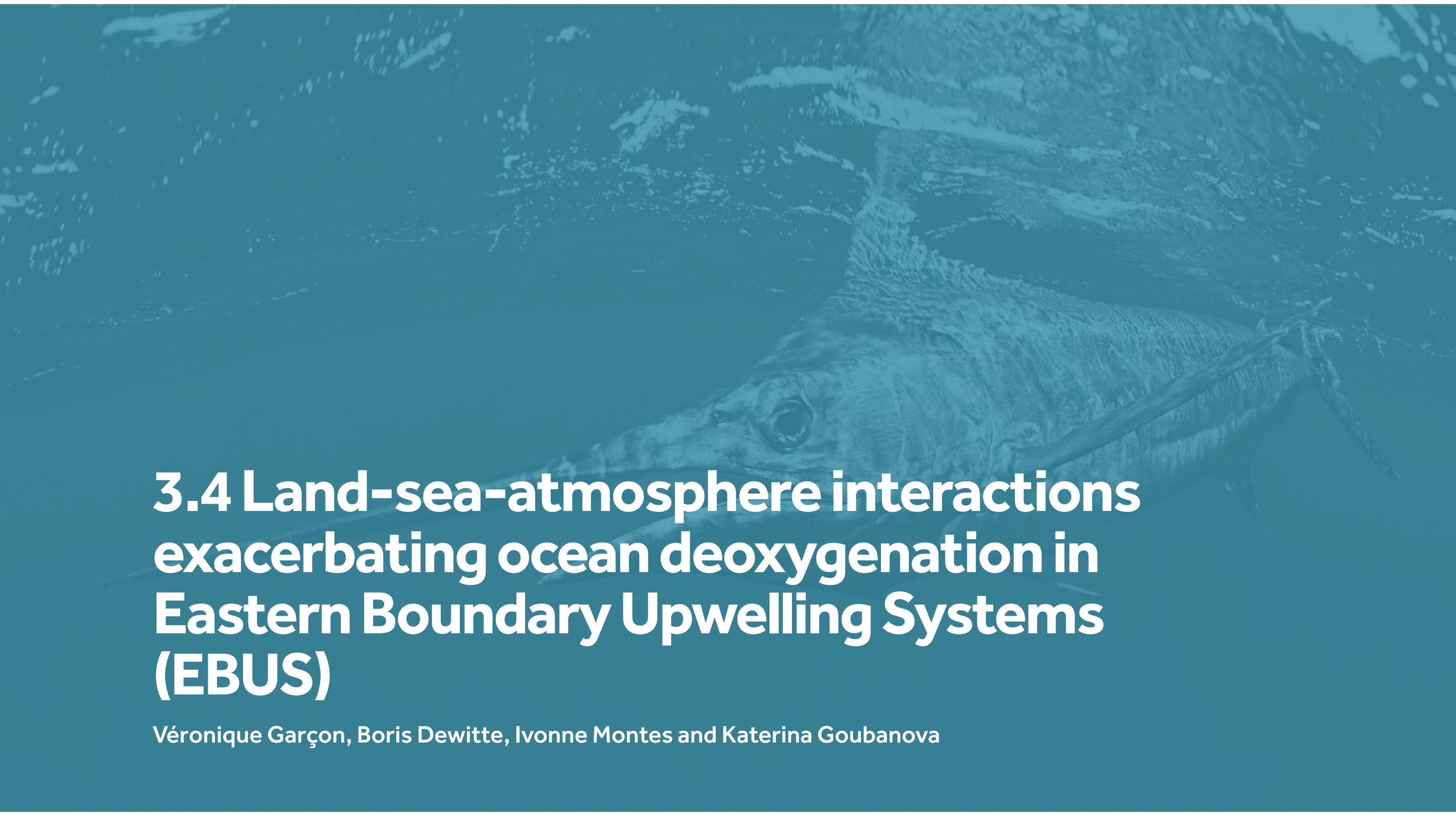
Ocean deoxygenation: Everyone's problem

Causes, impacts, consequences and solutions

Edited by D. Laffoley and J.M. Baxter



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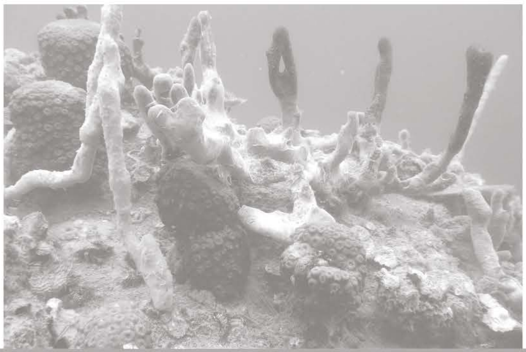
Véronique Garçon, Boris Dewitte, Ivonne Montes and Katerina Goubanova



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3.4 Land-sea-atmosphere interactions exacerbating ocean deoxygenation in Eastern Boundary Upwelling Systems (EBUS)

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Summary

- While the biogeochemical and physical changes associated with ocean warming, deoxygenation and acidification occur all over the world's ocean, the imprint of these global stressors have a strong regional and local nature such as in the Eastern Boundary Upwelling Systems (EBUS). EBUS are key regions for the climate system due to the complex of oceanic and atmospheric processes that connect the open ocean, troposphere and land, and to the fact that they host Oxygen Minimum Zones (OMZs), responsible for the world's largest fraction of water column denitrification and for the largest estimated emission (0.2-4 Tg N yr^{-1}) of the greenhouse gas nitrous oxide (N_2O).
- Taking into account mesoscale air-sea interactions in regional Earth System models is a key requirement to realistically simulate upwelling dynamics, the characteristics of turbulence and associated offshore transport of water mass properties.
- Land-sea-atmosphere interactions modulate warming-induced ocean deoxygenation. For instance, the effect of nutrients delivered to the surface ocean by atmospheric deposition may be to stimulate primary production and CO_2 uptake but also to release N_2O, which could exacerbate warming, offset the increased CO_2 uptake, and thereby accelerate deoxygenation.
- Global warming will alter ventilation and source water properties, oceanic stratification, near-surface wind, mesoscale activity, upwelling rates, low cloud cover, and air-sea exchange of gases and particles. Understanding these changes and their compensating/synergistic influences on the future trajectory of ocean deoxygenation is challenging due to the scarcity of available biogeochemical data and global model biases in EBUS. Regional coupled physical-biogeochemical modelling offers an opportunity for addressing the range of variability in timescales relevant to OMZ dynamics (i.e. from hourly to decadal timescales) in a realistic framework.

Air-sea-land processes/phenomena in EBUS	Mechanisms of their impact on oxygen content in the ocean	Spatial scales
Wind-driven coastal upwelling.	Physical mechanism where cold, nutrient-rich and low-oxygen waters outcrop supporting the high abundance of ocean plants (primary productivity) that produce almost half of the atmospheric oxygen we breathe, absorb a large amount of CO_2, and supply food for fish; which under future scenarios (global warming) could modify the export production and deoxygenation as well as other services, e.g. fisheries.	1-100 km
Ocean-atmosphere exchange of gases.	When OMZ waters upwell and impinge on the euphotic zone, there is a potential release to the atmosphere of greenhouse gases such as N_2O, CO_2 and CH_4 which further exacerbates global warming with feedbacks onto stratification, biological productivity and the oxygen inventory.	1-1000 km
Near-coastal mesoscale atmospheric circulation-induced by orographic effects and underlying sea surface temperature.	Alongshore wind decrease towards the coast (drop-off) influences upwelling dynamics and thereby primary and export production together with oxygen and distribution.	1-100 km
Sub-meso and mesoscale air-sea interactions.	The current feedback (i.e. the effect of the relative wind in the estimate of wind stress) and the thermal coupling between wind and SST at the scale of the eddies are critical processes to determnie the biogeochemical properties distribution, including oxygen, through their effect on oceanic mesoscale activity.	1-100 km
Low-level cloud cover and aerosols.	Stratocumulus clouds cover and aerosols particles of natural and anthropogenic origin control incoming solar radiation at the ocean surface, thereby playing a modulating role in either reducing or enhancing primary production with consequences on organic matter production and fate in the water column, and ultimately on subsurface oxygen depletion.	10-1000 km

3.4.1 Introduction

Ocean deoxygenation and acidification, along with ocean warming, form a trio of threats to marine life. These pressures are of critical importance to marine ecosystems because they are accelerating within a short timeframe (Breitburg et al., 2018a; Gruber, 2011; Levin, 2018; Mora et al., 2013). The future status of dissolved oxygen in the coastal and open ocean will in large measure depend on the scale and rate of global environmental change in warming, human population growth especially along coasts, and agricultural practices. Open-ocean deoxygenation, warming and ocean acidification are all driven by increased atmospheric CO_2.

While the biogeochemical and physical changes associated with ocean warming, acidification and deoxygenation occur all over the world, the imprint of these combined global stressors is expected to have a strong regional and local nature, which is exemplified by the Eastern Boundary Upwelling Systems (EBUS). Top predators in the marine food web such as pelagic billfishes and tunas which might be important for the economic development of certain regions are impaired by deoxygenation, ocean acidification and temperature increase (Breitburg et al., 2018a, b; Stramma et al., 2011).

The EBUS are key regions for the control of the climate system because they connect the open ocean and the troposphere through a complex of oceanic and atmospheric processes, and they host Oxygen Minimum Zones (OMZs), vast oceanic regions responsible for the world's largest fraction of water column denitrification. These regions (Figure 3.4.1), which include: 1) the U.S. West Coast-Oregon and California, 2) the Humboldt Current off Chile and Peru, 3) the Canary Current/Iberian Peninsula, and 4) the Namibia/Benguela upwelling systems, are among the most productive marine ecosystems in the world and support some of the world's major fisheries (Bakun, 1990; Pauly & Christensen, 1995). Production in the EBUS is controlled by two main physical factors. Firstly, equatorward winds along the eastern boundaries of the

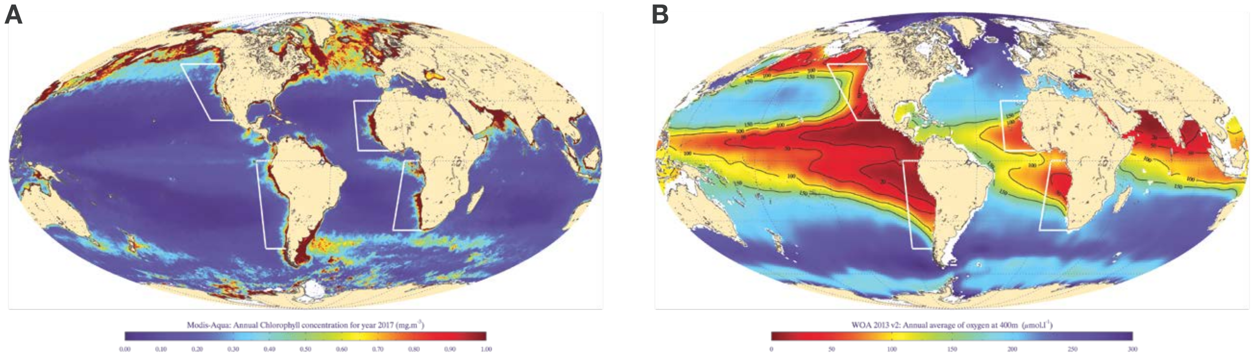


Figure 3.4.1 Eastern Boundary Upwelling Systems (EBUS) (white contour boxes) over an annual 2017 mean of A) chlorophyll-a concentration (derived from MODIS-Aqua), and B) dissolved oxygen concentration (derived from World Ocean Atlas, 2013) at 400m depth.

Atlantic and Pacific Oceans are linked to atmospheric mid-latitude high-pressure systems and force Ekman transport and pumping that drives upwelling of deep nutrient-rich waters into solar illuminated surface waters, enhancing export production and its ultimate decay (or consumption), with increased respiration and draw down of oxygen (Figure 3.4.2). Locally, mesoscale low-level atmospheric circulation may also be affected by land-sea-atmosphere interactions (Chelton et al., 2007; Oerder et al., 2016; Renault et al., 2016a, b) which impact upwelling and productivity (Astudillo et al., 2019; Renault et al., 2016c). Secondly, remote forcing may modulate upwelling at timescales from intra-seasonal (e.g. Kelvin waves) to inter-decadal (e.g. gyre circulation, El Niño-Soiuthern Oscillation (ENSO)) and longer.

The physical state of EBUS oceanic regions varies on a range of time scales that includes intra-seasonal and longer. At interannual timescales, this variability is often associated with tropical modes (ENSO in the Pacific (Dewitte et al., 2012; Frischknecht et al., 2015), the Benguela Niño (Shannon et al., 1986) and the Atlantic Equatorial mode in the Atlantic (Zebiak, 1993)) but also with extratropical modes (the North Atlantic Oscillation (NAO) (Cropper et al., 2014) or the Northern and Southern Annular Modes (NAM and SAM, respectively) (Thompson & Wallace, 2000)) as well as lower-frequency climate modes operating at the basin scale (the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997), the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2008) and the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001)). Ecosystems respond strongly to these variations through the physical influence of winds, light, and temperature, and their effects on micro-and macro-nutrient supply to plankton and oxygen supply to marine life.

In tropical and subtropical regions, EBUS are characterized by high primary and export production that, in combination with weak ventilation, causes natural oxygen depletion and the development of midwater oxygen minimum zones (OMZs) (Karstensen et al., 2008). Low oxygen, low pH values and shallow aragonite saturation horizons co-occur within them, affecting nearly all aspects of ecosystem structure (Chavez et al., 2008) and function in the water column, including the present unbalanced nitrogen cycle (Paulmier & Ruiz-Pino, 2009). The coupling between upwelling, productivity, and oxygen depletion feeds back to biological productivity and their role as sinks or sources of climate active gases. There is for example a net nitrogen loss to the atmosphere of N_2O (particularly in the South-East Pacific OMZ, Arevalo-Martinez et al., 2015). In addition, where oxygen concentrations are extremely low, poisonous hydrogen sulphide (H_2S) gas may erupt to the surface (Bakun, 2017; Schunck et al., 2013; Weeks et al., 2003). EBUS also play a critical role in atmospheric chemistry and climate through emission of active trace gases (Law et al., 2013). In the context of climate change, ocean warming contributes to deoxygenation through two main processes: warmer water holds less oxygen and causes increased stratification which reduces ventilation of both the ocean interior and estuaries.

While there is no doubt that ocean deoxygenation is an ongoing process, there is still a critical gap in knowledge of understanding the exact driving mechanisms, the intensity, and the spatial and temporal variability of ocean deoxygenation as well as its impact on marine food webs and biogeochemistry. Therefore, understanding how land-air-sea interactions control the dynamics behind the OMZs and what may potentially exacerbate deoxygenation becomes not just a matter

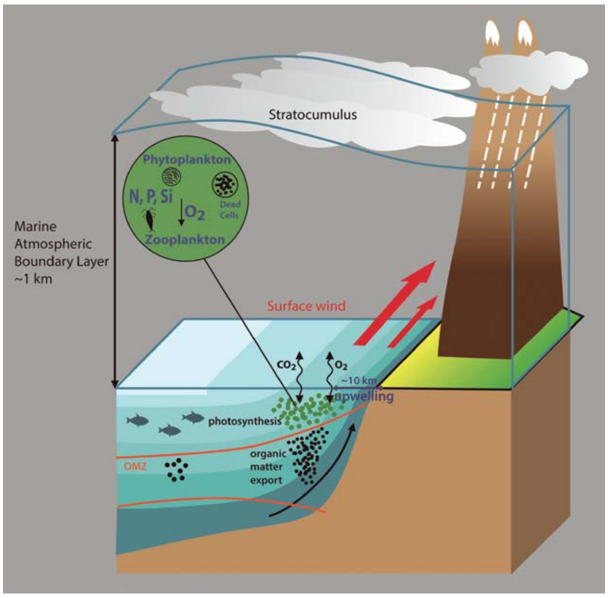


Figure 3.4.2 Schematic of air-sea-land coupled system in upwelling regions.

of scientific interest, but also a major societal concern. The economies of the countries neighbouring upwelling zones, are largely reliant on adjacent marine resources for food and employment (Figure 3.4.3). These countries urgently need improved capacity to predict variations in ecosystem structures and coastal water quality relating to deoxygenation and acidification to define sustainable management strategies for their marine resources.

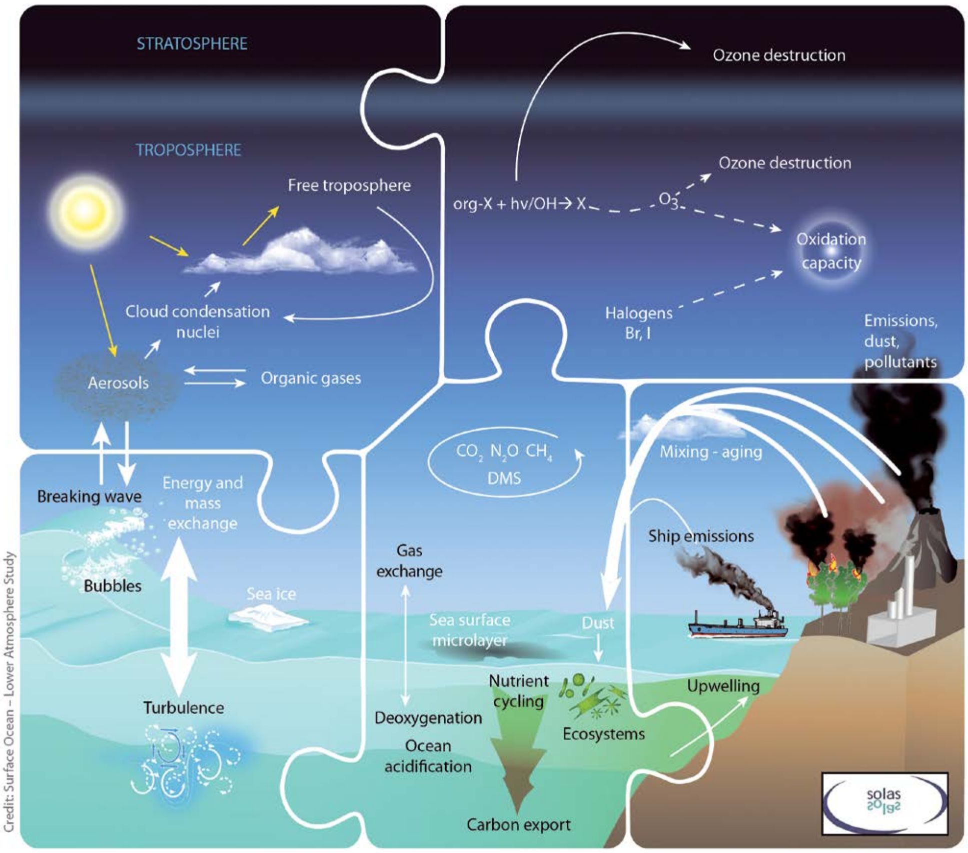
This synthetic overview focuses first on intricate interactions between the ocean, atmosphere and land in the EBUS by emphasizing the processes driving these interactions, their time-scale modulations, their impacts on oxygen depletion and on future rates of deoxygenation within a changing climate. Second, on local forcing factors that are believed to be key to understanding the sensitivity of ecosystems and OMZs to changes in mean state, e.g. ocean-atmosphere interaction of gases; mesoscale atmospheric circulation (i.e. near-coastal cross-shore wind gradients); submeso- and mesoscale air-sea interactions; and cloud cover and direct and indirect effects of aerosols. Finally, the remote influence of climate modes and their changes in a warming climate is discussed.

Figure 3.4.3 Banjul, Gambia, local fishing boats getting ready to leave © Salvador Aznar / Shutterstock.com.

3.4.2 Land-air-sea interactions over the EBUS

To study the intricate interactions between physical and biogeochemical processes in upwelling systems requires an integrative approach that links ocean, atmosphere, land, and coastal areas impacted by human activities as well as socio-economic dimensions. This approach has been adopted by the SOLAS 2025 Science Plan and Organization (Brévière et al., 2016) that addresses greenhouse gases, oceanic impacts on atmospheric chemistry and linkages between upwelling and air-sea exchanges of biogenic gases, ecosystem structure, deoxygenation, and acidification (Figure 3.4.4). The impacts of both submeso- and mesoscale variability in ocean (eddies, fronts, filaments) and near-surface atmospheric (winds and its spatial fluctuations) circulations on OMZ dynamics and air-sea exchange, which is also likely impacted by as yet unidentified variations in sea-surface surfactant activity in response to ecosystem variations, are not yet understood. How aerosols link ocean temperature and stratocumulus clouds that impact regional radiative budgets in upwelling zones is a further gap in knowledge that needs to be addressed. Finally, at low latitudes, upwelling systems are often bounded by desert landscapes, and the balance between micronutrient inputs from above versus below is still uncertain, particularly at different time scales.

Low resolution Coupled Model Intercomparison Project (CMIP)-class climate models do not resolve well the essential characteristics of the EBUS where alongshore winds exhibit mesoscale features such as a nearshore decrease in intensity (Astudillo et al., 2017) and the upwelling is confined to a coastal band of only tens of km in width (Estrade et al., 2008). Model errors are amplified by air-sea interactions, yielding a severe warm sea-surface temperature (SST) bias in EBUS (Richter, 2015) (Figure 3.4.5), which has eluded the interpretation of long-term trends in OMZs (Cabré et al., 2015; Stramma et al., 2008, 2012). In addition, processes occurring on a scale smaller than the model grid used may drive the relationship between key ecosystem properties and the physical system, making



Credit: Surface Ocean – Lower Atmosphere Study

Figure 3.4.4 Jigsaw puzzle schematic of processes involved in ocean-atmosphere-land interactions (with permission from Brévière et al., 2016).

it difficult to understand the consequences of changes in the physical system for marine ecosystems based on the outputs of Ocean Model Intercomparison Project (OMIP) and CMIP class models alone. Several sources cause these biases and owing to ocean-atmosphere coupling it has been difficult to rank them by importance and criticality (Richter, 2015). Among them: i) underestimation of alongshore winds causes poor simulation of upwelling and alongshore currents and the cooling associated with them, ii) underprediction of stratocumulus decks and their effects on shortwave radiation and low-level atmospheric circulation, iii) inadequate representation of offshore transport of cool waters by mesoscale turbulence is impacted by inadequate spatial resolution, and iv) aerosols provide a further problem for low resolution global models as the models overestimate their effects with respect to observations (Boucher et al., 2013). The large range

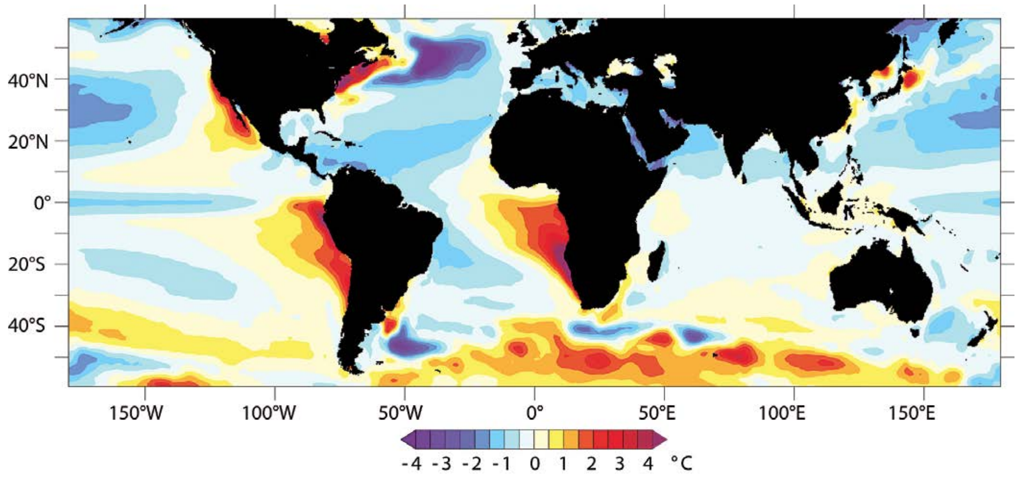


Figure 3.4.5 Annual-mean SST error, relative to the Reynolds SST dataset (Reynolds et al., 2007), of an ensemble of 39 coupled GCMs from the CMIP5 dataset in the historical integration (1982-2005).

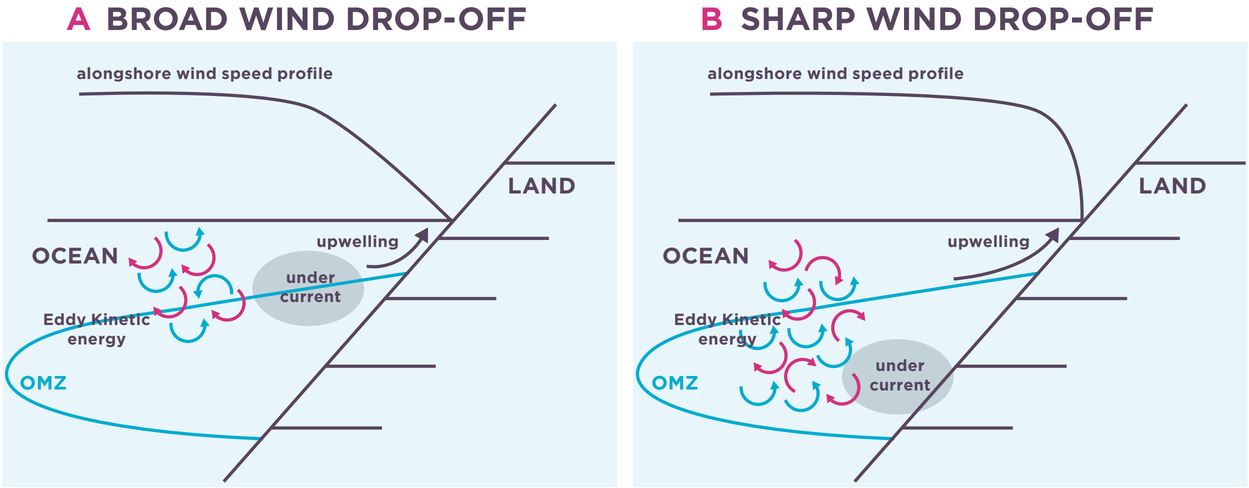


Figure 3.4.6 Schematic of the role of the wind drop-off in upwelling regions : A) Broad wind drop-off, B) Sharp wind drop-off.

of spatial and temporal scales of variability at which physical and biogeochemical processes interact make modelling and prediction of the location, strength and temporal variability of OMZs in EBUS a challenging task (Cabré et al., 2015; Karstensen et al., 2008; Oschlies et al., 2017). In addition to physical causes for OMZ biases, biogeochemical causes include a particulate organic carbon flux at 100 m that is too high compared to observations, and a too deep expansion of the OMZ due to low remineralization in the upper ocean that is associated with a transfer of particulate organic carbon to depth that is too great (Cabré et al., 2015).

By better constraining boundary conditions and allowing the relevant resolution to address coastal upwelling dynamics, regional coupled biogeochemical modelling nonetheless has provided a complementary approach to study the dynamics of OMZs and their relationship to climate (e.g. Gutknecht et al., 2013; Machu et al., 2015; Montes et al., 2014; Resplandy et al., 2012). However, the use of atmospheric reanalysis products for oceanic downscaling in EBUS has severe limitations (Astudillo et al., 2017; Cambon et al., 2013; Goubanova et al., 2011; Machu et al., 2015) calling for a regional focus in the treatment of atmospheric forcings.

3.4.3 Ocean-atmosphere interactions of gases

When OMZ waters upwell and impinge on the euphotic zone, they release significant quantities of greenhouse gases, including CO_2, N_2O and CH_4, to the atmosphere (i.e. Arevalo-Martinez et al., 2015; Babbin et al., 2015; Cornejo & Farias, 2012; Cornejo et al., 2015; Farias et al., 2015; Kock et al., 2012; Naqvi et al., 2010) exacerbating global warming with feedbacks to stratification, biological productivity and the oxygen inventory.

Keeling and Shertz (1992) documented changes in atmospheric oxygen concentrations and found they were dominated by the seasonal cycle of net biological production and by a long-term decline due to the burning of fossil fuels. These changes are small, however, in the order of parts per million and thus negligible compared to observed changes in oxygen in low latitude thermocline waters. Recently, Eddebbar et al. (2017), using atmospheric potential oxygen ($APO \approx O_2+1.1{*}CO_2$), showed that air-sea O_2 exchange is modulated at interannual timescales by ENSO through its effect on equatorial upwelling rather than through its effect on biological productivity or thermally driven O_2 exchange, suggesting that the dominant processes behind air-sea interface gas exchange are likely to depend on timescales and regions. Closing budgets of dissolved elements is a key issue that deserves further investigation.

3.4.4 Mesoscale atmospheric circulation

Historically, upwelling indices have been mostly based on estimating Ekman transport from the magnitude of alongshore wind speed. However, within approximately 50-km from the coast alongshore winds are typically strongest offshore, becoming weaker towards the coast owing to orographic effects and, to a lesser extent, the cooler sea-surface temperature of upwelling that stabilizes the marine boundary layer

(Renault et al., 2016a). The wind stress curl induced by this wind drop-off modulates the position and intensity of the undercurrent. In the California system, a broader drop-off induces a shallower and more intense undercurrent (Capet et al., 2004; Renault et al., 2016c) while in the Central Chile upwelling system, the intensity of the wind drop-off is more influential on the surface current (Astudillo et al., 2019). In both cases, this influences the production of eddies near the coast through baroclinic and barotropic instability (Capet et al., 2008), with consequences on the off-shore export of water mass properties. For instance, in the California system, by modulating the coastal circulation, the wind drop-off changes the composition and origin of the biogenic material of coastal zones and thus the upwelling efficiency and OMZ properties (Renault et al., 2016c). The latter showed that the coastal wind shape, by modulating the baroclinic instabilities, modulates the Eddy Kinetic Energy (EKE) levels (Figure 3.4.6). In the open ocean, and in particular in low-nutrient environments, mesoscale processes increase the net upward flux of limiting nutrients and enhance biological production (Garçon et al., 2001; McGillicuddy et al., 2007; Oschlies & Garçon, 1998). In the EBUS, eddy activity can be a limiting factor, which progressively prevents high levels of net primary production as the number of eddies increases by subducting nutrients below the euphotic layer (eddy quenching) (Gruber et al., 2011; Nagai et al., 2015). Thus, in some EBUS, less EKE means a more productive system. Considering wind forcing at fine scales is thus essential to realistically simulate mean current flow in coastal systems, whose characteristics determine the level of mesoscale activity through instability processes (Capet et al., 2008) and thus off-shore transport of water mass properties with likely consequences for oxygen content. Another potentially important factor that is associated with mesoscale atmospheric circulation is related to low-level coastal jets in the atmosphere (as found off Central Peru (Dewitte et al., 2011), Central Chile (Muñoz & Garreaud, 2005), and off Namibia (Patricola & Chang, 2017)) that provide a source of oceanic mixing and variability of the undercurrent.

3.4.5 Submeso- and mesoscale air-sea interactions

Air-sea interaction at sub meso- to mesoscales (horizontal scales of the order of 100 m - 100 km) modulates the properties of the oceanic boundary layer with rectified effects on the mean circulation in EBUS. For instance, sea-surface temperature gradients at ocean fronts and eddies can modify the surface wind field through processes previously considered for warm waters and larger scale circulation. These processes include the downward transfer of momentum flux to the ocean surface (Koseki & Watanabe, 2010; O'Neill et al., 2010), as well as changes in the pressure gradient across the SST front that generate low-level wind anomalies. Scatterometer observations together with micro-wave observations of SST have facilitated the collection of data that allows the investigation of these processes at the mesoscale. Chelton et al. (2004) and Small et al. (2008) identified a link between modification of the dynamics of the atmospheric boundary layer by SST and the feedback of this modification on the ocean through wind surface stress and heat flux. This link has been observed between sharp SST gradients and surface winds - the so called 'Chelton effect', where winds tend to accelerate over warm and decelerate over cold waters in frontal zones. This effect results in a quasi-linear relationship between the curl (divergence) of the wind and the SST gradient according to a perpendicular (parallel) direction to the wind. These fine scale interactions influence the ocean dynamics through acting on both momentum and heat fluxes and consequently distribution and evolution of biogeochemical properties.

Recent regional coupled modelling studies by Seo et al. (2016) and Renault et al. (2016b) have highlighted the importance of current-wind interaction for the energetics of the California Upwelling System, distinguishing the thermodynamics and dynamics associated with air-sea interaction. In particular, consideration of oceanic currents in estimating wind stress (so-called current feedback) yields a reduction in oceanic EKE in high-resolution models. Wang and Castelao (2016) showed also from satellite observations that a strong coupling between SST gradients and wind stress curl at fine scales is observed in many mid-latitude regions throughout the world, especially in regions with strong fronts like the Western and Eastern Boundary Currents, which challenges how high-resolution oceanic models should be forced by atmospheric re-analyses, the latter encapsulating the effect of the observed turbulent oceanic flow. These processes have yet to be implemented in high-resolution physical-biogeochemical atmosphere and oceanic models, which will help address still unresolved effects on mesoscale eddies, oxygen content and their distribution.

Figure 3.4.7 Stratocumulus clouds © Kingcraft / Shutterstock.com.

3.4.6 Cloud cover, aerosols direct and indirect effects

The EBUS regions are hotspots where global climate models diverge when trying to estimate the top-of-atmosphere radiative effect (Nam et al., 2012). They are characterized by persistent stratocumulus clouds topping a shallow, stable marine boundary layer maintained by the cool SST of upwelling. Stratocumulus clouds (Figure 3.4.7) are highly reflective and modify the net radiative balance at the top of the atmosphere more than any other cloud regimes. Yet, these cloud formations are also amongst the largest source of uncertainty in estimating the radiative budget of the Earth's atmosphere (Boucher et al., 2013).

Aerosol particles of natural and anthropogenic origin play a key role in the radiative budget and more globally in the climatic functioning of EBUS since they modulate the greenhouse effect of long-lived gases through their indirect effects on cloud formation (Boucher et al., 2013). The extent of interaction of the aerosols with radiation and clouds depends on their nature, in particular their chemical composition and size distribution. Aerosols may also influence primary production by modifying low level circulation and the re-emission of sensible heat by altering the penetration of short-wave radiation into the marine boundary layer, with feedbacks to ocean dynamics, and fertilizing the surface ocean through dust deposition (Figure 3.4.4). Together they influence the biological feedbacks associated with variations in short-wave radiation penetration into the mixed layer that are associated with changes in production. For instance, by absorbing or reflecting light, the direct radiative effect of aerosols could induce a decrease of 15 to 20% in primary production along the Senegalese coast (Mallet et al., 2009). Atmospheric deposition to the ocean through the fertilizing role of micro- and macronutrient inputs has a direct positive effect on primary production (Capone & Hutchins, 2013; Ito et al., 2016; Neuer et al., 2004). Ito et al. (2016) showed in a modelling study that the effect of aerosol deposition on oceanic oxygen is most pronounced at low latitudes despite deposition being greatest in mid-latitudes, due to oceanic transport favouring a regional increase in productivity, respiration and consequently subsurface oxygen depletion. These competing effects of reduction and enhancement are probably modulated by the oceanic circulation. For instance, in the Benguela/Namibia upwelling system, aerosols produced by biomass burning attenuate light and thereby primary production. They stabilize the troposphere and thus reinforce low cloud cover (Adebiyi

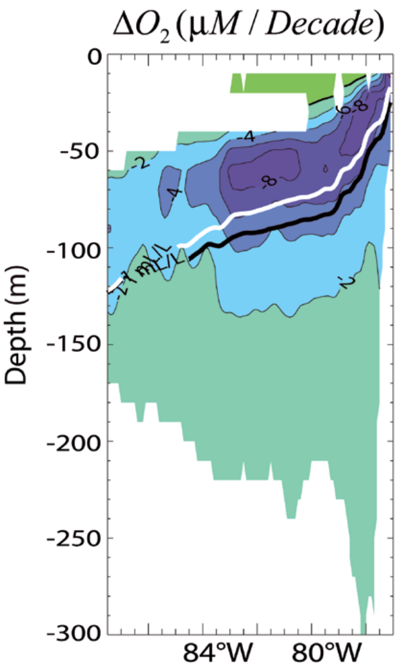


Figure 3.4.8 Long-term trend in dissolved oxygen (in μM decade^{-1}) at 12°S over the period 1958-2008 as simulated by a regional coupled model in a configuration similar to Dewitte et al. (2012). The black thick line indicates the iso-oxygen surface at 1ml L^{-1} (i.e. oxycline depth) over the full period whereas the thick white line is for the period 2000-2008. Only the values significant at the 95% level are shown.

et al., 2015; Formenti et al., 2017). On the other hand, oceanic stratification is reduced (colder SST), inducing a more efficient upwelling and thus an increase in production. Jousse (2015) showed the importance of representing accurately aerosol spatial variability and the associated indirect effects on the Liquid Water Path for realistically simulating solar radiation in the north-east Pacific.

Atmospheric deposition of nitrogen to the ocean (NO_x and NH_3) has tripled since 1860 to 67 Tg N yr^{-1} and is expected to grow further (Duce et al., 2008). Including this increasing atmospheric forcing of anthropogenic nitrogen in model simulations, Ito et al. (2016) and Oschlies et al. (2017) both found a reduction of the simulated tropical thermocline oxygen, but with different amplitudes due to their treatment of nitrogen cycle feedbacks, in particular via nitrogen fixation. Since factors controlling nitrogen fixation and absolute rates are still poorly understood (Landolfi et al., 2015), the impact of atmospheric nitrogen deposition on ocean productivity and thereby on oxygen content still constitutes an important knowledge gap.

Deposition of volcanic ash during explosive eruptions can impact phytoplankton and marine foodwebs by releasing iron especially and other nutrients into sea water (Garçon et al., 2015; Olgun et al., 2011, 2013). Explosive tropical volcanic eruptions are sufficiently strong to inject aerosols into the stratosphere. These aerosols backscatter incoming solar radiation and can reduce global surface temperature by a few tenths of a degree Celsius for up to two years. Ocean fertilization by volcanic eruptions may also affect marine biomass within the ash-fall and neighbouring areas. How these antagonistic mechanisms operating on different scales will impact primary productivity and oxygen concentrations is a topic which will require further study.

3.4.7 Influence of climate modes and changing climate

The contribution of climate modes to variability in the oxygen inventory is poorly understood mostly because of the scarcity of oxygen data. In the open ocean, changes in ventilation and oxygen supply are considered to be major drivers of trends in the oxygen inventory. How existing processes and pathways of ventilation are being perturbed by climate variability in the ocean within a regional context (in particular OMZs) or through implied mechanisms (e.g. zonal jets in the tropics, mid/high latitude subduction) is an active area of research. The scarcity of data has only allowed the temporal variability of dissolved oxygen to be documented at a few locations (e.g. Bograd et al., 2008; Farias et al., 2007; Fernandez et al., 2015; Graco et al., 2017; Gutierrez et al., 2008; McClatchie et al., 2010; Monteiro et al., 2011 ; Paulmier et al., 2006) and only over decadal time scales in the California upwelling system.

The investigation of the OMZ forcing by the climate modes requires dedicated modelling studies that incorporate as much as possible the aforementioned processes considering the chain of intricate interactions at different spatial and temporal scales. The influence of climate modes can be through either change in frequency of occurrence of climatic events or change in amplitude of the climate modes, which, through non-linearity, can change the regional mean circulation, producing a so-called “rectified” effect. This is illustrated by the results of a long-term integration with a regional coupled biogeochemical model of the Peru upwelling system which is connected to ENSO dynamics through the propagation of Kelvin waves along the coast. During extreme El Niño events, the coastal upwelling is switched off for several seasons. Conversely during

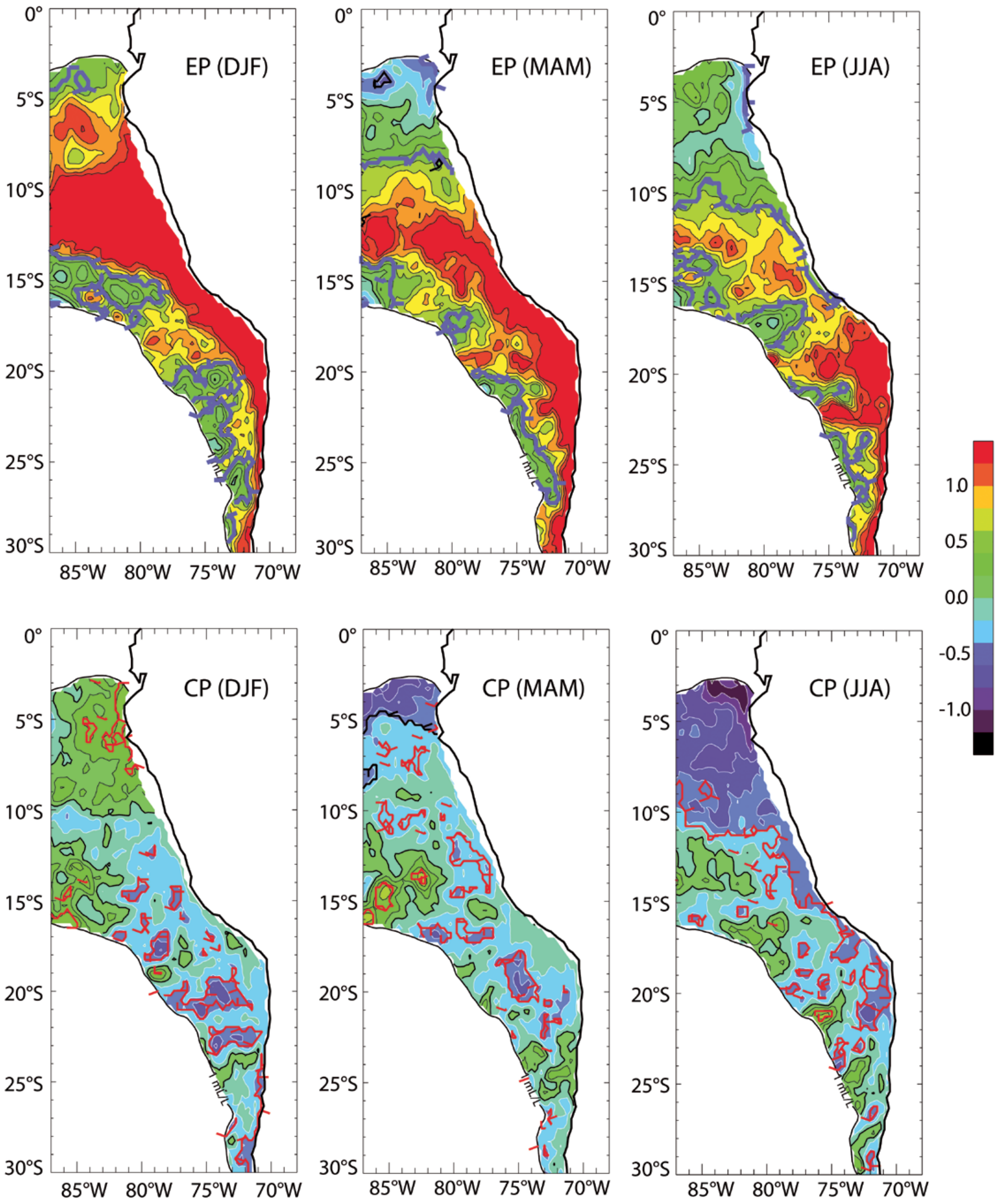


Figure 3.4.9 Composite evolution of dissolved oxygen concentration anomaly at 200m in the OMZ region to the west of South America during Eastern Pacific (EP, top panels) and Central Pacific (CP, bottom panels) El Niño events as simulated by a high-resolution biogeochemical coupled model. See Montes et al. (2014) for the biogeochemical model description and validation and Dewitte et al. (2012) for the ocean model setting and validation. Three seasons are considered with two, MAM and JJA following the peak season of El Niño (DJF). Anomalies are normalized by their variance over the length of the simulation (1958-2008) and so are in adimensionalized units. Anomalies are only shown inside the OMZ which is defined as the region where the O_2 concentration is lower than 1 ml L^{-1}. The significance of the composites is estimated using a bootstrap method with 6 CP and 5 EP events over the simulated period with the contours in red and blue indicating the 90% significance level for EP and CP events, respectively. Tick marks on the contours indicate the direction where the significance level is larger than 90%.

Central Pacific (CP) El Niño, near-normal to cool conditions prevail (Dewitte et al., 2012). The change in frequency of occurrence of the two types (CP and Eastern Pacific - EP) of El Niño as observed since the 1990s (i.e. more occurrence of CP El Niño events, cf. Lee & McPhaden, 2010) leads to an increase in mean upwelling conditions at decadal timescales (Dewitte et al., 2012) which is consistent with observations (Gutierrez et al., 2011). In the modelling study of Dewitte et al. (2012), the upwelling favourable winds have no trend. Embedding the BioEBUS biogeochemical model into the oceanic model configuration of Dewitte et al. (2012) yields changes that involve a long-term deoxygenation of the upper part of the OMZ off northern Peru (Figure 3.4.8). This deoxygenation trend above the oxycline of between -2 and -4 µM decade^{-1} over 1958-2008 agrees reasonably well with multi-decadal trend estimates of between -1 and -3 µM decade^{-1} over 1958-2015 estimated from the World Ocean Atlas (Ito et al., 2017), and can be interpreted as an ENSO-induced response of O_2 variations affecting the mean OMZ. Such a rectified effect results from the strong asymmetry of EP El Niño events in the far eastern Pacific (i.e. the fact that the EP El Niño events yield a strong warming off the coast of Peru converse to the CP El Niño or La Niña events). In particular the Peru-Chile Undercurrent brings O_2 deficient waters from the equatorial region (Montes et al., 2014) and is considerably reduced during EP El Niño events, which are associated with a depressed oxycline and have an anomalous positive O_2 concentration within the OMZ (Figure 3.4.9). Conversely during CP El Niño events, the OMZ is intensified, potentially favouring hypoxic conditions. This illustrates that the mechanisms by which climate modes influence OMZ dynamics are not straightforward and could not be limited to processes that influence the upwelling favourable winds (Bakun, 1990).

Similar to the Peru coast, the occurrences of interannual warm (Benguela Niño) and cold events along the coast of Africa have been intensively studied because of their effects on the local marine ecosystems, hypoxia events, and atmospheric circulation and rainfall. Using the same coupled physical/biogeochemical model, Bachèlery et al. (2016) showed that oceanic remote equatorial forcing explains more than 85% of the coastal interannual oxygen fluctuations along the Angolan and Namibian coasts up to the Benguela Upwelling System. These events, associated with poleward propagations of upwelling and downwelling coastal trapped waves, are at a maximum in the subsurface and are controlled by advection processes. The associated variation in the oxygen content in waters below the surface along the shelf may also affect the extension of the OMZ and enhance natural hypoxia.

Global model projections simulate an intensification of winds that favours upwelling in the 21st century at least in mid-latitudes upwelling systems (Rykaczewski et al., 2015; Wang et al., 2015). A weak confidence in future projections of the evolution of oxygen is mainly due to uncertainty associated with the competing effects of intensifying winds and increasing thermal stratification. Together they will determine the amount of nutrients entrained in the euphotic zone and thereby biological productivity and oxygen levels. This uncertainty in the modifications of ventilation processes and source-water pathways that supply the EBUS constitutes another difficulty. Indeed, Earth System model simulations suggest large changes in the oxygen inventory for the 21st century, although the agreement among models is weak and especially so for oxygen deficient regions (Bopp et al., 2017; Cabré et al., 2015). Observations in some EBUS have shown trends towards increased upwelling and declining oxygen levels (Garcia-Reyes et al., 2015). However, the degree to which these changes are attributable to climate change is unclear especially in tropical regions owing to the superimposition of natural variability in the climate and regional circulation, inducing a myriad of potential interactions. Understanding and predicting the resulting effects of all antagonistic/synergistic factors on the future trajectory of ocean deoxygenation is an immense and challenging task.

3.4.8 Conclusions / Recommendations

The relationships between upwelling dynamics, marine ecosystems, and atmospheric chemistry have implications for all coastal marine ecosystem services, including fisheries management and aquaculture, carbon sequestration, air cleansing, and cultural and recreational activities in these highly vulnerable coastal regions. Land-air-sea interactions that regulate EBUS-OMZ dynamics continue to be an area of high uncertainty in understanding the Earth system. Rapid changes in ocean-atmosphere interactions are under way and many knowledge gaps remain, raising questions such as:

- What is the magnitude of the EBUS OMZs net radiative forcing and associated climate effect?
- What is the role of these oxygen deficient environments in an oxygenated world for marine biogeochemical equilibrium cycles of: oxygen, nitrogen, carbon, phosphorus, silica, sulphur, etc., as well as for the resilience of marine ecosystems?
- How will these regions evolve under the combined action of multiple stressors (warming, stratification change, acidification and deoxygenation)?

These questions are at the heart of several international initiatives, the Global Ocean Oxygen Network GO_2NE

(http://www.unesco.org/new/en/natural-sciences/ioc-oceans/sections-and-programmes/ocean-sciences/global-ocean-oxygen-network/) (Breitburg et al., 2018a,b), the IMSOO (Implementation of Multi-disciplinary Sustained Ocean Observations)/GOOS OMZ demonstration theme with the VOICE (Variability in the Oxycline and Its Impacts on the Ecosystem) project (Garçon et al., 2018; Palacz et al., 2017a, b), and the SCOR Working group N°155 'Eastern boundary upwelling systems (EBUS): diversity, coupled dynamics and sensitivity to climate change' (http://www.scor-int.org/SCOR_WGs.htm) as well as part of the new science plans of several global research projects such as SOLAS, IMBeR and CLIVAR.

An assessment of the different levels of response is needed that includes further analysis of historical data and long-term observations, experiments and forecast models that take into account the impacts of multiple stressors at the physiological/biogeochemical, organism, and ecosystem levels. There is no doubt that the most effective solution to mitigate global environmental change and the deoxygenation trend is to curb carbon emissions. Recognizing and understanding these climate stressors which interact with other human activities is essential to sustainably manage ocean ecosystems. What the costs of no action will be is at present unclear due to a lack of information and understanding.

Acknowledgements

We would like to thank IOC-UNESCO for launching and supporting the Global Ocean Oxygen network GO$_2$NE which stimulated many fruitful discussions and interactions. VG is supported by INSU/CNRS funding to support SOLAS Chair activities. KG acknowledges support from FONDECYT (Grant N° 1171861). BD acknowledges support from CNES (SWANS project) and from FONDECYT (Grant N° 1190276). IM would like to acknowledge the Peruvian PPR068 programme "Reducción de vulnerabilidad y atención de emergencias por desastres" for financial support of her work and SCOR for funding WG155.. We would like to thank Prof. John Baxter and an anonymous reviewer for their careful reading and comments on this section which helped to greatly improve it.

3.4.9 References

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