doi:10.1038/nature13048

OCEAN SCIENCE

Eddy effects on biogeochemistry

Ocean eddies tens of kilometres in radius can delineate local ecosystems and contribute to biogeochemical budgets. The characterization of three such eddies in a coastal upwelling region provides insight into these wonders of nature.

AMALA MAHADEVAN

The eastern margins of oceans are exceptional regions. The alongshore winds drive a mean offshore flow of surface water that creates upwelling at the coast (Fig. 1). This draws nutrient-rich, cold water from the deeper layers into the sunlit (euphotic) zone, where it elicits the rapid growth of phytoplankton, resulting in highly biologically productive seas. The alongshore currents are unstable, and shed eddies and filaments of cold water 10–100 kilometres in length, which transport water offshore. These dynamic features affect the primary productivity of the regions, the fate of particulate organic carbon produced by photosynthesis, and the regions' biogeochemical budgets. Writing in *Biogeosciences*, Stramma *et al.*[1] provide a detailed biogeochemical perspective of three such eddies off the coast of Peru.

The eddies surveyed extended several hundred metres in depth and exceeded 100 km in diameter. The authors found that these eddies trapped waters at the time of eddy formation, and propagated westward as biogeochemically anomalous water masses for several months. As the eddies matured, the ecosystems sustained within them modified the properties of the trapped water, consuming nutrients (nitrate and phosphate). However, the ratio of nitrogen to phosphorus in the eddies was lower than is usually seen elsewhere. This suggests that the eddies harbour nitrate-reducing (denitrifying) bacteria typical of low-oxygen environments.

Stramma and colleagues observed a range of characteristics for the individual eddies. The two anticyclonic eddies (those having a rotation opposite to that of Earth) were low in nitrate, a nutrient used by phytoplankton, but high in nitrite — which was possibly produced as an intermediate of denitrification or secreted by phytoplankton[2]. The concentration of chlorophyll beneath the surface 'mixed' layer in these eddies was higher than in surrounding waters, which might indicate that they contribute positively to productivity. There were differences between the two eddies, however: phosphate was much deeper in the older of the pair. One explanation for this is that, as the older eddy propagated westward, some of its nutrients subducted without being consumed by phytoplankton, thereby suppressing productivity in the eddy compared with that of surrounding waters, in which phosphate seems to be more fully used. By contrast, the cyclonic eddy had elevated nitrate levels in its core, but no nitrite or signs of denitrification.

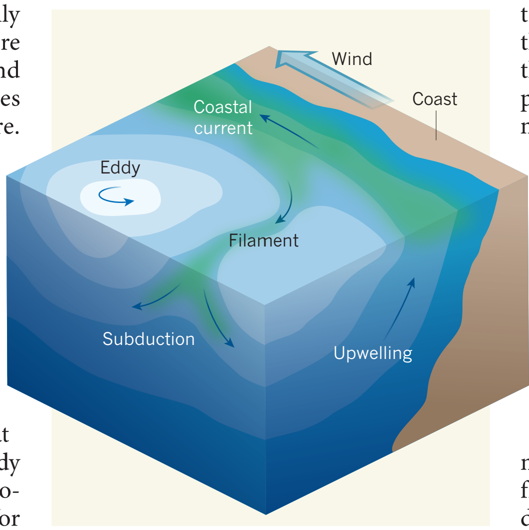

Figure 1 | An eastern upwelling ocean margin in the Southern Hemisphere. Alongshore winds heading towards the Equator transport surface water offshore (not shown) and generate upwelling at the coast. A coastal current, also heading towards the Equator, is created by the contrast in density between cold upwelled water at the coast (darker shades of blue) and warmer surface waters offshore (lighter shades of blue and grey). The upwelled water is nutrient rich and causes phytoplankton (green) to grow close to the surface. The coastal current is unstable and generates eddies, and the denser water that is upwelled nearshore is drawn offshore in filaments. The filament of colder, denser water is connected to (colder) subsurface water of similar density. As it is drawn offshore, downwelling occurs on the inner flanks of the filament, exporting phytoplankton carbon, nutrients and oxygen to the subsurface layers along isopycnals (surfaces of constant density). (Figure adapted from a graphic by M. M. Omand.)

The authors' study reflects a continuing interest in the effects of fronts (boundaries between waters of different density at which currents are intensified) and eddies, which are often formed by the detachment of frontal meanders. Eddies can persist for weeks, harbouring productive ecosystems[3] and generating anomalous biogeochemistry[4]. Fronts are highly dynamic and generate filaments — water streamers that infiltrate from one side of a front to the other and have a different density from their surroundings. Filaments transport cold, dense water offshore in coastal upwelling zones (Fig. 1). Fronts and eddies enhance primary productivity in areas lacking surface nutrients by inducing an upward supply of nutrients into the euphotic layer[5]. But eddies and filaments may reduce biological production[6] in coastal upwelling regions — such as those off Peru — because they contribute to the export (the lateral and downward transport) of phytoplankton-rich waters, whose nutrients are not fully consumed.

The potential suppression of phytoplankton production by eddies and filaments in upwelling ocean margins can be explained as follows. Assuming the existence of a steady state when averaging over time and space over the sunlit layers of an upwelling region, the levels of nutrients consumed by phytoplankton production (P) and nutrients exported (E) are balanced by the levels of nutrients supplied (S) to the upwelling region: $S = P + E$. Thus, if eddies and filaments that have formed from an upwelling front increase E, but do not affect S, which is driven by large-scale coastal upwelling, then P must decrease. If, on the other hand, eddies and fronts increase S, as occurs in subtropical gyres, then they lead to an increase in P.

The high primary productivity in upwelling regions generates particulate organic carbon of various forms. Phytoplankton pass through the food web, resulting in detritus that is heavier than sea water, and sinks. As it sinks, this organic matter decomposes, using up oxygen. At the surface, dissolved oxygen is replenished by photosynthesis and tends to equilibrate with the atmosphere. But at greater depths, eastern upwelling ocean margins are anomalously low in oxygen because the rate of oxygen resupply is insufficient to meet the high demand for organic-matter decomposition.

Eddies and filaments can influence the oxygen supply to these oxygen-poor layers beneath the surface. Filaments cause the subduction of productive phytoplankton-rich surface waters (Fig. 1), but this export of carbon-containing material differs in a crucial way from the sinking of particulate organic carbon. The downwelling water carries with it high levels of oxygen from the surface layer, and thus provides the necessary oxygen for decomposition of the organic carbon. In this way, eddies and filaments support carbon export without placing any demand on the oxygen of subsurface waters. Without the downward transport of oxygen by eddies and filaments, the subsurface waters in upwelling zones would be even more starved of oxygen.

Eddies also have a role in the transport of momentum, heat and mass. The physical structure of eddies off Peru was recently studied using three-dimensional modelling[7], ship-based measurements[8] and satellite observations[8,9], revealing an equal propensity for cyclonic and anticyclonic eddies to develop in this region. The transport of colder waters in the eddy cores made no contribution to the heat budget in the region[8], but whether the transport of nitrogen and carbon by these eddies affects biogeochemical budgets is difficult to assess from the measurements available so far.

The diverse characteristics of the three eddies sampled by Stramma *et al.* show clearly that assessing the integrated contribution of eddies to the primary productivity, carbon export and biogeochemistry of upwelling regions will require a much more statistically complete characterization of properties within eddies, filaments and their surroundings. Sustained time series and autonomous biogeochemical sampling (for example, see ref. 10) are needed, in concert with physical measurements at high resolution in space and time, to capture the episodic transport and biogeochemical transformations that occur in the dynamic and biogeochemically important coastal upwelling margins of the world. ■

Amala Mahadevan *is in the Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA.*
e-mail: amala@whoi.edu

1. Stramma, L., Bange, H. W., Czeschel, R., Lorenzo, A. & Frank, M. *Biogeosciences* **10,** 7293–7306 (2013).
2. Collos, Y. *Mar. Ecol. Prog. Ser.* **171,** 293–301 (1998).
3. McGillicuddy, D. J. Jr *et al. Science* **316,** 1021–1026 (2007).
4. Benitez-Nelson, C. R. & McGillicuddy, D. J. Jr *Deep-Sea Res. II* **55,** 1133–1138 (2008).
5. Mahadevan, A. & Archer, D. *J. Geophys. Res.* **105,** 1209–1225 (2000).
6. Gruber, N. *et al. Nature Geosci.* **4,** 787–792 (2011).
7. Colas, F., McWilliams, J. C., Capet, X. & Kurian, J. *Clim. Dynam.* **39,** 509–529 (2012).
8. Holte, J., Straneo, F., Moffat, C., Weller, R. & Farrar, J. T. *J. Geophys. Res.* **118,** 2295–2309 (2013).
9. Chaigneau, A., Le Texier, M., Eldin, G., Grados, C. & Pizarro, O. *J. Geophys. Res.* **116,** C11025 (2011).
10. Johnson, K. S. *et al. J. Atmos. Oceanic Technol.* **30,** 1854–1866 (2013).