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The Oceans: Discovering their Global Roles

Every man, woman and child on this earth is dependent on the oceans. They may not know it, they may not even have seen the ocean or know what it is. But the climate they live in, the rainfall which nourishes their food and quenches their thirst, the waterways which ease transport and promote trade, all are controlled by the oceans that cover two thirds of the earth's surface.

Nova Scotia, as a maritime province, is well aware of the importance of the ocean for food and for the wealth that it can bring, and has a long and distinguished maritime tradition that has taken its sailors to all the corners of the earth. Thomas Killam, grandfather to Izaak Walton Killam, was "one of the most successful shipowners and business men" of the town of Yarmouth. How appropriate it is therefore that the present series of lectures, made possible by the success of Izaak Killam and by the generosity of his wife Dorothy, should focus on "Living with the Oceans".

The Global Village Pond

Over the last few decades, there has been an increasing awareness throughout the world that all countries—all people—share one planet, and that there are limits to the damage which can be inflicted on it without detriment to humanity. Fast and cheap air travel has made us aware, as never before, of other countries and other races, and television has brought us face to face with poverty, war, disaster, deprivation and famine in hitherto remote regions. The ever-increasing number of natural history programs on radio and TV has helped to make us conscious of the immense variety of environments and of the fragility of many of them. It is now common to talk of the community of nations as "the global village," recognizing the way we should live and work together. I like to think of the oceans, which separate the components of the global village, as the "global village pond"—one from which we all can benefit and for which we all have responsibility.

In 1987 the World Commission on Environment and Development reported on the balance necessary between sustainable development and environmental concern in its book *Our Common Future*, also known as the Brundtland Report, which led, in 1992, to the United Nations Conference on Environment and Development held in Rio de Janeiro. This Conference, which generated Conventions on Climate Change and on Biological Diversity, negotiated in detail a 40-chapter document called *Agenda 21* which outlined principles of how such a balance might be achieved. The document recognized the vital role played by the oceans in determining the global environment.

Later lectures will deal with the problems of what mankind has done to the oceans and what measures can and are being taken to legislate and to resolve conflicts which arise. In this first lecture I will set the scene by outlining the origin and nature of the oceans, how they work and how they interact with both the sea floor beneath and the atmosphere above. Only by understanding the mechanisms can we accurately predict what the future health of the oceans will be and how we can improve it. I will talk about the geological evolution, the movement of the water and how it supports a complex web of life by the distribution of nutrients.

Geological Evolution of the Ocean Basins

If we were able to cut the earth in half, we would see that in the centre there is a core of molten iron and nickel surrounded by a mantle of hot and plastic rocks, rich in silica, which can slowly move under the enormous forces of thermal convection. Only above this mantle is there a thin brittle layer which we call the earth's crust. The waters of the ocean came from steam which was expelled from the hot interior of the earth and condensed as rain and which filled the depressions in the early crust. Although little is known of the early crust, it is believed that most of it got recycled back into the interior of the earth as it was broken u and moved around. The difference now between the oceans and th continents lies in the nature of the rocks composing this crust. Th continents are largely made of the less dense rock granite, whereas th ocean floor, having been erupted from volcanoes, is dense basalt. Th granitic rocks float higher in the mantle and are therefore not covered by water.

The shape of the sea floor has been determined by extensive surveying with echosounder, with side-scan sonar and more recently with satellites. We see huge mountain ranges, clusters of volcanic seamounts, arising from depths of several miles and sometimes breaking surface as islands such as Madeira or Tristan da Cunha and which fractures cut across the ocean floor for thousands of kilometres. We also see millions of square kilometres of mud and sand accumulated from the erosion of the continents and from the dead remains of the phytoplankton abundant in the sunlit surface waters. Around the edge of the continents are the continental shelves where, in times of lowered sea level during the ice ages, the waves cut away the coastline.

It is only in the last 40 years that we have understood the origin of all these features and how the ocean basins relate to the continents. Studies in marine geology, using techniques that were developed to conduct submarine warfare in World War II, showed the existence of a world-encircling mountain chain running through the centres of the oceans, the so-called mid-ocean ridges. These were shown to coincide with the position of earthquakes. At the centre of these mid-ocean ridges the rocks are very young whereas further from the centre they are older. However no rocks were found that were older than about 250 million years, whereas it was known that the earth is about 4500 million years old. Where had the old ocean rocks gone?

Geophysical data on the magnetization of the sea floor, as well as evidence from lava flows on land that the earth's magnetic field periodically reversed, combined with the geological data on age, produced the idea that new ocean crust was being created in the mid-ocean ridges, that this resulted in the earthquakes, and that the older crust on either side together with the bordering continents was being moved apart. The pattern of magnetic anomalies of the seabed could be read as a tape recorder for the rate of separation. Thus was born in the late 1950s the idea of sea floor spreading and the mobility of the continents.

Of course elsewhere the ocean crust must be consumed or the earth's surface would have to get larger, which we know it does not. It was later discovered that the deep trenches which surround the western margin of the Pacific Ocean, where another belt of earthquake activity is found, are where the oceanic crust returns to the interior of the earth, grinding its way down on an inclined plane several hundred kilometres long. The melting crust rises through the upper mantle of the earth to give chains of volcanic island such as those of Japan and the Marianas.

Thus the earth's crust is divided by the earthquake zones into a number of quasi-rigid plates, which move around driven by thermal forces in the mantle. The mechanism of plate tectonics, as the process became known, revolutionized not only marine geology but also land geology, for at last there was a unified theory which could account for the major features of the earth. It is hard to realize that such a revolution happened so recently. When I lectured last at Dalhousie in 1961, seafloor spreading had only just been proposed and the term plate tectonics had not been invented, and only a few years previously it was received wisdom that the continents were fixed relative to one another.

Detailed studies of the magnetic patterns of seafloor rocks, combined with direct sampling of the rocks by dredging and by deep drilling, have enabled the clock to be turned back stage by stage so that we can see how the continents have moved, and hence reconstruct past configurations. If we return to the Jurassic period, some 250 million years ago, all the continents were clustered on one side of the earth in a super continent which has been called Pangaea. As it split up old oceans were lost and new ones were created. A modern example of a new ocean in its youth is the Red Sea, which has a deep fissure up the centre, the result of the separation of Africa from Saudi Arabia.

Close-up Views of the Ocean Floor

So far I have talked about the large scene of globe-encircling mountain ranges and huge ocean basins. What does the ocean floor look like at closer range and what resources might it have to offer mankind?

Underwater photography, remote-controlled television and direct observation from the windows of deep submersibles have given us a fairly clear idea of what is there, although we have to remember that th range of visibility under water is limited to 10 metres or so and the are to be looked at is gigantic. Most of the seabed is mud, transported fror the continents by rivers as clays, silts and sands, or carbonate ooz derived from the calcareous remains of plankton living near the surface The sediments are sometimes rippled by the occasional strong current that can sweep across the bottom, or are disturbed by burrowing o foraging animals eking out a meagre existence in what is in effect ar underwater desert. The tracks made by these benthic animals may last for hundreds of years since in many areas the sedimentation rate is extremely slow—about one centimetre in a thousand years.

In some parts of the sediment basins where the sedimentation rate is exceptionally slow (say, one millimetre in a thousand years), and other conditions are just right, there are fields of manganese nodules lying on the surface like potatoes that have just been dug up. These oxides of iron and manganese are also rich in copper, nickel and cobalt and in the 1960s gave rise to great expectations of mineral wealth from the ocean floor. A huge area of nodule fields lay in the eastern Pacific southeast of Hawaii and mineral companies and consortia surveyed them and developed a variety of sophisticated methods for their recovery and processing. The only problem, apart from the economics which finally cooled industry's interest, was to whom the nodules belonged. The question was debated at the United Nations which declared that the wealth of the oceans was "the common heritage of mankind," and initiated the ten-year-long conference on the Law of the Sea which culminated in the Convention coming into force in November 1994.

On the higher parts of the ocean floor and away from the sediments streaming off the continents there are the volcanic rocks of the ocean crust itself. On the flanks of the ridges the rocks are often decayed and encrusted with a coating of manganese oxide which has also been considered as a potential mineral resource. But at the centre of the ridges the rocks are fresh and coated with glass, having been rapidly chilled by the sea water as they emerged from the volcanoes. The axis of the mid-ocean ridge is strewn with recently active volcanoes pouring sheets of fluid lava into lava lakes, exuding sticky lava from fissures, like toothpaste from a tube, or building up mountains with volcanic rubble. Many of these volcanoes have the typical hollow craters or calderas at their peaks where the lava has poured away or the magma chamber beneath has collapsed. The volcanoes coalesce into long ridges, aligned with the spreading axis, which are later torn apart by the separating ocean crust so that one half of a volcano may join one plate and the other be attached to another. The mid-ocean region is torn with fissures as the plates separate, and is fractured by enormous faults as the crust cools and deforms. So the terrain is extremely rugged with cliffs a thousand metres high running for tens of kilometres.

Sea water penetrates several kilometres into these fissures in the still hot crust and there is a convective circulation that drives the heated water back to the seabed. Here it emerges as jets of very hot water, up to 400 degrees centigrade (not boiling, because of the very high pressures), which show up as "black smokers." The color comes from the mineral sulphides which are precipitated out as the water suddenly cools, and which have been picked up from the deep hot rocks. Around these vents, which build up chimneys tens of metres high, small hills are formed which are rich in the sulphides of silver, zinc, copper, and tin. Research is now going on to see whether the accumulations of sulphides are worth mining for these metals.

Photographs are unable to give a sufficiently scenic view of this rugged terrain and yet conventional surveying with echosounders cannot resolve the detail. So the technique of side-scan sonar, that was originally developed for the detection of submarines, has been adapted for scientific use. It can build up sound pictures, or sonographs, of the seabed in the same way that television screens build up pictures by regular scanning. Long-range sonographs taken from the sea surface by the GLORIA system, developed at my laboratory, give the sort of views that you might have from an aircraft of a continental mountain range in the setting sun. The sonographs can be compiled into mosaics and from these many complex puzzles of seafloor geology have been resolved. For more detail other sonars operate near the seabed on a long cable, sending pictures to the ship.

Even satellites can now help to resolve the geology of the seabed in areas where ships have not been able to make measurements. Radar methods have been used to measure the height of the satellite above the sea surface at a range of about 900 kilometres to an accuracy of a few centimetres. An equally accurate position of the satellite relative to the centre of the earth can be determined so that the difference gives the undulations of the sea surface, which can be as much as 50 metres, relative to the centre of the earth. It turns out that these reflect the variations in gravitational attraction caused by the shape of the ocean floor and by the contrast in the densities of the sediments and rocks beneath.

Global maps have been produced recently that show the gravity field at the sea surface. These reveal an enormous amount of hitherto unknown detail of the mid-ocean ridges, the fractures zones and the submarine volcanoes in remote areas. This can help the submarine geologist unravel the movement of the continents and the geological evolution of the ocean basins.

So we know a great deal about the sea floor and its geology, and about prospects for mining, although I am quite sure that there are many surprises in store as new areas are investigated and new techniques used.

The Waters of the Oceans

What about the waters of the oceans? Although to a layperson sea water is salt water, the oceanographer wants to know exactly how salty and how warm. Different bodies of ocean water are characterized by their salinity and their temperature, which, together with the pressure, determine the water density. Differences in the density within the ocean drive the water masses from place to place. Cold dense water will slide underneath warmer water and fresh water will stay on top of salt water. Of course the waters are also driven by winds blowing across the surface and the movements are strongly influenced by the fact that the waters are confined to the surface of a rotating sphere.

Oceanographers can calculate the currents from measured sections of salinity and temperature, but they also make direct measurements using current metres strung out down the wire of a moored buoy, or by tracking drifting floats on the surface or in mid water. Surprisingly they have found that the currents near the bottom can be as strong as those on the surface, and that the oceans are very turbulent and full of eddies. In fact 90% of the energy of the ocean currents is in these eddies.

The eddies can be seen very clearly from satellites measuring the surface temperature with infrared sensors, and show up particularly strongly where the warm water of the Gulf Stream flows past the colder water of the Labrador Current. The eddies are generated by the shear between the two.

Every student knows that the Gulf Stream brings warm water to the west coast of Europe which maintains a climate abnormally mild for its latitude. This current is part of the North Atlantic clockwise circulation which is driven, as a huge heat engine, by the difference in temperature between the polar and the equatorial regions. Similarly, in the Pacific Ocean the Kuroshio Current bathes the northwest coast of North America. Variations in the currents have significant effects on the weather of these regions.

This brings me to emphasize the very close relationship between the oceans and the atmosphere, which interact with one another at the sea surface, exchanging heat, water vapor, gases and momentum. Weather and climate forecasting in the atmosphere require detailed data on these exchanges, details which are known only sketchily at present. Oceanographers are working together throughout the world in a program, known as the World Ocean Circulation Experiment (WOCE), to get a better understanding and more data. Even though earth observation satellites have contributed enormously to the quantity and the coverage of the data on the surface temperature of the ocean, waves, surface winds, ice cover, rainfall and cloud cover, they are unable to collect sub-surface data, which still needs to be done from ships or from automatic recording instruments in the sea.

Meteorological forecasts use elaborate computer modelling in which the atmosphere is divided up into grids of many layers, and the laws of physics are applied to predict how the conditions will change from the present. The grid size is determined by the resolution necessary to describe the depressions and fronts. Ideally this should be coupled with an oceanographic model which could also describe the eddies and fronts in the ocean. Unfortunately the ocean eddies are one-tenth the size of the atmospheric eddies and so require a grid with 10 times the resolution and hence a computer 1,000 times as large! Such models are now being developed for limited areas of the ocean. One such is the Fine Resolution Antarctic Model (FRAM) that was developed at Institute of Oceanographic Sciences Deacon Laboratory (IOSDL); it has been able to predict many of the eddies forming in the circumpolar current in the southern hemisphere.

The coupled ocean-atmosphere models are extremely important in predicting the climate changes that may arise from the increasing carbon dioxide in the atmosphere, since the oceans can absorb part of both the gas and the heat. It is a surprising fact that the heat content of the top five metres of the ocean is the same as the entire atmosphere, so the oceans act as a buffer to atmospheric change.

From time to time the oceans spring another surprise on the global climate. Every few years the catch of anchovies, which forms such an important part of the economy of Chile, dramatically fails. For instance in 1972 the catch fell to half a million tons from 12 million tons in 1970. As this usually happens at about Christmas the phenomenon is locally called El Nino, the Christ child. It turns out that this is but one manifestation of a global perturbation in both climate and in ocean conditions. It appears to have its origin in a massive seesawing of atmospheric pressure between the southeastern and the western tropical Pacific. This triggers a shift in the trade winds which allows warm water to flow eastwards along the equator towards South America and to spread over the nutrient rich, and colder, waters which normally come up to the surface and support the anchovy population. No food, no anchovies! At the same time the sea level rises, giving coastal flooding and excessive rainfall in California, Equador and northern Peru.

The impact of an ENSO (El Nino/Southern Ocean Oscillation) event is often felt worldwide because it disturbs weather patterns. In places such as the Western and South Pacific islands and Australia there are abnormally dry conditions giving droughts and sometimes resulting in forest fires. Some of the most notable failures of the Indian monsoon have coincided with ENSO events. Even the maize yields in Zimbabwe have been shown to be correlated with the sea-surface temperatures in the Pacific and predictions of crops can now be made from observations of the Pacific.

There is no doubt that the physical conditions of the ocean are strongly linked to the conditions of the atmosphere and hence to the global environment. A better understanding of the processes involved and the collection of relevant data on a global basis, together with more powerful computers to model the interactions, will lead to better predictions of the influence of the oceans on global weather and climate.

This is the target at which many scientists throughout the world are aiming.

Life Below the Ocean Waves

So far I have talked entirely about the physical aspects of the ocean without regard to the plants and animals that live there. These must be taken into account when considering the role of the oceans in human affairs. Ocean organisms range from the smallest bacteria, through the minute phytoplankton converting sunlight, carbon dioxide and water into chlorophyl, the zooplankton grazing the phytoplankton, and the whole chain of fish up to the sharks and squid, and the giant mammals of the ocean. The whole ecosystem is a web of interactions which use sunlight and nutrients to initiate a food chain that is caught up in a cyclic process. Organic debris from the upper layers of the ocean filters downwards to feed the biota in the lower layers, sometimes being cycled many times through feeding and defecation, eventually providing food for the sparse bottom-living community. Occasionally large lumps or aggregates of organic debris drop quickly to the bottom providing a feast which can quickly attract the benthic population to feed on it. Time-lapse cameras tethered above the bottom for a year or more have shown the arrival of this rich material and the movements of holothurians and echinoids to graze it.

The phytoplankton play an important role in determining the level of global carbon dioxide. There is a constant exchange of CO_2 between the atmosphere and the ocean as it dissolves in or is liberated by the surface water. The dissolved CO_2 is used by phytoplankton—the plants growing by photosynthesis—to create chlorophyl, although much of the CO_2 is recycled by respiration. Part, however, finds its way through the food chain and ultimately into the organically derived calcium carbonate sediments that accumulate on the floor of the ocean basins, and so is removed from the atmospheric system. Some proposals have even been made that, to increase the trapping of CO_2 in this way, the productivity of the surface waters should be increased by adding extra nutrients, especially iron which could be scattered on the surface as iron filings.

Any modelling of the global climate change due to the increase of greenhouse gases must include quantitative estimates of the permanent transfer of CO_2 into the ocean and to its sediments. These data simply do not exist at present. However, through an international program on Global Ocean Fluxes, the JGOFS (Joint Global Ocean Flux Study) Program, oceanographers are trying to measure these transfers and to understand the role played by the biology of the oceans. Once more satellites are able to contribute by making global measurements of chlorophyl by spectral analysis of the visual images, and are able to monitor changes from year to year.

The Gaia Hypothesis

Some scientists have gone even further in describing the impact of the living world on the global environment. It is a strange observation that the composition of the atmosphere has remained remarkably constant throughout a large part of geological time and that the present environment is favorable to plant and animal life. Without living organisms the earth's atmosphere would be largely carbon dioxide and would have no oxygen, as is the atmosphere of Mars and Venus. The Gaia hypothesis, first proposed some 20 years ago by Professor James Lovelock, suggests that the global environment is actually regulated by life on earth and that if life is seriously disturbed, it will recover and restore itself, even if this is at the expense of some species such as the dinosaurs or even man himself.

Under the Gaia hypothesis, the concentration of carbon dioxide in the atmosphere would be under biological control. An increase would raise global temperatures, increase biological productivity and the weathering of rocks, promoted largely by bacterial action in soils, which would transfer the carbon dioxide to carbonate rocks such as limestone and chalk.

Another possible feedback Gaian mechanism is the increase in cloud cover caused by an increase in productivity of the plankton. Dimethylsulphide (DMS) gas emitted by algal plankton in the near surface of the seas is converted by sunlight into acids in the atmosphere which form cloud condensation nuclei, which in turn promote the formation of clouds. These then reflect more of the solar radiation, reducing global temperatures and reducing the algal plankton productivity. Hence the control mechanism works by negative feedback. The emission of DMS from the world's oceans has been shown to exceed the production of sulphur from all of the world's power stations, so here again the oceans have an extremely important role to play. By no means do all scientists accept the Gaia hypothesis but it has made them look at the earth in a different way and has stimulated much new research.

Conclusion

I have tried in this talk to give you a "tour d'horizon" of the complex science of the oceans so that you will be able to appreciate better the problems that arise from human interaction with them, through exploitation, through overfishing, through pollution and through the release of greenhouse gases. Whereas scientists can discover how the oceans work and the nature of the damage that may have been done to them, it requires public understanding and pressure to persuade governments to act together to prevent or limit this damage. Through the international conferences convened by the United Nations, which result in legally binding Conventions, the global village is at last recognizing that it is in its own interest to maintain its village pond in good order, and that potential conflicts can and must be avoided.

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