

## DEVELOPMENT OF THE INTERNATIONAL INDIAN OCEAN EXPEDITION

ROBERT G. SNIDER  
*New York, N.Y. (U.S.A.)*

During the period of less than five years since the Special (now Scientific) Committee on Oceanic Research (SCOR) was established (July 1957), much of its effort has been devoted to the development of the International Indian Ocean Expedition. Recognition of the need for and the advantages of international cooperation in oceanic research arose from experience in the International Geophysical Year. As a site for the first coordinated effort, the Indian Ocean was selected.

Although the Indian Ocean's 28,000,000 square miles cover over 14% of the earth's surface, relatively little is known or understood about the region, which has an area five and a half times that of Antarctica, and greater than that of Asia and Africa combined. The Ocean's behavior affects all of these continents, yet only the most general features of its topography and circulation and the distribution of living organisms are known. For instance, more than three hundred times as many bathythermograph observations have been taken in the North Atlantic as in the Indian Ocean; almost half of the area has had no biological sampling, and in most of the remainder observations range from 4 to 1 per 5° square.

The Indian Ocean has several unique characteristics. Nowhere else in the world is there a similar seasonal reversal of the prevailing wind. The wind system in that part of the Ocean lying above the equator is characterized by the two monsoons, one blowing from the Northeast for approximately six months, and the other blowing from the South-west for the rest of the year. This phenomenon has a vast but essentially still unknown effect upon the currents and organisms in the waters.

Then again, there is some evidence that biological productivity is high. The upwelling of nutrient-laden bottom waters off each coast at least once a year, as a consequence of the monsoon shift, would tend to confirm this.

The Indian Ocean is one of our last unexplored frontiers. Between 1873 and 1957, only about two dozen vessels had carried out oceanographic investigations there. Modern techniques had only been used in quite limited areas. Limited coverage had left great gaps in both the areas visited and in the nature, intensity, and accuracy of observations. No systematic study had been attempted nor did the combined profiles of the observations reported give more than a preliminary picture of the Ocean's behavior and characteristics.

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Many of the nations lying in the tropical and sub-tropical regions which surround the Indian Ocean are among the world's most densely populated countries, with continuing rapid growth. Over a quarter of the world's people live in these countries.

Population pressures on the existing food supplies result in prevalence of diseases attributed to protein starvation. Such protein deficiencies are common in India, Ceylon, Indonesia, Malaya, and in parts of the east coast of Africa. Some of the nations bordering the Indian Ocean have a seafaring tradition and conduct extensive fisheries. To feed their crowded populations, they are interested in expanding these fisheries.

In 1959, after two years of discussion, formal planning was undertaken. SCOR had requested that national committees of scientists be established to provide local liaison. It drew from these and its own membership to set up an Indian Ocean Expedition Working Group. After correspondence this body, with Dr. G. E. R. DEACON of Great Britain as Chairman, met in Copenhagen in July 1960 to draw up a basic minimum plan for the Expedition. Programs in Physical and Chemical Oceanography, in Biological Oceanography and in Marine Geology and Geophysics were drawn up, agreed upon by national scientific representatives, and approved in August 1960 at Helsinki by SCOR. At this time the International Association of Meteorologists and Atmospheric Physicists (IAMAP) was asked to assist in developing a program in Meteorology.

These programs outlined the known and probable problems which might be subjected to investigation in each discipline, and established acceptable uniform procedures for observation under varying conditions. The Working Group also dealt with problems of comparability of differing systems of observations, precise navigation problems, tide gauge networks, special equipments needs, shore facility requirements. Some agreement was reached on general areas of operation and responsibility. It was recognized that recent reconnaissance cruises, and those to be undertaken in the near future, would enable nations to develop more precise individual plans. There was general agreement that the full-scale operation of the Expedition would begin about July 1962. We now approach that time, and it would be well to see what was achieved in planning in the nineteen months following Helsinki.

#### STATUS

As of April 1 1962, the organizing and preliminary planning phase of the Expedition appears to be drawing to an end. Emphasis hereafter will be primarily on operational and scientific coordination in timing, in disciplines and in areas, and on refinement and amplification of plans in the light of increasing knowledge obtained about the Indian Ocean.

Thirteen ship-operating countries and seven non-ship-operating countries or governmental units are participating; 40 vessels are now scheduled to carry out work in the Expedition, and at least seven more vessels are likely to participate. Their cruises vary from a few months in length to several of well over a year, and one of two years. Funding for the next twelve months is generally adequate.

During the two years beginning June 1962, an average of at least seven ships will be operating at any one time in the Expedition, although in any given month this may vary from three to twelve or more vessels. Most scheduled effort now is in the months of December, January, February and March. Least ship activity occurs in April and May, in October and November. However, many cruises are scheduled to cover the same area in each monsoon.

Some areas are attracting appreciably more ships than others. Eighteen ships are scheduled to operate in the Arabian Sea, whereas only eight operate in the Bay of Bengal and many fewer ship months are involved. Between 10° N and 10° S, fourteen ships operate in the western half of the Ocean and fourteen operate east of 78° E. Fifteen operate in the South West Indian Ocean and thirteen in the South East. There is much less intensive coverage in the region below 32° S than above, and very little below 40° S. However, twelve reconnaissance cruises to date by various nations have revealed problems attracting further investigation in most regions. On the basis of these, and the cruises now scheduled in the next two years, it is reasonable to expect an increasing activity running into 1965. Few nations have detailed plans right now beyond early 1964.

A slippage of approximately six months has occurred in a number of programs. This does not constitute a serious problem at this stage of the Expedition. At a later stage it might. Although full-scale financing for the immediate budget years has encountered some resistance, no major reductions are in sight. Planning for subsequent years is developing in greater detail, together with the identification and commitment of individual scientists. A number of new vessels will become available during the next several years and they are being scheduled for maiden cruises in the Expedition. Interest and backing for the Expedition seems to be developing at a satisfactory rate.

The stage has now been reached when each nation must begin to interrelate its plans with those of others. Firm international commitments properly drawn up at a series of regional meetings, as well as through correspondence, will be required to achieve maximum coordination of the Expedition in disciplines, areas and times.

#### PARTICIPATION

A substantial fleet of research vessels from thirteen nations will operate in the Indian Ocean during the next three years. Of the total of 39 ships, 25 will come from six major oceanographic nations outside the region. France will send three, with the possibility of two additional. The German Federal Republic sends one; Japan will provide five, several making more than one cruise. The Soviet Union has had two major cruises and has scheduled another with the same ship, and is reported to plan others. The United Kingdom will make several cruises with each of three ships and the United States will have thirteen vessels, most of them making more than one cruise, in addition to the three already completed. It may also have two weather ships on station for two years.

The seven ship-operating nations within the Indian Ocean will operate intensively in the waters relatively near their coasts, and with their larger ships Australia, India, Pakistan and South Africa will range to several thousand miles from their own shores. Participants, and the number of vessels they will operate, are as follows: Australia (2); India (5); Indonesia (1); Pakistan (2) with two possibly additional; Portugal, from Mozambique (1); South Africa (2); and Thailand (1) with possibly one additional. These nations, and their vessels, represent the core of a developing indigenous oceanographic science, the development of which is one of the major objectives of the Expedition.

In addition to nations with ships, seven other participants will provide scientists who will carry out research in shoal water from land installations; will ride other nations' vessels conducting their own research or under training; operate tide gauges along their own shores; and participate through their Meteorological Services in the international network which will contribute to the study of tropical circulation and related meteorological problems. These nations or governmental units are Israel, Ceylon, Nationalist China, East Africa through its component parts (Kenya, probably Tanganyika and Zanzibar), the Malagasy Republic, Malaya, and Mauritius.

It should be noted that in addition to ship operations, all the nations bordering or in the Indian Ocean, and several of those outside the region are making coastal and island tidal observations. They are also making major contributions in both observation from the land and analysis of data in the meteorological program which draws on these observations as well as on those of ships and airplanes.

Another important category of participation is that of the international and inter-governmental agencies. UNESCO, a co-sponsor of the Expedition with SCOR, has allocated substantial funds for training, for meetings, and for partial support of specialized research centers associated with the Expedition program. FAO has advised on several problems and has made technical information available to participants. WMO, which has a formal consultative relationship on meteorological problems with SCOR, has worked in close cooperation with Expedition meteorologists and nations in developing and implementing the meteorological program, in particular the arrangements for the International Meteorological Center (IMC) to be set up at Bombay. Finally, the U.N. Special Fund has collaborated with the Expedition and with the Government of India in preparing to receive a proposal for partial support of the IMC.

In each country the scientists who will actually carry out the research are being identified. They, in conjunction with their colleagues in other nations, are drawing up detailed programs, are working to achieve intercalibration of varying techniques to get comparability of results, are developing common standards of observations, and are training additional personnel to carry out the research.

#### SCIENTIFIC PROBLEMS

Ship programs and the overall scientific efforts are designed to investigate a series of

problems in each discipline and area. Discussions among participants over several years have led to general agreement on their identity. Each nation or laboratory has selected those most suited to the interests and abilities of its scientists and its available facilities and equipment. The descriptions of some of these problems, quoted below, are drawn largely from 'A Special Report by the Committee on Oceanography of the (U.S.) National Academy of Sciences – National Research Council (September 1961)' but reflect international exchanges of plans and thinking.

#### BIOLOGICAL OCEANOGRAPHY

- "A. Systematic biological survey of the entire Indian Ocean... should focus on these problems:
1. Three-dimensional distribution of the flora and fauna in relation to the major water masses and their boundaries.
  2. Geographical variations in the rate of primary production, the abundance of animals and their relation to chemical and physical oceanographic features, water masses and boundaries.
  3. Seasonal changes in the distribution and abundance of organisms and of primary production in relation to the monsoon circulation. The effect of monsoon-induced upwelling upon the productivity of the Indian Ocean as a whole.
  4. Productivity of the equatorial convergence region as compared with the Pacific. The occurrence of potential pelagic fisheries.
  5. The transport of larval forms by monsoon-induced currents and its effect upon the distribution pattern of adult organisms.
  6. Systematic study of rare or undescribed species of the plankton, nekton, benthos, etc.
  7. The occurrence and behavior of migratory scattering layers, their identity, and their correlation with aggregation of pelagic fish populations.
  8. The relation between benthic populations and the nature of the substratum.
- B. Special studies in areas of particular biological interest and of phenomena unique to the Indian Ocean include:
1. The dynamics of plankton populations in regions of coastal upwelling. Relation between nutrients, primary production, zooplankton, fish and benthos. Effects of water temperature on species distribution. Succession of phytoplankton in time and space. The extent of the geographical area affected by upwelling, and variations within the area.
  2. The occurrence of discolored water, bioluminescence, fish mortalities during and following periods of upwelling. Physiological studies of the causative organisms.
  3. Distribution of small pelagic fishes (*e.g.* sardines) in local coastal areas in the Bay of Bengal and Arabian Sea. Seasonal migrations. Correlation with monsoon circulation, primary productivity. Potential commercial fisheries.
  4. The dynamics of plankton populations in the equatorial convergence. Relation to large fish population (*e.g.* tunas). Abundance in relation to potential commercial fisheries, migrations, seasonal variations.
  5. Descriptive and dynamic studies of coral atolls in the Chagos, Maldive or Laccadive island chains. Metabolism of coral reefs. Comparison with Pacific coral reefs.
  6. Diurnal vertical migration of zooplankton. Species involved. Relation to scattering layers. Effects upon phytoplankton nutrient regeneration.
  7. Vertical distribution of phytoplankton in stratified and unstratified water columns. Light adaptation of photosynthesis. Accumulation at the compensation depth, at temperature discontinuity. Relation to vertical distribution of nutrients, oxygen minimum layer.
  8. Systematics, distribution and abundance of macroscopic algae. Latitudinal and vertical zonation. Relation to upwelling. Possible commercial exploitation.
  9. Abundance of benthic fish populations in coastal waters. Relation to benthos. Food habits. Relation to upwelling. Potential commercial utilization (edible fishes, fish meal sources).
  10. Determination of micronutrients, growth factors. Bioassay tests to determine limiting

factors. Measurements of dissolved organic compounds, antibiotics, fish toxins, etc. in upwelling regions, discolored water.

11. Occurrence of *Trichodesmium* blooms, other bluegreen algae. Nitrogen fixation in nutrient-depleted surface waters<sup>1</sup>.

#### GEOLOGY AND GEOPHYSICS

"... the problems of special interest and import can be grouped according to: the substructure of the Indian Ocean as deduced from seismic, gravimetric, magnetic, heat flow, and bathymetric measurements; the sedimentary processes, composition, diagenesis, and history as reconstructed from analyses of cores and other samples, bottom photography, and pertinent geophysical data; and the boundary relationship with the bordering lands and islands.

#### Trenches

Work done on the Indonesian trenches, mainly by the Dutch, shows similarities to, as well as differences from, the island arc and trench system of the western Pacific and Caribbean regions, and permits several problems to be well defined. Previous difficulties in obtaining suitable long cores from these narrow, deep areas is reduced by the high-powered echo sounders and large winches now available. The classical Vening Meinesz gravity studies, which are the foundation of many modern concepts of crustal deformation and mountain building by compression were first carried out in this area. New techniques have been developed for seismic exploration at sea and for the measurement of heat flow through the crust. Surface ships can now make continuous magnetic and gravity profiles. A re-examination of this area is needed, using all these techniques together with precise echo-sounding. Seismic refraction work will be especially useful in establishing crustal reference points to which the gravity interpretations can be related. It would be highly desirable to do similar profiles across the Andaman Sea to learn what happens to the geophysical anomaly belts northward toward the folded mountain belts of Burma and India.

#### Mid-ocean ridges

The mid-Indian Ocean Ridge that extends south from the Arabian Sea into the Antarctic Ocean south of Australia has by inference been linked to the mid-Atlantic Ridge and the East Pacific Rise as a zone of seismic and crustal instability more than 40,000 miles long. Like the median rises in other oceans, the Indian Ocean Rise is characterized by frequent earthquakes. The only two measurements available to date indicate a comparatively high rate of heat flow from it. A rift or depression along its crest is shown on hydrographic charts of its northern end and has been confirmed by several 'Vema' profiles. Some scientists consider this rifted ridge a symptom of large-scale tension and spreading of the earth's crust. No seismic refraction studies of it have been made, however, and detailed gravity data are lacking. Almost nothing is known scientifically about the reefs and islands at its crest or their implications for its origin and history.

Unlike similar ridges in the Atlantic and Pacific, the Indian Ocean Rise is complex, bifurcating near Chagos into the Maldivo-Laccadive and Carlsberg Ridge. A flanking ridge contains the Seychelles and Mauritius groups. Granites, rare to unknown in oceanic islands and taken by some to indicate continental affinity, are found in the Seychelles. Geophysical study of these mid-ocean ridges and the crustal structure separating them from one another and from Africa, Madagascar and the Comoros is critically needed. Accurate delineation of the submarine topography may be critical. Dredged rocks, cores, and samples of the insular outcrops should be analyzed by petrologists, geochemists, and paleontologists, and age determinations should be obtained both of the granitic rocks and of other historically significant samples\*.

\* As we go to press, the first-fruits of the Indian Ocean Expedition in this area are being off-loaded from H.M.S. 'Owen' into the columns of *New Scientist* for 7 June 1962. Dr. B. D. LONGAREVIC and Dr. D. H. MATTHEWS, of the Department of Geodesy and Geophysics in the University of Cambridge, make a preliminary report whereby: (1) the expected deep 'median' valley was found by echo-sounder on each of three crossings of the Carlsberg Ridge; (2) the postulated 'Mozambique geosyncline', lying east of the African continent, was delineated by a combination of bathymetric, gravimetric

#### Rift zones

In addition to the possible rift zone along the crest of the mid-ocean ridge, the boundary rifts of Arabia and Africa, and the inhomogeneities across these rift zones are peculiar to the Indian Ocean and should be studied in the same geophysical and geological detail as the ridge system itself. ... In the Gulf of Aden, dry-land geology indicates east-west rift across major north-south structures. Work on this highly unusual tectonic feature could be related to detailed geologic reconnaissance already done on land in connection with the petroleum geology of Arabia.

#### Basins

Enclosed deep regions such as the Wharton Basin off Western Australia, the deeps south of the Bay of Bengal, the Somali Basin, and the deeps south of Mauritius, all suggest subcrustal anomalies that need geophysical investigation. These basins receive sediments in varying amounts and of varying composition from widely separated source areas. For example, river-borne silts and turbidity-current deposition are probably most significant in the northern basin. Isolation of these basins makes a comparative study of rates and agents of sedimentation feasible. The scale of investigation should range from closely-spaced well controlled sounding lines with gravity and magnetic data, cores, sonoprobe studies, and examination of submarine canyons and channels in the Arabian Sea and Bay of Bengal, to occasional long cores, dredge hauls, and seismic refraction stations in the basins far from land.

#### Continental shelves

Most known varieties of continental shelves are represented around the Indian basin and should be studied as major crustal units for their bearing on the problem of oceanic and continental structure and development, as well as for their sedimentary and biologic records and characteristics.

#### Other geological problems

Problems whose very nature cannot yet be formulated will be discovered through intensive laboratory analysis of dredged and cored bottom sediments.

In other regions, ancient climatic conditions and current systems have been studied by analysis of bottom samples. Variations in the earth's magnetic field have been deduced from magnetic measurements of cores and rock specimens. Determination of clay-mineral ratios, quartz content and trace elements indicate what proportion of the sediments are derived from terrestrial, atmospheric, and biologic sources, and furnish clues to the tectonic history of the nearby land areas. Studies of organic content reveal periods of high or low productivity in the overlying waters and thus yield indirect evidence of the physical and chemical characteristics of these waters. Similar studies, basin-wide in scope, can be carried out on the dredged and cored samples collected during the Expedition.

One problem peculiar to the Indian Ocean, the possible effect on the sedimentary column of the biennial monsoon winds and currents, can be studied by intensive analysis of cores collected from the north and western Indian Ocean.

Bacteriological processes strongly affect the chemistry of bottom deposits and their interstitial and superjacent waters. These processes have direct but little-understood relations both to the formation of economically recoverable mineral deposits, and to the biological cycle. Studies of these processes require facilities for shipboard refrigeration and aseptic storage, as well as specialized laboratories and personnel ashore.

Some investigators feel that bacterial action is involved in the formation of the manganese nodules that litter vast tracts of the deep-sea floor. The field programs of dredging and bottom photography

and magnetic observations as a 200-mile-wide off-shore zone, presumably of sedimentary rocks of considerable thickness, extending from Socotra in the north to Madagascar in the south; (3) mica samples sent home from the granite of the Seychelles had been dated by Dr. J. A. MILLER in Cambridge as pre-Cambrian, 'making the Seychelles look much more than a continental fragment': 'Owen' discovered 'enormous magnetic anomalies' in the central part of the Archipelago, around the largest islands ... Seismic refraction experiments in this area are planned for the new 'Discovery', in the early part of 1963.

followed by precise chemical analyses in shore laboratories will establish the extent, abundance, and tenor (and economic possibilities) of the nodules as ores of manganese, cobalt and nickel.

Minor relief on the ridges and on the deep-sea floor must be studied by precise echo-sounding; on the very slightly-sloping abyssal plains this will indicate direction of the sources of sediment. In the Pacific, Tertiary sediment outcrops have been found on numerous small mounds rising only 25–100 fathoms above the deep-sea floor. Two similar occurrences from the southmost Indian Ocean have been reported. The reason for such apparently non-deposition environments is not yet known.

The Indian Ocean is certainly one of the few places in the world, if not the only one, where relations between the sediments of broad shelf and deeply founded trench areas can be studied. Deep trenches are believed to be the sites of the flysch-facies sedimentation which is characteristic of a stage in the growth of many of the world's great mountain belts. Because of the great difference in their resistance to later deformation, the shelf and trench sediments are ordinarily dislocated and jammed together so that the transition zone is difficult to identify and study. A special objective of the geological program should be to study exhaustively suites of long cores taken across the deep Timor Trench and the Sahul Shelf off northwestern Australia. Such core studies should be related to geophysical, bathymetric, hydrographic, and biological studies in order to give the results as much meaning as possible.

Why dolomite which has never been synthesized at atmospheric temperature and pressure should be so abundant in the geologic column is one of the major mysteries in geology. The only dolomitic sediments known to be forming in a marine environment at the present time are those of South Australia, but magnesium-rich and possibly dolomitic sediments have recently been reported to occur on the western coast of Australia as well. Study of this problem could be coordinated with other studies of the carbonate sediments and shelf atolls of the Sahul Shelf, and the shore ends of the 7 or 8 already scheduled deep-sea traverses approaching the west coast of Australia.

The silica-rich sediments that are said to blanket part of the southern Indian Ocean and the contiguous Antarctic Ocean should be studied. Thus we will learn more about the geochemistry, paleoclimatology, and productivity. Some other important problems involve the Indian Ocean atolls. Why are the world's largest, most complicated (and most poorly understood) atoll groups situated right on the crest of the central ridge; and is the bank beneath the Chagos Archipelago really an enormous drowned atoll? What can the paired Maldivé and Laccadive Islands tell us of the rifted crest and history of the mid-ocean rise?

Although studies of the beach and shoreline processes and of the geology of the bordering lands and included islands are of importance in the overall geological picture of the Indian Ocean area, these studies do not necessarily have to be done during the Indian Ocean Expedition, nor are they suited to accomplishment by a primarily oceanographic expedition. However, every opportunity should be utilized to put competent geologists and reef specialists on to the poorly-known islands of the Indian Ocean.

South Cocos Keeling, for example, is the only atoll ever studied in the field by Charles Darwin, and some effort to restudy it and compare present features with those described by Darwin would be of interest. Besides the reef islands there are plutonic, volcanic and metamorphic islands whose systematic study would undoubtedly contribute much to the interpretation of Indian Ocean history and boundary relations. When possible, field parties should collect samples of fresh, accurately located and labelled rocks. Samples weighing a couple of pounds will do for most purposes, but fifty-pound samples should be obtained of granitic rocks so as to permit radioactive dating. All samples should show the direction of true north and the vertical for paleomagnetic and petrographic orientation<sup>2</sup>.

#### METEOROLOGY

##### *"Description of large-scale atmospheric circulation"*

All features of the atmospheric circulation are, of course, interrelated. It is, nevertheless, useful to distinguish the following major features of the atmospheric circulation of the Indian Ocean region, for which description is incomplete and understanding inadequate.

1. Although the northern summer monsoon blows predominantly from the southwest at low levels, monsoon rains first begin over South China, apparently in response to upper tropospheric changes

initiated southwest of India. Onset of the Burma monsoon in May coincides with what seems to be intense cyclogenesis in the upper troposphere over the Bay of Bengal, while the final surge of the monsoon into central India in June and July may be associated with major upper-level changes over and to the west of the peninsula.

Over the ocean, description of the monsoon is still more uncertain. In the region west of 65° E, air at low levels probably flows massively across the equator, from north to south in the northern winter and from south to north in the northern summer. East of 65° E, however, the Asian and Australian branches of the monsoons are essentially confined to their own hemispheres and are not associated with large-scale, persistent transequatorial flow. A small net flow (5 knots) crosses the equator from the winter to the summer hemisphere, apparently through the agency of equatorial eddies, rotating clockwise in July and counter-clockwise in January. No data exist on equatorial circulation at higher levels.

In summary, the sequence of events and the spatial relations between events which make up the large-scale circulation have not been explained in theoretical or physical terms.

2. Wind soundings between 50,000 and 100,000 feet over the equatorial Pacific reveal alternate layers of persistent easterlies and westerlies. The boundaries between layers progress slowly downward toward the tropopause, where they weaken and disappear as new layers successively appear in the high stratosphere. The whole sequence, taking a period of 26 months, has so far proved inexplicable.

3. Equatorial eddies have been identified in the Indian Ocean region: but their relationships to tropical-cyclone (hurricane) development and to the larger monsoon circulation have not been described. An intermonsoonal dry region may exist in the region of the Seychelles Islands, but its relation to other features of the circulation is little known<sup>3</sup>.

##### *Determination of the vertical fluxes of water vapor, heat, and momentum*

Energy transfer between ocean and atmosphere is responsible in large part for the circulation of both fluids; determination of this transfer is, therefore, a basic and essential part of a comprehensive geophysical program. The Expedition gives an unparalleled opportunity for making more accurate calculations of these quantities than has been done in the past, and for comparing the results of calculations using different methods.

Comparison is essential in providing checks on inherently difficult calculations and in extrapolating from necessarily limited measurements to conclusions of general importance. Three basic methods for flux determination exist; and we recommend that all three be used, in so far as possible under compatible conditions. The first of these, the use of equations of continuity to infer large-scale fluxes through the air-sea interface from measurements of horizontal flux through vertical sections, is an indirect method. The second, based on measurements of the fluctuations of temperature, wind speed and humidity, yields a direct determination of the vertical fluxes. We recommend fluctuation measurements from aircraft at various heights and from platforms close to the atmosphere-ocean interface as described below. The third method is based on the measurement of vertical 'profiles' of the mean temperature, wind speed, and humidity in the lowest few meters of the atmosphere and is referred to as the aerodynamic method. It is direct in the sense that it is based on turbulence theory, but is indirect in the sense that the basic theory remains incomplete. The coordinated research program recommended here should contribute toward a more general theory, and may lead eventually to direct determination of surface stress, evaporation and turbulent heat flux from profile observations to direct determination of surface stress, evaporation and turbulent heat flux from profile observations<sup>4</sup>.

##### *Mean energy transfer (heat budget) for the atmosphere and ocean*

In order to describe and understand the mechanism which converts solar radiant energy to atmospheric and oceanic structure, and into the kinetic energy of motion on all scales, we need quantitative measurements of the total energy transferred at the ocean-atmosphere boundary and at the top of the atmosphere. We need these data not only for the limited areas and time periods studied in the programs described above, but also for regions and time periods as extensive as possible (at least the entire Indian Ocean region and for each month in a single year). Clearly, it will be necessary to extrapolate the intensive observations and calculations described above, but it will also be necessary to provide additional observations<sup>5</sup>.



## PHYSICAL AND CHEMICAL OCEANOGRAPHY

"Many research ships have passed through the Indian Ocean during the last 80 years so that a considerable body of data on the average three-dimensional distribution of the physical and chemical characteristics of this area has accumulated. However, because these ships avoided the monsoon season and because few of them made sufficiently closely spaced observations it has never been possible to describe in a reliable manner the *changes* in the water column which accompany the annual reversal of the monsoon winds. Although the average seasonal changes in the surface currents have been worked out through the accumulated reports of commercial ships we simply do not know how far down these currents extend.

The weather regime over the Indian Ocean provides a unique opportunity to attack some basic problems of physical oceanography. The results of this work will be applicable to all areas. How rapidly do wind currents form? How fast do they deepen after the onset of a new wind system? How long after the winds have reversed in direction do the old currents continue to flow? These are some of the very basic questions in physical oceanography that can best be studied through carefully planned field programs in the northern part of the Indian Ocean and in the powerful currents flowing along the eastern coast of Africa.

From the chemical standpoint, the unique feature of the Indian Ocean north of the heat equator, is that it is the only large ecological system where most of the coastline experiences off-shore winds during prolonged parts of the year. Thus upwelling of nutrient chemicals is more uniformly distributed here than in the other oceans. The question immediately arises as to whether or not this should sustain a greater annual total productivity of the surface waters. In any case, the distribution and intensity of the oxygen minimum layer should be different in interesting ways from low-latitude ocean areas with a more stable wind system.

Other aspects of the chemical program, such as the more specialized analysis of the 'library' of water samples, should provide further information on the effects of the pronounced seasonal changes in the wind system. While the Indian Ocean is at present the only considerable area experiencing a strong seasonal reversal of the wind system, there is no good reason to believe that this has always been so. Thus geochemists will probably find the peculiarities of the three-dimensional chemistry of the Indian Ocean of considerable interest and value in interpreting the past in other areas<sup>6</sup>.

There has been considerable interest in recent years in the currents at the equator; both the currents of the ocean and the currents of the atmosphere. The Cromwell Current was first discovered ten years ago and extensive measurements of it were made in 1958 (KNAUSS, 1960). The Cromwell Current transports about  $40 \times 10^6$  tons of water/sec (about half the transport of the Gulf Stream). It flows at a speed of two to three knots; it is about 400 kilometers wide and less than 400 meters thick. It is a subsurface current which flows to the east and is completely imbedded in the westward-flowing South Equatorial Current. A current similar to the Cromwell Current has recently been measured in the Atlantic.

One of the most remarkable features of the Cromwell Current is that it is centered on the equator. Within the accuracy of our observations to date, the flow seems to be completely symmetrical about the equator. In this respect (and perhaps, others as well) it is similar to the Berson westerlies, an eastward-flowing wind, speed about twenty kilometers, located at the base of the tropopause.

There have been several attempts in recent years to explain these equatorial currents, but our understanding is still far from complete, and this is one of the main reasons why it is of considerable interest to know the nature of the equatorial circulation in the Indian Ocean. The conditions in the Indian Ocean are so different from the Atlantic and Pacific that a detailed knowledge of the equatorial circulation here might shed some light on the problem of explaining such currents in other oceans<sup>7</sup>.

## PROSPECTS

These problems will be approached with a massive effort of skilled scientific manpower, highly specialized equipment, ships, shore installations, airplanes and laboratories during the next three years; 25 ships will conduct physical and chemical research, 23 will do biological investigations, 25 will work on geological and geophysical prob-

lems and 18 on meteorology. Most will conduct research in several disciplines. No information is available on 11 ships' programs. As of early April 1962, 212 ship months, or almost 18 ship years, were planned. Operating costs range, for major research vessels, from \$ 800 to \$ 2,100 per day. If a representative figure of \$ 1,200 per day is selected, this can be said to represent almost \$ 8,000,000 of ship operating time alone now planned.

In this connection, however, it should be noted that the programs and operations of 22 ships are not included because of inadequate information on schedules. Furthermore, many nations have no precise plans now drawn up for the period after early 1964. It is reasonable to expect that as more research leads to a more precise definition of problems, further investigation will be undertaken.

It must also be borne in mind that this rough cost figure does not take into account the cost of analysis of the data, the cost of the entire non-shipborne meteorological program, the cost of the tide-gauge program, publication costs, training costs, new plant and equipment costs and similar items. It seems reasonable to estimate the entire Expedition effort among the nations to be in the order of a number of tens of millions of dollars.

Such an outlay, by itself, cannot assure significant results. The growth of the program, the assurance of financial support, the results of reconnaissance cruises are all attracting a growing number of the world's ablest scientists to the Expedition. Efforts to achieve real intercomparability of results and standardization of procedures are encouraging. Growing exchange of advance information and collected data make the Expedition planning more effective. The growth of this type of activity augurs well for the program.

## REFERENCES

- <sup>1</sup> *A Special Report by the Committee on Oceanography of the National Academy of Sciences*, Appendix A, pp. 2 (mimeographed), National Research Council, Washington, D.C., September 1961.
- <sup>2</sup> *Ibid.*, Appendix B, pp. 1.
- <sup>3</sup> *Ibid.*, Appendix C, p. 2.
- <sup>4</sup> *Ibid.*, Appendix C, p. 5.
- <sup>5</sup> *Ibid.*, Appendix C, pp. 9.
- <sup>6</sup> *Ibid.*, Appendix C, p. 1.
- <sup>7</sup> JOHN A. KNAUSS, *Equatorial Circulation of the Indian Ocean*, (Processed) Appendix A to UCSD-992 of August 1961, p. 1, Scripps Institution of Oceanography, La Jolla, August 1961.