Intergovernmental Oceanographic Commission

Anton Bruun Memorial Lecture

OCEAN PREDICTABILITY

by
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ANTON FREDERICK BRUUN

ANTON BRUUN was born on the 14th of December 1901 as the oldest son of a farmer, but a severe attack of polio in his childhood led him to follow an academic, rather than 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 Thomas 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 marine animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to study 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 the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945-1946 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 1950-1952, 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 like SCOR, IACOMS, IABO, and the IOC and was elected IOC's first chairman in 1961.

His untimely death a few months later, on 13 December 1961, put an end to many hopes and aspirations.

In 1962, the former US Presidential yacht *Williamsburg* was converted into a research vessel and renamed *Anton Bruun* in honour of the great scientist. The *Anton Bruun* took part in the International Indian Ocean Expedition (1959–1965) and, in the late 1960's, circumnavigated the globe in one of the last great exploratory expeditions of modern oceanography.

THE BRUUN MEMORIAL LECTURES

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 "Anton Bruun Memorial Lectures" were established in accordance with Resolution 19 of the Sixth Session of the IOC Assembly, in which the Commission proposed that important inter-session developments be summarized by speakers in the fields of solid earth studies, physical and chemical oceanography and meteorology, and marine biology.

NINETEENTH SESSION OF THE ASSEMBLY, 2 - 18 JULY 1997

Common Resources, Conflicting Uses: The Economics of Coastal Resources Management, by John A. Dixon. Sixty-five Years of the Continuous Plankton Recorder Survey: 1931-1995, by Philip C. Reid; Sonia D. Batten; Harry G. Hunt.

EIGHTEENTH SESSION OF THE ASSEMBLY, PARIS, 13 - 26 JUNE 1995

Some Results of the Tropical Ocean and Global Atmosphere (TOGA) Experiment Application of El Niño Prediction to Food Production in Peru, by Pablo Lagos; New Applied Knowledge Resulting from the TOGA Programme in all Three Oceans, by James J. O'Brien.

SEVENTEENTH SESSION OF THE ASSEMBLY, 25 FEBRUARY - 11 MARCH 1993

The Role of Marine Research, Systematic Observations and Related Capacity Building and Technology Development for Ocean and Coastal Zone Sustainable Development: The Global Ocean Observing System, by John Woods; Long-Term Systematic Environmental Monitoring and Sustainable Development: The Role of WMO and of the National Meteorological and Hydrological Services, by G.O.P. Obasi.

SIXTEENTH SESSION OF THE ASSEMBLY, 7 - 21 MARCH 1991

Modelling and Prediction in Marine Science, Opening Statement, by Manuel Murillo; Overview of the Coastal Ocean Prediction Systems Programme, by Christopher N.K. Mooers; The Barents Sea/The Physical-Biological Connection, by Egil Sakshaug; The Real-Time Numerical Forecasting System for Marine Environmental Elements in China, by Chao Jiping and Wu Huiding. In: IOC. Bruun Memorial Lectures, Paris, UNESCO, 1992. (*Technical Series, 39)*.

OCEAN PREDICTABILITY

JOHN WOODS

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JOHN WOODS

John Woods is Professor of Oceanography at Imperial College, Honorary Professor of Oceanography at Southampton University, Fellow of the Plymouth Marine Laboratory, Fellow of Linacre College Oxford University, and Foundation Member of the *Academia Europaea*. From 1986 to 1994, he was Director of Marine and Atmospheric Sciences of the UK Natural Environment Research Council. Prior to that, he was a Research Fellow at the Meteorological Office (1966-72) and Professor of Oceanography at Southampton University (1972-77) and Kiel University (1977-86). He has contributed to the development of the Global Ocean Observing System (GOOS) as a member of the Joint Scientific and Technical Committee, where he was responsible for the *Prospectus for GOOS 1998.* He is President of EuroGOOS. From 1995 to 1998, he was a member of the Scientific and Technical Advisory Panel of the Global Environment Facility (GEF STAP), where he chaired the International Waters section. He has served on the steering committees of a number of international scientific programmes, including the Global Atmospheric Research Programme (GARP), the World Climate Research Programme (WCRP), the World Ocean Circulation Experiment (WOCE) and the International Geosphere-Biosphere Programme (IGBP). His work has been recognised by a number of awards including: honorary doctorates from Liege & Plymouth universities; and prizes from the Ministry of Defence, the Royal Geographic Society and the Royal Meterological Society. In 1995, the Queen made him a Commander of the British Empire. Professor Woods's research interests include ocean forecasting and plankton ecology.

OPENING REMARKS

"A scientific attack on the limits to predictibility of the ocean can only be mounted after we have gathered sufficient data."

■ PRESIDENT, DISTINGUISHED COLLEAGUES, LADIES AND GENTLEMEN,

It is a great honor to be invited to deliver the 1999 Anton Bruun Memorial lecture. I thank you for your kind invitation.

I last delivered a Bruun lecture in February 1993. Then as now my subject was the Global Ocean Observing System, which we affectionately call GOOS. That lecture was published in the *Journal of Marine Policy* (1994, Vol. 18 (6) pages 445-452). It was based on a paper I had prepared for the Intergovernmental Oceanographic Commission called The Case for GOOS which addressed the economic arguments for the first time.

I recall the excitement at the Second World Climate Conference in 1990 when GOOS was launched by the Intergovernmental Oceanographic Commission. There was a feeling that the oceanographers had, as it were, captured the high ground in climate research. Our colleagues in meteorology immediately set about creating a rival Global Climate Observing System, which suffers from having a more elegant acronym: GCOS. Since 1990, GOOS has extended its intellectual lead, with pioneering studies of the science, technology and economics of ocean observing. And it has established vigorous regional programmes in North East Asia (NEAR-GOOS), Europe (EuroGOOS) and elsewhere.

This time my lecture will be based on the *Prospectus for GOOS* 1998 (published by the IOC as GOOS Publication No. 42). I planned that volume to provide a comprehensive and coherent account of this rather complicated and ambitious international enterprise. The success of the *Prospectus* owes much to the skill and hard work of its author, the distinguished meteorologist, Dr Peter Ryder. We should all show our appreciation of Dr Ryder's great service to GOOS.

My theme today is Ocean Predictability, which must be thoroughly understood before we can design an effective GOOS. To many oceanographers, predictability is a fiendish mathematical discipline involving chaos theory, and having little immediate value in our great enterprise. Yes, we know it is important, but there are many more urgent practical problems to be solved before we reach the mathematical limits set by predictability. I tend to agree with that sentiment. A scientific attack on the limits to predictability of the ocean can only be mounted after we have gathered sufficient data. And that will only happen when we have a comprehensive ocean observing system in place.

Happily this 'Catch 22' situation need not impede progress in developing GOOS. Like the great marine explorers of the past, we are not daunted by the lack of a precise knowledge of our goal. However, like any cautious navigator, we need to be aware of our level of ignorance, and to be alert to the possibility of surprises.

At the start of the 21st century, the problem we face in not yet being able to chart the limits of predictability reminds me of a similar problem in the 18th century, namely the problem of determining longitude at sea. For most of the 19th century, the ships of the East India Company (the famous 'John Company') set sail for Asia in the knowledge that they would not know their longitude accurately. Seamen had to navigate cautiously because of the ever-present risk of disaster through ignorance of longitude. But, spurred on by the prospect of profitable trade, they lived with that risk. The alternative would have been to stop investment in long-distance maritime trade until the longitude problem was solved. The alternative overland route was well-proven, but it posed different risks. The merchant strategists of John Company balanced the risks of long-range maritime trade against the benefits it promised, and built up a great enterprise on the basis of their analysis. Happily, in 1760 John Harrison solved the longitude problem with his H4 chronometer, and within twenty years chronometers were being purchased in great numbers by the captains of East Indiamen and men-of-war. A chronometer cost 80 pounds, which was James Cook's annual pay in 1762. But by 1815 there were 5,000 marine chronometers in use (Sobel 1995).

The problem of ocean predictability is for GOOS what the longitude problem was for mariners 200 years ago. We must invest in scientific research and engineering to solve it. Meanwhile we must navigate cautiously, always bearing in mind that our continuing vagueness about ocean predictability may spring some surprises as we develop operational oceanography.

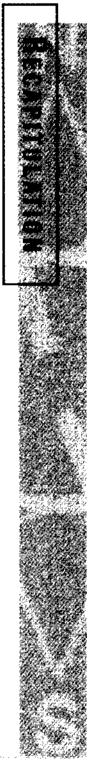
We are not totally ignorant about the limits to predictability. We know how it affects weather forecasting. Mathematicians and physicists are making rapid progress in complexity theory: they are the Harrisons of predictability. My lecture will not dwell on those difficult theoretical issues. Rather, I shall focus on the immediate practical challenge. How should we take account of our remaining ignorance about ocean predictability in designing a Global Ocean Observing System?

I shall argue that we can adopt a robust design philosophy that will reduce the risk of hitting the uncharted rocks of predictability. The prize is too great to justify being over-cautious. We must go ahead vigorously with globalization of operational oceanography. Once that is done, the data flowing in routinely will provide the information we need to assess the limits to our enterprise set by chaos theory. Those limits cannot be discovered unless we go ahead and establish global operational oceanography. By having courage now, we shall gain the resources needed to cut through the Gordian knot, to blow away the "Catch 22" and then, having charted the borders of what is theoretically possible, it will become clear how to design a better GOOS.

My lecture will start by briefly revisiting some fundamental questions.

Why should we want to predict the ocean? What are the expected socio-economic benefits? How in principle might it be done? How can we best combine models and data at a local level and globally?

Following that introduction the lecture will review the status of ocean prediction at the end of the 20th century and consider the prospects for the next century. The emphasis will be on practical methods and on the real issues confronting those involved in developing ocean prediction around the world. The leitmotif of predictability will emerge at the end as the dominant theme. I shall conclude that addressing it should have high priority in GOOS. Predictability should be the subject of a series of carefully designed scientific experiments.



WHY PREDICT THE OCEAN?

"Predicting water quality presents us with an inter-disciplinary challenge that is unprecedented in science."

FIRST I RECALL THAT MANKIND HAS BEEN ATTEMPTING TO PREDICT THE OCEAN for over two thousand years, starting with currents, tides and waves. In 322 B.C. Aristotle was commissioned to predict the oscillatory currents in the Straits of Euripus, which he failed to do, and is said to have drowned himself in despair. I do not have the time to go into a detailed history of the subject, but refer you to books on Prediction of the Upper Ocean by Eric Kraus (1977), on Wave Prediction by Komen *et al.* (1994) and on Tides by David Cartwright (1999). The stimulus in every case has been a combination of intellectual challenge, on the one hand, and practical application, on the other.

Research in the past has produced effective methods for predicting the tides, wind waves and upper ocean temperature structure for the benefit of port management and coastal protection, shipping and naval operations. Research continues on improving these forecasting systems, and applying them to new regions.

In 1992, the focus for ocean prediction was dramatically changed by the Rio Earth Summit, which emphasized issues which had not previously been supported by ocean forecasting: coastal pollution, the health of the ecosystem, and health problems in man caused by diseases in marine organisms. These issues were spelled out in Chapter 17 of *Agenda 21.*

They have led to the International Agreement on Marine Pollution from

Land-based Sources (1996) and the plan for a Global International Waters Assessment, the ocean equivalent of the Intergovernmental Panel on Climate Change (IPCC) reports on climate.

At the end of the 20th century, governments are introducing legislation designed to reduce the societal problems of pollution in coastal waters. The need for accurate descriptions of today's polluted environment, and the ability to predict the likely consequences of proposed courses of action provide the spur for forecasting water quality.

Predicting water quality presents the oceanographic community worldwide with an inter-disciplinary challenge that is unprecedented in science. It can only be achieved by combining know-how in the primary disciplines of physics, chemistry, biology and sedimentology.

The oceanographers' answer has been to introduce a rolling programme that starts with forecasting the physics of ocean currents, then gradually embraces chemistry, biology and sedimentology at increasing levels of sophistication.

This plan is based throughout on the strategy of serving customers by extracting products from mathematical models into which observations have been assimilated.

Before we can make a convincing case to governments for funding a permanent global system for ocean forecasting we shall need an explicit statement of requirement, expressed as model products and accuracies, and a tested design that will satisfy those requirements. We need to demonstrate that the underpinning science is sufficiently advanced to justify the investment.

As expected, the science of GOOS has benefited from the outstanding success of the World Ocean Circulation Experiment. The WOCE conference last year confirmed that the experiment had achieved and in some respects exceeded our most optimistic plans. The WOCE data base contains the first high-quality synoptic description of the physical properties of the ocean, from top to bottom, from pole to pole. That magnificent data set is not only consistently of the highest quality, but it contains far more hydrographic profiles than had been collected in the whole history of oceanography. WOCE data will serve as the primary source for designing GOOS.

Twenty years ago, we decided that WOCE should be designed conservatively using proven technology, in particular the techniques of deep ocean soundings by Conductivity-Temperature-Depth profiler from ships, deep ocean moorings, deep drifters based on John Swallow's, and surface drifters. All these were progressively refined before and during the field phase of WOCE (1990-97) and all performed magnificently. But they were labor-intensive and depended on expensive research ships. WOCE signaled the end of the heroic age of oceanography. The future of operational oceanography lies in automation, and in unmanned robotic observing systems.

In my 1993 Bruun lecture, I drew on WOCE experience to assess the resources needed for a permanent global ocean observing system: how many satellites, current meters, floats and deep drifters? Nothing has happened in the last six years to sharpen up that rough estimate. But one item is certain: the number of research ships. In 1993 and again in 1999 I state that the number will be zero. In that sense GOOS will be very different from WOCE.

In designing WOCE we had to predict how the observations would be used. Our answer was that they would be used to test mathematical models of the ocean circulation. We assumed that before the data had been quality checked and assembled in international data centres, oceanographers would have adopted the practice of meteorologists, who do not seek understanding from the direct analysis of data, but from the indirect technique whereby the observations are first assimilated into a model, which is then used to simulate the atmosphere in far more detail and more consistently than is possible with the original observations on their own. Without the model, the data are mere numbers; with it they are samples of Nature. The model provides added value through the Laws of Nature, represented in its equations.

To use an ecological metaphor, this is like moving up one trophic level in the food chain. The old oceanographers (trained to use the classical dynamic method) were like herbivores, feeding directly on their observations. The new oceanographers (who use data assimilation) are like carnivores, which feed on the flesh of other herbivores: the models serve as their cows, which digest the raw data and provide more energy-rich food. Meteorologists became carnivores twenty years ago: oceanographers are learning how to do so at the start of the 21st century. The Global Ocean Data Assimilation Experiment (GODAE) is to help us make that transition, which is a pre-requisite for GOOS.

Carnivory depends on the evolution of productive herbivores. In oceanography it depends on the evolution of productive models, which in turn depends on the availability of high performance computers. In 1980 we planned WOCE on the assumption that teraflops computers (capable of 10^{12} sums every microsecond) will be available within 20 years. That gamble paid off: teraflops computers are now available commercially. They make it possible to model the global ocean circulation with sufficient resolution (say 10 km) to describe major currents like the Gulf Stream realistically. Those models are now being used to extract information from the WOCE data set. Such models will lie at the heart of GOOS.

Looking further ahead, models of water quality, with equations for physics, chemistry, biology and sedimentology, demand computers with much higher performance. Scaling up from the limited area models available today, I estimate that we shall need petaflops computers capable of 10^{15} sums every microsecond, before it will be possible to adopt data assimilation in global operational systems for water quality prediction. Petaflops computers should be with us by 2020. Meanwhile we shall remain herbivores in the water quality business.

WOCE has prepared the way for GOOS. We now have the technology for making routine observations, and powerful computers for modelling the ocean in sufficient detail to extract information from those data. Analysis of the WOCE data set will improve our understanding of the global circulation. And that will permit the design of smart sampling schemes, to provide the data for the models to graze on.

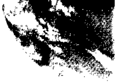
THE ECONOMICS OF GOOS

"The OECD Megascience Forum assessed the value of the customer base for ocean prediction as about US$ 1 trillion."

■ WHILE WOCE WAS IN THE FIELD, THE PLANNERS OF GOOS TURNED THEIR attention to the economic question. They assumed that ultimately the investment of public money would be needed to create a global observing system, as in atmospheric weather forecasting, which costs about US$ 2 billion per year. Various attempts were made to estimate the cost of GOOS. They all concluded that it would cost more than atmospheric weather forecasting, but estimates varied. We know that WOCE cost about US$ 1 billion, but we hoped that an operational system could benefit from economies of scale, and the benefits of technological developments.

Things are going well. For example, the cost of satellites is dropping fast thanks to improved technology: so they will probably cost only one tenth of the 1992 estimates of US$ 1 billion per year. Equally, the high cost of ship-based hydrographic profiling is likely to be greatly reduced by adopting new unmanned systems based on a judicious mix of pop-up drifters and autonomous vehicles, which were not available for WOCE.

These developments in technology will help to make GOOS more affordable. However we cannot estimate the annual cost until we have a specification for the sampling rate. At present we have only the vaguest idea of what density of observations in space and time will be needed. Before we



can begin to design that sampling strategy we need a clear statement of requirement. What products, and with what accuracy, do we need to extract routinely from the global model into which the operational observations are being assimilated?

Once those products are specified we can use Observing System Simulation Experiments (or OSSE's) to discover what appears to be the most economical mix of observations capable of constraining the models so that they yield those products to the specified accuracies. And we can promote field experiments to check out the predictions of those OSSE's. Experience in the Tropical Ocean and Global Atmosphere (TOGA) programme, aimed at learning how to forecast the El Niño, shows what will be needed.

The Organisation for Economic Co-operation and Development Megascience Forum assessed the value of the customer base for ocean predictions as about US$ 1 trillion. A study by the UK Government's Marine Foresight Panel estimates that the existing global market for non-defense ocean prediction is about £ 10 million per year for open tendering and ten times that for tied work by national agencies.

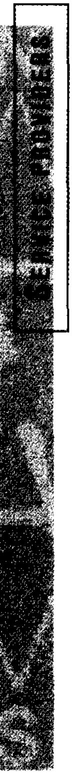
Analysis of the existing customer base and projections for the future indicate that there are only two customers for truly global products. The first is ship-routing, which is concerned with waves, currents, and ice. The second is climate prediction, which is concerned with the global patterns of sea surface temperature and the heat fluxes which create them.

All other customers (who provide 90% of the billings for marine forecasting) are concerned with quite small (order 100 km) theatres of operations, usually located in coastal waters. This large customer base includes: off-shore extraction of minerals, oil and gas; defense; recreation; fisheries and aquaculture; coastal shipping; and human health.

Tourism: Recreational use of the sea provides one of the most important sources of maritime income in both industrialized and developing countries. For example, in the UK it ranks second only to the national income from off-shore oil and gas. In many countries it is top of the list. However, the industry is notoriously volatile. Tourists switch away from locations that have bad publicity because of environmental problems. Governments sponsoring their tourist industry are responsible for maintaining standards in their coastal waters.

Off-shore oil and gas: The industry started in relatively shallow water, where there are now mature systems in place to provide the required marine environmental information, notably on waves, currents, and sediment movement. But in recent years oil extraction has moved into deeper water, of order one kilometer at sites on the continental slopes, where there are additional environment problems, in particular strong, fluctuating currents running along the slope, and the risk of sediment slumping.

These customers are served by a combination of government agencies and commercial companies, who have developed local operations based on



observations and models which focus on the theatres of operation of their customers. There are hundreds of such operations at locations all around the world. The majority (about 90%) are managed by government-owned agencies, but a growing fraction are served by commercial organisations. The latter have billings of some US$ 10 million p.a., which is expected to grow to US$ 100 million p.a. over the next decade or so.

The services that exist today are based on local observations in the theatre of operations of their customer. In a few cases those data are assimilated into operational models to generate the products required by the customers. Examples are ship-routing and storm-surge prediction. However operational services depend on direct interpretation of the local observations: examples include current measurements around off-shore oil fields and regular surveys of fish stocks and chemical contaminants in coastal waters.

Most government customers are rather conservative in the systems they specify. That is particularly true in the case of overseas aid agencies, like the World Bank, which fund projects to address the problems identified in *Agenda 2000.*

There is considerable scope for improving the performance of these local services, by switching to model-based generation of products. That normally involves a re-design of the sampling strategy for observations.

The service provider finds the most economical way to deliver the products his customers want, starting with local monitoring. Making observations costs much more than modelling, so he may be able to generate the products with fewer or cheaper observations when they are assimilated into a model. As this system is refined, it will approach the limits of predictability for local operations.

Many applications of ocean prediction are based on predicting wind waves, which are generated, as their name suggests, by the wind. Examples are ship-routing and coastal flooding by storm surges. Wind speed is also a crucial factor in computing the depth of the surface mixed layer, which is central to predicting water quality and sound propagation (for defense applications).

Meteorologists have established that it is theoretically impossible to predict the weather more than a week or two ahead. That discovery was the start of chaos theory, which has since been applied to establish the limits to prediction in many other systems, from medicine to ecology. Later I shall discuss how we might apply chaos theory to the internal fluctuations of the ocean; at this stage I shall merely state that we expect the limit to be much longer than the week or two set by the weather.

FLOW OF INFORMATION INSIDE THE OCEAN

> "To design a smart observing scheme (...)
> requires a scientific understanding of how
> variations in the catchment influence
> the products in the theatre of operations."

THE MARINE ENVIRONMENT IN THE THEATRE OF OPERATIONS CAN ALSO BE influenced by changes arriving through the water. These can arise in two ways: advection by ocean currents, and propagation of waves. In some applications, for which the local weather is less important, the products needed by the customer may be more influenced by these internal changes.

For example, in oil recovery from deep sites on the continental slopes, the kilometer-long riser (which carries the oil from seabed to ship) may be vulnerable to ocean currents, the fluctuations in which are not controlled by the local weather but by upstream influences inside the ocean.

Another example is the prediction of water quality in the North Sea, which depends not only on inflow of contaminants from the surrounding land, but also from the open Atlantic Ocean.

Thus, for some activities, the limits of prediction may be set not by the local weather but by changes occurring in the ocean beyond the customer's theatre of operations. To improve the products he gives his customer, the service provider will need to extend his area of monitoring and modelling beyond the local theatre into an extended *catchment* from which the influences come.

The challenge is to develop a strategy for monitoring the changes occurring in those *catchments*. They are potentially large, perhaps extending across a whole ocean, so a strategy based on comprehensive forecasting in the *catchment* is likely to be expensive; and probably more than the customer will pay for the modest improvement it generates in the products he needs in his local theatre of operations. So there is motivation to design a smart observing scheme which will collect only the data which are most effective for improving those products.

That requires scientific understanding of how variations in the *catchment* influence the products in the theatre of operations. We are still rather ignorant of this process. However, we expect that there will be rapid progress as oceanographers analyze the data sets created by high resolution models fed with observations from WOCE and satellite remote sensing.

As the number of customers grows, each with a distinct theatre of operations, their upstream *catchments* start to overlap. It then makes sense to share the cost of monitoring and modelling in these overlapping open ocean *catchments*. Already, some commercial operators are introducing regional systems which serve a number of their customers at sites with overlapping catchments. And the EuroGOOS consortium of 35 national agencies is introducing collaborative operations in the Mediterranean, Baltic and NW European regions.

There is an obvious economic benefit to be gained from such collaboration. However, the cost of monitoring the open ocean is high, and so far collaboration has been limited to regional *catchments* of modest extent.

Looking further ahead, the logical extension is to monitor and model whole ocean basins. And eventually it might be useful to design a single global system that will serve local operations all around the world.

Meanwhile it may be helpful to think of a simple "cartoon" which shows how products in the customer's theatre of operations are influenced by variability in the open ocean. This cartoon is based on the idea of changes in one oceanic location leading to others elsewhere at some later time. An example is the change in mixed layer depth and temperature off Indonesia leading some months later to an El Niño off Peru.

We can think of this as a flow of information inside the ocean from one place to another. At any instant, there is a vast number of such signals moving along a variety of trajectories. The task for the service provider is to identify which of these trajectories enters his theatre of operations, and what signals flow along them, and which influence the products he supplies to his customers. His smart monitoring system will focus on these signals. His aim will be to trace them upstream along their trajectories to their source. The further he can go, the earlier the warning of their arrival in his theatre of operations will be.

Assuming this cartoon is useful, the challenge is to understand the flow of information through the ocean. Information is carried through the ocean by two processes: *teleconnexions* and *advection*.

Teleconnexions involve the transmission of information by waves. Here are two examples:

SHIP-ROUTING. In the case of wind wave forecasting (e.g. for ship-routing) it has become necessary to predict the inflow of swell generated by distant storms. This is done in the WAM system used operationally at the European Centre for Medium Range Weather Forecasting (ECMWF).

EL NIÑO. In the case of El Niño forecasting, the information is carried by Kelvin waves along the equator in the Pacific towards America. The skill in forecasting El Niño comes from a combination of monitoring and modelling of this flow of information before it arrives at the theatre of interest located in the Eastern Tropical Pacific.

Information is also advected across the ocean by ocean currents. This second mechanism is necessary for the transport of chemicals and plantkon. Uncertainty about the inflow of these properties into a local theatre of operations can limit the predictability of water quality and fisheries production. Again, the solution, in principle, is to monitor the ocean upstream and to use those data in a model of the open ocean to predict future variations in the chemical and biological properties at the boundary of the local theatre of operations.

GOOS will be designed to collect information about the predictable variations in ocean conditions entering a theatre of operations. We hope to identify those signals in advance by looking upstream along the trajectories of information flow. Looking further upstream should produce earlier warning.

However, we also know that information is progressively dissipated. So the further we look upstream, the fainter will be the signal, and eventually it will provide no value for operational forecasting. At present we do not know how far upstream we can usefully monitor fluctuations. Answering that question must be one of the primary goals of GOOS.

What causes the dissipation of useful signals radiating and advected across the ocean? We assume that the primary mechanism is refraction and dispersion by the unstable eddies, jets and fronts which make up the weather inside the ocean. These transient motions have the same chaotic behaviour as the weather inside the atmosphere. They can be described by a suitably high-density of synoptic observations, including satellite altimetry and radiometry, combined with hydrographic profiles and direct measurements of velocity. When those observations are assimilated into a high resolution model (one that has a horizontal grid spacing of 1 km) the development of the weather systems can be predicted with useful skill for a few weeks. In practice this has not yet been done, because of the difficulty of collecting a sufficient density of observations to initialize the integration, and to verify its predictions.

It is important to undertake such costly and onerous experiments to establish the limits to predictability of ocean weather systems, which are ultimately set by chaos theory. Assuming that the limit for ocean weather scales with the limit for atmospheric weather according to the Lagrangian time scale of ocean eddies, we expect the theoretical limits to prediction for ocean weather to be of order of one month. Beyond that limit the ocean weather becomes unpredictable noise, which can only be predicted statistically.

So even if it were possible to resolve the ocean weather within a future operational GOOS, the large scale signals which we need to monitor and predict would be subject to random noise when we attempt to trace them back upstream for more than one month. It is not clear what impact that noise would have on the usefulness of the upcoming signal. We need experiments (under GOOS) to learn that.

However, the situation is likely to be worse than that. It is unlikely that practical observing systems will resolve the ocean weather sufficiently to permit its description and prediction to the limits set by chaos theory. So the noise will start less than one month upstream.

To summarize, we want to look beyond the theatre of operations into the *catchment* area, in the direction from which waves or *advection* bring external changes, so that we can take them into account in our forecasts for the customer. However, looking upstream is like looking into a fog. Close objects are fairly distinct, but those further away are lost in the fog. In our case the objects are fluctuations in the ocean environment whose arrival we would like to be able to predict. We do not yet know how far we shall be able usefully to look upstream. Discovering that should be the subject of experiments promoted by GOOS.

GOOS

EXPERIMENTS

"Oceanographers have not yet studied

the flow of useful information

in the ocean."

■ THE CUSTOMER FOR OPEN OCEAN MONITORING IS THE *SERVICE PROVIDER* WHO operates local systems in his customers' theatres of operation. The goal is to focus on those open ocean signals that will improve the performance of local operational forecasting systems. Will the customer be prepared to pay more for the improved product?

Assessing the cost benefit of such operations is difficult. Usually it depends on experiments that are funded by government. A good example is the 10-year TOGA experiment which established the feasibility, cost and value of monitoring the tropical Pacific in order to extend the prediction of El Niño from weeks to months. There is a need for similar experiments to address forecasting of *Agenda 21* problems.

The Global Ocean Observing System (GOOS) provides the international framework for promoting such pre-operational experiments. The goal for GOOS experiments will be to discover whether it is possible to design an affordable system of ocean monitoring that can yield products which improve the performance of existing local operational systems. For example, a GOOS experiment in the Atlantic Ocean should be designed to improve the performance of operational systems located along the coasts of Europe, Africa and America, which lie downstream in the flow of information by *teleconnexions* and *advection*.

Interestingly, oceanographers have not yet studied the flow of useful information in the ocean. The obvious exceptions are the information carried by waves. We are still rather vague about what exploitable information is carried by ocean currents. There is a need for basic scientific research on the nature of information flow across the ocean.

The oceanographic research community has developed a number of global models which do a good job of simulating the physical features of the ocean described by the WOCE data set. They are being extended to simulate chemical and biological properties. Computers of sufficient power will soon be available, and their cost will then fall rapidly. So modelling will become more affordable.

The cost of monitoring the open ocean is also expected to fall as unmanned instruments communicating by satellite replace instruments lowered from research ships. And the cost of remote sensing from satellites is falling dramatically: this is particularly true for altimeters. It has been estimated that these new systems would make it possible to repeat WOCE for less than 10 % of the cost. So early estimates of the cost of a global ocean monitoring system may have been unduly pessimistic.

These GOOS experiments are likely to be much more affordable than 20th century global experiments like WOCE. The task for those experiments will be to discover the limits of predictability in the ocean, expressed in terms of the benefits to local operations servicing paying customers in the public and private sectors. The first GOOS experiments will be based on observing systems that already exist, notably satellites, plus some new systems, like the proposed 3,000 Argo undulating floats. They will provide data which will allow us to design more focused experiments in the future. At this stage it is unclear how many experiments will be needed before we have a sufficient scientific understanding of the flow and dissipation of information through the ocean to assess whether it makes economic sense to invest in a permanent Global Ocean Observing System. Perhaps the ocean is so dissipative that ocean forecasting will remain for ever local, apart from short term predictions of wind waves.

CONCLUSION

"The (...) task for GOOS is to design experiments (...) to reveal the limits to prediction in the ocean."

Let me conclude by re-stating the case for investing in GOOS, as presented in the *Prospectus for GOOS 1998.*

It is built on three facts:

1. There is a substantial, and rapidly growing market which is paying for ocean forecasting either directly by contracts to service providers, or indirectly through taxes which governments spend on service providers.
2. The customers require environmental information in their local theatre of operations, which are mostly of order 100 km across.
3. Marine science and technology will be able to deliver those products early in the 21st century. It will involve learning how to exploit observations by data assimilation into models. I described this as evolving from oceanographic herbivory to carnivory. GODAE will show the way.

The limits to predictability of the products sold to customers depend on two factors:

1. The local weather in the theatre of operations.
2. The inflow of disturbances from outside the theatre of operations.

We know the limits of atmospheric weather prediction: about one week; but we do not yet know the limits set by the dissipation of signals as they move around the ocean: the ocean weather. We assume the limits are controlled by weather inside the ocean, which tends to have longer time scales than atmospheric weather.

The working hypothesis is that we can extend operational oceanography to the theoretical limits of ocean weather predictability by making and analyzing routine observations in the open ocean.

However we have not yet begun to test that hypothesis. That is the scientific challenge of GOOS.

Addressing that challenge will require a series of GOOS experiments comparable to the TOGA experiment, which established the practical design of an observing system to forecast El Niño.

To explain the purpose of these GOOS experiments, I used a "cartoon", in which information is radiated and advected along various trajectories into a customer's theatre of operations. Ideally it will be possible to predict these incoming signals, and so to take account of them when forecasting the environment in that theatre. We assume that the signals are themselves disrupted by the oceanic weather. So there is a limit to how far one can usefully search upstream for incoming signals. Further upstream offers longer warning times, but increasing risk of error.

The purpose of the GOOS experiments is to discover how far upstream one can usefully detect such signals. The experiments will establish the scope of the *catchment* area around each operational theatre.

We assume that these *catchments* will be substantial, and that *catchments* of different local operational services will overlap. That will justify collaboration in creating a shared open ocean observing system, provided that a common system can satisfy the needs of each of the customers each in a different location, and with their own priorities for forecasting products.

The immediate task for GOOS is to design those experiments, and to get them funded. They will reveal the limits to prediction in the ocean.

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