ANNEX V

FINAL REPORT - WORKING GROUP 34

INTERNAL DYNAMICS OF THE OCEAN

1. INTRODUCTION

Ocean currents are now known to be highly variable in both space and time with a great deal of energy occurring on temporal scales of weeks to months and spatial scales of tens to hundreds of kilometers. Such variability is prevalent throughout the world's ocean, occurring almost everywhere that observations exist with sampling adequate to resolve the phenomena. The variability is heterogeneous with energy levels and dominant scales varying widely from place to place in the ocean. Moreover, the structure of the variability takes many forms including: the meandering of narrow currents, semi-attached and cast-off ring currents, advective vortices which extend throughout all or part of the water column and which may occur in isolation or in groups, planetary and topographic waves, etc. All of these forms of variable form are commonly referred by the generic term 'eddies'. For more than a decade physical oceanographers have devoted a very large and vigorous international research effort towards the description of eddies, towards the discovery of their kinematics, statistics, and local dynamics, and towards an understanding of their role in the general circulation of the ocean. Although many of the fundamental questions remain to be answered and vast areas of the world ocean remain unexplored, substantial and definitive results have been obtained. The conceptualization of the dynamics of ocean currents and circulation is now more realistic, and the term 'eddy science' is used to identify knowledge and study of the variability phenomena.

The dynamics of eddies is first of all characterized by a nearly geostrophic balance of horizontal momentum and the term 'geostrophic eddies' is sometimes used generically. They are also often called 'quasigeostrophic eddies' but this term, as used by theoreticians, has a precise dynamical meaning; that the stretching term in the quasigeostrophic potential vorticity of the eddy field be generally comparable to the relative vorticity and that advections be approximately horizontal. This is the case for motions which have a horizontal scale on the order of the Rossby internal deformation radius (i.e. the vertical scale of the motion multiplied by the ratio of the Brunt-Vaisala buoyancy frequency to the Coriolis parameter). In the atmosphere, midlatitude cyclones and anticyclones which are thousands of kilometers in extent have this property and are often referred to as synoptic scale motions. By dynamic analogy then many authors refer generically to ocean eddies as 'synoptic eddies'. On the other hand, because the variability is of intermediate scale (i.e. less than gyre scale) the descriptive term 'mesoscale eddies' is very commonly used generically. At this time it seems best to designate the general phenomenon simply as 'eddies'. As more is learned about distinct kinds of eddy motions, more special general terms such as rings, planetary waves, etc. will naturally occur and generizeable dynamical processes and their dependencies on critical non-dimensional parameters will hopefully emerge.

This report constitutes the final report of Working Group 34 and deals with research dircetions for eddy science as indicated by the present status of eddy science and its relationship to ocean science generally. It is based upon the major review volume *"Eddies in Marine Science"* prepared during the past three years under the auspices of WG 34 which is being published in book form. *"Eddies in Marine Science"* summarizes and overviews our experimental and observational knowledge of eddies throughout the world ocean, the modelling of eddies, and the opportunities for application of that knowledge in marine science generally. The reader is referred to that volume as background material and for its comprehensive bibliography. Ideas and information from that volume have been used throughout this report with no attempt at specific citations. The brief reference list at the end of this report includesonly a few review articles and general sources for information on research related to recently finished field experiments. Working Group 34 has been active since 1971 in providing a forum for the discussion of problems in eddy science and the means of dissemination of timely information, in the planning and coordination of international experimentation and modelling. A list of the relevant meetings of WG 34 is appended.

2. Eddies and the Dynamics of the General Ocean Circulation

a. Eddy-Mean Field Interactions.

A major significant result of the research of the past decade has been the identification of a primary mechanism for eddy generation by internal non-linear processes, finite amplitude processes related conceptually to baroclinic, barotropic, and mixed instability mechanisms. These processes occur in limited regions of the ocean, notably in the Gulf Stream System (separated current, extension, and recirculation regions) and the eddy energy generated there is exported by transport and radiative mechanisms to populate large regions of the sub-tropical and sub-polar gyres with eddies. This knowledge is not the result of direct measurement of eddy-mean field interaction terms and fluxes in the Gulf Stream System, but it is arrived at from the synthesis of the general analysis of numerical experiments carried out with eddy-resolving general circulation models (EGCM's) with the picture emerging of the observed geographical distribution of low-order statistics (e.g. eddy kinetic energy). The eddy-mean field interactions are believed to be complicated, heterogeneous, and highly variable in space and time. They are believed to be processes which lie at the heart of the question of the effect of eddies on the general ocean circulation, effects which include both direct eddy fluxes and also the transports by mean currents whose very structure and strength relate to the existence of the eddy field. The actual interaction processes that occur in the real ocean are essentially unknown but are expected to occur in all western boundary current systems as well as suspected to occur in other special regions of relatively strong current such as exist near the equator, eastern boundaries and polar regions. The Antarctic Circumpolar Current processes are known to be baroclinic and the resultant eddies to transport a significant amount of heat.

Because of the central importance of these processes, the scope of research required to resolve them and the relatively large amount of related information in the North Atlantic, WG 34 strongly recommends a dedicated and coordinated research programme for the Gulf Stream System (separate current, extension, and recirculation regions) to be undertaken and initiated in the second half of the 1980's with the general objective of determining the eddy-mean field interaction processes. The availability of satellite altimetry and other sensors should be exploited if possible. In any case, a mix of instruments and dedicated modelling should be utilized. In order to make this programme possible and successful the interim period should be devoted to the vigorous pursuits of model development and numerical experimentation including observation system simulations in EGCM's. During this period experimental and instrument and deployment system development (moored and free floating instruments) are also essential to allow for adequate data gathering capability in the strongest current regions.

b. Global and Regional Distribution of Kinematics and Dynamics

Much progress has been made in determining the geographical distribution of low order eddy statistics, i.e. amplitudes and scales, and in developing the taxonomy of eddies, i.e. identifying types of variability such as rings, mid-ocean mesoscale eddies, and smaller geostrophic blobs and lenses. Some regions, however, are essentially unexplored, vast gaps exist in maps of the distribution of eddy properties, and it must be expected that new eddy types will be discovered in unexpected places. Longer time scales need to be examined since some of the few existing spectra of relatively long time series are "red". There are regions of the World Ocean which have vigorous eddy activity and others which are relatively weak. As noted above, consideration of the distributions of eddies and with that of strong currents indicates regions of internal production. Similarly, the geography of wind forcing, bottom topography, and thermohaline processes, etc. is indicative of other eddy energy production and conversion processes and their location. External wind forcing is thought to produce significant eddy energy in special and/or weak regions but this process is more poorly understood than are the internal production processes and additional research is required.

The transitional zone between the region dominated by equatorial scales and processes and the higher latitude region of the non-linear mesoscale eddies should be identified and investigated.

SCOR WG 34 recognizes the critical importance of a continuing research activity towards defining the global distribution of eddy kinematics and dynamics. In unknown regions even single moorings such as used in the NEADS programme provide valuable information. Ships of opportunity should be used for XBT lines with mesoscale sampling especially in remote areas. In this activity the cooperation of the CCCO which is planning an XBT programme for climate research purposes, could be of great help (i) to individual eddy scientists in facilitating arrangements and (ii) to eddy scientific research with mesoscale sampling along tracks sponsored by the CCCO. The IGOSS programme could serve as a basis for a dedicated XBT programme and WG 34 requests the SCOR Executive Committee to consider forwarding this report to IGOSS.

Ships of opportunity have been and can in the future be used to deploy drifting instrumentation trackable from satellites. Remote-sensed global coverage from satellite altimetry and other sensors will ultimately be of the greatest importance to this type of research and other new large-scale techniques such as acoustic tomography also hold promise for the future. Regional dynamical studies, such as POLYMODE and Tourbillon, have provided the basis for major research advances and such studies with various levels of effort must be continued in selected regions. Tailored regional and process models need continued development and their relationships to intensive regional data sets, for the testing of physical hypotheses and for optimal field estimation will become more intimate via new techniques of data analysis and assimilation (c.f. Section 5).

3. Eddies and their Interaction with Smaller-Scale Phenomena

The eddy models of the 1970's concentrated almost entirely on the dynamics of the internal radius of deformation scale motions themselves. The mechanisms whereby energy was finally lost were treated by ad hoc diffusion terms (typically of fourth or sixth order), just as the eddies themselves were and are parameterized in coarse resolution models. This situation needs improvement during the next decade. Ideas from models must still be regarded as preliminary since frictional parameterizations are probably oversimplified. The effect of phenomena like intrusions, double diffusion, and breaking internal waves will all have to be studied and included in the diffusive terms. A basic problem here is that there is no satisfactory model of mixing along isopycnals. Indeed, in models without eddies, fluid tends to spread only about one deformation radius from its source unless mixing or frictional terms are included to aid the spreading process. Both the mixing by internal waves, and the interaction between eddies and internal waves, also need study. The stirring by eddy and larger scales along isopycnal surfaces and the possibility of significant subsequent diapycnal mixing because of smaller-scale processes is another important research topic.

The effects of fronts need to be studied and parameterized. Fronts of all sizes tend to be unstable and shed eddies, each of which has its own small deformation field and front associated with it. Much of the dissipation by eddies may be due to this frontal hierarchy. Some known examples include the violent frontal eddying in the West Spitzbergen current, and the observed intrusions and double diffusion on strong fronts like the Mediterranean outflow. Even lenses like the "meddy" may have their own unstable fronts.

Studies are only just beginning on 'blobs' or lenses of water (tens of kilometers in the horizontal and a few hundred meters vertically), which seem to be able to propagate long distances in the ocean. This phenomenon appears in a variety of forms and sizes, usually with a surprisingly gradual change in water mass properties. Some lenses appear to have produced their own water mass by some form of vertical circulation and/or mixing over lengths of a few hundred meters, with little signature above and below those depths. Some, like the meddy, have carried a water mass from some far-distant origin. It would be useful, but difficult, to follow one or more lenses to watch their evolution. Each of these must have very different fluxes of buoyancy, momentum, and vorticity, and require urgent study. The statistics of such lenses should also be studied.

Scientists now know that previous methods of data quality control have removed evidence of real physical phenomena from data sets; we recommend the examination of older data sources for evidence of small-scale phenomena. The problem of differing length (e.g. in the Tourbillon experiment, there was a distinct 10 km central mass within a 100 km eddy) will require further attention to finely-spaced observations.

4. Eddies and the Large-Scale Distribution of Properties

During the decade of the 1970's there was a rapid development in numerical models of basin scale ocean circulation, particularly models with fine horizontal resolution suitable for resolving the eddies explicitly in the larger scale flow. These have been called eddy-resolved general circulation models - EGCM's. This class of model came along to supplement earlier coarse resolution models that had been developed to examine the time-averaged World Ocean circulation in which the effect of eddies is completely parameterized (ocean general circulation models - OGCM's). Most recently, the EGCM's have begun to show the ability to simulate realistically the geography of variability in an ocean basin, reproducing the multiple sources of eddy energy in the North Atlantic basin. This work needs to be continued and the comparison with observation refined to determine how well such models can do in simulating real ocean transients, including the mean flow and a whole host of eddy statistics.

The development stage of eddy-resolved models is far from complete. Future studies will require more vertical resolution and the inclusion of more realistic thermodynamics and thermohaline forcing. The role of bottom topography and the influence of realistic wind forcing (with observed space and time scales) need exploration. An understanding of the role of parameterized friction and boundary conditions is also needed. All of this implies a vast amount of work and development of additional kinds of models in the next few years.

This kind of modelling activity should be expanded to other basins, like the North Pacific, where comparable data for comparison is becoming available and where presumably a somewhat different physical environment will provide new tests of the models. An immediate objective, in support of observational programmes in the North Pacific, would be to compare and contrast the amplitudes and patterns of eddy variability in the North Atlantic and North Pacific oceans with the view of understanding basic differences between the basins.

Other subregions of the World Ocean are,of course,also of interest, e.g. the Southern Hemisphere oceans with their very different geometrical constraints. These are particularly important since little is known about their variability, particularly in the South Atlantic and South Pacific. In this regard there can be a particularly useful handshake between the modellers and the observationalists. Data gaps (in mean quantities as well as eddy variability) need to be filled. This would allow critical tests of the models, while the models would produce predicted distribution of eddy variability for these data sparse regions, pinpointing critical areas for observation.

The current class of efficient high resolution eddy-resolving models, based upon quasigeostrophic dynamics, is not suitable for the study of density outcrop regions, i.e. the high latitude regions where water masses have their origins. Therefore it seems necessary to develop new models as well as to bring earlier primitive equation models to bear on this problem. This is critical in particular for the understanding of the distribution of properties, as well as of the rates and mechanisms by which such water masses are produced. The hypothesis that along isopycnal mixing is the fundamental mixing process in the ocean will require new studies and perhaps new models if we are to understand this critical mechanism for water mass production. This is particularly true for the study of transient tracers, such as tritium and the fluorcarbons, which are currently showing us some of the basic time scales and pathways for deep water production and thermocline ventilation.

A research topic of great importance for which progress may be expected during the next decade is the parameterization of eddy effects in coarse resolution (non eddy resolving) general, ocean circulation models. Empirically the unexpected result is emerging that the diffusivity is directly proportional to eddy kinetic energy. Schemes must be tested by reproducing mean EGCM results via a correctly parameterized OGCM, including the indirect effects of eddies, (e.g. the existence of deep currents which are not locally supported by Reynolds-stress-like processes.

5. Techniques, Methods, and Resources

We recognize the important and growing contributions of satellite remote sensing of the ocean, especially when combined with the array of existing and newly developed in situ measurement systems. Satellite sensors have several unique characteristics, combining global repetitive coverage and good resolution with the consistency deriveable from a single or limited number of instruments. For eddy science, radar altimetry will play a major role when future systems, based on the Seasat results, become available in five to ten years. At the same time, surface wind stress obtained from scatterometry will be providing an essential input to the accurate wind fields needed to drive realistic numerical models. At the present, visible infrared, and microwave radiometers for sea surface colour and temperature, as well as satellite-tracked drifters, play a useful and unique role in the investigation of the global geographic distribution of eddies and currents. When repeatedly deployed from ships-of-opportunity, drifters with lifetimes exceeding one year represent a cost-effective means of obtaining daily surface velocity information. The radiometer data are also proving to be extremely useful for providing guidance to research vessels before and during experiments such as the Gulf Stream warm rings project.

Special problems arise in the management of satellite data, requiring special computer facilities to help speed, handle, and reduce the data volume, while retaining information content. We recognize the efforts of NASA and CNES in providing systems to address these porblems for oceanographers, and encourage similar efforts by others planning to launch satellites.

For several decades meteorologists have recognized the important problem of data assimilation, i.e. the construction of regular fields from irregularly spaced observations of mixed type and quality. In the last ten years, the essential role of interpretive numerical models in the utilization and the assimilation process has also become widely appreciated by atmospheric scientists and carefully explored. As ocean satellite systems develop over the next ten years, it will be important to benefit from past meteorological experience. For example, an interpretative model can use SST to estimate upper layer and thermocline positions. The best field estimates comes from a combination of data and dynamical models (the dynamic-stochastic method). For example, future altimeter systems will provide surface geostrophic current along lines spaced perhaps 200 km apart, every ten days. Sparse measurements from individual ships, moorings and drifting buoys will provide crucial additional subsurface temperature and velocity information. Driven by wind stress fields mostly derived from satellites, numerical models with correct dynamics and properly constrained by these data must be used for spatial and temporal interpolation and extrapolation, including hindcasting and forecasting. As meteorologists have come to learn, this type of approach is the only practical means by which diverse data can be analyzed over regional and global dimensions, in a manner consistent with the known but complex physical processes. Although we have stressed satellite measurements in this paragraph, data assimilation methods are of great importance now for mixed in situ data sets. In particular, we mention the value for eddy research of continually-seeded Lagrangian drifter arrays.

Computer resource availability has placed limitations on the development and testing of eddy-resolving general circulation models, as well as the processing of large volumes of satellite-derived data. As has occurred in meteorology, we expect in ocean science a convergence of these two separate problems, as stochastic-dynamic model techniques evolve. We therefore recommend that the new SCOR Working Group dealing with satellites and future groups that may address synoptic scale oceanography, data assimilation, and numerical modelling, not operate in isolation from each other.

6. Applications and Implications

The preceeding discussion has dealt with the progress and problems in the physical science of eddies themselves and of their interactions with other physical phenomena on other (shorter and longer) time and space scales. However, the existence of the eddies as the dominant flow over much of the world oceans has profound implications on other branches of marine science (e.g. biological, chemical and coastal oceanography) and on technical questions of a practical nature associated with the management of the sea and the exploitation of its resources, which are of great concern to society.

Most importantly, the various types of eddy motions provide a variety of direct and indirect transport mechanismsfor dissolved substances and other particles which are totally or partially forced to drift with the currents. Such substances, often referred to as tracers, include naturally occurring and anthropogenic chemical tracers, (oxygen, tritium, etc.), biological nutrients and organisms (e.g. phytoplankton. fish larvae), and pollutants or waste materials either accidentally or intentionally released into the oceans (e.g. oil, chemical and nuclear wastes). Observing the distribution and redistribution of geochemical tracers such as tritium, helium and freon can be used to infer the oceanic general circulation, and the next several years should see an enhanced and vigorous interaction between geochemists and physical oceanographers involving the application of numerical modelling.

Biological productivity in many areas of the world's oceans is closely linked to eddy-related transport of nutrients or of the organisms themselves. Strong mesoscale features such as rings and fronts which are advective are known to provide distinct boundaries for biological variables. The biological consequences of mid-ocean eddies and situations where planetary wave-like propogation effects dominate are essentially unknown. Factors which are now known to vary across mesoscale boundaries include characteristics, concentrations and structures of populations, mixed layer properties, the diurnal vertical migration within a species and the partitioning of the standing crop between species. Much research is needed in this general area involving biological sampling on the mesoscale with simultaneous chemical and physical measurements.

The climate of the earth and its change from year to year and on larger time scales is thought to be governed in large part by oceanic processes. Eddies play a role directly via eddy heat flux in some areas (e.g. Antarctic Circumpolar Current, the Gulf Stream System) and also indirectly through their effects on general circulation features and large scale air-sea exchange at the boundary with the atmosphere. Near coastal boundaries, eddies generate topographic waves which are, in part, radiated to the rise, shelf and slope regions; providing a dissipation mechanism for mesoscale features. Eddies can induce upwelling, maintain long-shore pressure gradients via momentum flux, and onshore eddy fluxes of heat, salt and nutrients can contribute importantly to shelf-wide budgets.

Forecasting of the synoptic/mesoscale variable currents is becoming feasible and will be of considerable utility for commercial and management purposes such as fisheries, transportation and resource exploration and acquisition. Moreover, the transmission of sound through the sea is known to be significantly affected both by advective effects of eddy currents and most importantly by the range dependent environment caused by eddy induced variability of sound speed. Eddy currents, their statistics and transports bear on a number of planetary scale management issues such as chemical waste dumping and seabed or sub-seabed disposal of nuclear waste material. Eddy transport may influence the degree to which the ocean acts as a reservoir for anthropogenic CO_2 (and the time scale of the process) which has a significant impact on world climate modification due to human industrial activity. Eddy exchange processes across the shelf break impact questions of coastal zone pollution and management.

Many fruitful areas of scientific and practical application of the growing body of knowledge of eddy science are now ripe for research and development activity. At this point in time if expert physical scientists work hand in hand with other marine scientists, engineers and managers, rapid progress can be expected in a number of important problem areas.

APPENDIX I

Meetings of SCOR WG 34

9 August,	1971	-	Moscow. SCOR Proc. Vol. 8 No.1 1972. Planning for Mid Ocean Dynamic Experiment and New Models.
23, 24, 28 June	1974	-	Melbourne and Canberra. SCOR Proc. Vol. 10 No. 1 1974. Plans for US-USSR POLYMODE programme and broader international cooperation.
5 Sept.	1975	-	Grenoble. SCOR Proc. Vol. 11 1976. Discuss POLYMODE, recommend NEADS, and modelling parameterization study.
30, 31 March	1976	-	Wormley. SCOR Proc. Vol. 12 1976. NEADS subgroup plans field programme.
23, 27, May	1977	-	Helsinki. SCOR Proc. Vol. 12 1976 and Vol. 13 1977. Modelling study conference jointly with JOC/WGNE

12 Dec. 1979	-	Canberra SCOR Proc. Vol. 16 1980. Plans for 'Eddies in Marine Science'.
29 July, 1 August, 1982	-	Halifax. Discuss future directions for eddy science.

APPENDIX II

Conduct of WG 34 Meeting in Halifax, NS. August 1982.

Sunday, August 1: SCOR Working Group 34 meeting held from 9:00 am to 6:00 pm. The following SCOR members participated in the meetings:

Professor A. Robinson	Chairman	
Dr. L. Fomin	USSR	
Dr. R. Bernstein	USA	
Professor G. Siedler	FRG	
Dr. W. Holland	USA	
Professor G. Needler	CAN	
Dr. J. Gonella	France	
Dr. C. de Verdiere	France	
Dr. P. Killworth	UK	(alternate for A. Gill)
Professor B. Nelepo	USSR	
Professor H. Charnock	Executive Reporter	

Present as observers and also as participants:

Dr. K. Fedorov	Inst. of Oceanology, USSR.
Dr. T. Spence	ONR, Washington, D.C. USA.

Monday, August 2: The morning prior to the day's meetings, members spent drafting materials; afternoon was opening session of JOA. From 6:00 pm to 9:00 pm, the second meeting of WG 34 was held. All above were present, with the exception of the two observers.

In the course of these two meetings, the status of eddy research was drafted and discussed.

APPENDIX III

References

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Kort, V.G., and V.S. Samoylenko (eds), 1974: "Atlantic Hydrophysical POLYGON - 70", Science Publications House, Moscow, 314p (Russian).

Koshlyakov, M.A., and A.S. Monin, 1978: "Synoptic Eddies in the Ocean". Ann. Rev. Earth Planet. Sci., 6, 495-523.

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Nelepo, B.A., N.P. Bulsakov, I.E. Timtchenko, *et al.*, 1980: "Synoptic Eddies in the Ocean", Naukova Dumka, Kiev, 286pp (Russian).

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