

We investigate the effect of enhanced riverine freshwater input on the circulation of the northern Atlantic. It has been suggested by several authors that during the last deglaciation the melt water may have blocked the formation of deep water in the Atlantic and, consequently, reduced the meridional heat transport. The subsequent cooling of this region is identified with the Younger Dryas epoch. We found that the freshwater input rates of the deglaciation were more than sufficient to change the Atlantic circulation significantly. A doubling of the present St.Lawrence river could also be critical for the present circulation.

1. INTRODUCTION

It has been known for a long time that the last deglaciation was not a monotonic development (cf. Ruddiman and Duplessy 1985, and Broecker *et al.*, 1988). Particularly in the region of the northern Atlantic, it was characterized by an oscillatory behavior which was most pronounced between 10,000 and 11,000 years before present. The return of the glaciation, in the form of the Younger Dryas event, was preceded by a strong release of melt water into the northern Atlantic, probably due to a deflection of the melt discharge from the Mississippi to the St.Lawrence river. It has been suggested (e.g.Broecker *et al.*, loc.cit.; Berger and Killingley 1982) that the reduction of deep water formation by the resulting strong stratification could drastically reduce the meridional heat transport of the Atlantic and, consequently, provide a substantial cooling of the Arctic. The basic mechanism of this process is clear. However, it is an open question whether the actual amount of glacier melt was sufficient to trigger such an event.

The Atlantic is widely acknowledged to be a very sensitive ocean with respect to the details of forcing mechanisms. Recently experiments by Bryan (1986) with an idealized model of the Atlantic have shown that with a given forcing of the circulation with freshwater fluxes, the ocean can develop at least two completely different stable states of circulation, depending on the initial state. This result was postulated on the basis of a careful examination of geological evidence by Broecker *et al.* (1985). It must be noted, however, that the design of Bryan's basic experiment was not entirely realistic: there is no way to increase the salinity of the northern Atlantic suddenly by so much as 2 permille.

A rough estimate of the mean deglaciation rate yields a glacial melt of about 0.1 Sv. The major part of this originated from the continental ice sheets of the northern hemisphere, with about 60 % attributable to the Laurentide ice sheet (cf. Hughes *et al.*, 1981). It is unlikely that the glacial melt reached more than twice this value at intermediate episodes (Ruddiman *et al.* loc.cit.). In this paper, we describe some experiments in which the assumed melt rate of the Laurentide ice sheet is varied in strength and in the location of inflow to the Atlantic.

The conventional way to run OGCMs is to determine the surface fluxes of momentum, heat, and freshwater by prescribing climatological fields of wind stresses, and by requiring the surface values of temperature and salinity to adapt to the prescribed climatological surface data. For a simulation of the glacial ocean, such a procedure is not suitable, as we do not know the surface salinity of former climatic states with sufficient accuracy. However, as the ice edge in the preceding Alleroed epoch was at almost the same position as it is today, it can reasonably be assumed for the present experiment that the ocean circulation in the Alleroed period was similar to that of today. Thus we introduced the freshwater inflow as a perturbation of the present day circulation, driven by present day wind stress, atmospheric temperature, and freshwater fluxes. By comparison of this experiment with a control experiment without freshwater input, the impact of the glacier melt can be identified.

2. THE MODEL

The model is based on the standard set of equations used in numerical models. These are the conservation laws for salt, heat, and momentum, the latter in a linearized form. The equation for the vertical component of momentum is replaced by the hydrostatic approximation. The discretisation in time is written in a rigorously implicit way: all equations are taken as Euler-backward differences. The resulting systems of linear equations for the velocity field are solved iteratively for the velocity shear between neighboring layers (baroclinic modes) and by elimination for the vertically integrated transport (barotropic mode). Details are given in Maier-Reimer *et al.* (1989). This formulation almost completely filters out gravity waves which necessitate a rather short time step in conventional circulation models.

The equatorial Kelvin waves are formally included, but because of the coarse grid and the long time step, they are strongly damped. Outside the equatorial region, the motion is essentially geostrophic, with frictional effects near the boundaries. Adjustment of the density field to the forcing is provided almost entirely by Rossby waves, as proposed by Hasselmann (1982).

For the experiments described in this paper, the model was run with a horizontal resolution of 3.5 degrees in the zonal and meridional directions and with 11 levels of depth. The topography is as realistic, as far as possible in such a coarse grid. The minimum depth of shelf regions was assumed to be 200 m. The model was run with a time step of 30 days. In the basic run, the model was driven by the Hellerman data of monthly wind stress (Hellerman and Rosenstein 1983), and by the freshwater flux resulting from a soft restoring to the observed annual mean (Levitus 1982). The thermal driving was given by a similar restoring relation of the surface temperature to the monthly mean values of atmospheric temperature from the COADS data set (Woodruff *et al.* 1987). At high latitudes, the heat flux is reduced by the presence of ice which is simulated by an ice model (Stefan 1891) with simple thermodynamics and advection with viscous rheology.

Originally, the model was spun up from a state of homogeneous water with a salinity of 34.6 and temperature of 2.5°. After 10,000 years of integration, the model ocean reached an almost stationary state: the global mean temperature in the lowermost level changed by 1.7 milliKelvin during the last millennium; the corresponding salinity change was 4.1×10^{-8} permille/year. From this run, the effective fresh water fluxes resulting from the boundary condition were stored. In the following experiments, the ocean was driven by the same wind field and atmospheric temperature as in the basic run; the salinity changes now result from an explicit prescription of freshwater fluxes. As the model now contains no stabilizing restoring term for salinity, it must be expected that this change in the boundary condition will cause the model to drift away from the former state, particularly as the convective adjustment is a highly nonlinear process which acts as an effective stochastic forcing. The drift, however, is so slow that within the first centuries of integration the deviations can barely be detected. We compare this control run with the anomaly runs, in which the melt water input is prescribed as an additional freshwater input at isolated points.

3. THE CONTROL EXPERIMENT

In the control experiment, the circulation is characterized by a pronounced difference between the circulation patterns of the major oceans, as observed in the present day real ocean. Figure 1 shows the zonally integrated meridional mass transport stream function. In the Atlantic, the cross equatorial transport of water reaches 20 Sv. This large overturning yields a substantial heat transport across the equator, as deduced also from atmospheric observations (Hastenrath 1982). In the Pacific, the meridional circulation is dominated by the equatorial Ekman cell and a slow deep ventilation from the Antarctic. The resulting heat transport is almost antisymmetric around the equator (Fig.2).

These meridional circulation patterns cannot be directly measured in the real ocean, but are deduced from the distribution of geochemical tracers, most clearly from the field of natural ^{14}C. The ^{14}C distribution can be simulated fairly realistically with a simple passive

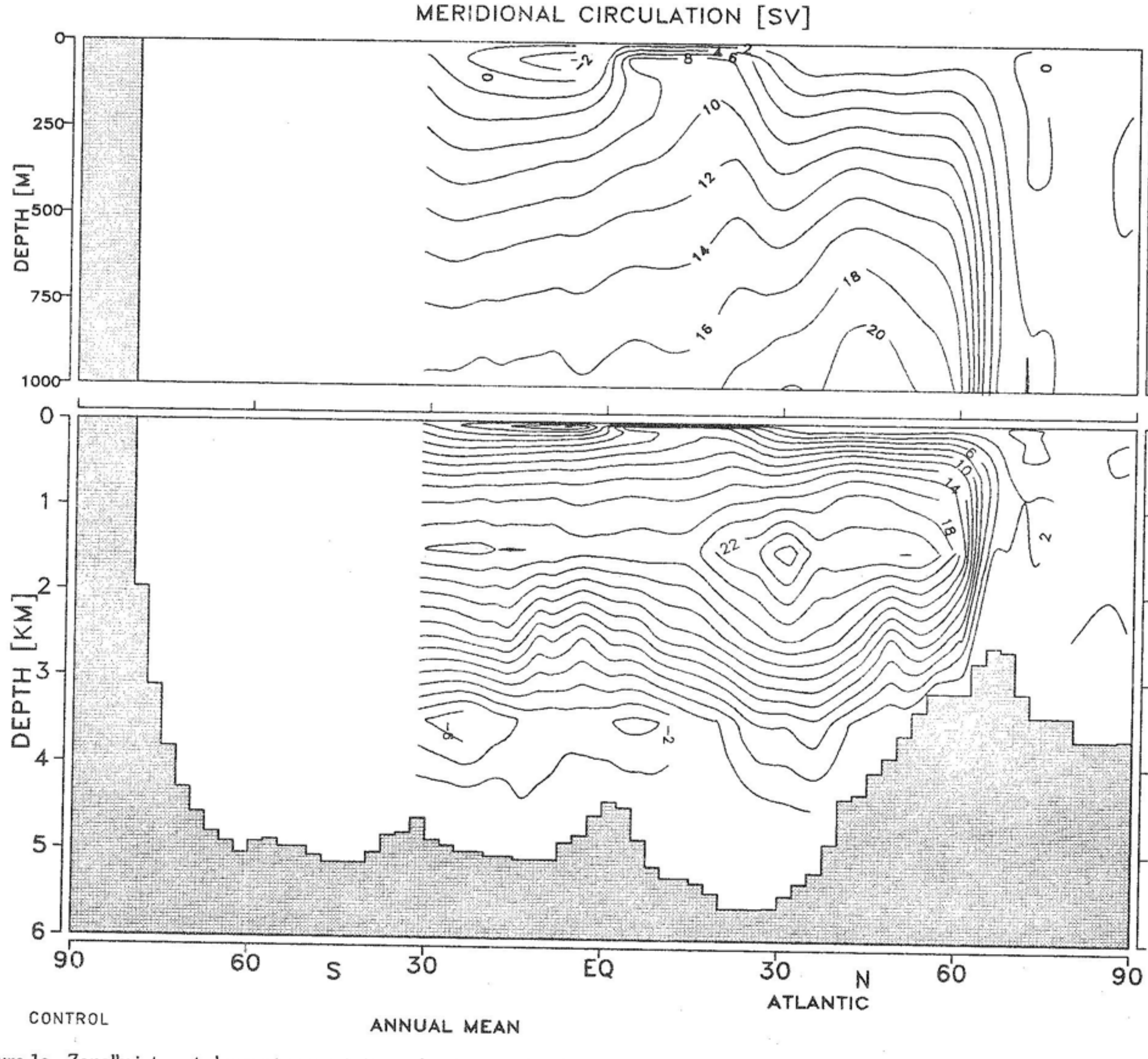

Figure 1a. Zonally integrated mass transport stream function in Atlantic. Contour interval is 2 Sv.

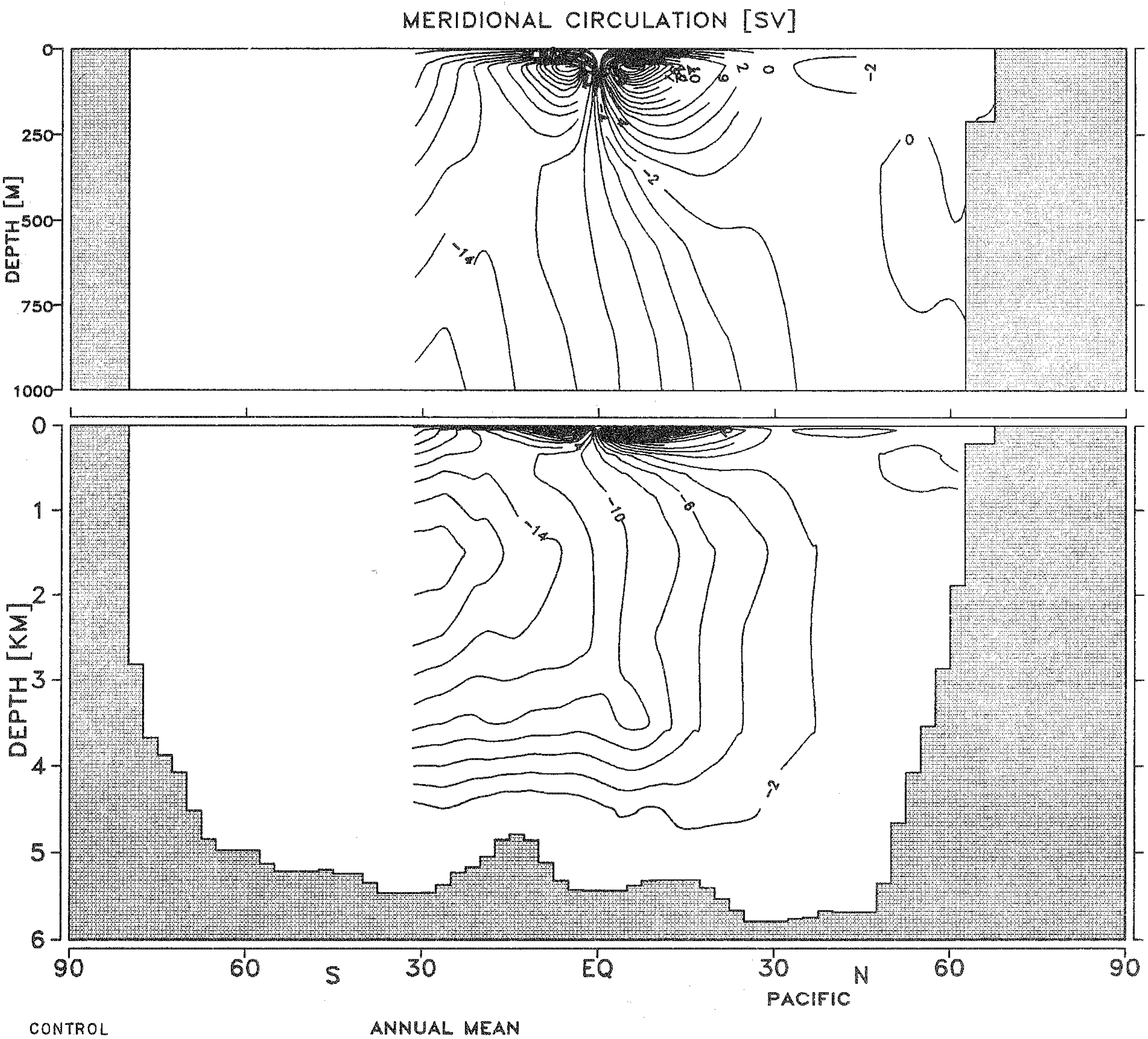

Figure 1b. Zonally integrated mass transport stream function in Pacific. Contour interval is 2 Sv.

tracer model. The differences between this simulation and more complex ocean carbon cycle models (Maier-Reimer and Hasselman 1987; Bacastow and Maier-Reimer 1989) are minor in the deep ocean. We prescribe the gas exchange with the atmosphere by a constant piston velocity of 6 m/year and treat the advection and radioactive decay as a stationary problem. The resulting set of equations is solved by a simple iterative procedure which yields the stationary distribution in a few minutes of computer time. This "quick ^{14}C " computation has proven to be a very effective diagnostic tool for the validation and discrimination of different circulation fields obtained with different choice of boundary conditions. Figure 3 shows the resulting distribution for the present day ocean. There is good agreement with the corresponding GEOSECS sections (Stuiver and Östlund 1980; Östlund and Stuiver 1980).

Figure 4 shows a block diagram of the large scale transports in the form commonly used in box models. The upper panel shows the horizontal transports in the top 1,500 m, the meridional components in the laterally

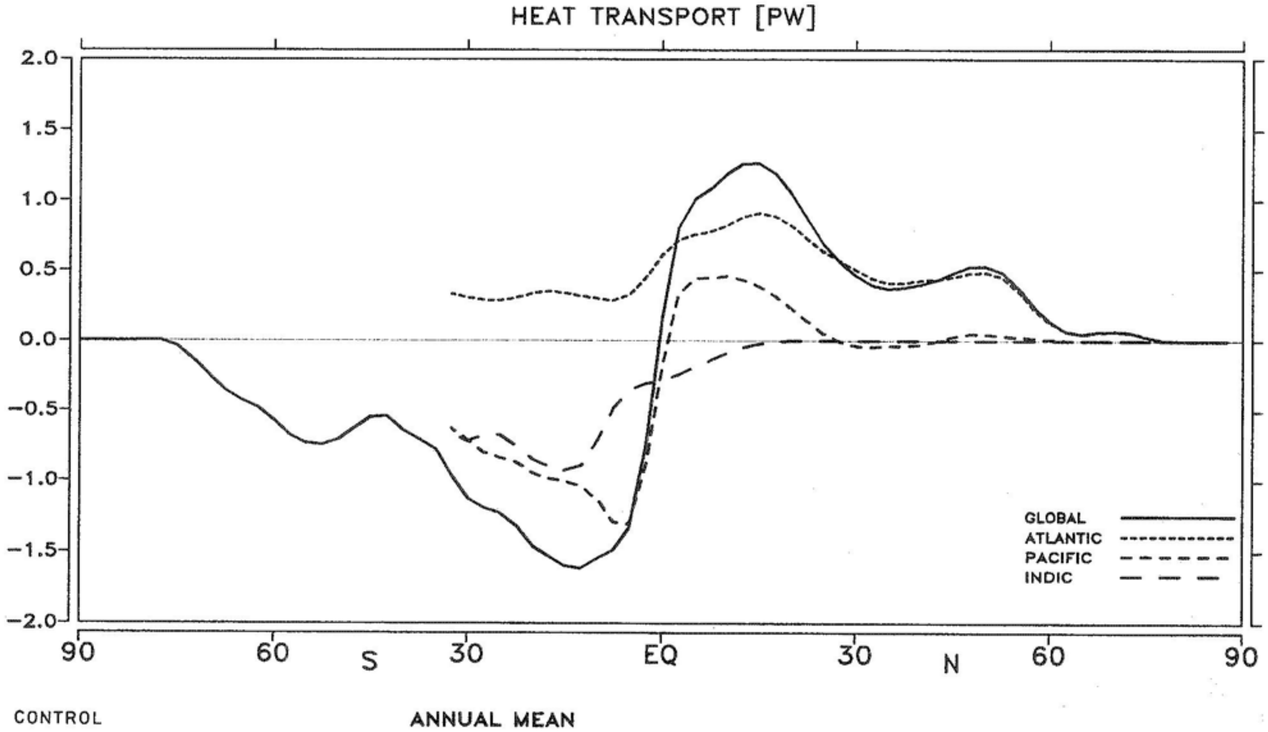

Figure 2. Heat transport of the major oceans in the control run

bounded oceans across 10 and 40° N and S, resp., and the zonal component in the southern circumpolar ocean. The middle panel shows the vertical component across the level 1,500 m, integrated over the areas defined by these bounds. The lower panel shows for the deep layers the values corresponding to the upper panel . This summary shows that the model clearly reproduces the structure of the conveyor belt (Gordon 1985): the salty water from the northern Atlantic spreads into the deep layers of the global ocean. With the model topography, the transport through the Banda strait is only 1.8 Sv. The return flow occurs almost entirely through the Drake Passage.

The deep circulation is driven primarily by the spreading of dense water produced in the regions of strong cooling. Figure 5 shows the locations and strengths of the production zones of deep water in the control run. The most important regions are the Irminger sea and the shelves around Antarctica.

4. THE MELT EXPERIMENTS

In a first experiment, we prescribed a very large melt water inflow (six times the estimated mean postglacial melting rate), distributed equally at three points: Gulf of Mexico, St. Lawrence River, and Norwegian Sea, respectively. After 10 years of integration, the thermohaline circulation in the Atlantic had completely collapsed . The heat transport of the Atlantic was directed southwards everywhere. As this assumption of melt water input is probably unrealistic, we will not discuss it further.

In a series of further experiments, we examined the influence of the individual locations of melt water inflow, reducing the flow rate from experiment to experiment. The main features of these experiments are summarized in figure 6, which shows the development in time of the

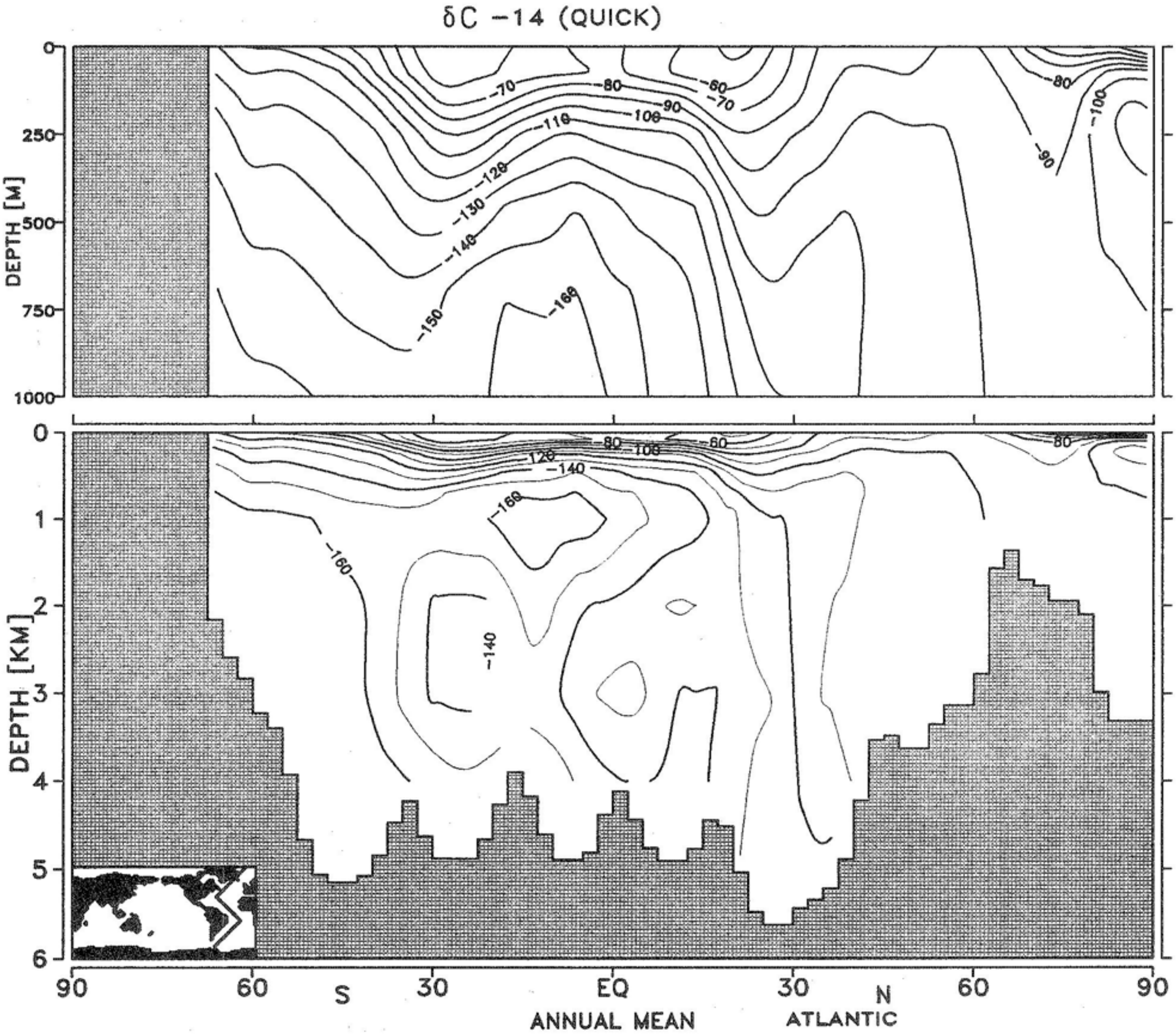

Figure 3a. Distribution of natural ^{14}C for the control run obtained with a constant piston velocity of 6 m/y. Atlantic.

surface heat flux, integrated over the region north of 30° N in the Atlantic, including the Arctic Ocean. In a stationary state, this quantity is balanced by the meridional heat transport in the Atlantic across 30° N. The heat flux responds immediately after the moment when the surface salinity is reduced to the point where the brine released during ice formation can no longer penetrate the underlying haline water. In all experiments, the switch off of the driving mechanism of the heat transport, when it occurs, is found to be a rapid event. It is followed by an oscillation with a period of some twenty years which may be explained by the generation of large amplitude Rossby waves on the arrival of the applied distortion at greater depths. We have not yet analyzed these oscillations in detail.

Figure 7a,b show the resulting meridional stream function and heat transport after 200 years of integration for the experiment M 0.22 in which an additional release of 0.22 Sv was introduced at the Mississippi River. The contrast to the reference run is striking. The heat transport is completely reversed; the Atlantic no longer exports heat from the Arctic across the equator. The climatic feedback of this reversal would have been dramatic. These figures are not, of course, to be interpreted as stationary states. The integration time was too

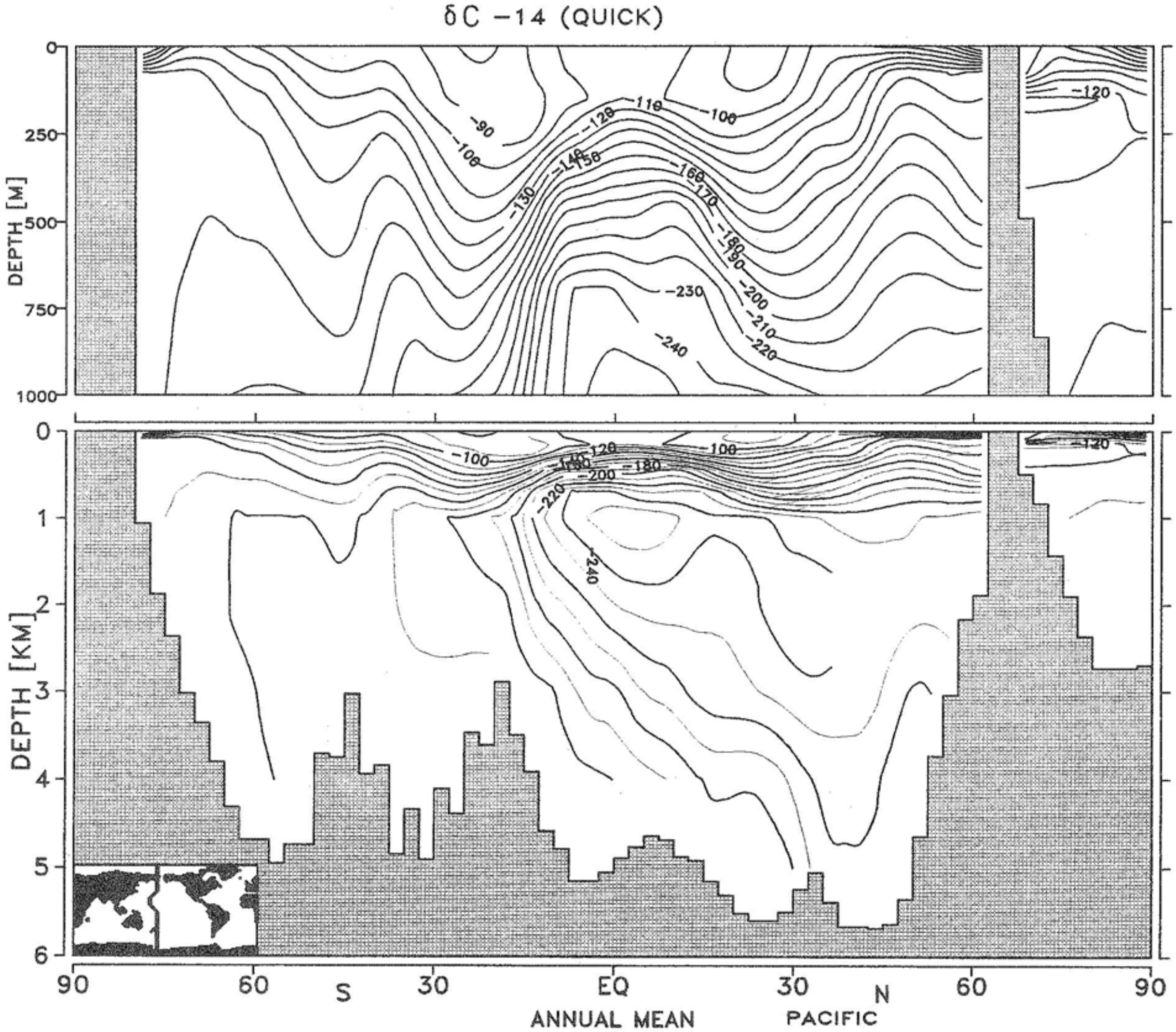

Figure 3b. Distribution of natural ^{14}C for the control run obtained with a constant piston velocity of 6 m/y. Pacific.

short for a new equilibrium to be established. They represent rather a snapshot of a changing circulation.

As the Mississippi outflow is transported to the polar front by the Gulf Stream, the overall perturbation introduced by this outflow is not as would be immediately inferred from an examination of the local stratification. One major difference lies in the timing: the Mississippi water needs a longer time to reach the sensitive region of deep water production. On the way to this region it is diluted, and part of it recirculates in the subtropical gyre. However, a melting rate of only 0.07 Sverdrup at either of the two locations is sufficient to return the Atlantic circulation to almost the same mode as in the first melt experiment within 200 years of integration. For the Mississippi case, the rapid change of the heat flux is delayed by some 60 years relative to the St.Lawrence case. With a melting rate of 0.02 Sv, released via the St.Lawrence river, we still obtain a strong reduction of the heat flux to about one third of the undisturbed state for the St.Lawrence outflow after 30 years. The same melting rate, released at the Mississippi, produces no

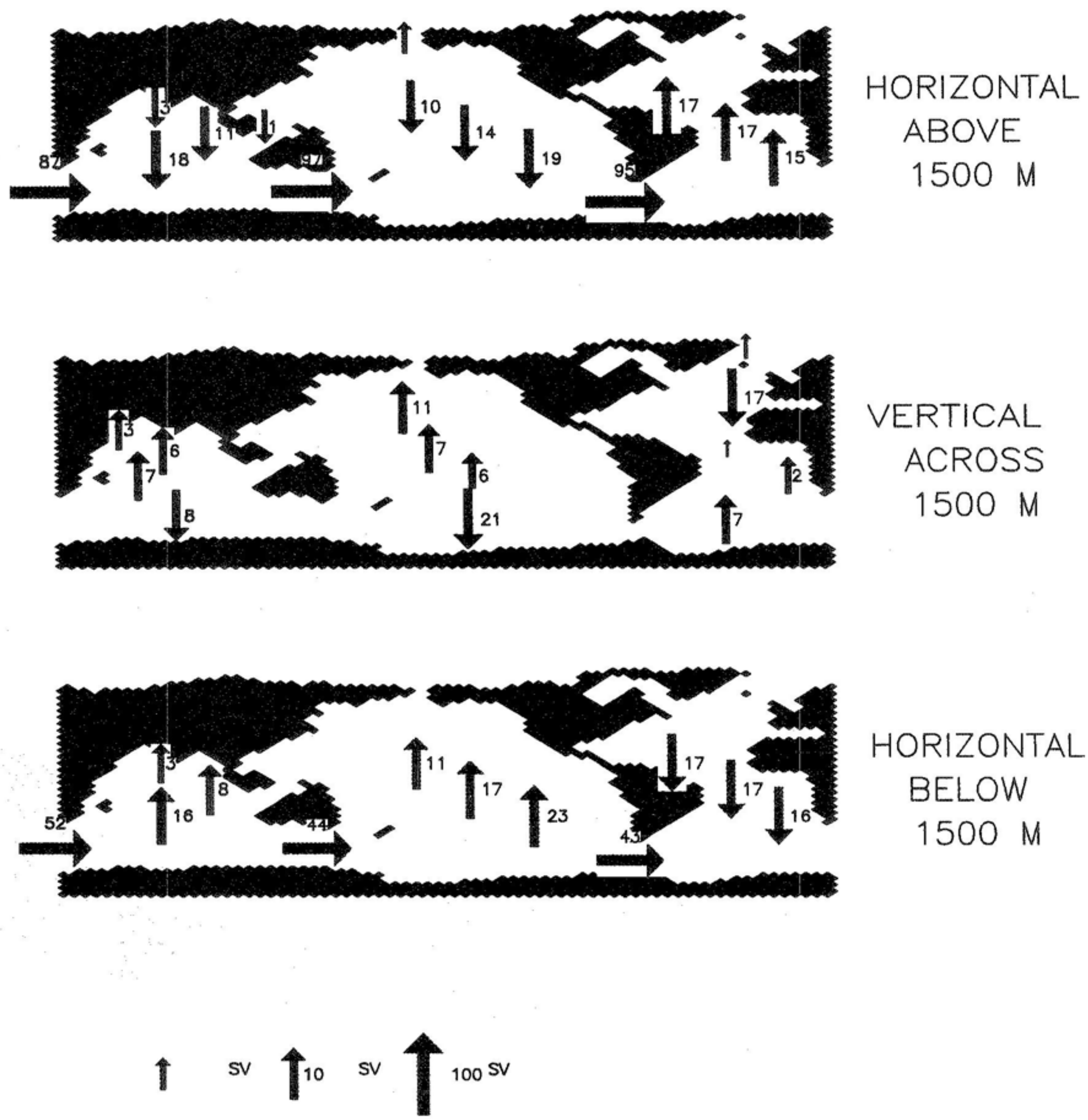

Figure 4. The conveyor belt of the control run

substantial changes of the heat flux and the circulation even after 500 years of integration. A similar cutoff of efficiency is found with a St.Lawrence output only after the meltwater input had been reduced to 0.007 Sv. (It should be emphasized again that most of the experiments assume a smaller melting rate even than the long term average of the deglaciation. Today the Mississippi is estimated to carry 0.017 Sv, the St. Lawrence river 0.01 Sv (Baumgartner and Reichel 1975). These modern river discharges are reflected in the fields of surface salinity which were used to force the basic run).

When comparing the effect on the heat flux of these experiments with the total amount of freshwater input, we observe a maximum efficiency at the moderate melting rates. Very weak releases are compensated by dilution; the stabilizing effect in the regions of deep water formation is not strong enough. On the other hand, very strong melt water outlets cannot do more (within the framework of this study) than block the exchange of surface water with the deep sea, and it takes some time for the additional fresh water to reach the region of deep water formation. For the St. Lawrence outflow, a

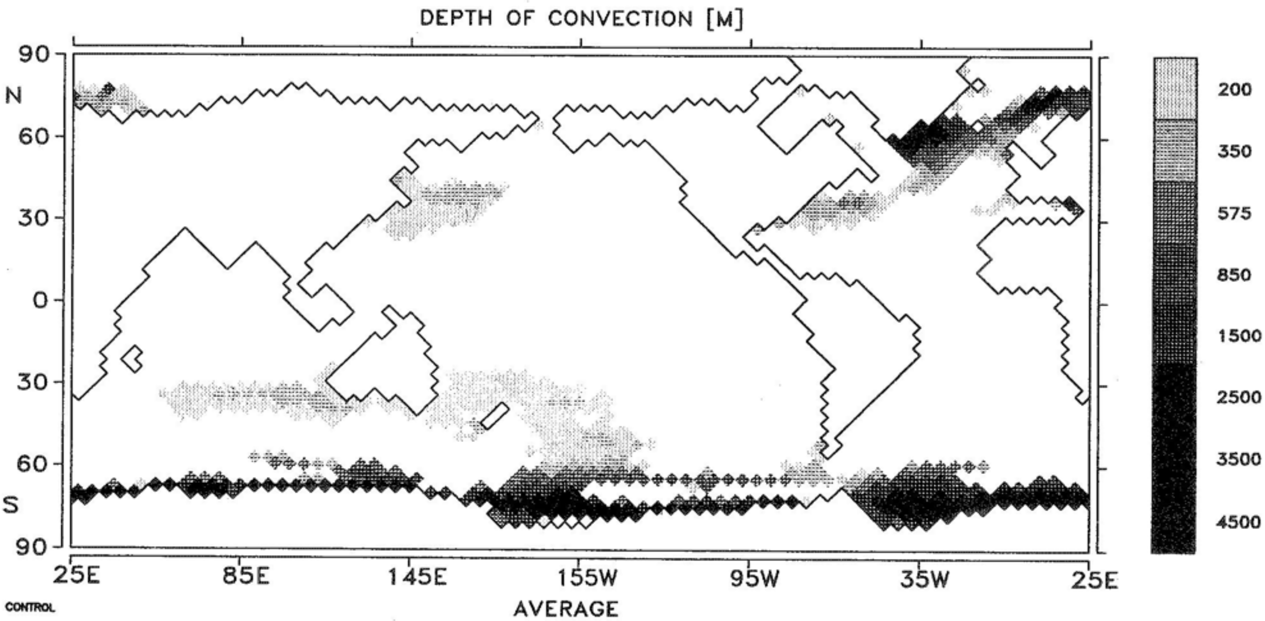

Figure 5. Deep water formation of the control run.

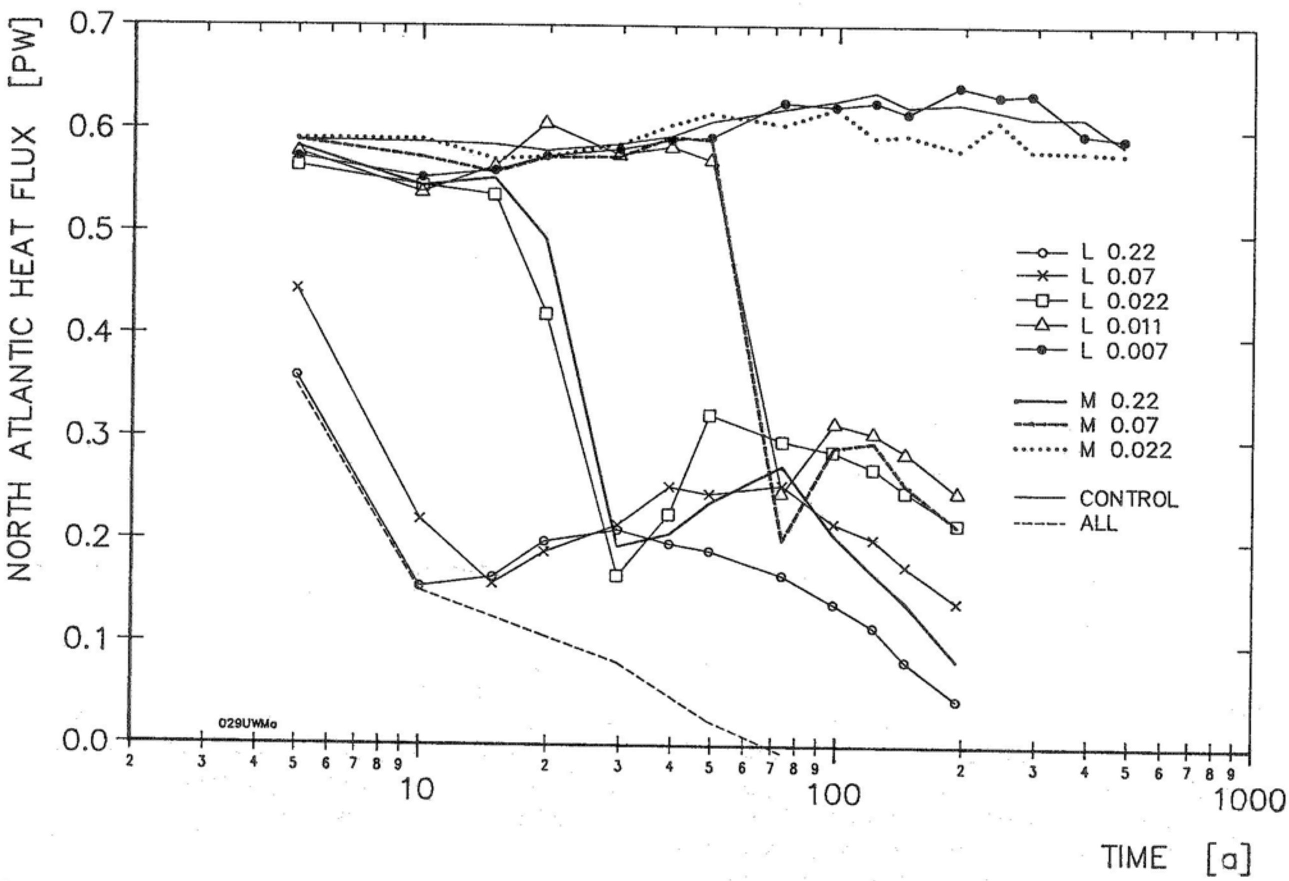

Figure 6. Time series of the North Atlantic heat flux from the melt Experiments. L and M denote release at St.Lawrence River and Mississippi, resp. The numbers indicate the strength of the melt water inflow in Sv. "All" denotes the experiment with six times the mean deglaciation rate.

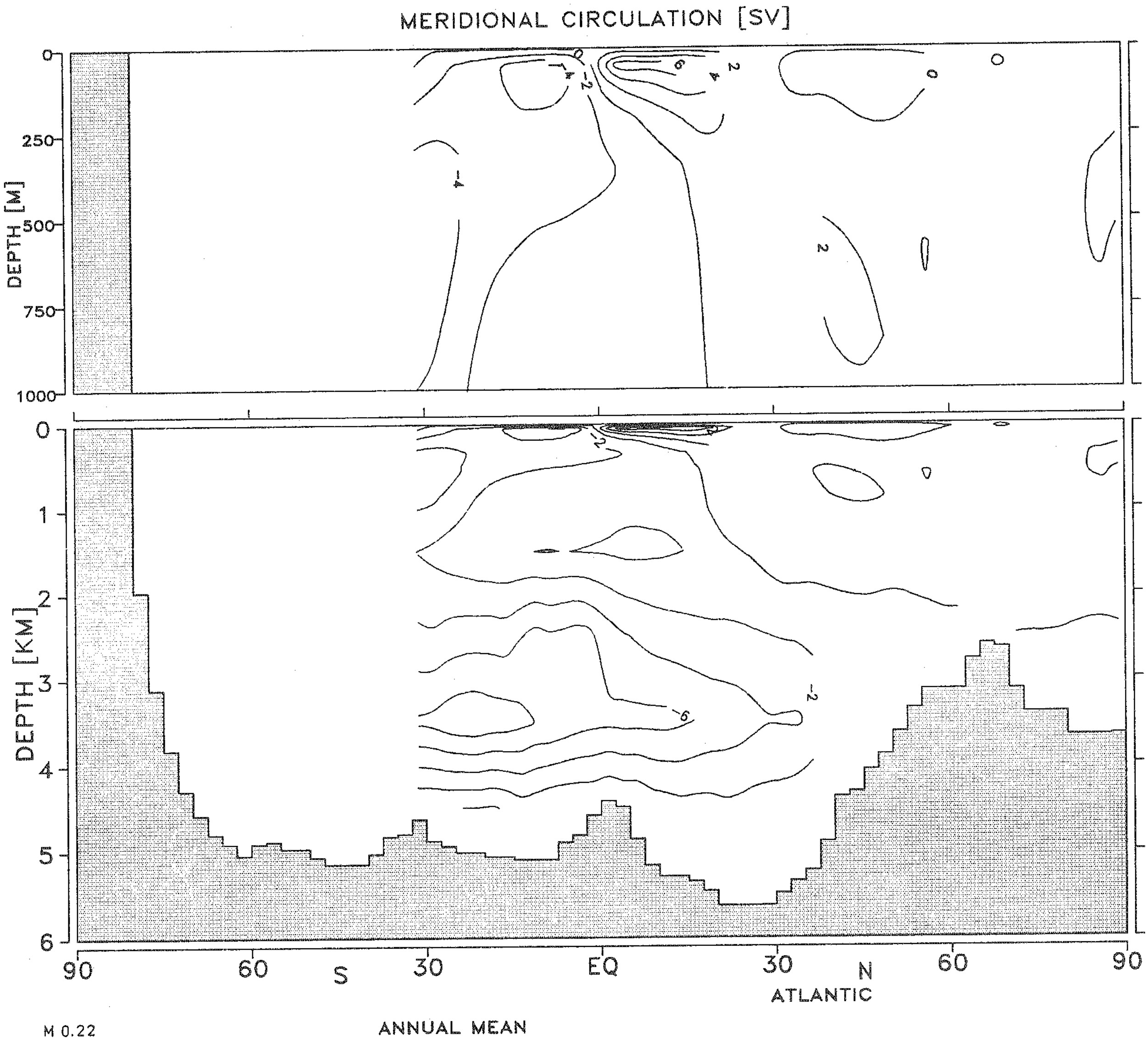

Figure 7a. Meridional stream function of the experiment M 0.22 after 200 years.

threshold value lies between 0.007 and 0.011 Sv. The reduction of the melt water input by a factor of 3 extends the period in which the heat flux remains stable by at least an order of magnitude. For the Mississippi outlet, the corresponding threshold lies between 0.02 and 0.035 Sv.

So far, we have discussed only the heat flux. A more direct climatic feedback is seen in the ice coverage. The melt experiments were forced by exactly the same temperature field as the control run. The creation of a fresh water lens at the surface makes it more difficult for the brine released by the ice formation to penetrate to greater depths. As a consequence, the melting of sea ice by heating from below is inhibited, and the ice coverage increases. Figure 8a shows the March ice coverage of the control run. The polar front is clearly seen north of Iceland. The ice edge is represented by the last 20 cm isoline. The Labrador sea ice is bounded by a line from Cape Farwell to Newfoundland; the Irminger sea is ice free. Figure 8b shows the same for the experiment M 0.22. Now, the Irminger sea is ice covered in March, and the polar front lies across Iceland.

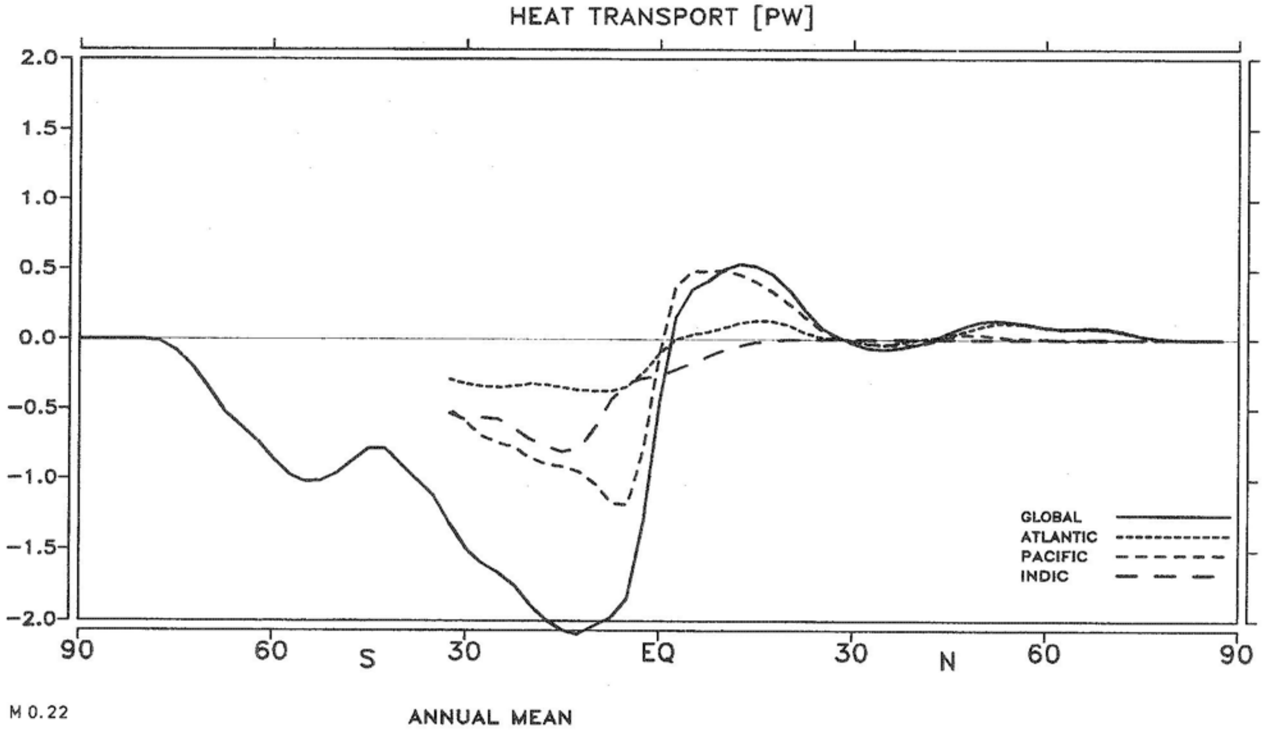

Figure 7b. Heat transport of the experiment M 0.22 after 200 years.

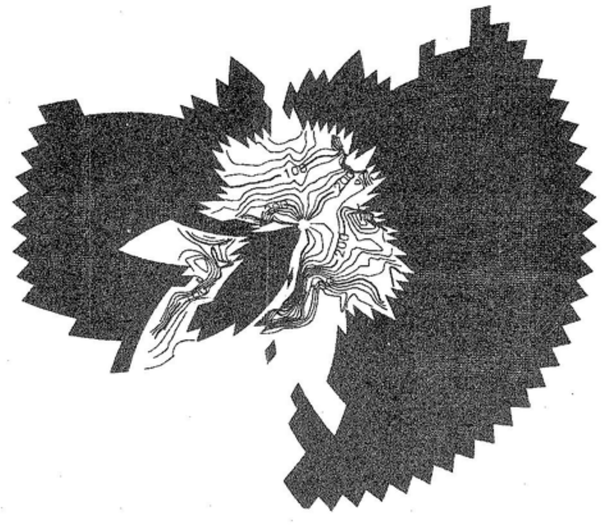

Figure 8a. March sea ice coverage of the control run after 200 years.

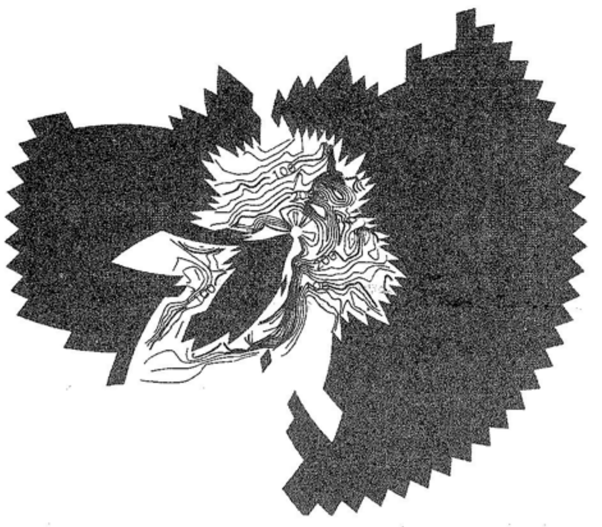

Figure 8b. March sea ice coverage of the experiment M 0.22 after 200 years.

5. CONCLUSION

We have found again that the circulation in the northern Atlantic is extremely sensitive with respect to the assumed boundary conditions. A perturbation significantly smaller than assumed in Bryan's experiment is sufficient to create substantial changes of the circulation patterns. For the interpretation of the Younger Dryas event, the present experiments are not, of course, the whole story: the assumption of constant atmospheric temperature and constant freshwater exchange with the atmosphere is not realistic for a changing ocean circulation. With decreasing oceanic heat transport, the overlying atmosphere must become colder and act as a negative feedback. However, we have demonstrated that a realistic estimate of melt water inflow is more than sufficient to trigger some form of substantial climatic fluctuations. We have also confirmed Broecker's hypothesis that the location of the inflow plays a critical role. The deflection of the Mississippi melt water at a rate of 0.011 Sv in our experiment was sufficient to switch off the meridional heat transport of the Atlantic within 200 years.

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The Role of Hydrological Processes in Ocean-Atmosphere Interaction

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ABSTRACT

In the traditional view of the coupled ocean-atmosphere system, the ocean is driven by momentum flux from the atmosphere and by a latitudinally dependent radiational heating of the upper ocean. In turn, the atmosphere is driven by the surface heat fluxes, in particular those from the ocean, and by the gradient of latent heating in the atmosphere resulting, in part, from these fluxes. Within this scheme the hydrology cycle plays a relatively passive role. We suggest a more significant part for the hydrology cycle in the coupled ocean-atmosphere system. Instead of a passive role, we suggest that the hydrology cycle possesses a zero order influence on the interaction of the two spheres. A central theme of this study is that cloud and precipitation are zero order contributors to the total diabatic heating and the body force structure of the atmosphere and the ocean.

1. INTRODUCTION

1.1 A Traditional View of the Coupled Ocean-Atmosphere System

Figure 1 presents a schematic version of a very simple interacting ocean-atmosphere system. The atmosphere contains a gradient in cloud amount that allows a horizontal variation of the incoming solar radiation through a reflection at the cloud top (Sa_c, where a_c is the albedo). The long wave radiation flux (IR) is often assumed to have a relationship to cloud that is only second order. Overall, the heating gradient due to the convergence of radiative flux in the vertical between the cloudy and clear regions is very small $\nabla Q_{rad} \approx 0$. Such small values are in sharp contrast to the estimates of Ramanathan (1987) who placed the radiative effects at near 50 % of the latent heating gradients. The vertical mixing and the mass transports associated with the wind stress τ and the net radiation budget at the surface of the ocean together determine the oceanic temperature gradients ∇T that, in turn, drive density currents. The fluxes of latent and sensible heat (Q_{sen} and Q_{lh}) associated with the oceanic and atmospheric temperature gradients determine an initial heat input for the atmosphere. The latent heating gradient ∇Q_{lh} across the ocean associated with the ascending and descending motion field modifies and drives a vigorous tropical circulation. In this simple view of the coupled system, the radiation budget and the hydrology cycle are essentially passive and the distribution of radiative heating is primarily a function of latitude, varying little in longitude.

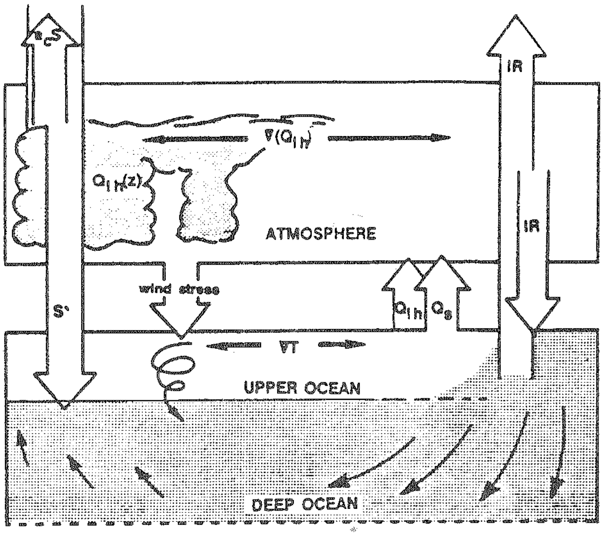

Figure 1. Schematic view of the interactive coupled ocean-atmosphere system where the atmosphere drives the ocean through momentum flux, and the ocean drives the atmosphere through heat flux. In this view, the hydrology cycle is passive, and the effect of clouds is merely to alter the total radiation at the surface.

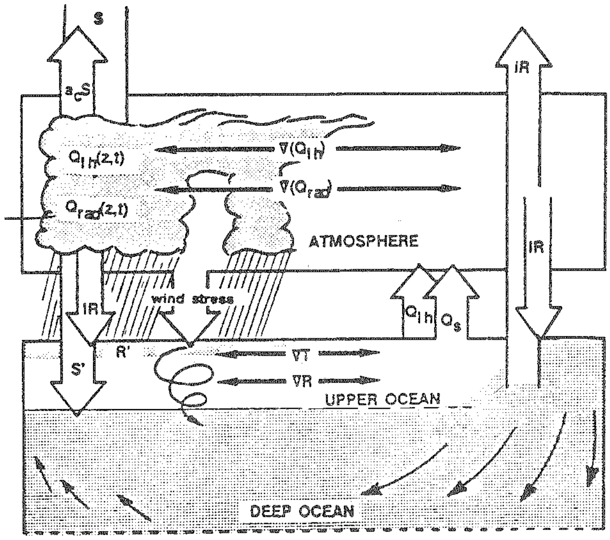

Figure 2. Schematic view of the coupled ocean-atmosphere system where, in addition to the traditional momentum and heat flux driving of the system, the hydrology cycle is completely interactive. The implications of the differences between the traditional system and this are discussed in the text. It is argued that the active hydrology components of the system are zero order.

1.2 The Coupled Ocean-Atmosphere System with Interactive Hydrology

The implication of a fully interactive hydrology cycle allows a richer array of joint modes to develop between the ocean and the atmosphere than are evident from the simple system shown in figure 1. The determination of whether or not these modes are of the same order of magnitude as the wind stress and heating, the primary driving mechanisms, is the major purpose of this note.

Figure 2 shows a schematic diagram of the coupled ocean-atmosphere system where the atmospheric part of the hydrosphere -- clouds, precipitation and the ambient moisture distribution -- are allowed to become fully interactive with the radiation field both within the atmosphere and the ocean, and, in the case of the precipitation, with the density structure of the ocean's upper layers. The ocean-atmosphere interaction through stress and surface fluxes is still important but now these components of the hydrology cycle modify significantly the basic driving mechanisms. We will show that the modification of the radiative flux divergence between cloudy and clear regions, for example, provides a radiative heating gradient ∇Q_{rad} which is of the same sign and between 30 and 50% of the magnitude of the latent heating gradient ∇Q_{lh}.

Another aspect of clouds is that they severely perturb the surface radiation balance in that while they heat the atmospheric column above them, clouds cause a decrease in the amount of solar radiation reaching the sea surface (S'). Below the clear regions an anomalous heating of the upper ocean layer is generated creating a heating gradient between clear and cloudy regions. Ramanathan (1987) estimates that the differential heating is about 1°C/month averaged over 100 m within the ocean. The cloud structure also influences the vertical heating distribution in the ocean by changing the proportion of infrared and solar radiation. This partitioning of the radiative stream possesses a strong spatial variation with the changes in the cloud distribution and also with the variation of the ambient moisture distribution, especially below the cloud. It will be shown that the downwelling IR from the cloud base is much more variable at high latitudes so that much of the reduction of the solar beam by the clouds is canceled by the increased downward IR flux. However, at low latitudes, the extremely moist boundary layer impedes the downward flux so that the apparent radiating surface at the ground may be well below the cloud base. The impact of this will be to reduce the impact of cloud on the downward IR flux at the ground.

It should be noted that the ocean surface layer heating gradient imposed by the cloudiness differences is in the opposite sense to the atmospheric radiation and latent heating gradients. In section 3.2 and 3.5, we will show that this may cause feedbacks between the systems that will move the warm water and consequently the convection successively eastward. Furthermore, we will show that small changes in the ocean temperature where the ocean is warmest can invoke very large changes in the atmospheric hydrology cycle, and, in turn, in the nature of the coupled ocean atmosphere system.

Finally, the ocean density gradient ∇R is a strong function of both salinity and temperature, the distribution of the former quantity depending to a great deal on the fresh water input to the ocean from rivers and precipitation and the output of evaporation. Together, these effects cause a perturbation in the density field (R').

In the following paragraphs, we shall investigate, successively, the following processes and attempt to assess their relative importance in the scheme of the interacting ocean and atmosphere:

(1) Cloud and the total surface radiation flux,

(2) Impact of cloud on the heating distribution in the ocean upper layer,

(3) Precipitation and fresh water input into the ocean,

(4) Episodic momentum fluxes from the atmosphere to the ocean through moist tropical events,

(5) Clouds and total diabatic heating in the ocean atmosphere system, and

(6) The relationship between convection and the sea surface temperature in the tropics.

The six processes and phenomena listed above will be discussed in detail in Section 3.

In the following section we will discuss why a detailed description of the hydrology cycle is necessary in order to understand some processes that have been assumed to be independent of moist effects. It appears that the perturbed climate of the tropical atmosphere is transmitted to a global scale in a relatively short period of time by atmospheric processes through what are known as teleconnection mechanisms. It will be argued that the basic state through which the teleconnection pattern propagates is determined by the long term aggregate of the convection over the warm tropical ocean regions. Such regions are also assumed to be the source of transients within the slowly evolving basic state. It will be argued that the long term teleconnection patterns are aggregates of these transients.

2. ATMOSPHERIC TELECONNECTIONS : LINKAGE BETWEEN TROPICAL CONVECTION AND GLOBAL CIRCULATION

2.1 The Slowly Evolving Basic State at Low Latitudes

Figure 3 (from Webster 1983a) shows two cross sections along the equator representing the flow in the longitude-height plane for the two climate epoches associated with large positive and negative values of the Southern Oscillation Index (i.e., the SOI; the normalized difference in surface pressure between Tahiti and Darwin) which correspond to cold and warm events in the tropical Pacific Ocean. The stippled area denotes sea surface temperatures greater than 28°C. Over this warm pool are regions of mean ascending air, which with the ascent over the continents forms a series of east-west cells along the equator (or "Walker" cells, named by Bjerknes 1968, after Sir Gilbert Walker whose statistical analyses earlier in the century indicated that very large scale circulations existed in the tropical atmosphere) which were identified observationally by Krishnamurti (1971). The location of the cells and their associated easterlies and westerlies show considerable interannual variation. Theoretical explanations of the mean circulation, in which the cells are described as stationary or steady state trapped equatorial modes forced by latent heating gradients, associated with the gradient of sea surface temperature across the tropical oceans, were put forward by Webster (1972, 1973) and Gill (1980).

The circulation described in figure 3 represents a slowly evolving basic state with which all transient motions, on time scales less than seasonal or interannual, must contend. It is worth pointing out for future reference that this base circulation is very much dependent on the hydrology cycle. We note, though, that there is a hidden assumption that we know why the mean ascent in the tropics (the mean convective regions) is associated with the warmest sea surface temperatures. We shall tackle this problem in Section 3.6 and will argue that the solution lies within a blend of basic equatorial dynamics and the hydrology cycle.

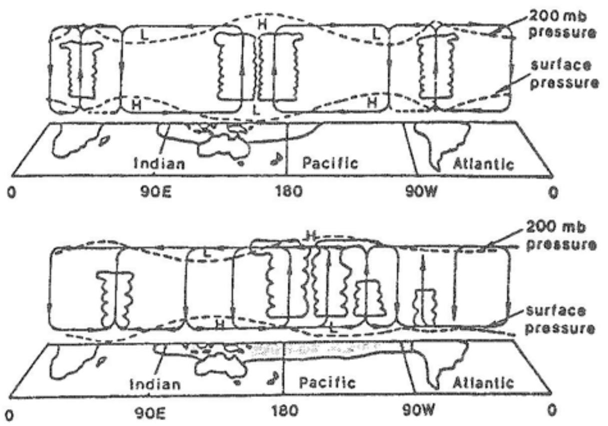

Figure 3. Schematic diagram of the zonal circulations ("Walker circulations") along the equator during periods when the SOI≥0 (upper panel) and SOI <<0 (lower panel) (Webster and Chang 1988).

2.2 Relationships Between Transients, Sea Surface Temperature and the Slowly Evolving Basic State

Figure 4a shows the long term average boreal winter (December, January and February; DJF) and summer (June, July and August; JJA) sea surface temperature distribution corresponding roughly to the SOI>0 panel of figure 3. The heavy isopleth corresponds to the 28°C isotherm. Figure 4b (from Lau, private communication) shows the variance of the OLR (outgoing longwave radiation, used as a proxy quantity for convection) in the 1-5 day period band for JJA and DJF. Figure 4c shows the same variance but in the 40-50 day period band. The heavy isopleth corresponds to the 28°C sea surface temperature isotherm transposed from figure 4b. Clearly, the majority of the tropical convection on transient time scales lies within the 28°C isotherm or in the case of the higher frequency band, over the tropical continents. It is aggregates of these convective transients that form the long term diabatic heating gradient across the tropical Oceans.

There is an apparent paradox in that the region of maximum mean and transient convection lying within the 28°C isotherm does not correspond to the region of maximum transient or perturbation kinetic energy (PKE). Arkin and Webster (1985) showed that maximum PKE was colocated with the regions of maximum westerlies in the upper troposphere over the central and eastern Pacific Ocean and the mid-Atlantic Ocean. Figure 5 (from Webster and Chang 1988) shows sections along the equator of the long term averages of the zonal wind component (U, ms^{-1}), the OLR equivalent temperature (°K) and the PKE (i.e., $(u'^2 + v'^2)/2$, $m^2 s^{-2}$). Clearly, minimum OLR (i.e., maximum convection) corresponds to minimum PKE.

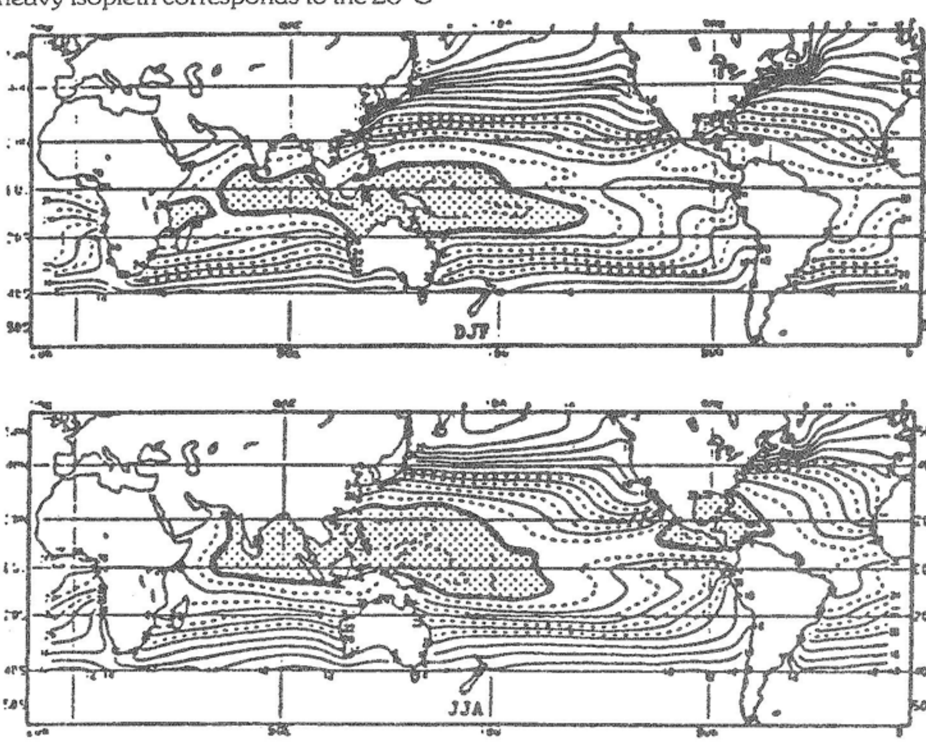

Figure 4(a). Long term average sea surface temperature distribution for boreal winter (upper panel) and boreal summer (lower panel). Temperatures greater than 28° are stippled.

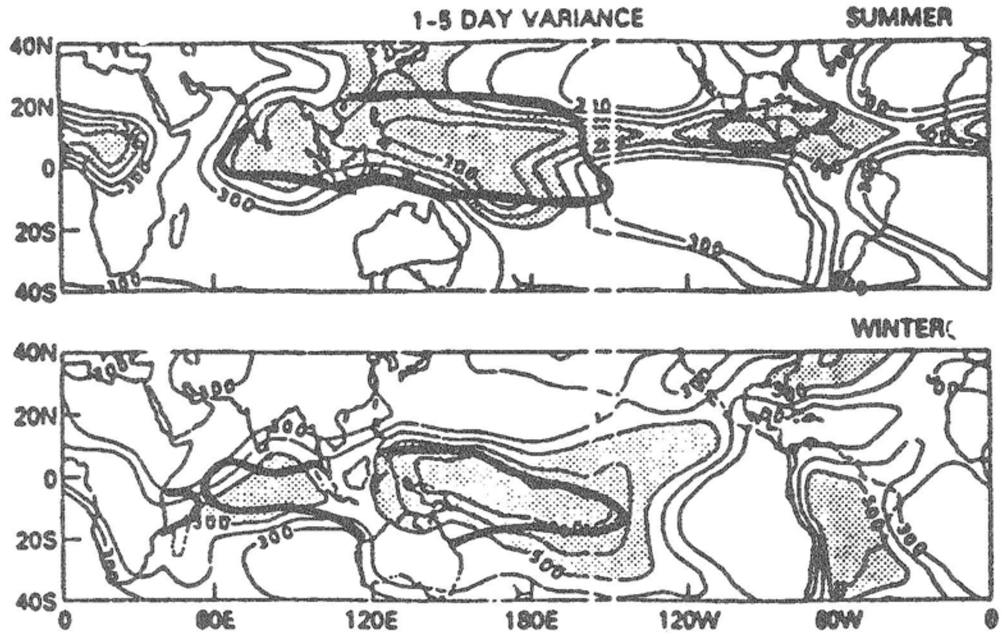

Figure 4(b). Distribution of the variance of OLR in the 1-5 day band for the boreal summer (upper panel) and the boreal winter (lower panel). After Lau (private communication).

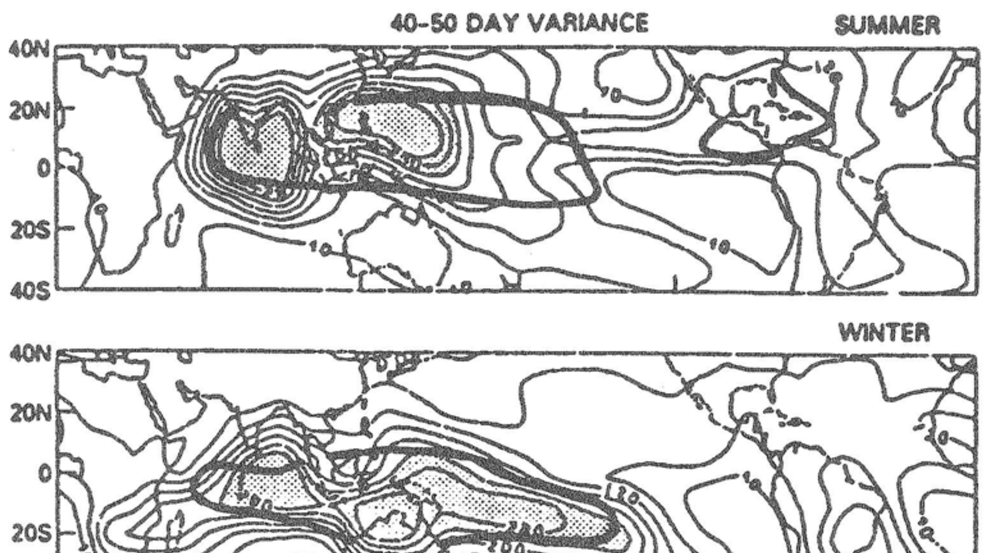

Figure 4(c). Same as Figure 4(b) except for the 40-50 day band. After Lau (private communication).

In the next section we will pose three hypotheses which attempt to solve the convection-PKE paradox. They all are relevant to the dynamics of teleconnections which relate the tropical heating to the circulation of the global atmosphere.

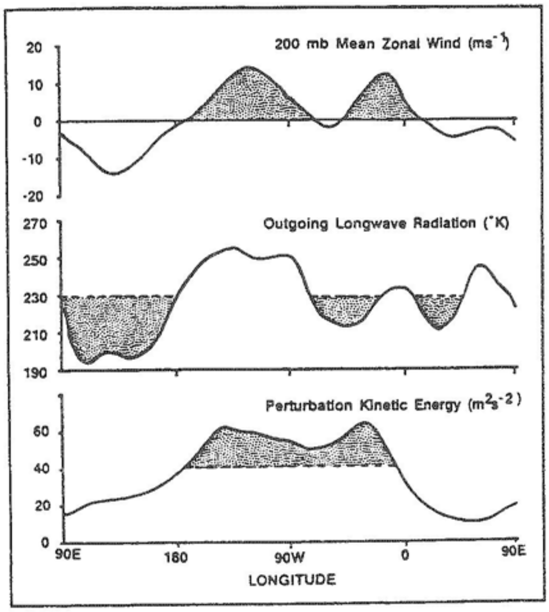

Figure 5. Distribution along the equator of the 200 mb zonal wind (ms^{-1}), the OLR (°K) and the perturbation kinetic energy (PKE; m^2s^{-2}) for the mean boreal winter. Note the strong correlation between westerlies and strong PKE and the association of convection (cold OLR) with the easterly regime (Webster and Chang 1988).

2.3 Dynamic Theories of Teleconnections

The three dynamic theories of teleconnection and the manner in which they relate to the hydrology cycle of the atmosphere are listed and discussed below

2.3.1 The Westerly Duct Theory

The Westerly Duct Theory considered the role of the equatorial migration of extratropical rotational waves through the regions of upper tropospheric equatorial westerlies which exist within the slowly evolving basic flow (see Section 2.1). Webster and Holton (1982) developed the theory to explain the large values of PKE existing in the equatorial westerlies and to show the manner in which transients and stationary waves of one hemisphere influence the other hemisphere. Although there is some observational evidence for Webster and Holton's "westerly duct" theory (M. Yanai, private communication), it does not establish a role for the mean convection or transients originating within the convection either in communicating their influence to higher latitudes or in producing the PKE maxima along the equator. Within this model, the tropics are passive, at least locally, and the PKE maxima are the result of energy produced outside the tropics.

2.3.2 The Wave Train Theory

The Wave Train Theory (Opsteegh and van der Dool 1980, Hoskins and Karoly 1981, Webster 1981, 1982) was developed in order to explain the anomalous perturbation height fields in the extratropics first noted by Bjerknes (1968) which appeared to correlate with the anomalous tropical heating occurring during El Niño. The theory postulated that a wave train would emanate from the anomalous heating towards middle latitudes. An example of these theoretical results (specifically the 250 and 750 mb response of a steady state model, Webster, 1982, for DJF and JJA zonally symmetric basic state relative to a heat source placed on the equator) is shown in figure 6. The extratropical anomalies were, according to the theory, the differences between the steady state solutions consistent with the heating generated by the sea surface temperature fields of figure 3. While there is some compelling evidence that a wave train does emanate from the tropics such as a consistent seasonal variation which agrees with observations (see Webster 1983b), there is little evidence from observations that a wave train actually emanates directly from the heat source. Furthermore, the theory ignores the divergent character of the basic and associated equatorial trapping of the response. The theory finds no need to consider the transient nature of the convection as discussed in Section 2.2 and does not address the problem of PKE maxima in regions of strong westerlies or of minimum PKE associated with convection.

2.3.3 The Wave Energy Accumulation/Emanation Theory

The Wave Energy Accumulation/Emanation Theory of Webster and Chang (1988) suggested that the transient disturbances produced by the convection over the warm tropical oceans produced equatorially trapped modes which propagate along the equator away from the energy source. The characteristics of these modes are completely governed by the slowly evolving basic state of the tropical atmosphere (see Section 2.1). Specifically, in the regions of negative stretching deformation (i.e., when $U_x<0$ i.e., to the east of the equatorial westerlies where PKE was a maximum in figure 5), a convergence of wave action flux occurs, creating an energy accumulation region. Furthermore, as shown in figure 7, in this region, because of conservation properties (see Webster and Chang for details) the longitudinal wavelength of the mode must shorten and the period lengthen when $U_x<0$. The regions of wave energy accumulation were also shown to be regions of emanation for Rossby wave trains to the extratropics. These

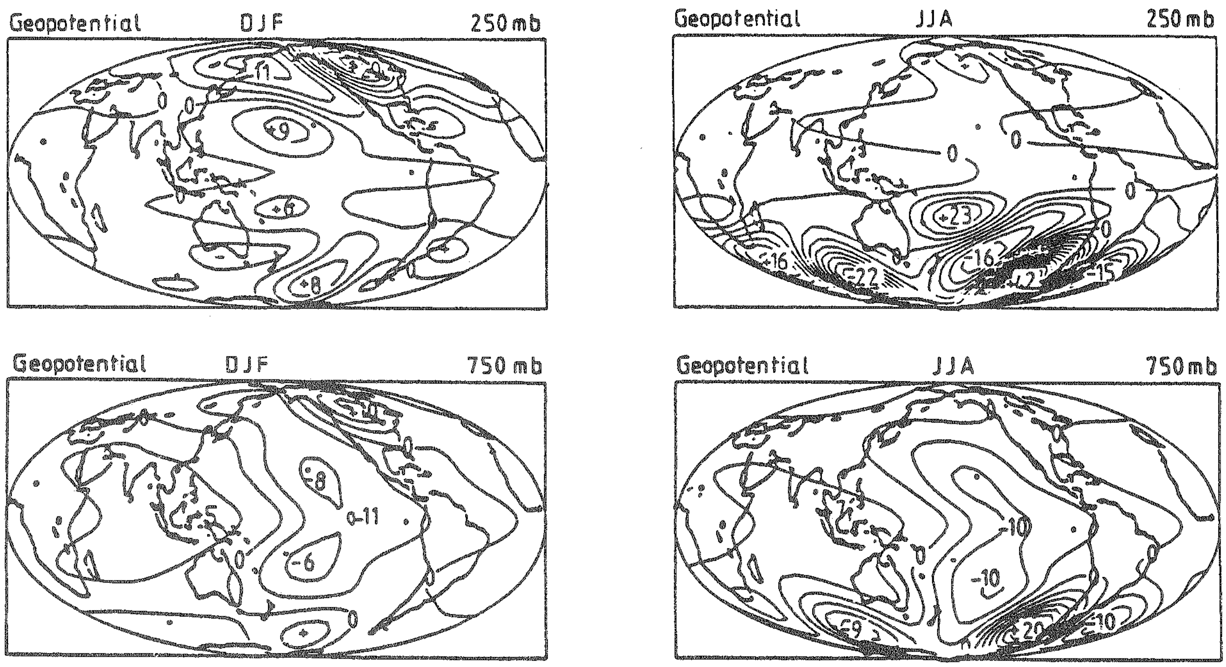

Figure 6. The 250 and 750 mb geopotential response of zonally symmetric boreal winter (left panel) and summer (right panel) to a heat source placed in the central Pacific Ocean (0° N, 180° E). Note the selective response of the winter hemisphere to the forcing. The model used was the iterative, steady state model of Webster (1981).

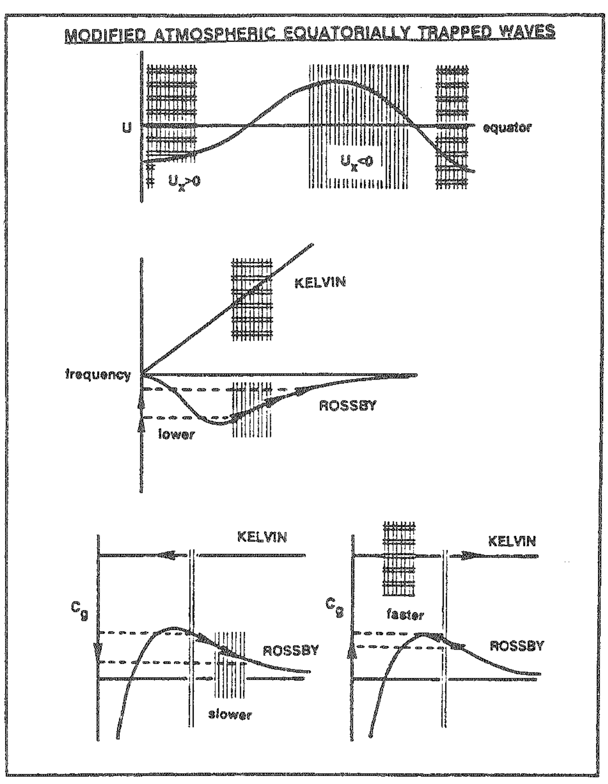

Figure 7(a). Modification of equatorially trapped modes as they propagate through regions of longitudinal stretching deformation along the equator. As the modes (e.g., eastward propagating Rossby waves) propagate into regions of negative stretch (i.e., U_X, hatched region of upper panel), they must shorten their longitudinal scale and increase their period in order to conserve their Doppler shifted frequency, as mandated for modes propagating through a time invariant basic flow. In changing their characteristics, the modes may posses zeros in their Doppler shifted group speed and accumulate energy in the negative stretch regions (Webster and Chang 1988).

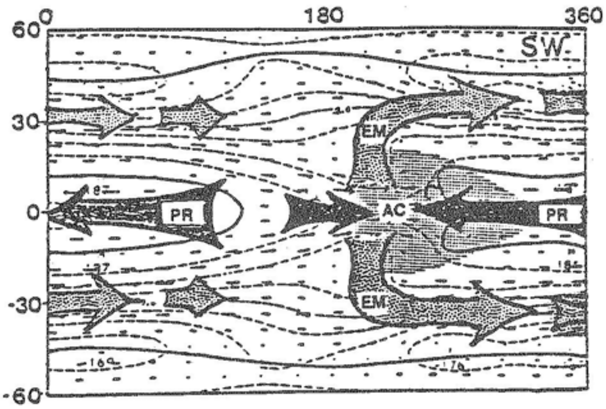

Figure 7(b). Diagram showing a basic state (heavy line shows the U = 0 contour) with the characteristics of the forced equatorial modes indicated by heavy arrows. Waves forced in the convective regions of the easterlies propagate westwards (PR) and accumulate in the region of negative stretch (AC). The energy accumulation region also acts as an emanation region to higher latitudes (EM) as a Rossby wave train. The transient forcing along the equator is manifested as a very low frequency wave train which is phase locked relative to the basic state (Webster and Chang 1988).

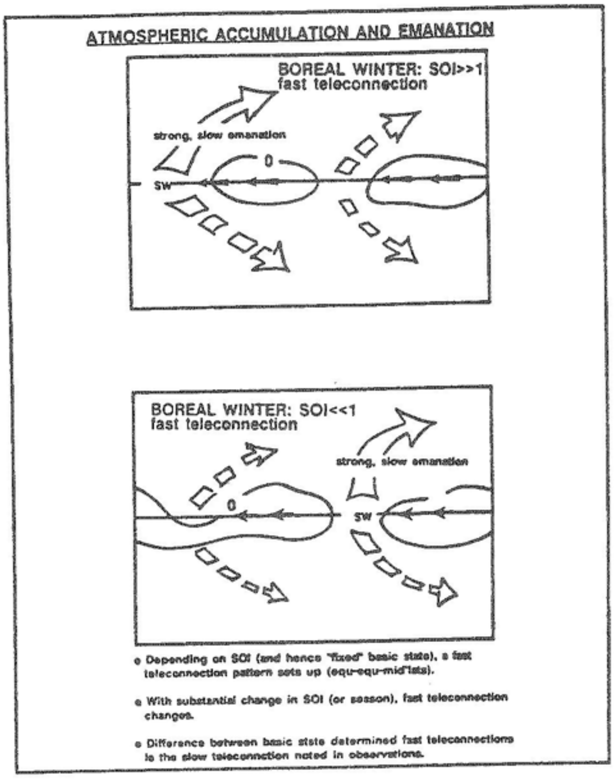

Figure 8. The energy accumulation/emanation phenomenon is determined strictly by the structure of the basic state and hence possesses both annual and interannual variation. It is hypothesized that the difference between these "fast" teleconnection patterns for basic states indicative of SOI>0 and SOI may explain the interannual variability noted in the extratropics. ⇒

equatorial modes possess the same low frequency character as the modes in the accumulation region. Thus, the impact of the high frequency transient forcing in the convective regions is to produce a very low frequency response , where $U_x<0$, and an equivalently low frequency wave train to high latitudes. For a given basic state, then a phase locked response at high latitudes may be expected. Webster and Chang termed this accumulation -emanation phenomena for a given basic state the "fast" teleconnection pattern. The difference between the fast teleconnection patterns for slowly evolving basic states when the SOI<<0 and SOI>>0 (as shown in figure 3) they termed the "slow" teleconnection pattern from which the observed anomaly patterns between warm and cold episodes would arise. The relationship between "fast" and "slow" teleconnection phenomena is shown schematically in figure 8.

The appeal of the theory 2.3.3 is that it incorporates a role for the transient modes produced in the warm sea surface temperature regions and allows for a wave train response theory 2.3.2 but one that is phase locked! Further, it suggests a mechanism for the production of the PKE maxima and minima which is consistent with the theory of equatorially trapped modes in a flow with longitudinal stretching deformation while, at the same time, being consistent with the westerly duct theory of Webster and Holton (1982) where extratropical influence propagates into the tropics.

Clearly, the accumulation/emanation theory as well as the wave train hypothesis, require a thorough understanding of the mechanisms that control the diabatic heating in the tropical atmosphere. Such mechanisms are functions of the joint system and the hydrology cycle which we will explore in the subsequent sections.

3. HYDROLOGICAL PROCESSES AND THEIR IMPACT ON OCEAN-ATMOSPHERE INTERACTION

In Section 1.2 six processes were listed. These involved the direct interaction of the hydrology cycle and the ocean-atmosphere system, some of which have not yet received full scientific scrutiny. Our aim will be to describe the process and assess its order relative to other key processes that possess an established role in the interaction of the ocean and the atmosphere.

3.1 Cloud and the Total Surface Radiation Flux

The processes that determine the net flux at the surface of the ocean are shown in figure 9. The Stephens parameterization, as discussed in Stephens (1978) and Stephens and Webster (1983), relates the cloud emissivity (ε) and the cloud albedo (a_c) through the liquid water content of the column. The total emissivity, of course, is also a function of the non-cloud water vapor in the atmospheric column, a point that is particularily relevant to the tropics. The upper panel of figure 9 shows the emissivity and albedo curves as a function of the logarithm of the liquid water path. Along the upper scale, clouds characteristic of the different water paths are indicated (Stephens and Webster 1983). The albedo slowly increases almost linearily with liquid water path whereas the emissivity rapidly approaches unity for quite small values of liquid water content. That is, clouds that are fairly transparent to solar radiation may be black in the infrared.

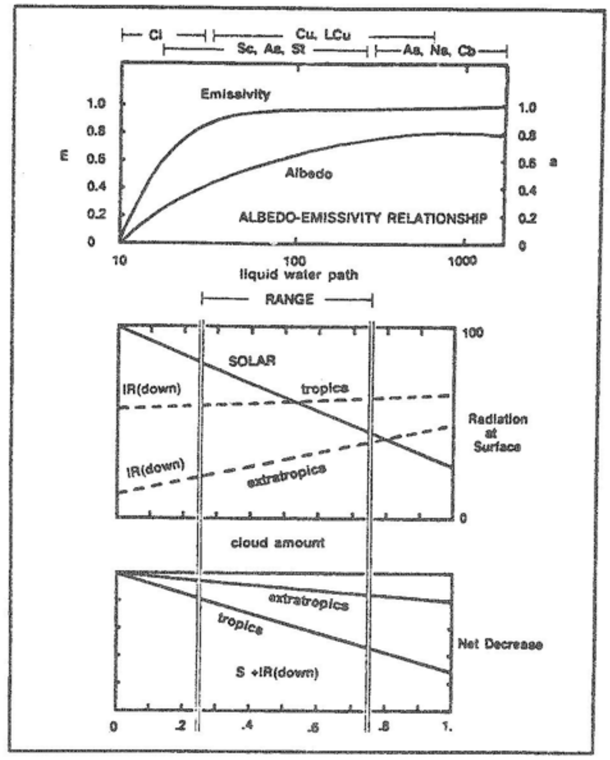

Figure 9. Diagram representing the impact of cloud on the surface radiation budget at the surface. The upper panel relates the albedo and emissivity through the liquid water path (Stephens 1978). The middle panel shows the relative variation of the downwelling IR and solar radiation reaching the surface for the tropics and the extratropics. The bottom panel shows the net irradiance decrease at the surface due to cloudiness.

Some consequences of the ε-a_c relationships pertaining to the ocean-atmosphere system may be seen in the bottom two panels of figure 9. Consider a cloud within a dry environment. A cloud mass will decrease the solar radiation reaching the ocean surface in proportion to the liquid water content of the cloud. However, the downwelling infrared radiation from the cloud base ($F\nabla_c$) will compensate somewhat for the depletion of the magnitude of the solar stream in proportion to the fourth power of the cloud base temperature. However, if the cloud exists within a moist environment, will be partially absorbed by the moist boundary layer. In the warm ocean regions of the tropics, especially, $F\nabla_c$ the ambient moisture distribution may be so large that the boundary layer itself becomes black. Thus, the impact of clouds in such warm water regions of the tropics on the downwelling infrared radiation at the surface $F\nabla_g$ is minimized. At higher latitudes, where the boundary layer is dryer, the downwelling IR almost compenates for the depleted solar radiation. These effects, for both the warm ocean tropical regions and the extratropics are shown in bottom panel of figure 9.

Clearly, the variation of the solar radiation due to cloudiness is the critical factor near the equator. Consequently, for ocean-atmosphere studies, a detailed climatology of solar radiation in the tropics is mandatory. Atmospheric models, on the other hand, must possess parameterizations that express the real latitudinal and longitudinal variation of the component form of the surface energy flux. This includes, at *all* latitudes, the variation of $F\nabla_g$. Even in the western Pacific ocean, the net long wave flux, ΣF_g, varies between ±10-15%. This translates to a variation between 40-80 wm^{-2} difference between cloudy and clear regions which is four times the TOGA tolerance for monthly mean quantities. In the next section we will discuss why it is important that the magnitudes of the components of the surface flux (i.e., S_g or $S_o(1-a_c)(1-a_g)$, ΣF_g and $F\Delta_g$) be known quite accurately in addition to the net flux ($\Sigma R_g = S_g - \Sigma F_g$).

3.2 Impact of Cloud on the Heating Distribution in the Upper Ocean

In the last section we discussed how clouds, besides varying the magnitude of the total surface radiative flux, ΣR, change substantially the proportion of long wave and shortwave at the surface. Over land areas, where short and long wave radiation alike is attenuated in the skin layer of the soil or in the biosphere, the heating of the surface is determined by ΣR. Over the oceans the story is entirely different because the attenuation coefficient of the radiation is a strong function of the wavelength.

Radiation incident at the surface of the ocean is dispersed in a number of ways. Downward directed terrestrial radiation ($F\nabla_g$) is absorbed in the first few millimeters of the ocean. The shortwave end of the spectrum (ΣS) is absorbed with a strong spectral dependence. The red end of the spectrum is absorbed within a very few meters whereas the blue-green radiation is absorbed at considerably greater depths. Simpson and Dickey (1981) express the attenuation function of S as:

$$S'(z) = S_g(R.\exp(z/\psi_1) + (1-R).\exp(z/\psi_2)) \quad (1)$$

where R is the proportion following the "red" absorption characteristics with attenuation depth of ψ_1 . (1-R) is the proportion in the bluegreen end of the spectrum with an attenuation depth of ψ_2 .ψ_1 ,ψ_2 and R are also strong functions of turbidity, which, in turn, depends on S_g through biospheric feedback.

Figure 10 shows the attenuation of incoming solar radiation as a function of wavelength and depth in meters. The histograms denote the proportion of radiation in the following wavelength bands: .2-.6, .6-.9, .9-1.2, 1.2-1.5, 1.5-1.8, 1.8-2.1, 2.1-2.4, 2.4-2.7 and 2.7-3.0 relative to Table 1.

The histograms, set at various depths in the upper ocean, show clearly the strong spectral behavior of the visible radiation with depth as indicated in (1). The percentages refer to the amount of solar radiation, integrated over all wavelengths, reaching a particular depth. The infrared terrestrial radiation is attenuated at the same attenuation rate as the near infrared of the solar stream.

TABLE 1
Energy distribution with depth of incoming solar radiation with S_g= 1000 for specific wavelenghts (data, G.L. Stephens, private comm.)

wavelength	depth (meters)								
μ	0	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}
.2- .6	237	237	237	237	236	229	237	172	14
.6- .9	360	360	360	359	353	305	129	9	
.9-1.2	179	179	178	172	123	8			
1.2-1.5	87	86	82	63	17				
1.5-1.8	80	78	64	27					
1.8-2.1	25	23	11						
2.1-2.4	25	24	19						
2.4-2.7	7	6	2						
2.7-3.0	4	2							
Sum	1000	993	952	859	730	540	358	181	13

The insert at the bottom left of figure 10 shows another perspective of the ocean radiation attenuation for both the infrared and the solar streams. Both the upward and downward infrared fluxes, $F\Delta_g$ and $F\nabla_g$ are represented. As $F\Delta_g > F\nabla_g$, the infrared cooling of the ocean takes place in a very shallow layer. However, the solar radiation is spread much deeper through the upper ocean. The depths labelled A, B, C and D show the average thermocline depths for the summer extratropics, the average tropics and the east and west equatorial Pacific Ocean during non-Niño periods when the SOI≥0. During warm events (SOI<<1), the average thermocline depth is somewhere between C and D. Note, now, the importance of the magnitudes of the attenuation depths $\psi_{1,2}$. If $\psi_2 > z(A,...D)$ in a particular location then the slow dynamics of the deeper ocean must be taken into account to compensate for the diurnal heating at depths greater than the thermocline depth, h_c. Woods (1984) contended that during periods of rapidly varying thermocline depth in the Pacific Ocean, for example during transitions from SOI≥0 to <1 with the subsequent variation in cloud (e.g., between the vertical bars shown in the bottom diagram of figure 9), solar heating may occur below the thermocline in regions of originally large h_c and high cloudiness (the western Pacific; SOI≥0). Woods felt that this anomalous heating could be significant in a climate sense as it could not be redistributed rapidly by mixed layer dynamics which possess a strong diurnal variability and thus the ability to disburse a diurnal signal. In summary, if $h_c >> \psi_2$, then variations in the radiation balance will be constrained to effects within the mixed layer. On the other hand, if $h_c < \psi_2$ then solar radiation may be

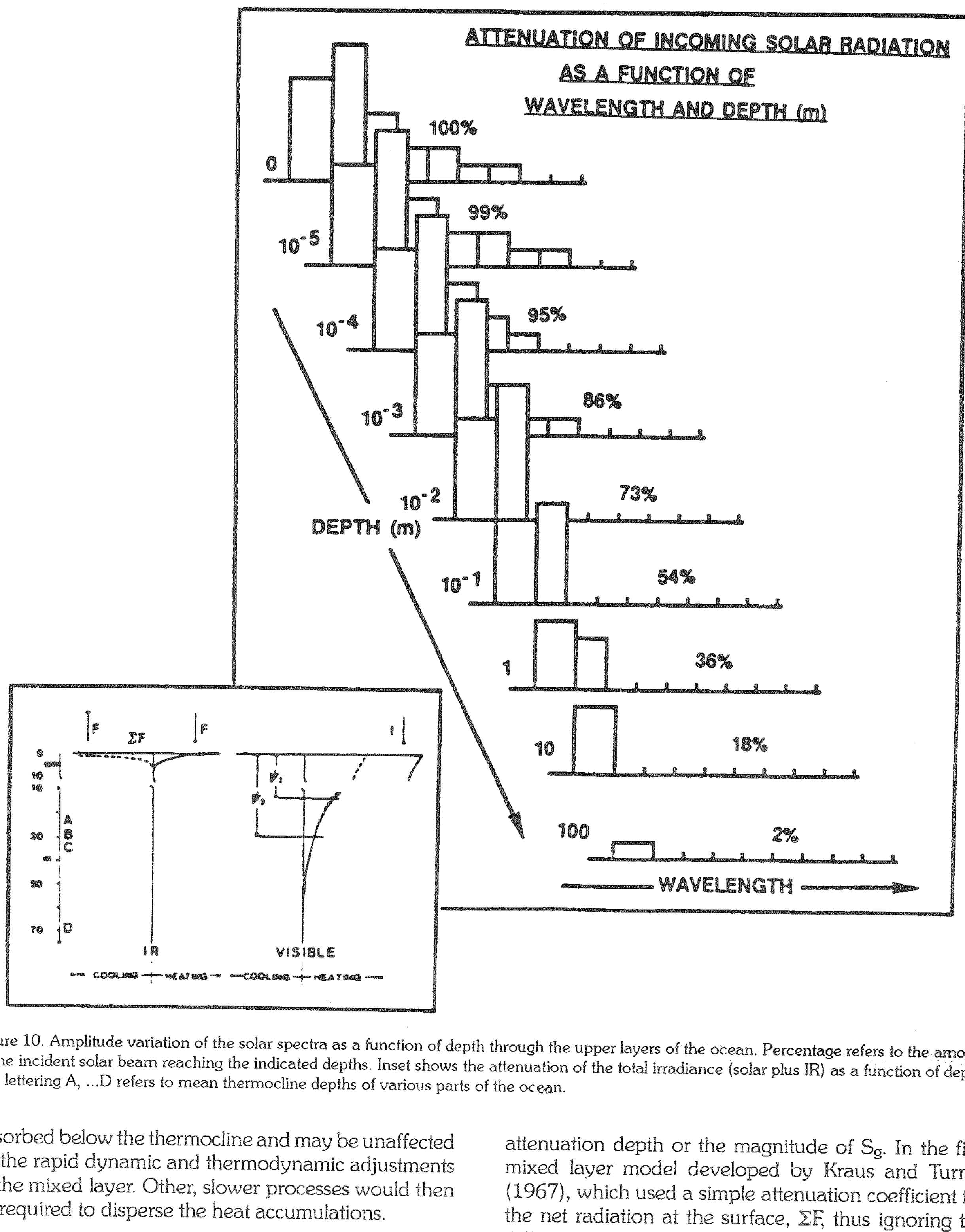

Figure 10. Amplitude variation of the solar spectra as a function of depth through the upper layers of the ocean. Percentage refers to the amount of the incident solar beam reaching the indicated depths. Inset shows the attenuation of the total irradiance (solar plus IR) as a function of depth. The lettering A, ...D refers to mean thermocline depths of various parts of the ocean.

absorbed below the thermocline and may be unaffected by the rapid dynamic and thermodynamic adjustments of the mixed layer. Other, slower processes would then be required to disperse the heat accumulations.

A number of studies have attempted to test the sensitivity of the ocean mixed layer to variations in the attenuation depth or the magnitude of S_g. In the first mixed layer model developed by Kraus and Turner (1967), which used a simple attenuation coefficient for the net radiation at the surface, ΣF, thus ignoring the differential absorption of the radiation spectra and, thus, a major effect of clouds, an extreme sensitivity was found to the variation of the magnitude of the net radiational heating. Within the confines of their model, they showed that the predicted minimum depth of the summer thermocline was 80 m if the attenuation e-folding depth was 20 m but 57 m if the e-folding depth were changed to 10 m. Such variations in the net flux at the surface may be interpreted in terms of variations in the magnitudes of the individual streams by the variations of cloudiness. From these considerations, it seems plausible that the interannual variation of cloudiness, and the corresponding variability in the magnitude of the upper ocean heating and the variation in the heating structure with depth, associated with the El Niño-Southern Oscillation (ENSO) sea surface temperature variations could produce important feedbacks to the ocean structure.

3.3 Precipitation and Fresh water Input into the Ocean

In the previous paragraphs we have addressed mainly the direct influence of the hydrology cycle on the temperature of the upper ocean. However, this being a dynamic system, the temperature is a function also of the body forces applied to the system. In addition to the momentum flux from the atmosphere to the ocean, body forces arise from the variations in the salinity of the upper ocean.

The density of the ocean is a function of its temperature and its salinity; i.e., $\rho = \rho(T,S)$, so that large scale body forces arise from variations in temperature and salinity. In a given region of the ocean in the tropics, the salinity varies as a function of the fresh water input from precipitation, from output through evaporation and by advection of anomalously saline water from other regions or depths and by river inflow. In the ocean regions of maximum interannual variability,for example, in the western and central Pacific Ocean, the former three processes are most important. The first two (precipitation and evaporation) are integral parts of the hydrology cycle. The third, advection, may be partly a response to the body forces modified by hydrology cycle.

How important are these fluxes of fresh water? In the western Pacific Ocean total annual rainfall averages somewhere in the range of between 2 and 4 meters. A heat flux required to evaporate the fresh water input, thus leaving unchanged the density distribution of the western Pacific, would be roughly 40 wm^{-2} per meter of precipitation. If the fresh water input is not balanced by evaporation (which it is not, as diagnostic and modeling studies suggest that the areas of major precipitation are also regions of net moisture convergence) then the density gradient in the upper ocean must adjust relative to the fresh water. We note, too, that the injection of fresh water into the system stabilizes the mixed layer considerably. Of course, the slowly varying structure of the upper layer of the ocean, and thus the coupled ocean atmosphere system must accommodate the aggregation of a multitude of such events. During the periods of Pacific Ocean warmings, when the convection moves eastward following the warm water, anomalous rainfall in the central and eastern Pacific is measured in meters. In these regions the anomalous adjustment of the upper ocean must be substantial.

3.4 Episodic Momentum Fluxes from the Atmosphere to the Ocean Through Moist Tropical Events

In the main, the general easterly flow of the trade winds and the near-equatorial surface winds produce a wind stress that produces a west to east slope of the ocean surface. With ENSO, this wind stress is relaxed causing a flattening of the ocean surface. However, throughout the ENSO evolution, and particularily during the periods when the SOI$\geq$0, the system is subject to strong local stochastic forcing. In the last section, it was suggested that episodic convection associated with organized convection varies the salinity distribution substantially. In addition to large amounts of fresh water input into the warm water regions of the tropical oceans these moist meteorological events can produce abrupt and episodic anomalous momentum fluxes from the ocean to the atmosphere. The resulting momentum fluxes have been observed to produce a significant oceanic response in the form of an eastward propagating Kelvin wave (Knox and Halpern 1982; Luther, Harrison and Knox 1983). Although it is a controversial assertion, it is widely felt that the anomalous Kelvin wave may be significant in producing changes on the grand scale throughout the ocean basin leading to the initiation of the warm events themselves.

Figure 11 shows the variation of the surface zonal winds at Ocean Island between 1953 and 1980. Out of a background of moderate easterlies (mean $\approx$ -5 m^{-1}) episodes of sustained strong westerlies lasting a number of days and of order 5- 10 ms^{-1} occur a number of times per year. Corresponding to the "westerly burst shown to be near 175° E during April, the lower diagram of figure 11 shows the eastward migration of an oceanic Kelvin wave depicted through the eastward transport per unit width of the 0-250 m average zonal current along the equator at 152° W and 110° W and by the sea level variation at Isabela Island in the Galapagos (Knox and Halpern 1982). The pulse arrives at the three stations

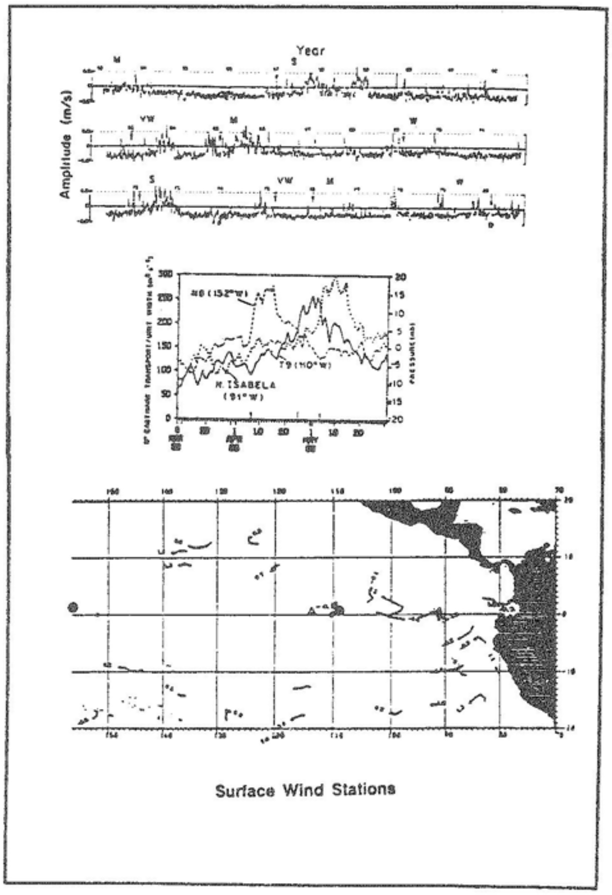

Figure 11. Surface wind speed variation at Ocean Island (170° E) along the equator. The second panel shows the variation of mixed layer characteristics along the equator at the locations indicated in the lower panel following a westerly "burst" in the western Pacific in April, 1980. Observations suggest that the burst initiated a Kelvin wave that propagated eastwards at a speed of 2.7 ms^{-1} (Knox and Halpern 1982; Luther, Harrison and Knox 1983).

on April 7, April 25 and May 3, respectively, indicating phase speeds between each station pair of about 2.7 ms^{-1}.

Although something is known about the frequency, and spatial and temporal variability relative to climate epoches, little is known about their genesis or form. There is some evidence that the "bursts" originate as incursions in to the tropics during cold surge events (Williams 1981, Webster 1987, Love 1985). The first panel of figure 12 shows the surface pressure pulse following a outbreak of cold air from Siberia (i.e., a cold surge) along or near the 105°E meridian. It is interesting to note that there are two time scales involved in the propagation towards the equator. The first, defined as an equatorially trapped edge or Kelvin wave (Webster

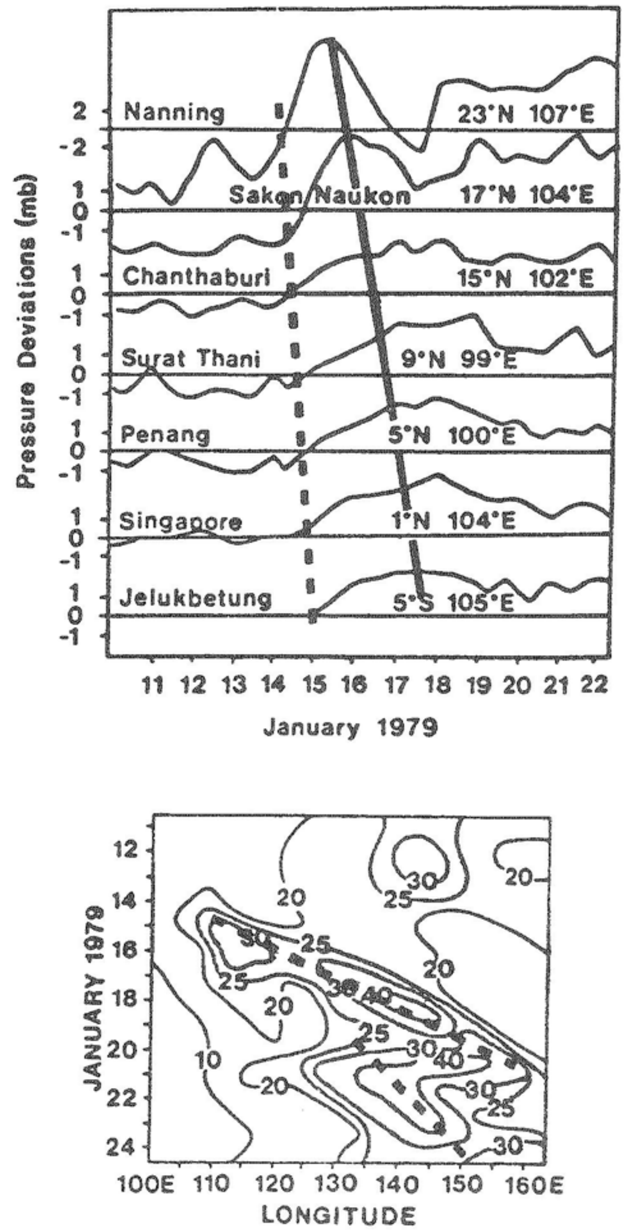

Figure 12. Surface pressure variation (upper panel) about the 150° E meridian between 23° N and 5° S following a cold East Asian surge on January 14, 1979. The two lines indicate propagation speeds of 40 and 10 ms^{-1} of the gravity and Rossby wave components of the surge (Webster 1987, Leathers 1986). Lower panel shows the magnitude of the 850 mb westerly winds along 5° S between 100° and 160° E following the surge (knots). Propagation speeds are about 30 ms^{-1} to the east.

1987, Leathers 1986) possesses a phase speed of about 35 ms^{-1}. A slower Rossby or shelf wave moving with the cold air possesses a phase speed of nearly 10 ms^{-1}. The second diagram of figure 10 shows the westerly wind speed at 850 mb along 5°S following the surge. The time-longitude section indicates an eastward propagation of between 20 and 30 ms^{-1} with winds over 40 knots or 20 ms^{-1}. Associated with the westerly burst was a vigorous westward propagating convective system (Williams 1981). It would be tempting to associate all bursts with cold surges. However, cold surges of different intensities propagate equatorward a number of times per month during the boreal autumn and winter. Clearly then, given the frequency of bursts indicated in figure 12, not all surges initiate westerly bursts. Clearly, the determination of physical processes that generate and maintain the bursts is a pressing problem in coupled ocean atmosphere climatology.

Case studies of westerly bursts by Ramage and colleagues (private communication) indicate an association with strong convection, consistent with the findings of Williams (1981). The observations seemed to suggest a sequence in which a westerly wind along the equator was detected and was followed by an intense development of organized convection. With this development, the westerly winds accelerate along the equator. Often the acceleration was followed by the formation of dual cyclone pairs on either side of the equator at which time the convection on the equator subsided. The westerly winds, however, were then sustained for an even longer period by the developing cyclone pairs.

It is possible to form a conceptual model that satisfies the observations and that would be testable through modeling or ancillary observation. The initial westerly winds, from where ever they arise, are convergent towards the equator and thus equatorially trapped. Consequently, the westward flow must be associated with moisture convergence and thus with convective development. Equatorial westerly winds are also consistent with downwelling in the ocean so that the sea surface temperatures may be expected to remain warm and supportive of organized convection. Furthermore, the input of fresh water from convection will stabilize the mixed layer and so reduce the mixing up of the colder water via an enhanced wind stress. The strengthening of the westerlies along the equator may increase the lateral shear in the westerlies invoking barotropic instability to the north and south of the equator. Through this mechanism, there is an initial energy source for the cyclone pairs before moist processes take hold.

3.5 Clouds and Total Diabatic Heating in the Ocean-Atmosphere System

In figure 2 it was indicated that the gradients of radiative flux convergence in the troposphere (∇Q_{rad}) was a substantial fraction of the latent gradient (∇Q_{lh}) and of the same sign. We shall now compute an order of magnitude estimate of the two gradients. Further, we shall assess the importance of the decreased heating in the ocean column consistent with the atmospheric radiative structure and compare the sign of the resultant gradient with the atmospheric heating gradients.

We can consider a very simple atmosphere represented by two columns, A and B, representative of western and eastern Pacific Ocean conditions. We assume an incident solar radiation, S_0, a total cloud albedo, a_c and an absorption coefficient of solar radiation in the cloud of α_c . The surface temperature of the two columns are T_{Ag} and T_{Bg} , respectively. The cloudy region is assumed to be sufficiently thick so that the cloud radiates to space at the cloud top temperature T_{At} and towards the ocean surface at the temperature of the cloud base T_{Ab}. The boundary layer below the cloud is moist with an emissivity ε_b so that partial absorption of the downwelling longwave flux from the cloud occurs in the boundary layer. The temperature of the boundary layer is set at T_{Abl}. An expression for the radiative flux convergence in the cloudy column A is:

$$Q_{Arad} = S_0(1-a_c)\alpha_c+\sigma T^4_{Ag} -(1-\varepsilon_b)\,\sigma T^4_{Ab} - \varepsilon_b\,\sigma T^4_{Abl} - \sigma T^4_{At} \tag{2}$$

In column B we assume that the emissivity is ε_a (<1), the clear air absorption is α_{cl} and that the atmosphere radiates at some temperature T_{Ba}. Then, the radiative flux convergence in this clear column is:

$$Q_{Brad} = S_o\alpha_{cl} + \varepsilon_a T^4_{Bg} - 2\varepsilon_a\sigma T^4_{Ag} \tag{3}$$

If we assume that the temperatures $T_{At} = 300°K$, $T_{Ab} = 275°K$, $T_{Abl} = 285°K$, $T_{Ag} = 300°K$, $T_{Bg} = 290°K$ and $T_{Ba} = 260°K$ with $S_0 = 345\ wm^{-2}$, $a_c = .4$, $\alpha_c = .3$, $\alpha_{cl} = .1$, $\varepsilon_b = .8$ and $\varepsilon_a = .6$, we obtain for the two equations;

$$Q_{Arad} = 62 + 460 - 64 - 299 - 91 = 68\ wm^{-2} \tag{4}$$

and

$$Q_{Brad} = 34 + 241 - 311 = -36\ wm^{-2} \tag{5}$$

so that the gradient of the radiative flux convergence across our model Pacific Ocean is:

$$\nabla Q_{rad} = Q_{Arad} - Q_{Brad} = 104\ wm^{-2} \tag{6}$$

If we assume that the average precipitation in the western Pacific Ocean is 3 meters/year and that generally there is little precipitation in the eastern Pacific Ocean, we can obtain an estimate for the latent heating gradient across the Pacific Ocean as:

$$\nabla Ql_h = Q_{Alh} - Q_{Blh} = 289\ \mathrm{wm}^{-2} \tag{7}$$

Thus, within the confines of this very simple model we find that the gradient of the radiative flux convergence due to the gradient of cloudiness across the Pacific Ocean is a factor of three of the latent heating gradient which parallels the estimate of Ramanathan (1987). Of course, better models may give more accurate comparisons between the two gradients. The simple model used here was constructed merely to provide an order of magnitude estimate. However, it is unlikely that the model give errors beyond factors of two. In other words, in all probability radiative forcing due to the presence of clouds cannot be neglected.

It is interesting to note that the latent heating and radiative gradients *will always be of the same sign*. That is, when the dynamics of the atmosphere-ocean coupled system conspire to provide moisture convergence and ascent and, thus establish the gradient of latent heating, a corresponding radiative heating gradient will be set up. In a sense, the radiative heating *locks in* the latent heating gradient through positive feedback.

The depletion of the solar radiation below the cloudy regions was discussed in Sections 3.1 and 3.2. It is a simple matter to calculate the upper ocean heating gradient between the cloudy and the clear regions. For example, Ramanathan (1987) estimates that the gradient is about 1 to 1.5 °C/month averaged over a 100 m layer of the ocean. The interesting fact is that the heating gradient is in the *opposite sense* to the radiational and latent heating gradient in the atmosphere! Figure 13 shows a schematic representation of the three heating gradients.

Viewed alone, the opposite influence of the hydrology cycle on the signs of the heating gradients in the atmosphere and the ocean suggests interesting feedback mechanisms between the two systems. Basically, it means that the ocean atmosphere system cannot exist in a steady state if a hydrology cycle is considered. For a given sea surface temperature distribution convection will establish itself over the warmest regions (see Section 3.6). Once the latent and radiative heating gradients are established in the atmosphere, ocean cooling immediately commences in the ocean layer below the cloudy region with heating elsewhere in the upper ocean below the less cloudy regions. Because of the Clausius-Clapeyron relationship, small changes in the ocean temperature in the warmest regions will cause very large changes in the saturation vapor flux and in the latent heating gradient. The impact is to shift continually the region of warmest sea surface temperature along the equator and with it the convection and clouds. The consequence of the feedback has yet to be explored.

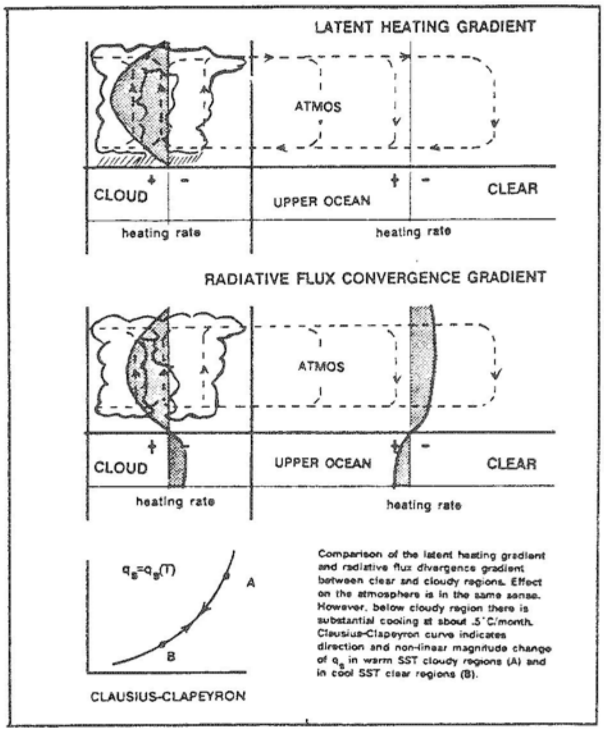

Figure 13. Comparison of the latent heating gradient and the radiative flux divergence between the west and east Pacific (SOI). In the atmosphere the latent heating gradient is enhanced by the radiative effects. However, in the ocean the region below the cloud is cooled relative to the clear region. Differential heating of the upper ocean layer has been estimated by Ramanathan (1987) to be about 1° C/month averaged over a 100 m depth. Clausius-Clapeyron curves indicate the significance of cooling in the ocean below the convective regions.

3.6 Organized Convection / Sea Surface Temperature Relationships: Interaction of Hydrology and Dynamics

In the tropical oceans, deep organized convection tends to fall within the 28° C sea surface temperature isotherm as shown in Figure 4. This has been, and still remains, a major mystery. Many attempts have been made to show that 28° C is the threshhold temperature at which some instability arises. We will now argue that the physics that control this relationship are a combination of controlling dynamics of the tropical atmospheric and the moist thermodynamics of the hydrology cycle. In fact, we propose that the only special quality of the 28° C isotherm is that it is within a degree or so of the maximum ocean temperature observed on Earth.

Figure 14 describes the relationships between convection and the sea surface temperature portrayed as a schematic sequence. In this sequence we consider two regions (e.g., the western and eastern Pacific Ocean) with temperatures T_1 and T_2 where $T_1 > T_2$ and $T_1 \simeq T_{max}$. The following processes are relevant:

(i) The Clausius-Clapeyron relationship shows that the saturation vapor pressure, e_s is a nonlinear function of T such that $e_s(T_1) > E_s(T_2)$ (panel 1, Fig. 14).

(ii) The free convective height (i.e., the level at which a parcel rising moist adiabatically asymptotes to a dry adiabatic ascent) is a nonlinear function of the surface temperature, following Clausius-Clapeyron, assuming the same relative humidity distribution exists in each column (panel 2, Fig. 14).

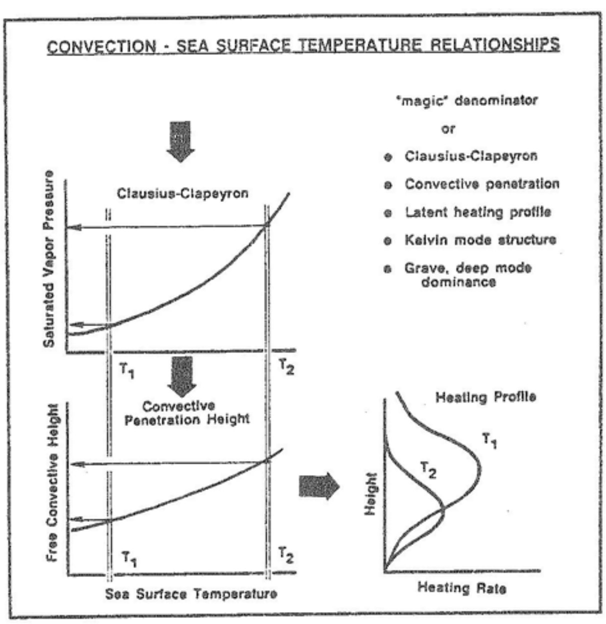

Figure 14. Schematic sequence attempting to relate the distribution of organized convection over the oceans with the sea surface temperature. The first panel shows the Clausius-Clapeyron equation $e_s = e_s(T_{SST})$ and its relation to the free convective height (panel 2). Assuming the same vertical distribution of relative humidity in the cold (T_1) column as in the warm (T_2) column, and if convection were to occur, the warm column would have a higher, stronger distribution of latent heat release than the cooler column.

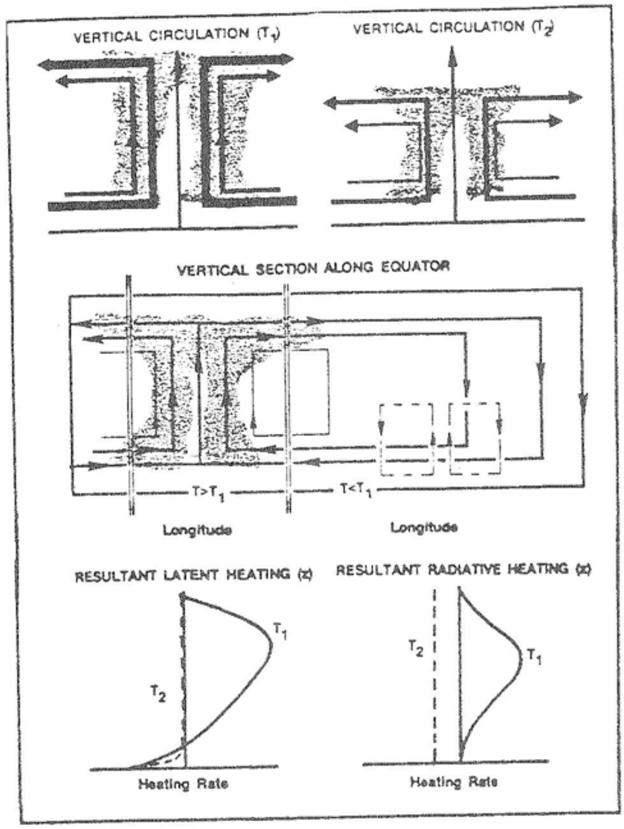

Figure 14 (continued). The latent heat release in the warm region will produce a stronger, and thus deeper viscous Kelvin wave than that produced in the cooler region. Although both will be of planetary longitudinal scale, the warm region Kelvin will dominate over other incipient convection elsewhere (fifth panel). The last panel shows the final latent and radiational heating. With the development of convection, the radiative flux duivergence "locks in" the total diabatic heating gradient, as discussed in Section 3.5. The significance to the 28 °C isotherm is that it is very close to the maximum sea surface temperature and thus approximates the ascending location of the strongest, deepest viscous Kelvin wave.

(iii) The magnitude of the latent heat release is a function of the surface e_s, given the caveats of (ii) above. The distribution of the heating in the vertical is given by the convective height in the particular column. Thus, the warmer, more moist column will have a higher and larger maximum heating rate than the cooler column (panel 3, Fig. 14).

(iv) In an equatorial easterly basic flow, the principal mode that will be excited is the equatorial Kelvin wave. The mode closest to resonance is the gravest horizontal mode (Webster 1972) so that regional forcing produces a planetary scale response in longitude. The magnitude of the response depends on the amplitude of the forcing (panel 3). However, the vertical scale of the Kelvin mode depends on the vertical scale of the heating as this will determine the structure of the viscous Kelvin wave (Chang 1977) or the height to which cumulus mixing will occur. Thus, even though the horizontal scales relative to the forcing in the two columns may be the same, the vertical scale is very different (panel 4, Fig. 14). Thus the Kelvin wave in the cooler column must grow within a strong subsident region forced by the dominant Kelvin mode by the higher and stronger heating distribution of the warmer column. In other words, the Kelvin wave associated with the warmest sea surface temperature regions will dominate over all other tropical modes controlling the latent heating distributions (panel 5) and the radiative structure. The total effect is to produce a vertical circulation along the equator controlled by the viscous Kelvin wave produced in the warm region (panel 6) that dominates over all parts of the tropics.

4. SOME CONCLUSIONS

4.1 Remote Observations of the Hydrology Cycle

Currently, we probably know quantities such as area averaged precipitation to within a factor of two only and subcloud layer and upper ocean fluxes and surface balances to a not much better accuracy. Clearly, given the discussion above, a high priority must be ascribed to the satellite determination of precipitation. Active and passive microwave radiometers, such as those planned for TRMM (the Tropical Rainfall Measurement Mission), will provide estimates of area averaged rainfall, it is hoped, to within 10 % averaged over one month, easily fulfilling TOGA requirements. Furthermore, the satellite will also allow cloud structure and hydrometer distribution to be measured for the first time on a tropics wide basis which will provide data to aid in the determination of subcloud layer radiation fluxes. However, such space experiments must be coupled with carefully designed ground truthing and experimental activities and modeling program such as those described below.

4.2 Ground Truthing and Coupled Ocean Atmosphere Field Experiments

Observations from space are probably only as good as the ground truthing. Ground truth observations may come from such endeavors as TOGA COARE (Coupled Ocean Atmosphere Response Experiment) the feasibility of which is being studied by a group of U.S. investigators for the western Pacific . Aimed ostensibly at understanding the maintenance of the warm ocean regions, the large scale convection-sea surface temperature relationships and the response of the ocean to episodic forcing through convective events and westerly burst phenomena, such an experiment may offer the opportunity for the determination of flux structure through the coupled system over an extended period and a large and important region of the warm tropics. Another important observational tool is the US TOGA Doppler radar that has been placed in Darwin, Australia for a two year period under the auspices of a joint venture between NASA/TRMM, the US/TOGA Office and the Australian Bureau of Meteorology Research Center. A major aim of the TOGA radar experiment is to extend the climatology of the convection within the "maritime" continent region beyond that gathered in the same region in EMEX (Equatorial Mesoscale Experiment) and in the Atlantic in GATE some years before.

4.3 Coupled Ocean Atmosphere Modeling Experiments

The principal aim of the TOGA Programme is to assess the predictibility of the climate system on the interannual time scale. The ultimate tool used in this ambitious program is the coupled ocean atmosphere model. Clearly, the most straightforward way to assess the importance of some of the processes discussed above is through numerical experimentation. The observations gathered from the remote systems or from the field experiments couple well with the model development.

Many of the activities discussed in this section are already underway. Observational satellite systems that will approach many of the objectives described are being planned. For example, the TRMM experiment is undergoing active development. The international scientific community is considering the design of the next generation of satellites that will provide global coverage of the hydrology cycle (GEWEX). The Joint

Scientific Committee (JSC) of the World Climate Research Programme, realizing the importance of the radiation fluxes in the climate system has recently established the Radiation Fluxes Committee to foster research in this area. The TOGA Scientific Steering Group has discussed the concept of a coupled ocean atmosphere field experiment in the western Pacific Ocean and will consider the subject in more depth at future meetings. A group of U.S. scientists has responded to these initial deliberations by convening a feasibility meeting in Hawaii (September, 1987) which resulted in the concept of TOGA COARE. Finally the Numerical Experimentation Group of TOGA (TOGA-NEG) is actively engaged in numerical experimentation of the coupled system.

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CHAPTER 3

HYDROTHERMAL PROCESSES

Ólafsson, J., S. Honjo, K. Thors, U. Stefánsson, R.R. Jones and R.D. Ballard. 1989. Initial Observations, Bathymetry and Photography of a Geothermal Site on the Kolbeinsey Ridge, p. 121-128. In: A. Ayala-Castañares, W. Wooster and A. Yáñez- Arancibia, eds. *Oceanography 1988*. UNAM Press, México D F, 208 p.

Initial Observations, Bathymetry and Photography of a Geothermal Site on the Kolbeinsey Ridge

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ABSTRACT

A site of geothermal activity was discovered in 1974 on Kolbeinsey Ridge, 110 km north of Iceland. A plume of boiling (185 °C) and sub-boiling water and gas bubbles emanates from the top of a small volcano at 90 m depth. A photomosaic of the site shows that the thermal activity is scattered around a small crater. The small size of the site coupled with rapid dilution of the thermal water have made sampling difficult in the past, but initial analyses show that the thermal water is less enriched in manganese relative to silicate than in the springs at the Galapagos Rift or in the high temperature vents of the Pacific and Atlantic Oceans.

1. INTRODUCTION

Volcanism and geothermal activity are common in Iceland, particularly within the neovolcanic zone which runs from the Reykjanes Peninsula in the south to the northeastern coast from where it connects with the slow-spreading Kolbeinsey Ridge in the Arctic through the Tjornes Fracture Zone. The spreading rate of the Kolbeinsey Ridge has been estimated as only 1.6 cm/yr (Johnson *et al.*, 1972). A survey of annals revealed several accounts of eruptions both on the Reykjanes Ridge and off the north coast, the most recent being the Surtsey eruption (Thorarinsson 1965). Yet there are only a few unconfirmed accounts of geothermal activity on the Iceland shelf except for nearshore extensions of subaerial systems (Benjaminsson, 1988).

A peculiar feature on the bottom, 110 km off north Iceland and 6.6 km from the islet Kolbeinsey was known to Saemundur Audunsson, Captain of R/V *Bjarni Saemundsson* and a former trawler skipper. During a hydrographic survey on 29 May 1974, he brought us to this site . It was a calm day and gas bubbles were seen emerging at the surface within an area not more than 50 m in diameter. On the echosounder a plume of gas was seen rising from the summit of a hill at 90 m depth (Fig. 1). Samples collected from the water column had a sulfide smell and dissolved silicate concentrations up to 10.8 μmol/kg, which was 5 μmol/kg above the ambient concentration. In the following years we confirmed several times the presence of a gas plume at this site by the use of an echosounder and occasionally collected water samples above the site using standard oceanographic water samplers on a hydrowire. It has proved to be a difficult task to collect water samples with strong hydrothermal signatures at this site by this technique. Turbulent and advective mixing processes on the shelf rapidly dilute the hydrothermal signal, and even in calm weather currents make it difficult to maintain a vessel stationary above the area of activity.

A further study of this site was conducted in 1987 in the NICEVOR programme, a joint venture between the Marine Research Institute (Iceland), the BBC Natural History Unit (U.K.) and the Woods Hole Oceanographic Institution (U.S.A.); further results will be reported elsewhere (Ólafsson *et al.* in prep.).

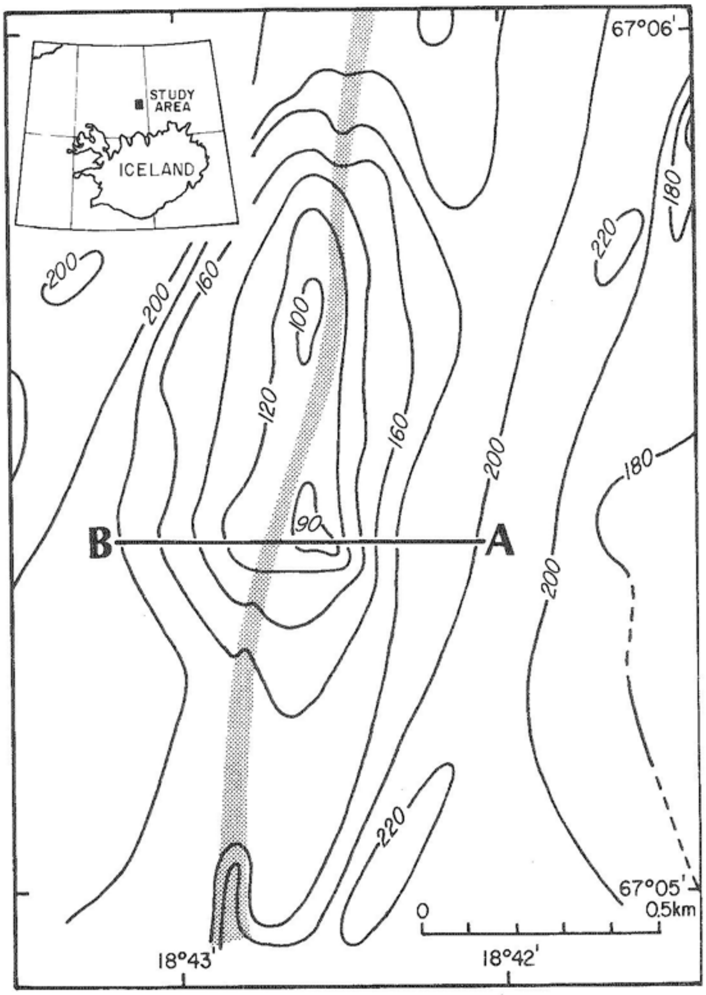


Figure 1a. Index map and bathymetry of submarine volcano near Kolbeinsey. Shading indicates fissure. Depths in meters.

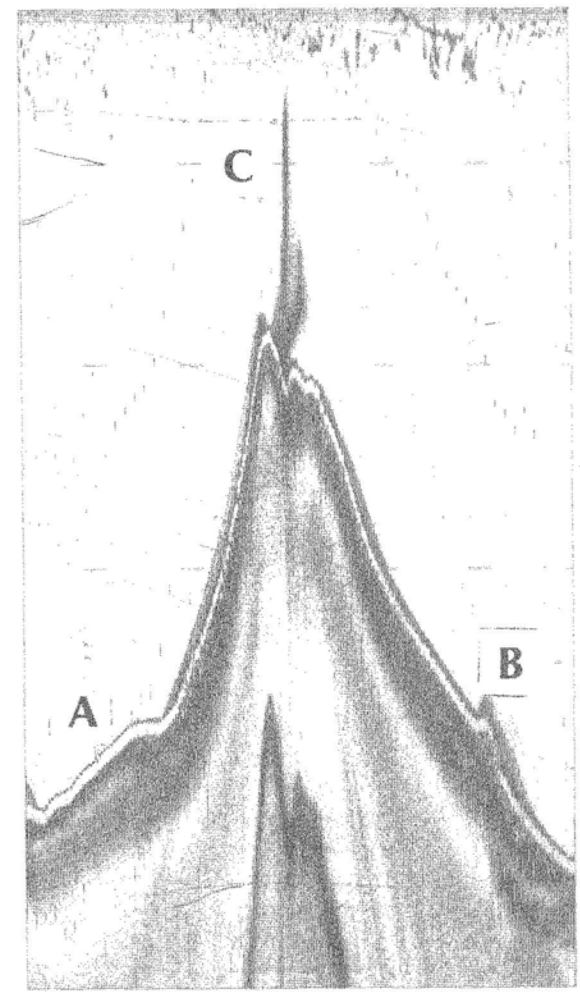


Figure 1b. Echosounder profile across southern summit of volcano showing plume of gas bubbles (C) emanating from summit area.

2. MATERIALS AND METHODS

All observations have been conducted from R/V *Bjarni Saemundsson* which is equipped with a Simrad EK-38 echosounder. Water samples were collected with Hydrobios and Go-Flo water bottles which were suspended on a stainless steel wire. Dissolved silicate was determined by the method of Mullin and Riley (1955). Up to 1981 total dissolvable manganese in acidified samples was determined by atomic absorption after Chelex-100 resin preconcentration (Kingston *et al.* 1978). From 1983, the analysis was done by automated colorimetry based on leuco-malachite green (Ólafsson 1986). Comparability of the manganese methods was ascertained by analysing the NASS-1 and CASS-1 Certified Seawater Reference Materials from NRC, Canada.

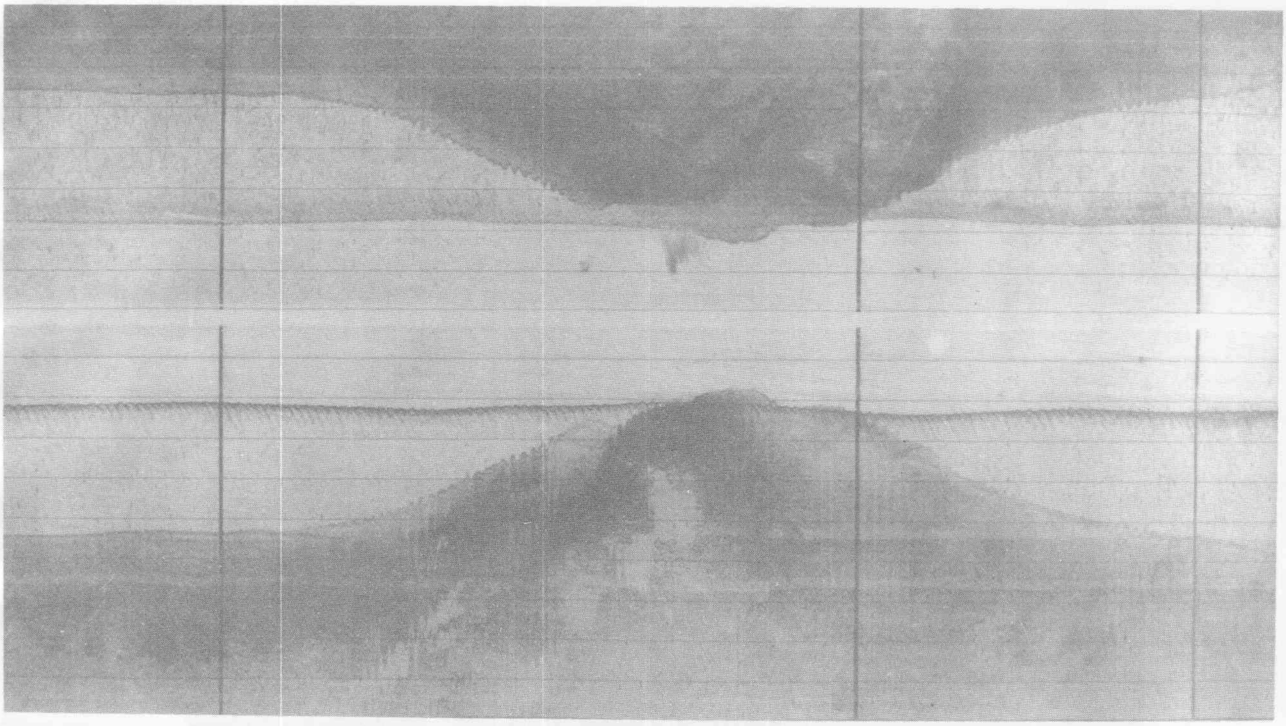


Figure 1c. Sonograph across summit on a SW-NE line. Fissure shows up clearly. In this area the fissure seems to form a zone of several fractures. Direction of travel left to right. Plume of gas seen on port (northern) side. Strong surface reflection on both channels. Scale line interval 25 meters.

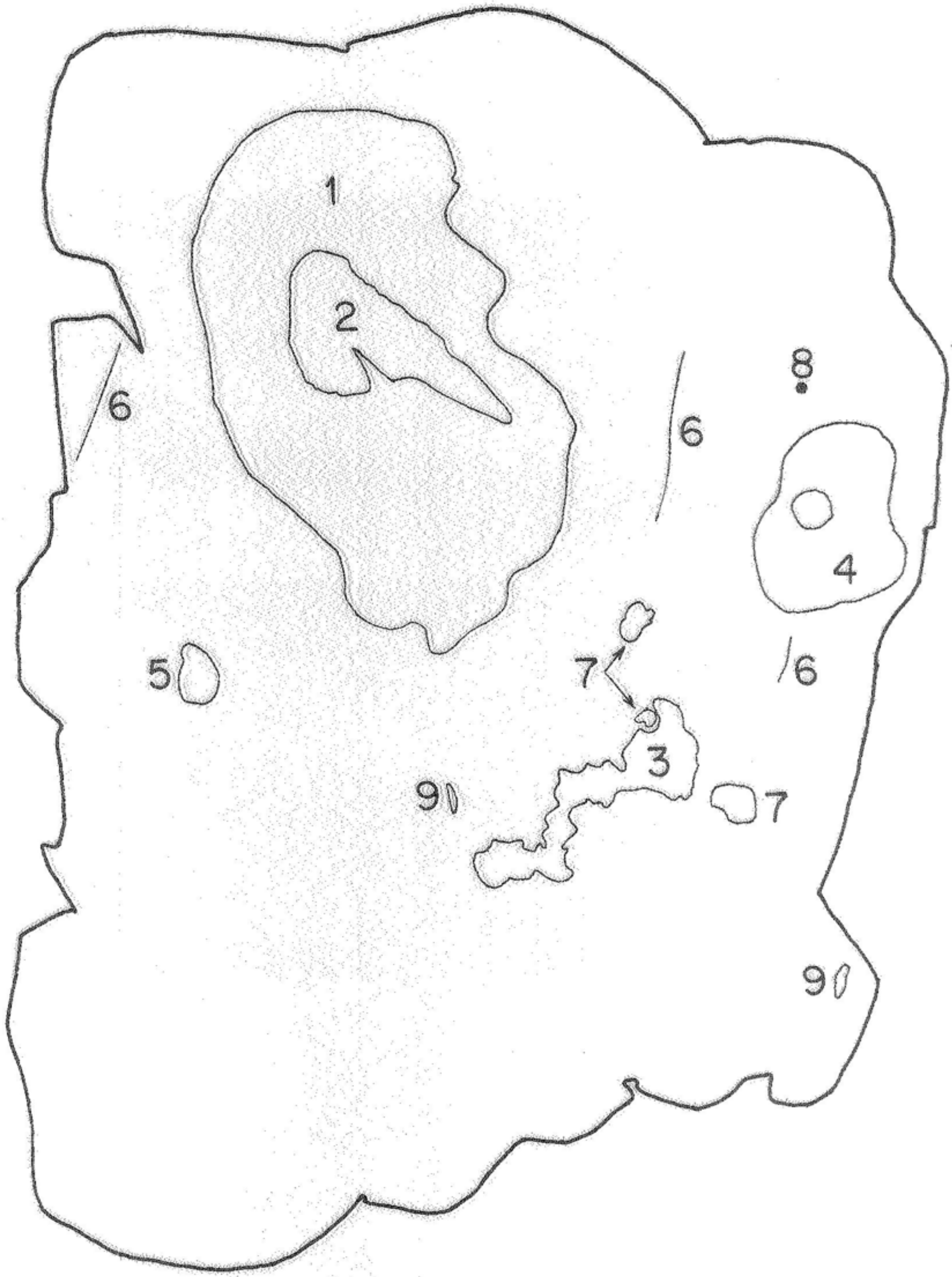
In 1981 the bathymetry was investigated, and a side scan sonar survey was conducted with an EG&G instrument. In the 1987 NICEVOR project, a towed camera survey was carried out with the MINI-ANGUS camera system, a modification of ANGUS (Ballard, 1980). It had a thermistor probe for the detection of temperature anomalies and two cameras with 16 mm and 28 mm lenses. It was flown 5-7 m off the bottom as it took color photographs every 20 s. During this operation the vessel was either sailing at less than two knots or was anchored above the site. A photomosaic was constructed from black and white enlargements of photographs from the 28 mm camera.

3. RESULTS AND DISCUSSION

Physical Characteristics of the Site

The geothermal site occurs on the crest of an elongate volcano, some 1.3 km long and 0.6 km wide (Fig. 1 a,b). Sonographs show that the crest is cut by a fissure which may be followed both north and south of the hill (Fig. 1 a,c). The volcano thus stems from a local eruption on a long fissure, a common ocurrence in the subaerial neovolcanic zone. The geothermal site itself lies to the east of the fissure, within the southern summit area. The precise details of the topography in this area are too small to be resolved with an echosounder, but the film material from the MINI-ANGUS system allowed a photomosaic to be made of the site itself (Fig. 2). There is some uncertainty regarding the scale of the mosaic but we estimate that it covers an area roughly 20 x 25 m. In it is a crater about 12 m in maximum width and 6 m in depth. The floor of the crater is flat and covered with volcanic ash tinted with yellowish precipitate in places. The area around the crater is of blocky lava with volcanic ash in hollows. Pillows are conspicuously absent. The main thermal area is on the rim and side of the crater, and in this region there are both large and small patches where light colored filamentous bacteria cover

Figure 2. Photomosaic (approximately 20 x 25 m) of geothermal site from MINI ANGUS material: Crater. 2: Gas bubbles in the water column swept over the crater by currents. 3: Particularly dense bacterial mat. Most of the bottom, especially on the right hand side of the mosaic, is covered with bacteria. 4 : Region of major gas outflow. A circular pit occurs within this region. 5: Broken lava pipe. 6 : Fractures. 7 : Pits issuing hot water. 8 : Center of Figure 3. 9 : Redfish (*Sebastes* sp) in the water column.



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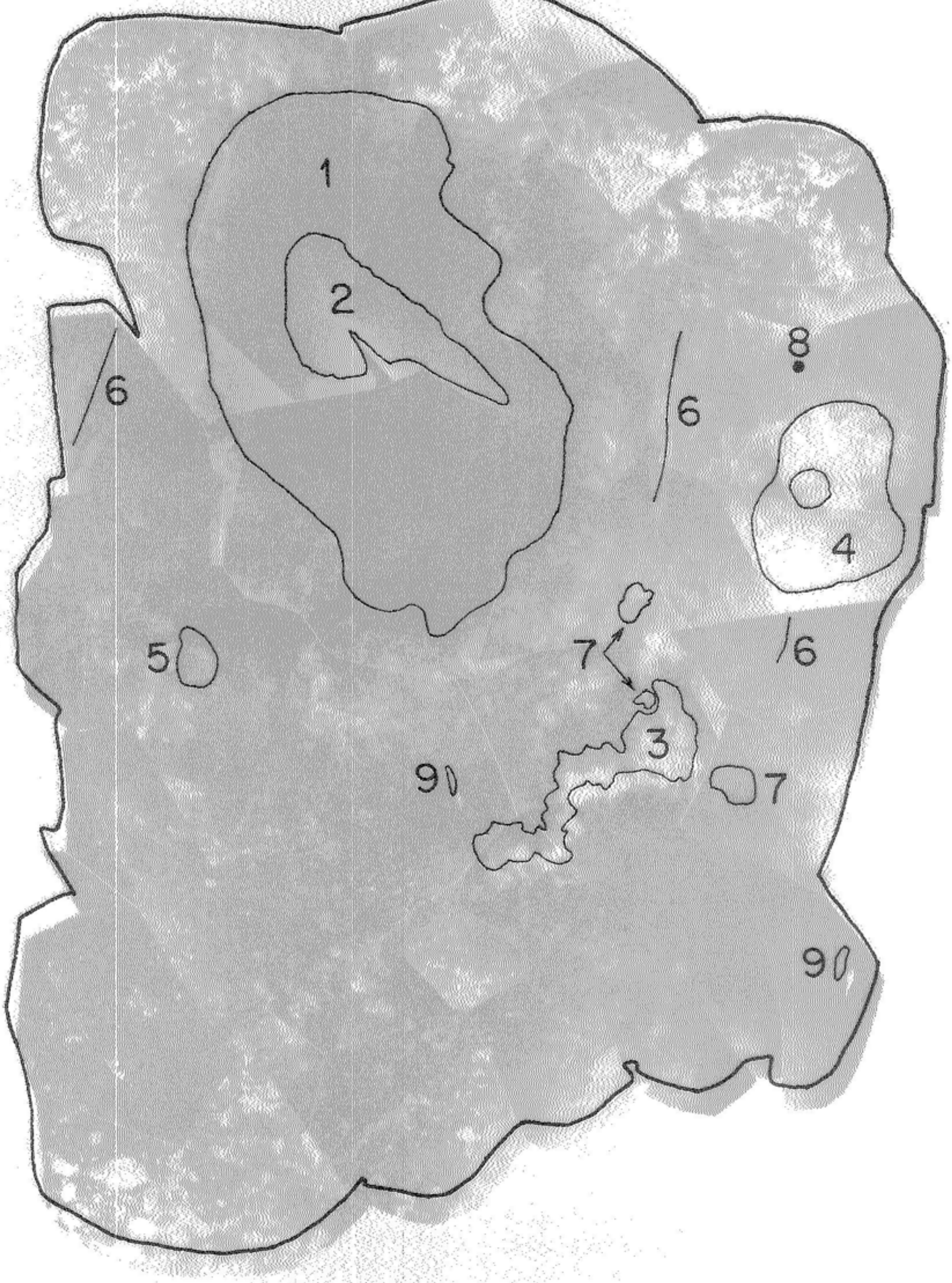

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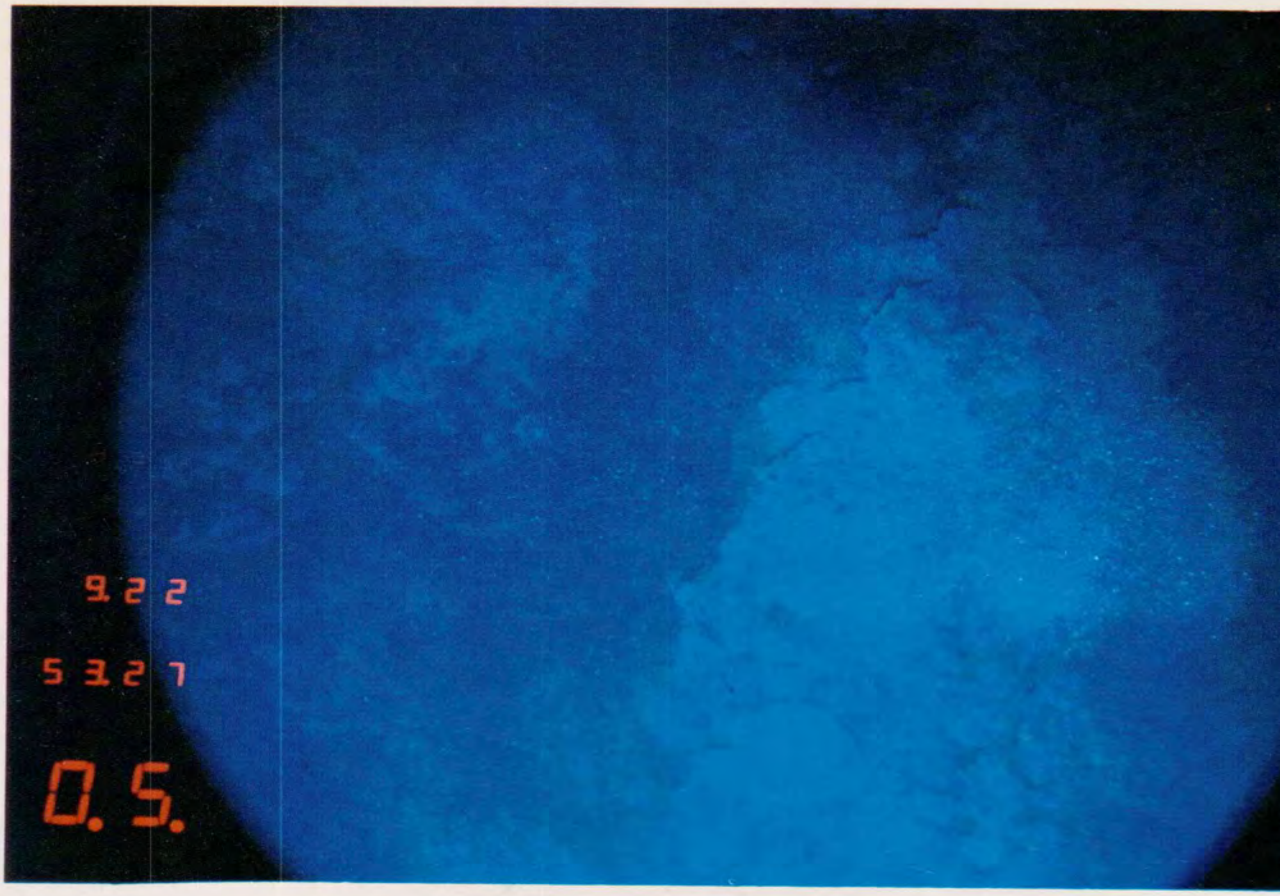

Figure 3. MINI ANGUS photograph from 16 mm camera showing a stream of gas bubbles (right) over rocky bottom with bacterial cover. For location see Figure 2.

the rocks (Ólafsson *et al.* in prep.). The BBC video records show several hot water vents discharging boiling (185 °C at 100 m depth) and sub-boiling water (Ólafsson *et al.* in prep.), but the evolution of volcanic gas is most pronounced on the rim of the crater (Fig. 3). There are no chimneys or other major structures formed from hydrothermal precipitates.

When being operated over tbe main thermal site, the MINI-ANGUS system frequently indicated large temperature anomalies. It also indicated thermal anomalies about 130 m south of the summit, in the fissure region (Fig. 1), and bottom photographs from there show fractured rocks where light coloured streaks,presumably of bacteria, line the fractures.

Water Chemistry

Dissolved manganese, helium-3 and silicate are sensitive indicators of hydrothermal activity. At the Kolbeinsey Ridge the ambient silicate concentration is no more than 8 mol/kg at 100 m depth, and this makes this parameter a more sensitive indicator than in the deep Pacific Ocean where the ambient silicate concentration is typically over 20 times higher. The results of dissolved silicate and manganese analyses on four sample sets collected over a period of 10 years (Fig. 4), show a linear trend with a Mn/Si slope of 4 mmol/mol. Taken individually, each sample set shows a linear Si-Mn trend, but the slopes range from 2.9 mmol/mol in 1977 to 8.6 mmol/mol in 1986. This variation is partly caused by differences in the seawater end-member concentrations or it may reflect variations with time in the hydrothermal fluid composition. Other results from the NICEVOR programme suggest, however, that the Mn/Si variability observed may be caused by differences in the spring water composition within the hydrothermal field (Ólafsson *et al.* in prep.).

The Mn/Si slopes are significantly lower than the range 21-60 mmol/mol found for the hot springs in the Galapagos Rift (Klinkhammer 1980) and an order of magnitude lower than observed at the 21°N site in the Pacific Ocean or the MARK site in the Atlantic (Campbell *et al.* 1988). The relatively low silicate concentrations of these Kolbeinsey Ridge samples show that they represent highly diluted thermal water, and for that reason determinations of changes from sea water in their major elemental composition, particularly magnesium, could not be conducted. The sample sets, therefore yield limited information on the composition of the hydrothermal end-member which makes further comparison with the deep sea hydrothermal sites difficult.

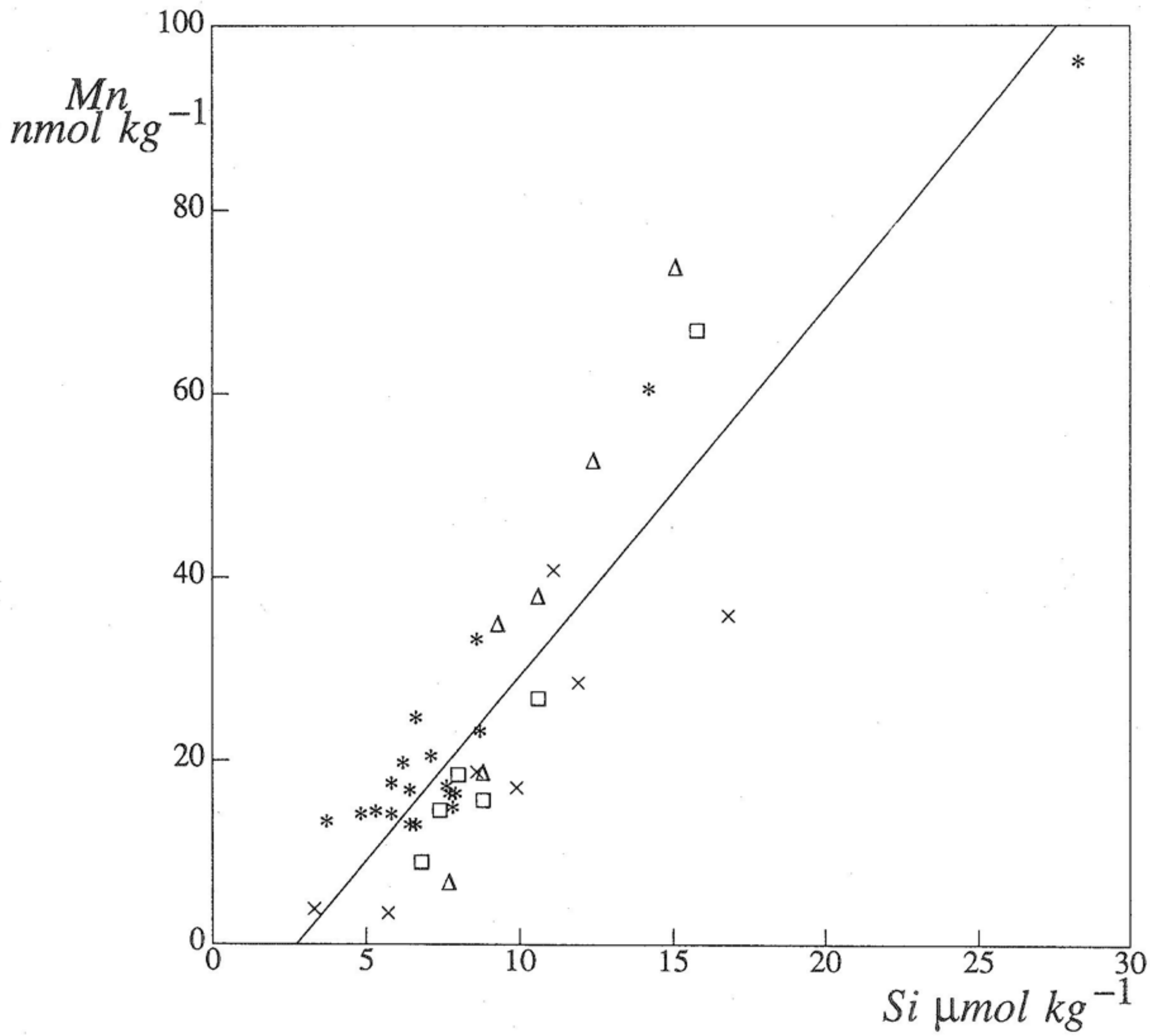

Figure 4. Concentrations of dissolved silicate and manganese in samples collected above the hydrothermal site over a ten year period. x: 1977, *: 1981, triangle: 1983, square: 1986.

4. CONCLUSIONS

The discovery of a hydrothermal site on the Kolbeinsey Ridge near Iceland is not unexpected in view of the extensive hydrothermal activity on the island. The investigations of the site have established the physical setting and surface features but the initial work did not yield satisfactory information on the chemistry of the thermal water. Further work on this aspect and on mineralogical studies will be reported elsewhere (Olafsson *et al.* in prep.). The site is unique with regard to water depth and the presence of a gas phase in the hydrothermal fluid. This physical setting may well yield a biological regime different from the deep sea geothermal sites. Therefore, further work is called for, involving more elaborate sampling equipment than hitherto used.

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Deep-Sea Ecosystems Based on Chemosynthetic Processes : Recent Results on Hydrothermal and Cold Seep Biological Assemblages

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ABSTRACT

Since discovery of unusually rich benthic biological assemblages around hot water vents near the Galapagos archipelago eleven years ago, our knowledge of the faunal structure and trophic organization of the so-called hydrothermal communities has increased rapidly. Later explorations of similarly rich benthic assemblages linked to brine and cold seeps and hydrocarbon-rich seepages have led to generalization of the concept of chemosynthetically based marine ecosystems. Hydrothermal assemblages of different species compositions have been described from the Galapagos Ridge, East Pacific Rise, Juan de Fuca and Explorer Ridges, Guaymas Basin, Gulf of California, Mariana back-arc basin, and Mid-Atlantic Ridge. Brine and cold seeps and hydrocarbon seepages have been found at the base of the Florida escarpment, off the Oregon and Japanese subduction systems, off Louisiana, on the Laurentian Fan, and near Barbados. Video records have been used to evaluate biomasses ranging from 10 to 70 kg/m^2 fresh weight. Basic microdistribution of species groups in aureoles centered around hydrothermal fluid vents reveals different levels of tolerance to harsh physico-chemical conditions. Two groups of primary producers can be recognized; a highly efficient cool water group characterized by large vestimentiferan tube worms and bivalves and a group characterized by decapods and colonies of alvinellid polychaetes adapted to hot hydrothermal fluids. Both groups are exploited by several carnivorous species. The food web is essentially based on sulfoxydizing symbiotic bacteria; anomalous isotopic ratios in invertebrate tissues suggested chemosynthetic production. Biochemical indices and experimental evidence give clear-cut conclusions in a few cases (*Riftia* and *Calyptogena*). Similar evidence for methanotrophic bacteria has recently been found in bivalves off Louisiana. The chemosynthetic mechanisms of cold seeps are not yet known; methane and sulfide have been suggested as potential energy sources. More than one hundred and fifty species new to science, together with higher rank taxa, have been described. An abnormally large number of "living fossils" have been discovered. The short life span of hydrothermal vents together with the world-wide distribution of several species raise questions concerning processes of species propagation and colonization.

1. INTRODUCTION

The discovery by Corliss *et al.* (1979) in spring 1977 of luxuriant benthic animal colonies clustered around hydrothermal vents on the Galapagos ridge at depth of 2,500 - 2,600 m was a tremendous surprise to marine biologists. The geological setting of this discovery has now been established : the hydrothermal fluid pouring from crevices and fissures in the sea floor at the ridge axis is the result of deep circulation of sea-water within fractured rocks reacting at 600 to 800° C with the basalt (Edmond and von Damm 1983, 1985). The primary hydrothermal fluid resulting from these geochemical reactions is anoxic, highly acid and rich in sulfides. Oases of life first pictured in 1976 by a deep-tow (Lonsdale 1977) and surveyed by the manned submersible ***Alvin*** one year later contrast sharply with the surrounding rocks where the fauna is extremely reduced, as is usual in the deep sea. Deep-sea benthic organisms and microorganisms have low rates of metabolism, growth and population increase, essentially due to a very reduced food supply and biochemical constraints of enzymes at low temperatures and high pressures (Grassle 1986). The totally unexpected occurrence of these oases of life surrounding hydrothermal openings, with large animals having rates of growth similar to shallow-water fauna, is therefore of particular interest to oceanographers.

Several years later, another discovery of similarly rich benthic assemblages was made in completely different geological environments : brine, cold seeps and hydrocarbon seeps were found to harbor similar populations of large benthic animals (Hecker 1985, Suess *et al.* 1985, Kennicutt *et al.* 1985, Laubier *et al.* 1986). From the biological point of view and despite the geological and geochemical differences, these two assemblages are basically identical; both are supported by chemolithotrophic symbiotic bacteria living in the tissues of several similar invertebrates, such as the large vestimentiferan tube worms and the giant bivalves.

2. BRIEF HISTORICAL ACCOUNT

This historical account is strictly limited to the first exploration of a given location by biologists. The Galapagos hydrothermal site discovered in 1977 by geochemists and geologists (Corliss *et al.* 1979) was the first to be explored by biologists two years later in 1979 (Galapagos Biology Expedition Participants 1979). This area is characterized by relatively low temperature hydrothermal fluids (15 to 20 °C above the ambient sea water temperature). A large tube worm (*Riftia pachyptila*), two large bivalves, one crab, a fish and others smaller animals were collected.

The next location to be studied by biologists was situated at 21°N on the East Pacific Rise. The first discovery, by the French submersible ***Cyana*** (Francheteau *et al.* 1978, 1979, 1981), of graveyards (cemeteries, accumulation of dead shells) of one species of a large bivalve previously known from Galapagos (*Calyptogena magnifica*) together with fossil chimneys in 1978 was followed one year later by the famous observation by the American submersible ***Alvin*** a few miles from this area of active white and black smokers where the hydrothermal fluid temperature reaches 350°C (Spiess *et al.* 1980). With the exception of the large mussel *Bathymodiolus thermophilus* which is not present at 21°N, a similar invertebrate assemblage occurs at 21°N and in the Galapagos. A large terebellomorph polychaete, the so-called Pompeii worm (*Alvinella pompejana*) occurs at 21°N and has colonized the white (the so-called "snow-balls") and black smokers.

In 1982, two different hydrothermal vent communities were added to the list : the French surveyed an area by 12-13°N on the East Pacific Rise, between 21°N and the Galapagos site (Desbruyeres *et al.* 1982), while the Americans discovered the Guaymas basin hydrothermal vent area, where the basaltic ridge is covered by some 500 m of hemipelagic sediments rich in organic matter ; the lavas intrude into the sediment, forming hydrothermal mounds at the surface, and the hydrothermal fluid percolates through the sediment at high temperatures and interacts with the organic content of the sediment to produce several hydrocarbons (Grassle 1983, 1984).

One year later, in 1983, the Canadian using their submarine ***Pisces IV*** discovered hydrothermal vent communities on an axial seamount of the Juan de Fuca ridge located at 46°N at 1,500 m depth. The macrofauna there is completely different from the East Pacific Rise and Galapagos faunal assemblages (Tunnicliffe *et al.* 1985).

In 1984, the first examples of cold seep communities were discovered in two different geological locations. The first was found by the submarine ***Alvin*** at the base of the Florida escarpment, at 3,260 m depth, where the abyssal sediment meets the wall of limestone : seeps of cold brine were surrounded by large tube worms and bivalves similar to the fauna of the hydrothermal vents (Paull *et al.* 1984, Hecker 1985). The second discovery was made on the Oregon Subduction Zone at 2,000 m, in a very active geological region. Again, the fauna living there comprises large tube worms of a previously known species (*Lamellibrachia barhami*) and several bivalves (Suess *et al.* 1985, Kulm *et al.* 1986).

The following year, 1985, brought the discovery of another set of new sites: in the Northeastern Pacific, at 50° N on the Explorer ridge, hydrothermal mounds and vents surrounded by faunal assemblages similar to the Juan de Fuca type were found (Tunnicliffe *et al.* 1986). Despite the low spreading rate of the Atlantic mid-ocean ridge, black smokers were clearly identified in the TAG area (NOAA Trans Atlantic Geotraverse), at 26°N in the rift valley (Rona *et al.* 1986) and in the Mid Atlantic Ridge at Kane site 23°N (Detrick *et al.* 1986). In a completely different geological setting, the accretion prism of the Japanese subduction trenches, small oases of several new species of the large bivalve *Calyptogena* were found at 3,000 m and 6,000 m: this is up to now the deepest known occurrence of cold seep fauna (Laubier *et al.* 1986, Ohta and Laubier 1987).

Bivalve assemblages were also found at this time by sampling the Louisiana slope, only 600 to 700 m in depth, in the vicinity of natural hydrocarbon seeps ; methane was immediately suggested as the energy source for the invertebrates (Kennicutt *et al.* 1985, Childress *et al.* 1986).

In 1986, hydrothermal activity in the Manus back-arc basin (New Guinea Papua, Western Pacific) was discovered for the first time in this geological pattern of extension basins (Both *et al.* 1986). On the accretion prism near Barbados, another type of cold seep fauna was surveyed by photographic deep-tow (Faugeres *et al.* 1987). The Soviet Union organized its first cruise on Juan de Fuca ridge, with a Canadian submersible (Pisces type). The samples collected led to the description of new species of polychaetes and pycnogonids (Detinova 1988, Turpaeva 1988).

One year later, the hydrothermal vent community of the Western Pacific in the Mariana back-arc basin was also found and sampled by the submersible ***Alvin***; there, the so-called hairy gastropod (*Alviniconcha hessleri*) appears to replace the giant tube worms and the bivalves (Hessler *et al.* 1987). From deep-tow videos, the same type of hydrothermal fauna assemblage was discovered by the end of 1987 in the North Fiji basin. Two hydrothermal fields were also found in 1987 on the upper portion of Loihi Seamount, near Hawaii, at depths of 1,000 and 1,200 m (Karl *et al.* 1988). There, warm hydrothermal fluids (30°C) are unusually rich in CO_2 (150 times more abundant than in the ambient sea-water) and surrounded by thick bacterial mats. Macrofauna is absent there, which can be the result of the isolation and relatively young age of Loihi, or of the acute toxicity of high concentrations of carbon dioxide or dissolved metals. Near Japan, the Japanese submersible ***Shinkai 2000*** made several dives in Hatsushima Bay, 700-900 m, and found large surfaces covered with bivalves (*Calyptogena soyoae*) and a tube worm more or less resembling that of the Oregon subduction zone assemblage (Okutani and Egawa 1985, Miura 1988).

In conclusion to this historical account of major biological discoveries, the following points must be underlined:

- Hydrothermal type communities, with different faunal compositions, occur in several geological settings : on active oceanic ridges, in the Pacific and the Atlantic Oceans, and in back-arc hydrothermal basins where the oceanic crust is extended by geophysical constraints.

- Similar communities also based on chemolithotrophic symbiotic bacteria develop on passive or active margin areas, where various reduced compounds occur at the surface of the sediments : hydrogen sulfide (H_2S), methane (CH_4), ammonia (NH_4).

- In all cases, the fauna comprises a large number of species new to science, belonging to new taxa ranging from genus to phylum.

General accounts of the biology of hydrothermal vents include those of Childress *et al.* (1987), Desbruyeres and Laubier (1983), Galapagos Biology Expedition Participants (1979), Grassle (1982, 1983, 1985, 1986), Hessler (1981), Laubier and Desbruyeres (1984, 1985), Lutz and Hessler (1983) and Wolff (1985).

3. PHYSICAL CHARACTERISTICS OF HYDROTHERMAL AND COGNATE ENVIRONMENTS

The depth ranges of hydrothermal vents and cold seeps environments differ greatly : 1,500 to 3,500 m for the former, 600 to 6,000 m for the latter. The major physical differences are, of course, the hydrostatic pressure and the temperature of the fluids, ranging from 15°C to 350°C and even 380°C for the hydrothermal vents, while it never rises by more than a few tenths of degrees Celsius above ambient temperature in cold seeps and hydrocarbon environments. Except for the example of possible ultrathermophilic bacteria (Baross and Deming 1983), the hydrothermal animals live at temperatures between local temperatures (1.7 to 2.5°C at such depths) and a maximum of 30-40°C for the Pompeii worms *Alvinella pompejana* and *A. caudata* (Desbruyeres *et al.* 1982). The chemical differences are also marked in terms of metal contents, high in hydrothermal environments (Von Damm *et al.* 1985a and 1985b), negligible in cold seeps, and organic matter, which can sometimes be important in hydrocarbon seeps such as the Louisiana hydrocarbon seep. Table 1 shows the trace metal contents of several hydrothermal fluids from the eastern Pacific and the mid-Atlantic ridge.

Biologically significant differences come from the hydrogen sulfide content, ranging from 1 to 8.5 m mol. kg^{-1} depending on the dilution of the hydrothermal fluid, and generally negligible in cold seep environments (at least in the surface water ; pore water may carry a significant content of hydrogen sulfide, coming from sulfate reducing bacterial activity in the upper layers of the sediment ; this possibility cannot be eliminated in some cases from several biological observations : *Calyptogena* from the Japanese subduction trenches may use their large foot buried in the sediments to pick up locally produced hydrogen sulfide, as suggested by the presence of sulfur crystals in the branchiae). It must be emphasized that geothermal methane is also present in rather large amounts in hydrothermal fluid, while differences in methane content can be related to different bacterial assemblages.

This fact suggests that the H_2S utilization by bacterial symbionts is a wide-spread adaptation compared to that of methane utilization. In some cases, hydrothermal fluid may contain a substantial amount of ammonia (Guaymas Basin), up to 10-15 m mol. kg^{-1}. The bottom waters of the Oregon subduction zone at 2,000 m show positive anomalies of 0.3 to 0.6 °C in temperature, similar to the anomaly recorded at 3,830 m along the wall of the Nankai trough off Japan (Kulm *et al.* 1986). The methane content of bottom waters sampled at 1 m above animal communities of the Oregon Subduction Zone varies between 180 and 420 nl. l^{-1}. These concentrations are three to six times greater than the CH_4 concentrations found in the ambient water (Kulm *et al.* 1986). The cold, sulfide-rich and hypersaline waters seeping out at the juncture of the Florida escarpment base and the abyssal plain sediment, at a depth of 3,270 m, represent an intermediate situation (Hecker 1985). The last important difference comes from the venting system itself. In the case of hydrothermal vents, the fluid uses the existing network of fissures and crevices, which is modified permanently by the deposition of polymetallic sulfide and other minerals, while in the case of cold seeps, the flow of pore water may create and maintain a sufficient porosity in the sediments for it to percolate.

In conclusion, high temperatures and high contents of different sulfides including hydrogen sulfide characterize the hydrothermal fluid, while cold seeps at temperatures comparable to ambient sea-water temperature offer a wider range of chemicals compounds : methane, other light hydrocarbons, ammonia, hydrogen sulfide.

Relatively high concentrations in metals and other elements in hydrothermal fluids at 21°N result in high concentrations of trace metals in *Calyptogena* (Roesijadi and Crecelius 1984). Compared with shallow-water mussels from an unpolluted area, concentrations of several metals were elevated an order of magnitude or more in whole soft tissues of *Calyptogena*. Antimony and silver exhibited the highest enrichments (116 times and 107 times, respectively). Other metals, such as Cr, As, Mo, Hg and Pb were present at values up to 30 times those of *M. edulis*. These concentrations would induce significant mortality in bivalves from other environments (Roesijadi *et al.* 1985). Similar results have been obtained with *Alvinella caudata* and *Bathymodiolus thermophilus* from 13°N (Chassard-Bouchaud *et al.* 1988a). Important amounts of Ni and Sn have been found in the digestive gland of the giant mussel : spherocrystals and lysosomes were the target organelles of metal concentration. Moreover, symbiotic bacteria were shown to be capable of elemental concentration (particularly for Ti). The Pompei worm contained a large number of intracellular elements, particularly Cr, Fe, Ti, Zn, Br, Sr, I, Ba, Pb, Al , La, Tm and Tl, while U is present on the external epidermis (Chassard-Bouchaud *et al.* 1988a). The correlations between the metal concentrations within the vent organisms and in the environment appear to be relatively good. A similar situation has been reported for the bivalve *Calyptogena phaseoliformis* living in deep cold seeps of the Japanese trenches (Chassard-Bouchaud *et al.* 1988b). The occurrence of metallothionein-like proteins has been established in *Calyptogena magnifica* (Roesijadi and Crecelius 1984), in the tube worm *Riftia pachyptila* and in the Pompei worm *Alvinella caudata* (Cosson-Mannevy *et al.* 1986). The question of their origin remains open : they could well be synthesized by symbiotic bacteria, as well as produced by the invertebrates as a detoxication mechanism.

TABLE 1
COMPOSITION OF HYDROTHERMAL FLUIDS FROM FIVE SITES AND OF AMBIENT SEA WATER (FROM VON DAMM *ET AL*. 1985A AND 1985B, AND MICHARD *ET AL*. 1984, IN GRASSLE 1986, AND CAMPBELL *ET AL*. 1988). **n.a.**= not analysed; += gain; -= loss.

		Galapagos	13°N	21°N	Guaymas	Mid-Atlantic	Sea Water
The alkalis							
Li	(µmol/kg)	689-1142	688	891-1322	630-1076	411-849	26
Na	(mmol/kg)	+,-	560	432-510	475-513	509-584	463
K	(mmol/kg)	18,8	29.6	23.2-25,8	32.5-48.5	17-23.9	9.8
Rb	(µmol/kg)	13,4-21,2	14.1	27-33	57-86	10-10.8	1.3
NH4	(mmol/kg)	n.a.	n.a.	<0,01	10,3-15,6	n.a.	<0.01
The alkaline earths							
Be	(nmol/kg)	11-37	n.a.	10-37	12-91	38.5	0.02
Mg	(mmol/kg)	0	0	0	0	0	52,6
Ca	(mmol/kg)	24,6-40,2	55	11.7-20.8	26.6-41.5	9.9-26	10.2
Sr	(µmol/kg)	87	175	65-97	160-253	50-99	87
Ba	(µmol/kg)	17,2-42,6	n.a.	>7->15	>7->42	n.a.	0.14
pH			Down to 3.8	3.3-3.8	5.9	3.7-3.9	7.8
Alk	(mEq/kg)	0	n.a.	-0,19-0,502,	8-10,6		2,3
Cl	(mmol/kg)	+,-	740	489-579	581-637	559-659	540
SiO2	(mmol/kg)	21,9	22	15.6-19.5	9.3-13.8	18.2-22	0.18
Al	(µmol/kg)	n.a.	n.a.	4.0-5.2	0.9-7.9	5.0-5.3	0.005
SO4	(mmol/kg)	0	0	0	-4.2-0	n.a.	27.9
H2S	(mmol/kg)	+	n.a.	6.6-8.4	3.8-6.0	5.9	0
Trace metals							
Mn	(µmol/kg)	360-1140	800, 1200	699-1002	132-236	491-1000	<0.001
Fe	(µmol/kg)	+	1050, 1850	750-2429	17-180	1640-2180	<0.001
Co	(nmol/kg)	n.a.	n.a.	22-227	<5	n.a.	0.03
Cu	(µmol/kg)	0	n.a.	<0.02-44	<0.02-1.1	0-17	0.007
Zn	(µmol/kg)	n.a.	n.a.	40-106	0.1-40	0-50	0.01
Ag	(nmol/kg)	n.a.	n.a.	<1-38	<1-230	n.a.	0.02
Cd	(nmol/kg)	0	n.a.	17-180	<10-46	n.a.	1
Pb	(nmol/kg)	n.a.	n.a.	183-359	<20-652	n.a.	0,01
As	(nmol/kg)	n.a.	n.a.	<30-452	283-1074	n.a.	27
Se	(nmol/kg)	0	n.a.	0-64	38-88	n.a.	2.5
Samples T°C			20°C	273-355°C	100-315°C	290-350°C	2°C

n.a., not analysed ; +, gain ; -, loss.

4. HYDROTHERMAL VENTS AND COLD SEEP FAUNA

Our present knowledge of the fauna of hydrothermal vent assemblages, including a few organisms described from cold seep environments, has greatly increased within the recent years (see Grassle 1986, Jones 1985, Laubier 1988b, Wolff 1985 for general review and bibliography, and Desbruyeres and Laubier 1986, Detinova 1988, Humes 1987, 1988, McLean 1988, McLean and Haszprunar 1987, Metivier *et al.* 1986, Okutani and Metivier 1986, Okutani and Ohta 1988, Pettibone, 1985a, 1985b, 1986, 1988, Turpaeva 1988, Waren and Bouchet 1986, Williams and Rona 1986, for recent taxonomic papers not included in the reviews).

Newman (1985) gave a list of 58 species from Eastern Pacific hydrothermal and cognate environments. Grassle (1986) recorded a total of nearly 130 species of invertebrates and fishes from hydrothermal vent communities. Added to these figures, recently described species from hydrothermal vents and cold seep environments lead to a total of some 160 species new to science, whose descriptions have already been published. Compared with the hydrothermal fauna, the cold seep and hydrocarbon environments have provided a relatively small number of new taxa, just over a dozen, but taxonomical studies are in progress. Within the hydrothermal fauna, the major groups of metazoans in terms of species richness belong to the phylum Mollusca with 41 species (Bivalvia, Gastropoda and Aplacophora), Annelida with 41 species (Polychaeta, Hirudinea) and Arthropoda 44 (Crustacea : Copepoda, Cirripedia and Malacostraca, Acarina and Pycnogonida), representing altogether 126 species, i. e. 77% of the total number of species. Since publication of the detailed analysis of the hydrothermal fauna by Grassle (1986), the main additions for the Mollusca are found within the archaeogastropods (McLean and Haszprunar 1987, McLean 1988), the mesogastropods (Okutani and Ohta 1988, Waren and Bouchet 1986), the Aplacophora (at least 9 undescribed species) and the Bivalvia (four new species of the genus *Calyptogena* have been described, one or two new species of deep-sea mussels occur at the Florida escarpment and Louisiana slope, and an interesting Pectinacea, *Bathypecten vulcani*, has been found at 13°N on the East Pacific Rise, Schein-Fatton 1985, 1988). The phylum Annelida is mainly represented by the polychaetes : new species have been described from hydrothermal and cold seep environments in the families Polynoidae (Pettibone 1985a and b, 1986, 1988) and Alvinellidae (Desbruyeres and Laubier 1986, Detinova 1988). Within the phylum Arthropoda, Humes (1987) has described 27 new species of copepods belonging to the orders Poecilostomatoida and Siphonostomatoida from the hydrothermal vent environment, and Humes (1988) added a new genus within the Siphonostomatoida, whose family remains unknown, for a new species from the West Florida cold seeps. The first Pantopoda from the northern Pacific has been recently described from the Juan de Fuca ridge ; the specimens were collected using the USSR submersible ***Pisces*** in 1986 (Turpaeva 1988). Compared with ordinary deep-sea environments, bivalve species are relatively few, while Peracarids (isopods and amphipods) and echinoderms seem to be absent from the hydrothermal and cold seep environments. This last remark is based on published descriptions only : for instance, ophiuroids have been seen but not sampled on the East Pacific Rise at 11 and 13°N, lysianassid amphipods are abundant in the plankton surrounding the benthic assemblages and large caprellids have been observed within colonies of *Calyptogena phaseoliformis* in the deep Japan trenches (Juniper and Sibuet 1987, Ohta and Laubier 1987). The new phylum Vestimentifera, recently established by Jones (1985), comprises five families and nine different species. The Lamellibrachiidae have been known from low temperature sediments since the original discovery of *Lamellibrachia barhami* (Webb 1969). A second family belonging to the same order, the Escarpiidae, also lives in sediments at low temperature, while all other Vestimentiferans are more or less adapted to warmer temperatures (between 2 to 29 °C, data gathered from Hessler and Smithey 1983, and Tunnicliffe *et al.*, 1985). It has been recently established that newly settled stages of *Ridgeia* have a functional gut and traces of larval ciliation, suggesting that they may have developed from a planktonic trochophore stage. The ciliated gut persists for some time after the development of the bacterial symbiosis in the trophosome (Southward 1988). As a conclusion, this author underlines that Vestimentifera and Pogonophora are closely related.

At present, most hydrothermal species are endemic. This high degree of endemism could be explained by a long evolutionary history or by a high rate of evolution. The average generic age of some hydrothermal invertebrates has been estimated by Newman (1985) by comparing these genera with some sort of a fossil record and, therefore, an inferable age. Tube worms are compared with Lophophorata and acorn worms with Graptolithina. Some of the endemic species belong to wide-ranging deep-sea genera and are probably relatively recent, middle to late Cenozoic immigrants. However, many others have been assigned to genera and even higher taxa, with apparently no close relatives elsewhere. According to evolutionary and biogeographical criteria (rank of endemism above the species level, distribution and geologic record), the latter are estimated to be relics of the Paleozoic and Mesozoic ages. The general hypothesis is that the ancestors of hydrothermal species living in warm shallow water during the Mesozoic found refuge in a hydrothermal shallow water environment against growing predation pressure, then migrated from there to deep-sea hydrothermal vents. Some organisms such as the bivalve *Bathypecten vulcani* found at 13°N and the Galapagos and representatives of different families and superfamilies of archaeogastropods are late Paleozoic to early Mesozoic relics, and a few genera such as *Calyptogena*, *Isaacsicalanus*, *Munidopsis*, are Tertiary immigrants.

It is now well established that the zoological compositions of hydrothermal communities differ in separate geographical areas. The recent exploration of the Manus and Mariana back-arc basin hydrothermal vents revealed that there are no vestimentiferan tube worms, nor large bivalves in these assemblages : the hairy gastropod *Alviniconcha hessleri* replaces them and hosts symbiotic bacteria in its mantle. There are more important differences between the typical East Pacific Rise hydrothermal community and the mid-Atlantic ridge fauna in the TAG area : the main feature is the tremendous number of bresiliid shrimps of the genus *Rimicaris* (two species of *Rimicaris* have been described by Williams and Rona 1986) which graze upon bacterial mats developing on the sulfide particles from black smokers (Van Dover *et al.* in press). Compared to such examples, differences between northern Juan de Fuca and the southern East Pacific Rise hydrothermal fauna indicate that geographical differentiation has occurred rather recently : vestimentiferan tube worms differ at family level, bivalves are absent in the northern area, sister species occur within the genus *Paralvinella*, etc. The vicariating vent fauna of the Juan de Fuca ridge has since formed an endemic assemblage of generally lower diversity than that found at East Pacific Rise vents (Tunnicliffe 1988).

The question of the dispersal capacity of the hydrothermal fauna is of particular interest, due to the ephemeral life span of a given chimney or hydrothermal vent (between 20 to 100 years, 50 years on average, Lalou *et al.* 1985) and to the strong link between the animals and the hydrothermal environment. A majority of hydrothermal animals have lecithotrophic, non-pelagic larvae , which is also the case in several deep-sea animals. This seems inappropriate in view of the ephemeral character of hydrothermal venting at small scale (Berg 1985, Lutz *et al.* 1986, Turner *et al.* 1985). However, in the deep sea, where the food supply is very low, the fact that there are lecithotrophic larvae does not imply that the larvae do not have at least a short pelagic life. Short-term dispersal of such lecithotrophic larvae can take place through the hydrothermal plume (Grassle 1986). The plume rises 100 to 300 meters above the bottom, depending on the velocity of the flow, and is then laterally dispersed over several kilometres (Baker and Massoth 1986). This means of dispersal of course suits the planktotrophic larvae (*Bathymodiolus*, *Bythograea*), but can also accommodate lecithotrophic larvae. In the Galapagos, small and large mussels from Rose Garden and Mussel Beds sites, which are separated by 7.8 kilometres, are genetically different : they probably came from two different source populations (J.P. Grassle 1985). From one hydrothermal vent to another , it is understandable how, through several generations, species colonize the totality of what has been called a "hydrothermal archipelago"; the life-span of such an "archipelago", extending 100 to 150 km along a ridge segment, should be in the order of thousands years (Laubier 1988a). The question is completely different for long-range dispersal, e. g. for *Alvinella pompejana*, which has been found along the East Pacific Rise from 21°N to 17°S, over a range of 2,280 nautical miles! The fact that the hydrothermal vent assemblage of the western Pacific is very different from the eastern Pacific assemblages demonstrates the importance of geographical isolation for long periods of time (about 100-150 million years).

Like other deep-sea animals, a majority of hydrothermal species shows a tendency to direct or lecithotrophic development. The dispersal of these endemics from one site to another site for long distances (thousands of kilometres) is not understood, whereas the rise of the diluted hydrothermal plume is probably sufficient to explain short-range dispersal.

5. ECOLOGICAL CHARACTERISTICS OF HYDROTHERMAL AND COLD SEEP COMMUNITIES

Since our ecological knowledge of cold seep communities is still in its early stages, most observations made on the ecological characteristics of these communities come from hydrothermal vent sites. Generally speaking, for both types of communities spatial distribution consists of small patches of a few square metres to one acre with animals distributed in circles or belts surrounding the fluid opening. Biomasses have been assessed using photographs and videotapes and analyzed by photogrammetric methods (Fustec *et al.* 1987) for different sites; 13°N and Galapagos hydrothermal vents and Japanese subduction trenches. The results show somewhat higher biomasses for hydrothermal vent communities than in cold seep bivalve colonies, but the figures remain within the same order of magnitude, between 10 to 100 kg. m^{-2} in wet weight (Fustec *et al.* 1988, Hessler and Smithey 1983, Ohta and Laubier 1987). There could be some differences in the life-span; cold seep sites probably are longer lived than the average of 50-100 years of active hydrothermal vents. Cold seep assemblages, with the exception of the Florida escarpment assemblage, seem to be less diverse than hydrothermal vent communities, but this could very well be due to the state of our knowledge. At present, hydrothermal vent communities appear much more diverse and more complex. When high temperature(250 to 350°C) fluids are emitted together with more diluted fluid at lower temperatures (15 to 50-100°C), two different biological "poles" can be recognized : the "cold water pole", with vestimentiferan tube worms and large bivalves, and the "hot water pole" colonized by large quantities of *Alvinella pompejana* and *A. caudata* and their specific carnivore *Cyanagraea praedator* (Fustec et *al.* 1987).

Stable isotope ratios $^{18}O/^{16}O$ and $^{13}C/^{12}C$ in calcium carbonate exoskeletons of crustaceans or shells of molluscs have been studied extensively. Van Dover (1986) examined the stable isotope ratios of oxygen and carbon in the exoskeletons of *Alvinocaris lusca* and *Munidopsis subsquamosa* from hydrothermal vents of the Galapagos site. These ratios provide a record of post-molt water temperature and chemistry experienced by each individual. Shrimps and galatheids appear to occupy distinct environmental regimes which are well-defined in terms of ^{18}O and ^{13}C values, and which correspond to specific regions of vent habitats.

The principal ecological characteristics of hydrothermal vents and cold seep communities are their extremely high biomasses, comparable to the richest shallow-water ecosystems (mussel beds, coral reefs, giant kelp communities, etc.) and the ephemeral life-span of given vents. A comparison of sites at 13°N between 1982 and 1984 revealed many changes in habitat characteristics, which often had dramatic effects on the fauna. The significant growth of smokers and their rapid colonization by *Alvinella pompejana* have been reported, as well as a noticeable growth and recession of vestimentiferan and serpulid populations (Fustec *et al.* 1987). These changes are apparently related to fluctuations in fluid flow. More interesting, as yet unpublished results have been obtained on the same site in Fall, 1987 (Laubier 1988b, front cover picture) ; while populations of *Riftia pachyptila* totally disappeared on a given site, called Parigo, at 13°N on the East Pacific Rise, new dense thickets of a smaller vestimentiferan, *Tevnia jerichonana*, developed a few tens of meters from the dead site. Moreover, the collapse of the huge biomass of *Riftia pachyptila* induces a marked disequilibrium between the new population of the primary consumers *Tevnia* and the population of the carnivore *Bythograea thermydron*, which had previously adapted to the exploitation of a much larger food resource. This completely unbalanced situation seems highly unstable and will probably lead to a complete extinction of the hydrothermal fauna at this site.

6. CHEMOSYNTHESIS VERSUS PHOTOSYNTHESIS

At the time of their discovery, the astonishing high biomass of hydrothermal vent communitics was tentatively explained by two different hypotheses (Lonsdale 1977); the first involved a very high production in the hydrothermal fluid of free bacteria which were utilized by suspension and filter-feeding invertebrates, while the second considered the possibility of local convective circulation cells produced by the discharge of hot hydrothermal fluid accumulating particulate organic matter from the euphotic layers on small areas in the immediate vicinity of the vents. But neither hypothesis adequately explained the high biomasses of hydrothermal communities. Free bacteria occur in the hydrothermal fluid as well as on basaltic substrates and soft sediments, but their biomass and productivity are not sufficient to support the invertebrate biomass and rate of growth (Tuttle *et al.* 1983). On the other hand, convective cells induced by hot water emission exist, but are limited to rather small areas and cannot induce sufficiently strong currents to concentrate particulate organic matter from the euphotic layer (Enright *et al.* 1981).

The truth is probably more fascinating than suggested by these two hypotheses : lithotrophic symbiotic bacteria belonging to the Eubacteria of the group of the "purple photosynthetic bacteria" (Lane *et al.* 1985) live in the cells of special tissues (trophosome in the case of the vestimentiferan tubeworm) of invertebrates where they perform carbon incorporation, utilizing chemical energy coming from sulfide oxidation. The general physiology of the invertebrate hosts is adapted to fulfill special tasks such as carrying in their blood the highly toxic energy source, the hydrogen sulfide, together with the oxygen and carbon dioxide.

First evidence came from analyses of stable isotope ratios in several invertebrates hosting bacteria within their tissues (*Riftia pachyptila*, *Calyptogena magnifica*, *Bathymodiolus thermophilus*) or on their cuticle (*Alvinella pompejana* and *A. caudata*); the values of $\delta\ ^{13}C$ and $\delta\ ^{15}N$ are used to infer sources and utilization of dietary carbon and nitrogen. The isotopic dissimilarity between most vent animals and pelagic organisms clearly indicates that local, rather than photosynthetic or sedimentary sources of dietary carbon and nitrogen are quantitatively important to vent animal nutrition (Rau 1985). Similar data have been obtained in the case of some cold-seep animals (Paull *et al.* 1984, Kennicutt II *et al.* 1985, Kulm *et al.* 1986). However, the data are sometimes difficult to interpret; this is the case for the Florida escarpment community, where a complicated energy and food chain has been hypothesized by Paull *et al.* (1985). No primary sulfide discharge is found, but it is produced in the sediments secondarily by bacterial sulfate reduction. The same method was then used to identify the nutritional importance of chemoautotrophic endosymbiotic bacteria; for instance, Spiro *et al.* (1986) showed that several common bivalve molluscs belonging to the superfamily Lucinacea and several small species of Pogonophora show much greater depletions for $\delta\ ^{13}C$ than usual values (-16 to -20 per mil) for marine benthic invertebrates, ranging from -23 to -31 in the bivalves and from -35 to -46 in the Pogonophora. In this case, the organic carbon is produced by CO_2 fixation by the autotrophic bacteria, which oxidize reduced organic compounds, notably sulfide, to obtain energy.

In the meantime, another set of data coming from ultrastructural studies demonstrated the occurrence of numerous bacteria within special tissues (vestimentiferan tube-worms) or ordinary tissues and cuticles (gills of bivalves, cuticle of alvinellids). A large number of papers have been published (see Cavanaugh 1985, for review) including specific studies on the evolution of bacteria and bacteriocytes populations (Bosch and Grasse 1984). More recently, similar data have been produced in the case of the large *Calyptogena* species from the Japanese subduction zone (Fiala-Medioni and Le Pennec 1988). Histological, chemical and enzymatic evidence indicates that sulfur-oxidizing chemoautotrophic bacteria exist in the tissues of both the deep-sea hydrothermal vent tube worm *Riftia pachyptila* and the Atlantic coast bivalve *Solemya velum*. Further, other invertebrates, bivalves, vestimentiferans, pogonophores and oligochaetes from a variety of reducing habitats have also been found to contain chemoautotrophic symbionts (Cavanaugh 1985). Thus it appears that chemoautotrophic symbioses may be widespread in nature. All species that harbor such symbionts share certain striking morphological features, *i. e.* they are mouthless and gutless, or have a very small and reduced gut and small feeding appendages. The symbionts of the methanotrophic mussel from the Louisiana slope have a very peculiar structure with stacked intracytoplasmic membranes, typical of methanotrophic bacteria (Childress *et al.* 1986; Cavanaugh *et al.* 1987).

The physiological adaptations of the invertebrates have been studied in detail in the case of the well known *Riftia pachyptila*. This large tubeworm is totally devoid of a digestive tract. Nutriments are provided to the animal by the symbiotic bacteria harbored in the cells of a specialized organ of the animal, called the trophosome. The symbiotic bacteria are believed to fix carbon dioxide from the ambient seawater using the energy gained from oxidation of sulfide which is emitted by the hydrothermal vents. Carbon dioxide is transported in a freely dissolved form in the blood and, after fixation in the plume, is converted into 4-carbon compounds, mainly succinate and malate. The bacteria then either decarboxylate the 4-carbon compound or fix the dissolved carbon dioxide using the Calvin-Benson cycle. The sulfide which is oxidized by the bacteria is transported by a specialized hemoglobin which is abundant in the blood of the worm. The hemoglobin prevents spontaneous oxidation of the sulfide and poisoning of the animal's tissues by the hydrogen sulfide (Childress *et al.* 1987, Felbeck and Childress 1988). The hemoglobin of *Riftia* is an unusually large molecule (molecular weight as much as two million daltons) which circulates freely in the blood. It shows two different fixation sites, the ordinary one for the oxygen, and another for the H_2S. In such conditions, the H_2S is no longer toxic for the worm tissues and can be carried safely from the plume to the trophosome. The bacterial activity delivers organic carbon, sulfate and thiosulfate in the blood at the periphery of the trophosome cells. The organic carbon is directly metabolized by the worm tissues, while the sulfate is finally rejected through the plume system in the seawater. Several *in vivo* experiments with *Riftia pachyptila* have been carried out on board research ships, under pressures of 100 kg. cm^{-2}, and the consumption of H_2S and CO_2 has been studied in a very detailed way.

This discovery led to a re-evaluation of the feeding mechanisms of the phylum Pogonophora, and it has been established that all species of Pogonophora investigated also rely on chemolithotrophic symbiotic bacteria fueled by methane or other reduced chemicals (Southward *et al.* 1986). Similar but simpler mechanisms occur in bivalves such as *Calyptogena magnifica* and *Bathymodiolus thermophilus*, this latter species being mixotroph (diatoms from the euphotic layer have been found in the gut). Hemoglobin occurs in the blood of *C. magnifica* and other species of the same genus from the Japanese subduction trenches (Arp and Fisher 1984). Nevertheless, *C. magnifica* has a special transport protein to carry sulfide to bacteria in its gills. Other species have developed a protection from toxic sulfide : the crab *Bythograea thermydron* lacks endosymbiotic bacteria ; it is able to detoxify sulfide by oxidizing it to nontoxic thiosulfate in its liver-like hepatopancreas (Arp and Childress 1981).

Similar results have not yet been achieved for cold seep species hosting symbiotic bacteria, except for the mussel from the Gulf of Mexico, which lives in the vicinity of hydrocarbon seeps. This undescribed mytilid consumes methane (the principal component of natural gas) at a high rate. Methane consumption is limited to the gills and is apparently due to the abundant intracellular bacteria living in gill cells. Methane consumption is dependent on the availability of oxygen and is inhibited by acetylene. The consumption of methane by these mussels is associated with a dramatic increase in oxygen consumption and carbon dioxide production. As the methane consumption can exceed the carbon dioxide production, symbiosis may be able to satisfy its carbon needs entirely from methane uptake. The very light stable carbon isotope ratio ($\delta^{13}C$ = -51 to -57 per mil) supports this hypothesis (Childress *et al.* 1986).

The case of the Pompei worms *Alvinella pompejana* and *A.caudata* is of particular interest : there are no endocellular bacteria but only epicuticular bacteria of different types (Gaill *et al.* 1988). High concentrations of sulfur (Laubier *et al.* 1983) and of different elements such as As, Zn, Fe, Cu, Al and P (Gaill *et al.* 1984) have been determined in both species. *In situ* labelling experiments showed a weak absorption of dissolved organic compounds by the epidermis (Alayse-Danet *et al.* 1986), and incubation at *in situ* temperature and pressure conditions result in an intense precipitation of sulfur, indicating that filamentous epibiotic bacteria were involved in the metabolism of sulfur compounds (Baross and Deming 1985). It has been suggested that the worm and its tube, together with the associated bacteria, function as a biological unit. Hot (20 to 50°C) and acidic hydrothermal fluid with a little dissolved oxygen circulates through the open tube. The epibiotic chemosynthetic bacteria provide food for the worm in particulate form collected by the protractile buccal tentacles and dissolved organic material absorbed through the body wall (Gaill *et al.* 1988). The worms have blood pigments well adapted to such an environment (Terwilliger and Terwilliger 1984). Thus there appears to be a complex symbiotic association between the polychaete and its epibiotic bacteria.

As has been often stressed, due to this symbiosis between chemolithotrophic bacteria and invertebrates, the hydrothermal vent and cold seep communities are the only biological systems on our planet known to depend totally on energy coming from internal heat of radioactive origin, and the only ones that could survive as long as water exists if the sun collapsed. This fact is of great theoretical interest to ecology.

7. GROWTH RATES AND METABOLISM

Metabolic rates of deep-sea communities are low compared to those in shallow water. Correlation has been found between respiration rate and biomass of macrofauna, and their decrease with increasing depth is correlated with the primary productivity of euphotic layers (Smith and Hinga 1983). However, the available data, though fragmentary, suggest that deeper-living benthic animals in a variety of groups have about the same oxygen-consumption rates as comparable shallow-living species, once the effect of temperature is accounted for. The hydrothermal vent species examined (*Bythograea thermydron*, *Riftia pachyptila* and *Calyptogena magnifica*) have rates of oxygen consumption within the range found for active shallow-water species of the same group of animals. These rates probably indicate that the vent species are relatively active in some cases, or have bacterial endosymbionts (Childress and Mickel 1985).

It is generally admitted that growth rates of benthic deep-sea invertebrates are low (Grassle 1980). Deep-sea bacteria have their highest metabolic and growth rates at ambient temperature and pressure conditions in the guts of different limivorous invertebrates (Deming and Colwell 1981). On the contrary, high rates of CO_2 incorporation, substrate utilization and nucleotide concentrations at hydrothermal vents indicate high rates of microbial metabolism and growth (Karl *et al.* 1980, Jannasch and Wirsen 1979). Bacterial densities of 10^5 to 10^9 in waters near hydrothermal vents can be compared to shallow water figures. It has been suggested that bacterial production at Galapagos site takes place below the sea-floor, in the hydrothermal circulation.

Therefore, invertebrate growth rates have been a subject of interest since the first discoveries of hydrothermal vents assemblages. Radiometric techniques have been used by Turekian and Cochran (1981) for *Calyptogena magnifica*; the growth rate was 4 cm/year and 6.5 cm/year for 19 and 22 cm long individuals at Galapagos vents. At 21°N, another individual of the same species was estimated to grow at 0.58 cm/year (Turekian *et al.* 1983). These results have been compared with direct measurements of growth rates of tagged *Bathymodiolus thermophilus* at a Galapagos site. From the resulting growth curve, the oldest animals were $19^{\pm}7$ years old (Rhoads *et al.* 1982). Another method, based on the comparison of shell microstructure and fluctuations in stable isotopes ratios of carbon and oxygen, enabled Roux *et al.* (1983) to estimate an average growth-rate of 1.2 cm/year for the same species at 21°N. Both radiometric and mark-recapture analyses, when utilized for deep-sea animals, yield growth-rates for an extremely limited number of specimens : Lutz *et al.* (1985) underlined that at that time only three specimens of *Calyptogena magnifica* and ten specimens of *Bathymodiolus thermophilus* had been analysed using these techniques. Lutz *et al.* (1983, 1985) proposed a new method based on the hypothesis of a constant rate of dissolution of the outer shell layer (218 μm/year) to determine the growth curve of *C. magnifica* : a 20 cm long individual would be about 20 years old and the growth-rate decreases with age, from 55 to 5 mm/year.

All studies conducted on bivalves from deep-sea hydrothermal vents have yielded growth rates that are comparable to those of numerous species of shallow-water bivalves and are several orders of magnitude higher that those reported from bivalves inhabiting the ordinary deep sea. To the extent to which growth-rates of animals reflect the rates of biological processes occurring at the vents, these results provide strong evidence that biological processes at the vents proceed at rates that are extremely rapid for the deep-sea environment (Lutz *et al.* 1985).

Up to now, no similar data are available for the growth of the different species of bivalves (*Calyptogena* or mussels) occurring in cold seep and hydrocarbon seep areas.

8. FOOD WEBS IN HYDROTHERMAL AND COLD SEEP COMMUNITIES

The first food web model of an hydrothermal assemblage was proposed five years ago for the case of the Galapagos hydrothermal vent community by Hessler and Smithey (1983). They conclude that about 75% of the biomass at hydrothermal vents is made up by taxa with symbiotic chemoautotrophic bacteria. The greatest uncertainty concerns the plankton abundance, and its relationship to chemoautotrophic productivity. Predators in the Galapagos site include the *Bythograea* crabs that are attracted by bait and have been observed biting tubeworm plumes. Turrid gastropods, unknown octopods and macrurid fishes exist in vent areas and are normally considered as predators

A synthetic model of the hydrothermal food web based on the Galapagos and the East Pacific Rise at 13°N and 21°N would include the "hot pole" with alvinellids and *Cyanagraea*, which do not occur at Galapagos. Fustec *et al.* (1988) have compared the biomasses of three main trophic groups (primary consumers, carnivores and detritivores) in two "cold" and "hot" sites from the hydrothermal field at 13°N (Table 2).

TABLE 2
BIOMASSES (100 m^2) OF THE THREE MAIN TROPHIC LEVELS AT 13°N (FROM FUSTEC *ET AL*. 1988, WET WEIGHTS)

Site	Primary consumers	Carnivores	Detritivores
Pogosud	800 kg	45 kg	8 kg
Actinoir	220 kg	17 kg	2.8 kg

In these figures, taxa with symbiotic chemosynthetic bacteria represent nearly 90% of the total biomasses. Mussels, generally hidden within the *Riftia pachyptila* thickets, were not considered, so the results are underestimated. Deposit feeders rely mainly on free bacteria living on rocky substrates, while suspension feeders such as serpulids (polychaetes), sea anemonies, mussels, *Bathypecten*, etc, which are more abundant in terms of biomass than deposit feeders, rely on particulate organic matter originating mainly from the symbiotic primary producers and free living bacteria and to a small extent from phytoplanktonic production, as testified by the presence of diatoms frustules in the gut of the mussel. The possible role of dissolved organic matter is unknown at present. Comita *et al.* (1984) studied particulate organic matter at the Collapsed Pit site at 21°N. The proportion of extractable lipid declined linearly with temperature and the proportion of particulate organic nitrogen declined sharply at temperatures below 15°C. Amounts of particulate organic carbon (POC) and particulate organic nitrogen (PON) ranged from 91 μg C/l and 4.4 μg/l over pillow basalts, to 139 μg C/l and 9.2 μg N/l over a bed of *Calyptogena magnifica*, and to 210 μg C/l and 22 μg N/l at the base of a dense thicket of *R. pachyptila*. The efficiency of the different symbiosis between invertebrates and chemolithotrophic bacteria has consequences on particulate organic matter production: POM production (from water samples analyses) is maximum above the alvinellid colonies, and minimum above *Riftia pachyptila* thickets (Brault *et al.* 1985). Several carnivores are adapted to the available dominating biomasses, alvinellids and vestimentiferan tube worms : the decapods *Bythograea* and *Cyanagraea*, the zoarcid fish *Thermarces*. A major question is whether biomass is exported to the ordinary deep-sea environment through deep-sea large scavengers. While there is no evidence of such exportation, it is difficult to imagine that it never occurs.

The food web proposed by Juniper and Sibuet (1987) for the *Calyptogena* oases of the Japanese subduction trenches is based on spatial and abundance relations of macro and megafauna as determined from microcartographic reconstructions. Juniper and Sibuet distinguish between the likely direct use of reduced substances in seeping fluids by *Calyptogena*-bacteria symbioses and the indirect utilization of free-living bacteria organic matter produced by weaker and more diffuse pore water seepages surrounding the bivalve patches. The biomass of bivalves found in the Nankai trough at 3,830 m (*Calyptogena nautilei, laubieri* and *kaikoi*) produces small amounts of particulate organic matter collected by suspension-feeding serpulids, actinarians, and galatheids. In two deeper sites of the Japan Trench, at 5,640 and 5,900 m, the biomass of bivalves (*Calyptogena phaseoliformis* only) produces particulate organic matter exploited by numerous suspension feeding caprellid amphipods, while large numbers of deposit feeders, swimming holothurians (at Kashima Seamount only) and tubicolous polychaetes (at both sites of the Japan Trench) suggest the occurrence of a third major trophic pathway based on the enhancement of the productivity of free-living chemosynthetic bacteria. In all cases, the question of a possible exportation of organic matter by deep-sea scavengers arises. The occurrence of some large coiled gastropods within the *Calyptogena* patches demonstrates that the bivalves are at least exploited by scavenging gastropods.

In the western Pacific, the recently described hydrothermal community shows important faunal novelties; the hairy gastropod *Alviniconcha hessleri* replaces the vestimentiferan tube worm in terms of biomass and function. Published pictures reveal the importance of a *Bythograea*-like decapod, together with *Munidopsis* crawling on the gastropod continuous layer (Hessler *et al.* 1988).

One of the major ecological questions raised by the food webs of hydrothermal and cold seep communities is that of a possible exportation of biomass and energy through a possible intervention of large carnivores such as deep-sea sharks and dermersal fishes. Up to now, there are no factual observations of such a possibility. Still, theoretical ecological considerations favor such a dispersion mechanism from highly productive areas to the oligotrophic deep ocean bottom.

9. ANCIENT HYDROTHERMAL VENT AND COLD SEEP COMMUNITIES

The first record of fossil animals in ancient hydrothermal vent deposits is that of the Bayda massive sulfide deposits of the Samail ophiolite, Sultanate of Oman (Haymon and Koski 1985). Fossil tube worms of Cretaceous age are the first well-documented example of fossils embedded in massive sulfide deposits. The geologic setting of the Bayda deposit and the distinctive mineralogic and textural features of the fossiliferous samples suggest that the Bayda sulfide deposit and fossil fauna are remnants of a Cretaceous sea-floor hydrothermal vent similar to modern hot springs on the East Pacific Rise and the Juan de Fuca Ridge. Fossilized worm tubes of the Bayda deposit are 1 to 5 mm in diameter and are randomly oriented, preserved in a matrix composed of Zn- and Fe-sulfide minerals. Different types of tubes have been distinguished : tubes with longitudinal ornamentations, tubes with numerous closely-spaced annulations and tubes which are distinctly segmented by two prominent annulations. These fossil tubes recall those of alvinellid polychaetes found on white and black smokers at 21°N and those of *Riftia pachyptila*. Similar tube structures, interpreted as vent worm fossils, have also been described recently in Cretaceous massive sulfide ore from the Troodos ophiolite in Cyprus (Oudin and Constantinou 1984).

Fossil vent worms of Carboniferous age (approximately 350 million years old) have been reported from the Tynagh deposit of Ireland (Banks, 1985). The Tynagh deposit is a sediment-hosted, Pb-Zn sulfide deposit that precipitated from hot springs venting through a thick blanket of carbonate-rich mud. The Tynagh worms have been replaced with barite and are found inside tubes of pyritic mud much less than one centimetre in diameter. The Tynagh fossil worms and their tubes are morphologically and mineralogically different from fossils of the younger Bayda deposit, and apparently formed in a different geological setting; the Tynagh vents appear to have been active at relatively shallow depths in a basin receiving continentally-derived sediments. In all cases, fossilization took place before the cessation of hydrothermal activity.

A careful search for fossils and other evidence of life in hydrothermal deposits of the Paleozoic and the Precambrian eras is needed to extrapolate the history of the hydrothermal vent fauna through times beyond the Cretaceous worm tubes of the Samail ophiolite to the beginning of sea-floor hot spring colonization

10. OPEN AND CONTROVERSIAL QUESTIONS : ULTRATHERMOPHILIC BACTERIA AND THE ORIGIN OF LIFE

While reduced organic compounds that occur in cold seeps waters depend ultimately on preexisting organic matter, reduced elements occurring in high temperature hydrothermal fluids come from the deep mantle and do not depend on preexisting organic matter. The hydrothermal vents are a remarkable environment and are thought to have changed very little over the past 4 billion years of the earth history. They offer a carbon source which is exposed to high temperature under strongly reducing conditions and the main biogenic elements are present as H_2, N_2, H_2S, CO, CO_2 and possibly CH_4 (Lilley *et al.* 1983). The entire system was shielded by the ocean from the destructive effects of ultraviolet irradiations and meteoric impacts. Hydrothermal vents were soon proposed as a possible site for the origin of life (Corliss *et al.* 1981). They provide a multiplicity of physical and chemical gradients as a direct result of interactions between extensive hydrothermal activity and the overlying ocean and atmosphere, leading to multiple pathways for the abiotic synthesis of chemical compounds, origin and evolution of "precells" and, ultimately, evolution of free-living organisms (Baross and Hoffman 1985). One of the most controversial questions is that of the possible occurrence of ultrathermophilic bacteria able to grow under pressure at temperatures of 250°C. Baross and Deming (1983) described a community of extreme thermophiles that were cultured from the 350°C hydrothermal fluid sampled at 21°N in 1979. They claimed that these bacteria could be grown in the laboratory at 250°C and 265 atm. Subsequent investigations showed that the evidence for bacterial growth was likely to be the result of artefacts introduced during sample processing (Trent *et al.* 1984). There is still no solid evidence for bacteria growing at temperatures above 120°C (Deming and Baross 1986). Moreover, *in vitro* experiments have shown that organic compounds decompose rapidly at high temperature and pressure. The available stability data show that the essential organic compounds dissolved in sea water would have short lifetimes at temperatures above 200°C (Bernhardt *et al.* 1984). The high pressure would not greatly retard decomposition rates ; even assuming a large volume of activation of 50 ml $mol.^{-1}$, a pressure of 400 atm would decrease the rate of decomposition by hydrolysis by a factor of only 2.5. Miller and Bada (1988) recently claimed that the high temperatures in the vents would not allow synthesis of organic compounds, but would decompose them, unless the exposure time at vent temperatures was short. They even added that if the essential organic molecules were available in the hot hydrothermal waters, the subsequent steps of polymerization and the conversion of these polymers into the first organisms would not occur as the vent waters were quenched by the colder temperatures of the primitive oceans.

The field problem is in fact much more complex due to the high physical and chemical variability of the hydrothermal vent environment. A continuous range of temperatures occurs in hydrothermal fields such as the 21°N site, from low temperature vents (a few tens of degrees C) to white (200-250°C) and black smokers (350°C), due to secondary circulation processes. Local convective cells would also make it possible for a given molecule to be exposed several times to a given physical and chemical gradient. Hydrothermal vents are not as simple to observe and simulate as are laboratory experiments to control. Moreover, it must be stressed that present hypotheses on the physical conditions in the Archaean ocean include a relatively high temperature of water (70 to 120°C) and appreciable amounts of sulfate in the sea water actively reduced by sulfate-reducing bacteria (Kasting and Ackerman 1986, Ohmoto and Felder 1987).

The question of the possible origin of life at hydrothermal vents will certainly remain subject to discussion for a long time. However, it seems that the geologically short time interval between the formation of the earth's oceans and the appearance of microorganisms in the fossil records is an important point. The hydrothermal vents, which are believed to have functioned in the Archaean oceans, appear as one of the possible sites for the origin and evolution of life.

11. CONCLUSIONS

The rapid increase of our knowledge since the period of the first discoveries clearly shows that we must remain prepared for further new discoveries, in both hydrothermal vent and cold seep communities. We will soon be in a position to establish the relationship between plate movements on the earth's surface and the development of these microbial/animal assemblages free from photosynthesis. We must also expect to discover new types of faunal and functional organisation of these communities. The recently discovered western Pacific hydrothermal community, where the giant tube worm is replaced by the hairy gastropod, is interesting testimony for that possibility.

As far as ecology of the deep ocean is concerned, it is essential to determine whether or not these communities export part of their production to other deep-sea benthic environments. Some rough calculations based on thermal and helium-3 anomalies showed that hydrothermal production could account for only one thousandth of the euphotic zone production. Even so, the question remains and several hypotheses can be proposed; the large scavenging animals of the ordinary deep sea, the hydrothermal zooplankton and micronekton which are very abundant but very difficult to sample and estimate quantitatively, and the production of particulate and dissolved organic matters (POM and DOM) could contribute to the exportation process.

The question of the origin and evolution of the symbiosis is also an intriguing one. How do bacteria contaminate their hosts (the embryos of *Riftia* are devoid of bacteria)? How do the animals select the appropriate bacterial strain in hydrogen sulfide- or methane-rich environments? Is the association between bacteria and invertebrates a true symbiosis, i. e. the same bacterial species associated with the same invertebrate species through generations? The discovery of hydrothermal and cold seep symbiotic associations has also contributed to a better understanding of the physiology and trophic relations of the phylum Pogonophora, together with a reevaluation of the role and importance of chemosynthesis in the world ocean.

Geologically speaking, the hydrothermal environment can be considered one of the very ancient systems on our planet, while the cold and hydrocarbon seeps, on the contrary, are fairly recent environments that need preexisting organic matter and a sufficiently long interval of time for organic carbon burial in the deep sediments to take place. From a biological point of view, both environments are characterized by extraordinarily large biomass concentrated on small patches. In contrast, it is generally admitted that benthic assemblages of the deep ocean are very strongly limited by the scarcity of the food coming from the euphotic layers as small particles. Nevertheless, long period exposures of artificial substrates enriched in concentrated organic matter in the ordinary deep sea reveal the occurrence of several species displaying remarkable features (Desbruyeres and Laubier 1988). Some of them are similar to species belonging to the faunal assemblages linked with submarine hydrothermal vents and cold and hypersaline seeps. These opportunistic large benthic invertebrates depending on concentrated organic matter living in the ordinary deep sea probably have common ancestors with hydrothermal and cold seep organisms.

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Hydrothermal Metalliferous Sediments in the Southwest Pacific

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ABSTRACT

Hydrothermal metalliferous sediments in the southwest Pacific are preferentially located in two submarine volcanic settings, back-arc basins and volcanic arcs. Of these, the back-arc basins appear to be the principal locale for major hydrothermal deposits and contain all of the main classes of submarine hydrothermal minerals previously reported from mid-ocean ridges: sulfides, silicates and oxides. These submarine occurrences are generally surrounded by haloes of hydrothermal metalliferous sediments representing distal fallout products from hydrothermal plumes, and which considerably facilitate the finding of the more localised higher grade hydrothermal mineral deposits. In contrast, the volcanic arcs fringing the basins have so far been found to host only low temperature hydrothermal ferromanganese oxide deposits. Higher temperature hydrothermal minerals may occur below the sea floor in these areas, or in confined volcanic craters. A number of targets for future "hydrothermal" submersible operations in the S.W. Pacific are defined on the basis of metalliferous sediment distribution reported herein.

1. INTRODUCTION

Metalliferous seafloor sediments are those that exhibit metal enrichment from hydrothermal fluxes. Metals most commonly enriched in such deposits include Fe, Mn, Cu, Zn, As and sometimes Ag and Au. Because of hydrothermal contributions, metalliferous sediments are found located either in or adjacent to hydrothermally active submarine volcanic areas, most commonly mid-ocean ridges (see Cronan 1980 for a review). However, in recent years such deposits have also been found on intra-plate hot spots (cf. Loihi Seamount, Hawaii, Malahoff *et al.* 1982), in island arcs, and in back-arc basins (Cronan and Thompson 1978). It is the last of these settings that characterize most of the metalliferous sediments in the southwest Pacific.

The origin of metalliferous sediments is related to the precipitation of phases from hydrothermal plumes. The process starts with diffusion into the seafloor of seawater which becomes heated and reacts with newly formed oceanic crust in submarine volcanic areas, becoming enriched in metals before being discharged in the form of black smokers. Some primary magmatic contribution to the hydrothermal waters is also possible. Much of the dissolved material carried in the hydrothermal solutions precipitates in the immediate vicinity of the discharge vents, constructing chimneys and mounds of sulfide and associated minerals, but some fraction of the vent fluids also escapes from the sea floor in a hydrothermal plume which disperses away from the site of discharge, partly under its own dynamics and partly under the influence of ocean currents. Such currents can carry dissolved and particulate materials of hydrothermal origin for considerable distances from the vent site, as far as several hundred kilometres on the East Pacific Rise for example (Edmond *et al.* 1982). Gradually these materials precipitate from seawater to give rise to metalliferous sediments.

It is evident that this process will result in a localised area of highly concentrated hydrothermal precipitates in the vicinity of the vents, and that these will be surrounded by, or be adjacent to (dependent on the directions of plume dispersal), a much larger area of hydrothermally enriched metalliferous sediments. Such widespread metal enrichments have an obvious exploration value (Cronan 1976) as sediments containing them are much easier to find by conventional shipboard sampling techniques than are the more highly concentrated, localised, hydrothermal deposits with which they are associated. This knowledge has driven much of the exploration for hydrothermal deposits in the S.W. Pacific, and is a necessary precursor to more detailed submersible studies near the vents. Study of hydrothermal metalliferous sedimentation in the southwest Pacific is, among other things, providing targets for future submersible activities in the region, just as it did on the East Pacific Rise in the pre-submersible era there.

2. EXPLORATION TECHNIQUES

Geochemical exploration principles for hydrothermal deposits in the southwest Pacific using multi-element techniques have been described by Cronan (1983). Sediments are retrieved from throughout a region of possible hydrothermal activity and are analysed for their content of Mn, Fe, Cu, Zn, Ni, Al and Ca. Manganese, and to a lesser extent iron, are the most widespread and sensitive indicators of submarine hydrothermal mineralisation as they are the last elements to precipitate from the hydrothermal plumes and thus can be carried great distances from the hydrothermal source (Bignell *et al.* 1976; Edmonds *et al.* 1982). This gives rise in the sediments to widespread Mn dispersion haloes, zones of manganese enrichment surrounding the vents. Dispersion haloes of Fe are generally more confined to the emanating vents (Bignell *et al.* 1976). These haloes provide foci for more detailed sampling for hydrothermal deposits. Analyses of sediments for Cu and Zn content can provide an indication of the presence of sulfide minerals or their alteration products. Shearme *et al.* (1983) noted Fe, Cu, and Zn enrichments in sediments from the TAG hydrothermal field on the Mid-Atlantic Ridge which they interpreted as oxidised sulfide precipitates from a hydrothermal plume. Subsequent work in the TAG area demonstrated that these sediments were located quite close to hydrothermal vents discharging black smokers (Rona, personal communication, 1986). Analysis for Ni , when it occurs in association with Mn, can enable one to discriminate between hydrogenous and hydrothermal Mn enrichments in the sediments, as hydrogenous manganese oxides are invariably more enriched in Ni than are hydrothermal ones (Cronan 1980). Analyses for Ca and Al in the sediments facilitate the recalculation of the sediment analyses on a detrital or carbonate free basis to eliminate the dilutive effects of calcareous organisms and clastic materials on the hydrothermal precipitates.

Geostatistical analysis of sediment geochemical data can help to refine our understanding of the origin of metal enrichments in the deposits and to discriminate between hydrothermal and non-hydrothermal contributions. Factor analysis has been used on southwest Pacific sediment data to this end by Cronan (1983), McMurtry *et al.* (in press) and Walter *et al.* (in press). *Factor analysis* is a statistical technique which aims to resolve the variance in a data set of "n" variables in terms of less than "n" factors, and has proved to be very useful in sorting out the inter-relationships within large geochemical data sets. In sediment studies, the factors are usually related to differing element sources. The calculation of factor scores for each sediment sample further helps to clarify the origin of element enrichments, as these express the contribution made to each sample by each of the factors and thus each of the possible sources of elements to the sediments.

Even when metal concentrations in sediments are not particularly high, geostatistical analysis of sufficiently large data sets can help to highlight geochemical anomalies. Coward and Cronan (1985, 1987) have described a technique called *ridge regression analysis* which is a multivariate statistical technique by which one predicts the concentration of a dependent variable using several independent predictor variables. In the context of southwest Pacific sediment geochemistry, the aim of ridge regression analysis is to develop regression equations which predict the concentrations of elements at sample sites, based on the operation of one or more background processes and resolved using a principal components analysis of the whole data set. The resulting residual values (difference between predicted and actual element concentrations) define geochemically anomalous samples. These can be depicted diagrammatically as histograms. Throughout the diagrams in the present work, all the sample sites with histogram representations are anomalous. The bars on the histograms show all the residual values for the sample site expressed as a percentage of their respective thresholds. The horizontal dotted lines are positive (+ 100%) and negative (- 100%) thresholds. Residual values which break through the thresholds are anomalous.

An additional technique which can help to resolve the sources of element enrichments in marine sediments is *geochemical partition analysis*. The aim of this technique is to determine in which phases (constituents) of the sediments different elements present are principally located. Usually, any one element is variably partitioned between a number of phases, although it may often be more abundant in one phase than the others. In the partition method used on southwest Pacific sediments, a three part leach procedure after Chester and Hughes (1967) was adopted. Samples were first leached with acetic acid to dissolve calcium carbonate and elements contained therein, and adsorbed ions; secondly with a mixture of acetic acid and hydroxylamine HCl to dissolve carbonate, amorphous iron minerals and reducible ferromanganese oxides taking into solution elements associated with these phases, and thirdly with hot HCl to dissolve all the above and remaining iron oxides, and to partially dissolve detrital and authigenic silicate material. The amounts of elements soluble in each fraction were obtained by subtraction, as was the composition of the HCl insoluble residue which reflects the resistant detrital mineral content of the sediments. In essence, the principal use of geochemical partition analysis in the context of the search for hydrothermal metal enrichments in southwest Pacific sediments is to determine the form in which the enriched elements are present in the sediments, and thus the likely source of the enrichment.

Using combinations of the techniques outlined above, Cronan (1983) and Coward and Cronan (1985) studied more than 650 sediment samples from throughout the southwest Pacific. On this basis they were able to outline the areas of submarine hydrothermal activity shown in figure 1, and described in more detail in the next section. These have served as a focus for much of the subsequent work on hydrothermal deposits in the southwest Pacific.

3. AREAS OF METALLIFEROUS SEDIMENTS

It is evident from an inspection of Fig. 1 that the areas of likely metalliferous sedimentation in the southwest Pacific fall into two tectonic settings, the back-arc basins and the volcanic arcs. This is in contrast to mid-ocean ridges where the ridge itself is the main, if not sole, location of hydrothermal deposit formation, especially if near-axis seamounts are excluded. The duality of the settings of hydrothermal activity in the southwest Pacific make for a more complicated situation than on mid-ocean ridges but by the same token provide for comparisons between hydrothermal deposits from different tectonic settings in a way that is not possible on mid-ocean ridges. Each setting will be considered separately.

4. BACK ARC BASINS

Bismarck Sea

The Bismarck Sea (Fig. 2) is divided into the New Guinea Basin to the west and the Manus Basin to the east. According to Taylor (1979), this area is a back-arc basin with respect to the New Britain arc-trench system.

Cronan (1983) evaluated the possibility of hydrothermal activity occurring in the Bismarck Sea and concluded on the basis of Mn anomalies in sediments that hydrothermal deposits were most likely to be located along the plate boundary (Fig.2). Subsequent work confirmed this prediction when inactive chimney vents were discovered on the spreading centre in the

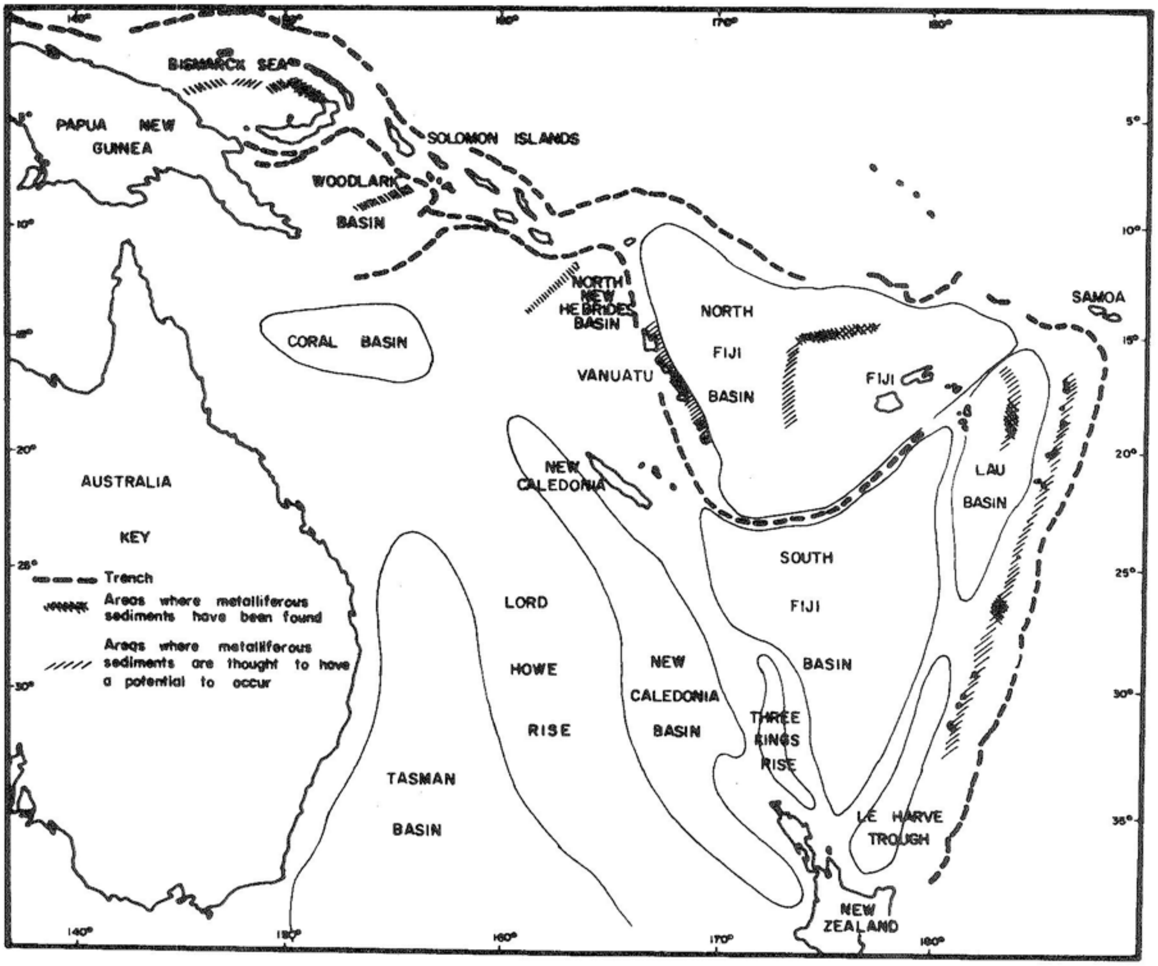

Figure 1. Proposed areas of submarine hydrothermal deposits in the southwest Pacific (from Cronan 1983)

Manus Basin (Both *et al.* 1986) and hydrothermal manganese crusts were dredged from their vicinity (Site B, Fig. 2) (Bolton *et al.* 1988). Hydrothermal manganese crusts were also dredged near Manus Island (Site A, Fig. 2) (Bolton *et al.* 1988). Hydrothermal gas anomalies measured in the water column near the Manus Basin spreading centre indicate that venting continues (Craig and Poreda 1987).

Additional work on Manus Basin sediments has shown that other sites of hydrothermal activity could exist. Using ridge regression analysis, Coward and Cronan (1985) recorded strong Mn regression anomalies at several Manus Basin sites (Fig. 2). Partition analysis of these samples showed that the Mn is most probably present in the sediments as Mn oxide of non-detrital origin (Coward 1986). The bulk of the sediment samples from the Manus Basin can be assigned to mixed and clay populations on the basis of principal components analysis (Coward and Cronan 1985). In these populations, the main background process responsible for Mn variation is hydrogenous deposition of Fe-Mn oxides and Mn scavenged from seawater. However, ridge regression analysis recognised Mn anomalies in the Manus Basin sediments on the basis that they are high in Mn and relatively low in trace elements (Coward 1986), quite unlike commonly occurring hydrogenous manganese oxides. Thus a hydrothermal origin for them is likely, and their location defines new sites in the Manus Basin where hydrothermal mineralization might be expected. Scattered Fe and Zn anomalies in Manus Basin sediments also possibly point to additional hydrothermal areas, distant from the main plate boundary where the bulk of the hydrothermal activity would be expected. The sample containing anomalous iron concentrations is quite close to the Site A hydrothermal manganese crusts of Bolton *et al.* (1988); another with a Zn anomaly near the N.E. end of New Britain is close to the

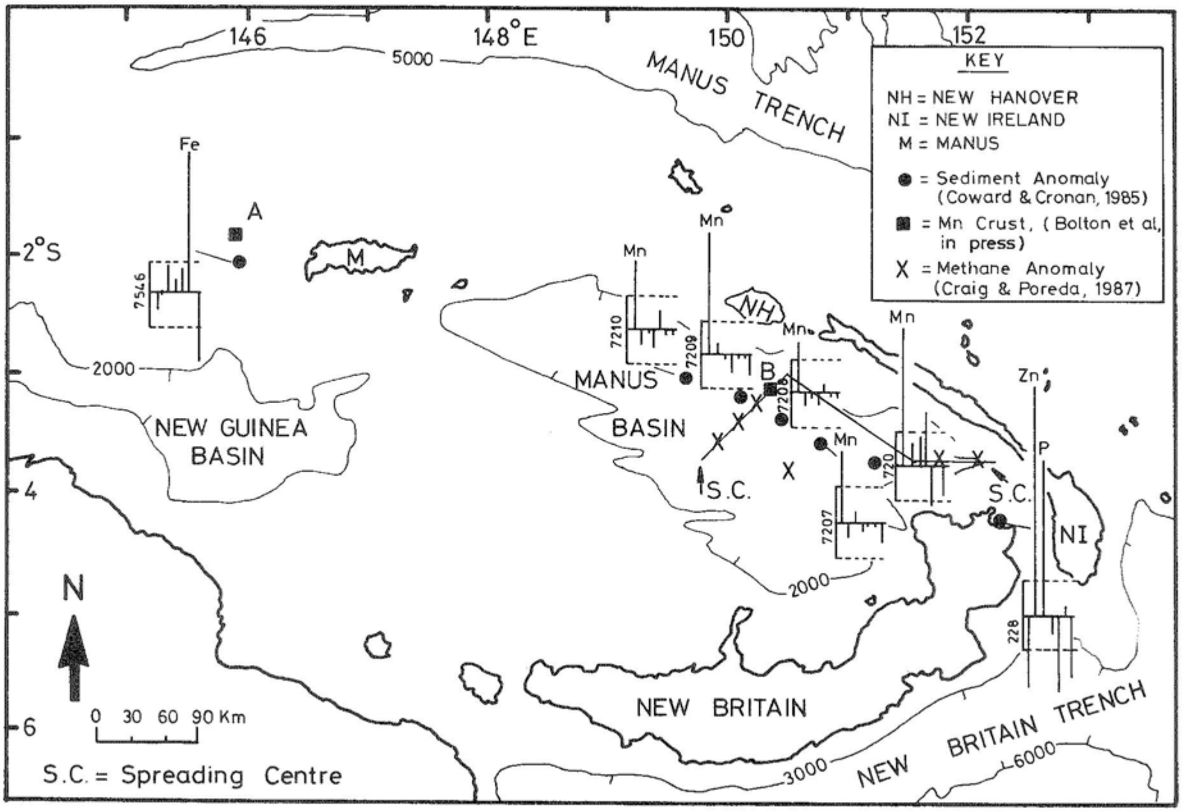

Figure 2. Locations of hydrothermal activity in the Bismarck Sea (modified from Coward and Cronan 1985).

hydrothermal activity in Matupi Harbor described by Ferguson and Lambert (1972). A hydrothermal contribution to the phosphorus in the latter sample is also possible. The locations of both of these sediment samples appear to be within the range of hydrothermal influences.

Woodlark Basin

According to Binns *et al.* (1987), the Woodlark Basin is an active sea floor spreading zone lying in the southern Solomon Sea, located between the south-facing Huon-New Britain Arc and the deep Coral Sea Basin. Opening of the basin is thought to have commenced before 5 million years in the east where, according to Taylor (1984), the spreading axis is being subducted beneath the Solomon Islands. Binns *et al.* (1987) thought the basin to be a possible modern analogue of the setting in which ancient volcanogenic massive sulfide ore bodies probably formed.

Most of our knowledge of hydrothermal deposits in the Woodlark Basin (Fig. 3) derives from the Paclark Expedition, Legs 1-3, 1986-88 (Binns and Scott 1988). Metalliferous sediments consisting of hundreds of centimeter-size fragments of orange to red-brown Si-bearing Fe oxyhydrate with an accessory Mn phase and micron size barite crystals, were dredged on the Franklin Seamount (Fig. 3). Venting of hydrothermal fluids at low temperature was thought to be an essential factor in the creation of these deposits (Binns *et al.* 1987) and they were considered to be analogous to some of the iron-silica deposits surrounding sulfide mounds and high temperature vent deposits on mid-ocean ridges.

Additional locations of hydrothermal activity in the Woodlark Basin have been identified on the basis of a variety of evidence (Binns and Scott 1988) and are shown in figure 3. They include manganese enriched hydrothermal plumes in the water column near Dobu Seamount close to the north of Normanby Island, and in the North and West Basins. Further manifestations of hydrothermal activity were obtained by dredging at site D3 (Fig.3).

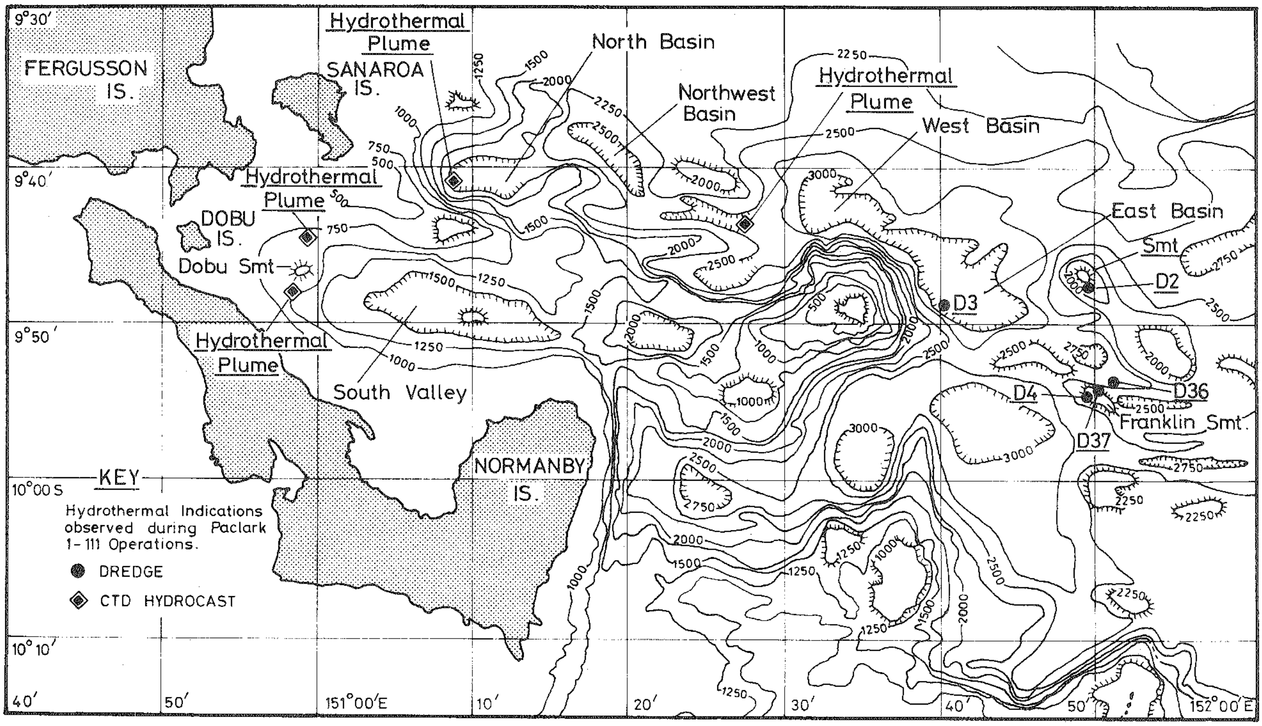

Figure 3. Locations of hydrothermal activity in the western Woodlark Basin (after Binns *et al.* 1987; Binns and Scott 1988)

North Fiji Basin

The North Fiji Basin is a back-arc basin, 2000m-4000m deep, averaging about 3000m (Fig. 1). It stands between the New Hebrides subduction zone to the west and the Fiji Platform to the east. It is thought to have originated by oceanic spreading about 8 to 10 million years ago and has since undergone several modifications in spreading activity.

North Fiji Basin sediment samples were extensively studied by Cronan (1983) in order to seek evidence of submarine hydrothermal activity. On the basis of this study, Cronan (1983) concluded that submarine hydrothermal activity and associated metalliferous sedimentation is most likely to be located along the north-south spreading centre and in an area of shallow seismicity northwest of Fiji (Fig. 1) which included the Braemar Ridge region (Fig. 7).

According to Auzende *et al.* (1988) the main spreading centre in the North Fiji basin is located between 173°E and 174°E and is defined by a central magnetic anomaly and lack of sediment cover as indicated on single channel seismic reflection profiles. The axis is considered to consist of a succession of *en-echelon* segments of oceanic crust offset by non-transform faults. This structure has been the main, but not sole, target for hydrothermal mineral exploration in the North Fiji Basin.

Most recently, on the Kaiyo 1987 expedition (Kaiyo 1987 unpublished Cruise Report), three sites to be surveyed by Deep Tow (DTS A, B and C) were selected along the spreading centre axis between 16°30'S and 18°10'S, in areas where some evidence of hydrothermal activity existed. DTS-A was the site of a large hydrothermal methane anomaly reported by Craig and Poreda (1987) at 18°08'S, and was also the site of a large water column manganese anomaly detected on the Kaiyo 1987 cruise. In DTS-B, a very strong acoustic reflector had been recognised by SEAMARK II and a large water column manganese anomaly had been detected at 16°58.61'S, 173°53.36'E. DTS-C was sited near a large water column manganese anomaly on the bottom at 17°10.74'S, 173°54.82'E. At DTS-A and DTS-C, no indications of hydrothermal deposits were found, while at DTS-B strong signs of hydrothermal deposits did occur.

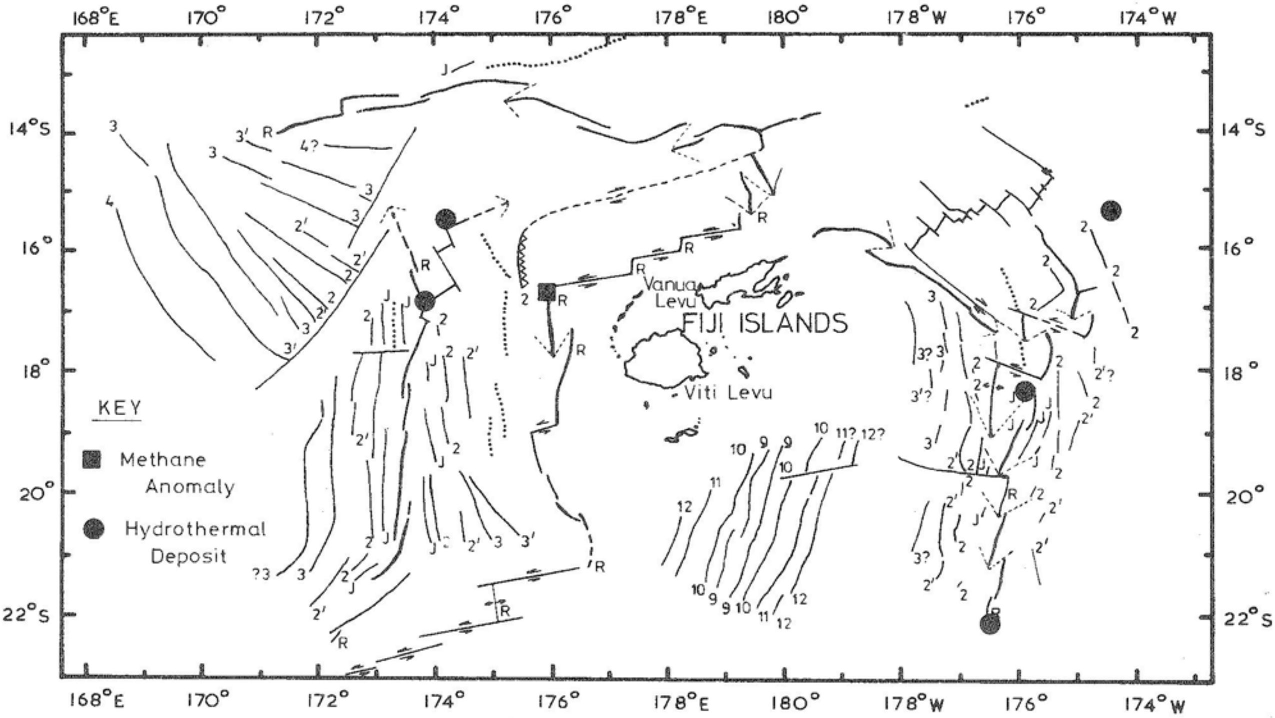

Figure 4. Magnetic anomaly lineation and rift location map of the North Fiji and Lau Basins, together with locations of hydrothermal activity (modified from Malahoff *et al.* in press)

Station DTS B was located within a rectangle defined by 16°56 S and 17°00'S, and 173°53'E and 173°57'E (Fig. 4). Dredging, one hydrocast sampling, and Deep Tow surveying were carried out at this site. Within the axial rift, many steep scarps 5-30 m in height are present on the sea floor, with which talus deposits derived from pillow and sheet flow lavas are associated . Yellowish brown deposits were photographed in the deeper parts of the graben on all survey lines. A few irregularly shaped yellowish-red mounds were also observed, possibly hydrothermal mineral deposits. Additionally, in the southern part of the central graben, deep sea biological communities associated with vents were found. The communities consist of giant clams, gastropods and barnacles occupying a yellowish knoll.

Thermal anomalies were observed in the bottom water at 16°59.44'S, 173°54.00'E; 16°59.37'S, 173°54.91'E and 16°59.42'S, 173°54.99'E. These anomalies consistently coincided with the points where yellowish brown deposits or small chimneys were observed, and the third anomaly coincided with the biological communities at the vents. Evidently, therefore, the hydrothermal system observed was still active.

Also between 16°54.66'S, 173°54.66'E and 16°58.67'S, 173°55.02'E a dredge on the Kaiyo 1987 cruise recovered manganese oxide coated pillow lava fragments in a water depth of 1979-1960m. Initial shipboard reports suggested a probable hydrothermal origin for them (Kaiyo 1987 unpublished Cruise Report).

Earlier, during the Sonne 35 Cruise (SO-35) from December 1984 to February 1985, a survey for hydrothermal deposits was conducted in the North Fiji Basin (von Stackelberg *et al.* 1985). At one site (Fig. 7) hydrothermal sulfide minerals were found at 1860 m depth. They existed as minute ($<100\mu$m) pyrite crystals along rock fractures in moderately fresh pillow basalts. The basalts were coated with Fe oxides and locally by yellowish brown sediment, possibly derived from hydrothermal nontronite (von Rad and Johnson 1985). Hydrothermal manganese crusts were also recovered from several localities near the Braemar Ridge (Fig.7).

While major hydrothermal activity in the North Fiji Basin is likely to be associated with the principal spreading centres (Fig. 4), there are several indications that it is not restricted to that setting. These indications come mainly from sediment geochemistry which, as mentioned, can identify the effects of hydrothermal activity over areas many times the size of the actual hydrothermal centres, and provides a record of hydrothermal activity over extended periods of time in a way that water column anomalies cannot.

McMurtry *et al.* (in press) have performed a factor analysis of geochemical data on North Fiji Basin sediments which has helped to outline areas of likely hydrothermal discharges (Fig. 5). Three areas where there are significant hydrothermal contributions of metals to the sediments are a broad area associated with the South Pandora Ridge which is a roughly east-west ridge at about 14°S, an area about 100 km to the east of the central North Fiji Basin spreading centre, and an area to the southwest. A clear signature of past hydrothermal activity was absent from the sediments associated with a northern extension of the North Fiji Basin spreading centre north of 16°S, attributed by McMurtry *et al.* (in press) to the relative youth of this feature. Possibly hydrothermal circulation has not been active for a sufficiently long time to build up a measurable record of hydrothermal activity in the sediments. Those areas of hydrothermally enriched sediments not clearly associated with any proven tectonic feature led McMurtry *et al.* (in press) to conclude that back-arc rifting in the North Fiji Basin might be producing scattered localised hydrothermal systems. Possible localised hydrothermal systems in the North Fiji Basin have also been indicated by the work of Cronan (1983) in the Braemar Ridge-Yandua Trough region and in the Balmoral Basin, on the basis of sediment Mn anomalies. This area overlaps with and extends to the east, the "eastern" anomalous area of McMurtry *et al.* (in press). Malahoff *et al.* (in press) have recently suggested a spreading centre in its vicinity (Fig. 4).

More recently, one sediment core from the "eastern" anomalous area of McMurtry et al. (in press) and Cronan (1983), PC03 (15°34.7'S, 174°10.1'E), has been subjected to more detailed study by Murphy *et al.* (1987). Sediments from this core were found by Cronan (1983) to be richest in Mn amongst all those examined. Geochemical data subjected to factor analysis exhibit a high score on the hydrothermal factor, so the core was considered to have received the greatest contribution of hydrothermal material (Cronan 1983). Partition analysis of this core (Cronan, 1986) confirmed the authigenic nature of the manganese phases. The more recent work of Murphy *et al.* (1987) has shown Core PC03 to have a Mn accumulation rate of 5.6mg cm^{-2} per thousand years, the highest yet reported in the North Fiji Basin. These figures indicate that metal accumulation rates at this site are comparable to those of mid-ocean ridge settings, and that the onset of hydrothermal activity in its vicinity was approximately 0.2 Ma B.P. based on ^{230}Th dating with an upper limit of 0.7 Ma B.P. based on micropalaentology. Re-analysis of the tectonic setting of the site of this core revealed that it was collected from adjacent to a spreading centre (Murphy *et al.*, 1987). This interpretation is supported by the recently prepared magnetic anomaly lineation and rift location map of the North Fiji Basin produced by Malahoff *et al.* (in press) which shows the site of Core PC03 to be close to a triple junction or spreading centre offset (Fig. 4). Clearly this core provides an excellent example of how geophysical models of tectonic evolution must be constrained by geochemical data on sediments when available. The site of this core is a prime target for further exploration for hydrothermal mineral deposits in the North Fiji Basin.

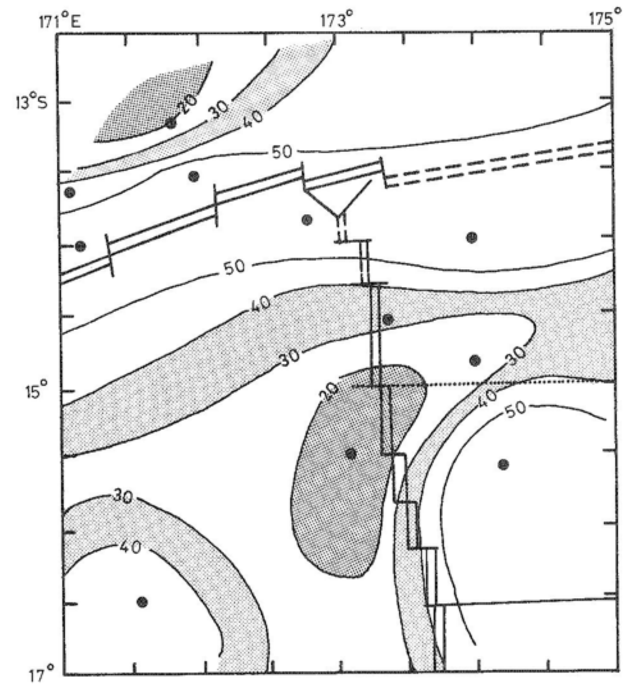

Figure 5. Contour plot in percent of hydrothermal component in <2 μm sediments based on factor analysis (from McMurtry *et al.* in press)

Although Core PC03 is now thought to be associated with a spreading regime, there are several other sites in the North Fiji Basin where geochemical anomalies that might reflect hydrothermal activity occur in tectonic situations as yet not clearly resolved (von Stackelberg *et* *al.* 1985, Coward and Cronan 1985, Coward 1986). Geochemically anomalous sediments from the northern part of the North Fiji Basin recognised by ridge regression analysis (Coward and Cronan 1985, Coward 1986) are shown in figure 6. Iron anomalies in Samples 121 and 247 lie to the north of the active South Pandora Ridge, although Sample 121 is close to the Ridge. Both fall within the zone defined as being hydrothermally influenced on the basis of factor analysis of sediment geochemical data by McMurtry *et al.* (in press). Thus these sites warrant further investigation for hydrothermal deposits.

Zinc and zinc/iron anomalies in sediments at Sites 230 and 226 (Coward and Cronan 1985) are close to the position of hydrothermal Mn crusts reported by von Stackelberg *et al.* (1985). Partition analysis on these samples shows that more than 70% of the Zn is non-detrital. These anomalies could be hydrothermal in origin, related to the activity that generated the manganese crusts.

Geochemical anomalies identified by ridge regression analysis in the central part of the North Fiji Basin (Coward and Cronan 1985, Coward 1986) are shown in figure 7. Sediments from this area generally have a greater detrital content than those farther north (Coward 1986) in keeping with their closer proximity to the Vanuatu Arc. A hydrothermal contribution of metals to these sediments was suggested by Cronan (1983) and hydrothermal manganese crusts and sulfide impregnations (von Stackelberg *et al.* 1985) have been recovered in the vicinity (Fig. 7), the latter from a spreading centre. Ridge regression anomalies of Fe, Cu and Zn, sometimes combined, are common in this area and, as mentioned, this combination of elements is a well known hydrothermal association (Shearme *et al.* 1983). Partition analysis of the anomalous samples indicate Fe to be present in the oxide form with Cu and Zn in non-detrital phases, supporting their possible hydrothermal origin (Coward 1986).

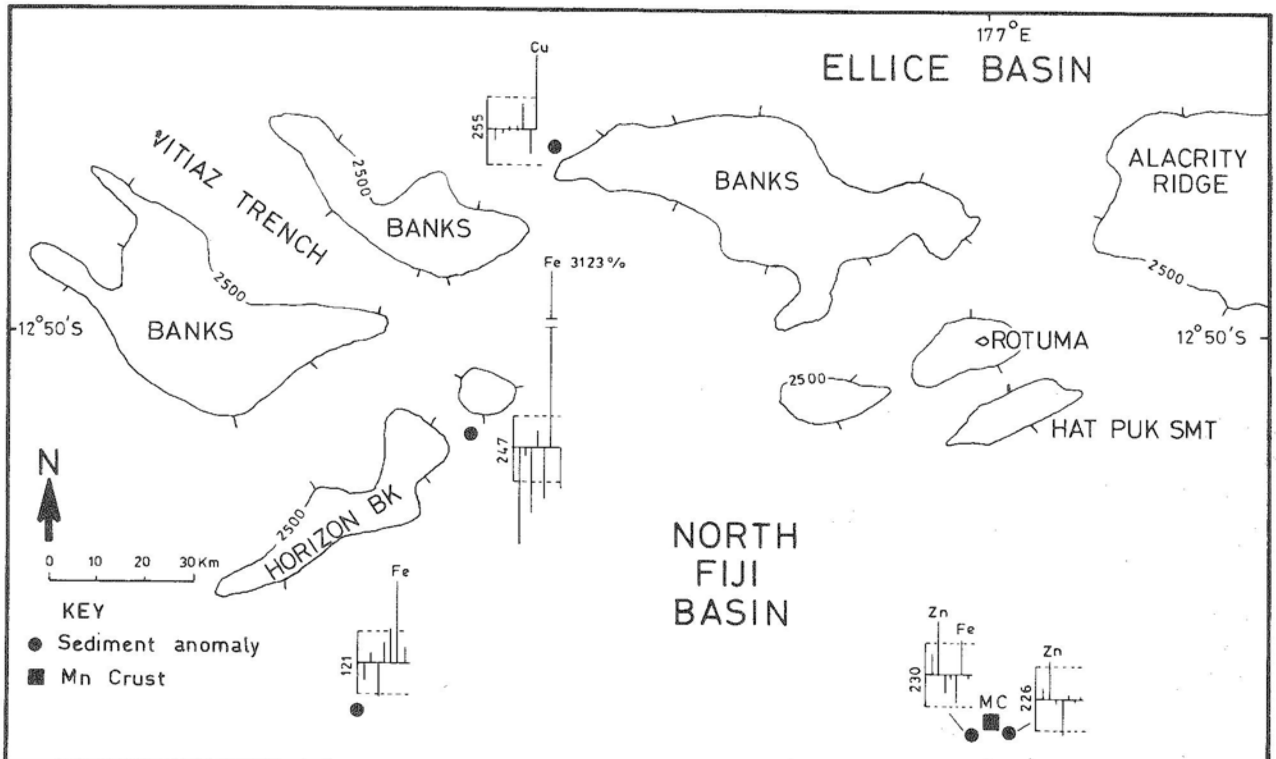

Figure 6. Manganese crusts and sediment geochemical anomalies possibly indicative of hydrothermal activity in the northern North Fiji Basin (modified from Coward and Cronan 1985).

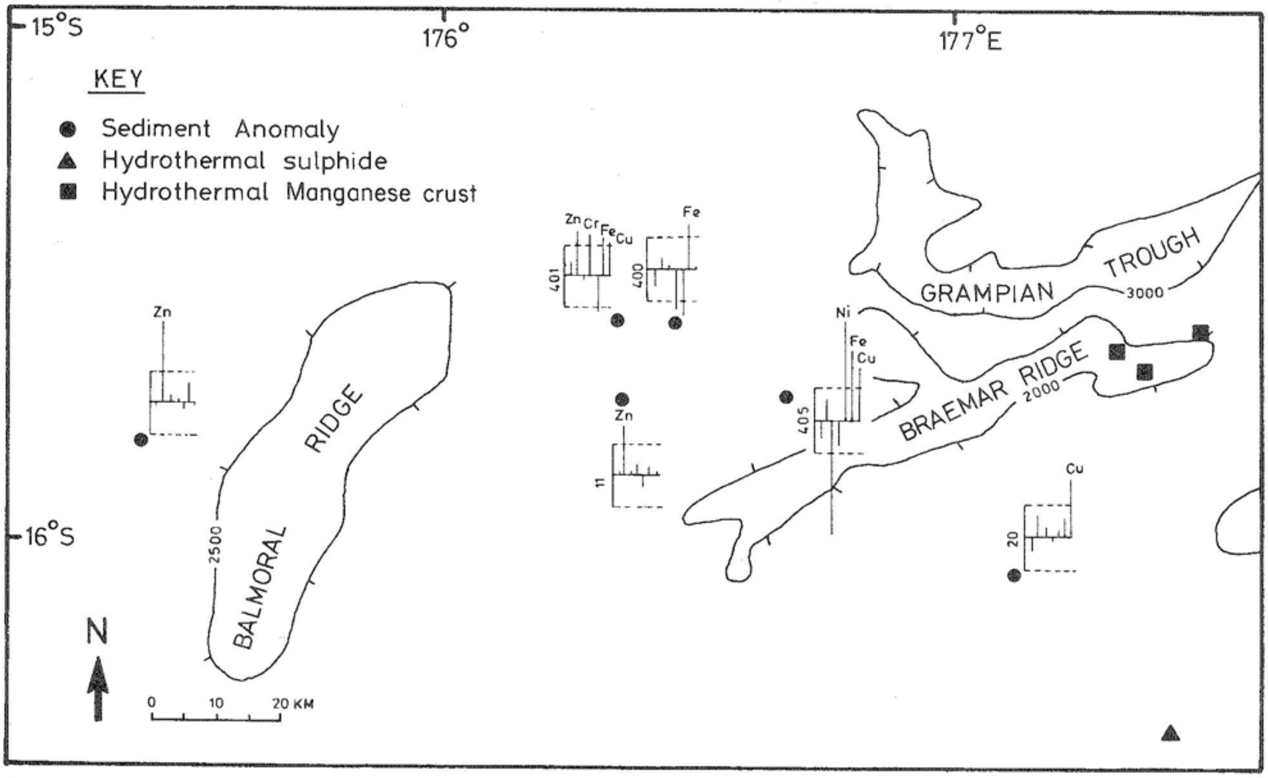

Figure 7. Hydrothermal deposits and sediment geochemical anomalies possibly indicative of hydrothermal activity in the central North Fiji Basin (modified from Coward and Cronan 1985)

Lau Basin

The Lau Basin separates the Tonga Ridge from the Lau Ridge (Fig.1) and is an active back-arc basin. According to Volpe *et al.* (1986) and Malahoff *et al.* (in press), oceanic crust in the Lau Basin has been formed by spreading of short ridge segments and at numerous seamounts over the last 3 million years. Based on GLORIA sonar surveys, the basin contains propagating rifts, abandoned rifts, and jumped spreading centres (Parson *et al.* unpub. Cruise Report 1988). All these are potential sites for hydrothermal deposits.

Figure 4 illustrates the interpretative compilation of the available magnetic data for the Lau Basin by Malahoff *et al.* (in press). This figure illustrates the location of spreading centres where hydrothermal mineral deposits might be expected. According to Malahoff *et al.* (ibid) the northern Lau Basin is characterised by a patchwork setting of northeast and northwest-striking magnetic anomalies that probably reflect intermittently active crustal segments alternately rifting northeast and northwest. Peggy Ridge (177°30'W, 16°00'S) is seismically active and is thought by Malahoff *et al.* (ibid) to be changing from a transform fault to a spreading centre. They consider a R-R-R triple junction located at 175°40'W, 17°30'S to mark the beginning of a relatively steady state back-arc spreading regime.

The possibility of hydrothermal deposits occurring in the Lau Basin was reviewed by Cronan (1983). On the basis of manganese anomalies in surface sediments, it was suggested that hydrothermal metalliferous sedimentation was taking place in the central Lau Basin in the vicinity of the proposed spreading centre. However, manganese anomalies in sediments were also identified in areas where the tectonics were little understood, and it was suggested that there may be a complex pattern of hydrothermal activity within the basin, associated with both spreading and non-spreading centres.

Hydrothermal deposits have been reported from a number of places in the Lau Basin. The first was a barite-opal deposit from the Peggy Ridge described by Bertine and Keen (1975). Subsequently, many more hydrothermal deposits were obtained during the SO-35 cruise (von Stackelberg *et al.*, 1985). This work identified two regions in the Lau Basin where there is evidence of hydrothermal activity. The first is in the northern Lau Basin near 18°30'S where a NNE-SSW trending spreading centre segment was identified. This area is close to that intensively sampled by Cronan *et al.* (1984) for metalliferous sediments (see below). Underwater photography indicated the presence of manganese encrustations together with what appeared to be hydrothermal nontronite. The second area was farther south near 22°S, and includes the Valu Fa Ridge (Fig. 4). Porous hydrothermal nontronite was recovered from this region, together with manganese crusts. Rocks dredged from the area contained impregnations of pyrite associated with barite and limonite. Hydrothermal deposits were also recovered to the east of the active spreading zone. Sulfide mineral impregnations of rocks together with manganese crusts and nontronite were recovered, as were manganese crusts to the west of the spreading centre.

Subsequent work in the Lau Basin by von Stackelberg *et al.* (1988) (Sonne 48 cruise in 1987 that followed up the Sonne 35 cruise) located many more hydrothermal deposits on the northern Lau Basin spreading ridge and in the Valu Fa Ridge area (Fig. 4). During a photo/TV survey on the northern Lau Basin spreading ridge, von Stackelberg *et al.* (1988) repeatedly observed ochre colored nontronite and, in one instance, an old sulfide chimney. A T.V. grab showed associated light colored hydrothermal sediments with benthic organisms and white Galathea crabs.

An additional occurrence of hydrothermal sulfides has been recorded in the northern Lau Basin by Hawkins and Helu (1986). Fragments of a dead "black-smoker" hydrothermal vent chimney were recovered from 15°23'S, 174°41'W. The fragments consist of concentric layers of sphalerite, pyrite and chalcopyrite, with sphalerite as the main mineral. The chimneys have been impregnated with barite. This dead chimney is located in the axial region of a spreading ridge at 2100m depth. Associated rocks are andesitic to basaltic andesite in composition, similar to those on the Valu Fa Ridge. Hawkins and Helu (1986) suggest the deposit may be located in a propagating rift zone. However, subsequent work in the vicinity of this deposit during the Sonne 48 cruise failed to find further examples of sulfides, suggesting that it is fairly localised in extent.

As in the case of the North Fiji Basin, there are indications in the Lau Basin from sediment geochemistry that the hydrothermal activity is not just restricted to the vicinity of the spreading centres. Cronan *et al.* (1984) found an enrichment of authigenic iron oxides in sediments throughout much of the central Lau Basin, and Cronan *et al.* (1986) reported elevated non-detrital metal accumulation rates in sediments both adjacent to and away from the spreading centre near 18°30'S, suggesting some localised hydrothermal contributions of metals to the sediments. Non-detrital Fe and Mn accumulation rates were similar to those on the East Pacific Rise. Walter *et al.* (in press) have found on the basis of geochemical analysis of SO-35 sediments that the highest hydrothermal component (as high as 35% on a carbonate free basis in the surface sediment) is on the southern part of the Valu Fa Ridge. However, factor analysis of geochemical data on sediments from throughout the Lau Basin by Walter *et al.* (in press) revealed other areas unrelated to known active tectonic features that contain a hydrothermal component in the sediments, further implying off-axis hydrothermal activity in the Lau Basin. Some of these components though may simply represent residual precipitates from the spreading centre plumes which become progressively less diluted by volcaniclastic sediments derived from the Tonga Ridge with increasing distance westward across the Lau Basin. Metals in Lau Basin sediments must be studied on a volcaniclastic component-free basis in order to gain an understanding of hydrothermal contributions of metals to the sediments there.

Ridge regression analysis of geochemical data on sediments from the Lau Basin by Coward and Cronan (1985) has demonstrated three zinc anomalies. Two of these are very close to the proposed spreading centre in the Central Lau Basin north of the Valu Fa Ridge and are probably hydrothermal in origin. The other is approximately 50 km to the west of the spreading axis. The latter may be a hydrothermal anomaly related to off-axis activity.

Havre Trough - Bay of Plenty

The tectonic evolution of the Havre Tough (Fig. 1) has been outlined by Malahoff *et al.* (in press) who thought of it as a young active inter-arc basin. Thus hydrothermal mineral formation might be expected in it. However, to date, no firm evidence of hydrothermal mineral deposition has been observed there.

A number of sediment samples from the Havre Trough were described by Cronan *et al.* (1984) and Hodkinson *et al.* (1986), none of which showed any obvious evidence of hydrothermal contributions. Furthermore, hydrothermal gas exploration during the Papatua Expedition recorded in the Havre Trough some of the lowest methane values in the southwest Pacific (Craig and Poreda 1987), again providing no indication of hydrothermal activity.

It is difficult to explain why hydrothermal deposits have not been found in what is considered by Malahoff *et al.* (in press) to be a young active marginal basin. According to them, the geophysical data indicate a half spreading rate of 2.7 cm/yr for the Havre Trough which, while admittedly less than the 3.8 cm/yr half spreading rate calculated for the Lau Basin, is still significant. A second possible explanation for the apparent lack of hydrothermal deposits is that the age of the Havre Trough which is younger than the Lau Basin (2 m.y. as opposed to 3.5 m.y), has resulted in insufficient time being available for significant hydrothermal deposits to accumulate there. As mentioned earlier in regard to the North Fiji Basin, McMurtry *et al.* (in press) have suggested that a lack of hydrothermal deposits associated with the northern extension of the North Fiji Basin spreading centre might be due to its relative youth. Likewise, hydrothermal circulation in the Havre Trough may not have been active for long enough to build up a measurable record of hydrothermal deposition in the sediments. A third possibility is that the hydrothermal deposits might actually be present but of limited areal extent. The relatively dissected nature of the Havre Trough (cf. Craig and Poreda 1987) could help in ponding of hydrothermal precipitates, and these could be buried rapidly by volcaniclastic detritus from the nearby Kermadec Ridge.

The only positive evidence, albeit slight, for hydrothermal sedimentation in the Havre Trough is based on two sediment samples which have been found to exhibit isolated Zn anomalies (Coward 1986 Fig. 8). No magnetic fraction was present in these samples, so they were poor in iron content. The sediments are pelagic carbonates containing small amounts of volcaniclastic material. That the Zn anomalies in these samples are not hydrogenous in origin is indicated by their low Mn and Fe contents and the absence of unusual concentrations of hydrogenous elements such as Ni. Coward (1986) considered a detrital volcaniclastic origin for the Zn anomalies unlikely, as a large part of the Zn in volcanic detritus on the Kermadec Ridge is present in Zn-rich magnetite, and the two samples in

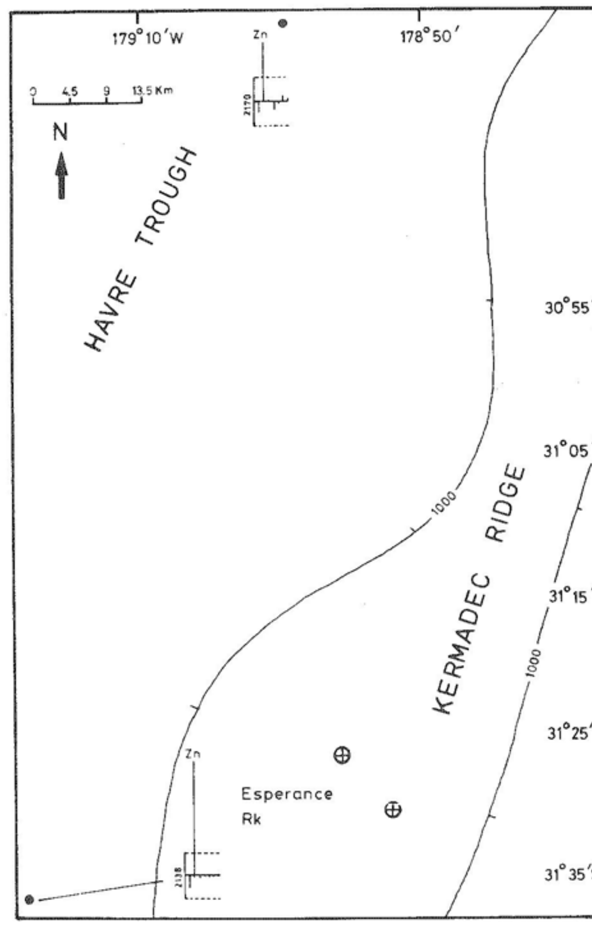

Figure 8. Zinc anomalies in sediments from near the Havre Trough (from Coward 1986)

question do not have a magnetic fraction nor do they show any iron anomalies. By analogy with Zn anomalies elsewhere in the southwest Pacific where hydrothermal activity is known to occur, these anomalies could possibly be hydrothermal in origin.

The Bay of Plenty just to the N.E. of New Zealand has long been known to host volcanic activity. White Island, an active volcano, is a good case in point, and submarine gas discharge has been observed in the Bay by Pantin (personal communication 1985). However, no major hydrothermal deposits have been found in the Bay.

On the basis of ridge regression analysis of sediment geochemical data, Coward and Cronan (1987) showed a number of manganese anomalies in sediments near New Zealand (Fig. 9) which would not have been recognised on the basis of simple univariate statistics. Partition analysis showed most of the Mn to be present in the hydroxylamine HCl soluble fraction, with a large part of the remainder of the Mn being soluble in acetic acid. This is in accord with the anomalous Mn being in the oxide form, the form in which both hydrogenous and hydrothermal Mn deposits occur. However, associated Ni partitions into the HCl soluble and insoluble fractions, suggesting that it, and thus by association the Mn, is not hydrogenous. Therefore the latter must be hydrothermal in origin. The Mn anomalies occur in a recently reported area of crustal extension (Malahoff, personal communication 1988) and where a recent GLORIA sonar survey has indicated the presence of a marked rift (unpublished 1988). This would support the Mn anomalies being hydrothermal in origin and suggests that other hydrothermal deposits might occur in their vicinity.

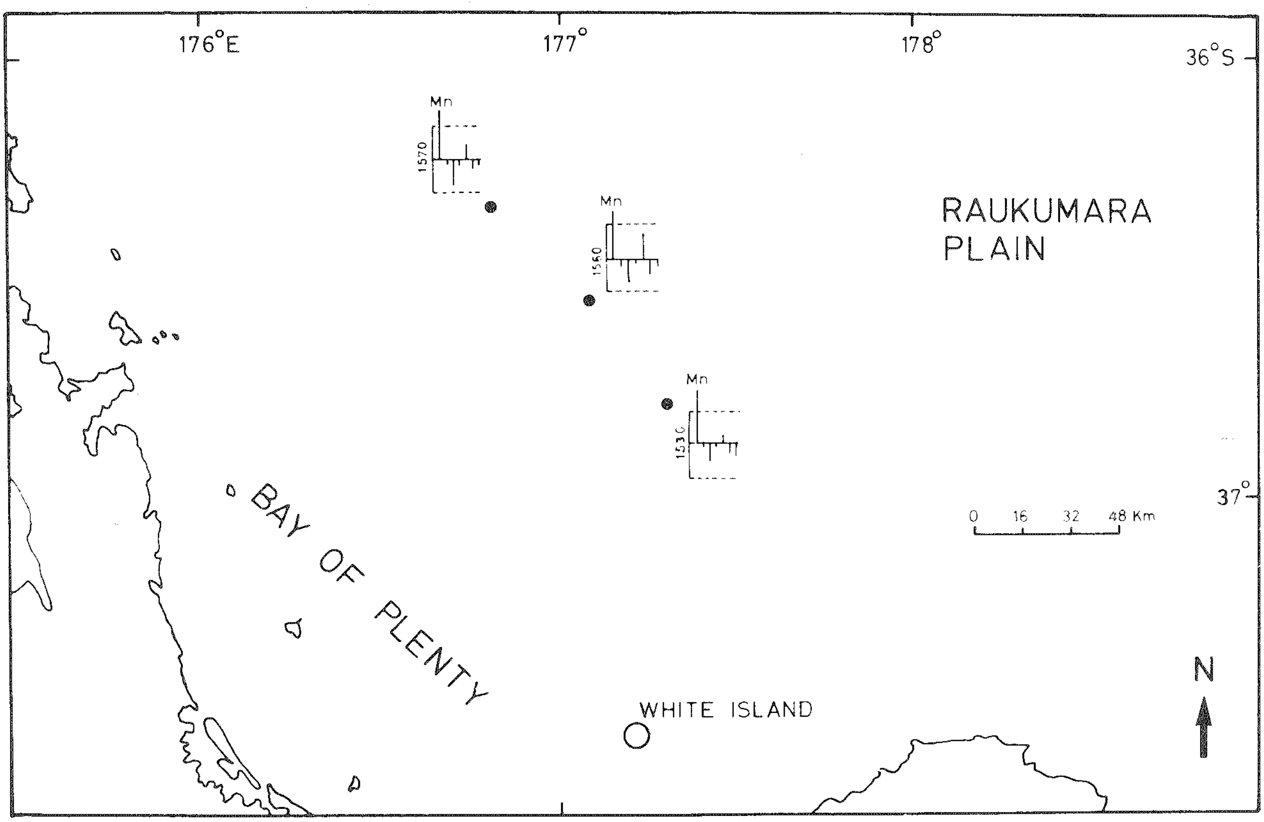

Figure 9. Manganese anomalies in sediments from the Raukamara Plain (from Coward and Cronan 1987)

5. VOLCANIC ARCS

Vanuatu

The New Hebrides (Vanuatu) Arc is a roughly NNW-SSE aligned series of troughs, submarine ridges and active volcanoes lying to the west of the North Fiji Basin. Cronan (1983) pointed to the submarine volcanoes and the troughs as possible sites of submarine hydrothermal activity. This has been confirmed on the volcanoes (see below) but evidence for it in the troughs is still limited.

Among the submarine volcanoes that have exhibited most evidence of submarine hydrothermal activity in the Vanuatu region are those off Epi Island (Cronan 1983, Exon and Cronan 1983, Greene and Exon 1988, Crawford *et al.* 1988).

The Epi-Tongoa area lies within the Pliocene to recent belt of volcanic activity in Vanuatu and contains four intermittently active submarine volcanoes, Epia, Epib, Epic and Karua (Crawford *et al.* 1988). According to

Greene and Exon (1988), Epia, Epib and Epic lie off the shore of Epi and are aligned along a generally east-west trending arc. The craters of these volcanoes are equidistant, approximately 3.5 km apart, and are thought to represent remnants of a breached caldera. In addition, Crawford *et al.* (1988) have described four other submarine calderas between Epi and Efate Island, all of which may have a potential for hydrothermal activity.

Of the three Epi volcanoes, Epib is the largest (Greene and Exon 1988). It was active in 1984, when plumes of fluid and gas were venting near the northern crater wall. Similar plumes were recorded during the 1984 ***S.P. Lee*** Tripartite Cruise. Thus Epib has a high potential for hosting submarine hydrothermal mineral deposts. Similar craters on Tyrrhenian Sea volcanoes have yielded sulfide minerals (Minniti and Bonavia 1984).

Geochemical studies on Epi sediments by Cronan (1983), Exon and Cronan (1983) and Coward and Cronan (in Greene and Exon 1988), have provided direct evidence of submarine hydrothermal mineralisation off Epi. Ferruginous sediments containing more than 20% Fe and enriched in several other elements of hydrothermal origin occur at shallow depth near the volcanic cones in the Epi caldera. While these deposits have no economic value, they point to the possible presence of higher grade, more valuable deposits in their vicinity.

Tonga-Kermadec Ridge

The Tonga-Kermadec Ridge is volcanically active. It has been little explored for hydrothermal deposits, but has yielded hydrothermal manganese oxide crusts (Cronan *et al.* 1982, 1984, Moorby *et al.* 1984, Hein *et al.* 1987)

Manganese oxide crusts have been recovered from several localities on the Tonga-Kermadec Ridge system. Samples have been described in detail by Cronan *et al.* (1982) and Moorby *et al.* (1984). Briefly they consist of layered to massive manganese oxide composed largely of birnessite but with subsidiary todorokite. Compositionally, the deposits are very rich in manganese, as high as 50% concentration, and low in most other metals. Hydrothermal enrichments other than Mn also occur in them (Moorby *et al.* 1984). Their hydrothermal nature is manifested by their high average growth rates averaging more than 50cm/million years, although some layers of the crusts do show hydrogenous affinities.

Unlike the manganese crusts found in southwest Pacific back-arc basins that are generally associated with sulfides or nontronite and surrounded by manganese or iron enriched sediments, the Tonga-Kermadec Ridge crusts appear not to be associated with other hydrothermal deposits. No sulfides or nontronite have been found in their vicinity, and their associated sediments are normal pelagic oozes. Metalliferous sediments of the type found elsewhere in the southwest Pacific appear to be absent here. Hein *et al.* (1987) have also described hydrothermal ferromanganese oxide crusts from the Tonga Ridge, in places sometimes associated with iron oxides but seemingly not with other hydrothermal deposits.

6. COMPARISONS BETWEEN BACK-ARC AND VOLCANIC ARC DEPOSITS

It is difficult to make firm comparisons between back-arc and volcanic arc hydrothermal deposits in the southwest Pacific because the amount of geochemical data available on the sediments is so limited. However, certain general features are apparent.

In the back-arc basins the complete range of hydrothermal deposits occurs, as found, for example, on the East Pacific Rise; sulfides. silicates (nontronite) and iron and manganese oxides. Further, these deposits are often associated with areas of metalliferous sediments, just as on the East Pacific Rise. By contrast, hydrothermal deposits on the arcs in the southwest Pacific seem to be confined to iron or manganese oxides, and there does not appear to be an associated zone of metalliferous sediments. Of course, the apparent lack of sulfides and silicates on the arcs could be an artifact of the limited sampling of these features in the southwest Pacific to date. Sulfides have been found within the crater of the Palinuro volcano in the Tyrrhenian Sea (Minniti and Bonavia 1984). However, Hein *et al.* (1987) reported on 66 successful dredges in the Mariana Islands arc, 40 of which contained ferromanganese oxide deposits but none of which were reported to be associated with sulfides or hydrothermal nontronite. Thus the contrast in hydrothermal deposit types between the back-arc basins and the arcs in the southwest Pacific reported here appears to have some general validity.

It is perhaps premature to speculate on the reasons for the apparent differences between hydrothermal deposits from back-arc basins and volcanic arcs in the southwest Pacific, as many more data on this subject will become available once submersible activities start there. However, there are at least two possible explanations. Either (i) the hydrothermal solutions on the arcs were extensively cooled sub-surface resulting in sulfide and silicate precipitation below the sea floor and leaving only lower temperature Mn-rich solutions to debouch onto the sea floor without the formation of a significant hydrothermal plume, or (ii) only low temperature leaching of volcanic rocks took place on the arcs, resulting only in the mobilisation of manganese. The observation of sulfides within craters of volcanoes in the Tyrrhenian Sea would support the former alternative, and suggests that such deposits might also occur below the sea floor or close to vents in craters on the southwest Pacific arcs. The apparent lack of associated metalliferous sediments in such cases could be due to the residual hydrothermal solutions having to pass through volcaniclastic sediments en-route to seawater on the arcs, during which much of their metals would be stripped out. By contrast, back-arc basin hydrothermal centres are often sediment free, leading to a wide dispersal of the hydrothermal precipitates, and thus widespread metalliferous sediment formation.

7. CONCLUSIONS

It is evident from the examples described in this work that most occurrences of hydrothermal metalliferous sediments and associated deposits in the southwest Pacific are associated with back-arc basin spreading centres. This is entirely in accord with what would be expected on the basis of the much better studied mid-ocean ridge settings such as the East Pacific Rise. Additional occurrences are found associated with the volcanic arcs but these are of minor importance relative to the back-arc basin varieties. However, this latter conclusion could simply reflect the limited amount of work done on volcanic arcs in the southwest Pacific relative to back-arc basins, and could change as more data become available. What is certain is that with the advent of submersible studies in the southwest Pacific in 1989, we are entering a new age of detailed studies of hydrothermal deposits there. The broad distribution of such deposits has been defined using conventional shipboard techniques and laboratory analysis, as described in this work. Submersibles will now refine our understanding of the nature and distribution of the deposits, just as they have done on the East Pacific Rise.

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CHAPTER 4

STATE OF THE ART

Fedorov, K.N. 1989. Physical Oceanography - Where do we Stand? p. 167-172. In: A. Ayala-Castañares, W. Wooster and A. Yáñez-Arancibia, eds. *Oceanography 1988*. UNAM Press, México D F, 208 p.

Physical Oceanography - Where do we Stand?

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About a week before the beginning of this Assembly, several American, Soviet, English and French physical oceanographers were united at a friendly dinner in Moscow. The evening was full of memories. All present had attended the Second International Oceanographic Congress in Moscow some 22 years ago. Only two were in Halifax for the 1982 JOA. None, except myself, was going to Acapulco. This gave me a feeling of regret, and somehow set the tone of my critical review lecture today. Have they, and many others also regrettably absent, missed something scientifically very important for their continuing research work? Did we feel their absence? It is in this spirit I approach today my extremely difficult task.

As one might have expected, scientific developments in our field over the past 6 years have in several ways completely overtaken the boldest predictions made in Halifax. Among these developments were some global natural phenomena such as El Niño 1982-83 with its tremendous impact on large-scale ocean-atmosphere interaction studies and on tropical oceanography. There was also an upsurge of interest in global environmental and ecological problems stimulated by the World Climate Research Program and the concepts of global change. Related to these factors, a number of global projects involving physical oceanography have come into existence, so that we now have a host of new acronyms, such as TOGA (Tropical Ocean Global Atmosphere), WOCE (World Ocean Circulation Experiment), JGOFS (Joint Global Ocean Flux Studies), and IGBP (International Geosphere Biosphere Program).

There was important progress in the field of remote sensing of the ocean from satellites, and here I wish particularly to refer to data analysis of the Coastal Zone Color Scanner of NIMBUS-7, the side-scanning radar returns of the Soviet "KOSMOS-1500" series, the ARGOS System, infrared data on sea surface temperature of the Advanced Very High Resolution Radiometer from the NOAA series and METEOSAT-2, and recent advances with GEOSAT altimetric data. Ocean modeling on all scales and for many purposes (global scale, basin scale, process-oriented, paleoceanographic, diagnostic, and prognostic) became unquestionably an extremely important and mature tool of research related to the progress in computers. We also saw the increasing importance of tracer studies and laboratory experiments for the most challenging pursuits in physical oceanography.

Coastal and sea surface phenomena, oceanic fronts and eddies, attracted a good deal of our attention during these years. In particular, the behaviour of isolated or solitary vortices has recently become a center of attention of both theoreticians and experimentalists. Double-diffusive processes and mechanisms of thermocline ventilation have also been the subjects of recent successful research.

Of no less importance were some recent meetings. I shall name only four:

1. The Symposium on Hydrodynamics of Stratified Flows, in Pasadena, USA, April 1987;

2. The 19th International Liege Colloquium on the subject of "Small-scale turbulence and mixing in the ocean", May 1987;

3. The IUGG/IAPSO Assembly, Vancouver, August 1987.

4. The 20th International Liege Colloquium on the subject "Synoptic and mesoscale coherent motions in the ocean." May 1988.

These were developments and events which set the stage for the JOA-1988 physical oceanography presentations. To what extent did the content of these presentations reflect the progress made since Halifax in understanding the physics of the ocean ?

El Niño, or rather a revitalized concept including the so-called Southern Oscillation, now known as ENSO, was indeed prominent in SCOR discussions at this JOA. J. O'Brien put his view on the state of our knowledge of ENSO this way "We may consider it firmly established that the beginning of the warm part of the ENSO cycle has its roots in the ocean." Perhaps other scientists have different views on this point. One can only regret that this statement was made at the SCOR General Meeting with its limited attendance, and there was no other meeting in the Assembly where there was a healthy argument over this point. Such a discussion would put into an important physical context the valuable findings reported earlier by such authors as M. England (Australia), S. Reyes (Mexico), H.Von Storch (FRG), U.Luksch (FRG), and N.E. Graham and W.B.White (USA) .

It is my view that global problems and projects were not reflected by the JOA program in their proper proportions in spite of the excellent presentations by J.McCarthy on IGBP and by H. de Baar and Dutch colleagues on JGOFS. R.W.Stewart (Canada) has greatly strengthened this aspect of JOA by his talks on possible global sea-level changes due to the "greenhouse" effect. He managed to demonstrate that in parallel with the results of a rather sophisticated ocean-scale modeling as had been shown by E. Meier-Reimer and K.Hasselmann (FRG), simple order-of-magnitude estimates made on realistic physical assumptions may give interesting geophysical results stimulating for further studies.

One would have expected here more discussion on WOCE concepts. It would be appropriate to remind the audience that the concept of repeatedly sampled standard oceanic transects (or "sections") now adopted by WOCE had in the past been twice rejected by the international oceanographic community on the grounds of impossibility of achieving the desired sampling frequency and spatial coverage. The first rejection occurred in the 1960s following the proposal of V.G.Kort (USSR) to the Intergovernmental Oceanographic Commission (IOC). The same fate befell the proposal by Acad. G.Marchuk made in the 1970s to the Committee on Climate Change and the Ocean (CCCO). It seems to me that the reasoning of WOCE scientists which made them reconsider and adopt the earlier twice rejected concept should be more widely known.

I also thought we would have here more discussions on TOGA - the project which, using an expression of R.W.Stewart, is "going full blast." An invited lecture on TOGA would have been particularly welcome here. Quoting again from Stewart's statement at the SCOR General Meeting "TOGA has changed the face of oceanography. We now have real-time data, we use predictive models, and we really forecast events which did not yet happen." No more hindcasting! To this statement, D.Halpern (USA) would gladly subscribe, judging from his excellent paper presented at the S10 symposium.

Modeling, and in particular numerical modeling, was prominent in many presentations. It is no more just a means to demonstrate capabilities of the hydrodynamic theory, but has become a real research tool in the hands of those who use it. Perhaps between one fourth and one fifth of all physical oceanography papers of this JOA contained and discussed important scientific results obtained with the aid of models of various kinds.

Yet laboratory modelling was represented by only one paper, that by H.J.S.Fernando (USA), and even this was a poster. Does this mean that numerical modeling will soon completely replace laboratory modeling? I personally don't think so. There is a good deal to say on the merits of laboratory experiments, in particular with rotating models. But this is exactly one point where at this JOA we miss contributions from a number of serious scientists.

Turning to recent advances in using satellite data in physical oceanography, I should first of all mention the opening general lecture of this Assembly, that of R.Cheney (USA) and co-authors on the monitoring of sea level from space. This was a remarkable presentation, well supplemented by EOS copies distributed by the American Geophysical Union. One of Cheney's slides illustrates an interesting systematic difference in sea level heights given by the GEOSAT altimeter and by a numerical model. The amplitude of the model data seems always to be smaller than that of the altimeter. This is so because the altimeter data usually contain the sum of more components than just the dominant geostrophic one represented by the model. This points to the difficult problem of appropriate filtering of altimeter data before they can be assimilated in ocean circulation models.

M. Taillade (France) should also be complimented for his lucid presentation of the ARGOS capabilities, present and future. It is worth noticing that satellite data analysis was used in many papers presented here on a very "matter of fact" basis. This, to me, is an extremely healthy sign. The "golden era" of a non-existing science of "satellite oceanography" is definitely over and instead we have already started to use satellite instrumentation like any other research tool in full knowledge of its advantages and shortcomings.

One interesting outcome of the increased use of satellite data, however, did not find its way to this Assembly. A number of new surfacw water dynamic phenomena have recently been discovered thanks to the satellite images of the ocean in various spectral bands. I should like to mention here briefly only two of these phenomena, vortex dipoles and transversal jets or filaments (also known as "squirts") in coastal upwelling areas and marginal ice zones. These new (i.e., previously unknown) forms of non-stationary localized motion received a good deal of publicity and attention at the 20th Liege Colloquium on coherent ocean motions in May. Papers on their dynamics have just started to appear, their laboratory modeling is in progress, and their role in the upper ocean dynamics may be of considerable importance. In particular, the vortex dipoles may be the primary sink for kinetic energy of non-stationary, impulse-like localized atmospheric forcing or kinetic energy of frontal instabilities. As such, they should be of universal or ubiquitous nature. We do not see them more often because of the lack of a label provided usually by a passive tracer (e.g., ice, plankton, suspended material or SST).

I spotted something like a vortex-dipole on a satellite image of the Mexican Gulf which was demonstrated by V.Vidal (Mexico) during his talk, and this to me is just one more proof of a now frequently observed decoupling (in both time and space scales) of the near surface layer dynamics from the general circulation dynamics as it is represented by the traditional dynamic topography.

Coming now to the new and important topics of research mentioned in the introduction, I should like to express here my disappointment (and it may be a personal one) at the evident lack of presentations on most of them:

Double-diffusive processes: only 2 communications, by J. Ochoa (Mexico) and H.J.S. Fernando (USA) plus some mention of these processes in V.T. Paka's (USSR) poster.

Intrathermocline eddies: thanks to V. M. Kamenkovich (USSR) and W. Zenk (FRG) these peculiar eddies have not been forgotten, but no studies specifically on them were reported.

Dynamics of isolated or solitary vortices: the subject was not considered except for a brief mention in Kamenkovich's excellent review lecture on synoptic processes.

Synoptic (mesoscale) variability: one review lecture and two papers, one by A. D. Kirwan *et al.* (USA) and another by V. Vidal (Mexico), are definitely not enough for this challenging topic.

Oceanic fronts: only 3 papers were listed; W. Zenk (FRG), J. Launiainen (Finland); E.Wolanski (Australia). [*last not present*]

Coastal upwelling filaments: no papers at all, but fortunately we heard some reference to these in a most interesting paper by G. Cresswell (Australia) on the Leeuwin Current offshoots, which may be not so casual an analogy, and so I will return to this later.

Marginal ice zones: no papers at all.

Thermocline and deep ocean ventilation: no papers presented, but the importance of the subject was stressed in the film on the ***Snellius-II*** Expedition.

It appears from these examples that this JOA scientific program in physical oceanography did not adequately represent the overall world effort. Neither was attendance of this JOA by scientists particularly representative. Too many could not come, perhaps being preoccupied by the new global projects or having been quite sufficiently informed on the progress in their fields of interest at the other excellent meetings of 1987-1988 already mentioned. As a result, one has an impression of witnessing here a kind of happy return to the familiar topics of good descriptive physical oceanography of the early 1960's. Is this good or bad?

It is difficult to answer this question in any clear cut sense: "yes" or "no." It is, probably, both. In compensation to what we have evidently missed here, we have heard at this JOA the results of many very specific regional studies, e.g., in coastal oceanography - the subjects which inevitably escape attention of the newly devoted globalists. Findings on coastal oceanography are definitely refreshing for those who, like myself, have been too much involved over the past years with problems of the open ocean. But there is also a serious drawback in that those younger scientists who are now at the very start of developing programs in ocean physics in their countries (and they are numerous here) may draw from this particular JOA a misconception of the current study of the whole field. It is they who feel most the absence in the JOA meeting rooms of those whose names they know so far only from the literature. And this reflection on the present composition of the JOA brings me to another important point.

Science as we know it has no national boundaries. However, some reflections on the geographical or national distribution of papers presented here may be of interest. In 1982 in Halifax, ocean physics was largely dominated by North American authors, which was natural taking into account the geographical location of the Assembly. This time we have an excellent representation of Mexican oceanographic research. But I would argue that this is not only because of the geography. I happened to visit Mexico 20 years ago. We could not then have had the same kind of JOA since Mexican physical oceanography was practically non-existent. The situation is totally different today.

It is also gratifying to see the significance and wide variety of presentations of scientists from India. That country is geographically separated from Acapulco by an enormous distance, so it is not solely geography that matters.

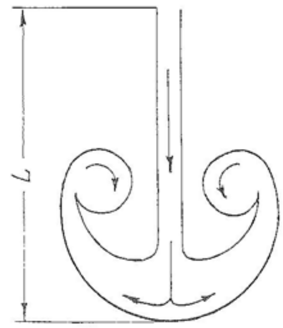
In fact this is an Assembly which is particularly representative of the efforts of those nations which yesterday were called "the developing countries". There is one common denominator in all the papers which came from these nations, namely that they demonstrate their present day skill in obtaining and using modern physical oceanographic instruments and knowledge to serve (often on an operational basis) some very practical tasks and activities, e.g., related, for example, to their offshore drilling for oil, or to their fisheries.

I think, in this sense, the Acapulco JOA has given a rightful recognition to the fruitfulness of continuous efforts by SCOR, Unesco, and IOC to promote the development of marine science, including physical oceanography in coastal countries of the Third World.

If asked which symposia, lectures, or talks should be singled out as particularly interesting and scientifically important, I could only express a purely personal view. I should first of all name in this context the S6 Symposium on Small Scale Processes in the Surface Layer, jointly chaired by I. Jones (Australia) and Y. Toba (Japan) and also the G3 Symposium on Hydrothermal Processes convened by E. Suess (USA). The first could, of course, have been much more complete in terms of the topics of the sea surface and near-surface layer covered by the eight presentations. The second was excellent but did not lead to a seemingly natural companion discussion on the extremely interesting physical conditions in stratified ocean waters surrounding hydrothermal vent areas. Boundary processes there should be of great interest both as a complex physical phenomenon and as a means of remote detection of vents, e.g., from towed submersibles. However, questions relating to these boundary processes have not even been formulated here, except for one anonymous poster with references to Stewart Turner's research.

Separately, one should mention S11 Symposium on Sea Level, all the papers of which were of excellent quality. Among lectures, I would single out those by R. Cheney and V. Kamenkovich as two very different but thorough presentations in many ways related to future promises of the WOCE project. And I don't think I should dwell upon the question as to what precisely this relation is.

Among shorter talks, my preference leads me to select, on purely subjective grounds, of course, the presentations by V. Vidal (Mexico), J. Nihoul (Belgium) and G. Cresswell (Australia). The last, on the Leeuwin Current offshoots, calls for some careful theoretical thought. You remember, of course, what was said about the salinity of this warm current: near the west coast of Australia, its salinity is lower than that of the ambient water outside and below the coastal current. Then, after turning east, the current enters less saline waters and its own salinity progressively becomes relatively higher than the ambient one. This means that the transverse baroclinic density gradient diminishes along the course of the current and at some point should no longer be in balance with the sea level slope normal to the coast line as should have been the case for a quasi-geostrophic frontal jet. Would this not be exactly the point where an offshoot starts developing driven by the unbalanced pressure gradient due to the sea level slope? This seems to me a plausible hypothesis, given the rather great inertia of large scale sea-level variations demonstrated by K. Wyrtki (USA) in his talk today. If so, this may be the common mechanism for the formation of the transversal jets, filaments or "squirts" also in the coastal upwelling zones and the marginal ice zones where fronts are usually highly thermoclinic, i.e., have considerable thermal and salinity gradients along isopycnal surfaces. I hope this question will be answered before the next JOA.



But when will this new JOA occur? And where? The answer, it seems to me, depends today very much on our ability to redefine the goals of such large-scale meetings. With the improved communications (telex, fax, telemail) and frequent meetings on narrower subjects, the necessity for such JOA's would seem definitely to have diminished. However, from the experience of this JOA in Acapulco, I see one particular requirement to stand out very sharply. This is a need to have from time to time a synthesis of all the particular small advances in each specific field made over a certain period of time. Perhaps, if suitable topics for such syntheses are carefully selected, if the best authorities to prepare such syntheses are found and are available, and if animated discussions are organized around these inspiring topical review lectures, then we may have a chance to run a new successful JOA within a foreseeable span of time. If not, other activities, and in particular global projects, will make JOA uninteresting or redundant. It is up to us to decide whether we wish this to happen or not.

Stromberg, J.-O. 1989. State of the Art: Biological Oceanography, p. 173-176. In: A. Ayala-Castañares, W. Wooster and A. Yáñez-Arancibia, eds. *Oceanography 1988*. UNAM Press, México D F, 208 p.

State of the Art : Biological Oceanography

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Biological oceanography encompasses a wide variety of topics. Some may be purely biological, e.g. life history studies, studies of abundance and distribution of particular organisms, reproductive potential, etc., but in most cases there is a need to look into adjacent disciplinary fields, e.g. those related to physics, chemistry or geology. This need is becoming more and more evident, and to my mind is well reflected in the contributions to this Assembly, in both the oral and poster presentations.

In the three general sessions, eight out of fourteen talks had a more or less strong bearing on biological features and problems. The special symposia showed a strong biological input in most of the sessions and, even excluding the pollution and fishery resources sessions (S4, S9 and S12), more than half of the contributions, or about 60 percent, addressed biological scientific aspects as part of more general problems.

Among the IABO (International Association for Biological Oceanography) sessions, talks and posters, only about ten dealt with problems where non-biological disciplines were not included, while the remaining 55 contributions in one way or another involved physical oceanography, marine chemistry or marine geology.

There is a common tendency to believe that this interdisciplinary dependence is unilateral rather than mutual, and it might be true that the biologist is more dependent on relations with adjoining marine scientific fields than the reverse. However, in examples brought out at this JOA like understanding paleoceanographic situations by using radiolarians or foraminiferans as indicators of certain temperature regimes, the role of bioturbation and biological activity in sediments to understand sedimentation and geochemical processes, the role of organisms in relation to the chemistry at hydrothermal vents or cold seeps, and the role of ice floras for the melting of sea ice and physical processes involved in this, biology can be seen as contributing significantly to other fields of study.

It was disappointing that so many of the announced contributions were never presented. In the IABO sessions, 11 oral presentations were not given and about 70 posters (of 104) did not turn up. There may be many reasons for this -- lack of time, other meetings, funding problems, etc --but it is nevertheless regrettable.

On the positive side, however, is the large attendance from developing countries in this Assembly. I am particularly impressed with the efforts in Mexico where there is a strong movement not only to observe and record biological phenomena and features but also to understand them in a marine ecological or broader context. The special symposium on oceanography in Mexico and the poster session in particular brought this out clearly.

The contributions, mainly dealing with coastal or shelf waters, ranged from energy sources for heterotrophs, factors influencing phytoplankton production in various areas, zooplankton grazing, population dynamics of fish (mainly pelagic) to studies of particular animal groups, like bivalves, gastropods, ostracods and sponges.

All the work is essential to improve knowledge of the coastal ecosystems and, although rather traditional in its scope, its importance must not be underestimated. Modern ideas and techniques are also being used as exemplified in co-operative studies, largely with U.S. scientists, of primary production in the Gulf of California with remote sensing techniques and studies of the vent faunas and nearby sediments in the same Gulf by means of submersibles (***Alvin***).

Now what turned you on when it came to biological oceanography during this JOA? Maybe it was:

- new techniques that will open up possibilities for future research (sediment cameras, remote sensing, helicopter carried CTD's), or

- progress in modelling various parts of the marine ecosystems or even whole ecosystems, or

- progress in research in special geographical areas, like the hydrothermal vents, cold seeps, the deep sea, the Arctic or Antarctic seas, or

- our improved understanding of fluxes and rates of processes, or

- the explanation of why the green alga *Codmium* can fix molecular nitrogen via cyanobacteria.

Perhaps you were not turned on at all, finding that there were few novel findings and that most of the presentations were not very exciting even though they added to knowledge.

I am inclined to take an intermediate stand. Certainly our knowledge has been increased, but there has been no mindblowing experience. We might say that new techniques have been put to more extensive use and that the main thrust of science as presented at this Assembly has been to deepen our understanding of biological problems by digging into areas which have to some extent already been exploited.

However, there are a few topics that are particularly challenging for the future. One concerns the program that has been called JGOFS, the Joint Global Ocean Flux Study, which has the following goal: "To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean and to evaluate the related exchanges with the atmosphere, the sea floor and continental boundaries." The program that will have its first test run in the North Atlantic beginning in 1989 is clearly of such breadth that no single group of scientists or even scientists in a single country would be able to carry it out. Cooperation among scientists from different countries is essential because of the comprehensive nature of the program and the high costs involved. The predicted returns are, however, also big, since a better knowledge of fluxes of carbon dioxide and other biogenic elements will undoubtedly facilitate modelling efforts for both ocean ecosystem analyses and ocean climate development and predictions. The value of such capabilities can hardly be overestimated. The program is now being developed under the aegis of SCOR, the Scientific Committee on Oceanic Research. It seems likely that it will fit well into the larger program on global change, the International Geosphere-Biosphere Program (IGBP).

Another topic touching on the ocean and climate is the effort to understand global ocean circulation during the last ice age. There is no doubt that the effect of the development of continental ice-masses on the sea level had dramatic effects both on the surface circulation and the deep water formation in the oceans. It seems likely that the Arctic Ocean, for example, was more or less sealed off from the rest of the world ocean during the peak of the last ice age, which then affected the conditions for life there. We still do not know whether the deep water in the Arctic basin became deficient in oxygen because of restricted exchange between surface and bottom waters. Our knowledge of the deep sea fauna of these parts, although limited, indicates that this fauna is very young, poor in species, and with a high degree of endemism. This might suggest such poor oxygenation. The geologists are planning to sample deep cores from this basin which will then reveal its past history. The practical problems for such coring are great but new technology is under development, and I have no doubt that within the next decade we will see this carried out.

On the technological side I see a big need for instrument development. Improved techniques for getting real-time data of biological parameters that can be matched with chemical and physical data are important, particularly in programs of a regional or global character. Automated buoys, although costly to develop, will in the long run be cheaper to deploy than research vessels. For synoptic purposes such buoys will be necessary complements to satellite or other remote sensing systems.

One topic that still attracts a lot of attention is that of the processes taking place at hydrothermal vents and deep seeps. This JOA was no exception. Since the first detection of the so called "rose garden" in 1976 many new sites have been found, and we have learned a lot about their physics, chemistry, geology and biology. Some 160 new species have been described from them, where polychetes, gastropods, copepods and protozoans clearly dominate over the more spectacular forms, like vestmentiferan worms and giant mussels. New for the Assembly was information on fossil hydrothermal vent faunas from the Urals, faunal assemblages estimated to be 400 million years old. This obviously shows that such faunas are old, but it also suggests that they might be more common than previously appreciated.

Problems that have still not been solved include how the mainly lecithotrophic larvae spread from one site to the other, how larvae adapt to both ambient sea water and the special conditions at the sites themselves, and how the symbiotic bacteria are transferred from one individual to the next during ontogeny.

The studies of seeps and vents have been examples of cooperative interdisciplinary research at its best. We need more of this sort.

I will here only mention one other group of contributions to this Assembly, the studies on life strategies in extreme environmental conditions. We heard a number of interesting talks on adaptations to cold conditions in the Arctic and the Antarctic or to the special environmental features of the deep sea. We also listened to the findings that closely related species of fish (tunas) can be either homeothermal or poikilothermal, a striking example of adaptational differences to life strategy rather than to the surrounding environmental abiotic conditions. One thing we may learn from this is the danger of generalizing from findings in one species to others. This certainly does not mean that we need to investigate every species, but we must study many species before we can achieve a good understanding of a more general character.

In this review I have not tried to cover the complete set of contributions within the field of biological oceanography, but rather to highlight some few points. I believe there are reasons to be optimistic for the future of this scientific field, even though big strides are not taken every year. What makes me particularly optimistic is the emerging strong cooperation between the various marine scientific disciplines.

Heath, G.R. 1989. State of the Art: Marine Geosciences, p. 177-182. In: A. Ayala-Castañares, W. Wooster and A. Yáñez-Arancibia, eds. *Oceanography 1988*. UNAM Press, México D F, 208 p.

State of the Art : Marine Geosciences

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1. INTRODUCTION

The *state of the art* of the marine geosciences is difficult to present other than in the context of the evolutionary development of the field. Like ancient Gaul, the history of marine geology and geophysics can, simplistically, be divided into three parts:

Pre-early 1960's: Exploration and Description

This era, which spanned almost a century, focussed on the determination of the character of the ocean basins (the bathymetry and nature of the sediments and igneous rocks of the sea floor). Prior to the Second World War, direct-sampling tools were crude and remote sensing was virtually non-existent. Nevertheless, by the early 1960's, the major features of the bathymetry of the ocean basins were known, as was the basaltic nature of the oceanic "basement" and the general distribution of the major sediment types. The systematic differences between the seismic characteristics of continental and oceanic crust were well documented, as was the difference between sediments laid down during glacial and interglacial periods.

Because hypotheses to explain such patterns were not couched in ways that facilitated easy testing, however, papers of that era tend to be heavy on speculative interpretations of data and light on rigorous testing of existing (or new) theories.

Early-1960's to mid-1970's: Explosion of Concepts

By the early 1960's, the descriptive data base for the ocean basins was sufficient to support major conceptual advances. The first of these, the plate tectonics paradigm, provided an intellectural framework that allowed numerous puzzling observations to be explained in a simple and consistent way.

The plate tectonics concept forms the basis for modern models of margin subsidence and sedimentary basin development on both active and passive continental margins, it leads to testable models of crustal formation and evolution, it allows displaced pelagic sedimentary facies to be restored ("backtracked") to their depositional depths and locations, and it specifies the location and character of virtually all global seismicity. Plate tectonics has become so much a part of our thinking that its fundamental importance in studies of today's problems (such as the origins and histories of exotic terrains and the nature and evolution of mid-ocean-ridge hydrothermal systems) is easy to overlook.

A second conceptual breakthrough of this era was the development of quantitative paleoceanography. The use of microfossil census data to reconstruct past ocean temperatures, the recognition that the oxygen isotopic composition of microfossil tests records past changes in continental ice volume (such ice sequesters ^{16}O in preference to ^{18}O) and thereby allows precise global correlation of sediment cores, the application of time series analyses of paleoceanographic data and of the earth's orbital parameters to demonstrate that variations of the seasonal insolation received by the earth due to the orbital variations are responsible for the waxing and waning of the ice ages (the Milankovich hypothesis), and the CLIMAP reconstruction of oceanic and continental conditions during the height of the last ice age, eighteen thousand years ago, revolutionized our view of the degree to which the ocean can deviate from its present state, and of the impact of such changes on global climate.

A third area of conceptual advances was in the application of sophisticated mixing models to petrologic studies of oceanic igneous rocks and to studies of the composition and character of pelagic sediments. In both cases, the combination of multivariate statistical analyses, linear programming, and shrewd deductions about the nature of pure source materials have helped show that any sample of the sea floor, whether igneous or sedimentary, can be accounted for by simple mixing and modification of a small number of well defined end-member source materials. By using a large suite of elemental and isotopic analyses, such models can be severely constrained. In the case of igneous rocks, for example, these models, backed by intensive surface vessel and submersible sampling and mapping, and by experimental petrology, have helped make sense out of very complex mid-ocean ridge systems.

Post-mid-1970's: Technology and Hypothesis Testing

The past decade or so has seen an exponential growth of marine geological and geophysical data as a result of the application of new technology. Key items include:

Synthetic Aperture Echo Sounding Arrays

A ship fitted with an array of transducers controlled by a computer can map a strip or swath of the sea floor, rather than the single profile directly beneath the ship recorded by a conventional echo sounder. Swath mapping of complex topography (mid-ocean ridges, for example), eliminates interpolation errors associated with contouring conventional data, and provides a level of completeness and detail that allows completely new structural interpretations, as well as sampling strategies that are much more target-oriented.

Satellite Altimetry

The elevation of the sea surface relative to the geoid is determined by the local gravity field and by the presence of ocean currents. Physical oceanographers use the variations in sea-surface elevations measured from satellites (SEASAT,GEOSAT) to infer changes in geostrophic currents.

The time-invariant anomaly, which dominates the signal, however, is due primarily to gravity anomalies in the solid earth. By determining the wavelength of such anomalies, it is possible to determine which are due to bathymetric features (such as seamounts), and which are due to density variations deeper within the earth. The short-wavelength data have provided a global view of the structure of the sea floor that could never have been derived from existing ships' tracks, particularly in sparsely-surveyed areas such as the South Pacific and Southern Oceans.

Multi-Channel Seismic Profiling

The use of high intensity energy sources and very long hydrophone streamers (or streamers deployed from two or more ships) has allowed the sophisticated seismic data collection and processing techniques developed by the petroleum industry to be applied to studies of thick sedimentary sequences and crustal rocks in the ocean basins. The resulting improvements in record quality and depth of penetration are providing new insights to the structure of the oceanic crust and of continental margins.

Advanced Ocean Drilling

The application of petroleum drilling techniques to the deep sea floor began in the 1950's and has proceeded virtually continuously since 1968 from the Drilling Vessels ***Glomar Challenger*** and ***JOIDES Resolution***. In recent years, however, the development of new techniques for recovering cores of undeformed sediment, for spudding and drilling in igneous rock with little or no sediment cover, and for collecting *in situ* log data on a broad spectrum of physical and chemical properties of the sea floor have provided important new samples and material properties on which to base interpretations of paleoceanographic changes and of crustal petrogenesis.

Submersibles

Both manned and unmanned submersibles allow marine geoscientists to observe the sea floor and carry out manipulative experiments at a scale comparable to those long possible on land. These vehicles are proving invaluable on both mid-ocean ridges and continental margins. The quality and level of documentation of polymetallic sulfide samples (for example) recovered by submersibles would be difficult or impossible to match from a surface vessel.

Analytical Tools

The advances in field instrumentation are matched by new laboratory tools. Accelerator and small-sample mass spectrometry allow paleoceanographers to look at Cenozoic sequences in sufficient detail to assess possible forcing mechanisms. Rapid analytical techniques allow individual components of a rock or of a sedimentary sequence to be examined in detail, and new gas chromatograph-mass spectrometer systems are finally allowing organic geochemists to understand the full cycle of key biogeochemical markers.

The past decade or so has also seen a change in focus from simple exploratory mapping and sampling followed by *ad hoc* interpretations of the resulting observations to hypothesis testing and model development. The new emphasis leads to more efficient use of increasingly scarce and expensive resources,but can easily overlook or underemphasize new or poorly understood phenomena. The discovery of complex animal communities based on the energy supplied to the ocean by mid-ocean-ridge hydrothermal systems should give pause to anyone who believes that all the first-order phenomena of the oceans have been discovered.

Among the concepts that have greatly influenced geoscientific marine research during the past few years are the Milankovich hypothesis on orbital forcing of climatic change, mentioned earlier, the Vail model of Cenozoic sea level variations that is derived from seismic profiles across marginal accretionary sequences, and the hypothesis that fluid circulation through oceanic hydrothermal systems determines many of the chemical characteristics of seawater and the oceanic crustal layer.

2. GEOLOGY AS AN EXPERIMENTAL SCIENCE

The marine geosciences of today are more process-oriented than they have ever been. Presentations at this Joint Oceanographic Assembly, as well as at other recent national and international meetings, emphasize the change.

The "Climate Machine"

The parallel development of powerful computers capable of solving the equations that make up modern general circulation models of the atmosphere-ocean-cryosphere system, and of very detailed histories of late Quaternary climate change have highlighted a number of key problems. The roles of the polar oceans are still in doubt. The virtual absence of long paleoceanographic records from the Arctic Ocean, for example, leaves the modelers without guidance as to the appropriate boundary conditions for their models, or without independent data to validate the model predictions for this climatically important area. Current international efforts to address this information gap are likely to yield high payoffs.

The rate of climate change is still a subject of debate. As the climatologists find sedimentary records less and less disturbed by bioturbation or physical mixing, the periods of time required for major climate changes such as the isotopic 5e - 5d change, the "termination I" change from the last glacial interval to the Holocene,and the reversal from interglacial conditions to the colder Younger Dryas interval early in the Holocene are interpreted to be shorter and shorter. What are the mechanisms responsible for these changes which now appear to be rapid enough to be significant over a human lifespan?

One of the sensitive indices of climate change is global sea level. This property of the oceans also affects the well being of a large fraction of the world's population. How rapidly sea level is changing globally and locally, how this affects coastal erosion and vulnerability to storm surges, and what mitigation measures should be adopted are topics of active research around the world.

Mass Fluxes in the Oceans

The widespread deployment of moored and drifting sediment traps is producing a data base on vertical particle fluxes through the oceans that can be compared to models of regeneration of labile components in the biogeochemical cycle,and to longer-term fluxes of more refractory components into the sedimentary record. All the questions surrounding the validity of sediment-trap measurements have not yet been answered, but the data for refractory elements like aluminum show good agreement between measured trap fluxes and sediment accumulation rates. It appears that even seasonal flux variations are recorded in the properties of bottom sediments.

The current problem challenging geochemists is to solve the inverse problem, that is, to reconstruct the composition and flux of the rain of particles as a function of time on the basis of properties preserved in the sedimentary record. Given the importance of this question in addressing the consequences of climate changes greater than those experienced during historical times, and in extracting the maximum useable information from the paleoceanographic record, it is distressing to see the first major flux experiments (under the aegis of GOFS and JGOFS) paying so little attention to the solution of this inverse problem.

Deep Structure and Tectonics of the Earth

The third example where geoscientists are working with timescales so short that they have become "experimental" is in the field of tectonics and structural geology. Direct strain measurements by satellite geodesy and very long baseline interferometry (VLBI) allow plate tectonic displacements to be measured within years, rather than reconstructed for the hundreds of thousands to millions of years recorded in the magnetic-reversal fabric of newly formed oceanic crust. Seismic tomography is starting to provide "snapshots" of the three-dimensional velocity structure of the earth, again allowing surficial seismic phenomena to be related to deep structure and possible source mechanisms.

The energy flux in mid-ocean hydrothermal systems is so great relative to that available from the rate of creation of new oceanic crust that the geologic life expectancy of any individual vent field must be short; decades to no more than centuries. Such a prediction has encouraged marine geoscientists to design and begin to emplace long-term observational systems or observatories on the mid-ocean ridges to record the life history of hydrothermal systems and to test theories about their origin and demise.

3. INTERDEPENDENCE

For much of the first two phases in the evolution of the marine geosciences, they were largely self-sufficient. They shared facilities with other marine sciences, but were intellectually separated by the exploratory nature of their investigations and the incompatability of their time scales (10^4 -10^7 years) with those of their physical, chemical, and biological colleagues (10^{-2} -10 years). Now that the geoscientists have the tools to look at phenomena in real time, their interaction with and dependence on other scientific disciplines has increased markedly. Some examples of such interactions from this Assembly include:

In the Area of Climate History

Paleoceanographers working with climate modelers both to develop boundary conditions for models of different climate states and to test the outputs of such models; geochemists working with chemists and organic chemists to understand the transformations that convert particles in the water column to sediments; paleoceanographers working with physical oceanographers and atmospheric scientists to develop physically plausible models of the oceanic conditions hindcast from the sedimentary record; and sedimentary geologists working with coastal engineers and ecologists to interpret past sea-level changes and assess the impact of possible future changes on coastal structures and ecosystems.

In the Areas of Mid-Ocean Ridge Studies

Geologists, geophysicists, and geochemists working with chemists, biologists, physical oceanographers and experimental petrologists to understand the "plumbing" of hydrothermal systems, the role of rock-seawater interactions on the properties of the superheated waters, the impact of vent communities on the composition of hydrothermal solutions and *vice versa*, and the impact of hydrothermal fluids on oceanic circulation and properties.

Such interactions provide both opportunities and challenges to marine geoscientists. On the one hand, they offer the possibility of an accelerated understanding of marine geologic processes, and of making the transition from qualitative to quantitative explanations of these processes. On the other hand, the geoscientists must couch their problems in terms that their colleagues can deal with, and must be prepared to defend the validity and precision of their interpretations, particularly when remote sensing data or paleoceanographic hindcasts are expressed in physical units. Once the geoscientists have established their credibility, there is every reason to believe that their contribution to the "global change" problem, for example, will be substantial. After all, the geologic record is the only evidence we have of worlds that differ significantly from our own.

4. ECONOMIC ISSUES

This Assembly has been much less sanguine about prospects for the prompt exploitation of marine minerals than were its predecessors. This subdued tone is a reliable indication of the current world situation. Offshore oil and gas development is inhibited by the depressed petroleum market which has resulted from global over-production. This situation is likely to change before the end of the century, but in the meantime, exploration and development of challenging frontier areas (such as continental slopes, and high latitudes) will proceed slowly. The extraction of construction materials from continental shelves continues to expand, particularly in densely populated industrial nations as onshore deposits are exhausted or rendered inaccessible by urbanization. The recovery of shallow-water placer deposits is, like petroleum production, strongly affected by metals markets, so the past few years have not seen the strong growth of earlier times.

The discovery of complex ("polymetallic") sulfide deposits formed at mid-ocean ridges by seawater hydrothermal systems has generated great scientific interest and an effort by the U.S. Government to sell commercial leases for the portion of the Gorda Ridge within the U.S. Exclusive Economic Zone. Industrial interest has been limited, however, because of depressed global metal markets, doubts about the magnitude of the resource, and the large investment that will be required to develop new mining technology to recover such sulfides. This lack of interest, coupled with substantial and unanswered questions about the environmental impact (on the unique "vent" animal communities, for example) of mining polymetallic sulfides have eliminated any serious proposals to start such enterprises in the near future.

Deep-sea ferromanganese nodules and crusts, long the subject of research, exploration and pilot-scale mining, have lost much of their near-term economic appeal. The depressed copper and nickel markets and the high cost of the capital investment of 1-2 billion dollars required to mount a deep-sea nodule-mining venture have caused interested organizations and consortia to scale back their development plans, in some cases drastically. Cobalt-rich crusts on rocky slopes at shallower depths (less than 3 km) are still objects of intense study, particularly as most such deposits lie within national exclusive economic zones. The economic recovery of the thin cobalt-rich crusts from highly irregular volcanic terrains is technically challenging and, as yet, unsolved, however, so that large-scale mining is still many years away.

The current economic forces that have discouraged deep-sea nodule mining have eclipsed the legal and institutional issues that dominated discussions during the 1970's. In the long term, however, the issues of industrial property rights and the administration of operations beyond national exclusive economic zones, and of the impact on offshore development of onshore subsidization of mining operations in order to generate foreign exchange will determine when and if nickel, copper, and manganese are produced from the deep sea.

SUMMARY

The focus of the marine geosciences has evolved from largely autonomous studies thirty years ago to multidisciplinary interactions with other oceanographic specialists and numerical modelers today. The result is increased quantification and rapid progress in studies of mid-ocean hydrothermal systems, of paleoceanographic reconstructions of intervals of rapid climate change, of the transformation of settling particles into pelagic sediments, of sedimentary dynamics in the nearshore zone, and of "real time" measurements of plate tectonics.

The accelerating rate of progress has been boosted by new technology which produces global views of the gravity field, highly detailed bathymetric swath maps, multi-channel seismic records, high quality sediment and rock cores, and *in situ* observational and sampling capabilities. New analytical tools onshore are helping to keep pace with the flood of samples. The offshore extractive industries are depressed and may well remain so into the next century. In the meantime, however, there is every reason to believe that the rapid rate of scientific progress will continue and will provide the knowledge base on which all future users of the ocean will depend.

McIntyre, A.D. 1989. Pollution and Living Resources, p. 183-186. In: A. Ayala-Castañares, W. Wooster and A. Yáñez-Arancibia, eds. *Oceanography 1988*. UNAM Press. México D F, 208 p.

Pollution and Living Resources

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One feature of the Joint Oceanographic Assembly is that while some themes are selected, and even a few papers may be specifically commissioned, the great majority of the hundreds of abstracts are submitted because some scientist, somewhere in the world, feels there is an important point to be made. An analysis of the contributions, in terms of topics, will therefore provide a useful index of where attention is currently focused, and if we do this for the abstracts related to pollution we have at least a pointer to the main causes of concern at the present time. Such an analysis on all the abstracts received in 1988, classifying them not entirely by title but rather on the major thrust of their content, gives the following result:

OIL	20%
SEWAGE	13%
METALS	9%
OTHERS	13%
GENERAL	27%
METHODS	18%

The *others* category includes papers on radionuclides, organochlorines and titanium dioxide, as well as a number of less common contaminants. The *general* category is a large one since it covers not only coastal activities such as construction and development, which come within the broad definition of pollution as set out by GESAMP, but also considerations of regulation and control.

It is interesting to compare this listing with the general review of main pollution which introduces Special Symposium S.4 (Large Scale Changes from Human Activities). That review drew attention, among other things, to the problem of non-biodegradable plastics as an increasing cause for concern in the marine environment. These materials come in several forms. With natural fibres now replaced by synthetic formulations in fishing gear, nets and warps lost or discarded at sea present a long-term hazard to shipping, and 'ghost fishing' continues for long afterwards, killing fish, birds and marine mammals. Plastic straps from cargoes and other packaging, even the ubiquitous yokes for six-pack beverage cans, entangle marine organisms and eventually prove lethal. Other plastics as sheets or particles are widespread and damaging to life in the sea, and reduce amenity in recreational areas. The good news is that legislation at both national and international levels is beginning to take account of the issue.

The S.4 review, however, indicating that the main sources of pollution to the oceans were from ships and from the atmosphere, noted the low concentrations of metals, organochlorines and radionuclides in the sea, and drew attention to the declining importance of oil pollution. Even the metal, lead, for which the most enhanced levels had been recorded as a result of atmospheric transport from the continents, was declining in some regions in correlation with reduction in the use of leaded gasoline.

The generally encouraging tone of the review may seem at odds with the other contributions, but in fact there is no conflict, since the review dealt with the open sea beyond the continental shelf, and it is true that pollution there is insignificant. Most of the other contributions dealt with shallow coastal waters, where the situation is clearly different. Oil is a significant concern, but chemical pollution in the water column is not now seen as the major threat, rather tarry residues and oil slicks, which concentrate on the sea surface, damaging seabirds, and eventually ending up in the intertidal zones of exposed beaches, resulting in severe amenity reduction. Many beaches are today quite unsuitable for any recreational purpose and many others are available only after intensive clean-up effort. Since the source of much of this oil is not spills but operational discharges from shipping, it is relevant that we do have at least the mechanisms for control. Thanks to the series of treaties and agreements administered by the International Maritime Organization there is increasing pressure to reduce these discharges, and if the subject of oil comes up at the next JOA the situation described should be much more acceptable.

However, there are still habitats, mostly along the coastal margins, where oil spills can do great damage in areas of low water exchange. We heard, for example, an excellent account from Brazil of how basin mangrove stands could be seriously impacted by oil; how the effects may be difficult to detect from an initial superficial study, but how the chronic effects may last for a decade and may eventually be lethal. A useful monitoring scheme for assessing the impact of oil on mangroves was proposed.

This reference to mangroves points us accurately toward the real pollution problems. The introductory review already referred to dealt with the oceans beyond the continental shelf, and rightly indicated that problems there were not major and were declining. On the shelf, and especially along the immediate coastal zones, the picture is different. Sewage is a priority concern. It contributes to serious public health problems, both from recreational exposure to faecal pathogens and from consumption of contaminated seafood. In addition when sewage is discharged into the sea in places where agricultural fertilizers and wastes from intensive animal husbandry also reach the coast, it can cause eutrophication resulting in exceptional plankton blooms, alterations of pelagic and benthic community structures, and in reduced fisheries. Coastal ecosystems are damaged on much more than local and transitory space and time scales. It has to be recorded that several papers sounded a note of caution in this context. In the Delaware estuary, for example, we learned that adverse hypoxic conditions have been improved by efforts to alleviate pollution, and also that the impact of pollutant inputs themselves varied greatly depending on the geochemistry of the area. Again, in the Gulf of Mexico, low oxygen conditions on the shelf, thought to be attributed to the outflow of the Mississippi river containing anthropogenic effluents, might well be explained in terms of natural effects. Clearly, a much better understanding of normal processes in the sea is required, and the diversity of expertise available at a Joint Oceanographic Assembly facilitates the discussion of such matters.

Another problem that was highlighted, again in the coastal zone, is that of sedimentation. It is well recognized that fine particles of silt and clay act as carriers for a wide range of contaminants, but a view of the importance of sedimentation largely in terms of the impact of associated contaminants is perhaps an over-emphasis. This came out clearly in several papers which drew attention to the adverse effects of increased turbidity and sedimentation caused as much by the physical blanketing effect as by any toxic property. The point was particularly well illustrated from the Philippines, where inland logging and deforestation has resulted in greatly increased sediment loads to the sea with associated effects on corals round the coasts. The correlation between regions of deforestation and adjacent areas with reduced coral cover is striking. This is just one of the many examples of the far reaching impact of inland operations.

But if large increases in the silt input to the shelf seas produce adverse effects, there are also problems from the opposite situation. The manipulation of hydrological cycles by man, mainly through the building of dams on major rivers, is increasing throughout the world. In most of the continents, a significant part of the total river flow is controlled by impoundments. In some places this has substantial effects on the topography and ecology of the coastline, and we were informed by one paper of the reduction of productivity and fisheries in the eastern Mediterranean resulting from the almost complete stoppage of the seasonal flow of silt with its associated nutrients from the Nile in consequence of the Aswan High Dam.

Clearly there are many activities of man in the hinterland that have significant effects at the coast, and when initiating these activities, the potential far field impacts are not usually taken into account.

What other message came through from the pollution papers? One was very clear from Special Symposium S.9 (Pollution in the Marine Environment), and its associated posters, - the value of international collaboration. We heard of several programmes stimulated by groups such as the I.O.C. and U.N.E.P. which could not have got off the ground without the support of such agencies. One activity for which concerted international action is particularly desirable is pollution monitoring, and we were told of plans for a major international project to use bivalve molluscs as indicators of pollution on a global scale. The next JOA should provide an opportunity to evaluate the success or otherwise of this initiative. We heard also of one considerable difficulty in the execution of such programmes - that of data quality. The routine collection and analysis of samples in an international collaborative programme involving a variety of techniques and different analysts brings difficulties in ensuring the validity of the data, and a comprehensive strategy for improving the quality of the data obtained from such large scale monitoring programmes was described.

So much then, for the contributions on pollution. I would like to turn now to those on living resources, and taking this topic in its broadest sense, and again allocating the relevant abstracts to topics, the result is:

FISH	42%
SHELLFISH	13%
SQUID	2%
SEAWEED	10%
MANGROVES	33%

Finfish and their fishery attracted the largest number of these contributions, of which 40% dealt with pelagic stocks, 24% with demersal stocks, and the remainder with a variety of individual species or related topics. Discussion on fish stocks must be in almost continuous session around the world, with much of the energy probably directed toward establishing total allowable catches; allocating quotas; and calculating the relative merits of mesh size change, reduction in fishing effort or area closure in halting the decline in stocks. The joy of listening to fisheries discussions at the Joint Oceanographic Assembly is that participants can stand back and take a longer view than that of the manager concerned with day-to-day regulation. In this context, the papers dealing with long-term environmental changes were particularly apposite. Of course, no final answers emerged, but it was clear that this sort of strategic thinking ought to go hand-in-hand with the more usual tactical approaches. These papers, with a suitable introduction, should certainly be brought to the attention of fishery managers.

While much of this resource discussion was related, directly or indirectly, to the open sea situation, the remainder was firmly directed to the shelf and coastal zones. In the shellfish contributions, interest in shrimps and prawns dominated, with emphasis again on stock fluctuations and their causes. The link was often referred to between adult stocks and their nursery areas, and in this connection the importance of mangroves was obvious. Indeed, as the list shows, mangroves, with a third of the contributions, were a major focus of interest. They clearly constituted a vital resource around the world, for the provision of fuel and building materials; in terms of coastal protection and, as already indicated, in their role as nursery grounds for many commercial species.

Mangroves are significantly at risk, not just from the classical pollutants, but perhaps even more from constructions and development work of man along the coasts. It is ironic that important fish nursery grounds are often destroyed in order to create facilities for mariculture. In the Philippines, more than half the mangrove stands have been converted to fish ponds. Clearly, some balance is required in integrating such coastal practices.

Effects such as those referred to above are more or less obvious and ought to produce appropriate and equally obvious reactions. But several problems which were much more difficult to define and to suggest solutions for emerged at JOA. The possibility was raised that increased U/V radiation resulting from changes in the ozone layer might have adverse effects on planktonic eggs and larvae, as well as on other organisms living near the sea surface. Again, the forecast rise in sea level could clearly have widespread and dramatic consequences, but in introducing a talk on this subject, one speaker was of the opinion that no topic had generated so much argument on the basis of so few hard data. On subjects such as these we can only speculate at present, and look forward to the next JOA when at least some of the first results of the current intensive international collaborations should be available.

In these brief comments summarizing contributions to JOA '88, it has been convenient to review pollution and living resources together. But quite apart from any such convenience, there is obviously a real linkage, and in this context it is useful to consider the most recent annual world fishery statistics from FAO, which show an increase in landings of 6.8% to a new global record of 91.5 million tonnes, with the confident forecast that the magic number of 100 million tonnes will be reached well before the end of the century.

This can only mean increased pressure on resources, and emphasizes the need for the sort of strategic thinking outlined in several of the JOA papers if the already overfished stocks are to be maintained. Also, it highlights the dangers of degradation of the coastal zone, referred to in so many papers, which if continued will further affect fisheries and inhibit the much needed expansion of mariculture. It seems clear that the case for sustainable growth with environmental harmony made so strongly in the Bruntland Report must be acted upon, and there is no doubt that the sort of multidisciplinary discussion which is the main feature of JOA will have much to contribute in the future.

ANNEX

LIST OF PARTICIPANTS

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