

he average air temperature at the surface of Earth has risen this century, as has the temperature of ocean surface waters. Because water expands as it

heats, a warmer ocean means higher sea levels.

We cannot yet say definitely that the temperature rises are due to the greenhouse effect; the heating may be part of a 'natural' variability over a long time-scale that we have not yet recognised in our short 100 years of recording. However, assuming the build-up of greenhouse gases is responsible, and that the warming will continue, as seems likely, scientists and inhabitants of low-lying coastal areas — would like to know the probable extent of future sea-level rises.

But calculating that is no easy task. Models used for the purpose have tended to treat the ocean as passive, stationary and one-dimensional. Scientists assumed that heat simply diffused into the sea from the atmosphere. Using basic physical laws, they would then predict how much a known volume of water would expand for a given increase in temperature. But the oceans are not one-dimensional, and recent work by CSIRO oceanographers, taking into account a number of subtle facets of the sea including vast and complex ocean currents — suggests that the rise in sea level may be less than some earlier estimates had predicted, although still of concern.

The 'Villach Conference' on climate change, held in 1986, produced widely publicised figures for likely sea-level rises of 20 cm and 1.4 m, corresponding to atmospheric temperature increases of 1.5 and 4.5°C respectively. But Dr John Church, Dr Stuart Godfrey, Dr David Jackett and Dr Trevor McDougall, of the CSIRO Division of Oceanography in Hobart, estimate that the ocean warming resulting from those temperature increases by the year 2050 would raise the sea level by between 10 cm and 40 cm.

That comparison does not tell the complete story, as the CSIRO model only takes into account the temperature effect on the oceans and their consequent thermal expansion; it does not consider changes in sea level brought about by melting of ice sheets and glaciers, and changes in groundwater storage. When we add on estimates of these from the work of others, we arrive at figures for total sea-level rises of 15 cm and 70 cm respectively.

HOW HIGH COULD

Predictions of sea-level rise due to global warming range from minor to catastrophic. Oceanographers have now delved into the complexities of the problem and produced some firmly based answers. B ut first, how did the CSIRO scientists arrive at their conclusions? It's certainly not easy trying to model accurately the enormous complexities of the ever-changing oceans, with their great volume, massive currents and sensitivity to the influence of land masses and the atmosphere. Indeed, nailing jelly to the wall could be easier.

For example, consider how heat enters the ocean. Does it just 'diffuse' from the warmer air vertically into the water, and heat only the surface layer of the sea? (Warm water is less dense than cold, so it would not spread downwards.) Conventional models of sea-level rise have considered that this is the only method, but measurements have shown that the rate of heat transfer into the ocean by vertical diffusion is far lower in practice than the figures many modellers have adopted.

To help visualise this diffusion of heat, imagine placing one end of a metal bar near a fire. Eventually, the other end will warm up. A similar limited vertical diffusion of heat from atmosphere to ocean was used in previous models.

Much of the early work, for reasons of simplicity, had to ignore the fact that water in the oceans moves in three dimensions. By movement, of course, scientists don't mean waves, which are too small individually to consider, but rather movement of vast volumes of water in huge currents. To understand the importance of this, we now need to consider another process — advection.

Imagine smoke rising from a chimney. On a still day it will slowly spread out in all directions by means of diffusion. With a strong directional wind, however, it will all shift downwind. This process is advection — the

transport of properties (notably heat and salinity in the ocean) by the movement of bodies of air or water, rather than by conduction or diffusion.

Massive ocean currents called gyres do the moving. These currents have far more capacity to store heat than does the atmosphere. Indeed, just the top 3 m of the ocean contains more heat than the whole of the atmosphere.

THE SEA RISE?

The origin of gyres lies in the fact that more heat from the Sun reaches the Equator than the Poles, and naturally heat tends to move from the former to the latter. Warm air rises at the Equator, and draws in more air beneath it in the form of winds (the 'Trade Winds') that, together with other air movements, provide the main force driving the ocean currents.

Water itself is heated at the Equator and moves poleward, twisted by the Earth's rotation and affected by the



How water masses move and temperature varies in the Southern Ocean.

Bill van Aken



Oceanographer lowering a probe that measures electrical conductivity, temperature and pressure as it falls. Each provides an ocean profile of salinity and temperature; many such measurements are needed to work out the complex pattern of water movement in the ocean.

positions of the continents. The resultant broadly circular movements between about 10 and 40° N and S are clockwise in the Northern Hemisphere and anticlockwise in the Southern. They flow towards the east at mid latitudes, and back to the west in the equatorial region. They then flow towards the Poles, along the eastern sides of continents, as the well-known warm currents — the Gulf Stream, the East Australia Current or the Kuroshio.

When two different masses of water meet, one will move beneath the other, depending on their relative densities, in a process termed subduction. The densities are determined by temperature and salinity.

The convergence of water of different densities from the Equator and the Poles in the interior of the oceans causes continuous subduction. This means that water moves vertically as well as horizontally. Cold water from the Poles travels at depth — it is denser than warm water — until it emerges at the surface in another part of the world in the form of a cold current.

For example, in our own hemisphere, water from the Southern Ocean sinks at the Antarctic convergence, at about 60°S, when confronted with warmer water from more northerly latitudes. It then flows northwards at a



depth of about 1000 m. It will still be about 600 m deep just south of the Equator and will then flow westwards at this depth, rising slowly back to the surface in the Southern Ocean.

Thus, ocean currents, in three dimensions, form a giant 'conveyor belt', distributing heat from the thin surface layer into the interior of the oceans and around the globe. (Don't be confused by the idea of a 'cold' current distributing heat; if the surface water at 60°S were heated just a degree or two more than usual, because of a warmer atmosphere, then it would carry a large quantity of extra heat into the ocean interior.)

Water may take decades to circulate in these 3-D gyres in the top kilometre of the ocean, and centuries in the deeper water.

With the increased atmospheric temperatures due to the greenhouse effect, the oceans' conveyor belt will carry more heat into the interior. This subduction moves heat around far more effectively than simple diffusion.

Because warm water expands more than cold when it is heated, earlier workers had presumed that the sea level would rise unevenly around the globe. However, Dr Church and his team point out that the inequalities cannot persist; winds will act to continuously spread out the expansion, and their model is the first to consider this. Of course, if global warming changes the strength and distribution of the winds — as it may do — then this 'evening-out' process may not occur, and the sea level could rise more in some areas than others.

The ultimate test of any model is how it fits reality. The CSIRO scientists can't test their predictions until the global temperature has risen substantially, but they can look at what has been happening in the past and see how it squares with what their model says should have happened.

Measurements from around the world during the last hundred years or so have shown that the sea level has indeed risen, probably by 10–20 cm. Most estimates fall in the lower half of this range. (The difference in estimates depends partly on whether scientists take into account the upward movement of the Earth's crust, which is 'rebounding' in slow motion after being pressed down by the weight of glaciers during the last Ice Age. The uneven distribution of sea-level gauges around the globe and inconsistent monitoring further confuse the picture.)

Recent work has shown that the contribution to sea-level rise made by melting around the edges of the ice sheets in Antarctica and Greenland is probably very small. Indeed, although in some areas the ice is decreasing, in other places ice sheets are actually growing because of increased snowfall brought about by greater evaporation from the warmed oceans.

Using estimates of 0.4–0.6°C for the increase in average global temperature from 1880 to 1980, the model put forward by Dr Church and his colleagues



produces a figure for sea-level rise during the past century of about 7 cm. The contribution from the melting of temperate glaciers is estimated to be 4-6 cm; added to Dr Church's value, this gives a total of 11-6 cm — in the range of the measured reality. The fact that these figures alone seem able to account for a good proportion of the rise lends support to the idea that the contribution of ice-melt in Greenland and Antarctica has so far been small.

The CSIRO scientists have concentrated on thermal expansion in their work on sea-level rise because they believe it will be the biggest component — at least for the near future. To arrive at estimates of total rises, they have used figures from others' work for icemelting.

The chart shows two sets of figures for three different temperature rises that may occur between now and 2050. One set of values represents the rise brought about by thermal expansion only; the other shows possible total figures, which include values for ice-melt.

Even the worst case — where a 4.5°C average global temperature increase produces a total rise of 70 cm — falls short of most previous estimates. However, as the scientists point out, the upper extreme of their estimate is still large enough to cause considerable concern for many nations.

The variability in the figures now lies less in our knowledge of the oceans' thermal expansion than in the predictions for global temperature rise, and the extent of ice-melting. Of course, estimating local changes in sea Gary Critchley

level is a different matter; they also depend on local winds and geography, and on changes in atmospheric pressure.

Whatever future awaits us, now that the CSIRO oceanographers have introduced the complexities of ocean behaviour into the debate, the greenhouse-model-builders will be incorporating the findings to give increasingly refined predictions, to enable society to make more informed decisions.

Roger Beckmann

Currents near Australia



This view of the situation around Australia indicates the complexity of surface currents.





rises brought about by thermal expansion
total rises (including ice-melt)

More about the topic

A model of sea level rise caused by ocean thermal expansion. J.A. Church, J.S. Godfrey, D.R. Jackett and T.J. McDougall. *Journal of Climate*, 1991, 4, (in press).