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Comparative biogeochemistry-ecosystem-human interactions on dynamic continental margins

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Abstract: The ocean's continental margins face strong and rapid change, forced by a combination of direct human activity, anthropogenic CO_2-induced climate change, and natural variability. **S**timulated by discussions in Goa, India at the IMBER IMBIZO III, we (1) provide an overview of the drivers of biogeochemical variation and change on margins, (2) compare temporal trends in hydrographic and biogeochemical data across different margins (3) review ecosystem responses to these changes, (4) highlight the importance of margin time series for detecting and attributing change and (5) examine societal responses to changing margin biogeochemistry and ecosystems. We synthesize information over a wide range of margin settings in order to identify the commonalities and distinctions among continental margin ecosystems. Key drivers of biogeochemical variation include long-term climate cycles, CO_2-induced warming, acidification, and deoxygenation, as well as sea level rise, eutrophication, hydrologic and water cycle alteration, changing land use, fishing, and species invasion. Ecosystem responses are complex and impact major margin services including primary production, fisheries production, nutrient cycling, shoreline protection, chemical buffering, and biodiversity. Despite regional differences, the societal consequences of these changes are unarguably large and mandate coherent actions to reduce, mitigate and adapt to multiple stressors on continental margins.

Keywords: anthropogenic factors, coastal biogeochemistry, climate change, eutrophication, ecosystem services, time series

Regional Terms: Continental margins, Europe, North Atlantic, North Pacific; Arctic

1. Introduction to dynamic margin ecosystems

The oceans' continental margins extend for some 150,600 km (Jahnke, 2010) and encompass estuarine, open coast, shelf, canyon, slope, and enclosed sea ecosystems. They are both gateway and window to the open ocean, where water, nutrients, energy, sediments, contaminants and organisms meet and are transferred through land-margin and margin-open ocean interactions (Levin et al., 2001). The continental margins include proximal estuaries, bays, lagoons and banks, and distal shelves, slopes and marginal seas. These are susceptible to changes in biodiversity, water quality, and productivity and have been increasingly perturbed by human activities.

Margin ecosystems include hard and soft-substrate habitats ranging from structurally complex wetlands, kelp forests, coral reefs, rocky reefs and sand beaches, to sedimented estuaries, slopes and canyons. Most of the habitat volume, however, occurs in the overlying water column, with variation linked to water masses, circulation, and land and atmospheric interactions. As one crosses depth contours from estuaries across the shelf to the continental slope, steep gradients in nutrient concentrations, temperature, salinity, oxygen, pH and suspended matter are found that impact the productivity, composition, diversity, and abundance of organisms (Cloern, 1996; Hofmann et al., 2011; Levin and Sibuet, 2012). Relative to their area, the margins account for a disproportionately large fraction of the global primary production (10 – 15%), nutrient recycling, carbon burial (> 60% of total settling organic carbon), and fisheries production (Walsh et al. 1988; Muller-Karger et al., 2005). They also are exceptionally dynamic systems with ecosystem structures that can oscillate slowly or shift abruptly, but rarely remain static.

The current continental margin seascape has been shaped extensively by climate change and human activities, yielding altered ecosystem services. Margin ecosystems provide key services in the form of physical protection from waves, storms, and floods, chemical buffering, food provisioning, nursery support, nutrient cycling, habitat fostering biodiversity, carbon sequestration, recreation, and aesthetic value. Finely tuned biogeochemical interactions drive these functions. Because human populations are disproportionately concentrated in coastal cities, there is heterogeneity in the human effects on margins, creating mosaics of heavily impacted and relatively pristine systems. Nutrient inputs, freshwater extraction, fishing, construction, species introductions, and contamination are but a few of the many ways humans alter coastal ecosystems. Also the steady increase of anthropogenic CO_2 inputs to the atmosphere will result in significant changes in water column temperature, oxygenation, pH, and productivity by 2100, with major consequences for margin ecosystems and the over 1 billion people that depend on them for food, employment and revenue (Mora et al., 2013; FAO, 2012).

While margin research has a long history among oceanographers (Banner et al., 1980. Walsh et al., 1988, Biscaye et al., 1994, Duarte et al. 1999, Antia et al., 2001, Liu et al., 2010), a synoptic view of dynamic coupled margin systems has emerged more slowly and the linkages between human and natural biogeochemical variations, ecosystem response and human social structures are only now being explored. The interactive effects of remote forcing from distant inland activities, from atmospheric processes, and from physical processes far out to sea are becoming more apparent. There are, however, gaps in our understanding of the combined effects of multiple drivers on coastal biogeochemistry and ecosystems across all continental margins. The objectives of this paper are to provide an overview of sources of biogeochemical variation on margins, associated ecosystem responses, and the societal and policy implications, with a focus on lessons from multiple continental margin time series (Fig 1).

This paper reflects the themes and discussions of the continental margins working group of IMBER IMBIZO III (Goa, India in January 2013). In this paper we examine drivers of biogeochemical variation on margins, distinguishing natural from CO_2-based climate variability, and more direct human drivers. We next compare temporal trends for multiple physical and biogeochemical parameters at geographically contrasting locations We then discuss the complex ecosystem responses to biogeochemical variation and trends on margins, in particular those related to warming, deoxygenation, acidification and hydrologic alterations. We subsequently identify the key roles played by continental margin time-series stations (Fig. 1) in identifying and attributing drivers of change and in understanding the associated ecosystem responses. Finally, we examine societal responses to changing margin biogeochemistry and ecosystems, highlighting areas where social and natural scientists must work together. Case studies (expanded in Supplement B) are synthesized to provide insights into the sensitivity of margins to natural and human perturbations, the ecological, social and economic consequences that stem from these perturbations, and the policy actions needed to mitigate impacts on coastal ecosystems and their resources.

2. Natural and human-induced drivers of biogeochemical variation on margins

Controls on biogeochemistry of margins are complex and dynamic. In this paper we distinguish drivers associated with natural *variability*, anthropogenic CO_2 –driven *climate change* and direct human (*anthropogenic*) impacts. It is often difficult to disentangle these three forcing mechanisms, as well as to distinguish local change from regional to global-scale pressures. Multiple factors act together – exerting top-down (often human) and bottom – up (natural or human) controls on ecosystem structure simultaneously.

Natural Sources of Variability

Natural variation in biogeochemical features affecting margin ecosystems occurs on a vast range of time scales, from millions of years to hours. Direct measurements during the past century in many of the systems discussed here have revealed large, abrupt, persistent changes in the structure and function (or state) of an ecosystem, which were sometimes interpreted as regime shifts (Mumby et al., 2007; de Young et al., 2008; Barnovsky et al. 2012). These may be manifested as simultaneous changes in phytoplankton, dominant consumer species, and trophic structure. Regime shifts often yield major consequences for fisheries and human livelihood (McFarlane et al., 2002; Zhang and Gong, 2005). Examples can be found in the North Pacific - Pacific Decadal Oscillation (Wooster and Zhang, 2004), North Atlantic (Alheit et al., 2014) Caribbean coral reefs (Hughes, 1994), Mediterranean Sea (Conversi et al., 2010), Northern Adriatic Sea (Conversi et al., 2009) and North Sea (Beaugrand, 2004). In the Northern Hemisphere, major ecosystem shifts were observed in the late 1980s to early 1990s, with synchronous shifts following an overall period of high variability. These ecosystem regime shifts were linked to changes in global-scale climate indices (Chavez et al., 2011; Conversi et al., 2010; Möllmann et al., 2011). It is cautioned that these abrupt changes are sometimes difficult to distinguish from random fluctuations or overfishing effects and their true nature often remains unclear (e.g., Hsieh et al., 2005).

Margins may also be subject to basin-specific and regional influences. For example, the California Cooperative Oceanic Fisheries Investigations (CalCOFI), one of the longest existing oceanographic time series (63 y), reveals major natural variations in water column temperature, oxygen, pH and current strength that are associated with changes in the regional hydrography of the California Current Ecosystem over multiple time and space scales (Checkley and Barth, 2009; McClatchie et al., 2010; Nam et al., 2011; Send and Nam 2012). In addition to the Pacific Decadal Oscillation, there are decadal scale ENSO cycles, seasonal and week-long upwelling events that alter productivity and/or ocean biogeochemistry with marked shifts in oxygen and pH (Fig 2). Variability in these environmental parameters results in changes in the regional biodiversity and ecosystem structure with significant impacts on ecosystem services we depend on (Doney et al. 2012).

Much natural climate variability and some manifestations of climate change occur abruptly over short time and space scales. Most margins experience episodic, extreme events that shape their ecosystems, often through biogeochemical modification. For example the Rhone River carries 80% of its solid flux during 5% of the time (Antonelli et al., 2007) with large biogeochemical consequences (Cathalot et al., 2010). Extreme storm events can reshape coastal systems with short-lived, dramatic changes in salinity and flushing rates and through more persistent alterations of channel openings (Paerl et al., 2001). Atmospheric deposition of nutrients associated with air mass outflow from the Indo-Gangetic Plain to the northern Bay of Bengal is significant and most can occur over 4 months in association with the NE monsoon, highlighting the temporal nature of these atmospheric drivers (Srinivas et al., this volume). These are likely to have direct consequences for eutrophication in Bay of Bengal surface waters triggering profuse algal blooms in the adjacent Sundarban wetland (Naha Biswas et al., 2013). Heat waves that last for a few weeks can induce mass mortality in coastal ecosystems of the Mediterranean Sea either directly (Garrabou et al., 2009; Marba and Duarte, 2010) or through the spread of disease and invasive species (Lejeusne et al., 2010).

As with short time scales, small areas of the ocean can play key roles in global biogeochemical fluxes on margins. For example, 1% of the ocean's water volume accounts for 50% of N removal through water column denitrification and annamox in oxygen deficient zones (Deutsch et al., 2011), and 60-70% of the annual denitrification rate occurs in shelf sediments (Codispoti, 2007). Submarine canyons carry 80-90% of the sediment and organic matter fluxes to the open seafloor sediments, with transport affected by climate-driven stratification, wind regime and winter cooling (Canals et al., 2006; Rabouille et al., 2013). It is proposed that the Congo River, with the second largest discharge in the world, carries 50% of the river's silica through an 800-km long submarine canyon to a 3000 km^2 deep-sea fan (Raimonet et al., this volume). The functions of submarine canyons as key removal agents via deep-sea fans and deltas may be diminished by climate change-driven reduction of dense water formation with less cascading and deep export (Herrmann et al., 2008; Rabouille et al., 2013).

An important question to emerge is whether natural variability associated with exposure to stressful conditions (such as hypoxia or hypercapnia) confers evolutionary pre-adaptation to further stress from climate change or direct human activities. Evidence suggests that animals in margin settings subject to upwelled, low-pH waters are resilient to such conditions (e.g., Thomsen et al., 2010; Yu et al., 2011; Hoffmann et al., 2014). In other coastal regions where hydrographic variability is also intense and there are multiple controls from land, detection of trends, sources and biological responses including adaptation can be difficult (Duarte et al., 2013). Whether hydrographic stressors that vary naturally (oxygen, acidification and warming) elicit more adaptation than 'unnatural' (man made) trace organic or metal/metalloid contaminants, remains an open question.

CO_2-driven climate drivers

Rising CO_2 in the atmosphere is reshaping margin ecosystems by increasing sea level, ocean warming, ocean acidification and ocean deoxygenation (Doney et al. 2012). There are also climate shifts that alter patterns of heat, drought, precipitation, and flooding that modify margins directly and indirectly through changes in land use, runoff, and human activities.

CO_2-induced warming and enhanced stratification have been linked to declining oxygen concentrations on the southern California shelf and upper slope (Bograd et al., 2008) as well as increased seasonal hypoxia on the inner Oregon shelf (Chan et al., 2008). These changes also involve lowered pH and high pCO_2 (Frieder et al. 2012; Alin et al. 2012), with consequences for biogeochemical cycling and ecosystem structure in the California Current (CC) system (Doney et al. 2012). Upwelling is intensifying and low pH (which promotes aragonite undersaturation) is spreading in the northeast Pacific (Feely et al. 2008; Gruber et al., 2012). The observed low pH conditions in the CC system are shaping characteristics of this ecosystem by affecting calcifying species and have resulted in the decline of cultured bivalves (Barton et al., 2012). Whether the oxygen and pH changes reflect a continuous, secular trend resulting from CO_2-driven climate changes or are part of a larger (50 y) natural cycle remains controversial (McClatchie et al. 2010; Deutsch et al., 2011). These changes are occurring in an ecosystem already subject to high natural variability (Fig. 2). Clear understanding of this complexity is needed for forecasting future conditions.

Beyond upwelling regions, perhaps the greatest manifestations of climate change are found on the shelves of the Arctic Ocean. Among the most massive of inputs, a full 10% of the freshwater reaching the oceans occurs in the Arctic, which has only 4 million people living there. Thawing of permafrost due to warming yields increased inputs of soil organic carbon and methane to the coastal ocean and atmosphere (Schurr, 2013), and will influence many aspects of the Arctic coastal ecosystem (Whiteman et al., 2013). The freshwater from melting sea ice combined with degradation of released organic matter is causing major perturbation of low pH in the Arctic. Baseline monitoring of the W. Arctic

Ocean reveals that 20% of the Canada Basin surface waters exhibit aragonite undersaturation (Robbins et al., 2013).

As temperatures continue to increase (Behrenfeld et al., 2006), warming is expected to reduce productivity over much of the ocean (Mora et al., 2013). It is uncertain whether lowered production will reduce oxygen depletion in midwater (from decomposition of sinking phytoplankton and respiration of vertical migrators), counteracting the deoxygenation effects of global warming (from increased stratification and reduced mixing). Alternatively, intensified upwelling in a warmer world may pump more nutrients into surface waters, increase respiration of microbes and other organisms, and increase the rate of deoxygenation. As a direct effect or through changes in currents such as the Gulf Stream, warming might increase methane emissions via dissociation of gas hydrates on continental margins (Phrampus and Hornbach, 2012). Massive gas hydrate deposits in the shallow Arctic Ocean are particularly susceptible and their release may exacerbate acidification and oxygen depletion via aerobic methane oxidation in the water column (Biastoch et al., 2011). There has yet to be exploration of modern biological responses to long-term increases in methane fluxes on margins, although the geologic past may hold lessons in this regard (Kennett et al., 2003).

Direct Human Drivers

Rivers are a primary conduit of nutrient loading to the shelf from terrestrial sources of nutrients. Since the development in the early 20th century of the Haber-Bosch process for fixing nitrogen for use in fertilizers, the global nitrogen cycle has become increasingly affected by anthropogenic inputs. The net anthropogenic nitrogen inputs (NANI) to a region include fertilizer application, atmospheric deposition, agricultural N fixation by leguminous crops, and the nitrogen associated with food and livestock feed crossing regional boundaries. Nitrogen flux in rivers is often highly correlated to the NANI of their drainage basins (e.g., Howarth et al., 1996; Han and Allen, 2008; Swaney et al., 2012). In areas of high population densities (e.g., coastal cities) or regions of industrial-scale livestock production, as is increasingly seen in India and China, the nitrogen associated with the trade of food and feed commodities may be very significant. In areas of high crop production, synthetic N fertilizer is typically the dominant source of N (e.g., Yan et al., 2010). In India, use of synthetic fertilizer has grown exponentially over the last fifty years, making Indian agriculture one of the most intense consumers of fertilizer in the world (Swaney et al., this issue). Between 1970 and 2000, the coastal Bay of Bengal has experienced massive N and P loading (50% and 35% increase, respectively) causing eutrophication; 70-80% of the loading is from agricultural sources (Sattar et al., 2014).

Margins play a key role in filtering nutrients and contaminants that enter the ocean via runoff and rivers. Productive estuarine ecosystems, particularly wetlands, are able to remove nutrients by denitrification, uptake by vascular plant, phytoplankton, and microbes, by promoting flocculation and enhancing deposition and burial (Kennedy 1984, Howarth et al., 2006; Dähnke et al., 2008; Lassaletta et al., 2011; Howarth et al., 2012). Intensive filter feeding by bivalves such as oysters and mussels can also remove particulate nutrients and control eutrophication (Cloern et al. 1982; Dame 2012). The filtering functions of margins have been greatly affected by massive wetland loss over the past century, due largely to changing land use and sea level rise. Globally, overfishing (of oysters) and species introductions (of invasive bivalves) have also had a major influence on water filtration functions (Dame 2011).

Human acceleration of nutrient cycles and eutrophication are among the best studied of the anthropogenic forcing factors and cause the most conspicuous adverse effects upon continental margins as witnessed by diverse case studies (Table 1, Fig. 1). Intensified nitrogen loading is widespread in coastal ecosystems receiving effluents from catchments with dense human populations (Rabalais, 2004; Glavovic et al., submitted). This yields continental margin dead zones (coastal hypoxic areas resulting from eutrophication), which number over 475 and are on the rise (Diaz and Rosenberg, 2008; World Resources Institute, 2013). The largest of these occur in the Baltic Sea, the Black Sea, the northern Gulf of Mexico and the East China Sea (Rabouille et al., 2008; Zhu et al., 2011), where historical hypoxia induced by natural climate conditions and circulation has been exacerbated by human nutrient input (Zillén et al. 2008; Rabalais et al., 2010; K.-K. Liu et al., this issue). The relative importance of natural and human (nutrient) drivers and efficacy of nutrient legislation has been under debate in recent years (e.g., Bianchi et al., 2008). For example, shrinking of hypoxic areas in the Black Sea appears to have resulted from reductions in human agricultural nutrient inputs, though the extent of the human impacts on this ecosystem is still not clear (Mee et al., 2005). In addition, as indicated above, the balance between N, P and Si is being modified by many factors that affect coastal production, both qualitatively and quantitatively (Ragueneau et al., 2005). CO_2-driven changes in warming, winds, upwelling, and precipitation will inevitably influence both the intensity and areal cover of hypoxia in many dead zones (Rabalais et al., 2009, 2014; Giani et al., 2012).

3. Comparisons across continental margins

To gain a broader sense of how shelf systems are responding to climatic forcing and direct human activities we have compared multiple physical and biogeochemical observations collected at geographically contrasting locations (Fig. 3, Table 2). Consistent with the global warming trend, three out of five margins (the Cariaco Basin, East China Sea and North Sea) have shown increasing temperatures over the last four decades (slope = X °C yr^{-1}; $p < 0.01$), except for San Francisco Bay (slope = -0.029 °C yr^{-1}; $p = 0.07$) where a cooling trend has been detected (For more detail see Supplement A). The cooling trend observed in San Francisco Bay is attributed to an increase in upwelling intensity accros the entire California Curruent system resulting from increasing northerly wind stress along the western coast of the US (Chavez et al., 2011). The warming trend in the Cariaco Basin, in turn, is the result of the weakening of the Trade Winds, and thus of upwelling intensity, along the southern Caribbean Sea (Astor et al., 2013; Taylor et al., 2012).

No significant trends in sea surface salinity (SSS) are observed at the Cariaco Basin or the North Sea. SSS in the Bohai Sea, however, shows a positive trend (0.0632 yr^{-1}) (Fig.

3b). The increasing salinity of the Bohai Sea is thought to be caused by decreasing freshwater discharge from the Yellow River (Fig. 3d).

The load of dissolved inorganic nitrogen (DIN) in Changjiang (aka the Yangtze River), which empties into the East China Sea, has increased by over two-fold (Liu et al., 2014) between 1970 and 2002 (Fig. 3c), while this river's freshwaterwater discharge has only increased slightly (Fig. 3d). This suggests that rising DIN concentrations in the Changjiang River is mainly due to the intensive use of chemical fertilizer (Yan et al., 2010). By contrast, and due to EU policy change, the DIN load discharged to the North Sea has decreased by 50% since 1977. Dissolved inorganic phosphorus (DIP) shows a similar decreasing trend at this location (Pätsch and Lenhart, 2011)

The sea surface chlorophyll-*a* concentrations in SF Bay have increased in the last two decades (Fig. 3e), which is consistent with the observed decreasing trend in SST . Simultaneously, however, chlorophyll-*a* in the Cariaco Basin shows a decreasing trend since the late 90's due to weaker upwelling events and stronger thermal stratification (Taylor et al., 2012). The monthly mean sea surface chlorophyll-*a* in the East China Sea derived from ocean color products by NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) also exhibits a significant increasing trend since 1998, which is thought to result from increased DIN loads from the Changjiang River (Fig. 3c) (K.-K. Liu et al., this issue).

In response to increasing phytoplankton growth, bottom water oxygen saturation in SF Bay and the East China Sea has shown a significant decline (Fig. 3f). Oxygen saturation shows a weak decline in the upper 3 m at the CARIACO Station (Fig 3f), probably due to warming and possibly to lower oxygen production by phytoplaknton (Fig 3e).

Different margins show markedly different responses to local stressors and to global-scale change. Variations in availability and temporal coverage of different environmental parameters highlight the need for comprehensive and sustained time-series observations on continental margins. These are required in ordert to understand ecosystem responses to natural, CO_2 climate-driven and direct human perturbations.

4. Ecosystem responses to biogeochemical change on continental margins

Some of the most apparent environmental and ecosystem consequences due to the common climate and human stressors discussed in this special issue are summarized in Table 1 and discussed below.

Human alteration of hydrological processes such as damming and water diversion (B3, B4), drives very noticeable physical changes in margins causing loss of habitats due to coastal erosion or reduced river discharge (e.g., S.M. Liu, this issue). When combined with climate effects, resulting salinity increases can lead to species invasions that reshape coastal ecosystems. Following massive water diversion and drought in San Francisco Bay, an invasion by Asian clams altered the timing and magnitude of phytoplankton availability, with cascading trophic consequences (Cloern and Jassby, 2012, B3). In the

Bay of Brest, introduction of an invasive limpet changed the seasonality of primary production, which in turn has changed benthic biodiversity and completely modified the benthic-pelagic coupling over a 30-year period (Grall and Chauvaud, 2002).

In a broad sense, land use change alters how rainfall interacts with the landscape. Some land-use activities result in increased soil degradation and erosion (i.e., agriculture, mining), and in eutrophication of rivers and continental margins through the use of fertilizers. The coastal zone's high primary productivity and the abundant filter feeders (e.g., Lotze et al., 2006) offset land-derived nutrient inputs to some extent, but are tested by eutrophication and overfishing (B2). Moreover, rising sea levels will lead to flooding of low-lying coastal regions like India and Bangladesh, movement of seawater farther up estuaries, and intrusion of seawater into groundwater reservoirs.

Eutrophication is among the most widespread of coastal insults (Table 1; B2, B3, B4, B5, B6), but the outcomes, which include productivity enhancement *and* hypoxia, can be complex. For example, several cross-system comparisons indicate that increased N enhances total landings of fish and mobile shellfish even in systems with hypoxia (Fig. 4), although individual species may decline and the overall composition of the catch can be affected (Nixon and Buckley, 2002; Breitburg et al., 2009b). On the downside, hypoxia - an endocrine disrupter in fish that experience chronic exposure (Thomas et al., 2006) - can favor gelatinous plankton and some bivalves (Breitburg et al., 2003), and create and eliminate shallow water refuges for small and juvenile fishes (Breitburg et al. 2009a).

Reversal of eutrophication trends have been observed in some areas such as the Danish straits (Carstensen et al., 2006), the Scheldt Estuary (Soetaert et al., 2006) and other continental European rivers discharging into the North Sea (Emeis et al., this volume), the open Northern Adriatic (Giani et al., 2012), and the NW Black Sea (McQuatter-Gollop et al., 2009). In some instances P reduction has been considered to be a primary driver of these changes. In the areas subject to oligotrophication, overfishing may act synergistically to diminish the trophic chain and reduce seafood resources (B5). However, along the Danish and Finnish coasts, dissolved oxygen in bottom waters continues to drop despite efforts to reduce nutrient discharge (Carstensen et al., 2014). In the Baltic Sea, which hosts nearly 20% of the world's identified coastal hypoxic sites, climate and nutrient drivers interact with regional circulation patterns and wastewater treatment technologies to produce a mosaic of faunal responses (Conley et al., 2011).

While eutrophication-induced hypoxia is spreading, warming also causes the ocean to lose oxygen due to the synergistic effect of reduced oxygen solubility and enhanced water column stratification (Bopp et al., 2001). This has been termed deoxygenation and contributes to global expansion of oxygen minimum zones (Stramma et al. 2010). Recent model results demonstrate the extreme sensitivity of the volume of suboxic water in the open ocean to changing climate conditions (Deutsch et al., 2011). Biological analyses suggest that equator-ward species boundaries are highly sensitive to changes in ocean temperature and oxygen content. Models predict a decline in metabolic scope of species (energy available for maintenance and reproduction) and functional habitat loss.

On margins both eutrophication and intensified upwelling typically increase production while drawing down oxygen and creating hypoxia at deeper water levels. Animal avoidance of hypoxia acts to aggregate species around or above hypoxic zones, and leads to habitat compression, both in estuarine settings and in open-ocean oxygen minimum zones (OMZs). The resulting aggregations are susceptible to overfishing (Craig, 2012, Breitburg et al., 2009b), but high catches may mask the consequences of ecosystem stress, making detection of habitat degradation difficult (Breitburg et al., 2009b). Such conditions also induce shoaling of the zooplankton biomass layer at the thermocline (upper oxycline boundary) and concentration of midwater biomass in a layer at the lower oxycline (Wishner et al., 2013). As oxygen declines and oxygen minima shoal in both the Atlantic and Pacific, large billfish are now found at shallower depths and are increasingly susceptible to overfishing (Prince and Goodyear, 2006; Prince et al., 2010; Stramma et al., 2011).

Upwelling margins, which host key world fisheries, exhibit strong vertical gradients in temperature, oxygen and pH associated with oxygen minimum zones (Paulmier et al., 2011). Across these gradients bathyal benthic assemblages reveal shifts in diversity, body size, zonation, carbon processing, bioturbation, colonization and resilience (Levin, 2003, Levin et al. 2009; Gilly et al., 2013; Levin et al., 2013). Intensified upwelling is predicted to result in changes in biodiversity and ecosystem functioning associated with the expansion of OMZs (Stramma et al., 2010; Gilly et al., 2013). Recent onset of seasonal hypoxia on the Oregon inner shelf now causes summer die-offs of fish and invertebrates (Grantham et al., 2004). Responses to intensified upwelling winds and increased stratification can also vary regionally. For example, comparative analyses of the California and Canary systems reveal substantial differences in the responses of biological production and air–sea CO_2 fluxes to upwelling intensification in these two systems (Lachkar and Gruber, 2013). These differences have been attributed to various drivers such as the contrasting shelf topography, eddy activity, coastal water residence times and basin-scale forcing in the two regions (Marchesiello and Estrade, 2009; Lachkar and Gruber, 2013). These differences also affect the vulnerability of these ecosystems to global anthropogenic perturbations such as ocean acidification (Lachkar, 2014). Other upwelling regions have received less attention and could exhibit additional (or alternative) response mechanisms.

CO_2-induced climate change is the predominant forcing on the ecosystem of the polar margins (S8). Warming of the Arctic is taking place two to three times faster than global rates (Trenberth et al., 2007); as a result sea-ice cover has been decreasing at a rate of >10% per decade with ice-free summers expected in a few decades. Arctic ecosystems are increasingly being challenged by tipping elements (Duarte et al., 2012; Naam, 2012; Wassmann and Lenton, 2012). In the future Norway may experience decreased primary productivity, while Russia will show increased productivity. Nowhere will adaptation be a more critical element of sustainability than in the Arctic, because the Arctic shelves have inordinate importance in feeding the world population. (See S8 for more details)

Among the many effects of rising atmospheric CO_2, the significant decrease of ocean pH (ocean acidification) and shift in seawater carbonate chemistry (Doney et al., 2001) may elicit some of the most economically significant responses from margin ecosystems. Acidification alters seawater chemical speciation, most notably the lowering of calcium carbonate saturation states, which impacts shell-forming marine organisms from plankton to benthic molluscs, echinoderms, and corals, all of which are abundant in continental margins. Ocean acidification is exacerbated in the coastal zone by increased land-derived nutrient inputs, which enhance, in turn, productivity of organic matter and therefore respiration and release of CO_2 (e.g., Borges and Gypens, 2010; Cai et al., 2011). A serious drop of aragonite saturation state has occurred in some coastal seas, such as the North Yellow Sea, threatening the aquaculture of shellfish (e.g., Zhai et al., 2014). Coral reef ecosystems, which provide key fisheries, critical shoreline protection and habitats for a large number of species, are highly susceptible (Andersson and Gledhill, 2013). Due to ocean acidification, rates of coral calcification may decrease, whereas rates of bioerosion and carbonate dissolution may increase, resulting in a transition from net accretion to net erosion. Impairment of the calcifying capacity of marine organisms is therefore expected to have negative impacts on coral reefs and other calcifiers (e.g., bivalves) and on the ecosystem services they provide.

The complexity of ocean biogeochemical-ecosystem interactions on margins means that some drivers will create responses that generate feedback – further altering a system. One example occurs when acidification-induced undersaturation of carbonate minerals adversely affects shell growth and settlement success of bivalves and coral polyps building reefs; this is predicted to ultimately reduce oyster, mussel and clam populations and coral reef building. Locally, the presence of large oyster populations buffers increasing CO_2 and decreasing pH through shell dissolution and alkalinity increase. So lowered pH ultimately reduces local buffering capacity, leading to further reductions in pH when the mineral buffer is exhausted. In addition, mass removal of shellfish (by harvest), could contribute to a deficit in the carbonate balance, as the shells form a dissolution buffer needed by many animals to survive (Waldbusser et al., 2013). Populations may be reduced to the point of unsustainability leading to 'recruitment overfishing'.

On some margins high-frequency climate oscillations are the dominant driver of biogeochemical variation and consequently, ecosystem structure. In the Bay of Calvi in the Ligurian Sea of the NW Mediterranean (Goffart et al., this issue) the biogeochemical condition is very oligotrophic during mild winters and mesotrophic during moderate winters (B7). During severe winters, the Bay sustains a "high nutrient - low chlorophyll" situation. With little human disturbances this Bay may serve as the baseline, against which ecosystem changes in the Mediterranean due to direct human impacts can be detected (see B7 for more details). In the East Pacific Ocean, interannual variations linked to ENSO induce low productivity (well oxygenated) El Nino and high productivity (low oxygen) La Nina conditions that affect fisheries production in the Humboldt and California and Benguela current ecosystems (Arntz et al., 2006).

5. Using time series to distinguish drivers of change

Hydrographic and ecological time series have provided data critical to evaluating and interpreting change on margins. Koslow and Couture (2013) have referred to ecological time series as the Cinderella (hard working drudges) at the climate change ball. Beyond this they may provide the "Anthropocene's canary in a coal mine" for many other forms of human disturbance. Below we address the approaches, benefits and limitations of time series in attribution of change on margins.

Several multi-decadal oceanographic time series measurements from a variety of coastal and pelagic systems have shown how lower and intermediate trophic levels, and biogeochemical cycling react to climate oscillations regionally and globally (Chavez et al., 2003; Black et al., 2011; Church et al., 2013) (Table 1). Multi-decadal time series of phytoplankton have been generated for many regions including San Francisco Bay (Cloern and Jassby, 2013), Chesapeake Bay (Lee et al., 2013), Narragansett Bay (Borkman and Smayda, 2009), the Cariaco Basin (Chavez et al., 2011, Muller-Karger et al., 2013), the North Sea (Wiltshire et al., 2008) and areas of the Mediterranean Sea (e.g. Goffart et al., 2002, Ninčević Gladan et al., 2010, Zingone et al., 2010, Goffart et al., submitted) including the Northern Adriatic (Bernardi-Aubry et al., 2012, Marić et al., 2012, Mozetič et al., 2012) and Gulf of Naples (Ribera d'Alcalà et al., 2004). There are also Arctic time series in the Bering, Chukchi, and Barents Sea. Most of these reveal oscillations associated with climate variability (Borkman et al., 2009; Harrison et al., 2010). Indeed, such long-term ocean time series have been fundamental for expanding our knowledge about the sensitivity of marine biodiversity, ecosystems and biogeochemistry to environmental change (Church et al., 2013; Koslow and Couture, 2013). However, moving forward an international network of time series is needed to evaluate regional linkages and interpret global changes.

There are some major gaps in time series monitoring. Whereas models of nutrient fluxes from watersheds abound, monitoring data to verify them do not. In the developing world, the scarcity of monitoring data adequate to characterize riverine nutrient flows has impeded our understanding of the relationships with human activities. Research and development of monitoring in these regions, should be made a priority, and would improve our management of coastal waters. It is important to add that not only the N cycle should be monitored, but also changes in nutrient ratios delivered by rivers. In particular the Si:N and Si:P ratios should be closely monitored as potential early warning indicators of disturbances (Billen and Garnier, 2007); indeed, they are often decreasing due to excessive N and P inputs and decreasing Si inputs due to damming (Humborg, 1997) and the proliferation of invasive species (Ragueneau et al., 2005) causing replacement of diatoms by dinoflagellates. South East Asia, where anthropogenic factors leading to decreasing Si:N and Si:P ratios combine, should be especially targeted for monitoring (Ragueneau et al., 2006).

Modern time series gain added value when used in conjunction with paleooceanographic studies (Black et al., 2011) and models (see Church et al., 2013); together these tools allow researchers to discern natural sources of environmental change from variations induced by climate change (warming, extreme flooding from river input or snow melt, or heat waves) and direct human drivers such as eutrophication, damming and fishing (Koslow and Couture, 2013). In some margin settings subject to long bouts of habitation and industrialization (e.g., Chesapeake Bay, the coastal SE North Sea, northern Adriatic), natural variability is a small signal relative to the influence of humans. In others (e.g., upwelling margins) natural variability produces an exceedingly strong signal and irrefutably detecting CO_2-driven climate change or anthropogenic forcing is difficult.

Sediment and glacial ice core climate records often provide the long temporal perspective needed to identify climate oscillations prior to high anthropogenic CO_2 (> 280 ppm) conditions or resulting from long-term changes in human population density and land use practices (Cooper and Brush, 1993; Emeis et al., 2000; Yasuhara et al., 2012). Some of these geological climate records are now complemented by oceanographic and biogeochemical time series observations, thus providing valuable insights into the effects of anthropogenic perturbations on the marine environment (see Black et al., 2011).

Time Series and Coastal Management. The motivation underlying the establishment of ecological time series varies. In California, CalCOFI was developed in the 1950s to understand the boom and bust cycles of the sardine (Bograd et al., 2003; Chavez et al., 2003). At its inception, the CalCOFI concept of monitoring the entire ecosystem, now widely accepted in the context of ecosystem-based management, was visionary and somewhat heretical. In Chesapeake Bay, a long time series of young-of-year fish abundances in Maryland waters was initiated in 1954 by the state fisheries agency to aid management of several anadromous species (Durrell and Weedon, 2011), a time series of jellyfish abundances was begun in 1960 by a University of Maryland researcher in response to the 'Jellyfish Nuisance Act' (Cargo and King, 1990), and bay-wide time series monitoring of water quality parameters was begun in the 1980s with funding from the States of Maryland and Virginia and the US EPA to aid management efforts to improve water quality conditions (Boesch et al., 2001). Governments of states bordering the western coasts of Europe (OSPAR) and the Baltic Sea (HELCOM) initiated monitoring programs in the 1970´s to protect the marine environment from all sources of pollution through intergovernmental cooperation.

Although each time series is fixed in space and provides local information, when data are combined across time series they can provide a powerful synoptic understanding of the link between climate variability and ocean biogeochemistry (Church et al, 2013). The ICES Phytoplankton and Microbial Plankton Status Report 2009/2010 exemplifies this for the North Atlantic (O'Brien et al., 2012). Records of sea ice cover and tipping points in the Arctic provide another example (Carstensen and Weydmann, 2012). Under optimal conditions, time series provide data prior to catastrophe (e.g., fishery collapse) so that causes can be discerned. It is important, however, to recognize the value of understanding regional differences and their forcing mechanisms.

Time series constraints. Spatially fixed time series may have limitations. Single-location measurements typically do not reveal spatial expansions, contractions or oscillations. They cannot recognize change due to relocation of organisms or features, making it difficult in some cases to untangle spatial and temporal change, although spatial comparisons can sometimes be used as proxies of temporal change (e.g., Wishner et al., 2013). Satellite remote sensing has typically been the tool of choice for extrapolating fixed time series observations to broader spatial and temporal scales. Some time-series stations (i.e., Hawaiian Ocean Time-series [HOT] and the Bermuda Atlantic Time Series

[BATS]) have been successful at using autonomous samplers and sensors (e.g., gliders, drifting profilers) for learning the regional significance of the measurements they collect. These are especially important for hard-to-reach areas like the Arctic and Antarctic, and can expand coverage for traditional time series in other regions. Autonomous sampling platforms, however, are expensive to operate and thus are out of reach for time-series programs with limited resources. Another approach is to engage platforms of opportunity. Industry with a presence on the ocean margins, such as offshore wind and aquaculture, fishing, fossil fuel extraction and minerals, may have a role to play in time series development in the future, and should be broadly engaged to support monitoring efforts. Expansion of programs like the World Ocean Council Smart Data/Smart Industries (http://www.oceancouncil.org/site/smart_ocean.php) may be useful.

Time, funding and facilities constraints often limit time series to the upper water column and basic hydrographic parameters. To link these to key resource needs and sustainable management – including aquaculture, fisheries, energy and minerals – it will be necessary to incorporate the sea floor and its organisms into time-series monitoring. Benthos monitoring can also provide critical information about biogeochemical feedbacks from the sea floor, processes often not included in large-scale climate or ecosystem models.

Most margin time series are not of sufficient duration to detect variation outside normal statistical variability (especially given decadal-scale cycles emerging in the atmosphere-surface ocean system). Often shifts and change are misattributed due to lack of knowledge about natural variability and its sources. Paleoceanographic records in ice cores, sediment cores or tree rings allow us to extend understanding of margin processes back in time, prior to the establishment of *in situ* observations (Gooday et al. 2009). Innovative analyses of scales, teeth, otoliths and ichnofacies may allow use of such records to reconstruct complex changes in exposure histories and food web dynamics (Gooday et al., 2009; Morat et al., 2014). Recent development of geochemical proxies for detection of fish exposure to hypoxia offers the promise of identifying past and present trends in oxygen concentration using otoliths (Limburg et al., 2011; 2014 [this volume]); fish scales and other skeletal elements may also prove useful, but require testing. Chronosequences from long-lived calcifying organisms (e.g., coldwater corals or bivalves) may provide excellent time series of temperature or pH as a basis for chronometric analyses similar to dendrochronology (e.g., Chauvaud et al., 2005, 2012; Black et al., 2008). Novel functional gene microarrays may be used to evaluate the diversity and composition of the denitrifying microbial community in hypoxic settings like OMZs, allowing us to better understand how microbial metabolism can impact the global climate through the production of N_2O, a bi-product of denitrification and a powerful greenhouse gas (Jayakumar et al., 2013). We need to further develop proxy variables for environmental reconstructions, expand the data bases for regional-scale hindcasts, and strive to detect and interpret interannual variability from low resolution archives.

While valuable in having fixed measurements, time series may also need to have an adaptive observation component focused on (a) identifying changes and their underlying causes and (b) monitoring parameters tied to the ecosystem services we care about, in order to directly address policy concerns for effective management of these services.

There is often a gap between what we can realistically measure, and what we want to achieve. This highlights the importance of research on basic processes and mechanisms that will identify indicators of change and incorporate process-based knowledge into our models. Often the early warning of degradation will come from land. For example, agricultural inputs, nutrient concentrations, N:P, Si:P , Si:N ratios or multiple nutrient concentration data together could be key indicators (Billen and Garnier, 2007).

The burgeoning number of time series and rising volumes of data highlight a need to engage more scientists in the analysis phase of time series research. There is also a challenge of maintaining continuity in the face of severe funding shortages; scientists must advocate for continuation of monitoring programs. Key to the successful continuation of time series is concise presentation of insight gained and raising the awareness of the public and policy makers of their value. It is here that social scientists can help natural scientists learn how to make a strong case without loss of integrity and accountability.

6. The continental margin in the Anthropocene: the convergence of biogeochemistry, ecosystems and society

To be effective, economic models must be able to weigh the costs of the unwanted impacts of stressors and forcings on ecosystem services discussed above and associated consequences against gains for society, and to attribute change to specific and controllable drivers. To date scientists have failed to convey the message of the overriding importance and societal consequences of CO_2 emissions (as well as other greenhouse gases) in the context of global warming. Investment in collaboration efforts between social and natural scientists, development of outreach and public communication skills, and advocacy about the importance of individual actions are required to manage margins effectively (Pidgeon and Fischhoff, 2011). A need to combine scientific with traditional and local ecological knowledge, especially in settings such as the Arctic, further argues for key social-natural science integration.

There is growing need for modeling of coupled human (social)-biogeochemical systems on margins. A pioneering example can be found for the surfclam fishery on the Middle Atlantic Bight (MAB) continental shelf (McCay et al., 2011). This million-dollar fishery has been managed since the 1990s with transferable quotas, one of the first in the US to do so. In recent decades the population has shifted to the north and overall abundance has declined (Weinberg, 2005). Simulations of surfclam growth that use 50-year hindcasts of bottom temperature obtained from an implementation of the Regional Ocean Modeling System for the MAB (Kang and Curchister, 2013) show that episodic warming events increase surfclam mortality and limit animal size in the southern portion of its range (Narváez et al, this issue). The resulting northward movement of the stock has negative economic consequences for the fishing fleet and processing plants. These studies point to a key role for natural scientists in assessment of the socio-economic consequences of climate change (McCay et al., 2011).

Disasters can sometimes serve as catalysts for action. In the United States, several disaster events have caught the attention of the scientific community and policy makers, and have resulted in the development of large-scale monitoring efforts that seek to mechanistically understand these events and mitigate their impacts by improving our predicting capabilities. One example is the unexpected failure of the oyster aquaculture fishery on the US Pacific coast due to upwelling of carbonate-undersaturated waters (Barton et al., 2012); this stimulated state-sponsored research programs on ocean acidification (Adelsman and Binder, 2012). Highly destructive Superstorm Sandy stimulated sea level rise preparedness, and massive fish kills resulting from hurricane-induced release of hog waste and sewage in North Carolina (Malin et al., 1999) have engendered public support for altered agricultural practices and backup treatment plants. These types of events are not one–time occurrences, but are likely to become more frequent. For example, low bottom-water aragonite saturation values on shelves are expected to have negative effects on shellfish in the Yellow Sea (Zhai et al., 2014) and off California (Gruber et al., 2012). The costs required for building community, industry and ecosystem resilience are now being weighed against the massive costs of disaster damage and disaster relief.

While continued and expanded time series measurements are essential to monitor status and trends, scientists often know enough to make strong policy recommendations regarding CO_2, nutrients and human activities. In many instances adaptation to change is required and distinguishing among drivers is not essential for policy decisions. Whether reduced sediment inputs to the coastal zone result from damming or from drought, it will still be necessary to prepare for climate-related sea level rise and associated consequences of limited land-building and net loss of coastal wetlands. For anadromous fishes, loss of freshwater inputs from damming versus drought will have similar consequences, as will loss of river-sea connectivity from eutrophication induced hypoxia versus upwelling-induced deoxygenation. For coastal shellfish, the corrosive effects of acidification may result from atmospheric CO_2 inputs, intensified upwelling, increased stratification, anthropogenic nutrient loads, precipitation or sea ice melting. Acting to reduce CO_2 emissions and limit the now-inevitable rise in ocean temperatures, acidification, and deoxygenation is critical.

There is growing consensus that direct anthropogenic stressors such as overexploitation of natural resources (fisheries, mining), habitat destruction, land use/cover change, alteration of river catchments, coastal construction, damming, species invasion and pollution will lower the resilience of populations, species and ecosystems and make them less able to cope with climate-induced stress (Bijma et al., 2013). For example, reducing fishing mortality in exploited populations can also reduce total mortality and be protective of declining populations, even where part of that total mortality was due to hypoxia, disease or habitat degradation (Breitburg et al., 2009b). Thus policy, law and management of margins must consider and address climate and direct human stressors together. Relevant lessons can be drawn from regional, time series and case studies where different combinations of stressors interact and their trends have been tracked over time. Understanding system connectivities, seeking indicators of regime change, and promoting adaptation-oriented policy to build functional resilience, are lessons from the Arctic (Carmack et al., 2012) that apply well to most margin ecosystems. The recently released IPCC AR5 report emphasizes the overwhelming need for societal adaptation to multiple stressors associated with climate change, especially in countries where poverty will exacerbate the consequences (Field et al. IPCC 2014).

The recognition of the importance of natural capital and ecosystem services to national wealth has come slowly to some nations. In the USA this is now evidenced by the generation of a National Ocean Policy (2004; http://ioc-unesco.org/images/stories/LawoftheSea/Documents/NationalOceanPolicy/nop.usa.pdf). To a large extent this policy addresses the continental margins, where most of the key services and commercial resources are provided. The Marine Strategy Framework Directive (Directive 2008/56/EC**, http://ec.europa.eu/environment/water/marine/ges.htm)**, adopted by the European Commission in 2008, marks an important milestone in the development of the EU's marine environmental policy and is the first framework instrument aimed expressly at protecting and preserving the marine environment with a holistic approach. In 2012 The EU launched its Blue Growth initiative (http://ec.europa.eu/maritimeaffairs/policy/blue_growth/) that addresses three crucial components of sustainable development of marine resources: gathering and channeling marine knowledge to improve access to information about the continental margins of Europe, maritime spatial planning to aid management of offshore resources, and integrated maritime surveillance. Other nations have national ocean policies in review (e.g., South Africa) or in early stages of formulation (Namibia).

Margin management strategies must move from mono- to multiple stressor considerations. Most policies and research programs address only one or two factors – nutrients, oxygen, ocean acidification, fishing pressure, disease, or invasive species, (e.g., Crain et al., 2008). We know that T, O_2 and CO_2 are changing simultaneously and interacting (Bijma et al., 2013). There is need for scientific consensus on a) what the multistressor questions are and b) how to approach the issues. How to integrate laboratory studies, field observations, monitoring, modeling, and use of proxies to address these questions remains a major challenge.

To incorporate natural variability and climate change into our decision making and management activities *we need research that identifies, quantifies and confronts management tradeoffs.* Stakeholder identification and finding equitable solutions is critical as every decision has winners and losers. We must quantify the economic costs of nutrient reduction for agriculture, fishers, and ecosystem services. Margin researchers have only just begun to tackle the larger question of valuing ecosystem services and biodiversity on the continental slope beyond the shelf –this is especially critical in deep waters where resource extraction activities (energy, minerals and deep-water fishing) are on the rise (Levin and Dayton, 2009; Jobstvogt et al., 2013).

As both top predators and guardians of the planet we face immense ocean policy challenges over the next 10-50 years. The mentality of many nations is of a land-based society. Managing a fluid -connected environment is fundamentally different than managing land use where discrete boundaries between impacted and more pristine areas can be maintained. There is a spatial disconnect between farm policies and their effects on the coastal ocean and our margins. Even international climate negotiations (Converence of Parties) involve remarkably little consideration of ocean processes, despite the large role the ocean plays in regulating climate. The concepts underlying sustainability in ocean margins must involve an educational thrust that starts early, as well as strategies to communicate at national and international levels. *We need to better understand the process by which science is introduced to policy, and target and fast track scientific approaches that meet those needs*. End-to-end efforts are needed that first bring together the natural and human component of socio-ecosystems; and then work with stakeholders and policy makers towards finding and implementing solutions.

This article focuses on the impacts of the 20th century; we recognize that the 21st century may involve a different suite of primary stressors, some of which are as yet unknown. The continental margins of the future will undergo further changes as the system is continuously perturbed. As human populations grow, needs for fresh water, energy, space, and food will create new demands of the coastal ocean including coastal aquaculture, wind farms, wave energy stations and desalinization plants, intensified shipping activities, and seabed mineral exploration.

Holistic consideration of margins facing the confluence of human, climate and natural stressors highlights the need to integrate science with societal needs. Building on work of others (e.g., Islam and Tanaka, 2004), we identify the need to:

- Formulate a clear understanding of the environmental, ecological and economic value of margin ecosystems and how these vary under different climate regimes.
- Enact water quality management that recognizes land-ocean-atmosphere exchanges controlled by climate and humans.
- Enact comprehensive monitoring to link policy-based changes in drivers to ecosystem responses
- Improve cooperation of stakeholders, regulators, scientists and civil society
- Scale and coordinate local, regional, national and international activities to maximize knowledge and promote modeling efforts
- Protect key services via ecosystem-based management
- Develop mechanisms to translate scientific knowledge into regulation and legislation, and the political realities needed to achieve action.

Ultimately, we will need to set priorities, accept tradeoffs and motivate creative solutions. These goals are very much in line with the approach of the Future Earth Initiative to meet the grand challenge of global sustainability (Reid et al., 2010). Interactions among social and natural scientists are nascent, but a growing number of national and international programs recognize their importance. Achieving sufficient energy, water, food and healthy margin ecosystems is a tall order, but a challenge that natural and social scientists must work together to meet head on.

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Table 1. Environmental drivers and ecosystem responses on continental margins: Case studies

Consequences & regional responses (Supplements*)	**Drivers of environmental change on continental margins from regional to global scale**										**Actions taken**
	Land use change	**Damming, diking, water diversion**	**Alien species**	**Anthropogenic nutrients & pollutants**	**Energy & mineral extractions from the sea**	**Overfishing**	**Changes in water cycle**	**Rising sea level**	**Warming**	**Climate change & oscillation**	
General consequences	Changes in soil qual. & erosion in watershed	Sed. retention, decr. runoff	Change in ecosystem structure	Eutrophication, change in nutrient ratios & plankton community, HAB, hypoxia	Change in seascape & marine environments	Decr. fish stock, trophic cascades	Extreme weather, flooding, drought	Lowland flooding, salt water intrusion	Incr. stratification, drop in O_2, incr. vulnerability	Change in ocean circulation, upwelling,	
American margins											
Cariaco Basin (B1)						Collapse of Spanish sardine (*Sardinella aurita*)	Freshening of surface waters due to higher regional precipitation		>1°C incr. since 1995	Decr. upwelling, PP and phytoplankton biomass; incr. N*, change in ecosystem structure; Increasing zooplankton biomass	
Chesapeake Bay (B2)	Degrading water qual. & clarity	Blocked migratory pathways for anadromous fish	Decreased oyster populations and increased piscivory	Seasonal hypoxia, decline of SAV, fish advisories		extirpation of sturgeon, collapse of oyster fishery	Salinity drop following Tropical Storm Agnes	Rate of sea level rise much higher than average		Change in water exchange rate	Acts for reducing nutrients & restoring SAV, oysters; removing blockages to fish
San Francisco Bay (B3)		Decreased sediment supply, shrinking mudflats, incr. salinity	Decreased phytopl. PP due to Asian clams	Degrading water quality			Drought and water diversion trigger invasion			Change in bio-community	1972 Clean Water Act
Asian margins											
Bohai Sea (B4)	Changes in tidal regime	Massive drop in water discharge and sediment load, fishery collapse in 1990s		High N, low P and Si, decrease in diatom/ dinoflagellate ratio		Decrease in fish biomass; dominant fish species changed from bottom to pelagic fish			0.011oC per year increase during the 1960s-1990s		Artificially controlled water discharge in Yellow River
European margins											
Mediterranean - N. Adriatic Sea (B5)				N/P increase, anoxic events (1970s-1980s), loss of macrobenthos; trend reversed recently.		Loss of demersal fish, small pelagic fish and top predators		Reduced river flow, salinity rise			Mandates of reduction in P loading
North Sea (B6)		Altered mudflat		Massive coastal environment deterioration in 1980s	Massive wind farming				Temporally and regionally faster than global mean, provoked ecosystem shift	NAO state determines circulation mode and nutrient inventories	EU wide mitigation, Marine Strategy Framework Directive

*Note: More descriptions and references about the case studies are presented in electronic supplements listed under each case heading.

Increase in N*. Whether this is due to increased N fixation is being explored

Table 2. The temporal trends of the environmental variables presented in Fig. 3. All trends are statistically significant except those shown in italics. (For more detailed information on the linear regressions see Supplement A.)

Site	SST (^{o}C yr-1)	SSS (yr^{-1})	Q (km^3 yr^{-1})	DIN (Kt yr^{-1})	DIP (Kt yr^{-1})	Chl (mg m^{-3} yr^{-1})	O_2 saturation (% yr^{-1})
Bohai Sea	*0.0022*	0.0632	-0.75$^{(1)}$				
Cariaco Basin	0.0895	-0.0097				-0.0462	*-0.105*
East China Sea	0.0282		3.34	26.1		0.0135	-0.536
North Sea	0.0376$^{(2)}$	*0.0007*	-7.44	-12.1	-2.3		
SF Bay	-0.0290$^{(3)}$	*0.0427*				0.131	-0.290$^{(3)}$

Notes: (1) Water discharge of the Yellow River that empties into the Bohai Sea. (2) The mean temperature of the top 10 m in the North Sea in winter months (DJF). (3) The bottom temperature of the USGS Station 18 in the San Francisco Bay.

Figure Captions

Figure 1. Map showing locations of time-series observations that exemplify the interplay of natural variability, CO_2-driven climate change and human activities to shape margin ecosystems. Each area is discussed in the manuscript or summarized in Table 1. 1. Arctic Sea; American margins: 2. Cariaco Basin, 3. Chesapeake Bay, 4. Gulf of Mexico off Louisiana, 5. San Francisco Bay, 6. Southern California Bight; African margins: 7. Canary Current System, 8. Congo River Submarine Canyon; Asian seas: 9. Bay of Bengal, 10. Bohai Sea, 11. East China Sea; European seas: 12. Baltic Sea, 13. Black Sea, 14. Mediterranean - Corsica (Liguran Sea), 15. Mediterranean - N. Adriatic Sea, 16. North Sea.

Figure 2. Data plots of O_2 and pH illustrating time scales of natural hydrographic variability in the nearshore southern California Bight, USA. (a) Decadal scale suggesting regime shifts (modified from McClatchie et al., 2010). (b) Interannual scale illustrating effects of ENSO at a site 6 km from Del Mar (from Nam et al., 2011) (c) Seasonal scale combining CalCOFI data at line 93 and continuous mooring measurements (from Send and Nam, 2012), (d) Event (week) scale illustrating upwelling (blue) and relaxation (green) phases (modified from Send and Nam, 2012), (e) semi-diurnal and diurnal scale variations in the La Jolla Kelp Forest during upwelling phase (blue) when there are strong semidiurnal signals and relaxation phase (green) when kelp influences the oxygen and pH variability (Frieder et al., unpublished).

Figure 3. Time series of sea surface temperature (SST) (a), sea surface salinity (SSS) (b), nutrient loads (c), riverine discharge (d), chlorophyll-*a* (e), and saturation of dissolved oxygen (f) from the Cariaco Basin and San Francisco Bay (SF Bay) in the Americas, the East China Sea (ECS) and Bohai Sea (BH) in Asia, and the North Sea (NS) in Europe (See Fig. 1 for location of time-series stations). SST time series include values obtained from satellite remote sensing monthly composites (lines without symbols) from NOAA's National Climatic Data Center (See Supplement A), and *in situ* observations (lines with symbols). Statistically significant regression ($p < 0.1$) results are shown as solid straight lines; insignificant ones are shown as dashed lines. (See text).

Figure 4. The relationship between nitrogen loading and fisheries landings as a function of hypoxic area for mobile species in estuaries and semi-enclosed seas. Modified from Breitburg et al., 2009b.

Figure 1

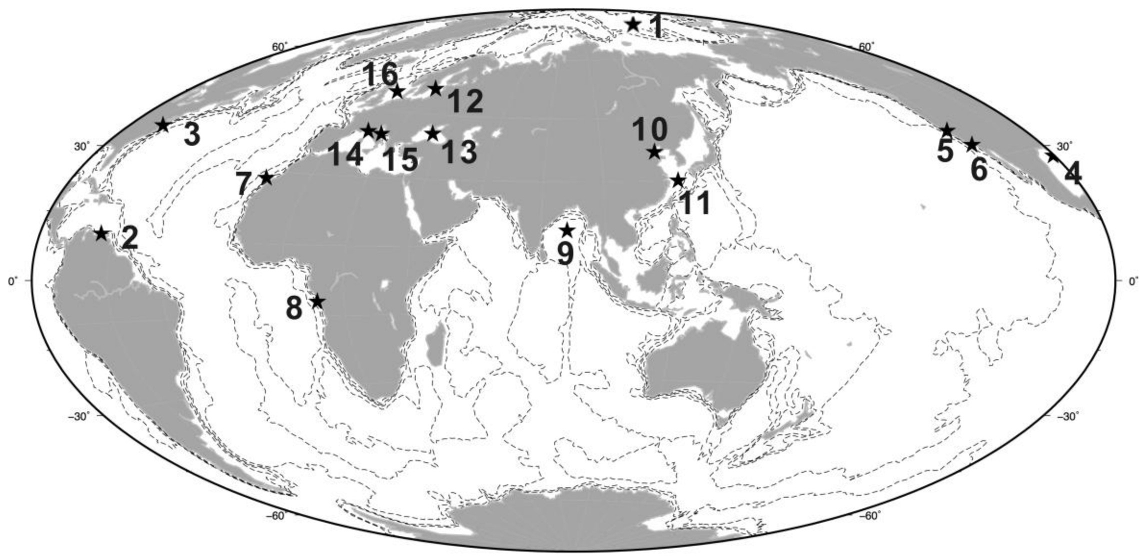
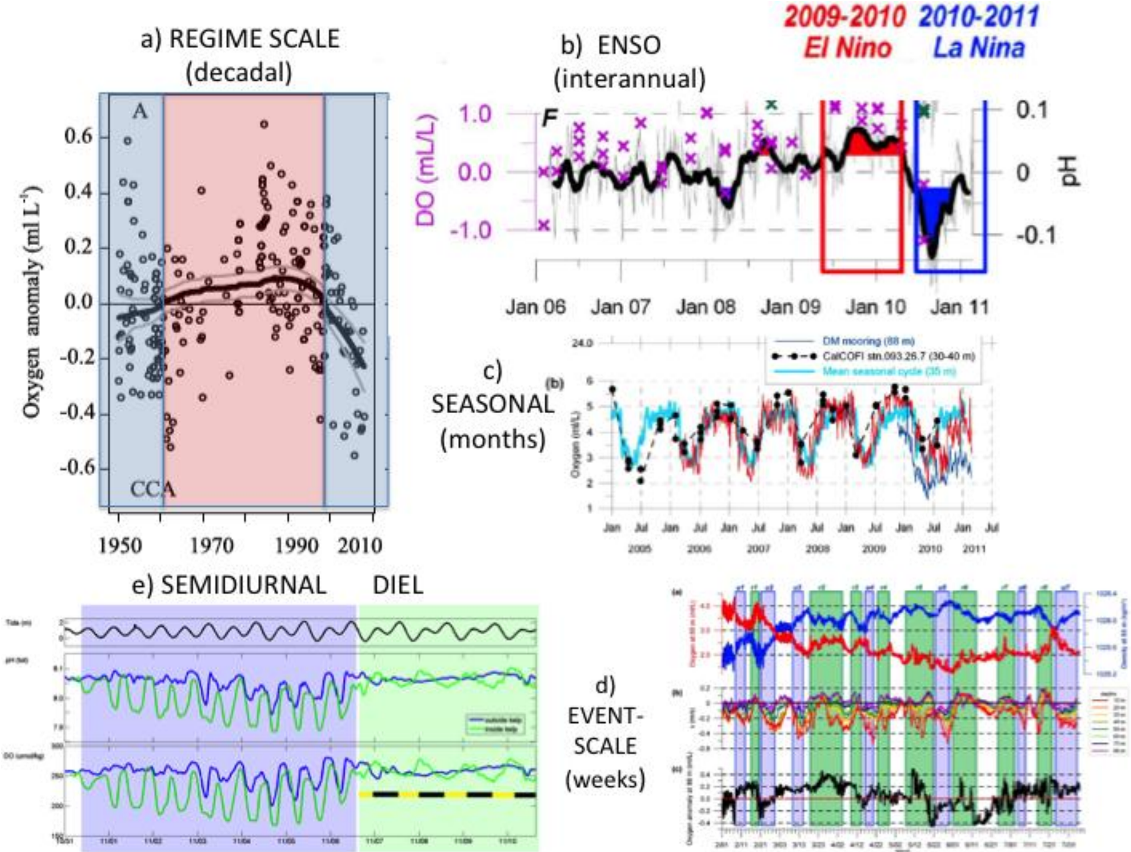
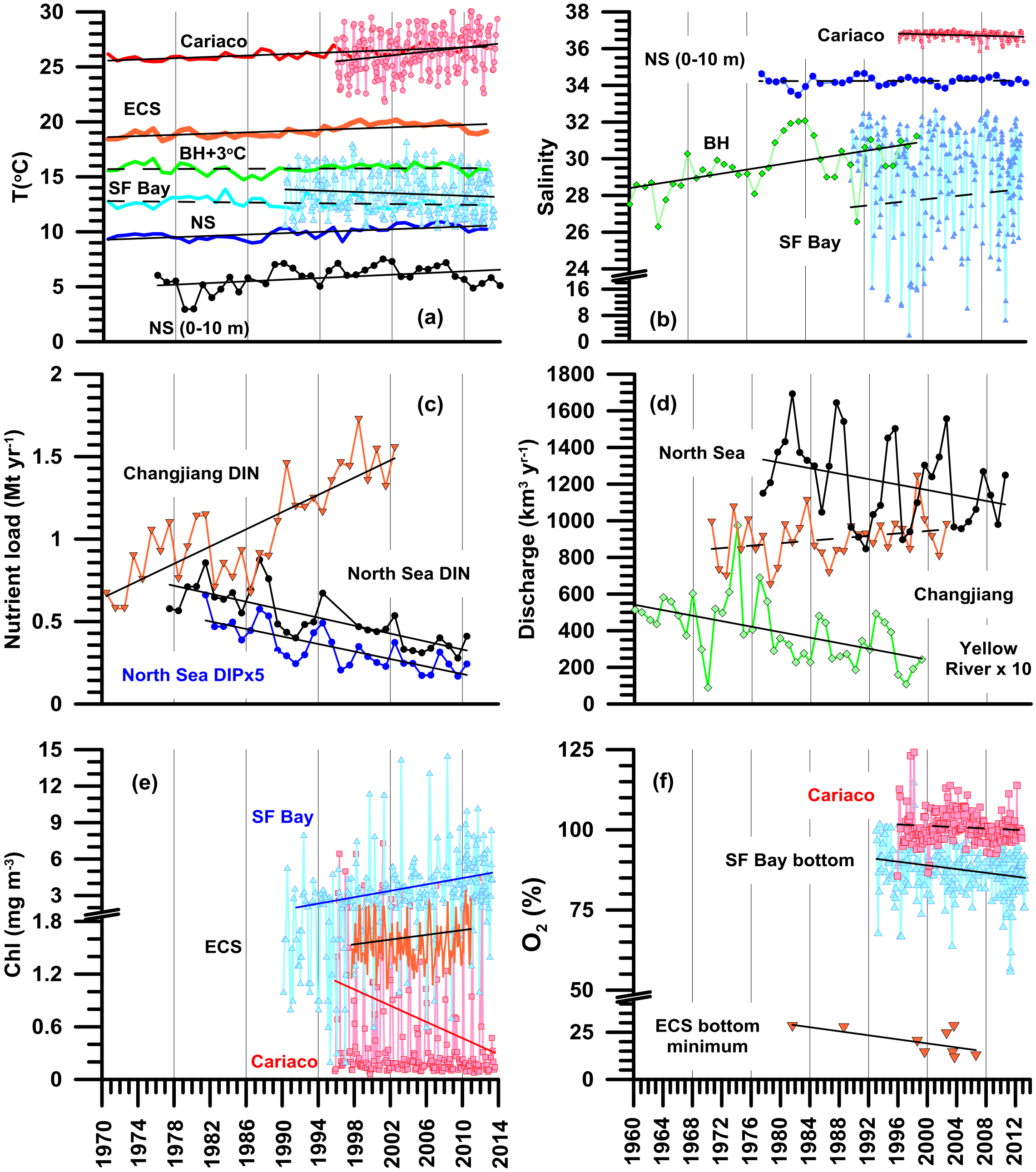


Figure 2


a) REGIME SCALE
(decadal)
A
CCA
Oxygen anomaly (ml L^{-1})
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1950
1970
1990
2010
b) ENSO
(interannual)
2009-2010
El Nino
2010-2011
La Nina
F
DO (mL/L)
1.0
0.0
-1.0
0.1
0
-0.1
pH
Jan 06
Jan 07
Jan 08
Jan 09
Jan 10
Jan 11
c)
SEASONAL
(months)
DM mooring (88 m)
CalCOFI stn.093.26.7 (30-40 m)
Mean seasonal cycle (35 m)
e) SEMIDIURNAL
DIEL
d)
EVENT-
SCALE
(weeks)

1551 **Figure 3.**

1552



1553

Figure 4.

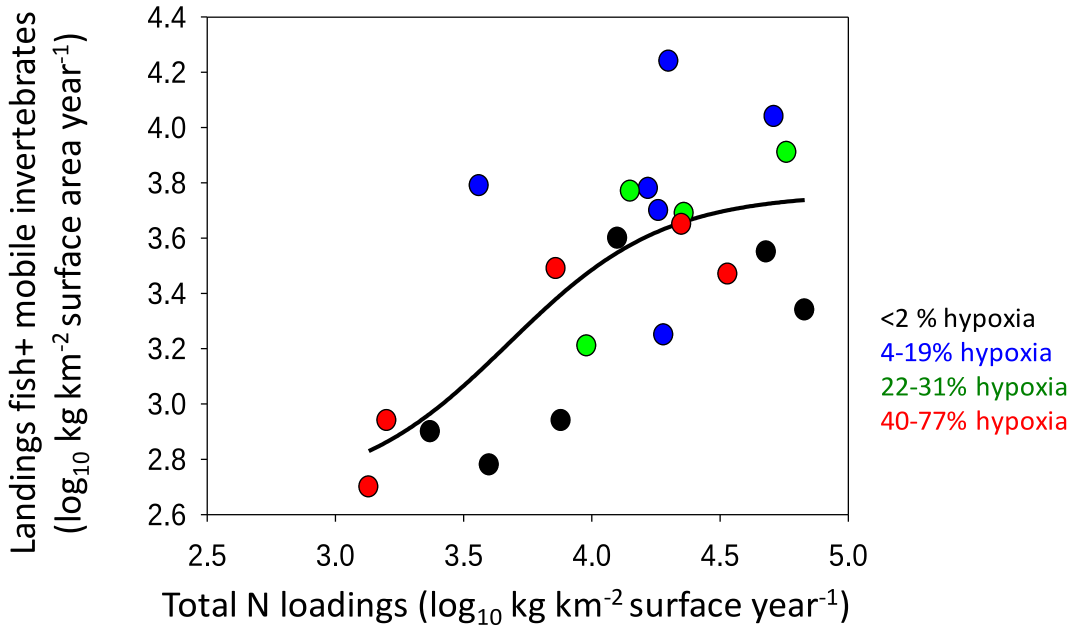

Landings fish+ mobile invertebrates
(log10 kg km-2 surface area year-1)
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.5
3.0
3.5
4.0
4.5
5.0
Total N loadings (log10 kg km-2 surface year-1)
<2 % hypoxia
4-19% hypoxia
22-31% hypoxia
40-77% hypoxia

Table A1. Locations of margin time series observations and data sources.

Sites	Coordinates	Data sources	Remarks
Bohai Sea	37-41°N, 117-121°E	SSS: Lin et al. (2001) Discharge: Liu et al. (2012); Liu (this issue)	Domain for satellite SST data retrieval
Cariaco Basin	10.2-11.0°N, -64~66°W	SST: See text	Domain for satellite SST data retrieval
CARIACO Sta	10° 30'N 64° 40'W	(http://imars.marine.usf.edu/cariaco/cariaco-ocean-time-series-program)	*In situ* observations
East China Sea	28-32°N, 121-125°E	SST: See text Discharge, DIN load: Liu et al. (this issue)	Domain for satellite SST data retrieval
North Sea	53~57°N, 4~8.6°E	SST, SSS: (http://www.ices.dk/marine-data/dataset-collections/Pages/default.aspx) accessed on March 31, 2014 Discharge, nutrient loads: Pätsch and Lenhart (2011)	ICES data
North Sea (L)	53-59°N, -2~8°N	SST: See text	Larger domain for satellite SST data retrieval
San Francisco Bay	38°50.8'N, 121°25.3'W	(http://sfbay.wr.usgs.gov/access/wqdata/index.html)	USGS Sta 18 (Point Blunt) Water depth = 43.0
Coastal zone adjacent to SF Bay	36.2-38.1°N, 122.5-124.7°W	SST: See text	Domain for satellite SST data retrieval

Table A2. Results of linear regression analysis of margin time series data. The statistically insignificant trends, defined as those with $p > 0.1$, are shown in italics.

Variables	Site	Period	Trend (per year)	n	R^2	*p*
SST (^{o}C)	Bohai Sea	1970-2012	*0.0022*	43	0.004	0.6830
	Cariaco Basin	1970-2012	0.0303	43	0.548	<0.001
	Cariaco Basin	1995-2012	0.0351	18	0.168	0.0917
	CARIACO Sta	1995-2013	0.0895	198	0.058	<0.001
	East China Sea	1970-2012	0.0282	43	0.438	<0.001
	North Sea (winter)	1976-2013	0.0376	38	0.160	0.0129
	North Sea (L)	1970-2012	0.0301	43	0.493	<0.001
	SF Bay	1990-2013	*-0.0126*	288	0.002	0.498
	Adj. SF Bay	1970-2012	*-0.0087*	43	0.053	0.138
	SF Bay bottom water	1990-2013	-0.0290	285	0.011	0.071
SSS	CARIACO Sta	1995-2013	-0.0097	188	0.048	0.0025
	North Sea (winter)	1976-2013	*0.0007*	38	0.001	0.846
	SF Bay	1990-2013	*0.0427*	287	0.004	0.300
	Bohai Sea	1960-1999	0.0632	40	0.287	<0.001
Discharge ($km^3\ yr^{-1}$)	Changjiang	1970-2002	*3.34*	33	0.068	0.142
	Huanghe	1960-2009	-0.750	40	0.251	<0.001
	North Sea	1977-2010	-7.43	34	0.103	0.064
DIN load ($kt\ yr^{-1}$)	Changjiang	1970-2002	0.0261	33	0.671	<0.001
	North Sea	1977-2010	-0.0121	31	0.601	<0.001
DIP load ($Kt\ yr^{-1}$)	North Sea	1981-2010	-2.28	30	0.596	<0.001
Chl ($mg\ m^{-3}$)	CARIACO Sta	1995-2013	-0.0462	201	0.039	0.005
	East China Sea	1997-2010	0.0135	152	0.021	0.073
	SF Bay	1990-2013	0.131	279	0.151	<0.001
O2 satu. (%)	CARIACO Sta	1995-2013	*-0.105*	180	0.009	0.198
	East China Sea	1981-2006	-0.536	9	0.390	0.072
	SF Bay bottom	1993-2013	-0.290	251	0.042	0.001