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Preface

"Deep Ocean Exchange with the Shelf (DOES)"

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1 Introduction

In 2007 the Scientific Committee for Oceanic Research (SCOR) and the International Association for the Physical Sciences of the Ocean (IAPSO) set up working group WG 129 to make recommendations for future research on Deep Ocean Exchanges with the Shelf (DOES). Further details about the members of the working group and its terms of reference may be found on the SCOR web pages at http://www.scor-int.org/Working_Groups/wg129.htm.

The joint WG consisted of physical, chemical and biological oceanographers, including both theoretical and observational experts. Although much of the work of the group was concerned with planning better physical understanding of the shelf break region through new observations and models, an important aim was to include the requirements of chemical and biological oceanographers for output from such models.

The shelf break is a region of steep slopes, strong narrow currents, internal tides, shelf waves and significant vertical motion. Improved understanding of the exchanges between the shelf and the deep ocean will be useful for more realistic models for studying climate, the carbon cycle, sedimentation and marine ecosystems. The increased detail in the improved models often leads to prediction of features that have not yet been observed. This can lead observational oceanographers to include fieldwork in their cruise plans that will either establish the existence of these new features or test the validity of the models.

Even as ocean models become more realistic by having much finer resolution in space and time, there are still significant problems in resolving the high variability that occurs around the shelf break between the deep ocean and continental shelves. Even with the finest resolution ocean models, the shelf region is poorly resolved with only a few grid points. Ocean observers have had difficulty in securing measurements at the edge of the shelf due to the narrowness of the currents and steep slopes. However, new technologies are now enabling measurements in such challenging environments. For example, swath bathymetry gives accurate bottom topography, dynamic positioning of ships allows precise placing of moorings and acoustic Doppler current profilers allow measurements throughout the water column even in strong currents. Towed samplers and gliders are now providing observations, continuous in time and space, in shelf areas and the Ocean Observing System is increasing the ability to observe shelf areas continuously. At the same time, fine-scale (1 km or less) coastal models such as the Regional Ocean Model System (ROMS) with multiple depth layers are now being used to model the movement of water, chemical species and sediments on the shelf, and are being connected to biogeochemical models of the local ecosystem. Meshing these models into larger-scale deep ocean models offers the chance to resolve some of the unknowns.

The exchanges and fluxes that occur near the shelf break in both directions, both on-shelf and off-shelf, are important components of the global ocean circulation. These fluxes include sediments and biomass as well as seawater. Coupled ocean-atmosphere general circulation models require, for example, the input of freshwater outflow from rivers. These inputs are generally added at the location of the river. But, in reality the fresher water flows along the shelf, sometimes for considerable distances, before it crosses the shelf break and enters the deep ocean (for example, along the Oregon coast, as has been modelled by Baptista et al., 2005). Similarly the formation of Antarctic Bottom Water and other dense water masses often occur over continental shelves before they flow offshore. An example of a biological flux is the movement of patches of krill on and off the Antarctic shelf, as described by

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Murphy et al. (2004), while the influence of the local wind field on the Mississippi plume strongly affects the delivery of river-borne nutrients to the Texas-Louisiana shelf and thus the size of the annual “dead zone” (Hetland and DiMarco, 2008).

Strong tidal mixing at the shelf break and over variable topography is an important feature in the energy balance of the Earth’s oceans (see, for example, Jayne and St. Laurent, 2001; Wunsch and Ferrari, 2004). Internal and surface tides are built into shelf models but are usually absent from deep ocean general circulation models. Strong mixing associated with significant topography is an important component in the theories of the global thermohaline circulation. Coastal models often use terrain-following coordinate systems (sometimes called sigma coordinates). Although this method deals better with the changes in shelf slopes compared with models using standard grid boxes, they introduce significant problems due to pressure gradient force error as described in Berntsen and Furnes (2005). A new generation of high-resolution models is under development including for example (i) the Nucleus for European Modelling of the Ocean (NEMO) begun in France but now forming the basis of a wider European project and using interactive nesting (see www.lodyc.jussieu.fr/NEMO/), (ii) the next generation of the Hamburg Shelf Ocean Model (HAMSOM), called the Vector Ocean-Model (VOM), including biological and physical coupling on an unstructured adaptive grid (see Harms et al., 2003), (iii) the Imperial College Ocean Model (ICOM) using an unstructured mesh (see Gorman et al., 2006) and (iv) the Hybrid Coordinate Ocean Model (HYCOM) a data-assimilative hybrid isopycnal-sigma-pressure coordinate ocean model (see Chassignet et al., 2006).

Improved models and observations leading to a better understanding of the processes that occur between the shelf and the deep ocean will be of benefit in maintaining fish stocks and dealing with threats of pollution from oil and gas wells, and for studying river runoff and sedimentation. Since coastal areas are often regions of enhanced primary production due to upwelling, understanding the carbon cycle in such ecosystems is also relevant to climate studies.

The Working Group’s main task was to establish the current state of knowledge and make recommendations for future research related to the following topics:

- processes due to shelf waves, internal tides, shelf break upwelling, storms and extreme events that produce effects over time scales of weeks to one or two years;
- transport over the shelf and shelf break of riverine and estuarine input of sediment and fresh water (this aspect includes the Arctic and Antarctic coastal zones, but does not include investigating the sources of sediment and fresh water on the shelves);
- dissipation of tidal motion along the continental margins on time scales of hours to days;
- the physical controls of chemical and biological fluxes between the shelf and the open ocean that can affect the ecology of such regions; and
- coupled physical-chemical-biological models, generally at local to regional scales, that have a more realistic description of the exchanges at the shelf edge.

2 Meetings

The working group held three meetings. An introductory meeting was held in Perugia at the IUGG general assembly in 2007 to plan the DOES workshop to be held in Cape Town in 2008. The Cape Town workshop consisted of invited lectures, contributed posters and six working sessions to discuss the future work needed to advance understanding of Deep Ocean Exchange with the Shelf through observations and modelling. Some of the lectures presented at the workshop have lead to papers in this special DOES issue of Ocean Science. The final meeting of the working group was held as part of a DOES symposium convened at the Montréal IAPSO meeting in 2009. The other papers in this special DOES issue of Ocean Science come from this Montréal symposium.

3 Recommendations for future DOES research

3.1 Chemical oceanography

While biogeochemists have worked out the basic cycles for important nutrient elements such as nitrogen, phosphorous, silicon, sulphur, and, most importantly, carbon, there is currently enormous interest in how these cycles are changing as a result of man’s activities. The continuing increase in the number of coastal regions affected by eutrophication (Diaz and Rosenberg, 2008) or the changing pH of the ocean as a result of the ever-increasing concentration of atmospheric carbon dioxide (Siegenthaler and Sarmiento, 1993; IPCC, 2007) point to unforeseen results of ongoing anthropogenic activities. For example, the oceans have changed from net sources of inorganic carbon and sulphur into net sinks (MacKenzie, 2010). While the immediate effects of such changes are being felt in the coastal regions, the shelf edge is where the transfer into the deep ocean generally occurs.

The importance of continental margins to general oceanography and in elemental cycling has been recognized recently by a number of books on the subject. Particularly comprehensive are Robinson and Brink (2005, 2006) and Liu et al. (2010). The cross-shelf exchange of inorganic and organic material remains an important, but poorly quantified component of global elemental cycling. For example, both nitrogen and carbon cycling are of significant scientific interest; nitrogen as it is the major limiting nutrient in the ocean and as its delivery to the ocean is undergoing dramatic anthropogenic perturbations, and carbon given the obvious importance of its partitioning between ocean and atmosphere for global climate and ocean acidification. Both elements have large sources and sinks on continental shelves. To what extent these processes affect global ocean inventories depends on the magnitude of shelf-ocean exchange. For instance, Jahnke (2010) has estimated that up to 50% of the biological pump transfer of organic matter is exported to the deep ocean across the shelf break.

Shelf-ocean exchange of material is difficult to quantify observationally. Waldron et al. (2009) in this special volume provide estimates of organic carbon export and sequestration in the southern Benguela upwelling system using three different methods, but their values vary by a factor of 50 depending on the assumptions made. Monteiro (2010) provides a separate series of estimates of the fluxes of different components of the carbon system in the Benguela upwelling system, based on a box model with three horizontal divisions (inner shelf, outer shelf, and slope). His numbers are intermediate compared to those of Waldron et al. (2009). Biogeochemical models that incorporate hydrography, nutrients, and sedimentary throughputs are becoming more useful for quantifying such fluxes (see Sect. 3.4 for further details). Fennel (2010, this volume) discusses nitrogen and carbon cycling over the shelves of the northwestern North Atlantic, finding that in this region the shelves are not much more productive (in terms of export to the deep sea) than the adjacent surface ocean. Similarly, Holt et al. (2009) discuss the off-shelf movement of carbon produced on the shelf and describe how much of this production eventually reaches the deep ocean. They find that about 40% of the carbon produced on the northwest European shelf is exported across the shelf break, and that about half of this eventually crosses the permanent pycnocline into the deep ocean, in rough agreement with Jahnke (2010).

The deep ocean also provides nutrients to the coastal region, primarily through upwelling along the shelf edge. This can be either through wind-driven eastern boundary systems, where nutrient-rich water is upwelled from depths around 200–300 m, or through kinematic upwelling along the inner edge of western boundary currents, such as occurs across the Agulhas Bank south of Africa (Carter and D'Aubrey, 1988). The influence of cross-shelf water transport from the Kuroshio on nutrients and phytoplankton in the East China Sea is looked at by Zhao and Guo (2011).

It is presently unclear whether such nutrient supply processes will be affected if the stratification of the upper ocean is changed through global warming, although the well-known effects of the regular switching between El Niño and La Niña conditions in the tropical and subtropical Pacific suggest they may be. In both eastern and western boundary regions, however, nutrients can be brought onto the shelf from the deep ocean at the same time as carbon and sediments are being transported in the other direction at the surface. Quantification of the relative importance of these processes is of major importance if we are to improve both models and forecasts of future exchange rates. We need to develop "diagnostic" approaches that can use basic parameter fields or climatologies to provide estimates of net fluxes over large regions, as well as models that can forecast potential changes in the fluxes. The idea here is to look for semi-analytical approaches constrained by observations of parameters for which we have relatively good whole-shelf knowledge.

Open research questions: What is the rate of nutrient supply to the shelf from upwelling of deep-water masses? What is the rate at which nutrients and carbon are transported off the shelf? Are coastal upwelling systems sources or sinks of carbon dioxide? Can upwelling and sinking be related to the carbon cycle in the shelf sea "pump"? What is the rate of carbon export from shelves (one of the important fluxes for climate studies)?

3.2 Physical oceanography

The dynamics of internal waves and tides and their role in mixing on shelves and shallow seas are well known (Garrett and Kunze, 2007). Required research includes, for example, measurements on the relationship between internal waves and mixing in various contexts including over the slope, with a slope current, with Mediterranean water or other dense overflows and in the seasonal thermocline. Good bathymetry, salinity, temperature data and fine resolution are needed for modelling. Mixing increases volume exchange in plumes and downflows. It also affects shelf-edge productivity and hence organic matter exchange. Non-hydrostatic models of internal wave generation are required to deal with nonlinear effects.

Tides often dominate the kinetic energy on continental margins. Tidal amplitudes can become huge when near-resonant geometries occur (such as in the Gulf of Maine or around Great Britain), and in this case tidal dissipation keeps the ultimate amplitude from being unbounded (Simpson, 1998). Secondary effects associated with tides can be enormously important. For example, tidal rectification can dominate the mean flow when tides are strong and the bottom slope steep. Also, a combination of tidal frontal advection with vertical mixing is a very efficient means of cross-frontal exchange that can, in turn, explain the biological activity at locations such as Georges Bank. Tidally driven turbulence (including surface-to-bottom mixing) is often overwhelmingly important in estuaries, and in locations with strong tides. The combination of mixing and tidal motions can lead, through several processes, to effective horizontal transports.

While tides themselves are fairly well characterized by models and observations, their dissipation can take place via at least two major pathways: internal wave radiation, or turbulent bottom friction. These two branches, and especially their relative weighting, deserve substantial further research.

In the internal wave case, the actual energy dissipation does not have to occur where the internal tides are generated. In the bottom frictional case, the dissipation and mixing occur at the same location where energy is extracted from the tides. For the internal tide case, can we predict where the actual dissipation (hence tidally driven mixing) will occur? If internal tides propagate shoreward, the mixing energy in shallow water can be very important. Dissipation (mixing) in deeper water, offshore of the shelf, will be less relevant to coastal ocean processes. Internal tides on the west-European shelf are discussed in Huthnance et al. (2009) in this Special Issue of Ocean Science.

Shifts in the seasonal heat cycle, precipitation and the strength of stratification at the shelf break are likely to alter shelf edge exchanges. In particular, the site, times and strength of mixing by breaking internal tides could change, impacting on biochemical rates and processes and ultimately the distribution of shelf edge fisheries. Similarly any shift in wind pattern could affect upwelling and downwelling and subsequently ecosystems and food supply. Hence there is a need to link emerging regional climate predictions to shelf edge processes.

Transport of sediments and fresh waters from the estuaries to the shelf edge across the continental shelf is an important exchange process between the shelf and the deep ocean, that ultimately determines the fluxes of materials important for global studies such as carbon cycling and climate change. For example, in addition to the general cross-shelf circulation, the southeast China seas have many cross-shelf penetrating fronts (CPF) (Yuan et al, 2005), which are large excursions of nearshore oceanic fronts moving offshore at periods from a few days to a few weeks. Analysis of ocean colour satellite images suggests that, on average, 25% of the cloud-clear scenes of the SeaWiFs measurements contain at least one CPF with penetrating distances larger than 50 km (He et al., 2010). The frequent occurrence and the large penetrating distances suggest that the CPFs are an important process of cross-shelf sediment and fresh water transport off the shelf in this region. However, the transport fluxes and the detailed structure of the current associated with the CPFs are not clear at present. Matsuno et al (2009) in this Special Issue is concerned with the Kuroshio exchange with the South and East China Seas, i.e. movement onto the shelf.

The oceanic processes in the marginal seas of China that are responsible for transporting the fluvial sediments and fresh waters across the shelf and the shelf break are also observed over the South Atlantic Bight (SAB) and along the east coast of the Australia. The nonlinear hysteresis of the western boundary current is suggested to be one of the characteristics of the Loop Current in the Gulf of Mexico. The offshore entrainment of coastal waters by the mean flow and the filaments of the western boundary currents are ubiquitous along the SAB shelf and off the east Australia coasts. The cross-shelf transport of the fluvial sediments and fresh waters of the northwestern Pacific Ocean is thus representative of the global Deep Ocean Exchange with Shelf process. In this Special Issue of Ocean Science, Matano et al. (2010) discuss the influence of the Brazil and Malvinas Currents on the southwestern Atlantic shelf circulation.

Open research questions: Can the relationship between internal waves and mixing be measured over the slope and in overflows? How does the balance between boundary layer and internal wave dissipation vary with ambient conditions (e.g., stratification, topography, fronts)? Can we predict for internal waves where the actual dissipation will occur? What are the actual mechanisms generating internal tides? Can the emerging regional predictions of climate change be linked to shelf edge processes? What are the transport fluxes associated with cross-shelf penetrating fronts (CPFs)?

3.3 High latitude oceans

Air-sea-ice interactions over the vast continental margins surrounding Antarctica are an integral component of Earth climate. Their oceanic link to outstanding global change phenomena like sea level rise and variability in the Meridional Overturning Circulation (MOC) hinges on the vigorous cross-slope exchange of water and property fluxes between the deep ocean and the Antarctic shelf regimes. Steady freshening of sub-surface waters during the past few decades has been reported in the Ross Sea, and similar decadal signals are also apparent along the major paths of Antarctic Bottom Water (AABW) outflows in the Australian-Antarctic and southwestern Pacific Basins (Rintoul, 2007). The formation and offshore export of dense AABW near the shelf-break controls the strength of the lower limb of the MOC and also provides a rapid conduit for conveying upper-ocean climate variability to the abyssal ocean. Klinck and Dinniman (2010) in this Special Issue of Ocean Science discuss the exchange across the shelf break at high southern latitudes including a model of the Ross Sea continental shelf.

The characteristics, dynamics and numerical modelling of cross-slope transport of Circumpolar Deep water (CDW) around Antarctica are only poorly understood. The inshore heat-flux is certainly relevant to sea level rise, but is also key to regulating the production of freshwater carried by the Antarctic coastal and slope currents (Whitworth et al.,1998). In the Pacific sector, anomalously large volumes of glacial meltwater generated in the Amundsen Sea are likely to influence the formation and export of local types of AABW farther to the west. Near-freezing and relatively salty Shelf Water forms during the winter in the southern and western Ross Sea. It is slightly modified by mixing and entrainment of ambient waters to form AABW, but sufficiently dense to slip across the shelf break and sink to the bottom of the deep ocean (Gordon et al., 2008). The multiple exports of new deep and bottom waters formed in the Ross Sea and off the Adelie Coast effectively ventilate much of the South Pacific and Indian Oceans (Orsi et al., 2002).

The Arctic Ocean has the broadest shelf in the World Ocean – about 36% of its entire area. The Eurasian shelf is a unique area, with respect to the hydrology and sedimentology, which are affected by the huge amount of riverine input into the shallow Arctic seas and further into the deep ocean. The coastal zone plays an important role because the major transport of fresh water, dissolved and solid material into the Arctic Basin is determined by the riverine discharges. Better understanding of horizontal and vertical fluxes of suspended matter is crucial for the understanding of processes in the Arctic shelf environment.

The horizontal fluxes of freshwater and suspended matter across the shelf can be assessed using current measurements and suspended matter concentrations at different depths. At present, there are very few direct current measurements from over the Arctic shelf. A modelling approach, with the assimilation of the existing observations, may be more productive. Vertical fluxes of suspended matter are controlled by biological factors (Lebedeva and Shushkina, 1994) but they also depend on the shelf water stratification that is determined by the riverine input and wind mixing. Wind forcing determines if the riverine water is transported across or along the shelf. Discharge fronts on the Arctic shelves need special investigation because of the extremely active dynamics and strong impact on exchange between the shelf and deep ocean (Savelieva et al., 2009).

Open research questions: Can the understanding of key dynamical and thermodynamical mechanisms regulating cross-slope exchange around Antarctic margins be improved to reduce the uncertainties in predicting changes in the Antarctic cryosphere, sea level rise and the meridional overturning circulation? Can improved understanding of fluxes of fresh water and suspended matter into the Arctic Ocean be obtained by using models assimilating existing observations?

3.4 Observations and modelling

As stated above, a significant research effort is being applied to the use of adaptive unstructured grids in oceanic modelling. Further development and validation of such models capable of resolving fine resolution shelf edge processes is required. For example, there is a need to test the propagation of shelf waves in these models and the explicit simulation of the break-up of internal tidal waves. A big problem, however, is the lack of suitable observational data for model validation. More at-sea observations of shelf edge processes are needed, with clear targets of data suitable for model validation. The rapidly emerging field of cheap (relative to ship time) autonomous platforms, particularly gliders, needs to be taken advantage of by encouraging modellers and observationalists to begin a dialogue prior to cruise planning.

Persistent upwelling can lead to the formation of eddies and filaments that display quite complex circulation features including two-cell circulation (Mooers et al., 1976) and the enhancement of production by topographic irregularities such as headlands (Haidvogel et al., 1991). The structure of eddies, filaments, coastal jets and undercurrents vary both in time and space since the upwelling that provides the potential energy for their existence is itself dependent on the wind stress, shelf topography, stratification and geographical origin. In this Special Issue Baker-Yeboah et al. (2010) look at water mass exchange in the Benguela current caused by the transformation of Agulhas eddies, and Serra et al. (2010) describe observation and modelling of eddies in the Gulf of Cadiz and their effect on the exchange of volume and salt between shelf and open ocean.

Heating by the atmosphere can also change the stratification in ways that differ depending on the frequency and duration of upwelling winds (Send et al., 1987). The offshore-export of upwelled water and marine biota by filaments and eddies is no less complicated (e.g., Roughan et al., 2006; Biggs et al., 2005). Continued high-resolution numerical and observational studies of filaments and eddies are needed to determine their enhancement of exchanges between shelf and deep ocean.

Shelf-ocean exchange of material is difficult to quantify observationally. Biogeochemical models informed by a rapidly expanding suite of observations are useful tools for quantifying such fluxes. For example, Fennel et al. (2006) described a model-based nitrogen budget for the Middle Atlantic Bight including estimates of the cross-shelf exchange of inorganic and organic nitrogen and Fennel and Wilkin (2009) presented expanded budgets that included organic particulate and inorganic carbon. A gap at present is the role of dissolved organic matter in these budgets.

Priorities for future research should include: continued development of nested regional models that couple physical and biogeochemical processes, development of data assimilation tools that allow biogeochemical models to take advantage of emerging ocean observations, OGCM model development using adaptive unstructured grids to deliver the detail needed for cross shelf break and along shelf break flows and fluxes, the use of autonomous observing systems including gliders (even in canyons), of HF radar, of sediment cores (for research into history of fluxes of material across the shelf including carbon), and of better bathymetry using multibeam surveys (as in near shore areas, bathymetry has a more dominant effect than offshore – particularly important for tides and internal tides). There is also a need for new instrumentation for continuous flux measurements, including sensors for specific ocean parameters.

Open research questions: Can dissolved organic matter and diagenetic processes be included in nested regional models that couple physical and biogeochemical processes? Can data assimilation tools be developed to allow biogeochemical models to take advantage of emerging ocean observations? Can automatic systems like ARGO be developed for the shelf region? Can the important components of filaments and eddies in upwelling areas be determined at regional level by high-resolution numerical and observational studies? Can unstructured grid models be developed to be capable of resolving shelf edge processes? Can suitable observational data be obtained to validate these models? How are shelf waves propagated in an unstructured grid model?

3.5 Topography

Much progress has been made on characterizing upwelling and downwelling regimes over canyons in the last two decades. In the next decade the net effect of canyons on shelf-break exchange needs to be determined. To proceed, the use of careful observations and validated numerical models are needed, including the exchange of tracers (heat, salt and more importantly nutrients, carbon and perhaps sediments) instead of simply water flux. There is a need to complement our knowledge and understanding of the interactions between the different hydrodynamic processes coexisting in submarine canyons. Various interactions have been observed with storm-induced downwelling, along-slope ambient currents, tides, and sediment resuspension, and these generally appear to strengthen the cascading of dense water. However, canyons can also act to funnel deep ocean water onto the shelf, as was observed many years ago at the Cape Canyon near Cape Town (Nelson, 1985: see also Allen and Durrieu de Madron, 2009).

Estimates of cross-shelf fluxes through canyons are made in Allen and Durrieu de Madron (2009) in this Special Issue. However, very few studies have estimated the cross-shelf transport of tracers. The strong biological response observed in the vicinity of canyons (Bosley et al., 2004) supports the presence of strong fluxes. Furthermore, estimates of the net nitrate flux through regions of canyons are large (Hickey and Banas, 2008). More detailed flux estimates for tracer fluxes through canyons are needed to quantify cross-shelf exchange. More field observations of tracer fields would be a large asset for determining these net exchange processes over canyons.

What is the exact contribution of submarine canyons to the overall export of dense shelf water to the ocean interior? The export of dense water through canyons increases the volume transport compared with export over a smooth continental slope because of larger mixing and entrainment of ambient slope waters. Understanding and quantifying mean flows in canyons are difficult and much research remains to be done. Quantifying the mechanisms of enhancement of tidal and internal energy adds another level of complexity. Progress may be possible using models and observational techniques designed for research of mixing over mid-ocean ridges (for example, Thurnherr et al., 2005; Morozov et al., 2010).

What is the real impact of dense water flow on the exchanges of biogeochemical elements from the shelf to the deep basin? Dense shelf water cascading can transport very rapidly, but episodically, large quantities of organic and inorganic, dissolved or particulate matter, originating both from the water column or the sediment. Canyons can be perceived as bypassing zones or accumulation zones. In a few cases, it has been shown that it could fuel the deep ecosystems by transporting labile organic matter. This is believed to occur, for example, off the Mississippi via the Mississippi Canyon (Bianchi et al., 2006).

Open research questions: What is the overall export of dense shelf water to the ocean interior? What is the contribution of submarine canyons to this export? How does episodic cascading of dense shelf water affect deep ecosystems? How does upward pumping of nutrient-rich water affect shelf systems, particularly in oligotrophic regions?

3.6 Physical control on biology

Understanding the links between shelf edge processes and shelf edge/slope ecosystems is important as globally the edges of continental shelves are sites of some of the highest fishing activity. Current paradigms have been generally fairly simplistic, linking upwelling or mixing of nutrients fuelling primary production to zooplankton and then up the food chain to commercial fisheries. This basic story is now looking a lot more subtle and interesting, for instance when the enhanced nitrate supply at the shelf edge shifts the entire structure of the phytoplankton community (e.g., Grantham et al., 2004 and other results from the Californian and Oregon shelves). It is the contrasting make-up of this community, compared to off-shelf and on-shelf populations, rather than the rate at which it grows, that plays the vital role in supporting higher trophic levels. Oceanographers tend to work from turbulence up to the phytoplankton community, and possibly as far as zooplankton. Fisheries scientists tend to start either with basic oceanography (salinity, temperature, chlorophyll) and focus effort from zooplankton/larvae upward to the fish, or work downwards from the fish themselves to phytoplankton. There is a real challenge in mixing these different approaches to get the complete picture.

Exchange between the deep ocean and the shelf can occur through a variety of mechanisms at time scales from days to years and space scales from kilometres to those of basins. There is a need to characterize the relative importance of these mechanisms by region and also by significance to the local biology since some may be dominated by extreme events rather than by events that are more frequent but of smaller amplitude – alternatively, the reverse could hold. One example of the former is the presumed removal of large quantities of fish larvae from the Benguela shelf by a filament captured by an Agulhas ring (Duncombe Rae et al., 1992). Other extreme events such as the passage of typhoons or lesser storms (e.g., on the northwest European shelf, Huthnance et al., 2009) which affect the transportation of fresh water and sediment may also be important to the overall transport of biomass, but should be estimated reasonably well by existing models.

In addition, the significance of the various DOES mechanisms needs to be evaluated in conjunction with the tracer that is being exchanged and its biophysical importance. For example, the upwelling of nutrients is important to shelf phyto/zooplanktonic systems that form food for schools of sardines and other small fish on the shelf. As pointed out by Roughan et al. (2006), there is a paradox in that upwelling along eastern boundaries requires strong wind forcing, but phytoplankton growth requires stability. The planktonic response generally takes several days (Hutchings and Nelson, 1985) and may be temperature dependent (surface warming may need to occur). In this case, the growth scale and residence time of zooplankton on the shelf may also be important. Possibly, the optimal DOES time scale for nutrient upwelling (in terms of zooplankton and sardine growth) need only be short (a week) but frequent (4–5 events per year), although the optimal residence time for zooplankton will generally be somewhat longer depending on their growth rates (Hutchings and Nelson, 1985). One extreme upwelling event may be less important if the planktonic system cannot take advantage of all nutrients during the residence time on the shelf (which may be short). Automatic observing systems like ARGO should be developed for the shelf region to assist in determining the effect of extreme events.

The most important process as regards biology is probably that of cross-shelf transport. Duncombe Rae et al. (1992) is one example from the Benguela; the Global Ocean Ecosystem Dynamics (GLOBEC) program gives many others from regions such as Antarctica, the northwest Pacific and Georges Bank (see the list of publications given at http://www.globec.org for an idea of the scope of this multinational program that ended in 2010). More recently, Roughan et al. (2006) examined how across-shelf structure in velocity and hydrography affect the retention (inshore) and export (offshore) of nutrients, plankton and larvae, in the context of the spatial structure of the coastal currents during wind-driven upwelling and relaxation on the northern Californian Shelf. Similarly, Zhao and Guo (2011) look at the influence of cross-shelf water transport on nutrients and phytoplankton in the East China Sea.

Open research questions: What are the effects of extreme events (like tsunamis and storms) on upwelling and plankton and the food chain? Are these more important than smaller-scale continuous events? Can autonomous, automatic observing systems be developed for use on the shelf in determining the effects of extreme events on the biology of the region?

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