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Preface

Presented during the twelfth session of the Assembly of the Interfovernmental Oceanographic Commission, this series of lectures is dedicated to the memory of the noted Danish oceanographer and first chairman of the Commission, Dr Anton Frederick Bruun. The « Bruun Memorial Lectures » were established in accordance with IOC resolution VI-19 in which the Commission proposed that important inter-sessional developments be summarized by speakers in the fields of solid earth studies ; Physical and chemical oceanography and meteorology ; and marine biology. The Commission further requested Unesco to arrange for publication of the lectures and it was subsequently decided to include them in the «IOC Technical Series ».

Anton Bruun was born on 14 december 1901, the first son of a farmer ; however, a severe attack of polio in his childhood led him to follow an academic, rather than an agrarian, career.

In 1926 Bruun received a Ph.D. in zoology, having several years earlier already started working for the Danish Fishery Research Institute. This association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C.G.Johannes Petersen and Th.Mortensen.

Of even more importance to his later activities was his participation in the Dana Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to studies of animals from the rich *Dana* collections and to the publication of his treatise on the flying fishes of the Atlantic. In 1938 he was named curator at theZoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945 to 1946 he was the leader of the *Atlantide* Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the *Galathea* Expedition in 1850-1952, which concentrated on the benthic fauna below 3,000 m. and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name « hadal ».

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies such as the Scientific Committee on Oceanic Research (SCOR), the International Advisory Committee on Marine Sciences (IACOMS), the International Association for Biological Oceanography (IABO) and the Intergovernmental Oceanographic Commission (IOC) ; he was elected first Chairman of the Commission in 1961.

His untimely death a few months later, on 13 december 1961, put an end to many hopes and aspirations, but Anton Bruun will be remebered for his inspiring influence on fellow oceanographers and his scientific contribution to the knowledge of the sea which he loved so much.

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Opening statement

Dr. Neil J. Campbell, First Vice-Chairman

Ladies and Gentlemen,

It is my honour to welcome you to the Bruun Memorial Lectures on the occasion of the XIIth Assembly of the Intergovernmental Oceanographic Commission.

The four lecturers today honour the name of Dr. Anton Bruun from Denmark, who was one of the founding fathers of this Commission, serving as our First Chairman in 1961. His untimely death in his first year of office led to the decision to honour his name through the dedication of these lectures at each Assembly.

The sessions today will deal with studies initiated by the Commission's Scientific Review Board. The IOC Executive Council requested the Commission's Advisory Bodies to make a study of « expected major trends in ocean research up to the Year 2000 ». The Scientific Committee on Oceanic Research (SCOR), took the lead in organizing this effort, known as future ocean research (FORE), in co-operation with the secretariats of IOC and UNESCO, the Advisory Committee on Marine Resources Research (ACMRR) of the Food and Agriculture Organization, and the Engineering Committee on Oceanic Resources (ECOR). The project is a follow-up to the 1969 study entitled, « Global Oceanic Research » and commonly known as the Ponza report. That report was subsequently used by the IOC in preparation of its Long-term and Expanded Programme of Oceanic Exploration and Research.

At SCOR's invitation, Professor Eugen Seibold agreed to chair, and Professor Warren Wooster to serve as Rapporteur of the study.

It was agreed that the principal questions of ocean research should be considered within the four basic subject areas of physics, chemistry, biology, and geology/geophysics, with interdisciplinary aspects and principal applications (climate, pollution, fisheries, and non-living resources) being covered as appropriate. For each subject area, a leader and three associates were selected to prepare a background paper.

The four speakers today, in order of presentation, are the principal authors of the FORE report :

Dr. Malik Talwani, Geoglogy/geophysics

Dr. Klaus Hasselmann, Physical oceanography and climate,

Dr. David Dyrssen, Marine chemistry,

Dr. Martin Angel, Marine biology and ecology.

We are indeed fortunate in having them with us and I would like to welcome them to our Twelfth Assembly.

As I mentioned before, our first guest speaker is Dr. Malik Talwani.

Dr. Talwani received his Master of Science degree in Physics at Delhi University, India, in 1953 and his doctorate in Geophysics from Columbia University in 1959. He served as a professor at Columbia Unersity from 1965 to 1982 and was Director of the Lamont-Doherty Geological Observatory of Columbia University from 1972 to 1981. At present he is head of the Centre for Marine Coastal Studies of Gulf Research, Pittsburg, Pennsylvania.

His research interests include application of gravity, magnetics and seismic methods to coastal structures and evolution of oceanic features especially mid-ocean ridges and continental margins.

He is the holder of many awards and honours including the Krishnan Medal from the Indian Geophysical Union in 1967 and 1981. In 1972 he was the recipient of the NASA exceptional scientific achievement award and in 1981 was awarded, further, a PhD (honoris causa) from the University of Oslo.

Ladies and Gentlemen, Dr. Talwani.

The ocean floor and what lies beneath it

Dr. Manik Talwani

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Summary

Research in marine geology and geophysics — exploration of the floor of the ocean and what lies beneath it will be full of excitement in the coming decades. There are challenging scientific problems which are sure to attract the best scientific minds, and the research has important practical uses which should ensure its financial support. Among the research problems that will engage the scientists are :

The geological structure and history of continental margins, particularly with a view to exploration for hydrocarbons ;

The study of « active » continental margins, the causes of earthquakes, volcanic eruptions and other natural hazards and their prediction ;

the study of processes at the mid-ocean ridges by which new crust is produced, and the generation of metallic ores at these locations ;

the study of the deep ocean floor, the study of manganese nodules that lie on it and consideration of the possibility of using the deep ocean as a site of radioactive waste disposal ;

the study of sediments on the continental slopes and the suitability of such areas for locating man-made structures on the ocean bottom ;

the study of sedimentary layering at the ocean bottom and the derivation from it of past climatic succession and the prediction of climatic variations in the future.

For many of the studies mentioned above, the development of new technology and the deployment of present technology in large unexplored parts of the ocean is essential. The history of marine geology reveals that most major advances have resulted directly from major technological advances and that connection is certain to continue to exist in the future.

This talk draws heavily on a paper outlining the future of research in marine geology and geophysics that I prepared jointly with D. Cronan, J. Thiede and Y. Lancelot.

In describing present day research and in anticipating future research in marine geology and geophysics, I would like to develop three principal themes.

The first is that in order to have excellent research there have to be scientific questions which are interesting and vital and which engage the interest of the very best scientists.

The second is that the development of new technology and the effective deployment of existing technology can be an extremely important element in making major advances in this field.

The third theme that I would like to advance is that at some level, directly or indirectly, the research must contain promise of being of help to society. The more costly the research, the more urgent becomes the need for relevance to the needs of society.

As many of you undoubtedly know, the field of earth sciences has in the last ten or fifteen years undergone a revolution and developed a unifying framework known as Plate tectonics. This framework postulates that the rigid crust of the earth is composed of a number of plates and it is the motion of the plates relative to each other which gives rise to phenomena such as earthquakes, volcanism, and, over long periods of geological time, mountain building. The plates are being pulled apart at the mid-ocean ridge and being pushed together at, for example, the margins of the Pacific Ocean. Perhaps the most important question in earth science is « What drives these plates — what are the causes of plate motions ? » This question has engaged the attention of some of the leading geologists and geophysicists. But it is not the kind of question which can be answered by a single experiment or by a single new development in technology. And, although the understanding of the underlying cause of plate motion is very important in deciphering the geological evolution of the Earth, it is not the kind of advance which will provide short-term benefits to society.

A second question is « What are the details of the nature and composition of the oceanic crust ? » It is a curious aspect of the development of Plate tectonics that while the details of plate motions in the horizontal direction over thousands of kilometres are beginning to be known in minute detail, our knowledge about what lies down in the vertical direction — that is, just what is it that this oceanic crust is made up of — is far from complete. Learning about the oceanic crust is indeed important because it underlies all the oceans ; but the subject is not just an academic one. Many believe that oceanic crust eventually gets assimilated into continental crust. In other words, much of continental crust may be recycled oceanic crust. If, for example, we can decipher patterns of emplacement of minerals in oceanic crust, this may give us valuable clues to looking for minerals in continental areas. New experiments and the development of new technology should play an important role in the exploration of the oceanic crust. Much of the new technology will involve seismic methods. Conventional seismic methods generally involve the phenomenon of seismic reflection. A large source of sound carried by a ship produces sound waves which are relected at the various sedimentary layers beneath the ocean and received by an array of receivers towed behind the ship. The time of travel of sound in the various layers can be measured and tells us about the properties of these layers. Conventional seismic methods, unfortunately, do not reveal much in the hard volcanic rocks which constitute much of oceanic crust. Here is an area where new technological developments involving complex and expensive seismic experiments are undoubtedly necessary and, in fact, are being conducted. If they are successful, they should greatly increase our understanding of the oceanic crust.

A third question is, what are the precise processes operating at the crests of mid-ocean ridge, the site where new material rises up from the earth's interior and solidifies to from new ocean crust. Fascinating questions pertain to phenomena such as hydrothermal circulation. Hot fluids appear to leach valuable minerals from rocks lying at depth and rise to redeposit them near the ocean surface. There is speculation that sulphide ores thus deposited may turn out to have a greater commercial value than the much better known manganese nodules. In this area, new knowledge has been a very direct consequence of the application of new technology. Direct observations made from submersibles — *Alvin* from Woods Hole Oceanographic Institution and *Cyana* from Cnexo are examples — yielded startling new findings. Dives on the crest of the mid-ocean ridge revealed phenomena which by now have become quite familiar even to the layman — plumes of superheated water charged with metallic ores which have the appearance of smoke coming out of chimneys. Worms of enormous size and the high concentrations of bacteria in the anaerobic hydrothermal waters represent big mysteries. The possible commercial use of metallic ores has been much discussed. What has not been considered but which might turn out to be of great value is the value of the superheated water as a source of energy, possibly through conversion to steam as pressure is lowered.

We now turn to a fourth series of questions that relate to passive continental margins. These are areas which, for example, border most of the Indian and Atlantic Oceans and which are now being passively rafted, lying as they are in the interior of the moving plates. But at one time in geological history these passive margins were the sites at which the super-continents broke up and the ocean came into existence in between. Buried under the large thicknesses of sediments which often exist over the passive continental margins are scientific puzzles as well as economic questions. The scientific puzzles concern the geological evolution of these margins — why did the super-continent break up in the first place. Subsequent to breakup what has been the history of subsidence, the thermal history, and the history of sedimentation of these regions ? Thes matters are particularly relevant to the questions of whether hydrocarbons — oil and gas were generated here and were able to accumulate and be trapped in geological reservoirs, and whether they have been preserved in the traps and not escaped. These questions are, of course, of great economic importance. The possibility of finding oil and gas in the sediments underlying the Continental Shelf and Slope has been highlighted during the law of the Sea negotiations which you are all undoubtedly aware of. What is generally not realized is how difficult and expensive it is to explore and to produce oil and gas as the depth of water increases to only a few hundreds of metres. Potentially the offshore *could* countain enormous reserves of oil and gas and I underline the word « could. » On the other hand, extensive exploration efforts could, in many instances, produce no hydrocarbons at all. Thus offshore exploration, especially drilling, could be an extremely risky business financially. The risks could be minimized by extensive research in exploration methods. Although technology is well advanced in this area, new technological innovations as well as the development of new exploration concepts could be extremely fruitful. If we are not innovative enough, we run the danger of running out of money to explore oil before we run out of oil itself.

In contrast to the passive margins, the active margins are areas where a large amount of geological activity is gouing on at present. Here is where the plates collide, with one plate often being subducted under the other one. The relative motion and jostling around of the plates causes earthquakes ; when the material subducted down to great depth melts and escapes to the surface, volcanic activity results. It is clear that if we can learn about the causes and details of plate motions we may take large steps toward the prediction of catastrophic phenomena such as earthquakes and volcanic eruptions. The active margins also often contain a large thickness of sediments. Some of these have been scraped off the subducting plate and on to the overlying plate. Other sediments had been deposited at earlier times on the overlying plates. The active margins could turn out to be as important as the passive margins as far as the accumulation of hydrocarbons is concerned. In the past the active margins have been considered less favorably in the belief that persistent geological activity there had « chewed » up the rocks and perhaps allowed any accumulated hydrocarbons to escape. Drilling carried out at a number of active margins as a part of the Deep Sea Drilling Project has changed some of these views. Both from the points of view of understanding catastrophic phenomena such as earthquakes and volcanism and for the search for hydrocarbons, active margins are areas where innnovative research and exploration are needed. As in the case of passive margins, the development of new techniques and the massive deployment of existing techniques could involve large financial outlays and risks but the dividends could also be substantial.

At this point I should like to talk briefly about *back-arc basins*. These are the areas that lie between the active margin areas that we have discussed above and the main continental blocks. Examples are the Bering Sea, the Sea of Japan, South China Sea, Philippine Sea, the Fiji Basin and a number of others. The back-arc basins are of interest for a number of reasons. In contrast to the mid-ocean ridges, ocean basins and the active and passive margins which are now understood in general terms within the framework of plate tectonics, the *geologic evolution* of back-arc basins could also have much economic interest. The proximity of the continental land masses provides a source of sediment so that these basins often contain a thick accumulation of sediments. Even though these may be geologically young the high temperature prevailing at depth beneath many of these basins may serve to convert the organic matter contained in these sediments to oil and gas. Secondly, if some of these back-arc basins opened up in the manner of mid-ocean ridges, one can envisage the emplacement of *sulphide ore* deposits as on the present day ridge crests. If, further, these deposits were rapidly covered by thick layers of sediments, oxidation of the ores would be prevented and the sulphide ores could be preserved for a long time. The possibility, thus, of the back-arc basins being the repository of hydrocarbons as well as metallic ores is an intriguing one. Consequently it is likely that much research and exploration effort will be concentrated on these areas.

Up to this point, I have talked about various geologic problems and areas, whether or not new technology will play an important role in solving these problems, and the usefulness of studies in these areas from the point of view of societal need.

I would now like to digress a little bit, and talk about a few specific technological innnovations. The point that I would like to make is that while new technology is often developed to address a specific problem, *it can, in addition,* yield information and open scientific vistas which were entirely unexpected, and can lead to great scientific progress. I am not advocating that we build expensive new instruments just to see what they might discover — such open-ended research may be much too expensive. What I am advocating is that when new technological developments lead to unexpected findings, we should be able to capitalize on them ; and good scientists have, of course, done just that. Let me give a few examples. An instrument called the satellite *altimeter* can, very precisely, measure the distance of the satellite from the sea surface in the manner of an echo sounder measuring the distance to the bottom of the ocean from a ship. And if the satellite is tracked very accurately, the altimeter can yield the varying height of the sea level surface. In the absence of waves, there are two principal causes for the distortion of the sea level surface. One is ocean currents and they tend to pile up the water and thus to distort the sea level surface. The Gulf Stream, for example, can distort the sea level surface by one metre or even more. The other cause is that density inhomogeneities can distort the gravity field and hence distort sea level which is a surface of equal gravity potential. Although the principal motivation to develop and employ the altimeter came frome physical oceanographers who wanted to use this device to map ocean currents, the results obtained have been of very great interest to the marine geophysicists. As I have just indicated, density inhomogeneities distort the gravity field which is reflected in a distortion of the sea level surface. By mapping this surface with the altimeter we can work backwards and deduce the gravity field and obtain the gravity anomalies. For anybody who has made measurements of gravity at sea aboard a ship and spent several months mapping an area, the fact that similar information can be obtained by a satellite in a fraction of the time is almost staggering. (It must be said, however, that resolution by satellite is not as good as by surface ship instrumentation at present.) It is also instructive to compare the gravity field with the morphology of the ocean bottom. The comparison, of course, reflects the fact that in deep water it is the sea bottom topography which gives rise to the largest variations in the gravity field. Thus the satellite altimeter data are able to provide us with ocean bottom morphology. Where the ocean bottom is flat, it is the sub-buttom features that give rise to the variations in the gravity field, and thus the satellite altimeter has the capability of detecting *sub-buttom features* — a capability that was not at all envisaged when the instrument was first planned.

I am really awed by this development of satellite technology. Here, all one is doing is measuring the minute distortions of the sea level caused by small amounts of excessive mass or deficits in mass, associated mainly with the submarine topography. But by making this measurement precise enough, we can obtain bathymetry from a satellite which is hundreds of kilometres above sea level. I cannot conceive of a better reconnaissance tool for finding out quickly the bathymetry in remote parts of the world's oceans, and even, in some areas, what lies under the ocean bottom.

A second technological development that I would like to talk about is the imaging of the ocean bottom with acoustic methods. While the development of side-scan sonars in shallow waters has been going on for a long time, their development in deep waters has been more limited. It was pioneered by the British at the Institute of Oceanographic Sciences. *Gloria,* as the equipment is called, is towed behing a ship in a stable configuration to prevent it from rolling and pitching. The sound beams emitted by the transducers carried in *Gloria* emit sound at a frequency of about 6 Hz. The horizontal beam width is 21/2° and the vertical angular beam width is 30°. At a depth of water of 5 km, about 30 km to each side can be seen by *Gloria.* The sonograms made by *Gloria* need some practice for interpretation. Slopes that are facing the instrument appear bright, and slopes that are facing the other way do not reflect any energy back to the instrument and are black. Because the range changes relatively slowly where the reflection is nearly vertical, the image is greatly distorded and the horizontal scale is considerably reduced in the area just below the ship. This has to be taken into account in viewing its sonograms. Several examples of *Gloria*'s findings can be given. The Equatorial Mid-Ocean Canyon was one of the surprising discoveries of the 1950's made by a number of closely spaced ships's tracks. We learnt that submarine canyons exist not only in continental margins but also in the middle of the ocean. By a single pass of *Gloria,* it was possible to map the mid-ocean canyon and it was also possible to discern the burial of the upper end of the channel by sediment, which indicates that it has been inactive for at least — it is estimated — one million years.

A spectacular field of sand waves in the Blake-Bahama Ridge, just east of the Bahama Islands, has been revealed by *Gloria,* along with another on the flanks of the East Pacific Rise — a mid-ocean ridge — off Peru, and depicting the strikingly linear nature of ocean floor morphology — interrupted only by an occasional cross-trending fracture.

The point of mentioning these examples is to demonstrade how with this new technology one is able to obtain sonic images of substantial areas of the ocean floor in rather impressive detail in a relatively short time. *Gloria* and other side-scan sonars will undoubtedly serve as important reconnaissance tools in conducting geological studies in the oceans in the future.

As a final example of new technology, I want to mention deep sea drilling. The drilling program on the *Glomar Challenger* is a splendid example of scientific discoveries well beyond what the initial planners of the program had thought about. Because, in general, there is far less erosion on the ocean bottom than on land, the chances of preservation of a continuous succession of sediments are much greater in the oceans. From the continuous succession of sedimentary layers much has been learnt about the succession of environmental conditions. In fact the deep sea drilling program has given a tremendous boost to the field of paleo-environment, and I have deliberately chosen the example of deep sea drilling to go back into the area of important scientific questions that remain to be solved in the field of paleo-environment.

An important question in paleo-environment is what causes rhythms and cycles in the pelagic sedimentary record. Some estimates indicate that these cycles are generally in the range of a few tens of thousands of years. The cycles obtained in the Quaternary record appear to be so regular that they can be best explained by the « Milankovich mechanism » which invokes regular variations in the Earth's orbital parameters as a cause for the succession of ice ages separated by warm interglacials. However, this correlation does not seem to extend into the Tertiary since the cycles observed in cores of Tertiary age do not seem to represent a succession of glacial and interglacial stages. Thus the causes for these cycles and the relationship to climate remain a mystery. It is important to solve it because if we can determine the causes for variation of climate in the past we may be able to predict changes of climate in the future.

Another important question concerns the causes and consequences of changes in sea level. It is now generally accepted that there are both short-term changes and long-term changes, and it is also accepted that many changes are not very well understood. The very sudden and large changes are particulary mysterious.

Still another question concerns the causes and timing of ice ages. The deterioration of the global climate since the end of the Mesozoic and the evolution of ice-covered areas since mid-Tertiary times are the most dramatic envents which have affected and changed oceanic depositional environments for the past 200 million years. Why large southern hemisphere ice sheets formed in the mid-Tertiary but large northern hemisphere ice sheets did not come into existence before late Pliocene times is not understood.

We have mentioned earlier that the sedimentary record in the oceans is likely to be more continuous than on land where erosion is more effective in removing some of the sediments. Thus the examination of the sedimentary record recovered by drilling in the oceans may answer some important questions about the evolution of marine organisms whose fossil remains are buried in the sediments. We should be able to test the emerging concept that evolution is not achieved gradually but that most evolutionary changes are concentrated in a relatively limited number of events.

A related question is whether instantaneous catastrophic events are responsible for changes at the Cretaceous-Tertiary boundary where an unprecedented mass mortality in the oceans is observed. Approximately 90 % of the biomass of the oceans was wiped out, apparently, in a few tens to a few hundred years, and pelagic environments of the ocean were so disturbed that it took tens of thousands of years for conditions to return to normal. What causes these catastrophic events ? Is it the collision of a large celestial body with the earth or is it series of massive volcanic eruptions ? In both cases a massive input of dust into the atmosphere which causes a « brown out » which in turn causes an instantaneous decrease in the solar radiation received by the earth.

In the above I have discussed briefly some of the questions which are of interest to scientists interested in paleo-environments. These questions are certain to be the focus of much research in the coming years.

I have tried where possible to link important questions in research with important applications. Before concluding I would like to mention two applications concerning the ocean floor which, because of their importance, will undoubtedly be the focus of much research.

One of immediate concern is the disposal of high-level waste from nuclear reactors under the deep-sea floor. Investigations at proposed dump sites will involve the question whether the sites are geologically stable and the sediments are thick enough to ensure reasonable burial. Engineering studies will be needed to evaluate the nature of canister emplacement, and finally geochemical studies on sediments and pore waters will be needed in order to assess the likely migration and uptake of radionuclides leaked from the canisters.

The geological stability of the ocean floor is also very important as we envisage the emplacement of man-made structures such as heavy platforms on it. Such structures may be needed for the recovery and transportation of hydrocarbons and other minerals. Devices such as side-scan sonars may find increasing use for these purposes. The detailed morphology of the ocean bottom at a scale needed for emplacement of structures is still virtually unknown. Vigorous investigations in this area could lead to unexpected scientific breakthroughs.

To conclude, let me re-emphasize the three basic themes, or perhaps, more properly, requirements for future oceanic research.

1. The research should be aimed at answering important scientific questions.

2. New developments in technology are very important in achieving new scientific breakthroughs.

3. The application of research findings for purposes that are valuable to society is an important prerequisite for funding expensive research.

N.J. Campbell

Our second guest speaker this afternoon is Dr. Klaus Hasselmann.

Dr. Hasselmann graduated from University of Hamburg in 1955 and received his doctorate at Goöttingen in Fluid Dynamics, 1957.

He carried out extensive physical oceanographic research studies in the United States at the Institute of Geophysics and Planetary of the Scripps Institution of Oceanography from 1962 to 1966. He is regarded by his colleagues as being the man who successfully solved the problem of ocean wave energy balance.

Dr. Hasselmann is presently the Director of the Max Planck Institute for Meteorology in Hamburg, a position which he has held since 1975.

He is the author of numerous research papers on ocean dynamics and ocean atmosphere modelling for climate.

He is a member of a number of meteorological and oceanographic societies, and has been honoured through invitation to numerous marine research institutions throughout the world.

He is the principal author of the physical oceanography and climate section of the FORE report.

Ladies and Gentlemen, please welcome Dr. Klaus Hasselmann.

Physical oceanography, climate and marine forecasting

Professor Dr. Klaus Hasselmann

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Summary

Understanding the role of the oceans in climate has been repeatedly stressed as one of the most urgent priorities of the World Climate Research Programme. An attack on this problem requires a new approach to ocean modelling and a long-term ocean measurement strategy. This in turn must be guided by the models. New techniques for remote sensing of the ocean from satellites could aid significantly in a global ocean measurement strategy. However, an optimal sampling strategy for long-term ocean measurements based on a combined system of conventional instruments and satellites has yet to be defined. The problems are discussed and illustrated with some results from an ocean climate model.

The FORE report

The Anton Bruun lecturers this year have been invited, as section editors of the report on « Future Ocean Research in the year 2000 », to jointly address the problems and challenges which oceanographers may be expected to face in the next two decades. The contents of the FORE report (IOC 1983) have been discussed in various forums, including the General Oceanographic Assembly in Halifax, July 1982. In considering the role of physical oceanography within the FORE context I shall therefore not attempt a comprehensive summary of the views of the report on this subject. I shall limit myself instead to discussing some possible general developments which may be anticipated as a result of expected advances in technology, considering then the implications of these trends for the structure of future research in physical oceanography. The speculative nature and dangers of such extrapolations into the future have been elegantly expressed in the FORE report itself and need not be reiterated here. It may be recalled only that, almost by definition, the most exiting innovations in research are precisely those which cannot be foreseen. Nevertheless, certain lines of progress can be recognized rather clearly already today, and it may be useful to consider ways in which physical oceanographers can prepare themselves for the changes these imply.

A strong thrust of physical oceanography in the coming decades will undoubtedly continue to be directed towards the role of the oceans in climate. Considerable advances in this field may be expected through the advent of global satellite observing systems, together with other technological advances, such as satellite tracked drifting buoys, sonar floats, automatic stations, expendable instruments and acoustic tomography, which together will make it feasible to obtain long-term measurements of many important ocean parameters on a far more expanded scale than has traditionally been possible.

The same technological developments may be expected to have a strong impact also on marine forecasting, a field of physical oceanography which has gained increasing economic significance in recent years. Quasi-synoptic global data on surface winds and ocean waves obtained from satellites will provide a greatly improved data base for short-and medium-range marine weather and wave forecasting, as required for ship routeing, offshore operations, coastal protection, and other applications. On longer time-scales, sea surface temperature (SST), radiation and surface wind data from satellites will similarly yield the required input for monitoring and forecasting large-scale vacillations of the ocean-atmosphere system, such as El Nino and the Southern Oscillation, or variations in local upwelling regions of interest for fisheries.

With respect to the time-scales and physical processes involved, the problem of long-term climate changes and the prediction of shorter term climate vacillations and marine weather appear to be reasonably well separated. However, the problem areas merge when one considers the required observing systems. Essentially the same satellite and instrument systems are needed in both cases. The problems are similarly non-separable with regard to the data analysis. The same sets of fields (surface winds, SST, fluxes through the air-sea interface, tec.) need to be constructed in both cases. It may be noted in this context that for a continuously operating long-term data collection system the real-time data analysis requirement for marine forecasting applies without significant reduction also for longer term climate studies, since the data stream must be processed at the same rate as it is generated if the data is to be fully utilized (a constant divergence between input and output data fluxes implies a constant data sink !). The optimization of a complex, heterogeneous, multi-national global observing system consisting of different satellites and a combination of conventional measurement systems, together with the rapid, efficient analysis of the greatly expanded data streams generated by these systems, will present major scientific and technical challenges to physical oceanographers in the next decades. The task can be successfully tackled only through a close collaboration between physical oceanographers and meteorologists, since both for climate studies and marine forecasting the ocean cannot be regarded as an isolated system, but must be considered as a component of the coupled system ocean-atmosphere.

In the following we summarize briefly the potentials and open problems of some of the ocean satellites and other observing systems which may become available towards the end of this decade.

Oceanographic satellites

A summary of present capabilities of oceanographic satellites is given in the SCOR Working Group 70 Report (Grower 1983). The report lists the various oceanographic satellites currently being considered by different space agencies for possible launch within the next five to eight years. A more extensive discussion of the operating principles of various remote sensing instruments may be found in Stewart (1984). Many of the techniques were first tested in space aboard SEASAT (which unfortunately failed after 100 days'operation in october 1978) and are discussed, for example, in the SEASAT Special Issues I. (1982) and II. (1983) of the *Journal of Geophysical Research.*

Wind and wave sensors

One of the potentially most useful instruments for both climate studies and marine forecasting is the wind scatterometer, as was flown on SEASAT, and is in discussion for several future satellites. Fig. 1. (from O'Brien 1982) shows the coverage which can be typically achieved by a pair of wind scatterometers viewing to both sides of a polar orbiting satellite within a 24-hour period. The swarth width for each scatterometer is approximately 400 km.

The SEASAT scatterometer winds have been compared against accurate wind buoy measure-

Figure 1. Surface projection of scatterometer data coverage during 24-hour period in North Pacific (from O'Brien 1982).

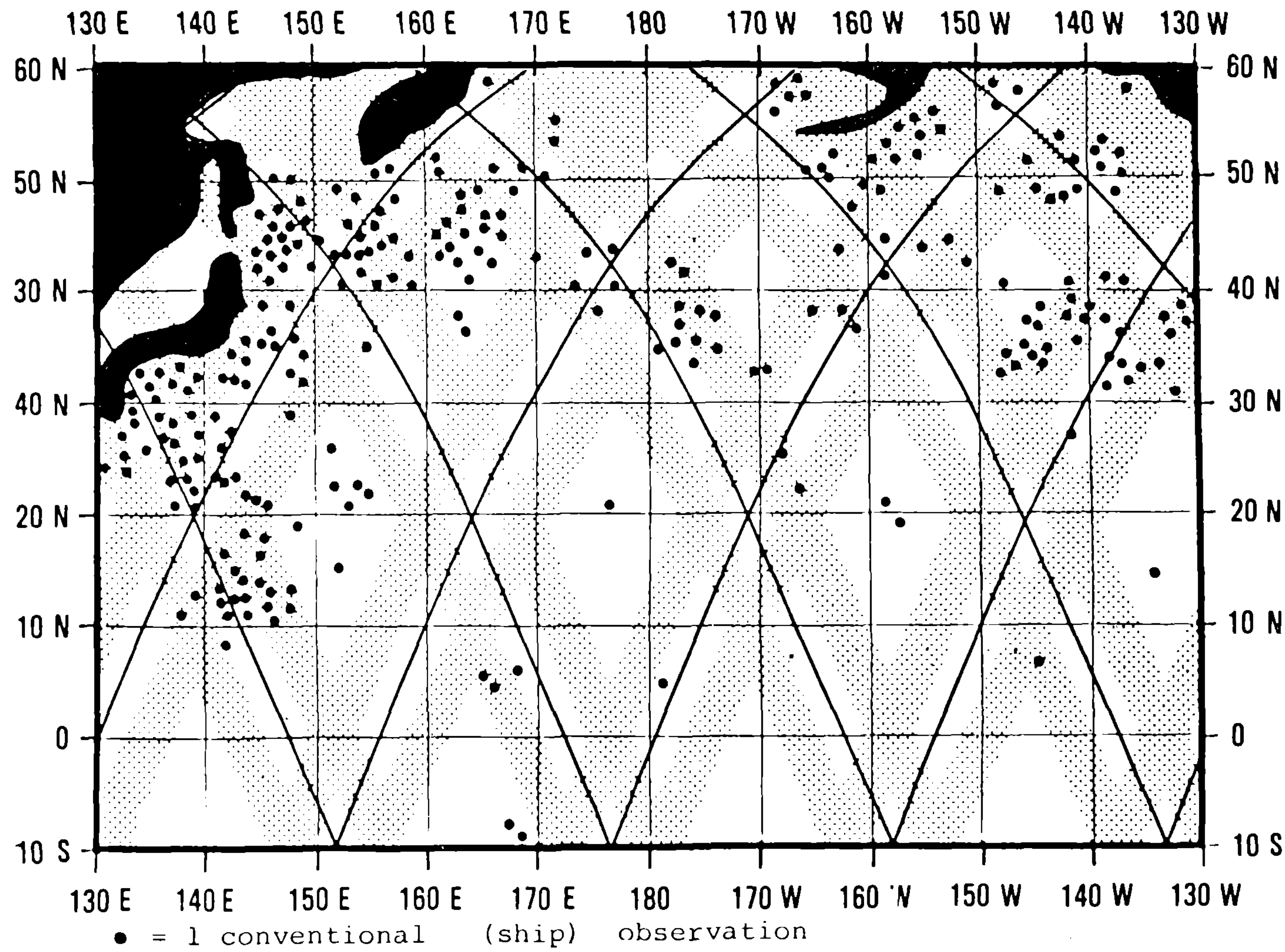


Figure 2. Comparison of scatterometer wind speeds (upper panel) and wind directions (lower panel) with surface wind measurements in the JASIN experiment (from Jones *et al.* 1981).

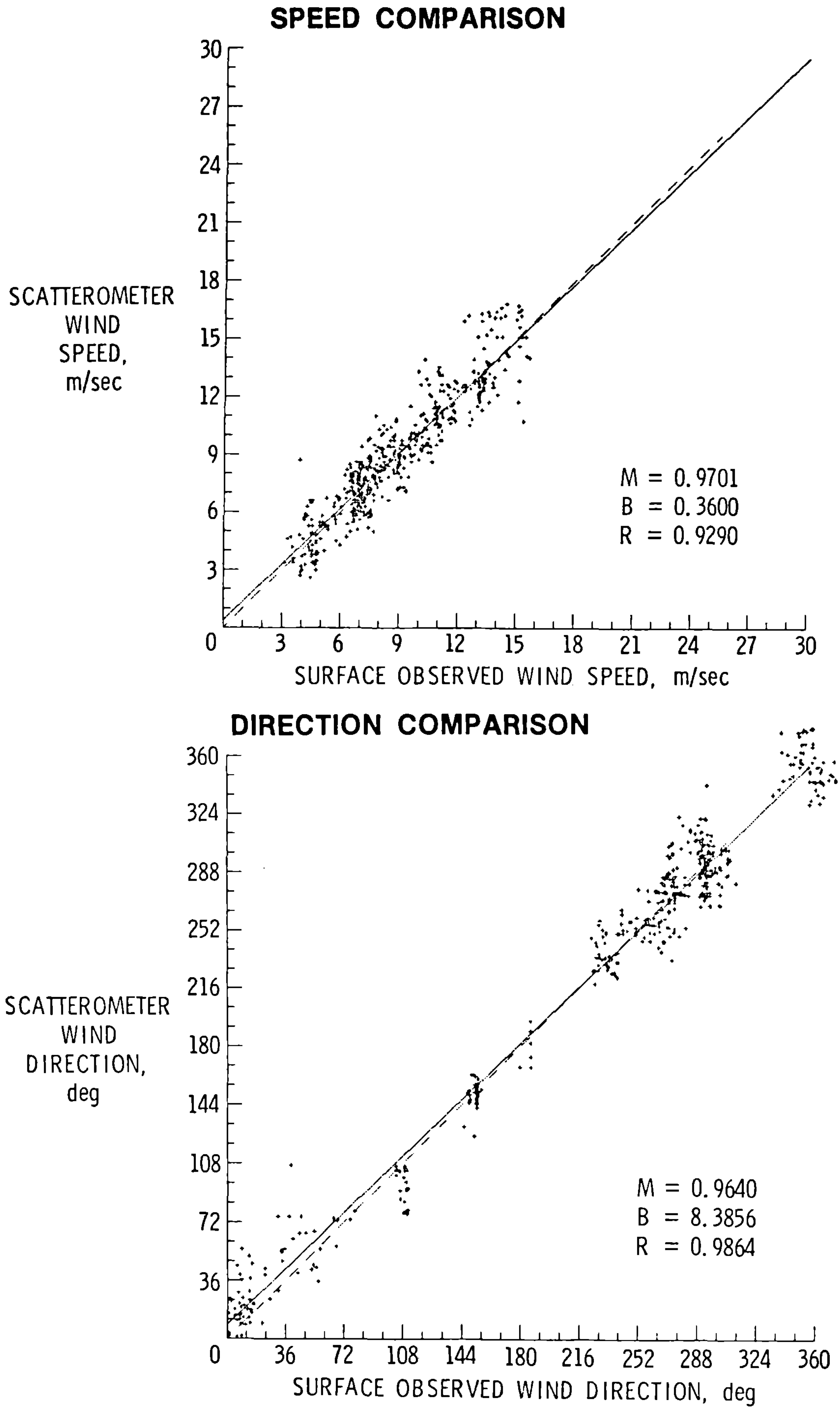


Figure 3 (a) NMC surface wind analysis for 000 GMT 11 september 1970 (from Hoffman 1982)

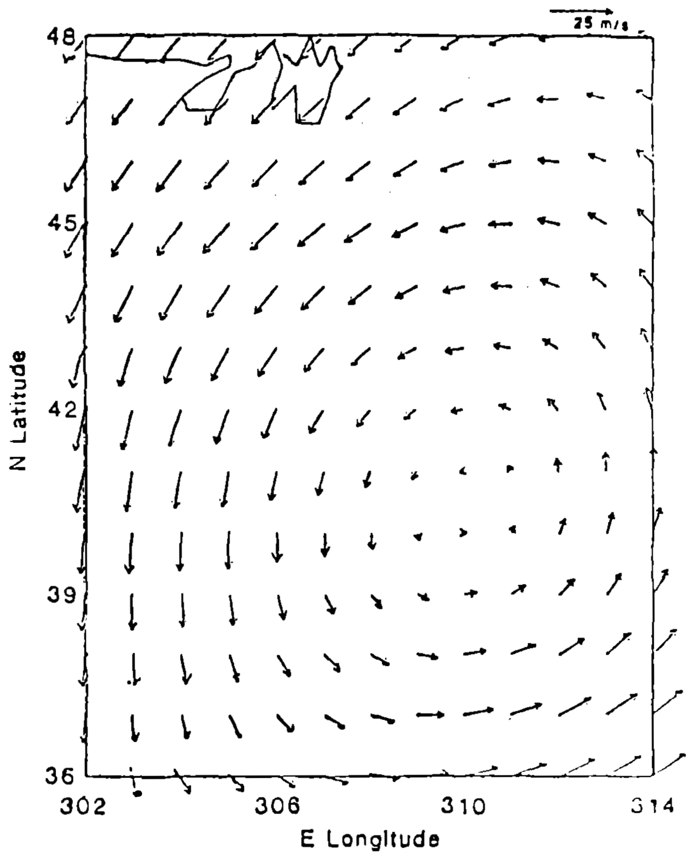
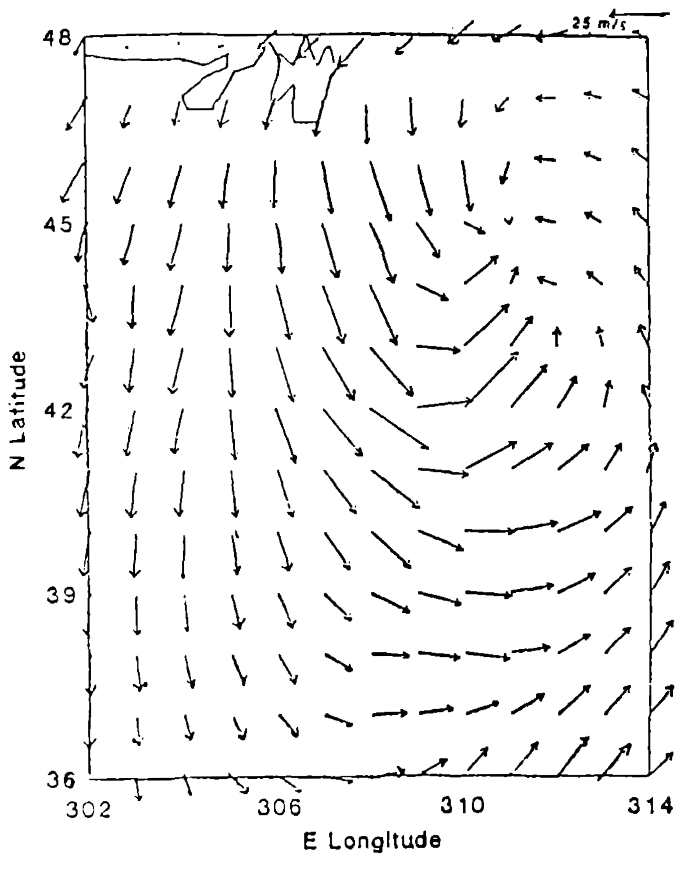


Figure 3 (b) Direct minimization analysis using SASS winds for 0000 GMT 11 september 1978 (from Hoffman 1982).



ments made during the JASIN experiment in the eastern North Atlantic (Jones et al.1981). Excellent agreement (± 2 m/s in wind speed, ± 20° in wind direction) was obtained (see Fig. 2). The usefulness of scatterometer winds for determining the surface wind field is illustrated for a particular case study in Fig. 3 (from Offman 1982). It is seen that without the scatterometer information, the wind field derived from the conventional meteorological observation network (left panel) severely underestimated the most intense regions of the storm, as reconstructed from the full data set (right). (The storm in question was of some practical interest, since it caused considerable damage to the liner *Queen Elizabeth II*, which passed through the storm without sufficient forewarning.)

The great potential of the scatterometer for reconstructing the wind field which drives the ocean circulation and generates the ocean wave climate, or for predicting future surface winds for marine forecasting applications is generally recognized. Nevertheless, the wind scatterometer poses a number of problems which need to be addressed more carefully in the application of such instruments in the future. A single scatterometer or even a scatterometer pair flown on only one satellite does not sample with sufficient density in space and time to avoid aliasing rapidly varying synoptic scale wind systems. Furthermore, the instrument flown on SEASAT was able to determine the wind direction only to within four possible solutions. (Planned future scatterometers will view a given area of the ocean from three instead of two look directions, thereby generally reducing the number of ambiguities to two.) For these reasons the scatterometer data cannot be considered independently of other meteorological data, but need to be imbedded in a general meteorological 4-D data assimilation scheme which provides the analysed surface wind field as one particular output from a complete, dynamically consistent reconstruction of the state of the atmosphere. This is clearly a meteorological rather than an oceanographic task, but the collaboration of oceanographers is essential to develop and apply the actual sensor algorithms.

Another difficulty in analysing scatterometer data is that in order to remove the directional ambiguities, and to obtain reliable wind speed values, the local wind sea and swell fields must be known. The backscattered microwave return from the sea surface is determined by the short (cm wavelength) ripples of the sea surface, which are known to be strongly affected by the modulation by longer surface waves (see Stewart 1984); (Keller and Wright 1975); (Feindt et al. in preparation). A reliable algorithm for recovering the surface winds from the backscatter data therefore requires the surface wave spectrum as input. This can be derived only from numerical computations with wave models, which must be driven by the estimated wind field itself, but will also make use of wave data from satellites and conventional instruments. The full interactive problem can clearly be treated only interatively.

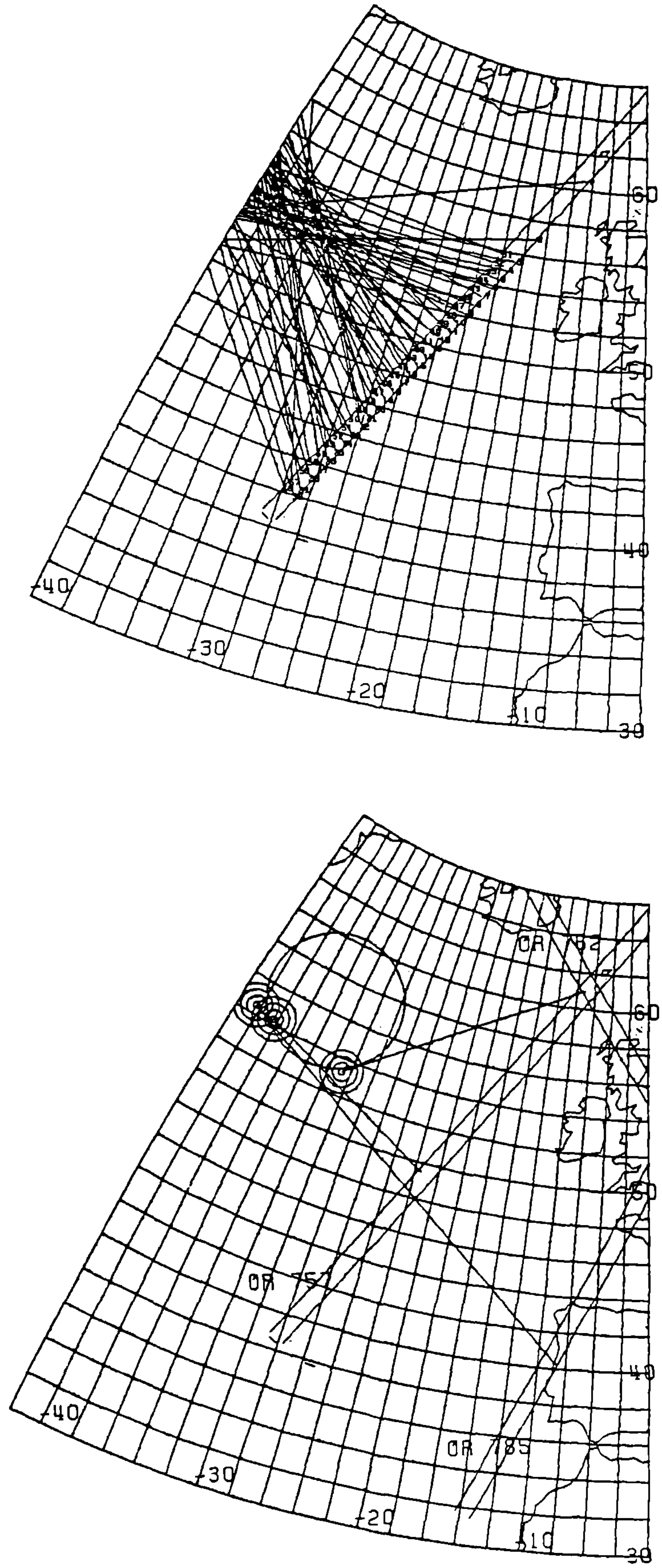
The interdependence of wind and wave data is illustrated further in Fig. 4, which shows the propagation paths of the principal swell components identified in SEASAT synthetic aperture radar (SAR) images obtained along three successive orbits (from Lehner 19844). From the swell rays and the swell wavelengths it was possible to infer the position, time, strength and direction of the maximum winds of the generating storm in the East Atlantic. In this case the usual input-output relation between the wind and wave field was inverted, and useful information on the extreme properties of the wind field was derived from the wave field. Since the inversion technique yields information on the wind fields at an earlier time (because of the finite wave propagation time) the method has natural limiations for forecasting applications and is probably most useful for reconstructing the space-time history of the wind field in data-sparse regions of the ocean for climate studies.

The example illustrates generally the nature of the problems encountered in attempting to extract the full information content from interdependent satellite data. Firstly, individual sensors cannot normally be regarded in isolation, since the algorithms for converting the sensor data to geophysical parameters depend on additional input data which can be obtained only from simultaneous measurements with other sensors, or, more typically, from a reconstruction of the required fields from a mixture of conventional and sattelite data, using models. (In the present example, wind and wave data were available not only from the satellite scatterometer and SAR, but also from the radar altimeter and microwave radiometer, as well as from conventional stations). Secondly, the various geophysical fields derived from the suit of satellite sensors and conventional instruments are normally interrelated dynamically, and an optimal reconstruction of the fields must allow for this interdependency. One is faced therefore with a complex mutidimensional data assimilation problem extending from the development of sensor algorithms to the simultaneous reconstruction of sets of dynamically interacting fields using large scale dynamical models.

The ocean circulation

Another important area in which satellites and new developments in measurement technique can be expected to bring significant advances in the future is global ocean circulation. Serious efforts are currently being undertaken by physical ceanographers to design a World Ocean Circulation Experiment (WOCE) directed towards this goal. The experiment should begin in the late eighties, when it is hoped that the required satellites will become available, and extend over a period of at least five

Figure 4 Propagation patterns of swell components observed along a SEASAT orbit (left) and reconstruction of principal scales and strength of generating wind field from the data from this orbit and two other orbits (right) (from Lehner 1984).



years. In addition to surface winds, SST and radiative fluxes, satellites yield essential data on the sea surface topography. After substraction of the geoid (which can be determined by other means) the sea surface topography yields the surface geostrophic current, thus providing the essential integration constant of the standard geostrophic current calculation which has proved so difficult (virtually impossible on a global scale) to obtain by conventional measurements. Fig. 5 shows successive sea surface profiles through the Gulf Stream obtained with the SEASAT radar altimeter (from Cheney and Marsh 1981, see also Wunsch 1981). The current can be clearly identified by the almost one metre change in surface elevation across the stream. An eddy is also seen to the south of the current. Fig 6 shows the rms eddy activity (rms surface height displacement) for the Western North Atlantic during the SEASAT operation period derived from the altimeter measurements (from Menard 1983).

Radar altimeters are most readily applicable to the study of time variable, small and intermediate-scale ocean circulation features such as the western boundary currents and eddies shown in these figures. Measurements of the large-scale time variable features or the mean ocean circulation pose more stringent requirements on the determination of the satellite orbit and the geoid. However, the feasibility of obtaining quantitative information also on these scales is illustrated by a comparison of the large scale (low pass filtered) global absolute dynamic topography derived from SEASAT altimeter data with the classical picture of the dynamic topography inferred from density data (see Fig. 7, from Tai and Wunsch, in press). In view of the very short period of only 100 days for the altimeter measurements, the general agreement is quite satisfactory.

To complete the description of the ocean circulation, satellite sea surface topography measurements need to be augmented by conventional mea-

Figure 5 Successive altimeter tracks passing through the Gulf Stream and a cold ring. The tracks span a period of 21 days (from Cheney and Marsh 1981).

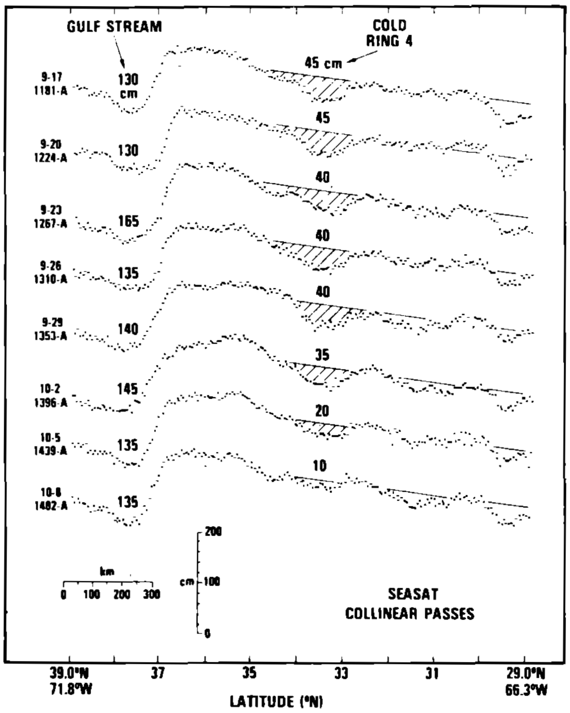


Figure 6 Variability of sea-surface topography from SEASAT radar altimeter in the NW Atlantic (from Meanrd 1983).

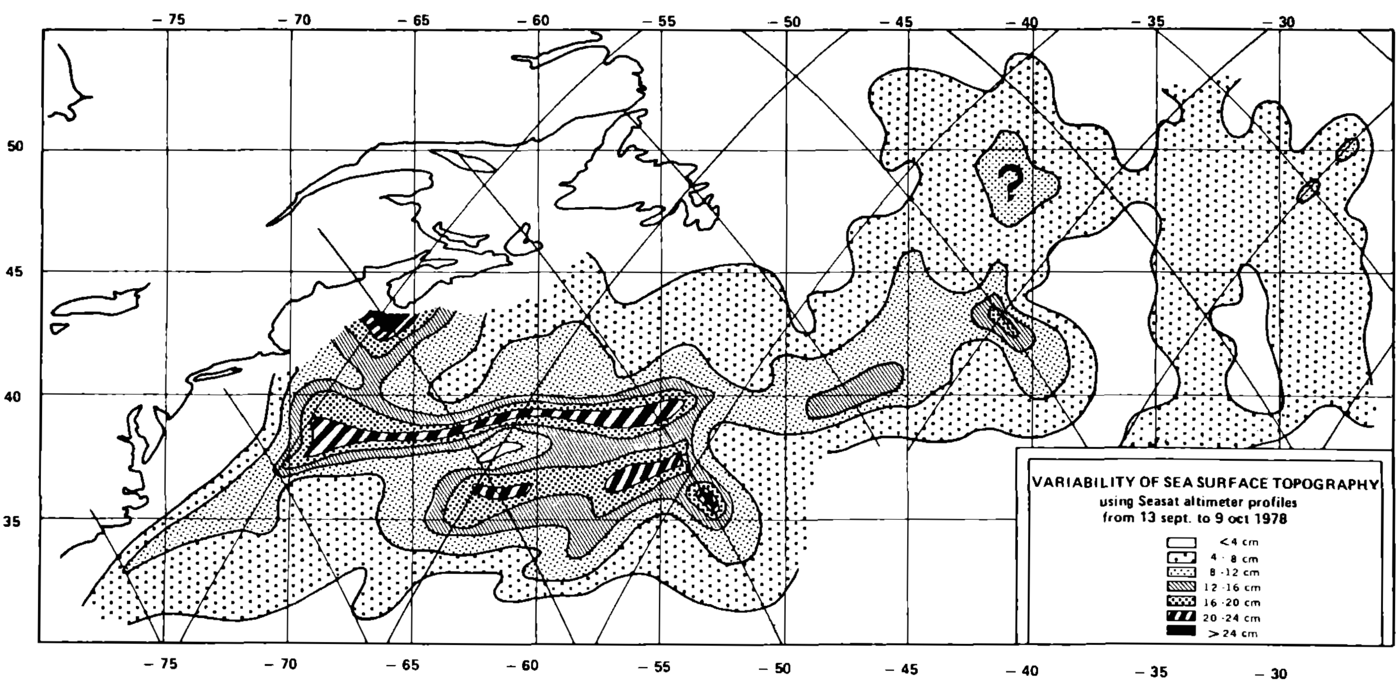
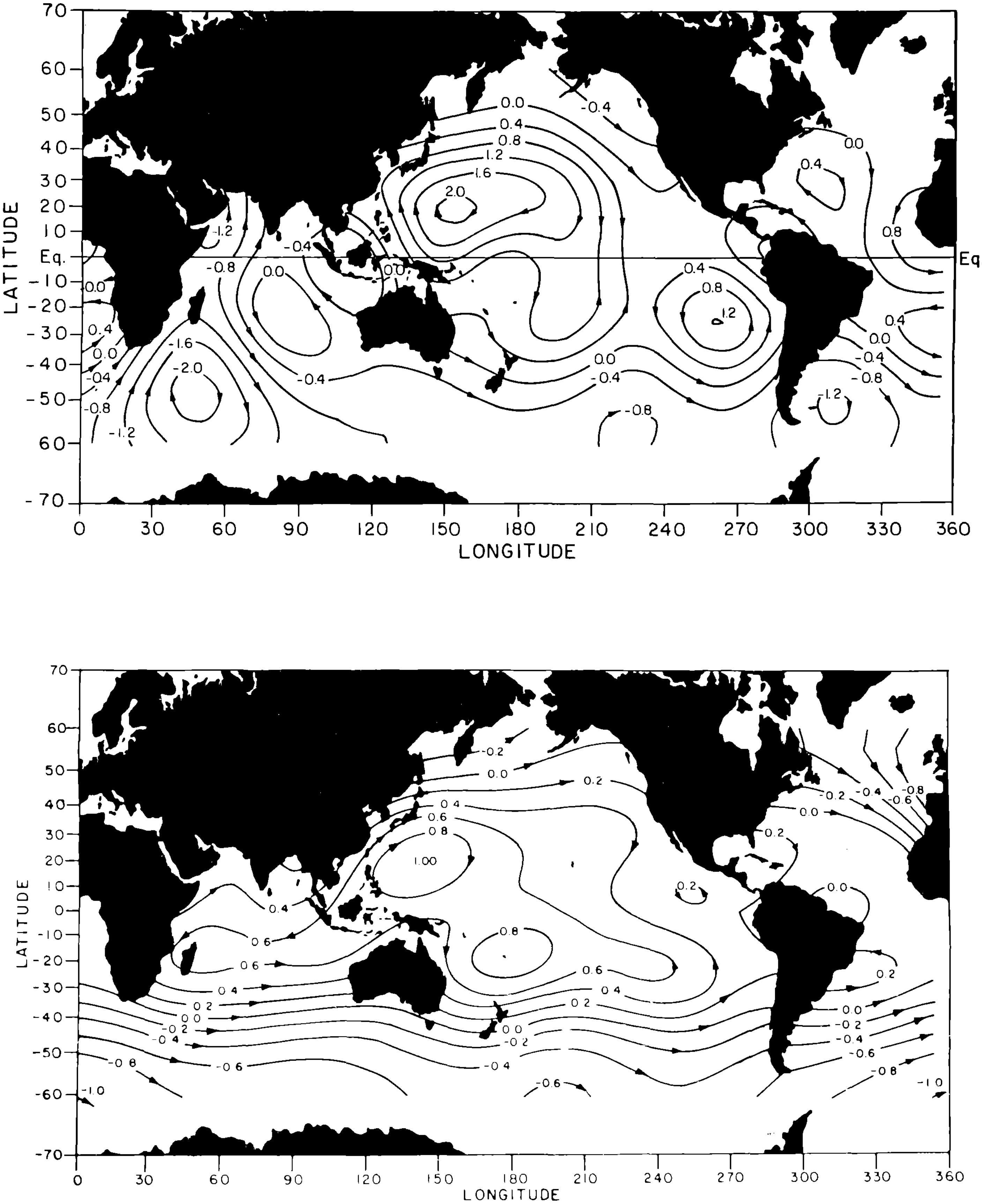


Figure 7 Large-scale (low-pass filtered) global dynamic topography derived from the SEASAT radar altimeter (a) and density data (b) (from Tai and Wunsch, in press).

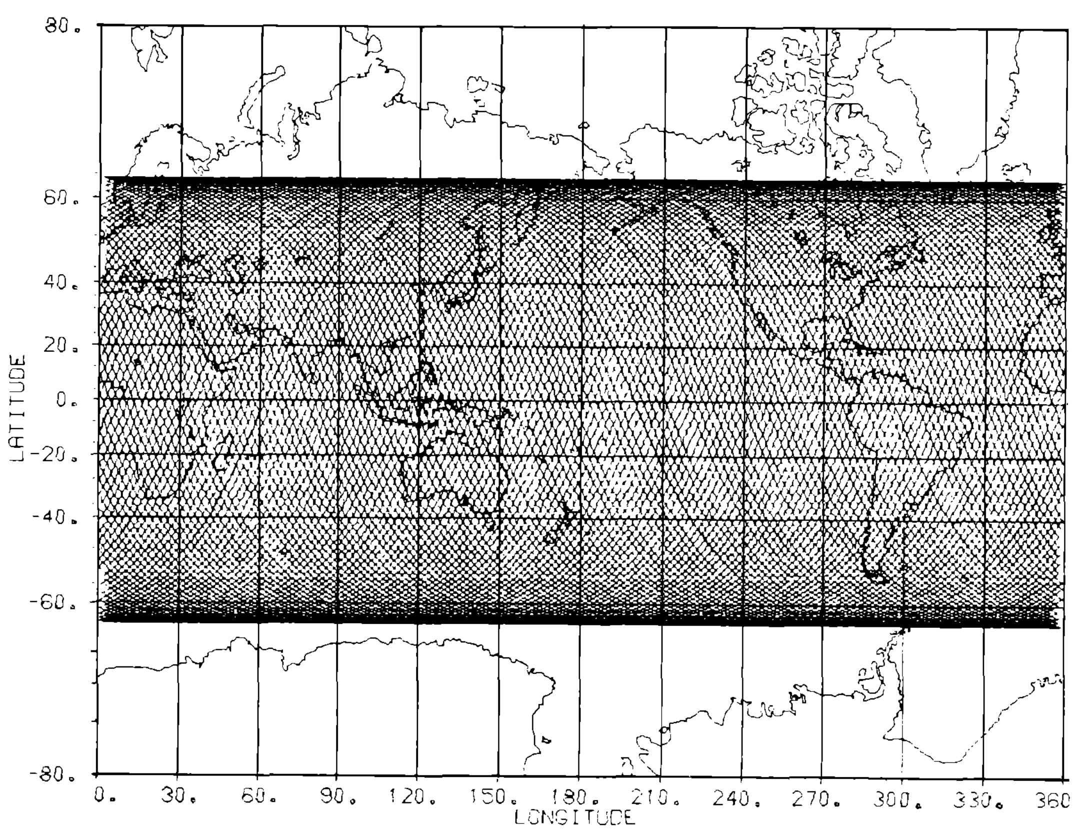


surements, particularly measurements of the density stratification. The later determine the baroclinic component of the currents (the thermal wind) while the sea-level data (together with the density data) establish the barotropic current, i.e. the vertically integrated mass transport. It is a fortunate coincidence that the separate measurement techniques are well matched to a natural separation of the time scales of these two modes of the ocean circulation. In most regions of the ocean, the baroclinic adjustment of the interior density stratification to changes in the external forcing occurs at least two orders of magnitude slower than the barotropic response of the sea surface (several years compared with severals days or weeks). Faster baroclinic response times occur, however, in the equatorial regions, in regions of intense currents and in the seasonal thermocline. The rapid rate of satellite altimeters makes it possible to study the fast global barotropic response with an acceptable space-time sampling trade-off, while the more slowly varying interior density distribution may be established (although with poorer spatial resolution) through ship surveys and other conventional techniques. Fig.8 shows the global sea-surface topography coverage achievable with a polar orbiting satellite for a 10-days repeat orbit, which provides a reasonable compromise between space and time resolution for the barotropic variability. However, aliasing is not entirely negligible, and a two-satellite system would yield a significant improvement in sampling density (and also measurement accuracy).

In regions of more rapid baroclinic response, such as equatorial and frontal regions, more frequent hydrographic surveys or equivalent measurements within the water column are needed to study the baroclinic flow and its interactions with the barotropic circulation. A quasi-automatic method for continously monitoring the interior hydrographic structure in these regions of the ocean would clearly be highly desirable. Acoustic tomography shows considerable promise of providing at least some of the information needed by continuous remote measurement. In this technique, the temperature structure over an extended region of the ocean is inferred by inverse modelling from the travel times of acoustic signals for a variety of ray paths through the regions (Behringer et al. 1982). The technique has been successfully tested for an approximately 400 km square box of the Atlantic south of Bermuda. It can be extended in principal to measure both the temperature structure and the current field through use of two way propagation.

Other techniques wich may contribute significantly to our understanding of the global ocean circulation are satellite-tracked drifting buoys, deep-ocean sonar floats, automatic ship-of-opportunity sampling systems, and moored continuous profiling instruments. The best combination of these different measurement techniques, howe-

Figure 8 Sampling density of a radar altimeter during a 10-day period for a polar orbiting satellite.



ver, and the optimal deployment strategy for each measurement system still has to be established. Although the advent of sattellites and other advanced instrumentation has brought the study of the dynamics of the global ocean circulation within the potential reach of large-scale experimental programs, such as the World Ocean Circulation Experiment, concerted theoretical and numerical modelling efforts will be needed on the part of the oceanographic community to develop effective measurement and data analysis strategies for such undertakings.

The nature of the questions to be addressed can be illustrated by considering one of the most important quantities affecting the ocean circulation and the interaction of the ocean with the atmosphere in climate studies : the net heat flux from the atmosphere to the ocean. A comparison of the measured heat flux for the Atlantic (Bunker 1980), Fig. 9, with the heat flux computed from a global ocean circulation model (Maier-Reimer et al.1982), Fig. 10, shows good general agreement for the North Atlantic, but a very poor correlation for the South Atlantic. The ocean model reproduces the mean temperature and salinity distributions, current fields and tritium distributions rather satisfactorily, so that there is not obvious reason to suspect the model heat flux comutations *a priori.* Does the discrepancy nevertheless reflect an error of the model, or are the data incorrect ? What measurements are needed to resolve the discrepancy ? Does a test of the model for the time averaged heat flux have any immediate bearing on the validity of the model for computing variations of the oceanic heat flux and heat storage on time scales of a few months to a few years relevant for WOCE ? Should investigations of the variability of the oceanic heat flux on this time-scale be weighted heavily towards the tropical oceans, as suggested empirically by the pronounced large-scale coupled ocean-atmosphere anomaly signals observed in the equatorial regions, and supported theoretically by the strong response of atmospheric models to tropical and sub-tropical SST anomalies (and as proposed in the Tropical Oceans-Global Atmosphere (TOGA) experiment) ? These and similar basic questions clearly need to be addressed through an extensive numerical modelling program in which the sensitivity of different types of models are tested for different types of parameterization, coupling and external forcing.

Figure 9 Net surface heat flux into the ocean (from Bunker 1980).

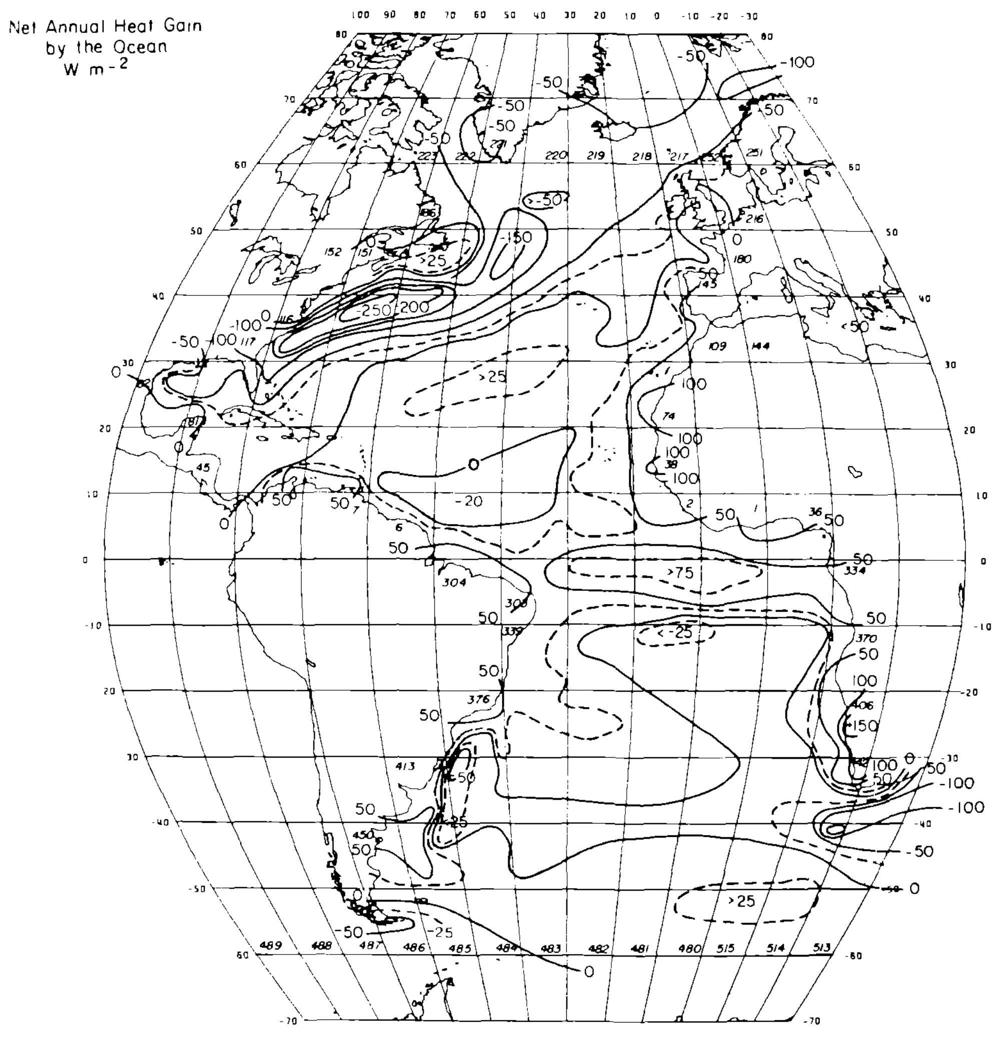
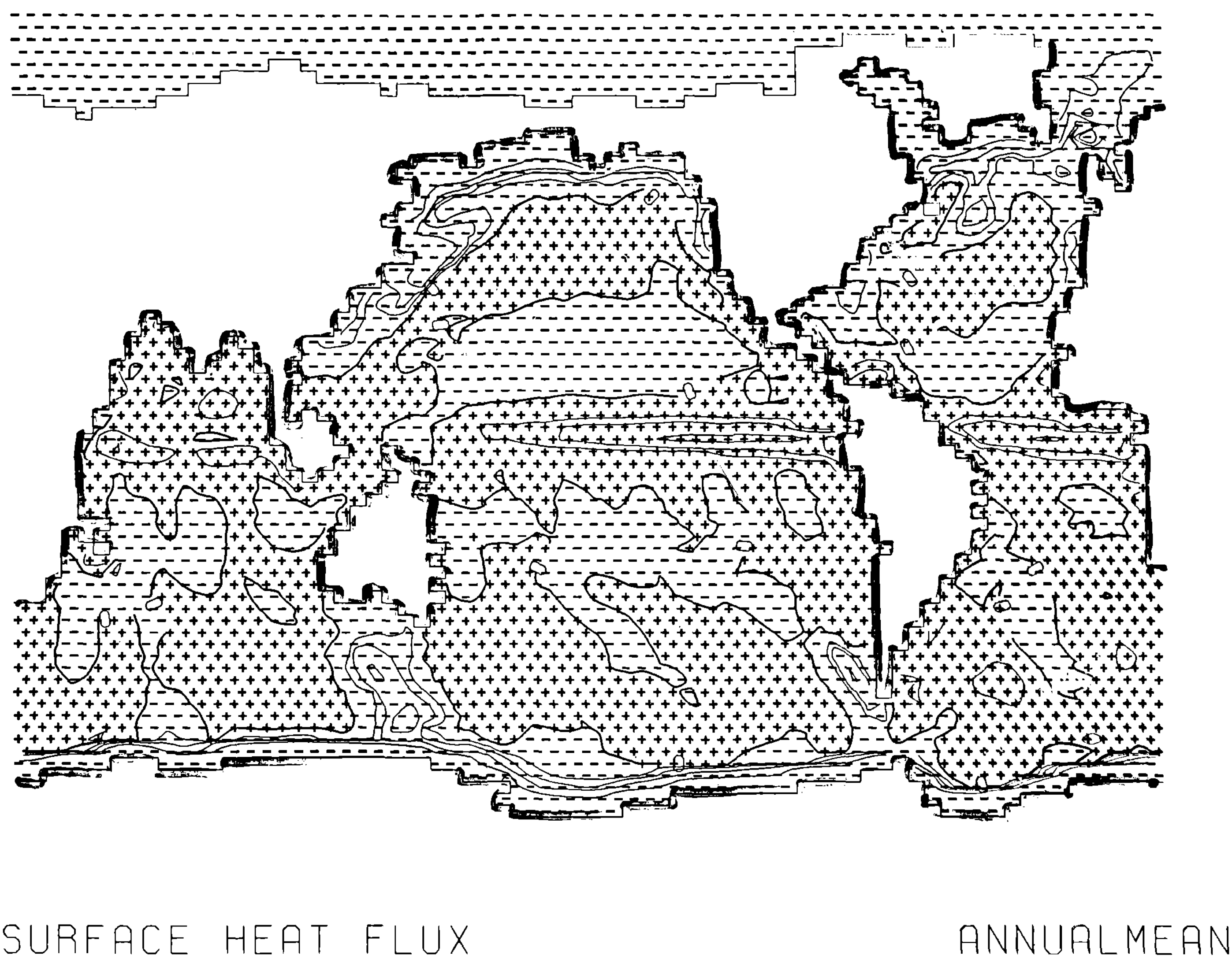


Figure 10 Net surface heat flux into the ocean computed with a global ocean circulation model (from Maier-Reimer *et al.* 1982).



Conclusions

The coming decades in physical oceanography will witness the advent of new measurement techniques for observing the oceans on a greatly expanded scale, both globally and regionally. The sensors from these advanced observing systems will produce continuous streams of data at rates significantly higher than physical oceanographers have been accustomed to work with. Ideally, research in physical oceanography has been carried out in the past in a sequence of logical steps : an oceanographic expedition is first planned, then carried out, the data is analysed, interpreted, and on the basis of these results, a new expedition is planned, and so forth. Physical oceanographers have nevertheless traditionally suffered from the fact that these logical steps are not always well separated in practice, and that the individual researcher is constantly engulfed in undigested data from previous expeditions while already planning the next. This complaint could achieve new dimensions when extensive, high data rate, continuous observing systems come into operation. The traditional style of oceanographic research may need to be basically restructured. Oceanographic analysis centres will need to be established, analogous to present meteorological analysis and forecast centres, with the routine task of continuously analysing the incoming data streams. As in meteorological analysis centres, the analysis will require the application of rather complex models in order to reconstruct dynamically consistent fields.

To interpret and apply the data, an ensemble of research and application models will be required, including global ocean circulation models, high resolution limited area models for particularly active regions of the ocean circulation, and global and regional marine forecasting models. In many applications, the ocean must be viewed as a subcomponent of the coupled ocean-atmosphere system, and a close collaboration of physical oceanographers with meteorologists will be necessary. Experience with data processing and numerical modelling in a continuous, quasioperational mode is still very limited in the physical oceanographic community. However, a successful response to these challenges can open the way to a new era in physical oceanography, in which the global ocean, as today the atmophere, is treated in its entirety, both in the study of the complex role of the oceans in the global climate system and in the global prediction of marine weather.

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N.J. Campbell

Our next guest speaker is Dr. David Dyrssen.

Dr. Dyrssen recived his doctorate in chemistry from the University of Stockholm in 1956 and thereafter held important research posts in a number of major research institutes in Sweden, including the Royal Institute of Technology in Stockholm, until 1963. In 1963 he was appointed as a Professor at the Chalmers University of Technology and University of Gothenburg, a position which he still holds.

He is a corresponding member of the Finnish Chemical Society, member of the Royal Society of Arts and Sciences at Gothenburg and is a member of the Royal Swedish Acadamy of Engieering Sciences. Dr Dyrssen is the author of over 340 papers covering the fields of solvent extraction chemistry and marine chemistry. He has served and still serves on numerous national and international committees, and on many as Chairman. He is eminently well qualified and will address us on ocean chemistry in respect to the future on ocean research.

Past and future ocean chemistry

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Summary

Marine chemistry deals with seawater as a medium for chemical reactions and their dependence on pressure and temperature. Chemical oceanography is concerned with the distribution of seawater constituents. This distribution is not only governed by general chemical relationships (laws), but to an equally great extent by biological, geological and mixing processes. The study of ocean chemistry has, therefore, not only a great impact on ocean sciences, including the best use of ocean resources, but may also increase our basic knowledge of chemistry and natural products.

Pollution research during the last decade has deepened our understanding of essential natural processes and pathways of different elements and substances in the sea. At the same time, our ability to evaluate and cope with pollution hazards has been improved. Pollutant measurements will certainly also be carried out during the next two decades. The sampling and analytical capabilities have improved considerably during the last decade and will continue to do so. The advance of our knowledge of the chemistry of the oceans will depend on the ability of the oceanographers to use up-to-date knowledge in different branches of chemistry and maintain an analytical capability by continual upgrading and incorporation of new techniques. The most advanced computerized techniques are costly, which calls for the establishement of a few well-equipped international laboratories. The sites of these laboratories should cover economically important areas, and they should also provide training courses for advanced research in ocean science for the benefit of all nations. In addition, research vessels should be designed with clean sampling areas and clean-air laboratories that can accomodate advanced instrumentation and allow first-rate trace chemistry work on board.

Introduction

It must have struck early man that seawater was salty and bitter while the water in lakes, rivers and pools of rainwater was tasteless and contained practically no salts. He could see how water evaporated in the heat of the sun, and he probably gave some though to the cycling of water even if he was not prepared to make a rock carving of the global cycle of water like Fig. 1. From the figure caption we see that the total amount of water leaving the mouths of the world's rivers is just over 1 million cubic metres per second — an impressive amount, but still small compared with the big ocean currents ; the Gulf Stream alone carries 70 million cubic metres per second over the North Atlantic.

Early man must have felt the saltiness of the winds from the sea, but he could barely have imagined that it amounted to a total transport to the continents of 1 000 million tonnes of sea salts per year. This is, however, only a small part of the total salt content of the seas, which is almost 50×10^9 million tonnes. The sea salts contain a limited number of major constituents with concentrations higher than 1 mg per kg seawater (see Table 1). Most of the sea salts are returned via river runoff together with weathering products from rocks and soils in the drainage areas. Table 2 shows that the concentrations of several major constituents such a sodium, potassium, magnesium, chloride and sulphate are considerably lower in river water than in seawater. The table also shows that during this century man's activities have increased the concentrations of most of the dissolved constituents in rivers that have their drainage areas within industrialized zones. Acid rain has lowered the alkalinity of the river water and increased the sulphate concentration. Since nitrogen, which is extensively used as a fertilizer on farmland, is the limiting nutrient in ocean water, the incresed amount of nitrate in river water tends to fertilize the coastal zones around the river mouth.

Early ocean chemistry

Robert Boyle (1627-91) may be considered the founder of scientific ocean chemistry. In his work entitled « Observations and experiments on the saltiness of the sea » Boyle describes the silver nitrate

Figure 1 The global water cycle. About 10 percent more water evaporates from the ocean than returns as rain. The excess, which is depleted of $H_2^{18}O$ is transferred as meteoric (air-borne) water to the continents where it precipitates as rain and snow. The net vapour transfer equals the runoff into the oceans, since *70 percent of the earth area A is covered by sea (1000-900) × 0.70 A = (700-470) × 0.30 A = 1.132 × 10^6* m^3/s.

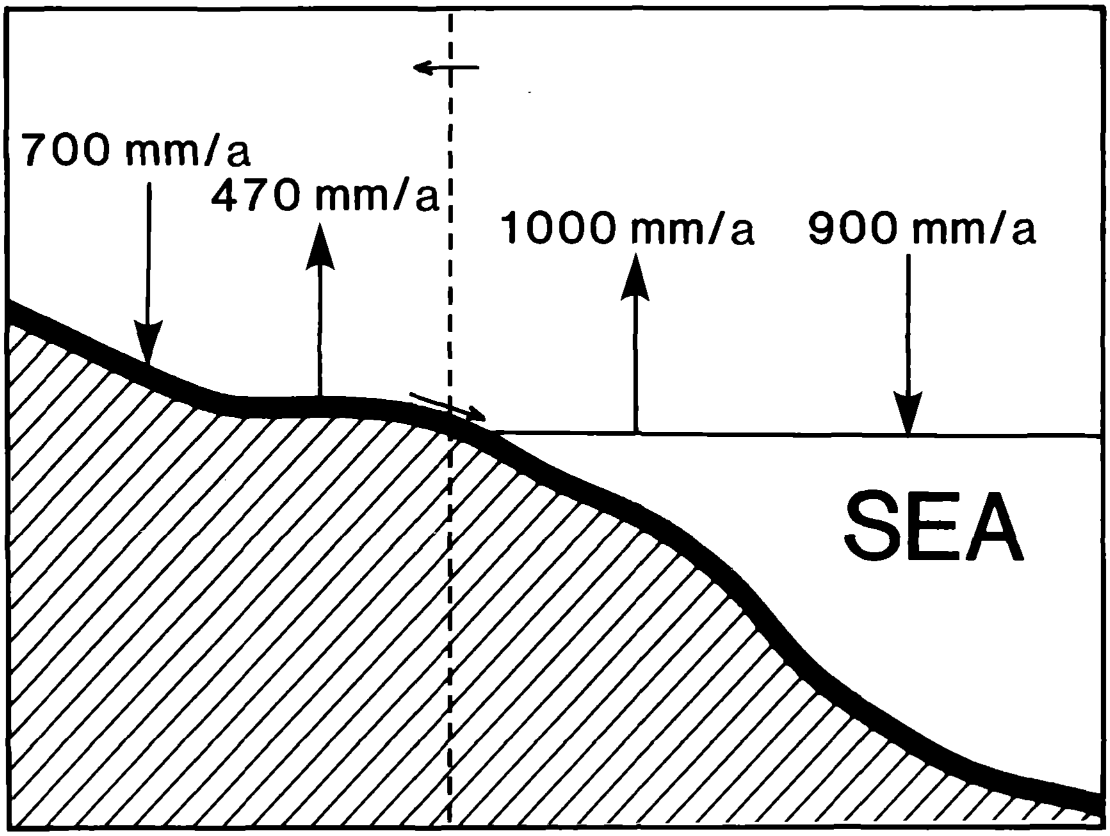


Table 1

The normal salt content of seawater is 35 grams per kilogram seawater. The Table shows the average concentrations of the main constituents. The sodium concentration is calculated from the ion balance: $[Na^+] = [F^-] + [Cl^-] + + [Br^-] + At + 2[SO_4^{2-}] - [K^+] - 2[Mg^{2+}] + [Ca^{2+}] + [Sr^{2+}]$). The alkalinity (At) is mainly $[HCO_3^-]$.

Constituent	mg/Kg seawater	mol/Kg seawater
Sodium	10766	0.4683
Potassium	399.1	0.01021
Magnesium	1292	0.05315
Calcium	412.7	0.01030
Strontium	8.14	0.000093
Fluoride	1.4	0.000074
Chloride	19353	0.54587
Bromide	67.3	0.00084
Sulphate	2712	0.02823
Alkalinity	(143)	0.00234
Boron	4.45	0.000412

Table 2

The main constituents of the upper Elbe river at Lovosice in Bohemia, Central Europe in 1892 and 1976 according to Paces and Pistora (1979).

Constituent	1892 mmol/l	1976 mmol/l
Sodium	0.42	1.50
Potassium	0.14	0.20
Magnesium	0.21	0.39
Calcium	0.85	1.44
Chloride	0.26	1.13
Nitrate	0.03	0.48
Hydrogen carbonate	1.97	1.60
Sulphate	0.20	1.08

test for salt water, and he found that the determination of the specific gravity provided an accurate measure of the salt content (see Riley 1965). Today, instruments are available that determine density rapidly and precisely.

A century later Antoine Lavoisier (1743-94), the leading chemist of his day, analysed seawater from the English Channel collected four miles off the coast of Dieppe. He evaporated the sample and tried to separate the salts by partial dissolution in alcohol, from which he was able to identify several different salts. At almost the same time Torbern Bergman (1735-84), who is considered the founder of modern analytical chemistry, obtained a seawater sample collected at a depth of 60 fathoms off the Canary Islands by Andreas Sparrman, a ship's doctor who joined James Cook (1728-79) on two of his voyages. Torbern Bergman showed that the seawater was slightly alkaline by the use of paper coloured with litmus and Brazil wood, and identified several constituents by precipitation reactions. He did not weigh these precipitates but tried instead to separate the sea salts in the evaporated sample. This is not a reliable method, and the quantities reported by Lavoisier and Bergman are rather misleading (see. Dyrssen and Ratti-Moberg 1974). It took another century before Svante Arrhenius (1859-1927) suggested that electrolytes in solution are always more or less broken up into free ions.

The Challenger Expedition (1873-76)

Analytical chemistry developed very rapidly during the nineteenth century. Robert Wilhelm Bunsen (1811-99) was probably the most out-standing analytical chemist of this century, and his former assistant Wilhelm Dittmar (1833-94) at the Andersonian University of Glasgow analysed the major components of the seawater samples from the *Challenger* expedition. Table 3 shows that Dittmar's results compare very favourably with modern figures. Only in the case of carbon dioxide do the results not agree. H.M.S. *Challenger* had a chemical laboratory on board and both the expidition's chemist, J.Y. Buchanan, and Dittmar titrated seawater in order to determine the carbon dioxide content and alkalinity (see. Riley 1965), but the numbers they reported for CO^2 were about half of the correct values. It was Kurt Buch (1881-1966) who first clarified the carbon dioxide-carbonate system in seawater. His publications on this system cover 40 years between 1915 and 1955.

Modern solution chemistry

During the two decades 1940-1960 great progress was made in solution chemistry and in the determination of the composition of complex ions in aqueous media. In Copenhagen and Lund the studies of complex formation equilibria were conducted by Jannik Bjerrum, Sture Fronaeus and Ido Leden. In Stockholm special studies of the hydrolysis of ions were carried out by Lars Gunnar Sillen, and in Zürich Gerold Schwarzenbach measured the equilibria between metal ions and polyaminopolycarboxylic acids such as EDTA. The first tables of stability constants of both inorganic and organic complexes were compiled by Bjerrum, Schwarzenbach and Sillen.

At the end of the 1950 Gustaf Arrhenius and Edward Goldberg asked Lars Gunnar Sillen to consider the equilibria between the different forms of the various elements in sea water. Sillen's work, which was presented at the international oceanographic congress held in New York in 1959, resulted in a seminal publication (Sillen 1961), which had a great impact on marine chemistry during the following two decades. Chemical reactions, including equilibria with solid phases, and their dependence on pressure and temperature were studied, and stability constants were determined in seawater media. Although the equilibrium concept is very helpful in understanding parts of the chemistry of the oceans, current models for seawater emphasize the balance between inputs and outputs (Mc Duff and Morel 1980). These inputs and ouputs can be affected by a variety of factors, e.g. changes in the drainage areas of rivers, hydrothermal vents, glaciation events, evaporite formation and biological changes.

Table 3
Composition of sea salts according to Dittmar (1884) and modern figures calculated from Tableau 1. The numbers are given in grammes per 100 grammes chloride + bromide.

Na^2O	74.486	74.726	– 0.32 %
K^2O	2.445	2.476	– 1.3 %
M g O	11.269	11.032	+ 2.1 %
C a O	3.025	2.973	+ 1.7 %
S O 3	11.558	11.639	– 0.70 %
C O 2	0.275	0.45-0.53	– 78 %

GEOSECS

Chemical oceanography of the 1970 was dominated by the Geochemical Ocean Sections Study (GEOSECS), one of the most important and successful programmes of the International Decade of Ocean Exploration (IDOE). Behind the design of GEOSECS were two prominent physicists, Joseph Reid and Henry Stommel, and three leading geochemists, Wallace Broecker, Harmon Craig and Derek Spencer. Two more people were important for this large programme, namely Feenan Jennings, head of the IDOE program, and Arnold Baindridge, head of the operations group (Edmond,

Figure 2 The data set from GEOSECS Station 202 in the eastern Pafific Ocean. Concentrations of oxygen, phosphate, nitrate, silica, alkalinity and total carbonate are given in micromoles per kg seawater ; barium and copper in nmol/kg.

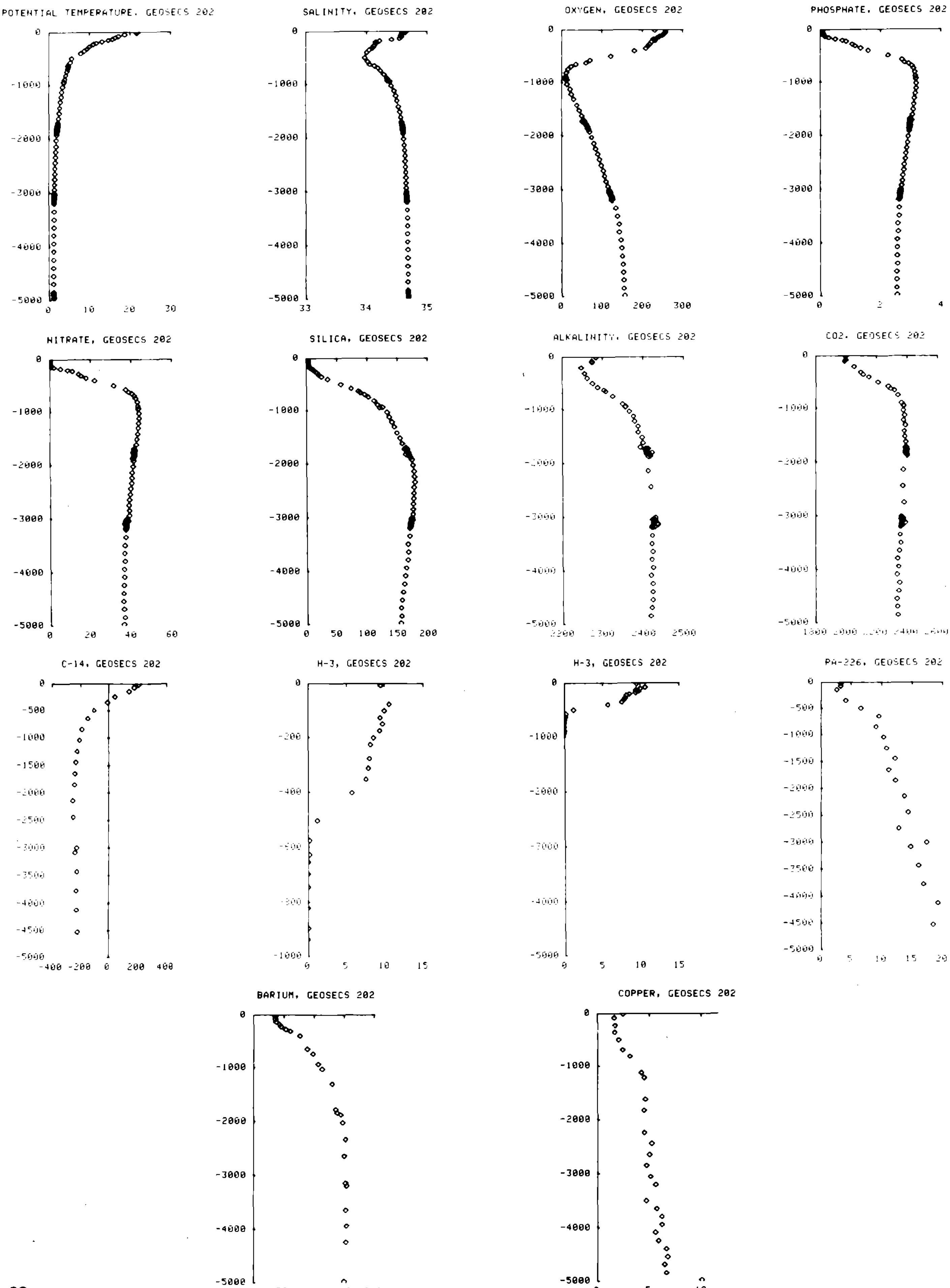
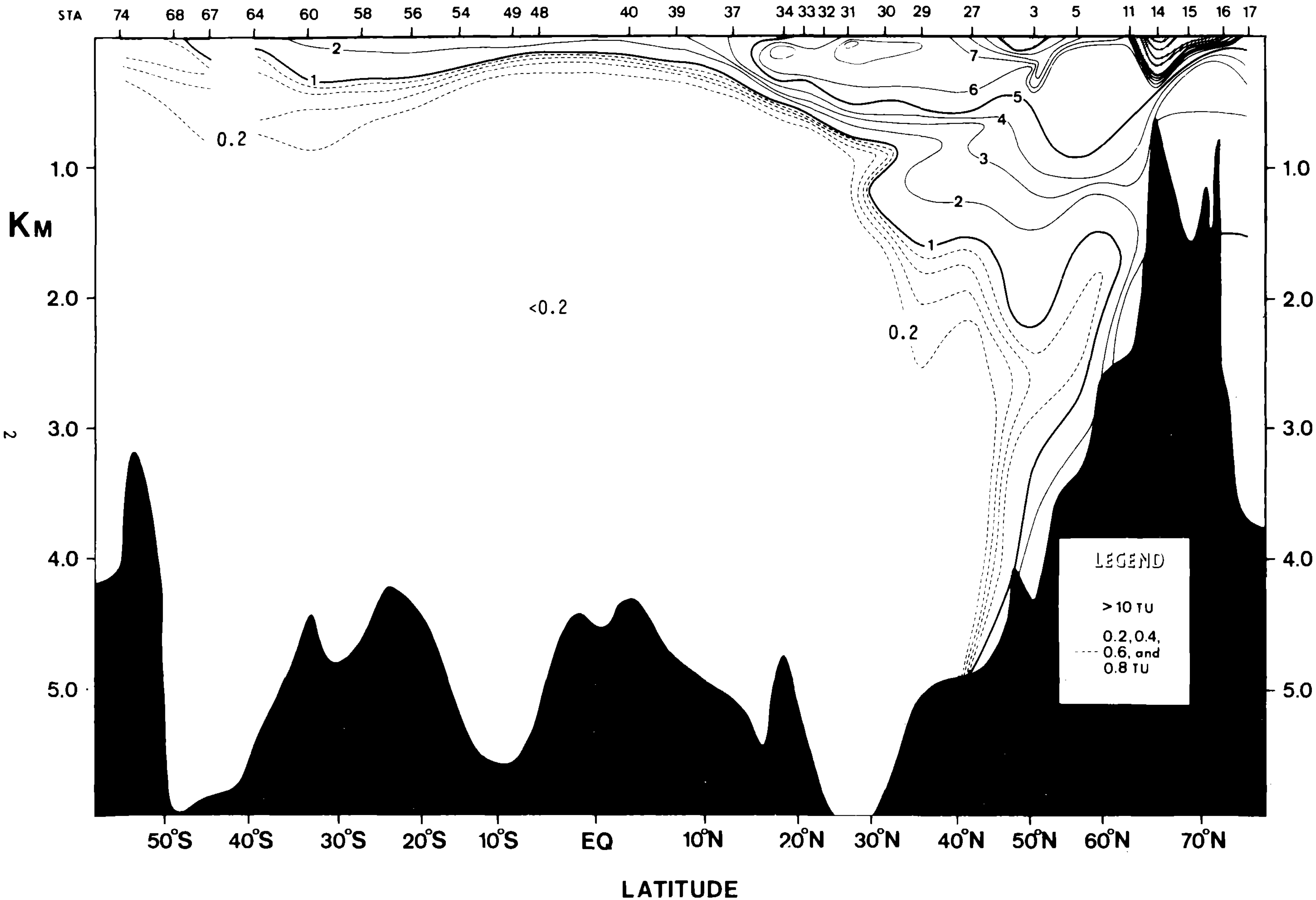


Figure 3 Tritium section of the western Atlantic Ocean in 1972 determined by Göte Ostlund, University of Miami.



1980). The quality of the first-rate techniques for sampling, analysis and data handling was remarkable. The probe for Conductivity, Temperature and Depth (CTD) with the rosette sampler should now be standard equipment in all major oceanographic expeditions. The GEOSECS data provide an invaluable source for testing future models of ocean circulation and chemical changes caused by biological, chemical and geological processes (see Fig.2). Measurements of the tritium contamination of surface seawater (Fig. 3) show the penetration of sinking water from high latitudes into the deep interior of the North Atlantic.

Hydrothermal fluxes

The present composition of the oceans (see Table 1) is the net result of inputs and outputs over millions of years. We often like to assume that there is a steady-state balance between the inputs and ouputs for the major ions, but we can only prove that these fluxes are small in comparison to the total content of the oceans. This precludes any large historical variations.

In the past decade the hydrothermal fluxes have been recognized as playing an important role in several giochemical cycles (Edmond et al. 1982, Mc Duff and Morel 1980). Cold seawater circulates through ridge crests and interacts with newly formed hot basalts resulting in the depletion of magnesium and sulphate and the enrichment of potassium and calcium. Table 4 shows that some of the hydrothermal fluxes are substantial compared with fluvial transport. In the case of magnesium this removal by hydrothermal reactions is especially large and resolves an apparent imbalance of the magnesium cycle (Drever 1974). Similarly the importance of sulphate removal has been realized only in the last decade (Berner, 1972).

FORE

The present report on Future Ocean Research (FORE) as well as the report by the Federal Republic of Germany (Hempel and Meyl 1979) should be considered in the light of past experience. Further efforts will be made to quantify the rates and mechanisms of the processes that control the chemistry of the oceans.

The new Transient Tracers in Oceanography (TTO) programme is largely based on capabilities achieved in the GEOSECS programme. The goal of TTo is to study the mixing processes in the oceans and to investigate the ocean as a sink for excess carbon dioxide. During recent decades the increase of atmospheric carbon dioxide has become the subject of extensive concern (Brewer 1978, Revelle 1982).

GEOSECS and TTO both make use of the contamination of ocean surface water by pollutants such as carbon-14, tritium and the freons. In the same way radioactive substances (such as Windscale effluents into the Irish Sea) and halocarbons (such as carbon tetrachloride and tetrachloroethylene) can be used as tracers for mixing processes (Dyrssen, 1982).

The pollution of the sea by biocides and other organic compounds is of great concern. During the last decade considerable improvements have been made in the analysis of trace organics with techniques such as fused silica capillary — gas chromatography, tandem mass spectrometry with selected ion monitoring and high-resolution liquid chromatography with sensitive detectors. Tracing organic pollutants in the marine environment will not only give an insight into important biochemical processes, but also help to evaluate potential hazards.

Photosynthesis in the upper layer and decomposition in deeper waters and on sediment surfaces are among the most important processes causing substantial changes in the composition of seawater. It is possible to explain The GEOSECS data with a stoichimetric model such as the one shown in Fig. 4, but in the future one would also wish to study the production and fate of dissolved organic substances in the marine environment. Some of these substances are bioactive and are therefore of special interest.

Organic films on the surface of the sea play an important role in the transfer of gases at the air-sea interface and the formation of marine aero-

Table 4

Inputs and outputs for major seawater constituents according to McDuff and Morel (1980). The numbers in brackets are the total ocean contents of the constituents in 10^{18} moles. The fluxes are given in 10^{12} moles per year.

Chloride (764)	+ 10.0	– 10.0		?		
Sodium (656)	+ 11.8	–9.3	– 1.9	?		
Magnesium (74)	+ 8.0	–0.5	– 1.2	– 7.8		
Sulphate (40)	+ 3.7	–0.5		– 3.8		
Potassium (14)	+ 3.2	–0.1	– 0.4	+ 1.3	– 4.0	
Calcium (14)	+ 17.1	–0.1	+ 2.6	+ 3.1	+ 2.0	– 24.7
Alkalinity (3.3)	+ 47.8		+ 0.5	– 0.4		– 49.4
Total carbonate (3.0)	+ 43.7			+ 0.5		– 49.4

Figure 4 The stoichiometry for the formation of carbohydrates, fats, proteins, opal and calcium carbonate normalized to one phosphate ester

$$m = s + t + 2u + 2V + 1 + y$$
$$n = u + v$$
$$p = v, q = x, r = y$$
$$z = s + 1.5t + 3.5u + 5.5v + 1$$
$$a = n + 2p - 2r - 1$$

Δz, Δm and Δa are the changes in the concentration of oxygen, total carbonate and alkalinity, respectively.

$$mCO_2 + nNO_3^- + pSO_4^{2-} + qSiO_2 + rCa^{2+} + MHPO_4 \xrightarrow{+ H_2O} (CH_2O)_s (CH_2)_t (NHCH_2CO)_u (NHCH_2CS)_v - (SiO_2)_x (CaCO_3)_y (CHPO_4M) + zO_2 + aOH^-$$

sols. These films are not simple lipids or surfactants, but consist of polymeric compounds with a high degree of hydroxylation, carboxylation and amination. FORE recognizes the importance of research on ocean-atmospheric interactions and the necessity to improve our knowledge of the composition of the organic films.

By reworking the surface of the earth man appears to have more than doubled the rate of erosion, and the flux of suspended river solids is now approximately 18 000 million tonnes per year (Goldberg 1972). Much of this material is contaminated and settles in the river mouths. Additional material is added as the result of coastal upwelling and the production and consumption of photosynthetic matter. The organic content of the coastal seabeds provides food for benthic organisms and microbes. Thus the seabed is reworked and substances are released to the seawater. These early diagenetic processes should be further investigated (e.g. by the use of benthic chambers) and their role in the cycling of pollutants and other substances should be quantified. The flux of matter from the surface water can be investigated by the use of moored or drifting sediment traps, nephelometers, and by large-volume filtration.

Reliable trace metal depth profiles are now being published (Wong 1983). Problems of sampling and reducing the risk of contamination have been solved. Clean-bench systems and clean-air laboratories are being employed. Techniques for determining the chemical state (speciation) of trace metals are advancing, and our understanding of the biochemistry of essential and toxic elements is growing (Wood 1982). In order to understand the flux of trace metals in the ocean and their interaction with the biota it will, however, be important to modify the water column and box model concepts, and consider more realistic mixing models including isopycnal advection. The risk of contamination is equally important in the study of trace organics. Most of the present research vessels are not designed for trace chemistry work, and many erroneous results have been reported. The use of uncontaminated chemicals and laboratory utensils is equally important in testing the physiological response of organisms to trace elements.

Today the analytical capability is far greater than ever before. The CTD probe can be lowered at a rate of one metre per second giving 30 readings of salinity, temperature and depth for each metre displaying the depth profiles on a TV screen and storing the data in computer memory. The CTD probe can also be supplied with an oxygen sensor. Nutrients can now be determined by automated analysis. All data are stored in a computer for subsequent analysis and testing of models for the distribution of various constituents in the oceans.

Sediments and concretions can rapidly be analyzed by X-ray diffraction and fluorescence. Particle surfaces are investigated by scanning the surface with electron beams and by electron spectroscopy and secondary-ion mass spectrometry. The composition of oil and natural gases can be determined on line, and there is a whole set of methods to determine the structure of unknown orgnic substances. The amount of substance needed for an analysis is often quite small.

One problem for marine chemistry research is the funding of the analytical facilities. The instrumentation requires a large capital investment, and it is not a one-time purchasse since there is a need for continual upgrading and incorporation of new techniques. The incentive to pay for these facilities could be purely scientific : we wish to know more about the flow of matter in the marine environment. But the facilities are equally useful in the exploitation of marine resources, regardless of whether they are organic (living) or inorganic (dead).

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N.J. Campbell

Our last guest speaker this evening is Dr. Martin Angel.

Dr. Angel obtained his Masters degree in 1960 in natural science from Cambridge University and his PhD in ecology from Bristol University, in 1967. He was a demonstrator at the Department of Zoology, Bristol University, during his career as a student, and held the John Murray travelling studentship awarded by the Royal Society.

In 1965 he joined the National Institute of Oceanography where he is presently located and serving now as Senior Principal Scientific Officer.

Dr. Angel has served oceanography in many capacities as editor of the Challenger Society Newsletter and reviewer of many journals including one for which I am responsible, namely the Canadian Journal of Fisheries and Aquatic Science.

He is a member and Chairman of many different British committees and is in addition a member of seven scientific societies.

He continues to be an active research scientist, having prepared over 40 major research papers and taking part in numerous scientific cruises and expeditions.

He is one of our leading authors on the future of ocean research in biological oceanography.

Biological oceanography and the FORE report

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Summary

There are three main objectives for the sensible and rational use of the oceans : firstly, to protect the processes which maintain life in the oceans ; secondly, to manage its renewable resources so that they sustain maximum yields ; and thirdly, the maintenance of genetic diversity. To attain these objectives biological oceanography needs to develop a predictive capability. It needs to pass through three main phases : (a) descriptive, what occurs where ; (b) functional understanding ; how does the ecosystem function and how fast are the processes taking place ? and (c) predictive understanding, the development of a body of theoretical knowledge that can be used to predict the short- and longer term effects of natural and man-made perturbations of the system.

Biological oceanography faces a range of problems ; some, but not all, in common with other branches of oceanography. There is the shear volume of the oceans, the complexity of biological systems, the dependence of biological work on a fundamental understanding of physical and chemical processes which force many of the biological responses, and the slowness with which biological sampling is converted into data.

There are five main areas where advances are needed : (a) the understanding of lower food-web dynamics, particularly in the measurement of primary production, the appreciation of the significance of primary production by nano — and pico-phytoplankton, and the role played by microorganisms and microzooplankton ; (b) higher food-wed dynamics, how food webs are structured, and how energy, nutrients and organic material flow and cycle through food webs ; (c) how ecosystems function as a whole, to establish how experience and knowledge gained from one system can be applied or extrapolated to others ; (d) the importance of time/space scales in influencing our concepts of oceanic ecosystems function ; is it possible to extrapolate from scales that relate to an individual organism's ambit or life expectancy to those that reflect year-to-year or longer term climatic or geological-time scale variations. A trend at one scale may be merely noise at a larger or longer scale ; (e) the special problems of coastal ecosystems which are the main interface between the oceans and man's exploitation for food, transport, disposal of waste, recreation, energy, minerals and land reclamation ; these problems are highlighted by the designation of EEZ's giving management of ocean resources to coastal states which lack the skilled manpower and research resources they need, to avoid making the same mistakes made by the states whose rapid industrial development outstripped their marine management skills.

The development of interdisciplinary interaction within oceanography is proving to be a real stimulus to scientific advance. Bilogical oceanography is providing important contributions to general bilogical knowledge and theory. It also offers the best potential source of information on the factors controlling recruitment to fish stocks ; our inability to predict recruitment is the major stumbing block to our efforts to manage these stocks effectively.

Advances in sciences are very much dependent on advances in technology. Biological oceanography is inhibited by the inadequacy of techniques for measuring primary productivity, pelagic and benthic sampling, the capture and maintenance of living oceanic organisms, the conversion of samples into data, and the management and dissemination of the data. Much of this technology is relatively trivial compared with the technology required for the Big Sciences of astronomy, fundamental physics, and defense science. Yet, in the long term, manking is more likely to survive on this, our only planet, because of the advances in biological oceanography, than anything achieved in the more spectacular sciences.

Why bother to do biological oceanography ?

The ocean cover over 70 % of the Earth's surface to an average depht of around 3 800 m, and oceanic organisms are responsible for at least half of the Earth's primary production. Oceanic ecosystems are an integral part of our planet's biosphere, and as such must be conserved and protected from the rapidly growing influences of Man. In the

World Conservation Strategy produced by IUCN and UNEP three basic objectives were defined for the management of the Earth's biosphere : (i) the need to protect processes which maintain life ; (ii) the maintenance of renewable resources and ; (iii) the preservation of genetical diversity. To achieve these objectives it is essential that we develop an affective predictive capability so that it will become possible to accurately forecast both the consequences of our activities and of natural variations in the environment, particularly those resulting from climatic fluctuations. Before any science can attain such a capability, it has to pass through an initial qualitative phase, which in biological oceanography corresponds to the establishment of an adequate systematic foundation and the description of what taxa occur where and when. In the next phase the emphasis shifts to quantitative studies during which the way in which the system functions is elucidated and the rates of its processes are measured. The final phase is theoretical during which the systems are modelled, often mathematically, so that the models can be manipulated to provide the predictions of how the ecosystem will respond to perturbations.

The major difficulties in biological oceanography

Biological oceanography is presented with a number of major difficulties, some but not all of which are common to all branches of oceanography. Firstly, there is the sheer size and three-dimensionality of the oceans. Their total area is 361×10^6 km² and their volume is 1370×10^6 km³ (0.13 % of the Earth's volume) ; collecting a large micronekton sample during which 50,000 cm³ of water is filtered, processes 3.7×10^{-14} of the total ocean volume. Secondly, there is the complexity of ciological systems and their interactions, which involve organisms ranging in size from over seven orders of magnitude from 10^{-6} to 30 m and with generation times ranging over six orders of magnitude from 10^{-1} to 10^5 hours. Thirdly, the dominance of the physical and chemical factors in determining the pathways and the rates of many biological processes, results in a thorough comprehension of the abiotic environment being a prerequisite for even beginning to understand many of the biological processes. Finally, biological oceanography tends to be highly labour-intensive. Whereas in physical oceanography measurement is direct so that at the end of a set of observations the data are already in a manipulatable form, in biology the conversion of samples into data may take several years. Consequently, advances in biology appear to be slow compared to the rapid development from theory to observational testing that is possible in physical oceanography, providing the technology is available to make the necesseray observations.

In trying to agree on what are the most important ocean research problems in biological oceanography, the contributors to the FORE report all recognized that the shift from purely descriptive programmes towards process-orientated investigations should be encouraged.

Already at many of the major centres of oceanographic research there has been a striking change from purely observational programmes towards the development of theories and conceptual models which are then tested observationally or experimentally. The slowness in our progress in understanding of the impact of pollution is to some extent because of the channelling of most effort into the intellectually-sterile activity of monitoring.

The important areas of biological oceanographic research

Lower food-web dynamics

The development of the 14 C method of measuring primary production resulted in significant advances during the last three decades. However, now a number of discrepancies are appearing between the results of this techniques and other less practically convenient methods, particulary when nutrients are limiting, light is above the saturation level and dissolved organic material and bacteria are abundant. Furthermore, the technique provides point values and does not allow continuous profiling. Even so, it is apparent even from the use of the 14 C method that the majority of primary production is carried out by very small cells that may be only 1 – 2 µm in size. In oligotrophic oceans over 90 % of primary prodcution may be by such tiny cells. Classical food chain work has concentrated on the consumption of relatively large phytoplankton cells such as diatoms and dinoflagellates by «net zooplankton» such as copepods. The very small primary producers are physically too small to be sieved out of suspension, and so cannot be exploited by the classical filter-feeders. Instead they must be grazed by microzooplankton such as ciliate Protozoa or mucus net feeders such as salps, so a major portion of primary production must cycle through these micrograzers. Yet it is uncertain how, or event if, these organisms link into foodchains that reach fish or other utilizable resources.

Just as the role in oceanic ecosystems of the very small autotrophic cells is unknown, so is the role of the small heterotrophs : bacteria, yeast, fungi and protozoans. Micro-organisms are responsible for the utilization of dissolved organic matter (DOM) and the production and degradation of particulate organic carbon (POC) throughout pelagic zones and in both shallow and deep benthic environments. The flux of organic carbon through marine ecosystems and the recycling and remineralization of nutrients within the water column and within sediments are dominated by the activities of the heterothrophs. These are processes that are central to the functioning of ecosystems. For example, the midwater communities living below the normal range of diel migration (i.e. 1000—1500 m) must rely almost entirely on the rain of sinking particulates as their energy source. It is uncertain whether the micro-organisms on the particulates form a major food source, of whether they act to reduce the organic material available to the midwater detritivores. Within the near-surface layers regeneration and remineralization appears to be a fundamental mechanism for the maintenance of phytoplankton growth within the photic zone in the absence of strong vertical mixing or upwelling. Deeper down, the same processes regulate geochemical profiles of biologically controlled substances, and within sediment play an important role in diagenesis, the chemical modification of substances.

The study of micro-organisms is complicated by the difficulties of their taxonomy, for example identification of bacteria requires them to be isolated and cultured, and even then there are no agreed criteria for their taxonomic separation. However, vertical profiles of biochemical parameters in the water column (e.g. RNA, DNA and ETS) are beginning to provide gross estimates of microbial biomass, respiration and growth rates. Marine bacteria are adapted to life in extremely dilute organic environments which raise basic physiological questions as to how their transport mechanisms operate at such low substrate concentrations. It is not known if they grow continuously with far greater efficiency than other marine organisms, or whether they live mostly at a minimum maintenance level, accelarating their metobolism and growth in response to short-lived improvements in surroundings.

Higher food-web dynamics

There has been a considerable amount of work done on the structure of food-webs based on the analysis of stomach contents. However, the analysis of stomach contents is fraught with difficulies. Identification is usually based on fragments of skeletal structures and other hard parts, so often less than 10 % of the contents are identifiable. Detritus and fragments of gelatinous organisms are unidentifiable, and it is frequently uncertain as to whether what is identifiable was eaten live by the animal or was in the stomach of its prey. Animals living at depths of 1000 m have been found to have phytoplankton remains in their stomachs. This phytoplankton may be consumed either live during a migration up into the photic zone, or by eating another migrant in the classical Vinogradov migration ladder, or by eating faecal pellets or marine snow containing the remains.

Almost nothing is known about the simple physiological rates of marine organisms from great depths. Metabolic rates, growth rates, ingestion efficiencies, food handling efficiency, reproductive investment are the kind of physiological parameters that must be measured for a wide spectrum of organisms before food-web structures can be used to model the flow of energy or material through ecosystems.

Ecosystem function

There is a fundamental belief in biology that there are patterns in nature and that the ecosystems we observe are not a series of unique snapshot of an everchanging kaleidoscope of chaos. At present, bilogical oceanographers are in a position similar to a group of hunter-gathers being presented with a jumbled pile of assorted car components and asked to assemble a collection of vehicules so that a transport system can be developed and managed. There is a considerable amount that can be learnt from an inter-comparison of ecosystems to explore how their functioning differs and why. How do lagoons and estuaries differ from openshore communities in sandy and rocky areas, and to what extent are the processes within the systems dominated by their boundary conditions ? In the open ocean where boundary conditions possibly play a less dominant role, how do oligotrophic and eutrophic ecosystems vary and how do high- and low-latitude systems differ.

In the open sea it is essential to know the winds, currents and turbulence that form the dynamic physical matrix within which the ecosystem is embedded. In biology, more than any of the other oceanographic disciplines, the advances in understanding are conditioned by the advances in physics and chemistry, and sampling technology. For example, the physics of the upper 100-200 m of the water column dominates many problems of biological oceanography. Turbulence, eddy diffusion, thermal stratification, internal waves and tidal mixing all serve to regulate the turbidity, the nutrient supply and the ability of the phytoplankton to maintain itself within the photic zone, and therefore regulate the productivity.

In ecosystems numerous processes interact continuously at a number of levels of organization. Attempts to model marine ecosystems have concentrated on coupled process models in which the system is represented by a number of state variables (functional groups such as herbivores, primary carnivores, etc.) with transfer between the variables being represented by sets of equations representing processes such as nutrient uptake, grazing, excretion and dispersion. These formulations are based on the concept of ecological pyramids derived from studies on terrestrial biota in which organisms can be unambiguously categorized as herbivores, carnivores, detritivores, etc. However, marine organisms frequently change their trophic level seasonally or as they develop, so that the food web structure is dynamic. Investigations into the properties of unstructured food webs have only recently been investigated theoretically, but still await experimental and observational testing.

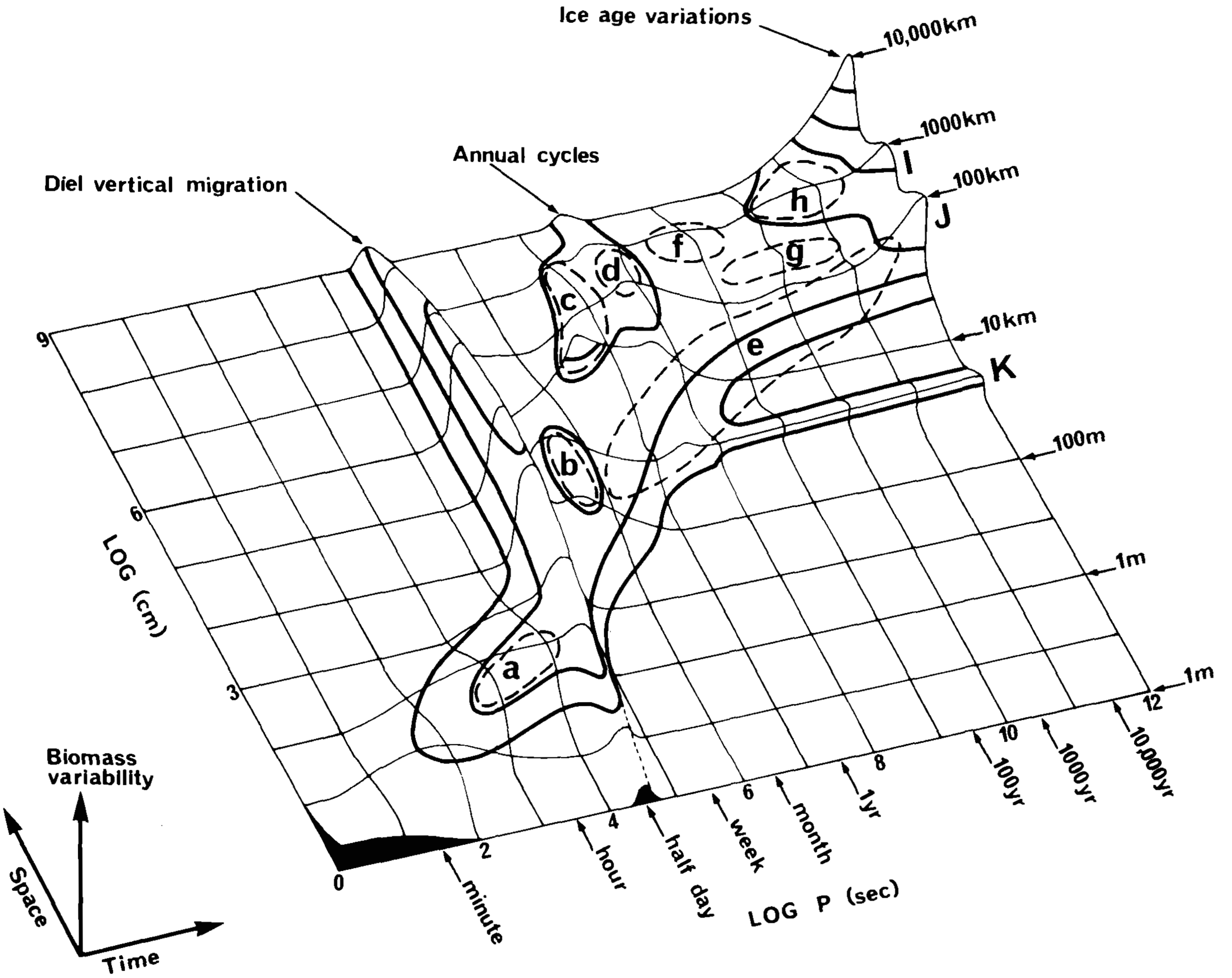
During the last fifteen years attempts to integrate multi-level process models have resulted in a general (but not universal) pessimism that such attempts to model the whole by adding the properties of the parts may never succeed. Ecosystems have homeostatic feedback loops that make total ecosystem models too complex to manipulate. Perhaps attemps to explore holistic models are more likely to be more rewarding. An analogy with physics will help to illustrate the point. Statistical mechanics bridged the gap between the gas laws and the apparently chaotic motion of molecules, so that once the constraints of the system are known a coherent body of predictions can be made. In ecology attemps are being made to discover similar unifying concepts. If such a new body of ecosystem theory were to become available, ecological research would make dramatic advances towards a greater predictive capability.

An alternative approach, that has begun to make an impact on marine community studies during the last decade, has been the experimental replicated manipulation of communities in artificial microcosms. Although the organisms within the microcosm are isolated from important physical factors such as advection and turbulence, the technique has provided an important experimental tool for testing hypotheses.

Time-space scales

Throughout oceanography the space/time characteristics of phenomena need to be understood, so that samplers and sampling regimes with compatible characteristics can be used in their study. Scales of patchiness warying according to the parameter studied, such that chlorophyll concentration, zooplankton biomass and the abundance of an individual species may have quite distinct distribution patterns in space. Matching data collected in the time domain (e.g. collected from moo-

Figure 1 The Stommel Diagram, a conceptual model of the time-space scale of variability of zooplankton biomass and the factors contributing to these scales. (from Haury *et al.* 1978).



rings) with data collected in the space domain (e.g. by continuous plankton samplers) is fraught with difficulties.

Haury, Wiebe and McGowan (1978) used a Stommel Diagram to provide a visual, conceptual model of the time-space of zooplankton biomass variability and the factors contributing to these scales (Fig. 1). It is important to recognized that the comparable diagram for phytoplankton would be quite different at time-scales of a week or less, because of the much more rapid growth response of phytoplankton, plus its relatively small behavioural ability to regulate its distribution by processes such as diel vertical migration. Similarly the diagram for long-lived organisms like commercial fishes would be totally different.

Most biological sampling has length scales of 10^{-2} to 10^{-1} km and time characteristics of minutes to weeks. There are inaccessibly small scales over which important biological processes occur, such as the uptake of dissolved molecules across membranes, the detection of phytoplankton cells by grazing zooplankton, and chemical communication by pheromones between organisms. The ability to measure chemical gradients across distances of 1 µm to 10 cm is needed for such studies. Even at scales of a few metres there are key questions that need to be resolved if we are ever to effectively manage resources. The major unresolved problem of fish-stock management is how to predict recruitment. In at least some species of commercial fish there is a critical period of a few days when the newly hatched larvae must encounter a relatively high minimum threshold concentration of food to survive. Similarly the factors determining the micro-layering of organisms particularly in the photic zone and within the seasonal thermocline are basic to an understanding of the dynamics of primary production and its utilization.

The recent rapide advances in the study of the physics of mesoscale features of 10^1 to 10^3 km, is being followed by striking advances in biology. Comprehension of the biology is more complicated because the pattern of change of the community within the eddy is partly determined by the initial state of the entrained community. Thus an eddy formed in winter will develop quite different biological properties from one formed in spring or summer. Despite the considerable research achievements of physicists, it is still uncertain to what degree eddies (as opposed to closed current rings) are advecting parcels of water which retain their identities, or are wave-like features, or whether they are a mixture of these properties with advection above the main thermocline and propagation below. These are the sort of questions to which study of conservative biological parameters may yield the answers more readily than study of physical parameters.

At large time/space scales there are a whole host of problems that are both scientifically stimulating and of immediate relevance to the need to rationally exploit and manage the oceans. There are low-frequency events such as the population outburst of the Crown-of-thorns starfish *Acanthaster planci* and the failure of the Anchovetta fishery off Peru beacause of El nino events which are seized on by the gloom-and-doom merchants as signalling disastrous consequences of Man's exploitation. Such events are now shown to be essentially spectacular examples of how natural variability is triggered, in the case of the El nino, by climatic factors thousands of miles away from where the events occurs. Each time such an event is blamed on Man's activities via pollution or overfishing and is subsequently demonstrated to be the result of natural variability, it exacerbates the problem of convincing governments and planning authorities to recognized real environmental dangers.

Present evidence suggests that the response time of marine communities to climatic variability may be of the order of tens of years. These are time-scales that are at the interface between biological, climatological and palaeontological studies. Resolution of large space and long time scales requires greater co-operation betwenn biology and geology and the collection of long time series. The initiation and maintenance of programmes involving long time series require changes in the attitudes of scientists and of funding agencies who will need to shift some input away from creaming off results in short-term projects into much longer term obsevations. Perhaps it is now that we should be planning the type of data base that will allow us to observe the influence of the general climatic warming expected to follow the increase in atmospheric carbon dioxide resulting from the burning of fossil fuels.

Coastal ecosystems

It is in these areas that three major influences for change are focussed ; the long-term variability of climate, the direct effects of exploitation of living resources and the chemical changes wrought by the full spectrum of Man's activities. Proper scientific management is going to be dependent on the ability to untangle the complex web of effects produced by these influences. At present, programmes to study coastal processes associated with weather, fisheries and pollution monitoring tend to be independent. Consequently they ignore the interactions and overlook essential elements in the system they are trying to define. This is an area where greater interdisciplinary interaction is badly needed.

Biological systems do not recognized boudaries to national jurisdiction. Furthermore, although each local area is dominted by a unique set of physical features which control biological processes, there are broad zonal patterns in ecosystems that transcend these local peculiarities. Following the United Nations Law of the Sea Conference defining the Exclusive Economic Zones of coastal states so that the individual states have full control over scientific research within these zones, there is a real danger that biological oceanography in coastal regions will become even more parochial, unless we are successful in persuading the politicians that it is everyone's interest, rich, poor, developed or developing, that oceanographic researchers are given freedom of access to all seas. It is up to the sicentists to recognized that such freedom carries with it obligations of sharing facilities and results and of training students from other countries. However, it is so important that the multitude of lessons learnt from the environmental blunders that have led to chronic pollution problems in the North Sea, the Baltic, Tokyo Bay and the New York Bight (to name but a few) are not ignored in the scramble for industrial development in the emerging nations. The present material wealth of the developed countries is all too likely to evolve into an environmental poverty that will be just as degrading as the present material poverty being suffered in some of the developing countries.

Relationship between biological oceanography and biology

Biological oceanography is providing a rich source of ideas and concepts which are proving to have much wider applications in general biology. Most marine ecosystems lack the structural complexity of many terrestrial ecosystems and also marine habitats tend to be less perturbed and better understood physically. Sampling and quantification of marine communities is potentially simpler over a much wider range of the size spectrum than for terrestrial communities. The development of ecological theory and its validation can potentially progress more rapidly in a marine context than in a terrestrial context, but then the theory, if valid, should be readily extrapolated into terrestrial and freswater conditions.

Physiological and anatomical adaptations to life in the deep ocean are of major interest. Examples are, the analogous physiological influence of high hydrostatic pressure and anaesthetics, the elaborate retinal adaptations in the eyes of deep-sea fishes, and the ability of a polychaete to inhabit and tolerate the high copper levels of the walls of the chimneys of the black-smoker hydrothermal vents on the East Pacific Rise. Hydrothermal vent communities based, not on photosynthetic primary production, but on chemosynthesis, may be analogues of early life forms on Earth. The relationship between vent metazoans and their symbiotic bacteria may be an analogue for how self-replicating organelles such as mitochondria and chloroplasts orginally evolved. Recently micro-organisms have been isolated from vents that appear to flourish at temperatures of over 200°C at high pressure.

Finally, it may only be possible to investigate a range of problems involving zoogeography, speciation and evolution and long-term population fluctuations through the study of marine organisms whose present range and distribution patterns are known and for whom there are long and more or less continuous geological records in the oceanic sediments.

Relationship between biological oceanography and fisheries

Fisheries science is the major area for the direct application of biological oceanography. Fishery scientists have been extremely successful in locating stocks, improving technology and investigating fish biology to such an extent that commercial fishes are probably more thoroughly understood than any other group of wild animals. However, attempts to develop effective management models have failed mainly because of the failure to predict one basic parameter — recruitment. Larval survival, growth and development are subject to a complex interaction of environmental factors in all time/space scales. Resolution of these sorts of problems requires a properly orchestrated multidisciplinary approach ; even the scale of the approach is not intuitively obvious, for example, the solution to what causes the El Nino phenomenon would never have been discovered by research programmes restricted to the Peruvian region or even to the Eastern Pacific Region.

There must be a better integration of fishery science with general oceanography, for without it there is no hope of being able to understand the variability of the inputs. Even commercially-exploited species live within the general oceanic ecosystem and cannot be understood in isolation from it. Furthermore, the development of the fishery for what is possibly the last great exploitable protein resource of the ocean, the krill resource of the Southern Ocean, should not be allowed to proceed in a chaotic, haphazard fashion determined by commercial and political expediency. The BIOMASS Programme, together with earlier data collected by national programmes such as Discovery Investigations, has begun to lay the foundation for the scientific understanding of the Southern Ocean, and this impetus must be maintained.

Improvements in technique

In all aspects of oceanography rapid advances in understanding follow after technical advances in instrumentation and data handling. Biology tends to be the poor-relation to the other disciplines with smaller investment in instruments and new technology. Even so, the electronic revolution in data acquisition and instrument control is at last beginning to expand the horizons of what can be achieved by the biologist. Every effort needs to be made to extend the limits of resolution of sampling techniques, to develop techniques for simultaneous collection of organism and physico-chemical information, and to improve the condition of the samples.

Primary production

The need for techniques allowing continous profiling of primary production has been referred to above. Sensors capable of automatically measuring *in situ* nutrient concentrations would dramatically improve our capability to follow biological processes in the photic zone, in the same way that fluorometers and particles counters used in conjunction with undulating instrument packages have already begun to revise our concepts of the dynamics of blooms.

Midwater sampling

The basic techniques of capturing organisms in midwater of using nets, water bottles and pump samplers have hardly advanced during the last two decades, apart from the application of techniques of electronic control. Each method samples only a limited section of both the size-spectrum and the time/space scales, with only slight overlap. Adequate sampling techniques still need to be developed for quantitatively sampling very large and active nekton, delicate gelatinous forms, and microzooplankton and micro-organisms which tend to be destroyed by normal preservation procedures. Certain zones are inaccessible to present sampling techniques, for example close to the sea bed in areas of rough topography. Alternative techniques for quantifying biological populations such as the use of large particle counters, acoustic methods, photography, holography and direct observation, have received some attention, but need further development.

Benthic sampling

Out of the great array of benthic sampling techniques available most are only semi-quantitative at best and need to be improved. The use of submersibles or divers in shallow water gives the biologist considerable control and precision, as illustrated by some of the recent work carried out on hydrothermal vent communities and the beautiful work by divers on coral reefs and in midwater on the biology of gelatinous organisms. But these methods have logistic limitations, of sheer expense in the case of submersibles, and of training and safety of diving scientists. Survey capabilities need to be developed so that localized bottom features can be found and refound. This will allow the effects of natural experiments — turbidity slumps, large accumulations of organic material, transient bed forms, etc. — to be followed. Remote experimental stations need to be elaborated that can be deployed on the sea bed and left to carry out a sampling programme. The importance of sedimentation, resuspension and the fluxes of chemicals into and out of the sediment to biological processes as well as geochemical processes requires the continuing development of measuring techniques for use in the benthic boundary layer.

Physiology

The measurement of rates of processes in oceanic ecosystems will require a large number of basic physiological parameters. The technology for the measurement of these parameters is well developed, but the ability to capture healthy, unstressed organisms is not. For quite a number of deep-sea organisms, capture in insulated samplers so they are not warmed much above their *in situ* temperatures is adequate. Others, like fish with swimbladders, need to be kept pressurized, at least to some extent, with all the associated problems of handling.

Remote sensing

Remote sensing from satellite or plane has less to offer open ocean biology than other branches. The only biological parameter that can be measured is surface chlorophyll, but its measurement is dependent on visual wave lengths and hence clear atmospheric conditions. The large scale of the observations do allow the discrimination of features that might otherwise be unsuspected. Remote sensing can also be used to set the large-scale physical context of biological sampling by locating fronts, eddies and upwelling zones. It can be used to track large organisms and to give time series observations on the spread or contraction of coastal ecosystems such as salt-marches and mangroves. Satellites are also being used to interrogate fully-automated buoy systems which can be further developed to monitor parramaters of interest to biologists.

Data handling

International exchange of cruise programme information and physical data has begun to dramatically improve the ability of researchers to carry out highly productive second generation analysis, and to encourage greater standardization of measurement. The complexity and heterogeneity of biological data has deterred significant extension of this facility into biological oceanography. Some individual institues are developing their own bilogical data bases which are mutually incompatible, others have no systematic system for the designation and full documentation of static data. Spiralling costs of journal production are resulting in less data appearing in scientific papers. The data are relegated to the grey report literature or lost in inaccessible notebooks. Data exchange could reduce redundancy of sampling effort. The saving of even a few days of shiptime would easily pay for the running of a data base.

Science is not done if its results are not disseminated. We are promised an electronic revolution in communication in the next decade, but the establishment of novel systems must not be allowed to create a hiatus in established systems of communication.

Finally, may I once again reiterate my conviction that the World in its stampede to improve material standards and to elaborate prestigious big science is neglecting environmental sciences. On political time-scales of up to five years biological oceanography in common with other environmental sciences offers few substantial benefits. On longer time-scales of decades it has the potential to provide the basis for environmental management that will be essential if any sort of quality of life can be created and maintained for the World population.

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