CLIMATE SCIENCE

Asymmetric response

The surface layer of the Southern Ocean connects the atmosphere with the deep subtropical ocean. Ocean observations reveal that the thickness of this layer — important for biological productivity — is controlled by the strength and position of the southern circumpolar winds.

Sarah Gille

The mixed layer at the surface of the ocean is the gateway for all exchanges between air and sea. This role as a gateway is especially relevant in the Southern Ocean, the band of ocean surrounding Antarctica, located south of about 40° S. Water in the Southern Ocean mixed layer has the same density as subtropical water at depths of several thousand metres. Because mixing readily occurs along surfaces of constant density, the density surfaces that connect the Southern Ocean surface layer to the deep ocean provide a conduit for the sequestration of heat or carbon dioxide from the atmosphere into the ocean's interior. As a result, evaluations of future climate depend in part on understanding the processes by which the Southern Ocean mixed layer evolves over time. Writing in *Nature Geoscience*, Sallée and colleagues[1] show that the mixed layer deepens in some sectors and shoals in others, in response to an intensifying wind pattern.

The Southern Annular Mode, essentially a zonally symmetric pattern that represents the atmospheric pressure difference between Antarctica and the mid-latitudes[2], is the dominant pattern of atmospheric variability in the Southern Hemisphere. High values of the Southern Annular Mode index correspond to intensified winds over the Southern Ocean. During the high-index phase, wind systems also tend to be shifted southwards relative to their mean. When the Southern Annular Mode index is low, the pattern is reversed with weaker winds that are positioned farther north. Over the past two to three decades, the index of the Southern Annular Mode is thought to have increased in response to both greenhouse warming and anthropogenic ozone depletion[3].

Wind is the most important factor driving the current systems in the Southern Ocean. It is therefore natural to consider that changes in winds linked to the Southern Annular Mode should lead to changes in ocean circulation. Indeed, climate models that were developed as contributions to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) suggest a clear ocean response to fluctuations in the Southern Annular Mode index. For example, one set of model comparisons predicts that a poleward shift in winds typical of high values of the index allows more mid-depth intermediate water to rise towards the mixed surface layer where it can equilibrate with the atmosphere. This invigorated exchange between mid-depth ocean and atmosphere ultimately results in greater uptake of heat and carbon dioxide by the global ocean, and therefore less atmospheric warming[4].

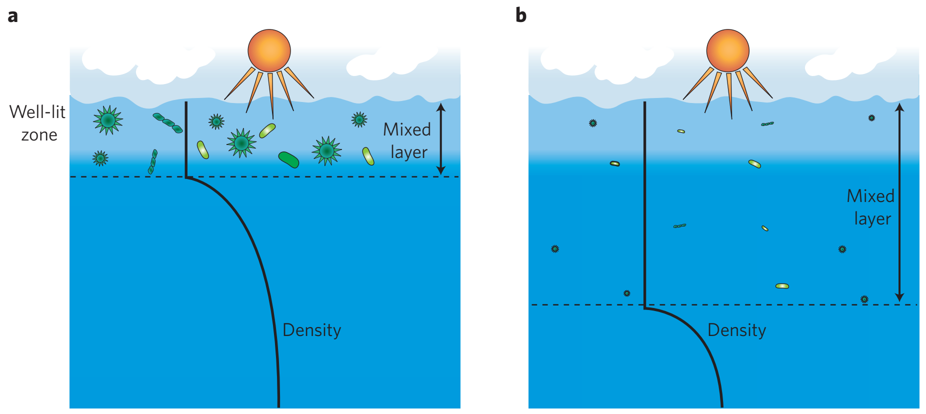

Figure 1 | Mixed-layer depth and marine productivity. **a**, When the mixed layer is shallow, phytoplankton mostly stay within the well-lit zone, where they thrive. **b**, Where the mixed layer deepens, phytoplankton are distributed over a larger volume of water, and sink more easily to depths too dark to sustain them. Sallée and colleagues[1] show that the mixed-layer depth in the Southern Ocean is closely linked to the winds that circle around Antarctica, and find indications for lower productivity at times when the mixed layer deepens.

However, air–sea exchange in the Southern Ocean depends not only on the state of the Southern Annular Mode, but also on the details of mixed-layer physics. A recent analysis of the ensemble of IPCC models suggests that the deep ocean takes up more heat from the atmosphere in models that form deeper mixed layers within the Southern Ocean[5].

Until recently, there would have been no possibility of obtaining *in situ* data at a sufficient resolution to explore the ideas raised by these modelling studies of Southern Ocean climate. The development of Argo floats[6] has changed that. Argo floats are autonomous instruments for measuring the ocean that, after deployment, settle to a pre-set depth of about 1,000 m, where they drift along with the ocean currents. Every ten days each float rises to the ocean surface and collects oceanic temperature and salinity data on its way up. The data are then relayed home by satellite, before the float returns to depth. The international Argo array consists of about 3,000 floats, spread uniformly across the globe. For the historically under-sampled Southern Ocean, the Argo programme has provided an explosion of observations.

Sallée *et al.*[1] capitalized on these observations to develop seasonal maps of mixed-layer depth, and to evaluate how this depth changed for high versus low index values for the Southern Annular Mode. Although the Southern Annular Mode is usually thought of as a zonally uniform pattern, Sallée and colleagues surprisingly find that the mixed-layer response to changes in the atmospheric pattern is far from zonally uniform. In their analysis, positive values of the Southern Annular Mode index correspond to deeper mixed-layer depths over the eastern Indian Ocean and in the central South Pacific Ocean, but shallower mixed layers in the western Pacific and Indian oceans. During these events, a small non-zonal component of the Southern Annular Mode leads to anomalous meridional winds[7] that bring cold air to the eastern Indian and central Pacific regions. The resulting air–sea fluxes cool the ocean, and sea surface temperature drops. When the top of the ocean cools regionally, it becomes denser, which allows surface water to sink. As a result, the mixed layer deepens[1].

The implications of the study by Sallée and colleagues extend to biology. Phytoplankton need both light and nutrients to grow. In most parts of the world, when the mixed layer deepens, nutrients enter the mixed layer from the deeper waters, fuelling greater biological productivity (Fig. 1a). However, Southern Ocean mixed layers are so deep that they can extend well below the region where phytoplankton receive enough sunlight to grow. When these deep mixed layers deepen further, phytoplankton have a greater chance of being mixed out of the well-lit zone, leading to lower biological productivity overall (Fig. 1b). The results of Sallée *et al.* are consistent with this scenario: for summertime data in three separate regions, they find that deeper mixed layers correspond to lower chlorophyll concentrations, implying lower biological productivity.

Sallée and colleagues[1] provide important ground truth for assessing the sensitivity of the depth of the Southern Ocean's mixed layer to climate change. The simulations from the ensemble of IPCC models generally agree in predicting an increasing index of the Southern Annular Mode in coming decades[3,8], but they disagree in their estimates of the resulting mixed-layer depths[4]. If we are to develop meaningful projections for future ocean impacts on climate, then attention will need to be focused on accurately simulating mixed-layer physics. ❐

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PALAEONTOLOGY

Safer in the south

Many species of nannoplankton with carbonate shells vanished during the mass extinction 65 million years ago. An analysis of extinction rates from the world's oceans reveals a geographic bias in the demise and recovery of nannoplankton species.

Paul B. Wignall

The impact of a large meteorite at the end of the Cretaceous period, 65 million years ago, triggered a biological crisis. The dinosaurs are the most celebrated victims of the catastrophe, but about 50% of other terrestrial species also succumbed, along with approximately 75% of marine species. The best evidence of the links between the impact and the extinction come from the marine realm. Fossils from seafloor sediments reveal that an abrupt extinction of many species of marine plankton occurred at the same time as the deposition of anomalous amounts of iridium, a tell-tale signature of a meteorite falling to Earth. Writing in *Nature Geoscience*, Jiang and colleagues[1] show that after the impact, populations of calcareous nannoplankton — shelled phytoplankton ranging from 2 to 20 μm in size — had higher rates of extinction and a longer period of recovery in the Northern Hemisphere oceans.

Descriptions of marine extinctions at the Cretaceous/Tertiary (K/T) boundary have come from the fossil record of organisms ranging from single-celled protozoans living at the ocean surface[2,3] to far larger molluscs at the sea floor[4]. Global darkness, cooling and ocean acidification have all been invoked as causes of the extinction, but for many groups the exact mechanisms remain unclear. Whatever the cause, the extinctions are thought to have led to the development of what have become known as 'Strangelove oceans': essentially dead seas with little primary productivity and the near-absence of a biological pump, which transports organic carbon in the form of dead surface-water plankton to the deep ocean[5].

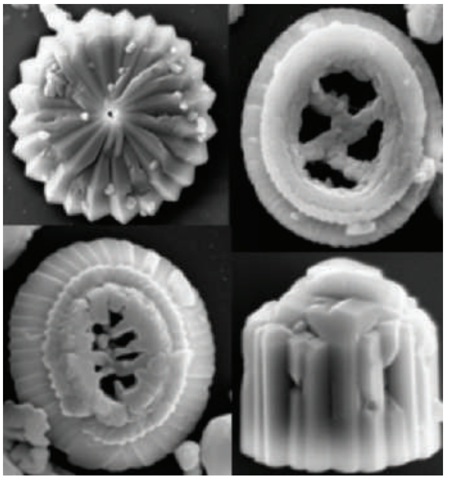

Figure 1 | The recovery of the nannoplankton. Jiang and colleagues[1] find that following the mass extinction at the Cretaceous/Tertiary boundary, eight new species of nannoplankton appeared in the Southern Hemisphere oceans about 80,000 years before they appeared in the Northern Hemisphere oceans. Among the nannoplankton found were (clockwise) *Discoaster multiradiatus, Chiasmolithus bidens, Fasciculithus tympaniformis* and *Toweius pertusus*. Images courtesy of Timothy J. Bralower.

Jiang and colleagues[1] find that this loss of primary productivity at the K/T boundary was not uniform across the globe. Fossils from marine-sediment cores in Southern Hemisphere oceans show that at latitudes greater than 50° S, nearly 25% of calcareous nannoplankton species survived. Of course, viewed the other way around, this indicates the loss of nearly three quarters of species, which is bad in anyone's book. But when compared with the near 100% losses in Northern Hemisphere oceans, a clear selectivity emerges. The southern oceans also seem to have begun to recover from the crisis well before the northern oceans. Jiang and colleagues record the first appearance of