

## CLIMATE SCIENCE

# Asymmetric response

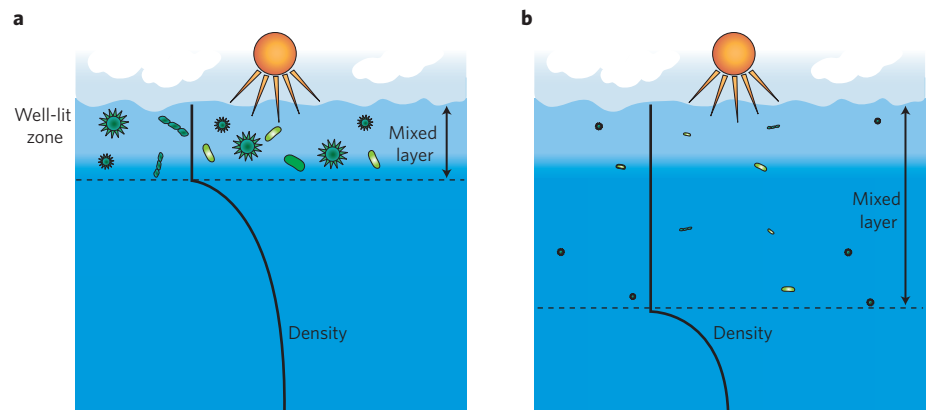
The surface layer of the Southern Ocean connects the atmosphere with the deep subtropical ocean. Ocean observations reveal that the thickness of this layer — important for biological productivity — is controlled by the strength and position of the southern circumpolar winds.

Sarah Gille

**T**he 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<sup>1</sup> 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<sup>2</sup>, 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<sup>3</sup>.

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



**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<sup>1</sup> 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.

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<sup>4</sup>.

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<sup>5</sup>.

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<sup>6</sup> 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.*<sup>1</sup> 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<sup>7</sup> 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<sup>1</sup>.

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<sup>1</sup> 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<sup>3,8</sup>, but they disagree in their estimates of the resulting mixed-layer depths<sup>4</sup>. 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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