OCEAN CURRENTS AND THEIR IMPACT ON MARINE LIFE

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Keywords: currents, eddies, fronts, gyres, larvae transport, patchiness, physical-biological interactions, rings, tidal currents, upwelling

Contents

Summary

Ocean currents and related processes exert relevant impacts on marine life; the most important of which is their enhancement of primary productivity. This is done mainly through their transport of nutrients back to the euphotic layer from which they continuously leak to deeper waters. The enhancement of primary productivity is frequently transferred along the trophic webs, translating into impacts throughout marine communities. Upwelling systems exert the strongest impacts of this kind. Major upwelling regions are found along the eastern boundary currents, and also occur in many other areas of the World Ocean, where they develop complex circulation features and exert local impacts on marine life. Intense currents and other forces induce the formation of eddies in a wide range of sizes and life spans. Rings, formed by the western boundary currents, are the biggest and longer lasting of these vortexes. As rings move to areas where conditions contrast with the water inside them, they generate large-scale biological patchiness. Depending on their direction of rotation, eddies can produce uplifting or sinking of the water inside them. Cyclonic eddies lift deeper water to the

surface, causing nutrient inputs and enhancement of primary productivity. Anticyclonic eddies produce a sinking of surface water, and therefore cause a local reduction in primary productivity. Nevertheless, anticyclonic eddies can also enhance productivity under certain conditions or generate patchiness through their transport of water and communities. Tidal currents can also enhance primary productivity on the continental shelves through mixing the water column over shallow areas, or through their interaction with islands. Associated with most of these processes and currents, a variety of fronts are frequently developed. In these fronts, diverse mechanisms operate to further enhance productivity and biological patchiness. The main impacts of shallow-sea fronts, shelf-break fronts and upwelling fronts are described. Other relevant impacts of oceanic currents are also presented. Distribution patterns of organisms and their patchiness are related to oceanic flows on a wide range of scales from the turbulence level to the full extent of oceanic basins. Transport of larvae is another important role of ocean currents and processes. Diverse organisms rely on them for the completion of their life cycle, a more efficient exploitation of resources or stocks definition. Their variability is found to be an important component of the ability of ocean currents to impact on marine life. Perspectives and impediments for advance in understanding of physical-biological interactions are briefly discussed.

1. Introduction

One of the most significant differences between the terrestrial and the aquatic environments is that in the latter the medium itself moves. This condition exerts important effects and impacts on the organisms that live in the oceans, of which the most straightforward is that they can be dragged along with water movement. Surprisingly for the non-specialist on marine ecology, the most significant impact of ocean currents on marine life consists of the enhancement of primary productivity, and that is the reason why this article is placed within the Topic *Productivity of the Oceans*.

This is so because primary production in the ocean is limited by availability of light and nutrients. Light is rapidly absorbed by water, so there is enough light for efficient photosynthesis only in the surface of the ocean, within a layer that does not extend below a depth of 150 m; this is called the euphotic zone. Within this layer, primary productivity is limited by nutrients (mainly nitrogen and phosphorous) availability in most of the ocean surface.

As in terrestrial ecosystems, nutrients follow a cycle that, after the assimilation of their mineral forms by primary producers to synthesize organic substances through photosynthesis, moves along the trophic chain. From each of the trophic levels, nutrients are remineralized back through excretion and decay mediated by bacterial action. A significant fraction of decaying organic particles and dead organisms sink regularly out of the surface layer of the ocean and are recycled to the mineral forms in the deep ocean, away from the euphotic zone. This continuos leak of nutrients out of the surface layer is responsible for the nutrient limitation of primary production in the areas of the ocean where replenishing mechanisms do not operate at a similar rate.

This is the case in tropical and mid latitudes and also on temperate latitudes for part of the year. In these areas permanent and/or seasonal pycnoclines (caused mainly by

thermoclines) form a barrier between the surface layer and the deep ocean to where nutrients leak. Because mixing different density layers requires a much higher amount of energy as compared to water of the same density, vertical mixing that operates regularly in high latitudes, where the pycnocline does not form, is hindered in the rest of the ocean.

Ocean currents and processes that cause the injection of deep-water nutrients back to the euphotic zone have therefore an impact on nutrient circulation and the potential of enhancing primary productivity. This is the case for most of the currents and related processes that are described in section 2. These include upwelling systems; gyres, rings and eddies; tidal currents and coastal and oceanic fronts. While each of them will also exert other impacts on marine organisms, they are grouped together in this section because their impact on nutrient circulation and productivity is the most significant to marine life.

Although they are probably more related to other articles in this topic, section 3 describes other relevant impacts of marine currents and related processes on sea organisms. One of them is the creation and maintenance of patchiness in marine organism distributions, particularly planktonic. The other is the transport of larvae of diverse marine groups, and the associated effects on the recruitment and other aspects of their populations.

2. Impacts on nutrient circulation and productivity of the oceans

A complete and detailed explanation of ocean circulation and of the factors governing primary productivity is out of the scope of this article. However, the description of some additional aspects of vertical movements in the ocean, and of the general pattern of events that seems to be required for the occurrence of high primary productivity will be useful for the better understanding of the impacts on primary production of the currents and processes described below.

As mentioned above, the strong density difference between the surface layer and the waters below it restricts vertical movements and water exchange between these two layers. However, in some areas of the surface ocean, water can increase its density and as a consequence sink towards a deeper level. This occurs in the high latitude areas where deep water is formed by seasonal cooling, like in the North Atlantic, and also in areas where seawater salinity increases significantly because evaporation exceeds rainfall, like the Mediterranean and Sargasso Seas.

The opposite does not occur due to the lack of mechanisms in the ocean that reduce the density of deep water and that induce its vertical ascent. Therefore, the ascent of deep water in the ocean only occurs when the energy required to move water of higher density to the lower density surface layer is supplied by an external source. Wind stress, major oceanic currents and tides are some of the energy sources that, through their interaction with the oceanic margins and bottom topography, give way to the diverse processes that involve a vertical flow of nutrients and are described in the following sections.

In the search for understanding the interaction between physical processes and primary productivity, it has been proposed that there is a basic mechanism common to the increase in phytoplankton production, operating under a variety of conditions and different spatial and temporal scales. The essence of this common mechanism is the alternation of nutrient input events to the surface layer followed by the stratification of the surface layer. In this hypothesis, stratification reduces phytoplankton sinking and therefore helps it to remain within the euphotic zone, beyond which light becomes the limiting factor.

Most of the water movements and related processes described below generate the necessary nutrient inputs to the euphotic zone. Some of them may occur as an intermittent temporal pattern, allowing for water stratification during the relaxation periods. In other cases, because they constitute spatial anomalies on a more regular oceanic field, stratification can take place in their surrounding waters.

2.1. Upwelling systems

Upwelling can be defined, in its more simple conception, as the vertical motion of subsurface water towards the ocean surface. Since nutrient concentrations are generally much higher below the surface layer, upwelling processes constitute an important, and probably the most conspicuous, mechanism by which nutrients from the deep ocean are circulated back to the surface ocean. Therefore they play a significant role in nutrient circulation both on the local and global scales. In this last sense, upwelling systems are considered an important component of the global thermohaline circulation of the World Ocean, as they contribute to the return of deep water back to the areas of formation and sinking.

The significance of the vertical transport of water and nutrients involved in upwelling does not lie in the speed and magnitude of the movement. Vertical speeds in most upwelling systems are found in the range of less than one to several tens of meters per day (10^{-3} to 10^{-1} cm s^{-1}, Table 1), while horizontal surface currents in the ocean exhibit speeds several orders of magnitude higher, ranging up to a hundreds thousand meters per day (10^{2} cm s^{-1}). This difference is due to the fact that much more energy is required to transport water vertically than horizontally, because of the increase of water density with depth. Therefore, the significant role of upwelling is in accomplishing the unlikely work of transporting denser water to the lighter surface layer of the ocean.

Upwelling	Vertical speed (cm s^{-1})	Nitrate concentration (μmol L^{-1})	Chlorophyll a concentration (mg m^{-2})	Total Primary productivity (g C m^{-2} d^{-1})	New Primary productivity (g C m^{-2} d^{-1})
Peru Current	3×10^{-2}	25	118	2.8	0.6
California Current	2×10^{-3}	23	154	2.6	1.8
Canary Current	1×10^{-1}	12	106	3.5	2.5
Benguela Current	3×10^{-2}	20	124	1.8	1.1
Equatorial Atlantic	n.d.	10	33	n.d.	n.d.
Equatorial Pacific	n.d.	> 12	n.d.	0.8	0.2
Somalia Coast	n.d.	20	58	2.1	1.9
Yucatan Shelf	4×10^{-2}	10	44	1.3	0.8
Cabo Frío, Brazil	6×10^{-3}	10	27	n.d.	n.d.

Samalga Pass, Alaska	7×10^{-3}	27	70	n.d.	1.8
Costa Rica Dome	1×10^{-4}	29	10	0.3	0.2

n.d. – data not available

Modified from Merino M. (1992) *Afloramiento en la Plataforma de Yucatán: estructura y fertilización*. Ph. D. Dissertation, Posgrado en Ciencias del Mar, UNAM, México, 285 pp.

Table 1. Mean values of some physical and biological parameters of upwelling regions of the World Ocean.

As a consequence, upwelling is also the physical process that most notoriously impacts marine life in the areas where it takes place. The nutrient enrichment of the ocean surface it causes exerts a fertilization effect that is generally translated into a significant increase in primary productivity that is transmitted through the food web. The major areas of upwelling have been recognized for a long time, because most of the more important fisheries of the world are associated with them.

Mean productivity in upwelling areas has been estimated at 300 g C m^{-2} y^{-1}, six times larger than the average calculated for the open ocean. This difference is indicative of the very strong impact that upwelling systems exert on marine life in their area of influence. However, their contribution to global marine productivity is limited to only 5% of the total because upwelling areas represent only 0.1% of the surface ocean.

Because production in upwelling areas is enhanced mainly by the transport of allocthonous, nutrients, production in these systems in mostly new production, as opposed to the open ocean, where production is driven mainly by local nutrient recycling. This difference, as discussed in the previous article, is not minor, since new production is also the fraction of production that the system can export (i.e. that can be extracted from it) continuously, in a sustainable way. That is, besides their magnitude, why upwelling fisheries are so important. In terms of the global cycling of carbon, and its consequences for climate change, the fact that upwelling systems enhance new production is also relevant, because this part of the production is also the core of the biological pump that drives carbon away from the surface layer, into the deep ocean and eventually to the marine sediments.

The impact of upwelling on marine life goes beyond the enhancement of primary production, into the structure of the communities. Upwelling areas exhibit marine communities so different to the ones found in the surrounding areas that they have even been called upwelling ecosystems. The main feature that distinguishes upwelling communities is the length of the trophic chains. In an upwelling, the main trophic chain is generally shorter and simpler, as a consequence of the significantly higher primary production, which tends to reduce the species diversity. The typical trophic chain of an upwelling will included normally only primary producers, herbivores and secondary consumers. This is another feature that favors the existence of important fisheries in these areas, which are frequently based on the herbivore level, like in the case of sardines and anchovies.

2.1.1. Eastern boundary upwelling regions

Upwelling regions are found throughout the World Ocean. Figure 1 shows the location of the better known upwelling systems on earth. However, there are regions where conditions are more favorable for upwelling to take place. Such regions are found on the eastern margins of the oceans.

Two main conditions favor the development and sustaining of upwelling processes on these margins: 1) winds of appropriate strength and direction, and 2) the existence of nutrient-rich water below the pycnocline closer to the surface, and therefore more readily upwelled.

Figure 1. Location of the main upwelling regions in the world ocean. Besides the four western boundary upwelling regions and the equatorial upwelling regions, the existence of other upwelling regions is exemplified with three cases: 1- Yucatan Upwelling, 2 – Brazil Upwelling, 3 – Somalia Upwelling

In these areas, upwelling is driven by what is considered the typical wind-driven upwelling mechanism. Wind blowing across the surface of the sea sets up a stress, which causes water to begin moving in the same direction as the wind.

The Coriolis force, originated by the earth's rotation, soon modifies the direction of the flow, causing the resulting current to deviate to the right in the Northern Hemisphere, and to the left on the Southern. After some time, the net movement of surface water is at a right angle to the wind direction, and this is known as Ekman transport.
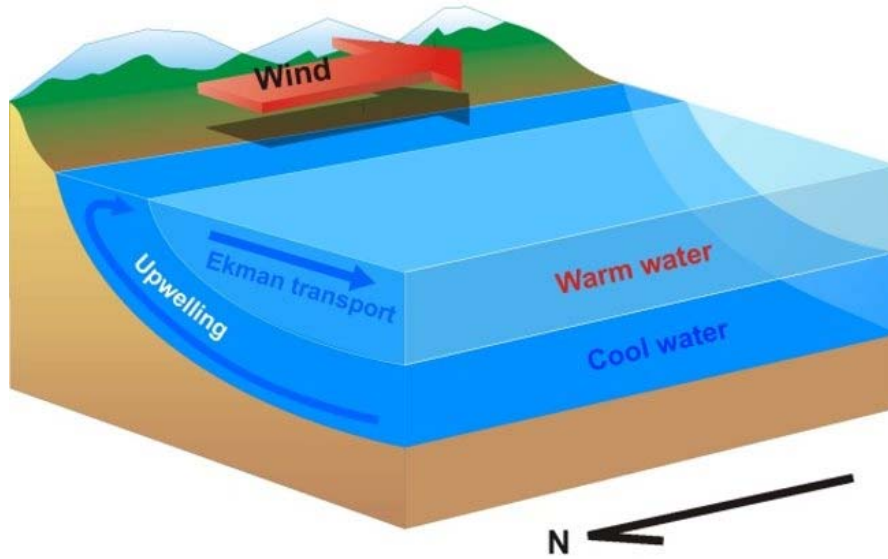
Figure 2. Perspective drawing through an upwelling region in the Northern Hemisphere illustrating the offshore Ekman transport in the upper layer being replaced near the coast by upward moving water from the lower layer.

When the wind blows parallel to the coast and toward the Equator, on an eastern margin of an ocean, the Ekman transport will be directed offshore (Figure 2). The water which replaces the offshore transport cannot be supplied by horizontal flow because of the coastal boundary. Instead, it is upwelled from the deeper layers.

These type of winds blow on a regular basis along the coasts off Oregon and California, and off Peru and Ecuador in the Pacific Ocean, as well as along the coasts off the Western Sahara, Mauritania, Namibia and South Africa. These upwelling systems are generally (except in the case of Peru) named by the eastern boundary current that streams in the area (The Peru Upwelling, the Canary Upwelling, The California Upwelling and the Benguela Upwelling, see Figure 1).

Although these four major upwelling systems share a similar upwelling mechanisms and analogous geographical features, they also exhibit significant variability within and among them. These differences are related mainly to changes in vertical transport. These variations take place both in time and space and are related to wind variations, but also to topographic features such as headlands and canyons.

This variability creates complex patterns of intense upwelling which in the course of time give rise to plumes, jets, squirts and gyres that penetrate varying distances from the coast into the main stream of the boundary current, as shown by satellite images (see Figure 3).
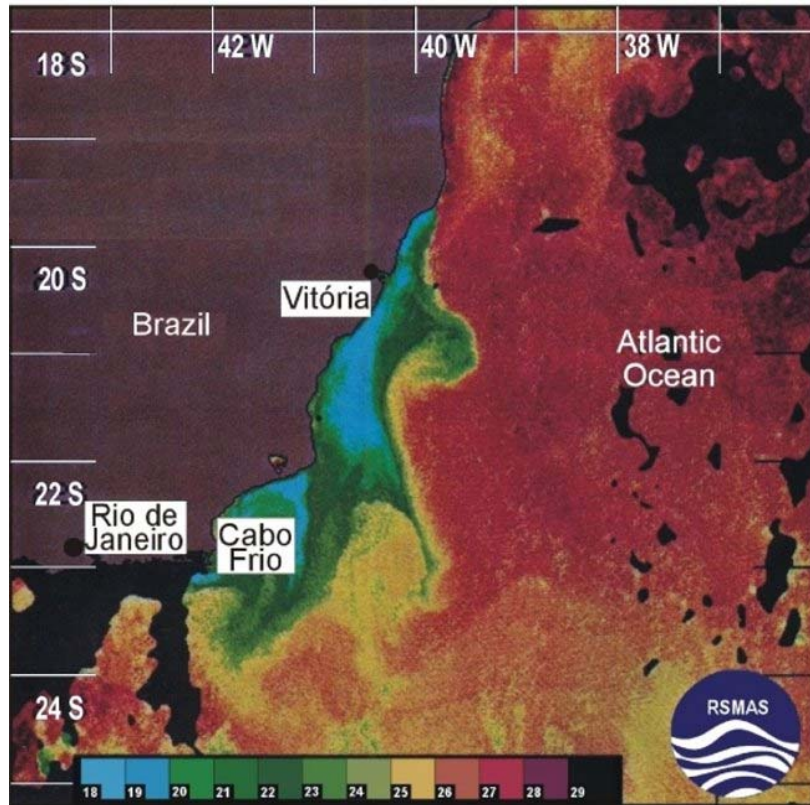
Figure 3. Satellite image of sea surface temperature of the Cabo Frio upwelling off Brazil. Upwelled water is detected by its low temperature (blue and green areas). The Brazil Current runs along the red area. The thermal front created by the upwelling extends southwards in the green to red transition. A cyclonic eddy can be seen forming off Vitória.
Source: Schmid C., Schäfer H., Podestá G. and Zenk W. (1995) The Vitória eddy and its relation to the Brazil Current. *Journal of Physical Oceanography*, 25: 2532-2546. Reprinted by permission.

Time variations related to changes in wind strength are also relevant. Off Peru the process may be continuous more or less year round, but in the California Upwelling it is confined to the summer season, and within this time it may exhibit several events of varying intensity of upwelling. In Northwest Africa, upwelling occurs year-round at Cap Blanc and northwards, but south of this cape, it occurs mainly in winter and spring, because in summer the Azores high-pressure cell that drives the equatorward winds has moved further north. The Benguela upwelling proceeds throughout the four seasons, but shifts its highest intensity from the south (near Luderitz and Cape Town) in the summer, to the north (near Cape Frio) in the winter. The Peru upwelling in turn is known to present important variations at a longer scale, reducing its intensity during the El Niño events.California and Peru upwelling regions share higher nutrient values in the upwelled waters as compared to the two African upwelling systems (see nitrate concentrations in Table 1) because they are located in the Pacific, where the thermohaline circulation has allowed the increase in deep water nutrient concentrations relative to the Atlantic. In contrast, the Atlantic upwelling systems take place in areas where the continental shelf is wider in comparison to the two Pacific upwelling regions, where the shelf width is restricted by the plate subduction that takes place there.

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Biographical Sketches

Martín Merino is a Senior Researcher-Professor at the Marine Ecology Department of the Marine Science and Limnology Institute of the National Autonomous University of Mexico (UNAM). He completed his Ph.D. in Oceanography at UNAM, with an integral study of the Yucatan Upwelling. In 1994, Professor Merino was awarded the National Award for Oceanographic Research. He has worked in a diversity of research lines, including coral reef ecology, seagrass ecology, eutrophication and the dynamics of primary production in marine, coastal and freshwater environments. He has always been interested in the coupling of physical and chemical processes with biological ones, and therefore focuses his studies with an interdisciplinary approach. At present, Professor Merino is the Coordinator of the Marine Science and Limnology Postgraduate Program at UNAM, where he teaches Chemical Oceanography.

María Adela Monreal-Gómez is a Senior Researcher-Professor at the Environmental and Marine Geology Department of the Marine Science and Limnology Institute of the National Autonomous University of Mexico. During her Ph.D. in oceanography, at the University of Liege, Belgium, she worked on barotropic and baroclinic models. She is currently working in physical oceanography mainly on modeling of mesoscale turbulence, cyclonic and anticyclonic eddies. She has worked in interdisciplinary research in the Southern Gulf of Mexico, Gulf of California and Gulf of Tehuantepec. Her interests include baroclinic processes and their impact on biological and chemical properties of the seawater. Professor Monreal teaches Physical Oceanography at the Marine Science and Limnology Postgraduate Program of UNAM.