Moon, tides and climate

Carl Wunsch

The view that much of the energy of ocean tides is dissipated in deep water, rather than in shallow coastal seas, now finds observational support. Curiously, the results bear upon our understanding of climate change.

The Moon is receding from the Earth at about 4 centimetres a year, as measured[1] by laser reflectors left there by astronauts. What does this motion have to do with the ocean circulation? By Kepler's laws, the recession implies that there is a continuing loss of energy in the Earth–Moon system of 3×10^{12} watts, or 3 terawatts, mostly in the ocean. But where in the ocean does this energy go, and what are its effects? On page 775 of this issue, Egbert and Ray[2] produce evidence for the seemingly lunatic conclusion[3] that dissipation of tidal energy in the deep sea, and the resulting mixing, are controlling features of the overall ocean circulation.

In the conventional picture of the oceans, there is a wind-driven upper circulation that gives rise to massive, near-surface flows such as the Gulf Stream and the Kuroshio and Antarctic Circumpolar currents. Superimposed upon this circulation is one often labelled, unhappily, the 'thermohaline' circulation. This is supposedly driven by surface-ocean density contrasts arising from temperature and salt variations produced by strong atmospheric cooling and wind-induced evaporation. In this process, dense water sinks at high latitudes through convection, driving a 'meridional overturning circulation', which many believe dominates the heat and freshwater budgets of the climate system. (The terminological problem with 'thermohaline' circulation arises because, for example, half the heat transport in the North Pacific Ocean is in the wind-driven upper circulation[4].)

As formulated in almost all models of the Earth's climate, both theoretical and numerical, the dense water sinking in the meridional overturning circulation at high latitudes then flows, close to the ocean bottom, throughout the world, returning to the surface by a uniform upwelling through the 'interior' ocean. Under the simple assumption that a uniform upwelling of cold water is balanced by a uniform downward mixing of warmer water throughout the water column, a steady state is achieved. Almost all numerical models of the ocean and climate systems represent this process through spatially constant vertical 'eddy'-mixing coefficients, as do the textbook theories.

It has become evident, however, that the actual circulation is much more subtle and interesting. Consideration of the stability and energetics of a fluid being heated and cooled at the surface[5] shows that the resulting motion would be extremely weak — a 'diffusive creep'. Such a fluid system is stable, and in a steady state it cannot produce the vigorous flow we observe in the deep oceans. There cannot be a primarily convectively driven circulation of any significance[3,6].

Figure 1 **The Moon was not usually believed to be involved in the general circulation of the oceans. But in Russian literature, Private Kozma Prutkov, regarded as quite dim, usually produces the right answers. When asked which is more important, the Sun or Moon, he replies: "The Moon, of course, because the sun shines only in daytime when it is bright anyhow…". (Drawing by M. Dormer[16].)**

Furthermore, as early as about 1970 it was clear that the picture of uniform vertical mixing was not correct in the upper ocean[7–9]. Both direct measurements of turbulence and dye-diffusion experiments[10,11] have shown the weakness of open-ocean mixing all the way down to the sea floor. Instead, measurements confirm an old hypothesis[7]: that the ocean is mixed primarily at its boundaries, including the mid-ocean ridges that rise from the sea floor, where the local mixing rates are orders of magnitude larger than those in the ocean interior[10,11]. The reliance of almost all numerical circulation models on uniform interior-ocean mixing calls into question inferences about the physics of the circulation based on them. Only in the past two years have models that eliminate such mixing[12] finally started to appear.

Surprisingly, it was only recently recognized that the need for an energy source to sustain the vertical mixing (lifting dense water through lighter) has important consequences. The difficulties of driving fluid motions by surface heating and evaporation mean that a mechanical source of energy must control not only the directly wind-driven flows, but also the deep-water components of the meridional overturning circulation. There are only two candidates for such a source: winds and tides.

For over 75 years[13,14] it was thought that the tides dissipated almost entirely by friction in the shallow seas above the continental shelves. But Munk and I concluded[3] that about half of the power required to return the deep waters to the surface was coming from mixing driven primarily by dissipation of tidal energy — principally lunar, but with a minor solar component — in the deep ocean (Fig. 1). Now, by fitting a dynamical model to satellite altimetric measurements of the tides, Egbert and Ray[2] have produced an observational estimate of 1 terawatt of open-ocean tidal dissipation. Their numbers are not definitive, but they are in agreement with the energy values required by the deep upwelling, and with the total — shallow (about 2 terawatts) plus deep — energy losses implied by the lunar recession.

If the hypothesis of tide- and wind-driven controls on the rates at which the ocean transports heat and fresh water survives further tests, there are several implications. One is that it brings into question the extent to which uniform-mixing models of the ocean circulation could either reproduce the present-day circulation or predict responses to external changes. The hypothesis also suggests that the rate-limiting[15] factor for oceanic heat transport is not primarily the surface density gradient imposed on the ocean; rather, it is the strengths and patterns of the wind, and the distributions of the tides.

What would be the consequences if the hypothesis is correct? One is that the atmospheric wind patterns would have to be known in considering past and future climate change. The other is that changes in tidal distributions and the consequent mixing would need to be understood over geological time. During the Last Glacial Maximum, the sea level was about 130 metres lower than today. This configuration removed much of the present regions of shallow-water energy dissipation and changed the deep-ocean tides, presumably affecting oceanic heat transport. Over longer periods in the past, the entire continental configuration was different, with radically different tidal distributions and mixing. It appears that the tides are, surprisingly, an intricate part of the story of climate change, as is the history of the lunar orbit. ■

Carl Wunsch is in the Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
e-mail: cwunsch@pond.mit.edu

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Demography

Greater lifetime expectations

Shiro Horiuchi

For early humans, the average lifespan was around 20 years, as estimated from skeletal remains. Now, in several industrialized countries, it is about 80 years. Much of this increase has happened in the past 150 years. But it was widely expected that as life expectancy became very high and approached the 'biological limit of human longevity', the rapid 'mortality decline' would slow down and eventually level off.

Such a deceleration has not occurred yet. On page 789 of this issue, Tuljapurkar *et al.*[1] show that during the second half of the twentieth century, age-specific death rates in the G7 industrialized countries — the United States, Canada, Japan, France, Germany, Italy and the United Kingdom — continued to decline at a remarkably constant pace. There was no noticeable sign of a slowing down. This report follows one by Wilmoth[2], published two years ago, which indicated that the mortality reduction in the United States, measured by the age-standardized death rate, was even faster in the second half of the century than in the first half.

Assuming a further continuation of the stable pace of mortality decline, Tuljapurkar *et al.* forecast that the life expectancy at birth is likely to increase faster than predicted by the governments of the G7 countries (Fig. 1). This implies that the elderly population in the near future will be greater than in the official forecasts. Depending on the general state of health, the larger elderly population could entail higher medical costs and demands for long-term care and other services, and higher pension payments.

The findings give rise to two interrelated questions. Why has mortality decline not started to slow down? And will it continue into the future? Studies in demography, epidemiology and the biology of ageing and longevity provide clues to the answers. Underlying the steady decrease in mortality level were shifts in the pattern of mortality reduction[3]. In the second half of the nineteenth century and the first half of the twentieth century, there were large decreases in the number of deaths from infectious and parasitic diseases, and from poor nutrition and disorders associated with pregnancy and childbirth. The reduction was pronounced among infants, children and young adults, but modest among the elderly. This led to a view that the fall in death rates at young and middle ages to low levels would soon exhaust the potential to prolong life expectancy further.

	Official forecasts for 2050	Forecasts of Tuljapurkar et al.[1] for 2050	Gap
United States	80.45	82.91	2.5
Canada	81.67	85.26	3.6
Japan	82.95	90.91	8.0
France	83.50	87.01	3.5
Germany	81.50	83.12	1.6
Italy	82.50	86.26	3.8
United Kingdom	82.50	83.79	1.3

Figure 1 **Official medium-variant forecasts of life expectancy in the G7 countries in 2050 compared with the forecasts of Tuljapurkar *et al.*[1]. The figures are for life expectancy for the sexes combined. They are taken from Table 3 of the paper on page 792, and those in the 'gap' column have been rounded to the nearest decimal point.**

But that view did not — and could not — take account of developments in the second half of the twentieth century. Mortality from degenerative diseases, most notably heart diseases and stroke, started to fall[4]. The reduction was pronounced among the elderly[5,6], and some suspected that it might have been achieved through postponing the deaths of seriously ill people. But in the United States at least[7,8], it seems that the health of the elderly greatly improved in the 1980s and 1990s, suggesting that the extended length of life in old age is mainly due to better health rather than prolonged survival in sickness.

Another shift in the pattern of mortality reduction might also have occurred. Despite the marked decrease in deaths from various degenerative diseases, the overall level of cancer mortality remained the same for many years. But, around 1990, a long-awaited decline in total cancer mortality finally started in economically developed countries. Whether that downward trend will continue for long remains to be seen.

These days, the existence of a biological limit to human longevity is considered questionable[9]. Biologists used to think that senescent processes might be programmed into the biological clock of the human body. But they have largely shifted to the view that senescence is mainly due to the body's imperfect systems of maintenance and repair, which allow the long-term accumulation of unrepaired damage in macromolecules, cells, tissues and organs[10]. Progress in ageing research may eventually lead to new medical approaches that lower the rates of damage accumulation[11].

Overall, the evidence supports the expectation that scientific, technological and economic developments will lead to more effective control of degenerative diseases and ageing processes, making it possible to sustain the rapid pace of mortality decline. However, this prospect is not unconditional. New threats to health and survival are arising, including the emergence and re-emergence of infectious diseases, increasing pollution, and the proliferation of nuclear, biological and chemical weapons. If we fail to control these hazards, some of the large gain in the life expectancy of the past 150 years may well be lost[3].

What about the world outside the G7 nations? The prospect of life expectancy soon exceeding 80 years is limited to these and other countries with highly developed market economies. They are mostly in Western Europe, North America and Eastern Asia. In the rest of the world, the life expectancy is on average still under 65 years[12]. In subSaharan Africa, it is under 50 years and may be falling because of the AIDS epidemic, as well as stagnated economic development and political conflicts. Some industrialized nations in Eastern Europe and the former Soviet Union have seen only slow increases, and even occasional reversals, in life expectancy.

It is not surprising that government forecasts of life expectancy and the size of the elderly population in G7 countries are