# THE TIDES OF CHANGE

World wide changes are happening to the environment. The atmosphere is warming, the composition of the upper atmosphere is changing. One of the most sensitive indicators to the health or otherwise of the planet is the sea level.

The first problem however, is to establish an accurate measurement of sea level. New electronic methods of data taking and data storage are making a huge difference to the amount of information we have available. Computer power too, promises the eventual prediction of global ocean circulation and, from that, global climate for ten years ahead.

Along the coasts of continents it is relatively easy to measure sea level, for plenty of instruments are available. They include float gauges, pneumatic systems, pressure sensors, acoustic recorders and capacitance probes.

Whatever approach is adopted, the sea level signal is converted to an electrical signal, smoothed and sampled electronically from a highly stable clock and stored in a data logger for subsequent processing and computer analysis. This is the interesting stage, when measurements from several instruments at different locations can be compared and correlated so that the physical processes can be described.

Today, the geographical areas that concern the oceanographer most are not conveniently situated along the continental coastlines: Interest has moved into deeper waters, to the shelf break and to areas such as the Southern Oceans. There are oceanic islands on which we can install instruments but many are remote and inhospitable; it may not be practical to man such stations, so instruments then have to be automatic, reliable and capable of operating in a harsh environment for up to perhaps two years. For example, on the islands of Tristan da Cunha and St Helena we have installed pressure sensors in the sea, remotely connected by armoured cable to shore installations where the data is stored. The system also records atmospheric pressure and sea temperature. A microprocessor at each station collates the data and transmits it daily by satellite link. This allows us immediate access to the data and enables us to monitor the reliability of the network.

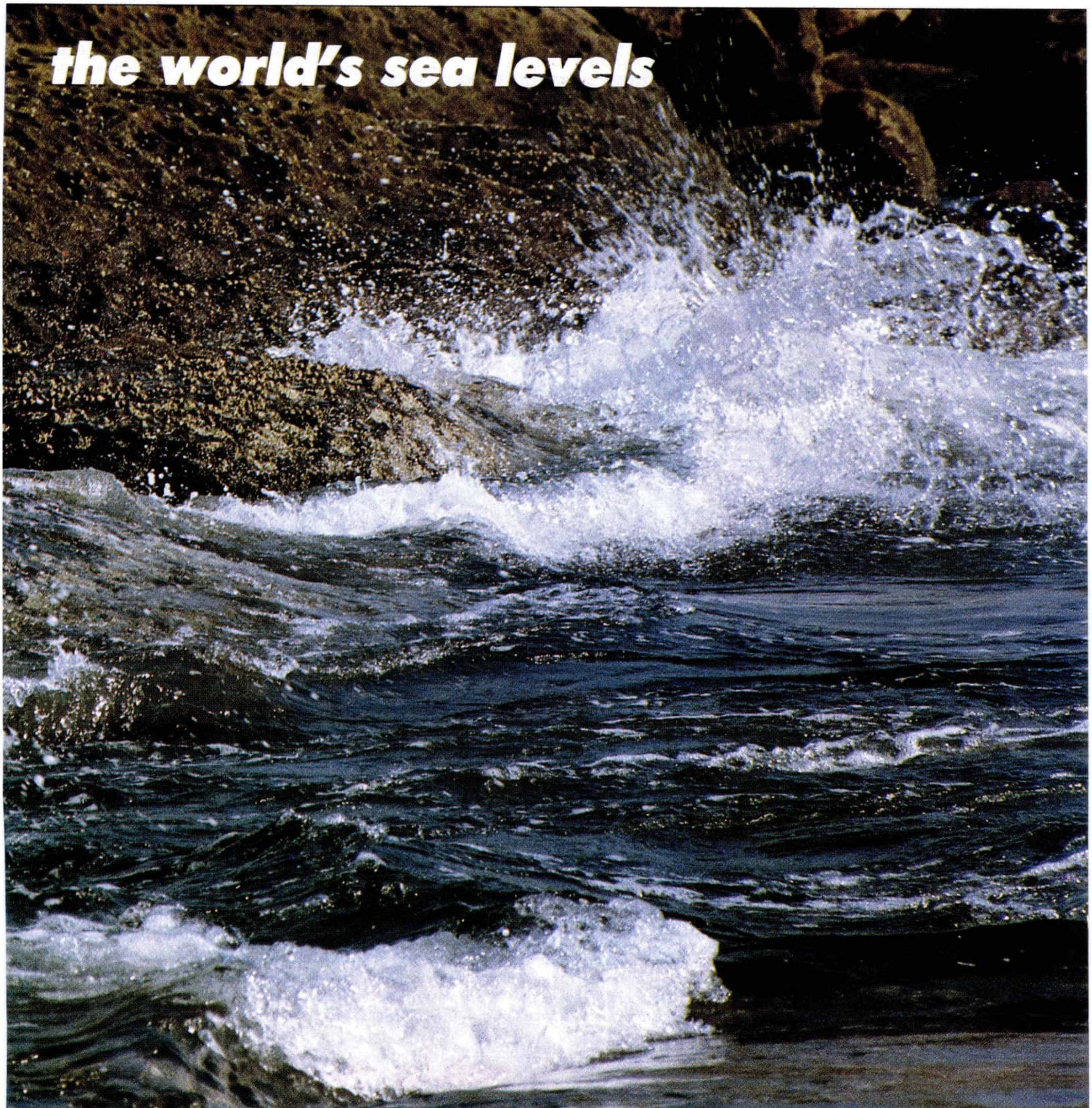
## *Depths of 6000 m*

In the open ocean the main method of inferring sea level changes is to measure variations in hydrostatic pressure near the sea bed caused by changes in the surface level. But most of the oceans have depths of more than 4000 m, and

Predicting changing sea levels is a traditional area of research important for navigation and for planning defences against the sea itself. Now, advances in oceanographic and satellite technology enable levels to be measured in the deepest oceans.

TECHNOLOGY

# the world's sea levels



to measure sea level to a precision of one centimetre requires highly stable instruments. Nevertheless, we have been working in this field for over ten years and have instruments capable of operating to depths of 6000 m. Such equipment is self-contained, is deployed from a research ship and falls to the ocean bed. Once in place, it measures and logs pressure and sea temperature for up to two years. To retrieve the equipment, the ship uses acoustic telemetry to locate it precisely and to release a heavy ballast frame from underneath the capsule. The main frame, containing buoyancy, acoustics and the instrument package, then rises to the surface.

Variations in sea level can be caused by changes in the thermal structure of

**'In most sea level records the tidal signal is the dominant feature'**

the water column, so we monitor such conditions with a device called an inverted echo sounder. It sends acoustic pulses from the sea-bed and detects their reflections when they return from the surface. The return travel time contains information about sea level and the thermal structure of the water.

Although there are thousands of coastal sea level recorders and several bottom pressure recorders operating around the world, large areas of ocean are inadequately covered. Satellites carrying radar altimeters can give better global coverage, especially if there are several operating simultaneously.

## *Altimetric method*

A satellite is placed in an approximately circular orbit above the Earth with a nadir-pointing radar altimeter on board. Several times a second the altimeter transmits a radar pulse to the sea surface which is then reflected and received back at the satellite by the altimeter dish. Half the travel time of the radar pulse tells us the height of the satellite above the sea surface, provided that the refractive index of the intervening atmosphere can be well modelled. Modern altimeters can measure the distance from the satellite to the sea surface with a precision of the order of several tens of millimetres for data averaged over one second. In that time the satellite travels approximately seven kilometres along its surface track, so the sea surface height is not sampled at just one point but is averaged over a short distance: the altimeter 'footprint', which is due to the transmitted pulse having a finite width and to spreading of the effective illuminated surface by the state of the sea, is of similar size.

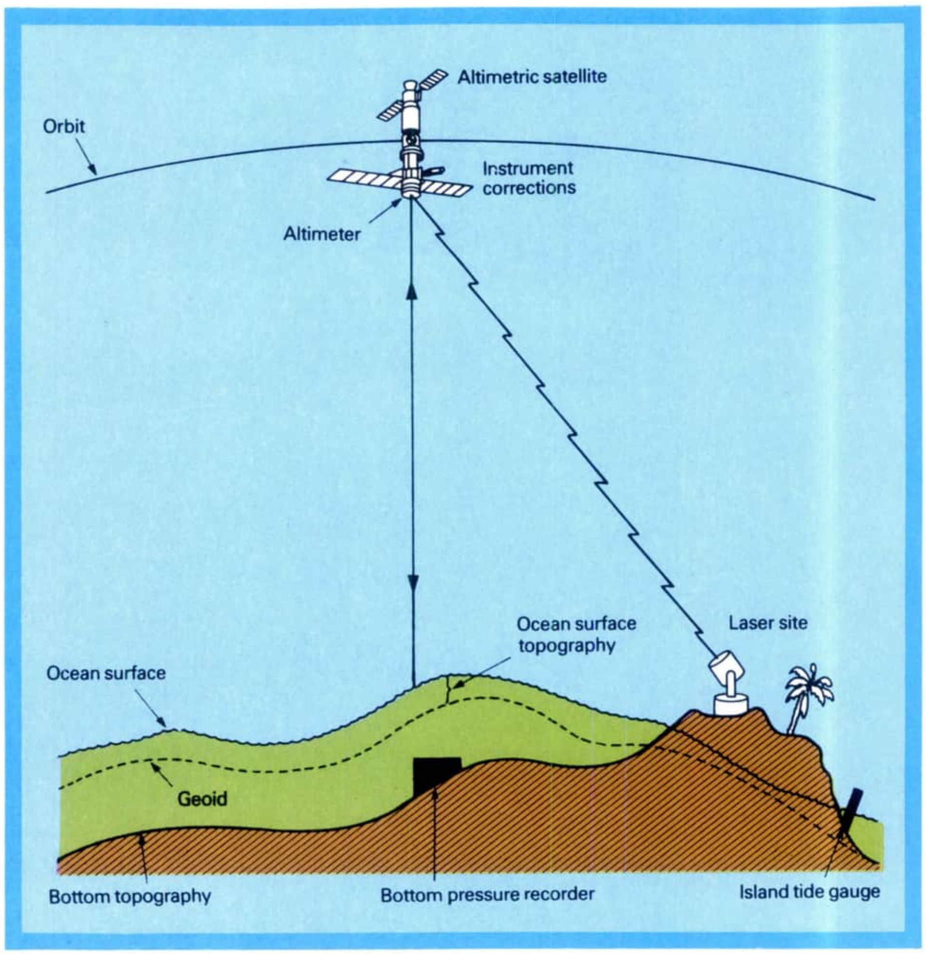
An altimetric satellite is usually placed in an orbit approximately 1000 km above the ocean at which height it circles the Earth in about 100 minutes. If one can accurately measure the radial distance of the satellite from the centre of the Earth, then one can calculate the height of the sea surface in a geocentric frame from the altimeter-sea surface measurement. The ephemeris of the

***An artist's impression of the ERS-1 satellite.***

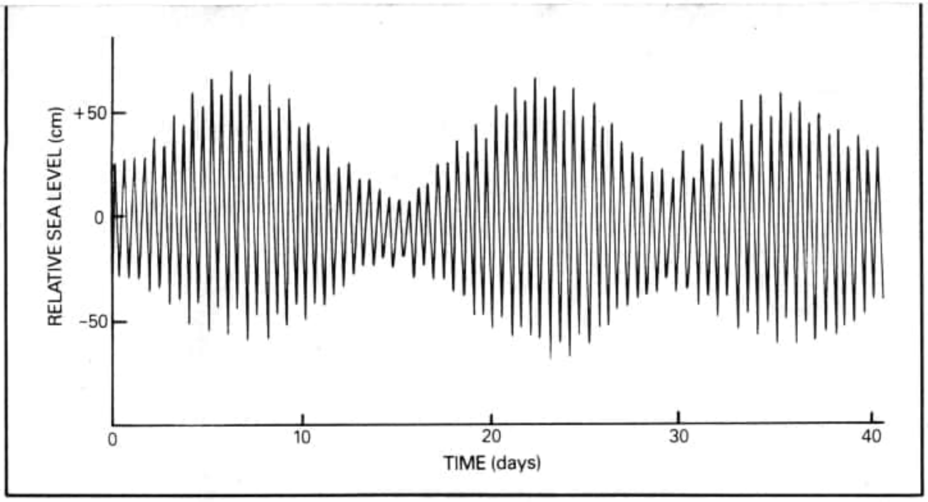
satellite is computed from knowledge of the Earth's gravity field, lunar and solar gravitational effects, solar radiation pressure, atmospheric drag and tidal forces at that altitude and from various range measurements taken by laser.

In practice, the radial distance of the satellite orbit can be calculated to only several decimetres. However, the dominant wavelength of this orbit error is of the order of one revolution or more and the computed error in sea-level slope, which for oceanographic purposes is usually more important than sea level itself, is typically around one decimetre per 1000 km, which is acceptable accuracy for many applications.

Apart from the early proving experiments of Skylab (1974), the first altimeter missions which yielded adequate information for scientific analyses were those of Geo-3 (1975-78) and Seasat (1978), both US satellites. There was a gap of several years, however, between the demise of Seasat and the launch of the US Navy's Geosat in March 1985. Fortunately, this situation will change




***How it works. The distance between the centre of the earth and the satellite is calculated by bouncing laser beams off the satellite. A radar on the spacecraft then measures the distance down to the sea immediately below.***




***The tides at St Helena in the South Atlantic. Sea level is monitored continuously and transmitted each day by satellite link.***

within the next few years with he launch of ERS-1, the first European altimeter satellite, in 1990. This unit will fly with an Australian designed instruments, and will be a major source of data for Australian scientists.

Topex/Poseidon, a joint project between France and the USA is planned for 1991 and NROSS, another US Navy satellite, should enter service soon afterwards, will also add significantly to the data available.

Altimetry measurements are used to find the global (time-invariant) mean sea surface (MSS). To first order, this is the geoid, which is simply the surface of equal gravitational potential of the Earth; that is a measure of the surface of the ocean in the absence of tides and currents. The geoid is approximately an ellipsoid, with geographical variations of up to 100 metres caused by lateral differences of density within the Earth. The mean sea surface consists of the geoid plus the time-invariant ocean topography, of the order $\pm 1$ metre, due to the time-averaged global ocean circulation. Variations of ocean currents then give variations with time of up to a few decimetres with respect to this MSS. The Proudman Oceanographic Laboratory is using altimetry to measure the global ocean tides and to investigate sea level variability associated with fluctuations in ocean currents.

## The tides

In most sea level records the tidal signal is the dominant feature. The chief influences in our better understanding of global tidal processes have been, firstly, the development of global hydrodynamic computer models and, secondly, our ability to measure tides in the open ocean instead of being restricted to coastal margins. As well as being of geophysical interest in themselves, the ocean tides must be accurately known if we are to investigate other sea level variations by means of satellite altimetric measurements.

Sir Isaac Newton in his *Principia Mathematica* (1687) showed that the gravitational forces due to the Moon and the monthly motion of the Earth around the common centre of mass of the Earth-Moon system produce two tidal bulges which are on opposite sides of the Earth. The rotation of the Earth on its axis then produces two tides per day, as the diagram shows. Similarly, the Sun produces two tides per day but their amplitudes are slightly less than half of those raised by the Moon. The ocean tides are really far more complicated than this simple picture suggests.

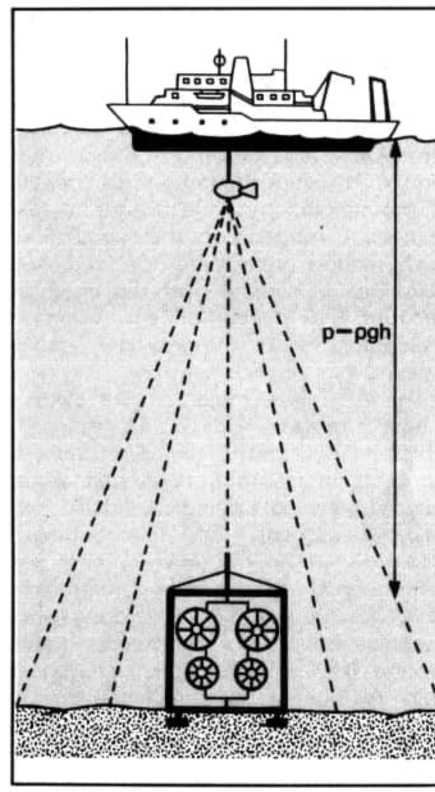
The first complication arises with the astronomy. The relative orbital motions of the Earth-Moon Sun system are well known from astronomical observations and must be taken into account when describing the tides. As well as periods near half a day, the orbital motions give tides with periods near one day, a fortnight, one month, six months, one year, 8.8 years, 18.6 years and 20,940 years.

Second, the dynamic response of the oceans themselves must be taken into account. They are not deep enough to allow the water to react instantly to tidal forces. Ocean basins are also constrained by continental land boundaries, chiefly along the North-South direction, that effectively block the natural westward propagation of the tides. The oceanic bathymetry is complex and varies substantially, especially at the shelf break; bottom friction, especially in continental-shelf seas, plays an important modifying role. Currents are induced, which move on a rotating frame of reference: the Coriolis force causes a deflection of the flow to the right in the northern hemisphere and to the left in the southern hemisphere. These factors cause the real tide to lag, on average, behind the gravitational forcing, and to move roun the ocean basins about a series of null points or amphidromes, where the amplitude is zero. There may be several amphidromes in an ocean basin and their positions will be different for the various tidal periods.

Computer models now solve hydrodynamic equations based on a spherical Earth with increasingly realistic ocean basin geometry. Many of the models contain measured data as boundary conditions and for interior calibration points. To a large extent the accuracy of the solutions depends upon the density of measurements available in specific areas.

## Ocean currents

In recent years interest has been growing in the use of sea level measurements to find changes in the main ocean currents. For spatial scales greater than about 50 km and time scales longer than about one day, the surface height is directly related to the surface current. This is because on such scales oceanic motions are mainly governed by the forces acting on the water particles. The Coriolis force due to the Earth's rotation is balanced by the horizontal pressure gradient (these forces are both at right angles to the direction of flow). At the surface, the pressure gradient can be calculated from the



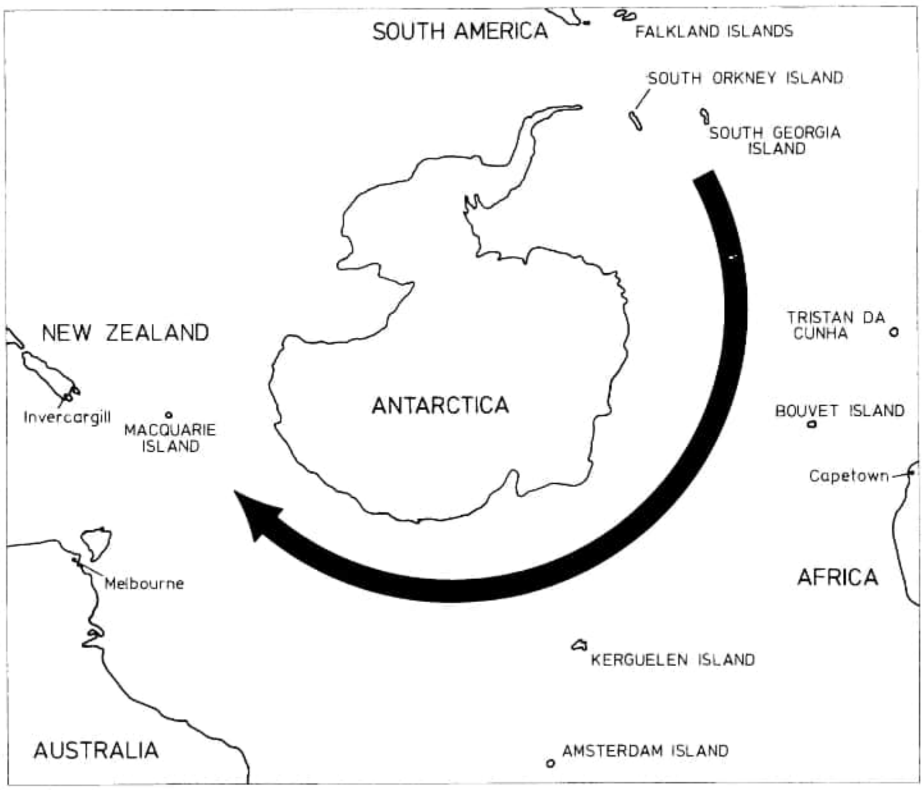

***Deep ocean pressure recorders measure the change in hydrostatic pressure near the bottom caused by fluctuations in sea level. They record automatically and are recalled to the surface by acoustic signals.***

sea-level height. The direction of the surface current is along contours of surface topography. This is directly analogous to the circulation of atmospheric winds around systems of high and low pressure.

A current of one metre per second at mid-latitudes is associated with a surface slope of one metre in 100 km (a slope of 1 in $10^5$). This figure is typical of currents such as the Gulf Stream. The surface topography of the oceans is superimposed on the topography of the ocean surface due to the geoid (up to 100 m), mentioned earlier. Unfortunately the global geoid is, so far, not known to better about ±1 metre. So tide gauge measurements or altimetric measurements cannot be used to determine the mean currents until the model of the geoid is improved using better gravity measurements from either satellites or surface gravimeters. Nevertheless, there are very important large variations in current (typically up to ±20 per cent); they can be worked out from the time variations of tide gauge and altimetry measurements.

Our laboratory has started a programme of sea-level measurements in the Southern Ocean with the objective of determining the variability with time of the Antarctic Circumpolar Current (ACC) and its geographical variations. This is part of the World Ocean Circulation Experiment (WOCE), which is an international collaborative project that aims to measure the large-scale aspects of the circulation of the oceans to test numerical models of the circulation. Such models are needed for predicting variations in climate over the order of decades; they depend critically upon an undertstanding of the way the oceans behave.

The ACC is a major current system (mean transport 125 x $10^6$ $m^3$ $s^{-1}$) which is important to climate because it transfers momentum, heat and water masses between the Indian, Pacific and Atlantic Oceans. So the Southern Ocean is of special interest and has been defined as one of the core projects of WOCE. Fortunately, there are several oceanic islands at strategic points around the ACC that can be used in pairs to look at the time variations in sea-level differences of up to 20 cm across the ACC. We plan to use observations from four pairs of islands, namely Falklands and South Orkney; Falklands and South Georgia; Tristan da Cunha and Bouvet, and Kerguelen and Amsterdam. In areas devoid of islands we plan to install bottom-pressure and inverted echo sounder instruments. All




***Fluctuations in the Antarctic Circumpolar Current affect the weather in our region, and show themselves as variations in sea level. Instruments can be sited at remote islands and then telemetry can be uplinked to satellites.***

the measurments will be used to verify the data from satellite altimetry measurements obtained with Geosat, ERS-1 and Topex/Poseidon. The altimetry will then be used to find the sea surface height variations in areas where no *in situ* measurements are available.

As well as the tidal and ocean circulation signals discussed above, coastal tide gauges also give important information on secular changes of mean sea level relative to the land. These are changes that are extremely slow, so at least 20 years of data are needed to evaluate the secular trend in sea level at any given place.

A rise in global mean sea level would be one expected outcome of the global warming of our planet by about 0.5°C which has been going on over the past 100 years. The consensus of opinion from the global tide gauge data set is that global sea level has indeed risen in the past century by approximately 100 to 150 mm, though in many places the rise is obscured in the data by vertical movements of the land upon which the gauges are fixed.

## Melting

As far as we can tell, the decimetric rise in sea level during the past century has been caused by two main processes, thermal expansion of the upper layers of the ocean and the melting of mounting glaciers at low latitudes. The polar ice caps are not thought to be a large net contributor to global sea level change, though the data from this area is not as complete as one would wish.

Estimates of the rise of global sea level to be expected in the next century vary widely because the projected 'greenhouse gas forcing' (from carbon dioxide, chlorofluorocarbons and so on) is uncertain, and the potential role of the polar ice caps, in particular the West Antarctic Ice Sheet, is unclear. Predictions of the rise in sea level by the year 2100 vary between several decimetres, at about the present rate, to several metres. Obviously, more research is needed if we are to understand the various climatic processes at work that influence global sea levels.

The recent technological advances in global measurements of sea level are beginning to make contributions in areas ranging from the study of crustal movements to research in ocean circulation and climate change. International programs have been set up to co-ordinate the work. ETI

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