

## **Chapter 2. EASTERN OCEAN BOUNDARIES PAN-REGIONAL OVERVIEW**

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#### **1. Introduction and overall classification of Eastern Boundary regions**

This chapter provides an introductory summary and intercomparison of the dominant physical, biological, geochemical processes and interactions (and their outcomes) along the eastern margins of the Pacific and Atlantic Oceans (Figs. 2.1-2.2). It is based on the much more detailed regional descriptions provided in this volume of *The Sea*, which cover the eastern Pacific in chapters 10 (Peru-Chile: Montecino et al., 2004), 11 (Equatorial East Pacific: Herguera, 2004) and 12 (California Current: Mackas, 2004); and cover the eastern Atlantic in chapters 21 (Benguela: Field and Shillington), 22 (Equatorial East Atlantic: Roy, 2004), 23 (Aristegui et al., 2004), 23a (Bay of Biscay: Lavin et al., 2004), 24 (Celtic Seas: Sharples and Holligan, 2004), and 26 (Norway Sea/Faeroe Islands/Iceland: Gaard et al., 2004). We also draw on a parallel overview of eastern ocean boundary physical processes provided in an earlier volume of *The Sea* (Hill et al., 1998) and a few key syntheses of oceanographic processes in these regions (Ajao and Houghton, 1998; Longhurst 1998; Mann and Lazier 1996; Bakun 1996; Summerhayes et al., 1995; Stabeno et al., 2004). Whereas the previous reviews stressed physical processes, this review stresses biogeochemical processes.

*(Insert figs 2.1 and 2.2 near here)*

The nine eastern ocean boundary regions fall into three sub-groups. Their distinguishing traits are set by large scale gradients in wind-forcing, coastal orientation/bathymetry and seasonality, and also by within group similarities in nutrient supply and food web structure:

- *Eastern Boundary Current mid & low latitude upwelling zones.* The regions in this group (the west coasts of South and North America, SW Africa, and NW Africa/Iberia) include four of the world's five major boundary current upwelling systems (the Peru-Chile, California, Benguela and Canary Current Systems). They are distinctively characterized by (in addition to wind-driven upwelling and high productivity of plankton and pelagic fish), strong alongshore advection, a poleward undercurrent, seaward extension of the boundary current and biological system beyond the continental shelf, physical forcing by both local winds and by larger scale teleconnections, and very low to moderate precipitation and coastal freshwater inputs.
- *Equatorial.* The two regions in this group (Equatorial Africa and Central America) are characterized by wet and warm climates. They include or adjoin the Inter-tropical Convergence Zone (ITCZ), and are strongly affected by the ITCZ throughout the year. Alongshore advection is again strong. Physical forcing by local winds is intense at some locations, but is probably of less overall importance to the entire regions than external forcing caused by variation in the strength and location of zonal winds and currents in the large-scale equatorial Atlantic and Pacific, including the influence of Kelvin and low-latitude Rossby waves.
- *High latitude, poleward surface flow and downwelling.* These regions include southern Chile in the southern hemisphere (there is no equivalent region off Africa), and in the northern hemisphere the Pacific coast of Alaska and Canada north of ~52°N, the Bay of Biscay, the "Celtic Seas" and the Norwegian Sea/Faeroe/Iceland regions off European coasts of the Atlantic. All have relatively large inputs of freshwater from precipitation and coastal discharge, large seasonal ranges of temperature, wind mixing, and productivity, and stormy winter conditions. A fresh, poleward coastal current is present off Norway, Chile and Canada/Alaska, and large inland seas adjoin each region. In contrast to the other regions, the Celtic Seas have weak advective throughput and much of the region is shallow. The dominant physical process in the Celtic Seas region is tidal mixing, the secondary dominant is episodic response to mid-latitude storms. The Bay of Biscay also has strong tidal mixing, but is deeper and has moderately strong alongshore flow (counter-flows of the offshore and slope/shelf currents), and considerable exchange with the Iberian upwelling region. The Iceland, Faeroe, Norway region has intermediate large scale advection, forced by exchange between the warm Atlantic and the cold Norwegian Sea and Arctic. Retentive circulation cells develop seasonally around both Iceland and the Faeroes. Ice cover is absent, but plankton and fish community structure suggest similarities and linkages to the Atlantic Polar regions, and to the Celtic Sea region. The three inland seas are being used for an expanding salmon farming industry.

There are differences between the Atlantic and Pacific eastern ocean margins (Table 1). The most important of these are consequences of the narrower Atlantic basin (and the resultant greater land-influence on the Atlantic), plus the "older" sub-pycnocline water in the Pacific, resulting in higher concentrations of macronutrients and lower concentrations of dissolved oxygen. The Atlantic coastal boundary also both starts and ends about 15° further north than the Pacific (Figs. 2.1-2.2), with a more direct connection to the Arctic Ocean than found in the North Pacific, but

lacking a high-latitude region in the Southern Hemisphere, similar to the inland sea regions of southern Chile, Alaska and Norway.

**[Insert Table 1 near here]**

Despite these between-region differences several research issues and oceanographic mechanisms are important in all or most of the eastern ocean boundary regions. Examples include:

- Mechanisms and rates of nutrient supply, and differences in these mechanisms and rates between macronutrients (N, P, Si) vs. micronutrients (Fe, Cu, ....)
- Within-region zonation of habitat utilization – ‘hotspots’ of high productivity and abundance, spawning centers, nursery grounds.
- Strong variability at interannual to decadal time scales. This variability is expressed at all levels of the system: currents and water properties, plankton productivity, biomass and species composition, and commercially-harvested fish stocks.
- Important (and potentially informative) between- and within-region contrasts in seasonal and event-scale timing and sequencing of key processes, especially relative phasing of nutrient supply, advection, mixing, and somatic and reproductive growth of biota.
- The role of topographic complexity: islands, capes, canyons and shelf-edge irregularities produce important and recurrent perturbations of distribution fields.
- The ‘export’ and ‘leakage’ of nutrients, biomass, and reproductive propagules from these strongly advective systems.
- The degree to which evolved life history strategies or behavioral adaptations may amplify or damp the response of population levels to differing modes of environmental variability at differing time scales.
- Occurrence and consequences of hypoxia for denitrification, changes in benthic ecosystem community structure and preservation of paleoceanographic time series in sediments.
- The effects of oxygen minimum layers on animal behavior and distributions in the upper ocean, including limitations on diel vertical migration.

## **2. Temporal scales and geographic controls on forcing and response**

The reviews by Hill et al. (1998) and Brink (2004) provide a thorough survey of the processes at work in eastern ocean boundaries. Here we discuss processes in terms of their time scales and the interactions between those scales, in keeping with this volume’s theme of ‘multiscale processes and their interactions.’ The emphasis of this section is on annual and shorter time scales, i.e., seasonal, intraseasonal, synoptic and diurnal scales. Interannual and longer time scales are considered in Section 6.

The most important fields of physical forcing consist of horizontal and vertical transports of different water properties by advection and mixing. For coastal ecosystems, these forcing fields translate into fields of nutrient supply; amount and “packaging” of primary, secondary, and higher trophic level biological productivity; sedimentation and export. Fields of surface heating and fresh water input are also important, due to their influence on vertical density stratification, which reduces vertical mixing. Limited mixing in the pycnocline, in turn, results in the typical vertical distribution of nutrients, which are depleted in the upper mixed layer and euphotic zone (where there is enough light for photosynthesis) and abundant below the pycnocline. Within this context,

the vertical advection of nutrients during upwelling is the most biologically important process in most of these systems. However, processes that raise and lower the pycnoline-nutricline (even without mixing) also affect primary productivity in coastal regions. Where oxygen minimum layers (OML) are present, vertical movements of their boundaries likewise affect the vertical distributions of animal populations. Changes in water properties caused by horizontal advection have other effects as well, such as altering the habitat in ways that favor different predators, providing top-down control on the ecosystem.

On all time scales, the fields of physical forcing on marine ecosystems are strongly influenced by fixed geographic controls. This is especially true of the annual and diurnal scales, due to differential heating of land and ocean by changes in solar radiation with annual and diurnal periods. The most important geographic controls include major overlying atmospheric circulation features (low and high pressure systems; storm tracks; and the ITCZ), continental margin geomorphology (shelf width and depth, coastline orientation, capes and embayments), tidal resonance and mixing, coastline influences on the prevailing wind speed and direction, latitudinal gradients in the magnitude of the Coriolis parameter  $f$ , and coastal freshwater discharge. Several key geographic characteristics of the eastern ocean boundary regions are summarized in Table 2, while Table 3 presents aspects of temporal variability on annual and shorter time scales. Note that the one-word or one-phrase characterizations in these and other tables are obvious simplifications; they are meant to provide a useful starting point in comparisons of the regions.

**[Insert Tables 2 and 3 near here]**

### *2.1 Annual time scales*

For the four eastern boundary current upwelling (EBCU) systems, the dominant modes of physical variability at annual time scales are the intensity and variability of alongshore wind stress,  $\tau$ , the efficiency with which unit  $\tau$  is converted to Ekman transport ( $\tau/\rho f$ ), and the divergence of Ekman transport. The strongest equatorward wind stress occurs in spring-summer in mid-latitude bands (Hill et al., 1998) between approximately 32°-37°S in the Peru-Chile Current system, 35°-42°N in the California Current system, 25°-30°S in the Benguela Current system and 20°-27°N in the Canary Current system. Closer to the equator in the Peru-Chile Current system, the persistent wind combines with small  $f$  to produce large vertically-integrated Ekman transports per unit  $\tau$ . The result is a strong upwelling response to a relatively weak secondary maximum in wind-forcing located between 10°-17°S off Peru (Bakun, 1996).

**[Insert Figs. 2.3 and 2.4 (each full page) near here]**

Broad-scale seasonal variations in phytoplankton productivity and biomass are closely associated with these alongshore variations in wind-driven upwelling. Figs 2.3 and 2.4 present average satellite-derived phytoplankton pigment concentrations and distributions during winter and summer seasons in each EBCU region. These show the development of well-defined regions of high pigment concentrations next to the coast in summer, along with summer decreases in pigment concentrations in the deep ocean regions, far from the coast. The low offshore values are due to the increased stratification and nutrient depletion during summer, which occur where there are no mechanisms for mixing or advecting nutrients up through the pycnocline into the surface layer or for raising the pycnocline-nutricline into the euphotic zone. During winter, pigment

concentrations increase slightly in offshore regions, as wind-driven mixing increases nutrient concentrations at the surface. The figures also indicate regions where coastal phytoplankton pigment concentrations increase and expand offshore in winter, such as the low latitude regions of the Canary and Benguela Currents.

Figs. 2.5 and 2.6 provide another view of phytoplankton response to wind forcing along the eastern boundaries. These present monthly mean offshore Ekman transports and surface pigment concentrations in a 100 km band next to the coast, as functions of time and latitude, covering the period from September 1997 to March 2004. The combination of these time-latitude plots and the maps in Figs. 2.3 and 2.4 illustrates the temporal and spatial variability of the forcing and response, including seasonal and interannual variability. The plots of wind-forced Ekman transports also demonstrate the latitudinal progression of maximum wind-driven upwelling, from low to high-latitudes. Winter maxima in upwelling forcing at low latitudes off Peru and NW Africa are caused by the movement of the ITCZ, which migrates north (July) and south (January). This produces maxima in offshore Ekman transport in austral winter (May-September) off the low latitude Peruvian coast and in boreal winter (January-April) off the low-latitude North Africa coast. The seasonal dates of these upwelling maxima in each hemisphere progress from winter at low latitudes to spring-summer at mid-latitudes, where the mid-latitude high pressure systems dominate the weather patterns and create the bands of upwelling-favorable wind stress described above. In the northern regions of the mid-latitudes, downwelling-favorable winds in winter storms produce extremes in the range of seasonal forcing (strong upwelling in summer, strong downwelling in winter). At high latitudes, downwelling is year-round, with wind stresses reaching maxima due to synoptic storms in winter, controlled by regional low pressure systems.

**[Insert Figs. 2.5 and 2.6 near here]**

The correspondence of summer maxima of upwelling forcing and pigment concentrations in the mid-latitude systems is well represented in Figures 2.5 and 2.6. In the equatorial regions, the winter increase in upwelling forcing and pigment concentrations along the low latitude (10°-20°N) Canary Current is also clear in Fig. 2.5. A late-winter maximum is found between 10°-15°S in the Benguela (Fig. 2.6), as expected from Fig. 2.4. Between 15°-25°S, however, the pigment concentration patterns in the northern Benguela are less consistent: winter maxima in pigment concentrations appear near 20°S in 1998-2000, followed by relative winter minima in 2001-2002. The high-pigment region in Fig. 2.4 may be wider during winter in those years, but more diffuse over the 100 km band next to the coast, leading to relative minima. The most surprising result is along Peru (Fig. 2.6), where the upwelling forcing is maximum in austral winter but the mean pigment concentrations in the 100 km next to the coast are maximum in austral summer. The winter map in Fig. 2.3 does not indicate a wider, more diffuse maximum in pigment concentrations in winter, leaving the temporal mismatch between wind-forcing and phytoplankton response on annual scales off Peru unexplained at this time.

Two low-latitude zonal coasts with strong annual variability are not shown in figures 2.3-2.6: the zonal southern coast of North Africa, forming the northern boundary of the Gulf of Guinea; and the zonal northern coast of Ecuador and Colombia, forming the southern boundary of the Panama Bight. When the ITCZ in each basin moves north in boreal summer, trade winds are deflected toward the east over both coasts, producing upwelling-favorable winds along the Gulf of Guinea coast and downwelling-favorable winds along the northern coast of South America. Boreal

summer is the major upwelling season in the coastal Gulf of Guinea, although fluctuations in SST are not correlated with fluctuations in the strength of the winds. This is thought to be due to the influence of CTWs (Roy, 2004). Along the northern coasts of Ecuador and Colombia, the eastward winds combine with strong freshwater discharge to create the eastward Colombia Current, a shallow feature (in the upper 100 m) with currents reported to be as large as  $1 \text{ m s}^{-1}$  (Stevensen, 1970; Strub et al., 1998). Neither of these zonal coasts has been well-studied over the past several decades.

In the high-latitude eastern boundary regions, the main geographic/topographic influences on annual scales include strong seasonality of insolation, wind speed and precipitation in synoptic storms, and stratification-convection (shared by all regions); exposure to cross-basin currents, tidal currents and mixing on the continental shelves (highly variable among regions); and the amount, location and seasonality of coastal freshwater inputs (also variable). Southern Chile, Canada/Alaska, the Norwegian coast, and Iceland are the most homologous, sharing relatively narrow continental shelves offshore of their inland seas and strong salinity stratification plus alongshore buoyancy-driven currents fed by freshwater inputs on their outer coasts and/or from rivers draining into adjoining inland seas. Annual forcing in the Bay of Biscay includes summer wind-driven upwelling, giving it some similarity to the Iberian region.

A final point concerning annual time scales involves regions with an apparent lack in seasonal wind forcing. In the SE and NE Pacific and the NE Atlantic, there are regions between the tropics and mid-latitudes where wind magnitudes and their seasonal changes are weak. These are found where the coastline produces a large “bight” (the Southern California Bight, the region of zonal coastline off southern Peru, the region between the Iberian Peninsula and NW Africa). However, seasonal changes in solar radiation in these areas produce strong summer increases in stratification and SST, which provide important spawning habitat for pelagic fish (Lasker, 1981). Thus they do not lack seasonal cycles in conditions that play an important role in coastal ecosystems. In the Benguela Current, where there is not a similar “bight,” the Agulhas Bank along the southern coast of Africa plays the same role in providing sheltered, stratified ocean habitat, favorable for spawning, (Shillington, 1998; Field and Shillington, this volume).

## *2.2 Intraseasonal Variability*

Two general processes contribute energy to the coastal ocean circulation on scales of 30-60 days: CTWs generated by winds along the equator or equatorward of an observation point; and slowly evolving meanders, filaments and eddies in alongshore currents. Meanders and filaments are usually generated “locally” by instabilities in an alongshore jet (which may also be enhanced by passing CTWs). Eddies may be the result of continued evolution of local instabilities in alongshore jets or may come from distant sources.

CTWs with time scales of 30-60 days have been described in most detail off the coast of northern Chile, including their influence on the coastal ecosystems. These are generated along the equator, as far away as the dateline. Their characteristic “50-day” time scale is attributed to the period of Madden-Julian oscillations in the equatorial winds (Shaffer et al., 1997; Pizarro et al., 2001). These have been observed in coastal tide gauge SSH records along the equator and the coasts of Ecuador, Peru and Chile, as well as in currents measured at moorings along north-central Chile (Shaffer et al., 1997; Hormazabal et al., 2004). Analyses of these data and of the fields generated by simple models depict the process whereby Kelvin waves travel along the equatorial wave

guide, reach the coast of Ecuador and propagate south along the coast of Peru and northern Chile, where they may initiate Rossby waves that carry energy westward, into the open South Pacific (Vega et al., 2003). The biologically important aspect of these waves is their role in changing the MLD, i.e., in raising and lowering the pycnocline-nutricline-oxycline, over periods of 30-60 days.

Intraseasonal time scales at fixed locations along the outer shelf and upper slope may also be caused by slowly varying meanders and eddies in coastal jets. These have been studied extensively in the California Current (Mackas, 2004), where they appear to originate as upwelling-front jets, move offshore and develop instabilities, creating complex fields of “mesoscale” variability (Ikeda and Emery, 1984; Brink and Cowles, 1991; Kelly et al., 1998; Hormazabal et al., 2004). The causes and consequences of this variability have recently been topics of active research in all of the EBCUs. The largest cold-core filaments and the most intense eddies are broadly coincident with zones of maximal alongshore wind stress, but are also associated with coastal capes/headlands in all regions. Their initial development each season is tied to the onset of upwelling forcing, at least in the California Current (Strub and James, 2000). Once the jet and mesoscale system moves offshore of the shelf, however, it is less responsive to direct wind forcing and evolves over the summer and fall with time scales of weeks to months and length scales of several hundred kilometers. Interactions between the mesoscale fields of currents and water properties and the biological populations extend through all trophic levels of the coastal ecosystem over a large-scale region that extends hundreds of kilometers alongshore and 100-200 km offshore (Batchelder et al., 2002; Barth et al., 2004, and other references in the same volume). Off Northwest Africa, the filaments interact with the Canary Islands (Barton, 1998; Aristegui et al., 2004), adding additional complexity to the fields.

Besides mesoscale eddies and features that are generated “locally,” coastal regions along eastern boundaries may be affected by eddies generated elsewhere, that move into the region and impact the outer shelf. A well-known example occurs in the Benguela Current, where anticyclonic rings shed by the Agulhas Retroflexion sometimes move northward and interact with the upwelling system, pulling filaments over 1000 km offshore of SW Africa (Shillington, 1998; Field and Shillington, 2004). Another region where this occurs on a regular basis is in the Gulf of Alaska. Anticyclonic eddies created along the eastern boundary of the basin propagate westward (Crawford, 2002), carrying populations of species from the continental margin (Mackas and Galbraith, 2002). Those generated in the NE part of the basin, travel along the shelf-slope to the west, interacting with the outer part of the wide shelf by pulling richer water off the shelf and around the eddy (Stabeno et al., 2004), as seen in satellite derived fields of surface pigment concentrations (Fig. 2.7). Similar anticyclonic eddies have been seen in winter off the northern California Current. Whether they are present in other high latitude EBCs is not known. The importance of these rings to the coastal ecosystem is in their potential to remove a significant proportion of a population of larval fish or zooplankton from the shelf and carry it to the deep ocean, in the same way that the eddy in the Gulf of Alaska is seen extracting phytoplankton-rich water from the shelf (Fig. 2.7).

**[Insert figure 2.7 near here]**

### *2.3 Synoptic Variability*

At the mid- and high-latitudes in winter, passing storms force the coastal ocean with strong downwelling-favorable winds with periods of 2-10 days. The ocean responds quickly close to the

coast, where winds, waves and currents combine to resuspend and redistribute sediment and passive components of the ecosystem. The high SSH fields that are forced by these winds oppose the equatorward currents and cause poleward surface currents in the higher-latitude regions of the California, Canary and Peru-Chile Currents. Over the course of the winter, these storms deepen the upper mixed layer and mix nutrients into the surface, establishing conditions favorable for phytoplankton blooms in spring.

Another process creates synoptic variability in winds at mid-latitudes along coasts where the atmospheric marine boundary layer (MBL) intersects a coastal mountain range (the California, Peru-Chile and Benguela Current systems). There atmospheric low pressure systems are generated next to the coast and propagate poleward as internal waves in the atmosphere, on the top of the MBL. As they pass a given location, these atmospheric “coastal lows” produce enhancements and relaxations in the upwelling-favorable winds, with synoptic time scales. They also generate poleward propagating CTWs in the ocean with periods of 3-10 days. Both the fluctuations in the upwelling strength and the CTWs affect coastal ecosystems by changing the MLD and associated nutricline and oxycline, as discussed in Rutllant and Montecino (2002) and Montecino et al. (2004).

Strong localized upwelling also occurs on synoptic time scales in the eastern tropical North Pacific, due to a process unique to this region. In boreal winter, while the ITCZ is at its southern extreme, pressure gradients drive wind jets through three narrow gaps in the Central American mountains (Herguera, 2004; Chelton et al., 2000). The intense wind stress in each jet moves the surface water directly offshore (unlike typical wind-driven Ekman transport), causing upwelling and generating dipole eddies in the surface ocean on either side of the jet. As described by McCreary et al. (1989), the cyclonic eddy is quickly damped, leaving the anticyclonic eddies to propagate westward. These eddies are persistent and strong enough to be tracked with altimetry, as they move to the west. Seasonal mean fields from satellites depict clear trails of low SST and high pigment concentrations to the west of each of the three major wind jets, evidence that they have a significant effect on MLD and marine ecosystems off western Central America.

#### *2.4 Diurnal Variability*

The most common processes operating on diurnal and semi-diurnal time scales are the tides, including both external and internal tides. Tidal currents and mixing dominate the shallow and wide continental shelf areas of the Celtic Sea, and are also very important in the Bay of Biscay, and around the Faeroe Islands. Tidally-driven currents and mixing are also intense in localized parts of the inland seas, where topography constricts the currents. In the deep, open regions of the inland seas, however, tidal currents may be only moderate to mild. For instance in northern parts of the Chilean Inland Sea, however, measurements show tidal currents of only  $0.05\text{-}0.10\text{ m s}^{-1}$  (Valle-Levinson et al., 2001; Caceres et al., 2003). Internal tides are created by the interaction of external tides and topography where the water column is stratified. They are more complex and quickly lose the narrow band periodicity of the external tides, due to their internal dynamics. They often take the form of internal bores, which may aid in the onshore transport of larvae (Pineda, 1999, Pineda and Lopez, 2002).

The diurnal cycle in solar radiation produces several effects on this time scale, including changes in upper ocean stratification, peak primary production during the day, and vertical migrations of zooplankton and fish (to escape the light and predators; or to find prey). Diurnal changes in

radiation also causes heating and cooling of the land and creates a “sea breeze” effect that includes alternating day- and night-time pressure perturbations. Thermal lows develop over the land in afternoon, which enhance the equatorward winds, while the thermal highs that develop in the night oppose and reduce those winds. The result is an alternation of enhanced (decreased) upwelling-favorable winds in late afternoon (early morning), over distances of tens of kilometers from the coast. Offshore of that, the winds driven by the larger-scale pressure systems are not affected. By decreasing and increasing the winds at the coast, a diurnal cycle of wind stress curl is created, which is superimposed on the upwelling caused by Ekman transport.

### *2.5 Interactions between processes with multiple scales*

Interactions between processes with different time scales can produce effects that would not be expected from any one process. Along the coasts of Peru and Chile, the traditional assumption is that the nutricline is depressed during El Niño periods, producing low primary production (PP<sub>r</sub>) and integrated Chl-a concentrations. The opposite is expected during La Niña conditions. However, many observations along the coast of Chile do not show this effect. Montecino et al. (2004) and Rutllant and Montecino (2002) point out that the overall depth of the nutricline is created by the superposition of signals from ENSO, the seasonal cycle, intraseasonal CTWs and synoptic upwelling events. Off northern Chile, the seasonal cycle in winds and MLD is weak, leaving the balance between interannual, intraseasonal and synoptic forcing. The classic picture (Barber and Chavez, 1983) is that synoptic or seasonal upwelling continues during El Niño periods but brings up nutrient-poor water. However, the addition of intraseasonal (“50-day”) fluctuations in the MLD changes the balance, especially if the intraseasonal CTWs become stronger during El Niño periods, as argued by Shaffer et al. (1997). If local, wind-driven upwelling continues with synoptic periods, then during the part of each intraseasonal fluctuation when the nutricline is shallow, synoptic upwelling will be able to bring nutrients into the euphotic zone and enhance primary productivity, despite the El Niño effect. Montecino et al. (2004) give further details of the effects of this interaction.

Equatorial Kelvin waves also interact with locally forced upwelling along the zonally oriented coast of the Gulf of Guinea, where the northward movement of the ITCZ in boreal summer (June-August) exposes the coast to upwelling favorable SE trade winds. At the same time, the region also responds to Kelvin waves that propagate eastward along the equator and then poleward and westward along the Guinea coast. The fact that local winds are not well-correlated with SST fields is attributed to the influence of distantly generated CTWs, at least during boreal summer (Roy, 2004).

On longer time scales, El Niño signals also interact with the annual cycles of winds, currents and SSH in the eastern North and South Pacific. Strub and James (2002) used altimeter data to follow the high SSH associated with the strong 1997-98 El Niño as it moved from the equator to mid-latitudes in each hemisphere of the eastern Pacific Ocean. The equatorial signal consisted of two periods of high SSH: May-July and October-December 1997. The first is during boreal summer and the second is during austral spring-summer. Each signal propagated into both hemispheres, but the signal moving into the summer hemisphere was attenuated and delayed. Strub and James (2002) hypothesize that this was due to the ambient equatorward winds and currents associated with the seasonal cycles in each hemisphere, providing the mechanisms for this interaction between annual and interannual time scales.

Although less well known, there are also analogs to ENSO signals with annual scales. These appear to be stronger in the eastern South Atlantic and to interact with the effects of locally wind-driven upwelling on synoptic and seasonal time scales. The forcing for this annual signal in SSH is provided by the movement of the ITCZ and the relaxation of trade winds over the equator in boreal winter. This results in the collapse of the cold tongue in austral spring and summer, at which time warmer SST and higher SSH signals move to the east along the equator, with some poleward propagation and generation of westward off-equatorial Rossby waves. Since these dynamics are similar to those associated with the ENSO cycle, they have been referred to as an “annual ENSO” or “annual El Niño (Tozuka and Yamagata, 2003; Schouten et al., 2004). The communication of this annual signal in SSH and poleward currents to mid-latitude regions is simpler and more direct off western South America and South Africa (less convoluted coastal pathways, neither NECC nor ITCZ along the path) (Strub et al., 1995; Schouten et al., 2004). The rise in SSH along western South Africa in austral spring appears particularly strong in the altimeter seasonal cycles of SSH and is also reproduced by global models of the ocean circulation (Schouten et al., 2004). However, details of the effects on mid-latitude coastal ecosystems remain to be investigated.

The interaction of multiple time scales can also involve life history strategies and behavior, as illustrated by an example from the Benguela Current, in which behavior with a diurnal time scale interacts with currents with synoptic-to-seasonal time scales (Field and Shillington, 2004). Various zooplankton and larval fish engage in diel vertical migration (DVM), rising to the surface at night and descending into the darker regions during the day. The usual explanation is that this allows the animals to feed during the night and hide from predators during the day. It has also been recognized for some time, however, that this diurnal behavior interacts with the seasonal patterns of currents in a way that helps to retain the animals at a given latitude and distance offshore (e.g. Peterson et al., 1979; Peterson, 1998; Barange and Pillar, 1992). In the night the surface currents carry the animals offshore and equatorward, while the currents beneath the Ekman layer carry them back poleward and onshore during the day. The DVM behavior increases during the late stages of development in some zooplankton and in anchovy larvae, providing a mechanism for not only maintaining position, but for moving onshore to more suitable “nursery” regions for spawning. This has been demonstrated by an individual based model of anchovy larvae, embedded in a coastal ocean circulation model (Parada et al., 2003). Without DVM behavior, anchovy eggs and larvae are advected from the Agulhas Bank to the region off the west coast, but do not reach the inshore spawning regions. The addition of DVM behavior provides the mechanism for the later larval forms to move onshore.

### **3. Water column enrichment, aggregation and retention processes**

Bakun (1996) argued convincingly that marine systems with very high productivity of upper trophic levels have three key interacting requirements. They have high nutrient input and primary productivity (bottom-up enrichment), but must also have physically-mediated features/mechanisms that concentrate food resources (aggregation), and that allow weakly swimming organisms/life stages to avoid advective washout before they can complete their life cycle (retention). This section discusses how, and how well, the requirements described by the “Bakun Triad” are met in the different eastern boundary regions.

#### *3.1. Nutrient input and primary productivity*

It is well known that primary productivity and phytoplankton biomass are highest at locations/time periods which bring together adequate intensity of light and adequate supply of macro- and micronutrients. At any given levels of nutrient, light, and phytoplankton biomass, photosynthetic reaction rates are also higher at higher temperature (see e.g. Behrenfield and Falkowski, 1997). Light supply to the sea surface and heating rate of the water column are functions of latitude, season and cloud cover; sub-surface light intensity is a steep negative exponential function of depth and transmittance of the overlying water column. Supply of inorganic nutrients is dependent on transport/mixing from high concentration sources – either terrestrial or remineralized and accumulated in deeper layers of the water column and at the seabed. For the macronutrients (N, P, and to a lesser degree Si) vertical supply from deeper layers dominates in the open ocean and along most of the eastern ocean boundaries. Inputs from land and sediments are relatively more important for micronutrients such as iron, in the eastern Gulf of Guinea, and within some coastal estuaries. The factors controlling vertical exchange of water and nutrients are described in Tables 2 and 4. An additional factor controlling rate of nutrient supply is the concentration of nutrient in the deep source water. Poleward undercurrents with very high nutrient (and low dissolved oxygen) flow along the continental slope or outer shelf in many eastern boundary regions. These provide a deep but in some instances important source for upwelled water. Because their flow is counter to the equatorward surface flow in the EBCU regions, they also act as a nutrient trap, especially off Peru (Montecino et al., 2004). Table 4 summarizes the relative magnitudes of nutrient sources and exchange mechanisms, plus estimates of resulting rates of primary productivity. Between-region comparison of the productivity rate estimates should however be done with caution – they are probably reliable to about a factor of two. *In situ* incubation measurements have high variance due to real spatial and temporal patchiness, and also to differences in methodology. Estimates based on remotely-sensed surface ocean color are sensitive to assumptions about depth distribution of the phytoplankton and the presence/absence of light scattering and absorption by things other than phytoplankton pigments. All of the physical processes leading to nutrient enrichment were discussed in much greater detail by Hill et al. (1998). Since the date of that review paper, there has been an increased research focus on three-dimensional mesoscale spatial structure, and on interactions between different time scales of forcing and response (for examples, see individual regional chapters in this volume).

**[Insert Table 4 here]**

All methodologies and indices agree that the highest annual nutrient supply and primary productivity are in the EBCU regions. Within this group, the ranking is less certain. Recent estimates suggest that the highest phytoplankton productivity and biomass per unit area are in the Peru-Chile or Benguela systems, closely followed by the Canary Current, and more distantly by the California Current and Iberian systems. Cross-shore extent of the zone of high phytoplankton biomass is largest for the Canary and Benguela Systems (Figs 2.3 and 2.4). Using SeaWiFS data from the first 2 years of its mission, Carr (2002) calculated highest productivity per unit area in the Benguela, followed by Peru-Chile system, and highest total production (rate x surface area) in the Benguela followed by the Canary system. However, interannual variability of wind forcing and pycnocline depth are large in these systems. The initial estimates from the SeaWiFS and OCTS satellite sensors used in Carr's analysis include the strong 1997-1998 El Niño event, during which the intensity and spatial extent of the high chlorophyll zone (in the surface waters seen by the satellites) were reduced along the Pacific margin. Figs 2.5 and 2.6 show time series of

upwelling intensity and average pigment concentration vs latitude for a longer time period (1997-early 2004). Note the post-1998 upward trends of Ekman transport and average pigment content in both the California Current and Peru-Chile Current systems. Note also how strongly the within-region seasonal and alongshore variability of seaward Ekman transport maps onto the average surface biomass patterns, and also the differences in seasonal timing of the upwelling maximum (discussed also in Section 2).

Despite the importance of wind-driven upwelling, there are additional important nutrient enrichment mechanisms in the EBCUs. Near bottom onshore flow occurs along the axis of submarine canyons, and also at the shelf edge in many systems. Tilting of density surfaces along the axis of strong surface geostrophic flows produces upward displacement of the pycnocline on one side of the strong current. This up-doming by filaments, meanders and eddies are thought to be particularly important for offshore parts of the boundary current regions – see e.g. the reviews of eddy/filament/wake phenomena in Aristegui et al. (2004) and Mackas (2004). Winter vertical mixing adds an important nutrient input to northern/offshore parts of the California Current system, off the Iberian Peninsula, and to the Agulhas Bank region off the southeast tip of South Africa (Field and Shillington, 2004). Mixing/entrainment of deep nutrient-rich water into the persistent estuarine discharge from Juan de Fuca Strait is the dominant nutrient supply to the southern British Columbia continental margin.

The high latitude eastern boundary regions can be sub-classified into three intergrading groups based on the seasonal timing and persistence of nutrient input and phytoplankton response. In the first group (Iceland, Norway, and to lesser degree the Bay of Biscay and the Faeroes), much/most of the annual macronutrient input is provided by winter mixing and convection, either locally or in “upstream” areas of currents approaching from the deep ocean. Most of the over-winter input is utilized (and depleted) during an intense but brief spring phytoplankton bloom. There may be an additional fall bloom in calm periods following pycnocline erosion by transient storm events in early autumn. In a second group (e.g. large parts of the inner Celtic Sea shelf, Faeroe shelf, east margin of the Bay of Biscay, and a shallow nearshore band in other regions), friction of strong tidal currents over shallow bottom prevents stratification (Simpson 1997) and provides ongoing nutrient replenishment from the underlying water column and seabed. Elevated primary productivity persists until either the entire water column is depleted of nutrients, or until light levels decline in late autumn. The frontal boundaries between tidally mixed and stratified water are especially productive (Sharpley and Holligan 2004). Prolongation of nutrient input into the summer season is also provided by a variety of other physical processes including the geostrophic “up-doming” in mesoscale eddies and alongshore jets mentioned above, flow up submarine canyons, and estuarine entrainment. Several of these have been shown to be important in the Alaska Current system (Stabeno et al. 2004).

In both equatorial regions, input of nutrients by nearshore wind-driven upwelling occurs seasonally in some locations, and ~year-round by divergence and up-doming within the equatorial cold tongues. Riverine input of nutrients is important along the African coast and perhaps off Panama but small elsewhere (Longhurst 1998). Estimates of primary productivity within the two equatorial regions vary widely, both spatially within each region, and among methods and investigators. For the Gulf of Guinea, Roy (2004) quotes an overall annual average of  $150 \text{ gC m}^{-2} \text{ y}^{-1}$ . Ocean color data suggest much higher productivity, especially nearshore (e.g.  $\sim 300\text{-}500 \text{ gC m}^{-2} \text{ y}^{-1}$  in Longhurst 1998 and Behrenfeld and Falkowski 1997), but remote sensing

estimates may include upward bias from riverine sediment and colored dissolved organic matter (CDOM). For the equatorial Pacific, Herguera (2004) reports local estimates ranging from  $<0.05 \text{ gC m}^{-2} \text{ d}^{-1}$  (in the most oligotrophic Eastern Tropical Pacific coastal waters) to about  $1.5 \text{ gC m}^{-2} \text{ d}^{-1}$  (during winter in the Gulf of California; and seaward of the three wind jet regions off central America).

### *3.2 Aggregation and retention/dispersal features*

Strong spatial patchiness of prey abundance/biomass and targeting of prey aggregations by predators (including humans) is characteristic of eastern ocean boundary regions. The most studied examples (Table 5) include the thin layers of high microplankton abundance that are often associated with the pycnocline in density-stratified regions, and tubular zones of high biomass abundance that extend along frontal zones and bathymetric edges

#### **[Insert Table 5 here ]**

Also common are life history and behavioral strategies that allow organisms to enter a zone of low or reverse advective transport. This is sometimes done for a portion of each day (usually by diel vertical migration), and sometimes only before a critical or especially vulnerable time period within the life cycle (either by horizontal migration or ontogenetic changes in depth preference). Retention features (usually larger and more persistent than aggregation foci) include

- features locked to particular shoreline or bathymetric locations (alongshore fronts, eddies on banks; lee zones behind capes and islands),
- offshore eddies that advect/propagate but retain water & organisms within them as they move,
- vertical and horizontal shear zones

Dispersal features/processes can also be ecologically important in eastern boundary regions, either as an advective loss term that must be endured, as a mechanism to colonize new habitat, or as a way to “hitch a ride” from spawning site to nursery ground to juvenile growth habitat.

Examples include

- upwelling plumes & filaments,
- sustained and rapid alongshore advection
- seaward/shoreward propagating eddies & their entrainment of adjoining water

Within the regions covered in this review, most of the research on biological mechanisms leading to aggregation, retention, and dispersal has been done in the Benguela, California Current systems and in the European coastal regions. Research on mesoscale eddies and filaments has been especially active in the Iberian, Canary, California, and Alaska Current systems. One significant latitudinal contrast is that the stronger and more persistent coastal-origin eddies and meanders are cyclonic in mid-latitudes, but anticyclonic in the high latitude downwelling regions. Eddies generated by tropical wind jets are initially dipoles, although the cyclonic eddy is quickly damped. Offshore eddies of both signs impinge on adjoining coastal regions and entrain coastal water around their margin. The example in Fig 2.7 discussed previously is from the Alaska continental margin. It shows three eddies, in different stages of development. The youngest eddy is in the southeast of the image ( $56^{\circ}\text{N}$ ,  $141^{\circ}\text{W}$ ) and contains a relatively uniform chlorophyll

maximum. The eddy in the center of the figure (58°N, 146°W) was initially formed in March along the northeast margin of the Gulf, so is 3-4 months old. Higher pigment concentrations are found around the outer ring of the eddy and in its center. The oldest eddy is barely visible in the southwest (56°N, 149°W). The patch of high pigment concentration is still visible in its center, along with higher pigment concentrations along its northern boundary, where it appears to be still extracting richer water from the shelf. In this part of the North Pacific, clear-sky days and complete SeaWiFS images are rare. This makes the altimeter maps especially valuable as a weather-insensitive tool for identifying and tracking eddies (or other time variable geostrophic flow features), and for directing ship-based sampling effort within them.

#### 4. Food web characteristics

Despite the diversity of environmental conditions among the different eastern boundary regions, there are several interesting recurring patterns in food web “structural” characteristics such as the dominance of pelagic vs demersal consumers and fisheries, cell/body size and coarse-taxonomic-level community structure in both plankton and fish, and dominant life history strategy (generation length and presence/absence of ontogenetic migration/dormancy).

In all regions, a “microbial loop” is present in the plankton (consisting of heterotrophic bacteria, very small photosynthetic autotrophs, and unicellular microzooplankton). However it is overlaid and often seasonally dominated by a “traditional” plankton food web consisting of medium-to-large photosynthetic autotrophs (diatoms and/or photosynthetic dinoflagellates) grazed by metazoan (often crustacean) herbivores.

##### 4.1 Equatorial regions

- In the Equatorial boundary regions, seasonal diatom blooms occur where there is episodic high nutrient supply, and a large fraction of the bloom production sinks without being grazed by zooplankton. The wind-jet upwelling cells are primarily exploited by phytoplankton in the 5-20 $\mu$  size range. At other locations, and in general outside the season of nutrient enrichment, the size spectrum of phytoplankton is shifted to smaller cell/body size, and to a greater fractional flow through the microbial loop. Mesozooplankton body size is usually smaller than at higher latitudes, and warm temperatures allow many zooplankton taxa to have fast development rates and short generation lengths. There is a general low synchrony of zooplankton reproduction and development, although in the Gulf of Guinea an important exception to this rule is the large copepod *Calanoides carinatus*, which enters dormancy at the end of the upwelling season (Longhurst 1998).
- Fisheries are diverse and include many long-range migratory species (e.g. tunas). But there is a larger biomass of and fishery on resident “small pelagic” fish species. Decadal variability in the small pelagic stocks is large.
- Coral reefs are few and small compared to tropical western ocean boundary regions and the Indo-Pacific islands, whereas coastal mangrove forests are common

##### 4.2 Eastern Boundary Current Upwelling systems:

Homology of community structure is especially striking among the EBCU regions. The list below is a brief summary of the typical dominant taxa (and their occasional but recurrent alternatives). More detail and explanation of upwelling zone food webs is available in an excellent review by Hutchings et al. (1995)

- Biomass and primary productivity by medium-to-large cell size diatoms is high, especially within a band of vigorous upwelling, next to the coast. Many species have cosmopolitan distributions. Diatoms are less dominant in offshore parts of the system.
- Patterns of productivity and consumption are leaky and time/space-lagged: the diatoms bloom after and downstream from the peak nutrient injection; herbivorous zooplankton often have their maximum biomass after and downstream from the phytoplankton maximum. Larger predators such as fish, squid, seabirds and whales “move in” rather than bloom, targeting prey aggregation foci (Batchelder et al., 2002).
- Mesozooplankton biomass is usually dominated by a few species of medium and large copepods, one or two euphausiid species, and one or two chaetognaths. Behavioral and life history adaptations favoring “retention” are common. Alternative biomass dominants among the “herbivorous” zooplankton include pteropods, salps, and doliolids (all able to feed on a very wide range of food particle sizes).
- Nearshore benthic species with meroplanktonic larvae often rely on shoreward frontal displacement associated with upwelling relaxation as a mechanism to return to settlement sites.
- The time scale of upwelling variability, and the transport velocities/distances associated with this variability are important determinants of recruitment success.
- There is often a pronounced “wasp-waist” (e.g. Cury et al., 2004) in diversity of biomass and energy flow at the size/trophic level of small pelagic fishes (anchovies, sardines). Much of the total productivity that gets past the microbial loop is channeled through a small number of species at this “wasp-waist.” Diversity is higher at trophic levels both above and below this.
- The “wasp-waist” species very often have localized spawning and nursery areas within the larger system, and also tend to have life spans short relative to decadal environmental variability. One consequence is that a 3-5 year sequence with persistent good or poor recruitment produces enormous changes in the stock size.
- Hake are dominant resident predators, supplemented by migratory fishes (jack mackerels and tunas) that enter the system to feed, but spend part of their life offshore.
- Benthic macrofauna populations can be very rich, but can be excluded/killed by water column hypoxia.

#### 4.3 High latitude/downwelling regions:

- Primary productivity varies seasonally in amount and size spectrum, using nutrients supplied primarily by vertical mixing and/or winter convection, but supplemented in summer by deep cross-shelf advection and raised isopycnals in eddies. A spring bloom of diatoms occurs in all regions, a fall bloom in some. Dinoflagellate-dominated harmful algal blooms are common during the summer. “White-tide” blooms of coccolithophorids are less common but striking when they occur (and perhaps important to atmosphere-ocean CO<sub>2</sub> flux).
- The dominant mesozooplankton are large calanoid copepods. Spring season dominants have life history strategies that are strongly synchronized with the average seasonal cycle, but this produces a potential for timing match-mismatch if the onset of seasonal stratification and the spring phytoplankton bloom is a few weeks early or late. There is also often a summer transition in surface layer species composition, with other genera (usually smaller body size, often producing benthic resting eggs, e.g. *Centropages* and *Temora*) becoming abundant after the spring dominants enter dormancy.

- Downwelling Ekman transport, and bathymetric steering of alongshore currents aid cross-shore retention, but seaward leakage occurs due to eddies and instability of the strong alongshore buoyancy currents.
- The fish community is relatively more dominated by long-lived demersal species, feeding at higher trophic level. Characteristic pelagic fishes include resident herrings and migratory salmonids.

## 5. Geochemical and climate feedbacks

Compared to the open ocean basins, the surface layers of ocean boundary regions have large exchanges with the adjoining continents, high rates of biological transformations, and often enhanced vertical/horizontal exchange with the deep ocean (via water column advection, sedimentation, and downslope movement in the benthic boundary layer and as bedload/slumps/turbidity flows). This means that their relative geochemical importance is far greater than suggested by their surface area. Several topics have received significant research effort.

### [Insert Table 6 in this section]

#### 5.1 Sedimentation and deposition rates and locations

Globally, large rivers are the primary source of terrestrial sediment input. Relatively few of these occur along the eastern margins of the oceans. The main source is the Congo River in central Africa (annual discharge  $\sim 10^{12}$  m<sup>3</sup>). Smaller but locally-significant inputs occur off Alaska, Chile and Norway (a few big rivers plus many fast, steep gradient smaller rivers, some with high sediment loads due to glacial erosion), and at the northern end of the California Current (Columbia River). Wind-borne dust input is large off NW Africa.

Flux and deposition patterns of marine-origin sediment result from a complex interdependence among local bloom and grazing dynamics, water column advection, resuspension/near-bottom advection, and slope/canyon slumps and turbidity currents (see e.g. Jahnke 2004). Final deposition and burial is more commonly over the continental slope than on the shelf, but important exceptions include parts of the Benguela and Gulf of Guinea systems.

#### 5.2 Hypoxia and denitrification

The eastern boundaries of the Pacific and Atlantic Oceans include two of the three major regions of natural hypoxia that impinge on the continental margins of the global ocean (Helly and Levin, 2004). These are the eastern Pacific (60°N - 40°S) and the southeast Atlantic (0° - 35°S) Oceans (the third and largest is the northern boundary of the Indian Ocean). In these systems are found oxygen minimum layers (OML), defined as layers within which dissolved oxygen concentrations are less than some criterion (often  $< 0.5$  or  $0.2$  ml l<sup>-1</sup>). In the Pacific, the top of the OML is as shallow as 200m from the surface in the Gulf of Alaska (at the shelf break), 500m in the California Current (off the shelf and part way down the slope), 0-100m off Central America (on the shelf), 200m at the equator, 0-100m (upper slope and shelf) off Peru and northern Chile (5° - 22°S) and 100-200m off Chile between 20° - 37°S (on the upper slope). In the southeast Atlantic, the top of the OML is below 200m off Angola, rising to near the surface off Namibia and dropping to 100-200m off South Africa. Thus, within the context of eastern boundaries, the OML is most important for the regions off Central America, South America and western South Africa. Where dissolved oxygen concentrations drop below  $0.2$  ml l<sup>-1</sup>, denitrification by anaerobic bacteria reduces nitrate to nitrite and eventually to elemental nitrogen, resulting in a “nitrate

deficit” compared to Redfield ratios. This can be used to trace the poleward undercurrents in these regions, even after oxygen concentrations return to more normal values. A more complete discussion of oxygen minima and their biochemical interactions is found in Naqvi et al. (2004).

The presence of the OML over the upper slope or shelf has several effects on the coastal ecosystem. For zooplankton and fish, it serves as a vertical barrier and limits the normal pattern of diel vertical migration. Under conditions of strong upwelling or La Niña, the OML rises to cover the entire shelf, causing die-offs of zooplankton, benthic invertebrates and bottom fish. Species adapted to the hypoxic conditions (*Thioploca* and *Beggiatoa*) expand their range at that time, and actually help to detoxify the sediments of acid H<sub>2</sub>S (Arntz et al., 1991). During strong downwelling and El Niño events, the top of the OMZ is depressed, increasing the range and biomass of some species, exposing usually-hypoxic regions of the bottom to oxygenated water and benthic species that increase bioturbation in the sediment layers (e.g. review by Levin, 2003).

### 5.3 Atmosphere ocean CO<sub>2</sub> exchange

Atmospheric carbon dioxide concentrations are rising rapidly due to burning of fossil fuels and other anthropogenic effects. However, there is considerable evidence that the oceans are at present a net sink, and are therefore moderating the rate of atmospheric increase. Ducklow and McAllister (2004) provide a detailed assessment of recent estimates of CO<sub>2</sub> exchange between the atmosphere and coastal ocean, and their underlying methods and assumptions. An important physical “source” term (decreased solubility due to warming of upwelled/upmixed deep water with high CO<sub>2</sub> content) and important biological “sink” terms (drawdown by “new” primary production followed by sinking and downward advection of particulate and dissolved organic matter) are both often large in eastern ocean boundary upwelling regions. A physical sink term (winter chilling and sinking of surface water) is large in high latitudes if lack of salinity stratification allows deep convection. The net exchange in each region is the time/space integral of these large and competing fluxes. Results are very dependent on the time resolution of measurements, and the phasing of the physical and biological processes. At present, the clearest results are that the NE Atlantic shelf regions are net sinks, and most of the low latitude upwelling regions are net sources (e.g. Torres et al., 2002, for northern Chile).

## 6. Temporal variability at interannual and longer time scales

All of the eastern ocean boundary regions are now known to exhibit large and persistent deviations from their local seasonal climatologies of both physics and biology/geochemistry. However, there are between- and within-region differences in their dominant time scale(s) and in the specific physical indices/processes that appear to be the most important drivers of ecosystem response. It is clear that, at least for higher trophic levels, fishery harvest rate and anthropogenic habitat alteration can and do cause some of these major changes. However, paleoceanographic studies have also demonstrated that large changes occurred at decade-to-century time scales long before there were large human impacts.

It is common and convenient to separate multiyear anomalies into three time scales, based on the persistence of the anomalies:

- “interannual” variability in which the deviations from the norm last 1-2 years (although they may be separated by longer time spans),
- “decadal fluctuations” (a.k.a “regime shifts”) in which the sign of the smoothed anomaly time series remains the same for time periods ranging from several years to a few decades, and

- “persistent trends” plus ~century-time-scale fluctuations (these are obviously difficult to differentiate based on time series shorter than several centuries)

### 6.1 *Interannual*

The dominant oceanic signal at the interannual time scale is El Niño/La Niña. However, the amplitude coefficient is widely variable from region to region –largest in the Pacific and generally larger nearer the equator. The ENSO phenomenon has been studied intensively; Chavez (2004) and Strub et al. (1998) provide useful reviews of present knowledge. The basic physical mechanism is that weakening of zonal wind stress in the equatorial Pacific allows the prevailing westward currents to slow, divergence to weaken, and the surface layer to warm by up to several degrees. The thermocline also deepens, and the resulting bulge(s) of warm water propagate eastward as equatorial Kelvin waves until they strike the coast of the Americas, and then poleward as coastal-trapped waves (“oceanic teleconnections”). This progression is readily followed in temperature anomaly and sea-surface elevation patterns (e.g. Strub and James 2002). The large changes in heat distribution also produce global-scale changes in weather patterns (“atmospheric teleconnections”). Effects along the eastern margin of the Pacific include higher air and water temperatures, higher precipitation in the dry subtropical regions, and lowered productivity/biomass, mostly due to “capping” of upwelling by a thicker, and more stratified, oxygenated, and nutrient-depleted surface layer (Barber and Chavez 1983). There are often severe consequences for growth, survival, and reproduction of fish, seabirds, and marine mammals. At mid- and high- latitudes, the strength of the El Niño signal is positively, but rather weakly, correlated to the strength of the initial equatorial signal (Wooster and Fluharty 1985). However, as described by Montecino et al. (2004) for northern Chile, ENSO effects in coastal regions can be offset by fluctuations in the nutricline caused by intraseasonal CTWs, making the relationship between El Niño conditions and productivity more complex.

ENSO effects are weaker in the Atlantic, but include warming after a 3-6 month lag, and weakening of the Atlantic trade winds (see Arístegui et al.; Field and Shillington). There is also a somewhat similar “warming/ Kelvin wave” phenomenon that is initiated in the equatorial Atlantic that has been termed “Benguela Niño”. Time between these events is longer (~ 10 years) than the typical gap between Pacific-origin Los Niños (~5-7 years).

### 6.2 *Decadal regimes*

During the past 10-15 years, there has been an ever-increasing awareness and interest in ocean variability patterns that persist for ~5-20 years. Within this range of time scales, there is some evidence that changes, when they occur, are rather abrupt (step-like), are correlated in timing among “physical” and “biological” indices and across very large spatial separations, and involve qualitative restructuring of biological communities as well as variations in total productivity and geochemical flux. All of these characteristics have invited comparisons with switching behavior in non-linear control systems, and a collective labelling as “regime shifts”. Interestingly, “biology” based indices appear to have a larger fraction of their total variance at these decadal scales (e.g. Hare and Mantua, 2000). Several different physical climatic forcing patterns can be identified at this approximate time scale, each with different amplitude time series, and different spatial correlation patterns (the Pacific Decadal Oscillation [PDO], the North Atlantic Oscillation [NAO] and the Arctic Oscillation [AO]). The main contrasts in relative strength of each mode are between Atlantic vs. Pacific and between high vs. low latitudes (however, note the circularity of this argument – the indices and the sea-surface temperature and atmospheric pressure patterns

they describe are also based on climate anomaly comparisons within the Atlantic or Pacific or between equator vs. polar). Whether or not ocean climate variability is step-like is currently hotly contested.

Decadal variability of climate and biology is presently one of the hottest topics in marine science. Several key papers (e.g. Bakun, 2004; deYoung et al., 2004; Collie et al., 2004) have recently reviewed in detail the topic of regime shifts in marine ecosystems. Based on the above characteristics, Bakun has proposed the following definition: “*a persistent radical shift in typical levels of abundance or productivity of multiple important components of the marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent.*” This is explicit enough to be useful, without prejudging the “shape” of transitions, and their chain of causation.

There are a number of eastern ocean boundary examples that fit this definition. Long time series are needed to carry out an effective analysis. A problem in deciphering how and why changes occur is that the longest series (weather, fish catch) are at opposite ends of the probable chain of causation. Perhaps the most influential suite of examples has been the evidence for duration and phase matching of fluctuations in sardine and anchovy populations within the Boundary Current Upwelling and Equatorial regions (e.g. Schwartzlose et al. 1999). Rapid changes in abundance and/or distribution of boundary current small pelagics occurred in several regions during the mid-late 1950s, mid 1970s, late 1980s-early 1990s. Zooplankton biomass and community composition data from the California Current system suggest similar timing (Mackas, 2004). In the Gulf of Guinea, sardine (*Sardinella aurita*) collapsed during the early 1970s, and biomass of triggerfish (*Balistes capricus*) became very high, but this situation reversed during to mid 1980s. Higher latitude regions provide many fisheries examples of strong decadal variation in both demersal (e.g. cod) and pelagic (e.g. salmon) stocks, and again there is developing evidence for correlation with zooplankton variability at the same time scale (e.g. Batchelder et al. 2002; Beaugrand et al. 2003)

### **7. Decadal “paradigm” shifts (scientific approach and emphasis)**

The title of this section had its origin as an error in a notice for a seminar on “regime shifts” by John Steele. Never-the-less, it makes sense to ask, “Have there been significant changes in what oceanographers and fisheries scientists working in ocean boundary regions do, know, or want to know?” In at least some areas, the answers are certainly “yes”.

In terms of current knowledge and hypotheses, changes include:

- Much more knowledge about the El Niño/Southern Oscillation, and its range of effects in both the Pacific and Atlantic.
- Much more knowledge about mesoscale physical structure in the coastal ocean, and some new data and ideas about how they are used by organisms.
- Despite the above, more fish stocks have collapsed, some others have recovered. An “ecosystem-based” approach to fisheries management continues to slowly win converts from single-species models.
- Decadal “regime shifts” and longer-term global warming trends are widely accepted as “real” phenomena. Understanding of these time scales remains far from complete: “regime shifts” are to some degree still a strong signal looking for convincing mechanisms, and “global

warming” is a convincing mechanism awaiting accumulation of statistically-significant signals.

In terms of improved data collection/processing/interpretation capabilities, key changes include:

- Several of the elements needed for an effective Global Ocean Observing System (GOOS) are now possible or implemented: High resolution satellite mapping of ocean color, sea surface elevation anomalies, and wind speed and direction; mapping of deeper water properties and flow by the Project ARGO drifter network.
- Diversification and extension of active biological time series, and data mining from dormant sample archives.
- Gradual acceptance by individual scientists of the advantages of “data sharing”
- Improving hardware and software tools for modeling and data visualization

An encouraging consequence of the above changes is that the next round of global comparisons may be able to draw on dense, synoptic, and similarly-specified data from many ocean regions.

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Table 1. Comparison of Pacific and Atlantic Eastern Boundaries

Latitude band	Pacific	Atlantic
50°-75°N	No direct connection to Arctic;, Northern coastal boundary at 60° (Alaskan coast); Large coastal freshwater input and year-round salinity stratification; More influence of mesoscale eddies.	Direct connection to Arctic; No northern coastal boundary; Large advective heat input; Variable salinity stratification;, Deep winter mixing; Wider shelf areas.
15°-50°N	Relatively narrow shelf, except in S. California Bight; Strong ENSO influence; Strong seasonal cycles in SSH; Stronger offshore flow in multiple filaments, influenced by capes.	Wide continental shelf; Mediterranean exchange at Gibraltar; Sheltered “bight” off Gibraltar; Aeolian dust from Sahara; Long filaments that interact with the Canary Islands.
~3°S-15°N	Narrow adjoining land mass, winter seasonal wind jets from Atlantic; Strong freshwater input along the zonal coasts of Colombia and Ecuador.	Zonal coastline orientation & seasonal coastal upwelling driven by Trade Winds;, Strong coastal freshwater input Stronger seasonal variability of equatorial cold tongue,
3°-40°S	Strong ENSO influence; Strong intraseasonal CTWs; Hypoxia, OML and dinitrification; Higher trophic efficiency and fish production.	Decadal “Benguela Ninos”; Strong coastal trapped waves; Mismatch of time scales of phyto-, zoo- and mero-plankton; Lower fish yield.
40°-50°S	Large coastal freshwater input (comparable to 50°-60°N).	Direct connection to Indian & Southern Oceans; No shoreline in this zone.
all	Sub-pycnocline water is “older”, with higher macronutrient and low dissolved oxygen.	Lower nutrient content, especially in N. Atlantic; Narrow ocean basin = increased continental influence and larger supply of micronutrients.

Table 2. Geographic characteristics and controls of eastern ocean boundary regions. See Hill et al. (1998) for additional detail and explanation. Ranking of “freshwater input” is relative to the other eastern boundaries; all regions have moderate to very low river input compared to the large rivers entering the western boundaries of the Pacific, the Arctic, and the Indian Ocean.

Region	<i>The Sea</i> XIII chapter #	Ranges of Latitude & Coriolis parameter f	Shelf width & orientation	Topographic features (capes, islands, submarine canyons, embayments; inlets)	Ekman upwelling/ downwelling	FW input/ buoyancy current	Winter convective mixing	Tidal mixing
<i>Equatorial:</i>								
Pacific	11	0°-30°N f = 0 to $0.6 \times 10^{-4}$	Large zonal component, narrow	Gulf of California at N end, gaps/passes in Central American mountains	Localized wind jets from Atlantic side Weak but persistent in Costa Rica Dome;	Large( rain + many small rivers)	minor	minor
Gulf of Guinea	22	10°S-10°N f = -0.2 to $0.2 \times 10^{-4}$	Zonal at N end; narrow,	canyons	Seasonal, driven by SE trades in boreal summer	Very large ( rain + river) Large nutrient load	minor	minor
<i>Eastern Boundary Current/Coastal Upwelling zones:</i>								
Peru/Chile	10	5°-45°S f = -0.1 to $-1.0 \times 10^{-4}$	0-100 (often <<25 km), bordered by trench	Gulf of Guayaquil at N end	Persistent upwelling at north, seasonal summer upwelling ~32°-40°S	Very low	minor	minor- moderate
California Current	12	23°-51°N f = 0.6 to $1.1 \times 10^{-4}$	0-100 km (most <50)	Several large capes, Southern California Bight	Persistent upwelling at south. seasonal summer upwelling north of ~36°N	Low in S, large at N end	minor	minor
Benguela + Agulhas Bank	21	15°-37°S f = -0.4 to $-0.9 \times 10^{-4}$	Mostly NS but zonal at S end; 30-250 km; deep shelf break	West-pointing capes in southern BCS are upwelling centers, Interaction with Agulhas Current at S end	Strong upwelling	None in S, large (Congo R.) at N end	minor	minor
Canary Current	23	15°-36°N f = 0.4 to $0.9 \times 10^{-4}$	75-100 km	Canary Islands, several large capes	Strong upwelling	Very low	minor	minor
Iberia	23	36°-44°N f = 0.9 to $1.0 \times 10^{-4}$	25-75 km	Rias at N end Separated from Canary system by Gibraltar Straight.	Summer upwelling	Low		minor

Table 2 (cont.)

<i>High latitude/ downwelling</i>								
Southern Chile	10	45°-56°S $f = -1.0$ to $-1.2 \times 10^{-4}$	Wide in inland seas	Chiloe/Aysan inland seas & fjord system, submarine canyons	Downwelling	Very large year-round, winter rainfall + snow/ice melt	Strong but restricted by salinity stratification?	moderate
Alaska Current system	[see Stabeno et al., 2004]	50°-60°N $f = 1.1$ to $1.3 \times 10^{-4}$	~200 km,	Many large inlets & fjords, Kodiak Island	downwelling	Buoyancy driven coastal current. Very large discharge year round, peaks in autumn	Strong but shallow (permanent halocline)	Strong nearshore
Bay of Biscay	23a	43°-48°N $f = 1.0$ to $1.1 \times 10^{-4}$	10 km (Spain)-150 km (France)	Land on 3 sides, significant river input	Upwell in summer, downwell in winter		minor	strong
Celtic Seas	24	50°-59°N $f = 1.1$ to $1.3 \times 10^{-4}$	Large shelf area ~50-250 km wide	Relatively sheltered from open Atlantic influence, many large bays/estuaries			Moderate but shallow (seabed)	Very strong
Norway and Faeroe/Iceland	25	58°-71°N $f = 1.2$ to $1.4 \times 10^{-4}$	10 – 150 km	Deep fjords, many coastal islands		Buoyancy driven coastal current along Norway. Mod discharge, peaks in autumn	Strong but restricted by salinity stratification	Strong around Faeroes, moderate elsewhere

Table 3. Seasonal and shorter time scale temporal variability in eastern ocean boundary regions.

Region	Tidal	Upwelling/Downwelling	“events	Monthly mean wind stress	Stratification
		Atmospheric fronts and waves	Coastal trapped waves		
			Storms, frontal passage		
<i>Equatorial:</i>					
Pacific	Weak	Downwelling in NH, except Lat > 4°N in NH winter ;	Equatorial CTWs; T=5-50d	Weak when ITCZ at 1°N (Jan); Moderate when ITCZ at 7°N (July)	Strong, heating. Freshwater line source in NH winter
Gulf of Guinea	Amplified fortnightly tide	Local + distant forcing. Major upwelling in July; Minor in January.	Equatorial CTWs; T=5-50 d	Weak, steady, SW	Strong. Fresh-water river plumes.
<i>Eastern Boundary Current/Coastal Upwelling zones:</i>					
Peru/Chile	Weak. Moderate off N. Chile. Strong in bays (Int. tides and solitons)	Permanent upwelling, 5°-33°S; Seasonal reversals, 33°-40°S. Propagating coastal lows in atmosphere; Small-moderate filaments, internally generated.	Equatorial CTW; T=5-50 days; Strong impact on nutricline depth.	Winter upwelling max in north; summer max & winter min/reverse in south-central	N. Peru: weak during upwelling; N. Chile: strong; moderate in south-central Chile.
California Current	Weak, stronger in the north. Internal tides and solitons.	Permanent upwelling, 23°-35°N; Seasonal reversals, 35°-50°N. Propagating coastal lows in atmosphere; Long filaments, internally generated.	Wind-driven CTW; T=3-10 days. Source 200-300km equatorward.	Abrupt spring transition to North Winds.	Stronger in south; moderate in north. Strong upwelling fronts.
Benguela + Agulhas Bank	Weak, semidiurnal	Permanent upwelling, 15 °-30°S; Seasonal reversals, 30°-34°S. Propagating coastal lows in atmosphere; Giant filaments pulled of by A. rings.	Wind-driven: T=3-10 days.	Strong spring-summer north winds, earlier in the north.	Moderate – strong.
Canary Current	Weak	Permanent upwelling, 10°-30°N; Long filaments interact with Canary Islands.		NE trade winds.	Moderate.
Iberia	Int. tides; solitons	Seasonal upwelling; Reversed (poleward) currents in winter.		NE winds in summer, reversals in winter.	Moderate.

Table 3 (continued). Seasonal and shorter time scale temporal variability in eastern ocean boundary regions.

Region	Tidal	Upwelling/Downwelling	"events	Monthly mean wind stress	Stratification
		Atmospheric fronts and waves	Coastal trapped waves		
			Storms, frontal passage		
<i>High latitude/ downwelling</i>					
Southern Chile	Moderate, semidiurnal. Locally strong near constrictions	Downwelling and upwelling within fjords. Complex flow fields. Storm-driven.	Intense winter storms	Poleward, maximum in winter. Frequent storms.	Moderate-strong from fresh-water input from rain and runoff (short drainage basins).
Alaska Current system	Moderate, strong in north and in bays/fjords	Downwelling and buoyancy driven; mesoscale eddies induce vertical motion.	CTW off Vancouver Is. Intense winter storms	Poleward, maximum in winter.	Moderate, salinity controlled.
Bay of Biscay	Int. tides, solitons; shelf tides are stronger in north	Weak downwelling and upwelling.	Strong winter storms.	Westerly, southwesterly.	Moderate; plume fronts.
Celtic Seas	Strong, internal	Weak	Diurnal period shelf wave, west of Britain Strong winter storms.	Winter storms, SW mean winds.	Moderate to none, where tidal mixing is strong. Tidal mixing fronts.
Norway and Faeroe/Iceland	Semidiurnal, moderate. Amphidromic systems along coast.	Upwelling within fjords	Intense winter storms.	Frequent storms	Freshwater input from Baltic and fjord inflow.

Table 4. Nutrient & light availability and primary productivity in eastern boundary regions. (\*) indicates productivity estimates based on satellite ocean color. Blank cells indicate that the process is of relatively minor importance in the region, “?” indicates potentially important but not yet thoroughly studied in the region, “+” to “+++” indicates moderately to very important regional influence.

Region	Micronutrient supply	Average macronutrient supply	Average Primary productivity & timing	Macronutrient concentration below pycnocline	Ekman divergence	Pycnocline depression	Eddies/Filaments	Estuarine entrainment	Light availability
<i>Equatorial:</i>									
Pacific		Mostly very low, much higher at localized upwelling sites	<0.1 to >0.5 kgC m <sup>-2</sup> y <sup>-1</sup> , extreme spatial/temporal variance (highest in wind jet regions and in the Gulf of California)	Very high	Localized & seasonal	El Niño & CTW			High
Gulf of Guinea		Moderate	0.15-0.5 kgC m <sup>-2</sup> y <sup>-1</sup> Large spatial/temporal variance	Medium	Seasonal	Equatorial Kelvin waves and CTW			High except where turbid due to sediments
<i>EBCU zones:</i>									
Peru/Chile		Very large	0.1-7 gCm <sup>-2</sup> d <sup>-1</sup> (wide spatial range) 0.9-1.2 kgCm <sup>-2</sup> y <sup>-1</sup>	Very high	Very large	El Niño & CTW	+	minor	High
California Current		Large	0.3-0.6 kgCm <sup>-2</sup> y <sup>-1</sup> <100 km from coast 0.15-0.25 kgC m <sup>-2</sup> y <sup>-1</sup> in SCB and further offshore	Very high	Large	El Niño	++	Large at N end	High but seasonal at N. end
Benguela + Agulhas Bank	High (dust)	Very large	Highest?*	High-very high	Very large	Benguela Niño	+++		High
Canary Current	High (dust)	Very large	0.2-2.5gCm <sup>-2</sup> d <sup>-1</sup> (spr/sum max) ~0.9 kgCm <sup>-2</sup> y <sup>-1</sup>	High	Very large	CTW	+++		High except when reduced by dust
Iberia	Moderate	Large	1-4 gCm <sup>-2</sup> d <sup>-1</sup> (spr/sum max) ~0.6 kgC m <sup>-2</sup> y <sup>-1</sup>	Medium	Large	CTW?	++		Weakly seasonal

Table 4 (cont.)

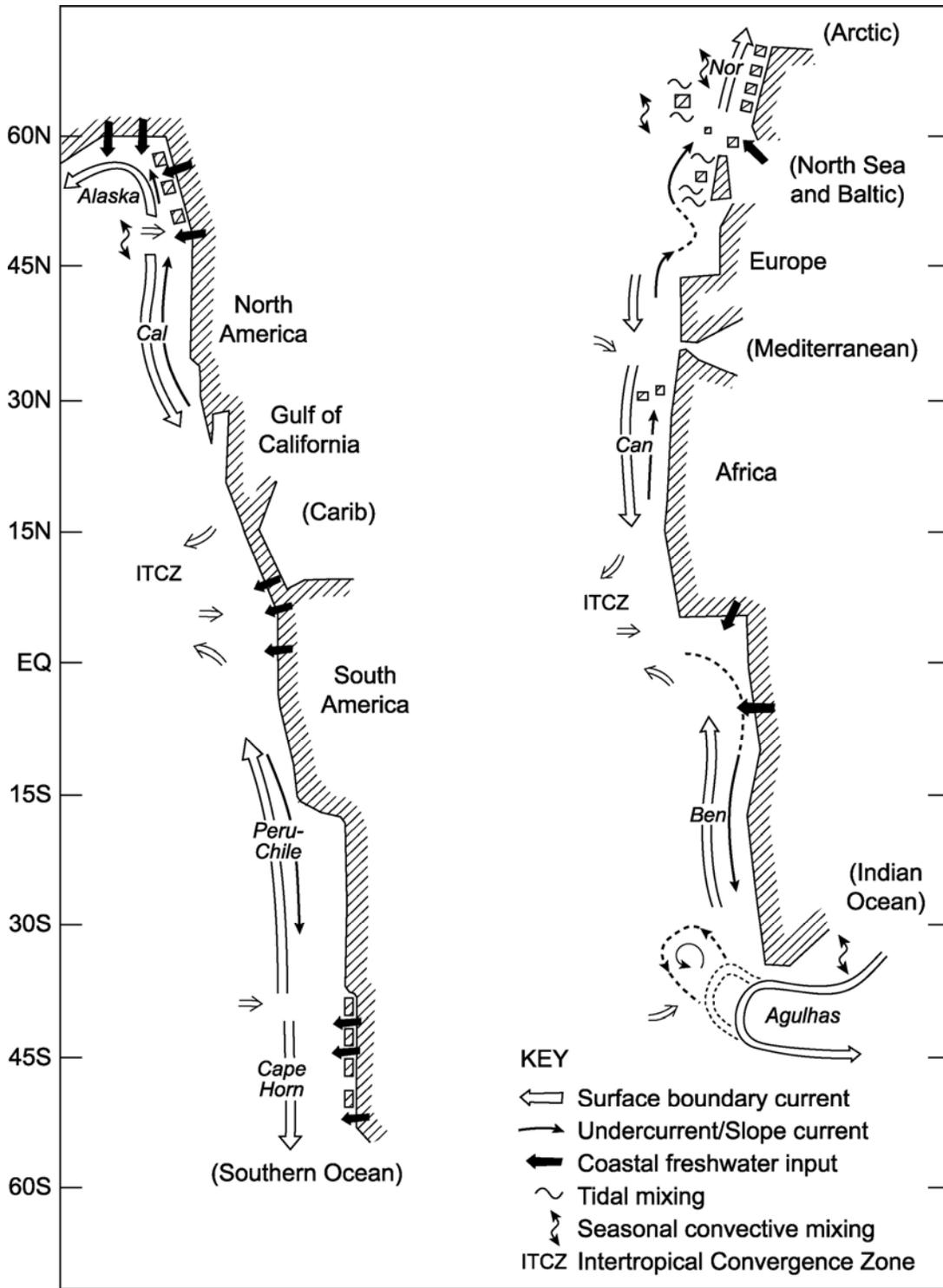
<i>High latitude/ downwelling</i>									
Southern Chile				Very high	Convergence			Large	Seasonal
Alaska Current system				Very high	Convergence		++	Large	Seasonal, FW stratification
Bay of Biscay		Winter-spring max.	~0.25 kgCm <sup>-2</sup> y <sup>-1</sup> (*) (spring max)	Medium					Seasonal, FW stratification
Celtic Seas		Winter-spring max.	~0.6 kgCm <sup>-2</sup> y <sup>-1</sup> (inshore areas) ~0.1 kgCm <sup>-2</sup> y <sup>-1</sup> (offshore, low tidal mixing)	Medium					Seasonal
Faeroe/Iceland		Winter-spring max.	~ 0.2 kgCm <sup>-2</sup> y <sup>-1</sup> (spring max)	Medium			Anticyclonic along shelf break		Very seasonal
Norwegian coast		Winter-spring max.	~ 0.1 kgCm <sup>-2</sup> y <sup>-1</sup> (spring max)		Convergence			Present	Seasonal, FW stratification

Table 5. Aggregation and retention features. See Bakun (1996) for an extended discussion of the “Bakun Triad” hypothesis that physically-mediated enrichment, aggregation, and retention features define “good” pelagic habitat. Symbol codings as in Table 4.

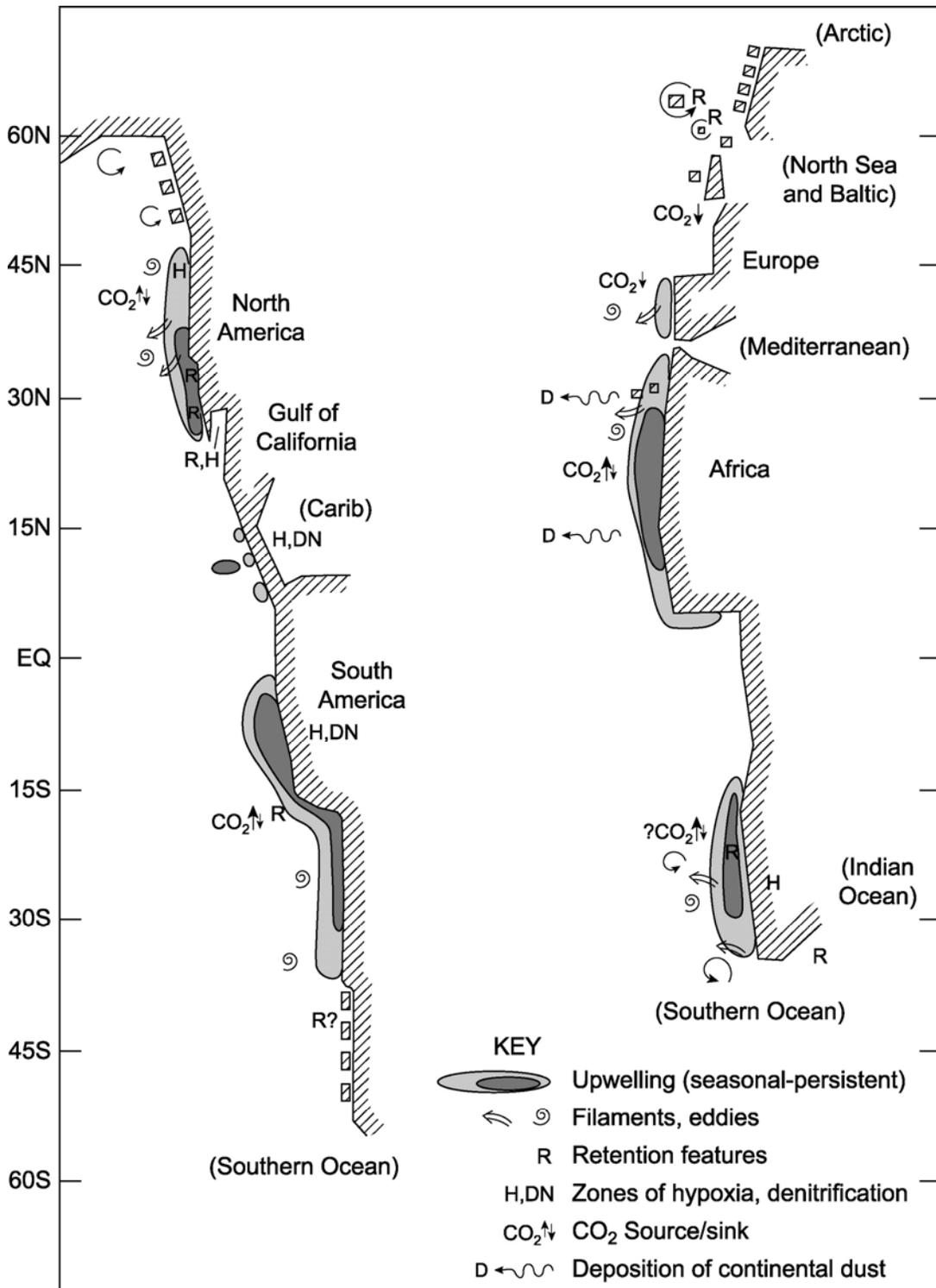
Feature	Aggregation.	Retention	Spawning/nursery	Mechanism	Where important	Where discussed	Other key refs.
Pycnocline/nutricline	++	?	Common in nursery areas	If in euphotic zone, high availability of phytoplankton, small zooplankton Favored by weak wind stress, so often competes with “enrichment”	Stratified areas	California Current	Lasker 1981
Bathymetric “edges”	++	+	?	Advective and behavioral convergence of organisms	All	Calif Current	Mackas et al. 1997
Convergent fronts	++	++		Advective and behavioral convergence of organisms. Episodic shoreward “relaxation” of upwelling fronts an important special case	All	Calif. and Benguela systems	Olson 2002
Internal wave trains	++	Shoreward transport of benthic larvae		Advective and behavioral convergence of organisms	meroplanktonic benthos, larval fish	Calif & Peru/Chile systems	Pineda 1999; Shanks 1983
Current shear zones	? (often at pycnocline or fronts)		?	Movement between zones with opposing velocity minimizes of net horizontal transport, Dominant time scales for migration are diel, seasonal, and ontogenetic (once per generation)	All regions with high mean flow	Benguela, and Calif. systems	Peterson 1998; Barange & Pillar 1992
Mesoscale eddies Around banks and islands  Offshore	?	++		“Orbital” movement along closed or nearly-closed flowfield streamlines; Can provide additional benefit via proximity to a center of nutrient enrichment or predation refuge	Agulhas Bank, Iceland, Faeroes  All	Agulhas Bank, Iceland, Faeroes  Calif and Canary systems	Sinclair 1988
Embayments and inlets	?	++	Often used as spawning and/or nursery areas	Refuge from advective washout	All regions with high mean flow		Parrish et al. 1981

Table 6. CO<sub>2</sub> Source/Sink , Oxygen Depletion and Denitrification

Region	Net CO <sub>2</sub> source/sink	Denitrification	Hypoxia on open shelf	Anoxia
<i>Equatorial:</i>				
Pacific	?	++	+++	++
Gulf of Guinea	Sink?			
<i>EBCU zones:</i>				
Peru/Chile	Source	+++	+++	++
California Current	Weak source (California) - weak sink (Oregon)		+ (new?)	+ (in stagnant basins)
Benguela + Agulhas Bank	Source?	?	++	+
Canary Current	Weak source			
Iberia	Sink			
<i>High latitude/ downwelling</i>				
Southern Chile	Sink?			
Alaska Current system	Sink?			
Bay of Biscay	Weak sink			
Celtic Seas	Sink			
Faeroe/Iceland	Sink?			
Norwegian coast	Sink			



2.1 Schematic map of the eastern boundaries of the Pacific and Atlantic showing major current systems, locations of major coastal fresh-water inputs, and regions of tidal mixing and winter convection (compare to Lohrenz and Castro, 2004; general format and symbol coding are the same as their figure, although longitude scale is compressed here). For clarity, current arrows are displaced offshore from their actual location.



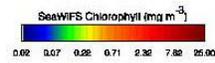
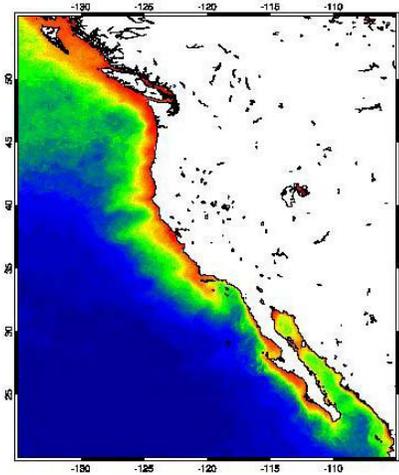
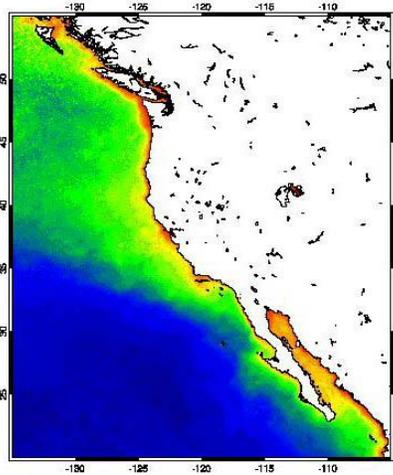
2.2 Schematic map showing zones of strong wind-driven upwelling, large or frequent mesoscale filaments and eddies, retention centers and spawning areas, zones of hypoxia and denitrification, and indication of atmosphere-ocean CO<sub>2</sub> flux.

## Pacific

Winter  
(Dec-Jan-Feb)

Summer  
(Jun-Jul-Aug)

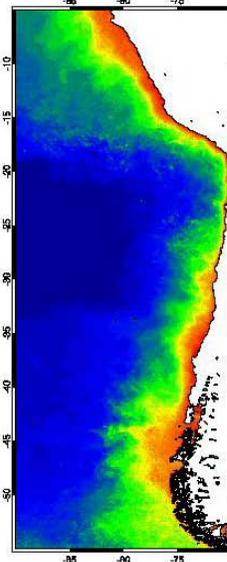
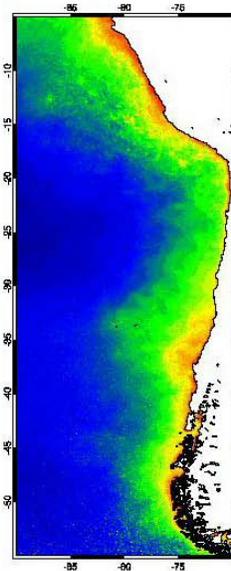
California



(Jun-Jul-Aug)

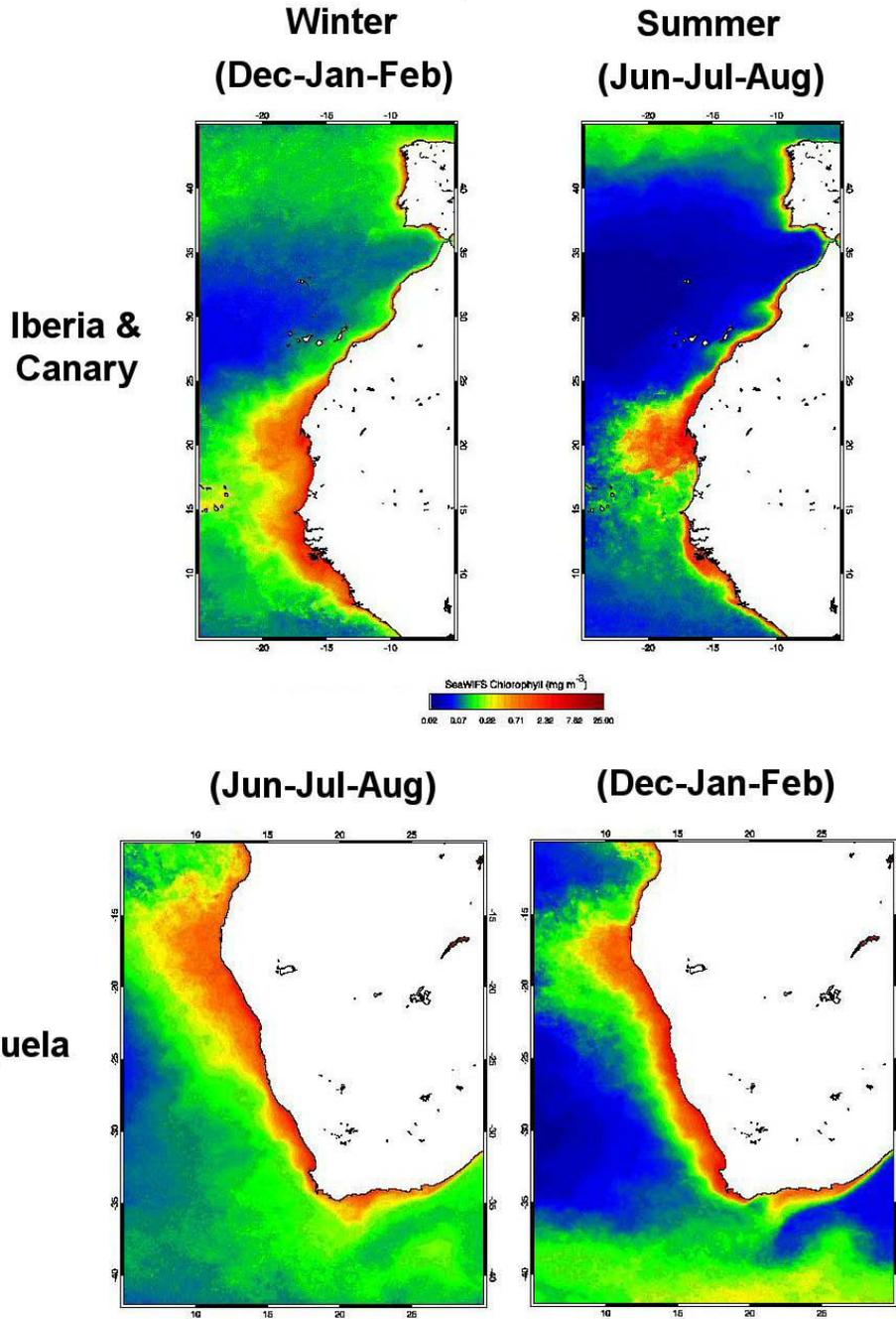
(Dec-Jan-Feb)

Peru-Chile

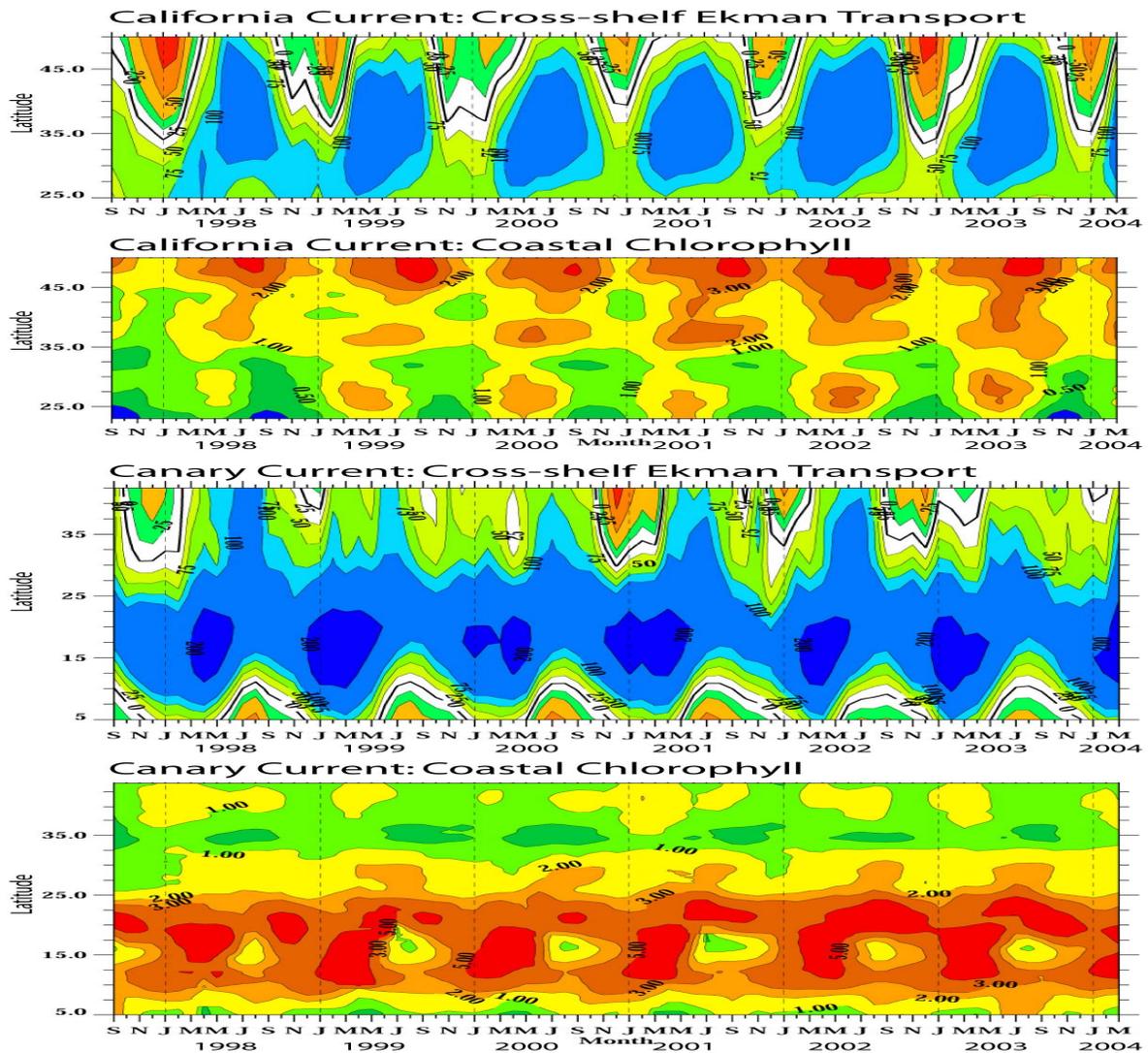


2.3 Comparisons of six-year averaged (1997-2003) winter and summer season distributions of SeaWiFS surface chlorophyll pigment concentrations in the Pacific EBCU regions: California Current (top) and Peru-Chile Current (bottom); winter (left) and summer (right).

## Atlantic



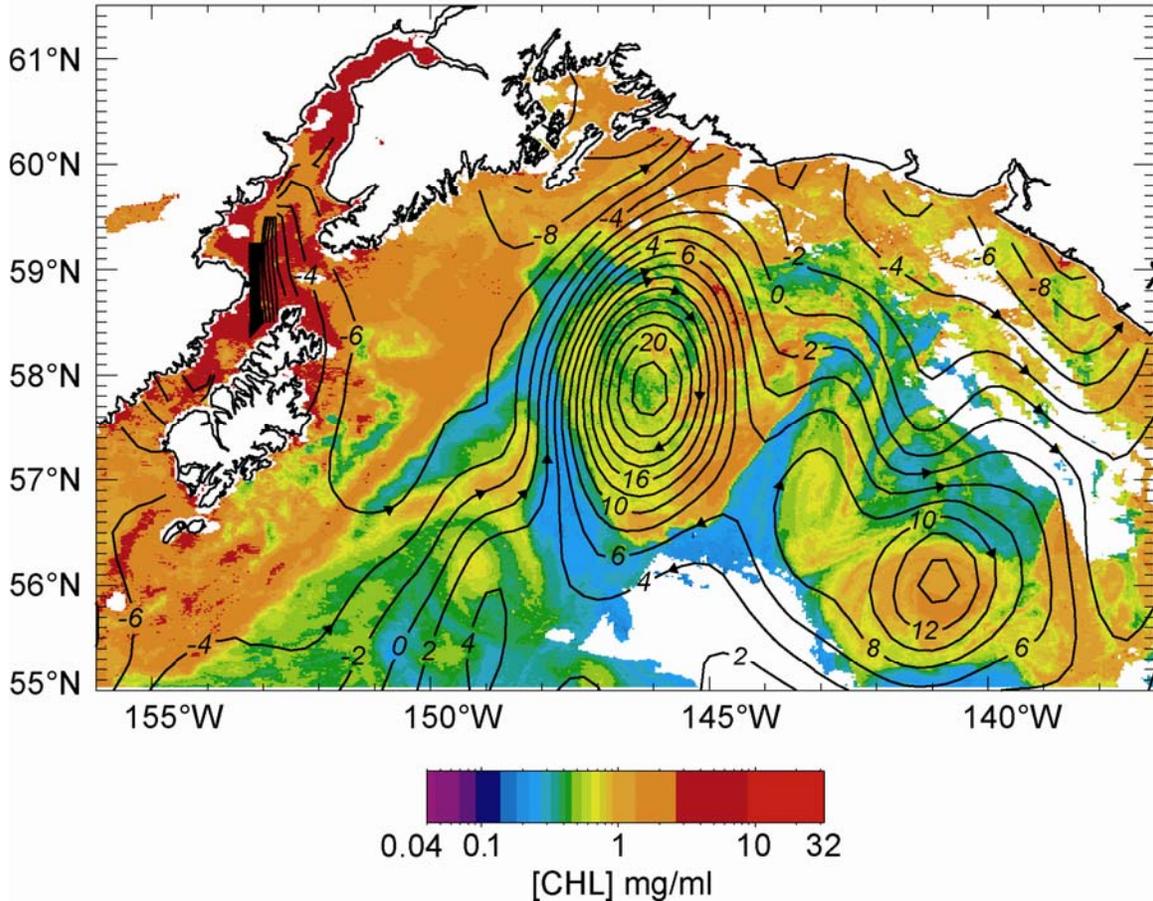
2.4 Comparisons of six-year averaged (1997-2003) winter and summer season distributions of SeaWiFS surface chlorophyll pigment concentrations in the Atlantic EBCU regions: Iberia/Canary Current (top) and Benguela Current (bottom); winter (left) and summer (right).



2.5 Comparison of six+ year time series of monthly-average upwelling/downwelling intensity (dark blue = strongest upwelling) and of SeaWiFS chlorophyll (spatially averaged within the 100 km from the coastline) in the northern hemisphere (California Current = top, Iberia/Canary Current = bottom) upwelling systems. Note the post 1998 increase in the California Current of upwelling intensity and in amplitude, alongshore extent, and duration of the high chlorophyll region. Upwelling intensity is the cross-shelf Ekman transport, estimated from analyzed atmospheric surface pressure fields from the U.S. Navy (Schwing et al., 1996).



### July 3–10 Pigment Concentrations and SSH



2.7. Mesoscale anticyclonic eddies in the Alaska Current system as seen by satellite sensors: SeaWiFS chlorophyll (color, red-orange = high pigment content) and TOPEX-Poseidon/ERS-2 sea-surface height anomaly (contour lines). Arrows indicate direction of geostrophic flow around the eddies. Two active eddies are present in this region (centered ~58°N, 146°W and ~56°N, 142°W). Note entrainment of coastal-origin water with high chlorophyll pigment concentrations by seaward flow along the stronger (and more nearshore) northern eddy, and elevated pigment concentrations throughout the more offshore southern eddy. A remnant of an older eddy is visible at 56°N, 149°W.