OCEAN–ATMOSPHERE COUPLING

Mesoscale eddy effects

Interactions between the ocean and atmosphere are complex. An analysis of satellite data from the Southern Ocean reveals a tight coupling of ocean and atmosphere on horizontal scales of around 100 km that modifies both near-surface winds and ocean circulation.

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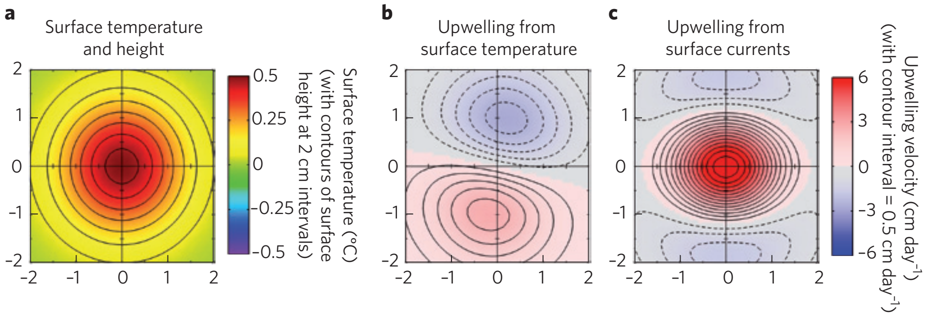

Figure 1 | Vertical ocean velocities induced by an idealized Southern Ocean eddy. **a**,**b**, Mesoscale ocean eddies have distinct patterns of surface temperature and height, with warm temperatures and elevated height at the centre of an anticlockwise-rotating eddy in the Southern Hemisphere (**a**) and vice versa for a clockwise-rotating eddy. Frenger and colleagues[4] show that the temperature patterns alter surface winds, cloud cover and rainfall, which in turn affect the eddies. For example, eastward winds of 10 m $\mathrm{s^{-1}}$ over the idealized eddy in **a** would induce vertical velocities with a dipole structure of downwelling in the northern half of the eddy, and upwelling in the southern half (**b**). **c**, The rotating surface currents associated with the eddies have an even stronger effect on the vertical velocities, in the form of a monopole structure of upwelling centred on the core of the idealized eddy in **a** under eastward winds of 10 m $\mathrm{s^{-1}}$. The signs of the surface temperature and height anomalies in **a** and the upwelling and downwelling patterns in **b** and **c** reverse for clockwise-rotating eddies (adapted with permission from ref. 6).

Because of its enormous heat capacity, the ocean plays a critical role in regulating the Earth's climate. Up to about a decade ago, it was generally believed that, outside the tropics, the ocean responds only passively to atmospheric forcing[1]. However, with the advent of satellite measurements of sea surface temperature and surface winds with resolutions down to about 50 km, it became apparent that the strong gradients in sea surface temperature that are associated with meanders in the Gulf Stream, the California Current and most other ocean currents can directly affect surface winds[1–3]. Writing in *Nature Geoscience*, Frenger *et al.*[4] present evidence of this same coupling between sea surface temperature and wind speed occurring over circular rotating eddies with radii of around 100 km (referred to as mesoscale) that are found throughout the ocean[5].

Over warm ocean regions, the marine atmospheric boundary layer — the lowest level of the atmosphere that is directly influenced by the ocean beneath — is locally heated. Likewise, above colder sea surface temperatures, the marine atmospheric boundary layer cools. As a result, strong gradients in the temperature of the ocean surface, for example where the Gulf Stream carries warm water northwards into a cooler surrounding ocean, affect the atmospheric temperature structure. These changes in atmospheric temperature, in turn, alter turbulent mixing of the air as well as atmospheric pressure anomalies in the boundary layer. Both effects create winds with higher speeds over warmer water and lower speeds over cooler water.

Frenger *et al.*[4] examined atmospheric conditions that are coupled to spatial variations in sea surface temperature, using more than 600,000 satellite observations of mesoscale eddies in the Southern Ocean. To do this, they studied multiple sets of collocated satellite data, consisting of radar altimeter measurements of sea surface height, microwave radiometer measurements of sea surface temperature and radar scatterometer measurements of surface winds. According to their analysis, cool sea surface temperature anomalies associated with cyclonic — that is, clockwise-rotating in the Southern Hemisphere — eddies weaken surface winds, whereas warm anomalies associated with anticyclonic eddies strengthen surface winds. The eddies not only leave a remarkably clear imprint on the surface wind field, but their relatively small-scale anomalies in sea surface temperature also modify low-level clouds and precipitation. The relationships apparently hold throughout the Southern Ocean.

The coupling between mesoscale ocean eddies and atmospheric conditions documented by Frenger *et al.* occurs globally[6], but seems to be restricted to the marine atmospheric boundary layer. Moreover, the eddy-induced perturbations of wind speed, clouds and precipitation amount only to a few per cent of the mean states of these fields. As such, it is unlikely that eddies have much influence on atmospheric circulation above the marine boundary layer, which is where the patterns of weather and climate variability are determined.

There is no doubt, however, that the eddy influence on the overlying atmosphere in turn affects the ocean circulation. Frenger *et al.* mention two such effects. Changes in wind speed and cloud fraction over eddies can dampen the sea surface temperature anomalies in the eddy interior, thus attenuating the eddies. Furthermore, anomalies in sea surface temperatures associated with mesoscale eddies affect the wind stress curl, a measure of lateral shear and rotation of the surface winds that is the key control of vertical velocities in the open ocean.

Vertical water velocities that result from the wind stress curl associated with eddy-induced sea surface temperatures anomalies — such as those identified by Frenger *et al.* from composites of many eddies — consist of a dipole structure: upwelling occurs on one side of the eddy and downwelling on the other (Fig. 1). It is not yet fully understood how this dipole structure affects eddy energetics; however, a numerical simulation found a decrease of about 25% in the kinetic energy of the eddy field[7].

Eddies also influence the curl of the surface stress through their horizontally rotating surface currents, an effect that is even

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stronger than that of gradients in sea surface temperature described by Frenger *et al.* Specifically, what matters for the surface stress that drives vertical velocity is the difference between the wind and the underlying surface ocean currents. At the scale of a rotating eddy, the wind field is almost uniform. Surface currents associated with eddies thus determine the curl of the surface stress and therefore vertical ocean velocities. This results in a monopole of upwelling or downwelling centred on the eddy core (Fig. 1) that is very effective at dampening the eddies[6,8,9], resulting in a decrease of about 50% in their kinetic energy in numerical simulations[10,11]. Current-induced upwelling can also inject deeper ocean nutrients into the upper ocean where photosynthesis occurs, thus influencing ocean biology[6,8,11] and hence the sequestration of atmospheric carbon dioxide by phytoplankton.

Frenger *et al.*[4] have clearly demonstrated the significance of coupling between the ocean and atmosphere over ocean eddies. A critically important aspect of their analysis is the use of simultaneous measurements from three different cloud-penetrating microwave sensors. Close coordination among international space agencies and scientific communities is essential to sustain these Earth-observing satellite missions and thus ensure continued advancement of our physical understanding of the Earth system[12]. ❐

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PALAEONTOLOGY

Extinction promoted fire

The extinction of megafauna in Australia roughly coincided with shifts in vegetation and fire regimes. Sediment geochemistry shows that the vegetation shift followed the extinction, indicating that the loss of browsers promoted fire and altered plant composition.

Beverly Johnson

Throughout much of the Quaternary period, large herbivores roamed the Australian continent. The extinction of many of these megafauna occurred about 44,000 years ago, shortly after humans arrived on the continent[1] and during a period of relatively quiescent climatic conditions[1,2]. At approximately the same time, large-scale changes in vegetation and fire regimes occurred. The links between megafauna extinction, human arrival and environmental changes have proven difficult to unravel. Human activity may have played a key role in the megafauna extinction, either through overhunting or landscape modification with fire, or some combination thereof[2–5]. Others believe climate change may have contributed to the demise of the megafauna[6,7]. Determining the relative timing of these events has been a major challenge to narrowing down cause and effect: the data that underpin the identification of extinction, human arrival and environmental change often come from disparate records, each with their own chronological uncertainties. Writing in *Nature Geoscience*, Lopes dos Santos and colleagues[8] assess the relative timing of changes in climate, vegetation and biomass burning from a single sediment core collected offshore from the Murray-Darling River system.

The arrival of humans in Australia was accompanied by a substantial shift in vegetation and biomass burning[2]. These changes led to the suggestion that human use of fire changed the vegetation regime to one that was more suited to burning; this would have eliminated key nutrient sources for large animals and contributed to their demise. Recent pollen and charcoal records from northeast Australia also show a shift to more fire-prone vegetation following human colonization[5]. However, at this site it seems

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Figure 1 | Fire in the bush. Using a marine sediment core from off the coast of southeast Australia, Lopes dos Santos and colleagues[8] show that changes in vegetation and fire regime occurred 43,000 years ago, after the extinction of the Australian megafauna. They suggest the loss of browsers allowed flammable plant material to build up, promoting biomass burning and a shift to a more fire-tolerant flora.

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