

# The oceans and climate\*

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This audience scarcely needs reminding that climate change has become a hot issue. With embarrassing haste, the Cinderella science of climatology is thrust, blushing and blinking, into the spotlight. Or, to use another metaphor, Chicken Little is suddenly being asked to prove the sky is falling.

The fuse was lit by Callendar (1938), who was the first to confirm that atmospheric CO<sub>2</sub> was increasing. Decades later the imagination of the world was ignited, fuelled by the experience of a sequence of extreme and disastrous climate excursions (probably not associated with carbon dioxide or climate change) and a growing awareness of the widespread deterioration of the environment brought about by the pressures of population and economic progress.

The signal that the atmosphere is warming or that the sea level is rising is scarcely greater than the noise level, and requires the eye of faith. Numerical models to simulate climate and its change, with CO<sub>2</sub> doubling, are defective in detail and vary in their predictions. Nevertheless, so convinced are leading politicians such as Mitterand, Thatcher and Bush (and Hawke) of the fall-out from public concern about climate change that they are beginning to institute massive responses that will transform the lives of all humanity, not to mention atmospheric and oceanographic science (see US Office for Interdisciplinary Studies (1989)).

Meteorologists and Oceanographers are trapped in a moral dilemma. We have justified our research interests and argued for resources for many years on the basis of the importance of the work for climate prediction. In relation to the more extreme predictions of climate change and its consequences we have tended to be pragmatic rather than rigorously critical. Anything that has lent weight to the argument for more resources has been deemed a good thing. Unfortunately, though we as a community are willing to acknowledge uncertainties and weaknesses in existing scientific predictions, the media, because they rely on news impact, have given greatest weight to the most extreme forecasts, and are not interested in emphasising uncertainty. To compound the diffi-

culty, we are greatly outnumbered (and outranked in political terms) by a community of experts in other such disciplines as economics, geography, geology and social sciences, all of which are pleased to justify their own activity in terms of the consequences of climate change.

If the predicted changes do occur all this effort will have been worthwhile, and in no sense am I seeking to minimise the massive social, political and economic consequences. The danger to the atmosphere/ocean community lies in

1. overstatement of the rate of climate change,
  2. overselling of our ability to predict it,
- because both cases will result in a loss of credibility on the part of governments and society and a premature withdrawal of the very support which is the only pathway to the provision of the correct answers.

A good example of current interest is sea level change. Four years ago at the UNEP/WMO/ICSU Conference in Villach, Austria, a statement on climate change was prepared which included the prediction for the doubling of CO<sub>2</sub>, of a rise in sea level of between 20 and 140 cm (Bolin et al. 1986). These figures have been widely quoted and indeed a figure of one metre was used by the President of the US Academy of Sciences only a month ago at the top-level symposium convened by French President Mitterand on 'Planet Earth'. Low-lying countries are deeply worried by the prediction and reaction is already occurring in many forms. One noteworthy example is the \$6.25M announced by the Australian Government for a climate monitoring network for the southwest Pacific. Such initiatives have occurred notwithstanding more cautious advice to which I will return later. To improve the quality of our prediction we certainly need a permanent (or at least long-term) observational network; that the network is now being created for political reasons does not augur well for its permanency.

This rather extended preface to my talk tonight has been given to emphasise not only the fragility of our opportunity to get our climate forecasting right, but also to introduce the fact that we are some distance from the goal, and are only now beginning to address some of the tasks toward its achievement.

I am not a climatologist but have the dubious

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honour of being the Chairman of the Joint IOS/SCOR Committee on Climatic Changes and the Ocean. The CCCO is for the ocean what the JSC of the WCRP is for the atmosphere. Although the CCCO's task is not confined to the World Climate Research Programme, its main tasks so far have been the creation and nurturing of TOGA and WOCE, which will probably be the largest international oceanographic programs yet undertaken. Having just returned from the annual CCCO meeting, followed by meetings of the inter-governmental parent, IOC, I am moved to convey something of the scale and complexity of what we are to undertake.

The ocean has a heat storage capacity very much greater than the atmosphere. For a given change in temperature, the first two and a half metres of the ocean surface will store as much heat as the whole atmosphere. The ocean is thus a massive 'flywheel' for global climate.

It not only moderates and limits climatic excursions (particularly with the powerful latent heat constraints of surface evaporation at high temperatures and ice formation at low temperatures) but the thermal and dynamical disequilibrium created within its depths provides a 'memory' of atmospheric forcing events with a range of time-scales from days (for propagating internal and planetary wave-modes) to centuries (for deep gyre circulation).

It is worth remarking that modern scientific efforts for the prediction of climate are centred largely upon the solution of mathematical models in which, to render the calculation tractable, certain aspects of the dynamical system are simplified or eliminated. Models are a completely artificial synthesis of the real world and the quality of prediction by models depends upon the selection of what can be simplified or eliminated. It must be recognised that we are still dependent on a detailed physical understanding of the workings of the ocean and atmosphere to make the correct selection. At present, therefore, models must be regarded primarily as diagnostic experiments, in which changes, synthesis and simplifications of physical reality can be introduced in order to see what changes are brought about.

Physics does give us some guidance on the limitations of a particular modelling approach. For weather prediction a few days ahead it is relatively safe to assume that the sea surface is a boundary with a static temperature distribution, which allows surface fluxes of heat, momentum and water to be defined in terms of this sea-surface temperature (SST) and atmospheric variables alone. Such a model can be run to reach a stochastic equilibrium describing the 'general circulation', and the quality of the model is judged by how closely this resembles the real climate.

Sensitivity studies can be conducted to find the atmospheric response to a given SST anomaly.

Thus it has been found that some of the climate variations associated with el Niño can be successfully reproduced by appropriate changes in Pacific SST. In short, they prove the climate is ocean-dependent.

Over periods of a week or longer, the SST is observed to vary appreciably. This is particularly important in the tropics where it is seen that the major cloud convection regions shift in response to movement of the zones of maximum temperature. The variation is mainly due to heat transferred to or from the surface by incoming and outgoing radiation, by insolation, evaporation, and by the motion of the layer of well-mixed water immediately beneath. This 'mixed layer' is presumed to be well stirred with a temperature approximately the same as the surface.

In the tropical Pacific, equatorially trapped planetary wave modes advect huge volumes of mixed layer water and provide a plausible teleconnection mechanism to define the form and time-scale of large scale shifts in SST.

The oceanic mixed layer can already be modelled quite successfully when forced by surface winds obtained from direct observation, and such models are providing the basis for 'operational' short-term (interseasonal) climate forecasting schemes.

It appears obvious that the first requirement of a climate prediction model should be the incorporation of bottom levels representing the mixed layer, responding dynamically to heating and wind forcing, and the deep ocean beneath. However, it is found that such models consistently diverge from realism by an excessive warming of the ocean surface (e.g. Schlesinger and Zhao Zong-Ci 1989). In reality it has been noted that there appears to be a very distinct ceiling to SST of 30°C (Graham and Barnett 1987). Under the most extreme tropical conditions temperatures above this are rarely sustained (Halpert and Ropelewski 1989).

The discrepancy indicates a serious deficiency in the method used in all models so far for the estimation of surface heating and evaporation, with estimates ranging from 0 to 100 W/m<sup>2</sup>.

There are many possible causes for the discrepancy, but they can only be resolved by direct experimental study. In this context I might make brief mention of recent important work by CSIRO scientists, using the R.V. *Frankin*:

- Lindstrom et al. (1887) who found in the WEPOCs experiment that the tropical 'mixed' layer is frequently salt-stratified, affecting the downward mixing of heat.
- Godfrey and Bradley (personal communication) who showed that outward heat and evaporation is enhanced at low wind speed and outward surface radiation is underestimated, these effects amounting to as much as 60 W/m<sup>2</sup>.

Because of the strong atmospheric driving provided by evaporation, and observed sensitivity to ocean-atmosphere coupling occurring within the tropical ocean regions (particularly the el Niño-Southern Oscillation signal) the first serious test of climate prediction has been undertaken with the creation of the international TOGA (Tropical Ocean Global Atmosphere) experiment (WCRP 1988). TOGA was deliberately limited to objectives considered to be achievable with existing technology, which are: to describe the atmosphere and tropical ocean as a time-dependent system and find whether the system is predictable for time-scales from months to years, including understanding of the physical mechanisms, the feasibility of predictive models, and the design of an appropriate observing system.

TOGA is one of the most ambitious oceanographic experiments ever undertaken and is presently the biggest active element of the World Climate Research Programme (WCRP).

It started in 1985 for a ten-year observing period, which has involved mainly the international strengthening of conventional ocean observations including regular XBTs sections using commercial shipping, and sea level monitoring. Australia is a major participant. This is supported by large and complex process experiments including the proposed TOGA COARE (US TOGA COARE Science Working Group 1989).

At its half-way point, TOGA has already shown that basic ocean observations of sufficient density in space and time, rapidly collated and quality-controlled in specialised data centres, can substantially aid the improvement of interseasonal climate prediction (WCRP 1988).

Furthermore the TOGA data sets are proving an invaluable adjunct to the experimental development of climate models. TOGA's success is centred in the Pacific and is of particular benefit to Australia because of our sensitivity to el Niño. The tropical emphasis of TOGA is proving less appropriate to the Atlantic which appears to be more susceptible to extratropical interactions and long-period interactions.

From the progress in TOGA so far, the interannual prediction of climate using observations confined to the upper ocean even now appears to be an achievable objective. The extension of an observing network of TOGA scale from the tropics to cover the whole ocean is, however, a mammoth undertaking, and clearly much more progress needs to be made in the methods for the remote synoptic measurement of surface fluxes. This will depend largely on the success of radar satellite measurement (scatterometry) in the experimental ERS-1, TOPEX/POSEIDON and ADEOS missions.

For the longer term prediction of climate change, especially that resulting from a monotonic change in thermal forcing due to the green-

house effect, the task is intrinsically more difficult.

It is evident, however, that the oceanic mixed layer will exert the most immediate influence. For the widely used scenario of CO<sub>2</sub> doubling, simple models yield a 3 W/m<sup>2</sup> increase in net surface flux. This flux would warm an oceanic mixed layer of 60 m average depth by 2.5°C in approximately five years. Since the CO<sub>2</sub> doubling time-scale is considerably longer, it can be supposed that the upper ocean would remain at close to thermodynamic equilibrium, if effects of the deeper ocean could be disregarded. This 'short period' response of the ocean might at least allow the sensitivity of global climate to shifts in SST, cloud convection, global wind distribution, and consequent alterations to regional terrestrial and oceanic climate to be modelled with some skill. Nevertheless the effect of the deeper ocean cannot be ignored.

The pressure gradients associated with the geographical variation in average wind determine the convergence or divergence of the surface mixed layer of the ocean, and therefore the distribution of upwelling and downwelling at the base of the layer. This distribution in turn defines the depth-integrated mass transport of the whole ocean beneath, but the stable density stratification of the main thermocline confines this circulation mostly to the upper few hundred metres in the major oceanic gyres. Downwelling occurs between low and mid-latitudes, driving water downward and equatorward. The return flow occurs mainly in warm, narrow currents along the western boundary of each ocean basin. Overturning and gyre circulations are responsible for a large part of the poleward transport of heat by the oceans, believed to be about equal to that carried by the atmosphere (Dietrich et al. 1980).

Within the wind-driven upper ocean circulation, thermal equilibration is relatively rapid, of the order of a few years. However, poleward of these gyres downward movement is suppressed, and the only direct influence of the atmosphere upon the water beneath the gyres occurs where the thermocline contours 'outcrop' the surface. Here the waters are 'ventilated' by surface water mixed by storms before resuming the intermediate and deep circulation (Woods 1984).

The deepest water originates at only a few places in polar regions where salt rejection during sea-ice formation causes deep mixing of salty, cold water (Woods 1984).

It is during their formation at the surface that the intermediate and deep waters receive their 'imprint' of atmospheric climate and atmospheric gases. The processes of their subsequent circulation and mixing are still poorly understood, and gaseous tracers of anthropogenic origin provide one of the best means of estimating their subsequent movement. The equatorward spread

of carbon 14 created during the 50s atomic tests gives an indication of the very slow rates of transport of deep oceanic water. Indeed, without vertical mixing and diffusion occurring on microscopic scales the deep circulation would eventually come to rest. The successful mathematical modelling of the deep ocean therefore ultimately depends on an adequate representation of these mixing and diffusing processes.

The circulation of the ocean beneath the surface mixed layer determines the 'long-period' contribution of the ocean to global climate by introducing a time delay between the formation and subduction of water at one time in the climatic regime, and its emergence through upwelling and mixing with the surface water decades to centuries later (e.g. Schlesinger and Zhao Zong-Ci 1989). If the change in climate forcing (due to the greenhouse effect for example) is rapid, the effect of deep oceanic circulation will at first be to moderate the change of SST and therefore ameliorate changes in global climate, but later to enhance the change.

Therefore not only will mankind's present interference with climate be transmitted far into the future, but once the climate begins to change noticeably it might require centuries of corrective action to reverse the trend.

Since the regions of downwelling and upwelling as well as greenhouse global warming are geographically distributed, the effect of deep ocean circulation will be to modify the pattern of global sea-surface temperature, thereby altering the pattern of global atmospheric convection and the position of the major oceanic convergence regions.

If greenhouse heating changes rapidly enough, a more serious scenario can be envisaged in which upper oceanic heating reduces horizontal gradients of temperature and increases the stable stratification of the main thermocline. This would weaken the moderating effect of upwelling and downwelling, and allow the climatic regime to 'flip' irreversibly by short-circuiting the climatic response of the ocean so that the deep ocean circulation would be suppressed and the capacity of the upper ocean to sustain life would be drastically reduced.

So far, discussion on the Greenhouse scenario has concentrated almost entirely on terrestrial effects. The marine impact may be equally dramatic and socially disturbing.

Our knowledge of the detailed workings of the deep ocean is presently too poor to allow more than a qualitative anticipation of the foregoing effects. The energetic scales of oceanic motion are much smaller than their atmospheric counterparts, and resolving these scales in numerical models requires the use of the most powerful computers. The most recent models (Semtner and Chervin 1988) successfully reproduce much of the

detailed structure of the real ocean but in many senses they remain essentially experimental.

Advancement of these models into a capability for climate prediction is very dependent on the global data sets needed for their initialisation and subsequent validation. The existing data sets are historical compilations spanning decades, with many gaps and enigmatic deficiencies.

Ultimately, successful climate modelling must depend on better data for the ocean for both models and the parametrisation of processes such as mixing and water formation. This need has spurred the creation of WOCE (WCRP 1988), a five-year program of ocean observation timed to include observations from the radar satellites mentioned earlier, but also involving a comprehensive range of deep ocean sections across the major basins and choke points, repeat sections, mooring arrays and the deployment of 2500 surface drifters.

The dynamics and variability of the Southern Ocean will also be studied, and a third 'core program' will be a close examination of the dynamics and processes of circulation in a single oceanic gyre system (yet to be decided). WOCE is accompanied by the intensified development and testing of ocean models, and will form the foundation for the creation of an ongoing global ocean observing system.

The developments of WOCE as an experiment, and the ground that is being broken in the development of working relationships for intergovernmental cooperation, interaction and data exchange, mean that we are living through a true oceanographic revolution. WOCE will form a foundation for other global experiments addressing climate, including JGOFS which is aimed at understanding the global carbon cycle, GEWEX and IGBP.

The special question of sea level rise illustrates the caution with which we must proceed in the future. The Villach Statement was based on a regression of past sea level rise with global atmospheric warming (i.e. no physics at all), yielding a range for CO<sub>2</sub> doubling of 25–165 cm. A thermal diffusion model for vertical warming of the ocean has yielded an upper limit of 60 cm (Hoffman 1984). In a very recent statement by the JSC it is noted that an estimate can be made by assuming a limit on the inward flux of heat. If the temperature expansion coefficient is taken as constant, the sea level rise will only depend on energy input and not on depth. A reasonable estimate of increase in heat input, 3 W/m<sup>2</sup>, yields a rise of 50 cm by 2100.

An attempt to include ocean dynamics has been made recently by Church et al. (personal communication) of the CSIRO. They computed changes to the global ocean structure resulting from the latitude-dependent warming of the surface and ventilated thermocline and estimated the resul-

tant oceanic thermal distribution for the surface temperature rise distributions given by three GCMs (GISS, NCAR and GFDL). The result is approximately 10–13 cm for each degree rise in average global temperature. They were also able to compare the modelled rise with Gornitz's observed record. It should be noted that this estimate involves no synthetic fudge factors, and is apparently the first to incorporate dynamics into sea level rise estimates. With better understanding of surface transfer and water formation processes, such estimates can be further refined.

TOGA and WOCE will, we hope, make significant progress toward the scientific tasks in the reliable prediction of physical climate. They are, however, experiments of limited duration. A system for the monitoring of critical oceanic variables on an ongoing basis will have to be in place for the predictive models to be exploited and improved.

This is not an insignificant task, since more than 40 per cent of the world ocean is under national territorial jurisdiction and there exists no oceanic equivalent of the World Weather Watch. Territorial difficulties have, until now, thwarted attempts to implement TOGA in the Indian Ocean, despite the obvious practical benefits that can accrue from that program to the very nations causing the most obstruction. Furthermore, most ocean observation until now has been related to research programs which are, by their nature, transitory.

A task for the CCCO expert group on ocean observing systems (OOSDP), augmented by IOC appointed governmental experts, will be the design of a comprehensive ocean observing system. The key elements of the system have already been defined:

- global sea level
- distribution of SST
- distribution of upper ocean temperature
- sea-ice concentration
- heat carried by ocean currents, initially in the Atlantic
- structure of the major elements of the ocean circulation
- statistics of the transient motions of the ocean
- global distribution of ocean heat content

plus work to develop methods to monitor such elements as air-sea flux and upper ocean salinity which cannot be adequately measured at present.

A system such as this will have to be resourced from new national and international channels independent of the existing research funding network. This presents difficulties in many countries and will require the active support of a scientific constituency much greater than can be mustered from the oceanographers. At the very least

an endorsement of its necessity by the meteorological community is a prerequisite.

I cannot pretend to be very optimistic, particularly since at the recent and influential meetings of the IGBP and the IPCC, which are determining the lines of future national and international climate change policy, physical oceanography was virtually unrepresented.

However, in closing I should like to draw attention to an oceanographic technique which may be the means of providing the first unequivocal evidence of climate change and sea warming. Walter Munk, of the Scripps Institution, has noted that the great circular acoustic pathway for sound in the 'sound channel' of minimum sound speed caused by the competing effects of falling temperature and rising pressure with depth, can traverse all the world oceans and can reach many coastal listening points if the sound source is located at Heard Island in the southern Indian Ocean. Sound speed is a thermometer of exceptional sensitivity (better than 0.003°C is easily achievable) and the very long integrating pathway and possibility of almost continuous recording, using a phase-encoded 50 Hz sound signal, may allow better resolution of climate-induced warming than any summation of point measurements in either the atmosphere or ocean. It is particularly gratifying that the Division of Oceanography is associated with the first trials of this exciting technique.

## Summary

- The ocean is a powerful moderator of global climate change.
- Prediction of climate change using numerical models cannot succeed without incorporating the dynamics of the ocean.
- The ocean exerts both short and long-term effects on climate; short-term effects are associated with changes to the mixed layer of the ocean. These are underlaid by long-term changes produced by the deep oceanic circulation, which transmits the effects of alteration in climatic forcing far into the future.
- Upper ocean observations are substantially improving our ability to predict short-term climate variability, but the oceanic data essential for long-term climate prediction is inadequate.
- A major new oceanographic experiment (WOCE) will provide the data for testing climate prediction models, but operational prediction will require a permanent ocean observing network.
- The recognition and support of the wider climate community for relevant oceanographic data and research is badly needed.

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## Glossary of acronyms

- COARE Coupled Ocean-Atmosphere Response Experiment
- CCCCO Committee for Climatic Changes and the Ocean (SCOR/IOC)
- GEWEX Global Energy and Water Cycle Experiment (WCRP)
- GFDL Geophysical Fluid Dynamics Laboratory (USA)
- GISS Goddard Institute for Space Study
- ICSU International Council of Scientific Unions
- IGBP International Geosphere Biosphere Programme (ICSU)
- IOC Intergovernmental Oceanographic Commission (Unesco)
- IPCC Intergovernmental Panel on Climate Change (WMO/UNEP)
- JGOFS Joint Global Ocean Flux Study (SCOR)
- JSC Joint Steering Committee (WCRP)
- NCAR National Center for Atmospheric Research (USA)
- OOSDP Ocean Observing System Development Panel (CCCCO)
- SCOR Scientific Committee on Oceanic Research (ICSU)
- SST Sea-surface temperature
- TOGA Tropical Ocean Global Atmosphere
- UNEP United Nations Environment Programme
- WCRP World Climate Research Programme
- WMO World Meteorological Organization
- WOCE World Ocean Circulation Experiment
- XBT Expendable Bathythermograph