OCEAN SCIENCE

Links between surface and abyss

The global ocean overturning circulation relies on dense deep waters being mixed back up to the surface. An observational analysis shows that turbulent mixing in the abyss around Antarctica varies with the strength of surface eddies and thus probably also wind speeds.

Parker MacCready

The global oceans support a continuous, but slow, overturning circulation, with dense water sinking to depth in the polar regions before they are mixed upwards, frequently over rough topography. This circulation has vast consequences for life on our planet. When deep waters rise to the surface, often after drifting for hundreds of years in the abyss, they bring with them the nutrients that plankton need to grow. Conversely, as surface waters sink they take heat and dissolved CO_2 from the atmosphere, strongly shaping regional and global climate change. Much progress has been made on describing the overturning, but the physics involved, and particularly the role of turbulence, has been more elusive. Writing in *Nature Geoscience*, Sheen *et al.*[1] report that turbulent mixing rates in Antarctic Bottom Water, the deepest of the global water masses, is probably modulated by surface winds around Antarctica — an unusual region in the ocean where surface and abyssal processes are not isolated from each other.

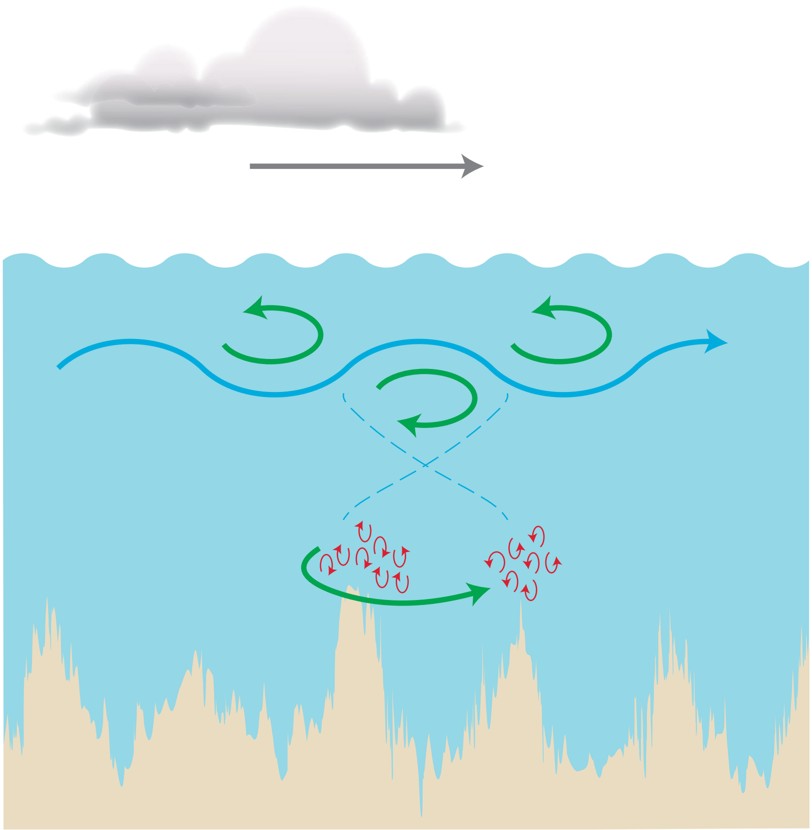

Figure 1 | Southern Ocean mixing. Strong westerly winds (grey) over the Southern Ocean force the Antarctic Circumpolar Current (blue). The current would keep accelerating over time except that it becomes unstable, giving rise to strong eddies that are visible to satellites as bumps or dips in sea surface height. Although the mean current at depth is weak, eddies (green) can be strong, leading to internal wave generation by flow over rough topography. The internal waves then generate turbulence (red) that provides a source of energy for the mixing of abyssal waters, which, in turn, hastens the global overturning circulation. Sheen and colleagues[1] show that surface eddies are linked to turbulence at depth, and suggest that this is how southern westerly winds modulate abyssal mixing.

Understanding the ocean overturning circulation has been an important goal for oceanographers over the past half century, but the task is daunting. The sinking of surface waters in the polar regions happens in winter, which makes field observations hazardous to both ships and instruments. Observing the gradual rise of waters back from the abyss is equally challenging, but for a different reason: the vertical velocities involved are too small to measure with current technology. Furthermore, although it is known that turbulence must occur (because a water parcel must mix with buoyant waters to become light enough to return eventually to the surface), our ability to measure it directly, and our theoretical understanding of how it is generated by internal waves, are both relatively recent developments[2].

Nonetheless, the rate and pattern of overturning have been defined remarkably well, with the help of the distribution of trace chemicals such as radioisotopes and anthropogenic gases that have been emitted over tightly defined time windows. The concentrations and characteristics of these within a given water mass can therefore be used to reconstruct the time when the water was last in contact with the atmosphere[3].

One important location for studying the return of abyssal waters to the surface ocean is the Southern Ocean around Antarctica, the only location where the ocean can circulate freely all the way around the globe without continental barriers. The resulting Antarctic Circumpolar Current is forced by strong westerly winds, and its transport and eddy activity are modulated by global weather patterns.

Sheen and colleagues[1] measured turbulence and eddy activity just downstream of Drake Passage between South America and the Antarctic Peninsula, an area that is known to be an eddy hotspot and a key choke point in the swift and eddy-rich Antarctic Circumpolar Current. Specifically, they moored instruments over the whole water column, and complemented these observations by several ship-based sections across the Antarctic Circumpolar Current with high-resolution turbulence measurements. The data reveal that, during the period of their measurements, turbulence in bottom waters was significantly correlated with surface eddy activity (Fig. 1).

This link between surface and abyss is not as improbable as it might sound. The fluid instability mechanism that makes eddies in the surface ocean leads to an intensification of currents in the top and bottom layers of the ocean. When such instability arises, strengthened bottom currents are assumed to interact with rough bottom topography to generate internal waves that eventually devolve into turbulence.

To put the variability they observe from a few ship-based snapshots into a longer-term context, Sheen and colleagues[1] use satellite altimeter measurements, stretching back over twenty years, to give a remarkably detailed picture of sea surface height in the generally data-poor Southern Ocean[4]. These sea surface height observations can be used to infer sea surface currents, including both the transport of the Antarctic Circumpolar Current and the energy of its eddies. Sheen and colleagues[1] then make cruder estimates of turbulence at depth, using data also spanning the past two decades from many other cruises across the Antarctic Circumpolar Current.

They find that these long-term turbulence estimates were also correlated with surface eddy intensity as derived from the satellite data, giving more weight to their suggestion of a link between surface wind forcing and abyssal mixing. Such a link provides a potential shortcut for Antarctic Bottom Water to return to the surface, allowing it to be entrained into mid-depth waters that will soon outcrop near Antarctica. If this link is strengthened by increasing wind forcing, it could significantly reduce the residence time of water in one branch of the global overturning circulation.

Nevertheless, the study covers just a small part of the global dynamics that govern the overturning circulation. As is clearly shown, a few measurements scattered over 20 years are insufficient to infer the variability of mixing, which seems substantial on a decadal scale. With the currently available measurements, the system is heavily undersampled. However, the advances over the past years in turbulence measurements, and the availability of long-term satellite data of sea surface height, give hope that this picture will improve.

The analysis presented by Sheen and colleagues[1] provides an important glimpse of the surface climate's influence on one part of the overturning circulation of the ocean at depth. As our tools improve, there are many more surprises to be expected from the global overturning circulation. ❐

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PALAEOCLIMATE

Broken tropical thermostats

During the early Pliocene epoch, tropical sea surface temperatures were thought to be similar to those of today, even though global mean temperatures were several degrees warmer. Temperature reconstructions now suggest that the Pliocene tropical warm pools were about two degrees warmer than those at present.

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Terrestrial fossils and stable oxygen isotope compositions of benthic foraminifera paint images of extraordinary polar warmth in the past, but much less is known about the tropics, which span about 40% of the surface of the Earth. Existing records suggest that the aerially expansive warm pools of the tropics have been relatively stable through time, even during periods of global warmth. This evidence supports the notion of a tropical thermostat driven by physical mechanisms that alter Earth's meridional temperature gradient, minimize global mean-temperature change and, as a result, appear to maintain negligible climate sensitivity to radiative forcing[1–3]. Writing in *Nature Geoscience*, O'Brien *et al.*[4] report reconstructions of warm pool tropical sea surface temperatures from a warm interval between three to five million years ago and show temperature variations that preclude the operation of a tropical thermostat mechanism.

A deficit of reliable tropical records has led us astray before. Early research using oxygen isotope compositions of carbonates to constrain Cretaceous warmth suggested that tropical sea surface temperatures were the same as, or colder than, those of today[5,6], even though polar regions exhibited sub-tropical-like conditions[7]. But we now recognize that the inferred cool tropical temperatures reflected the influence of cold-biased, diagenetic carbonates, rather than the climate system itself[8,9]. A growing library of Cretaceous temperature reconstructions[10] indicates that the tropics were substantially warmer, consistent with the expression of expansive warmth everywhere else at that time.

Depictions of ancient tropical temperature change are dependent on the methodologies used to reconstruct sea surface temperatures. For the markedly warmer world of the middle to early Pliocene, about three to five million years ago, tropical warm pool temperatures have been estimated from the magnesium to calcium ratio (Mg/Ca) of shallow-dwelling foraminifera.

O'Brien *et al.*[4] evaluate the veracity of these Pliocene temperature records by comparing temperature records from Mg/Ca ratios to those obtained from two alternative proxies based on molecular biomarkers: $U_{37}^{K'}$ and TEX_{86}^{H}. When $U_{37}^{K'}$-derived temperatures are below their maximum calculable limit, both $U_{37}^{K'}$ and TEX_{86}^{H} suggest warmer tropical temperatures associated with the pervasive global warmth of the early