Clues to predicting climate lie in understanding the interaction between air and sea in the warm waters to the north of Australia.

Oceans, atmosphere, and climate prediction

Australians may not welcome drought and flood, but we've come to expect them. Understanding their origins and predicting when they'll occur are another matter.

Scientists trying to come to grips with Australia's weather patterns are faced with a daunting natural variability. They have to start with the premise that, comparing one year with the next, Australia's weather has more chance of differing than it has of being the same. Now greenhouse gases and global warming add yet another complication.

Climatologists have always sought to understand the causes of climate variability, knowledge they hope will lead them closer to their Holy Grail — the accurate prediction of weather, months or years in advance. Computer models of the global circulation system are the treasure maps that guide this predictive quest. Unfortunately, the complexity of the interactions between the atmosphere, oceans, and our planet's countless biological components means that, inevitably, some parts of these new maps are missing.

One of the biggest gaps is in our understanding of the role played by oceans. If you've ever jumped into one on a warm day in early spring and then leapt straight out again covered in goose bumps, you have a useful insight into the different rates at which the ocean and the atmosphere respond to the changing seasons: the oceans change temperature very much more slowly than the air. On the other hand they have a much greater capacity to store heat.

We know that, most of the time, this huge capacity to store heat moderates and delays the atmosphere's extremes; but, oceans are not just passive heat stores, sometimes their currents induce big climatic changes. The best-known example is the El Niño–Southern Oscillation (ENSO) phenomenon that occasionally brings years of drought to Australia.

For the past 5 years, scientists from CSIRO and other research institutions in Australia and overseas have been working in the international Tropical Oceans–

Global Atmosphere program (TOGA) to understand what causes an ENSO event. Recently, they have turned their attention to longer-term questions about how greenhouse gases affect ENSO. In particular, will the frequency and the intensity of ENSOs change and what will that mean to Australia's climate, and can we expect more or fewer droughts in the future? Unfortunately, we still don't know enough about the ENSO phenomenon to answer these questions, but since TOGA began we've made rapid progress.

Sunny one day... raining the next

Returning to our seemingly fickle weather patterns: ironically, these are driven by the forces (laws of thermodynamics and fluid mechanics) that seek stability and equilibrium by redistributing thermal energy (heat) evenly around our planet.

Heat builds up in equatorial regions because they receive more solar radiation than higher latitudes. Atmospheric and oceanic circulation redistributes this heat towards the Poles. Warm air rises at the Equator (lowering the air pressure there) and descends in the mid latitudes creating a high-pressure belt that encircles the globe.

It's more complicated than this, of course. The spinning Earth generates a 'Coriolis force' that creates the easterly trade winds. And in the same way that air moves via a series of 'circulation cells' between the tropics and the Poles, it also circulates east–west along the Equator in cells centred over the oceans — the so-called Walker circulation.

Oceans, too, move heat via numerous circulating currents. In the Pacific Ocean, the larger ones carry about as much heat as the atmosphere towards the Poles, while anomalous equatorial currents occasionally lower, or even reverse, the temperature gradient normally present along the Equator.

As you may expect, the world's warmest water is found close to the Equator, much of it concentrated in huge pools that oceanographers usually define by a 28°C isotherm. Together these pools cover about one-eighth of the surface area of the globe. By far the largest lies in the western Pacific Ocean and the eastern Indian Ocean to the north of Australia (see the map). Its presence has a major influence on the Walker circulation and regional climate.

In the middle of this warm pool the mountainous Indonesian archipelago helps warm moist air to rise, resulting in clouds and rain. High in the atmosphere the warm air travels east before descending off the coast of Peru. At lower altitudes the air, now cooler, circulates back to the west as the well-known easterly trade winds.

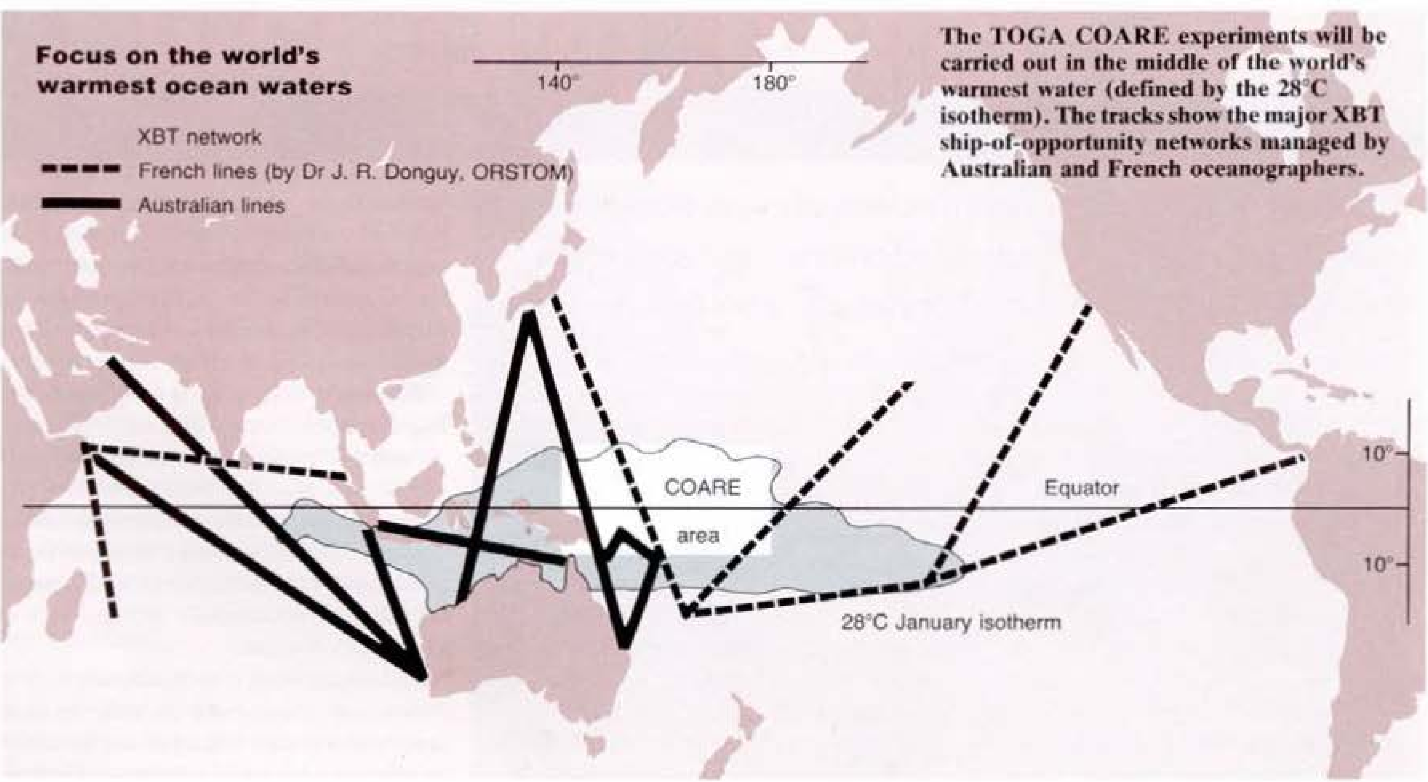
As these winds blow across the Pacific they drive surface currents towards the west, sucking cold water to the surface off South America and piling up warm water against Asia and Australasia. Because of this, and contrary to what experience with spirit levels and siphons would lead us to expect, the Pacific Ocean is normally higher in the west by about 40 cm. This height differential encourages more cold nutrient-laden water from the ocean depths to upwell along the Equator, as the presence of rich fisheries illustrates.

Occasionally, the centre of the 28°C warm pool moves east, the easterly winds change to westerly, the Pacific levels out, the upwelling off South America is cut off, Peru receives 400 times its normal rainfall and drought afflicts Indonesia, southern Africa, and Australia: an 'El Niño' is born. The phenomenon takes its name from the Spanish term for the Christ child because it usually occurs around Christmas time.

El Niño is closely linked to changes in the barometric pressure at opposite ends of the Pacific (recorded at representative stations at Tahiti and Darwin). More than a hundred years of data show that, usually, surface pressure is higher in the east. When El Niño occurs this condition reverses — a see-sawing called the Southern Oscillation. Scientists usually refer to El Niño–Southern Oscillation together, calling it an 'ENSO' phenomenon.

Because of its importance to our region's climate — witness the major drought of 1982/83 that apparently was directly related — scientists have been attempting to understand the onset of an ENSO, not only to predict its occurrence but because it is a clear example of a coupled ocean–atmosphere phenomenon with demonstrable links to climate.

Explanations for why an ENSO occurs fall into two camps. One view suggests that the seed of an ENSO episode is always present as an internal oscillation in the oceans and, given varying amounts of time, will inevitably develop. The other view



The TOGA COARE experiments will be carried out in the middle of the world's warmest water (defined by the 28°C isotherm). The tracks show the major XBT ship-of-opportunity networks managed by Australian and French oceanographers.

Tropical blitz for the '90s

Despite TOGA's substantial progress in providing an understanding of the coupled ocean–atmosphere system, scientists are still uncertain about the physical processes that maintain, and alter, the warm-pool regions of the eastern Indian and western Pacific Oceans.

More data are needed, and at a recent workshop the TOGA scientists proposed a new experiment — the TOGA Coupled Ocean Atmosphere Response Experiment (TOGA COARE) — to speed the information-gathering process. The experiment seeks to develop a thorough understanding of the major processes that affect the western Pacific warm-pool system. It will include a modelling component, a series of pilot studies, and an intensive observation period (the IOP).

The IOP is scheduled for November 1992 to February 1993 in an area bounded by 10°N and 10°S, 140°E and 180°E — well within the year-round 28°C isotherm (see the map) — and will use the largest array of resources ever focused on an area of tropical ocean. Intensive measurements will be made in the atmosphere, ocean, and ocean–atmosphere boundary layer.

The observations will provide a detailed framework to help with the interpretation of the less detailed data being assembled through 10 years of basic TOGA monitoring.

An important goal of TOGA COARE is to provide high-quality 'ground truth' oceanic and atmospheric data to help calibrate satellite imagery, particularly data from two satellites due to be launched in the early 1990s. In this respect, the experiment will run in conjunction with the World Climate Research Program's 'World's Ocean Circulation Experiment' (WOCE). The new satellites should enable continuous monitoring of the global ocean, once the techniques have been confirmed by comparison with direct observations.

A joint project by the United States and France, the TOPEX/POSEIDON remote sensing program has been specifically designed to fulfil WOCE requirements for ocean surface topography data to achieve near-centimetre accuracy in measurements of the height of the sea surface. It is expected that TOPEX will be launched in 1992. The other satellite to be used by WOCE is the European Space Agency's Earth Resources Satellite (ERS-1). Designed to monitor the ocean and coastal regions with microwave sensors, ERS-1 will be launched in late 1990. The orbits of the two satellites will complement each other. A degree of overlap will allow intercalibration.

The WOCE program calls for an intensive 5-year observational phase (1990–95) to establish a primary data base, followed by a longer monitoring phase to study longer-term variability and to test modelling performance. As *Ecos* goes to press, research-funding agencies in Australia have yet to decide on the level of our participation in this program.

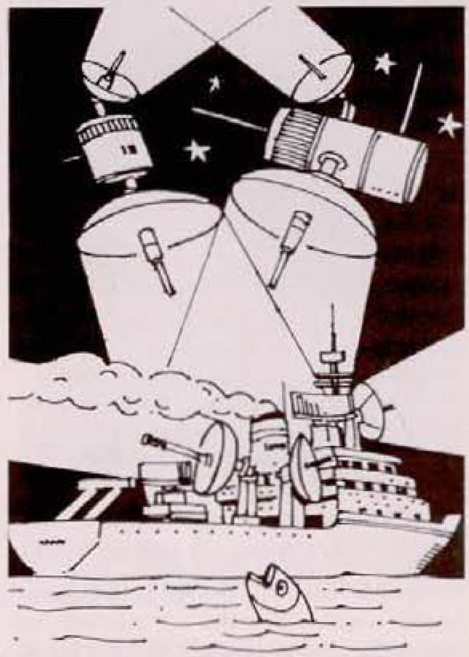


ILLUSTRATION: BRIAN GOSNELL

An overview of the TOGA Coupled Ocean–Atmosphere Response Experiment. *US TOGA COARE Scientific Working Group, February 1989.*

proposes that the onset of ENSO is an atmosphere-induced anomaly that grows rapidly into a mature episode. In either case, ENSO is the product of an inherently unstable system and, history has shown, will happen every 2–10 years.

Tropical Oceans–Global Atmosphere

TOGA, the 10-year international research program that has ENSO under the microscope, began in January 1985. The program has two major thrusts: to understand the physical processes that control ENSO and other longer-term climate anomalies, and to develop a model that will predict anomalies in the coupled ocean–atmosphere system on a time scale of 1–12 months.

Because our climate is so strongly influenced by the tropical ocean to our north, Australian scientists have been taking a major role in the TOGA program. A large part has concentrated on improving the quantity and quality of physical measurements of the air and sea in the tropical Pacific and Indian Oceans. Unlike the situation on land, where we have thousands of permanent weather-recording stations, out in the oceans we have relied on volunteer merchant ships to take simple measurements. This opportunistic approach has left us without a systematic collection of long-term records. But things are improving.

Since the early '70s, a few merchant ships have been measuring sea temperatures down to a depth of 400 metres using 'expendable bathythermographs' (XBTs) — small instruments dropped into the sea that, as they sink, relay the temperature back to the ship. Over the last 5 years the TOGA program has greatly increased the numbers of XBTs deployed in tropical oceans. Collaborating merchant ships have expanded their contribution to the point where they have been releasing about 12 000 in a network of tracks across the Pacific. Dr Gary Meyers of CSIRO's Division of Oceanography has been co-ordinating the part of the network that is Australia's responsibility — the deployment of more than 3000 XBTs last year.

TOGA has also provided the framework for improving other aspects of data collection and for encouraging closer interdisciplinary and international collaboration. For example, more sea-level gauges have been located around the western Pacific Ocean and the eastern Indian Ocean, and research cruises by such vessels as CSIRO's R.V. *Franklin* (managed by CSIRO as a national facility) have vastly increased the area covered by data measurement.

By the onset of the most recent ENSO event — 1986/87 — TOGA was in full swing. Many TOGA scientists are still analysing the masses of data collected during this episode and comparing them with measurements taken before and after this latest perturbation, and with the data available from previous ENSOs. For example, Dr Meyers, Dr Jean Rene Donguy from France's ORSTOM Centre de Brest, Mr Mathew England of the University of

Mr Rick Bailey, manager of the CSIRO XBT network, demonstrates how a probe, with temperature sensor in its nose, falls out of the launcher. The success of the network depends upon good working relations between merchant ship officers and scientists.

Sydney, and Dr Ron Reed from the NOAA Pacific Marine Environment Laboratory in Seattle worked together to examine the data from the XBT network and ENSO features such as the distribution of pools of water warmer than 28°C and their relation to the Southern Oscillation Index (a measure of air pressure difference), equatorial winds, and sea-level anomalies west of the dateline.

From the XBT observations, the researchers found that immediately prior to the last two ENSOs (1982/83 and 1986/87) the temperature gradient from the central to the western Pacific became much smaller than usual. They concluded that the onset of ENSOs was associated with the warming of the central Pacific by anomalous easterly currents and the cooling of the western Pacific due mainly to increased evaporation over a large area of the ocean by anomalous winds blowing from subtropical latitudes to the Equator.

But what produces these anomalous currents and winds? The researchers believe that the real key to understanding the ENSO phenomenon and the ocean's role in the climate system lies in a better appreciation of the heat budget of the surface layer. It is this, and the sea-surface temperature in particular, that governs the release of latent heat (by evaporation of water) in the tropics and the supply of energy to drive the global general circulation.

Compared with their position 5 years ago, scientists are now a lot closer to understanding the physics and dynamics of the system. Measurements of heat transfer in the western tropical Pacific, carried out recently by scientists on the *Franklin*, have produced important new information. The measurements challenge some traditional assumptions about the amount of heat transferred between the air and sea in the tropics.

Heat budgets in the tropics

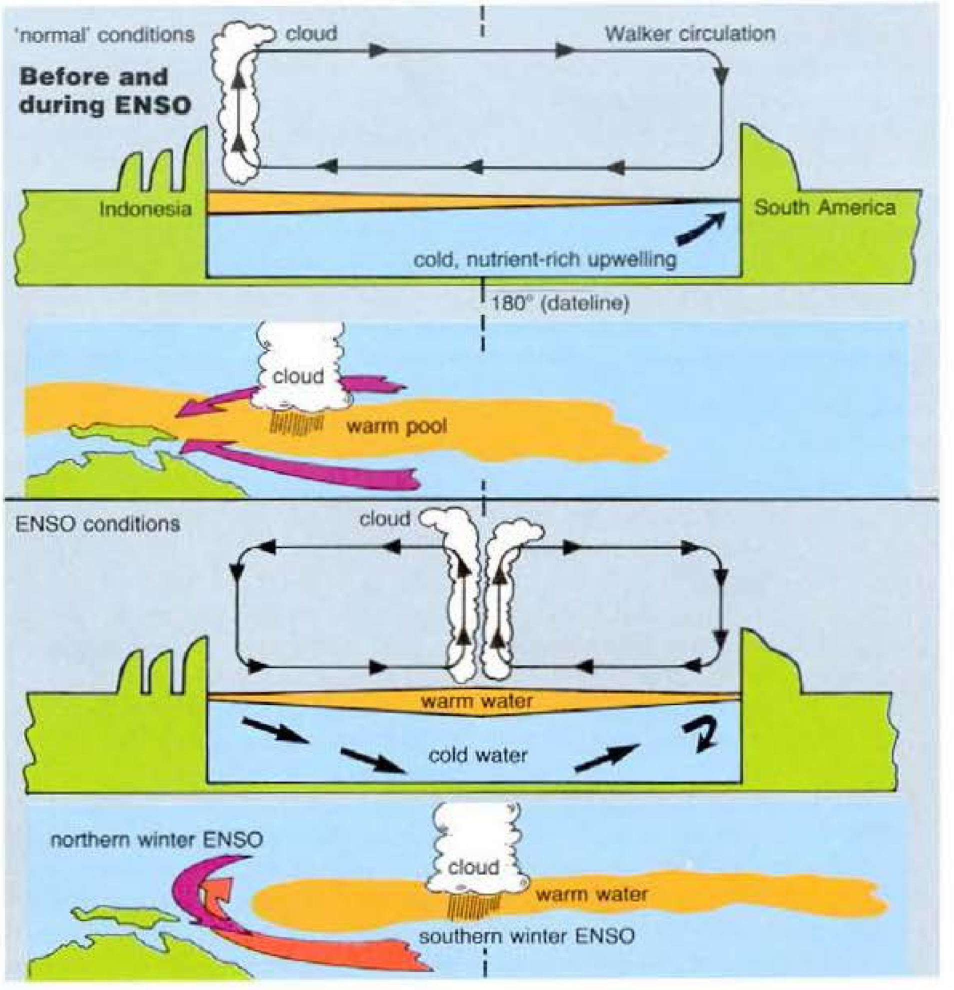
As mentioned earlier, much of what we know about the ocean–atmosphere interactions has come from measurements taken by volunteer merchant ships. For many decades they have recorded air temperature, wind speed, and humidity at a standard height of 10 metres above sea level. From these data, climatologists have estimated the heat transferred between the air and the sea through the mathematics of so-called 'bulk-transfer' equations. However, the bulk-transfer coefficients that form the core of the equations have evolved from data gathered largely in the cool mid latitudes of the Northern Hemisphere, where winds are moderate to strong. By contrast, the winds in the warm western equatorial Pacific Ocean are usually light, and the sea temperature is near the maximum value of 30°C.

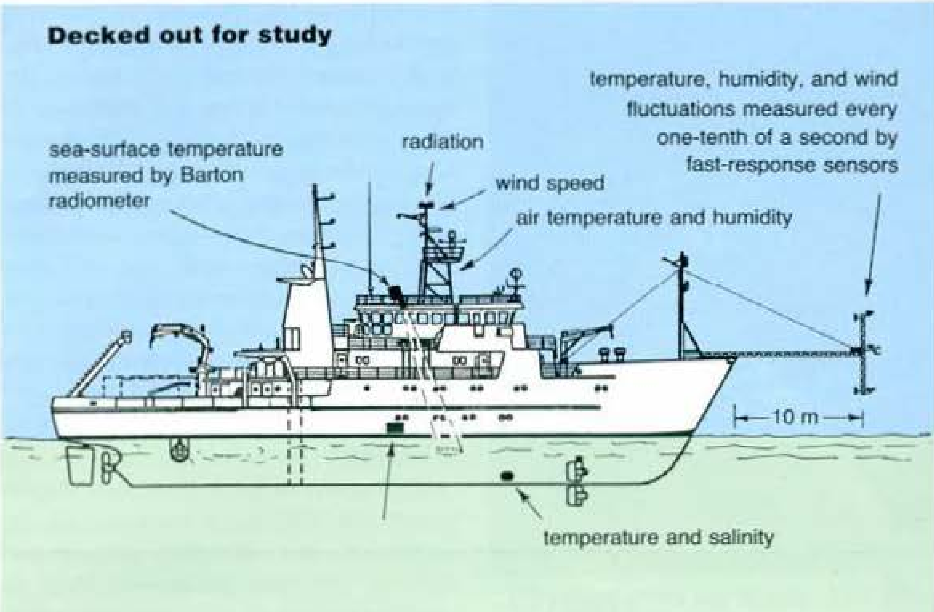
For several years Mr Eric Webb of CSIRO's Division of Atmospheric Research has studied the theoretical aspects of air–sea heat exchange in conditions of light wind and high sea temperatures. He has found that free convection over the warm water — an oceanic equivalent of thermals over land — results in heat exchanges that are not accounted for in the bulk-transfer equations.

Encouraged by Eric Webb's results and also by the findings by Gary Meyers and his colleagues about the role heat fluxes play in year-to-year climatic variability, Dr Stuart Godfrey of the Division of Oceanography and Dr Frank Bradley and Dr Peter Coppin, of CSIRO's Centre for Environmental Mechanics, decided to make direct measurements of heat exchange in the warm-water region to test whether the standard bulk-transfer coefficients were applicable there.

In May 1988, they joined the *Franklin* to work between the islands of New Guinea and the Equator. The light wind conditions allowed the scientists to mount instruments on a boom ahead of *Franklin*'s bow, keeping to a minimum the disturbances due to the ship's bulk (see the diagram).

During ENSO, the warm waters in the western Pacific cool, changing the pattern of convection in the atmosphere and the rainfall. Understanding the process is one of the keys to predicting climate. The likely cooling mechanism? Winds blowing from the winter hemisphere change to westerlies and generate currents that shift the warm pool east, leading to a split in the so-called Walker circulation.





The boom ahead of the *Franklin*'s bow supported the sensitive instruments that measured heat transfer during the ship's 1988 cruise north-east of Papua New Guinea.

The calm waters of the tropical Pacific Ocean enabled the scientists to mount sensitive instruments on the boom ahead of the *Franklin*.

Fast-response sensors at the extremity of the boom recorded fluctuations of temperature, humidity, and wind every one-tenth of a second. This apparatus provided a direct measurement of the heat-transfer components involved in sea–air heat exchange — 'sensible' heat (which directly heats the air or sea) and the much larger latent heat component.

The research team also calculated the average temperature and humidity over a longer term (every 15 minutes) using data collected from other instruments mounted on the vertical section of the boom at 10, 6, and 3 m above the surface. In addition, they measured true sea-surface temperature (with an infrared radiometer developed by Dr Ian Barton of the Division of Atmospheric Research) and, in much the same way as merchant ships do, recorded water temperatures from samples taken 2–3 m below the surface. Finally, they took direct measurements of incoming short- and long-wave radiation — usually estimated by climatologists from routine observations of cloud cover.

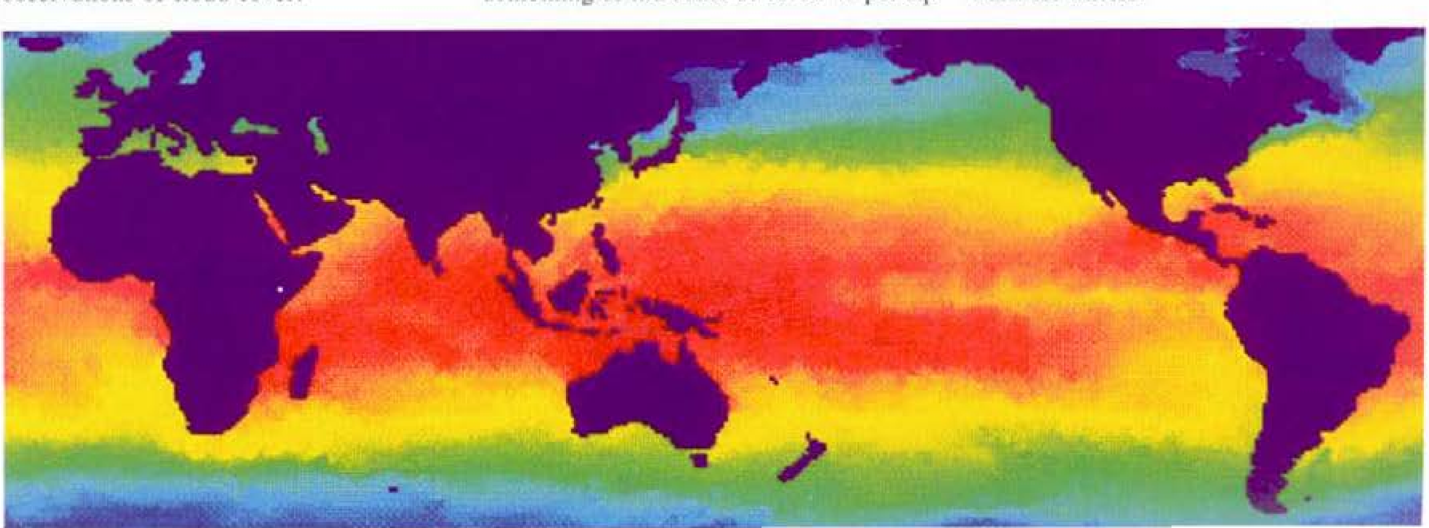
Using these accurate measurements of the sea–air component of the heat budget, the scientists could then deduce the amount of heat carried away to other parts of the ocean. This flux turned out to be much less than previously believed — not between 80 and 100 watts per square metre as the bulk-transfer equations estimate but some 70 W less. This is an important finding, as variations of less than 10 W per sq. m are known to be significant in determining climatic patterns. As suspected, reasons for the discrepancy lie with the particular nature of weather conditions in the tropical western Pacific.

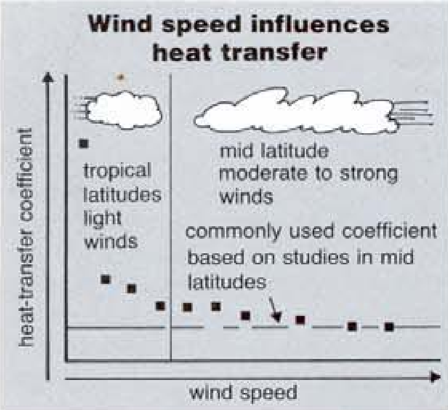
For reasons the scientists don't fully understand, they found that typical sea–air temperature differences were at least double the 0·5°C observed by merchant ships. Also, assumptions about the amount of radiation reflected back by clouds — based on simple observations of mean daily cloud cover — were found to contain significant errors. Because the Pacific warm-pool region is less cloudy at night, using the 24-hour mean tends to overestimate the amount of short-wave radiation reaching the sea surface by around 20 W per sq. m.

The new estimates of total heat flux taken over a 3-week period suggest that something of the order of 10–15 W per sq. m is transported away from the region by the oceans. However, Dr Godfrey and Dr Eric Lindstrom, also of the Division of Oceanography, have a theory that the long-term heat flux in and out of this region could be close to zero. It's a view shared by other researchers, who suggest that the surprising constancy of temperature in the moist parts of the tropics is due to a local balance between incoming solar radiation, outgoing long-wave radiation, and evaporation. Near 30°C, temperatures are held constant by a negative feedback that is strongly influenced by the temperature-dependent evaporation.

But if the ocean does, in fact, transport modest quantities of heat out of the region, where does it go? Is it transported downwards into the depths of the ocean or laterally, near the surface, towards the Poles?

Global sea-surface temperature patterns observed from a NOAA satellite and enhanced by the Remote Sensing Unit at CSIRO's Marine Laboratories in Hobart. The areas of deepest red are the world's warmest waters.





In the light wind conditions of the tropical ocean, bulk-transfer coefficients were found to be much larger than those in the more-commonly studied windier mid latitudes. This means that previous estimates of the amount of heat transferred between the ocean and the atmosphere, based on mid-latitude coefficients, are too low. Thus, climate predictions that are sensitive to sea–air heat transfer may be seriously in error.

In the early part of the 1990s, a new generation of satellites, like NASA's TOPEX, will provide oceanographers with their first opportunity to observe ocean topography and circulation on a global scale.

Not-so-mixed layers

In more collaborative research carried out under the TOGA banner during 1985/86, aboard the *Franklin* and two research vessels from the United States, Eric Lindstrom, Gary Meyers, and Stuart Godfrey worked with Dr Roger Lukas, Dr Rana Fine, and Dr Eric Firing, from the University of Miami, and Dr Mizuki Tsuchiya from the Scripps Institution of Oceanography in California to study the circulation of the western equatorial Pacific Ocean. The cruises were timed to coincide with the south-east and north-west monsoons.

It had been thought that a well-mixed layer about 100 m deep existed in the western equatorial Pacific, an estimate based mainly on temperature sections along the Equator. But the scientists found that it was actually much shallower and not so well mixed as the equivalent layer in other oceans. The mean depth was about 29 m — consistent with the light winds found in the region, which are not capable of massive ocean stirring. They found the greatest depth (106 m) not long after a burst of strong westerly winds.

Importantly, the team discovered that the region's very heavy rainfall results in a fresh-water layer that sits, like a lens, on top of largely unmixed layers that are much saltier. During the cruises, the scientists confirmed Dr Tsuchiya's belief that an equatorial undercurrent brings this highly saline water through the Vitiaz Strait from the Coral Sea. Dr Lindstrom and his colleagues concluded that these salty 'barrier' layers effectively insulate the deep ocean from the shallow fresh-water lens and the influences of the atmosphere. Because of them, very little vertical heat transfer occurs in the western equatorial Pacific Ocean.

At the moment, the longer-term implications of this discovery are still uncertain. What will happen if the sea–surface temperatures rise and the lens spreads further across the Pacific?

Long-term climate prediction

With two-thirds of our planet covered in water, much of it several kilometres deep, understanding the way oceans will respond to 'greenhouse-induced' global warming is crucial. In theory, the oceans have a huge capacity for absorbing heat. The amount required to raise the temperature of the whole atmosphere by 1°C would only raise the temperature of the ocean's upper 25 m by 0·1°C.

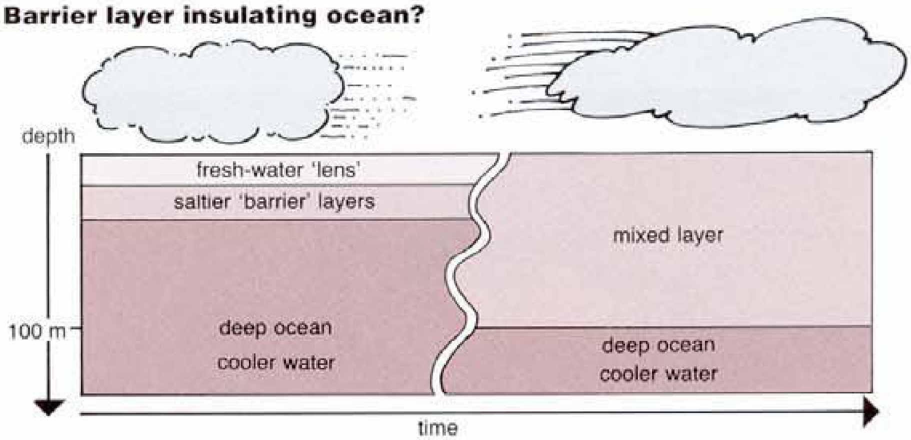
Regrettably, the problem is a lot more complicated than simply adding a few degrees to the present ocean temperatures and looking forward to swimming earlier in the summer. As mentioned earlier, the warmest part of the ocean — its surface — won't ever rise much above 30°C. Latent heat transfer to the atmosphere by evaporation prevents further temperature increase. However, more evaporation could mean more clouds, more rain, and less solar radiation. The possible feedbacks are many, complex, and, so far, unknown. So although a warming atmosphere will certainly heat the oceans, neither the extent of its warming nor its timing is easy to determine.

Obviously, in a warmer world, the oceans will continue to interact with the atmosphere and, of course, our climate. But the fact that oceans are likely to continue to respond to atmospheric warming long after greenhouse gases have stopped increasing and the atmosphere has stopped getting hotter is a major problem for modellers (and for the rest of us). The slow warming (and cooling) of oceans tends to act like the planet's 'memory' of atmospheric conditions.

Where storms stir the oceans, deep mixing occasionally occurs. It's here that the deepest parts of the oceans receive inputs that emerge (possibly through upwelling) decades or even centuries later. The effect moderates the change of sea-surface temperatures in the short term, but enhances the change later. Rather like giant flywheels, oceans will continue to spin in response to a change in atmospheric conditions — for days, months, or, in the case of deep ocean circulation, even centuries into the future.

Normally, in the oceans to the north of Australia, the deep ocean appears to be insulated from a shallow, surface, fresh-water 'lens' (and the influences of the atmosphere) by largely unmixed saltier layers. But, following anomalous bursts of strong westerly winds, mixing occurs that results in a lowering of the sea-surface temperature.

Barrier layer insulating ocean?



Dr Angus McEwan, Chief of the Division of Oceanography, suggests that even more disturbing is the scenario that upper-oceanic warming will reduce deep mixing. This would weaken the oceans' moderating effect on climate by suppressing deep circulation, upwellings, and downwellings. And if the number of nutrient-rich upwellings fell, the capacity of the upper ocean to sustain life would be drastically reduced.

Now at about its halfway point, TOGA has already fulfilled much of its promise. The program has provided modellers with extensive data sets that are helping to refine models that can predict the onset of an ENSO episode at least a season ahead. Australians well know the devastating consequences of El Niño-induced droughts and the value of being prepared.

The challenge now is to increase our understanding of the physics of the tropical oceans so that modellers not only can make confident predictions about the timing of the next ENSO months or years ahead, but are able to make much more confident forecasts of climate changes in a warming planet, decades in advance.

David Brett

More about the topic

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