Prospectus for CLIVAR Research
Focus on

Eastern Boundary Upwelling Systems (RF-EBUS)

A global false-colour compilation of satellite data on ocean chlorophyll from the MODIS Aqua sensor for the year 2011 showing the California, Peru, Canary and Benguela ecosystems (white ovals). Satellite imagery courtesy of NASA. From Capone and Hutchins, 2013
Prospectus for CLIVAR Research Focus on Eastern Boundary Upwelling Systems (RF-EBUS)

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Background: Why EBUS?

Eastern boundary upwelling systems (EBUS) cover less than 3% of the world ocean surface yet they have a significant role in the climate system (Large and Danabasoglu, 2006), and are home to the largest contribution of ocean biological productivity with up to 40% of the reported global fish catch (Pauly and Christiansen, 1995; Capone and Hutchins, 2013). Coupled with the vast coastal human populations, these regions play key biological and socio-economical roles. There are common features to eastern boundary upwelling regions: wind-driven flows, alongshore currents, steep shelves and large vertical and offshore nutrient transports. Despite the commonality, each of the main upwelling systems (California, Humboldt, Canary and Benguela Current Systems) exhibits substantial differences in their circulation, primary productivity, phytoplankton biomass, and community structures. The reasons for these differences are not fully understood.

The impacts of climate-scale variability on EBUS and consequently on their fish resources have become widely accepted in recent years (e.g., Lehodey et al. 2006; Parrish et al. 2000). One of the most compelling examples of climate-driven fish stock changes is the fluctuations of sardines and anchovies described since the early 1980s, the so-called Regime Problem (Lluch-Belda et al. 1989, 1992; Schwartzlose et al. 1999). Landings of sardines show synchronous variations off California, Peru, and Chile (and Japan), with populations flourishing for 20 to 30 years and then practically disappearing for similar durations. Periods of low sardine abundance have coincided with increases in anchovy populations. Benguela Current sardine and anchovies in the Atlantic Ocean appear to be in synchrony with Pacific stocks, but in opposite phase. As demonstrated through paleo-reconstructions (Baumgartner et al. 1992), and because synchrony takes place despite different fishery management schemes (Schwartzlose et al. 1999), those fluctuations appear to be fishery-independent. Due to the large spatial and coherent temporal scales involved, a single global driver linked to large-scale atmospheric or oceanic forcing has been proposed to explain the variations across different systems (Bakun 1996).
More specifically, a combination of the low-frequency component of different climate modes, including the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) (Chavez et al. 2003) and of the low-frequency variability in global ocean temperature (Tourre et al. 2007) has been suggested as leading climatic driver. However, a mechanistic understanding of how the climate forcing, local physical processes, biogeochemistry, and biology combine to result in the various patterns of synchronous variability across widely separated systems remains elusive.

EBUS also contribute to the global carbon cycle, albeit their contribution is highly uncertain. Globally, the oceanic uptake of anthropogenic CO2 is estimated as ~2 Pg C year^{-1} (Takahashi et al., 2006; Sabine et al., 2004; Fletcher et al., 2006). This estimate does not fully account for carbon fluxes on the continental margins where dynamics, biological processes, sediment-water interactions terrestrial inputs and human-induced perturbations are very complex and likely to change rapidly in the future. While the importance of the continental margins in the global carbon budget has been repeatedly pointed out in the literature, their role as either a source or sink of CO2 is yet to be established and quantified (Chen, 2009; Bates, 2006; Cai et al., 2006). Additionally, oxic–anoxic interfaces such as found at the periphery of EBUS are preferential sites for increased nitrification. The predicted expansion of oxygen minimum zones is likely to intensify nitrous oxide (N_{2}O) fluxes and nitrification (Capone and Hutchins, 2013)

Finally, and most importantly, many coupled climate models are characterized by very large SST biases in the coastal upwelling regions of the California Current System (CCS), the Humboldt Current system (HCS), the Canary Current System and the Benguela Current System (BCS), where simulated mean SSTs are much warmer than observed (typically in excess of 3°C and as high as 10°C) (Figure 1). Furthermore, these SST biases have significant remote effects on surface and subsurface temperature and salinity, and on precipitation and hence atmospheric heating and circulation (Collins et al. 2006), and affect the large-scale climate system through feedbacks (Large and Danabasoglu, 2006; Curchitser et al., 2011, Small et al., 2015). Large and Danabasoglu (2006) showed, in particular, that imposing observed SSTs along the BCS coast in an otherwise freely-evolving CCSM3 simulation improves significantly the representation of precipitation in the western Indian Ocean, over the African continent and across the Equatorial Atlantic. Also, imposing observed SSTs along the HCS coast reduces precipitation in the so-called double ITCZ region of the south tropical Pacific. The warm temperature biases associated with EBUS strongly limit the predictability of future evolution of these regions. Increasing model resolution improves simulations of the regional climate but resolution alone is not enough to remove the bias (Curchitser et al., 2011). Basin-scale advection must also be considered to understand regional upwelling variability (Rykaczewski and Dunne, 2010).
Improving upon the EBUS biases in climate models requires a more realistic representation of the physics of the eastern boundary regions. The dynamics in coastal upwelling regions exhibit a range of phenomena from well-understood Ekman divergence to complex instabilities in meso- and sub-mesoscale flows (e.g., Capet et al., 2008) and distinct linear and non-linear flow regimes. Furthermore, as shown, between others, by Small et al. (2015), eastern boundary upwelling requires careful treatment of air-sea fluxes strongly suggesting that the problem has to be investigated in the coupled context.

The importance of EBUS regions to the physical climate and the marine ecosystem coupled with improving modeling capabilities and increased observations make this research topic timely for a CLIVAR research focus. In the rest of this prospectus we set the scientific underpinnings for the work and outline proposed activities.

*Physical considerations*
Ocean currents, and the associated upwelling in the EBUS of interest are driven for the most part by surface wind stress. Recent work by Fennel and Lass (2007) and Fennel et al. (2012) has shown the importance of the spatial structure of the wind stress in determining the dynamical nature, the spatial distribution, the depth and the intensity of oceanic upwelling in the EBUSs. The two local drivers of upwelling are the along-shore wind stress within a region of a few Rossby lengths from the coast, which generates short-lived Ekman divergence and persistent Kelvin-wave mediated divergence by along-shore currents, and the wind-stress curl, which locally forces shallow (but not necessarily weak) upwelling via Ekman pumping. Dissipative numerical models like most of the ocean components of global climate models (GCMs) currently in use will over-represent upwelling generated by the wind-stress curl, and dissipate the wave-induced near-coastal dynamical component.

**Of particular importance to determine the nature and intensity of coastal upwelling and the associated meridional currents is the offshore distance of the maximum along-shore wind-stress.** The area between the coast and this point will experience both Kelvin- and Ekman-forced upwelling; beyond this point, and beyond a few Rossby lengths from the coast (whichever is farthest), there is no wind-induced upwelling. At least equally importantly, a broad area of cyclonic wind-stress curl between the coast and a distant along-shore wind stress maximum induces poleward surface flow, which typically acts to warm and stabilize the EBUSs, neutralizing the effects of upwelling (Fennel et al. 2012).

A look at the four main tropical EBUSs (Figure 2) highlights three conspicuous features. First, along-shore wind stress has a fairly well-defined maximum in the offshore direction; second, its intensity increases with decreasing distance from the coast, with the surface coastal jet appearing at a point poleward of the main upwelling area and petering off equatorward of it; and third, the wind stress curl is consistently cyclonic in the area between this maximum and the coast, and anticyclonic elsewhere. In summary, the strength and location of the along-shore wind-stress maximum characterizes much of the wind-stress forcing in the EBUSs. The Peruvian sector of the Humboldt system appears to be a special case, with a poorly defined surface along-shore jet and very intense curl; this area is characterized by unusually strong topographic steering and thermally driven diurnal cycle, cf. e.g. Zuidema et al (2009); it is also the closest to the Equator among the EBUSs, and, like the Angola upwelling north of the Benguela, strongly influenced by equatorial wave activity.
The temporal evolution of the along-shore wind stress in the mean annual cycle is represented in Figure 3. The two EBUS in the north hemisphere (NH) experience a maximum between April and September, i.e., in Spring and Summer. Similarly, the wind stress in two EBUSs in the southern hemisphere (SH) peaks between September and March. A notable distinction is visible between northern (low-latitude) and southern (high-latitude) sectors, with the latter experiencing an earlier, but also weaker onset. Such a distinction into low-
and high-latitude sectors may be also seen, although less clearly, in the other two NH EBUSs. Combined with the mean patterns from Figure 2, we choose to consider primarily the high-latitude sectors of the tropical EBUSs as those that are most intense and more clearly driven by wind-stress alone.

Figure 3: Along-shore surface jet strength (as wind stress in mPa, color scale on the bottom right) and its distance from the coast (green contour lines, contour interval 50 km) as a function of latitude and time of the year (month 1 = January) for the four semi-permanent tropical upwelling regions off the California, Canary, Chile and Benguela coasts. Data from the SCOW climatology (Risien and Chelton 2008). Figure courtesy of T. Toniazzo.

On the basis of this information, it appears that the four tropical wind-driven upwelling areas have essentially identical spatio-temporal patterns of wind-stress, which drive similar current systems in spite of otherwise significant hydrographic and bathymetric differences. **Such similarity appears to call for a common theory for the regional atmospheric circulation in the EBUS.**

The considerations made here lead us to reconsider the main outstanding issues related with modeling and predicting the evolution of upwelling in the EBUS. On the one hand, it minimizes considerations of changes in land-sea temperature contrast, as that will be a consequence, not a cause, of changes in the circulation and in the general thermal structure of the tropical troposphere in
the descending branches of the Hadley circulation. This is in contrast to the widely cited theory put forth by Bakun (1990). On the other hand, we find that upwelling is sensitive to the exact wind stress pattern near the coast, and that is in turn controlled by the structure of the properties of the low-level jet and the related structure and strength of the inversion at the top of the marine planetary boundary layer. Given the structure of the winds in the EBUS, the characteristics (temperature, oxygen, nutrients etc.) of upwelled waters will be function of the oceanic sources for these waters. A common feature of the EBUS regions is the presence of an undercurrent at several hundreds of meters depth. The relatively small scale of these currents means that a correct representation of the source and destination of upwelled waters remains a significant challenge for ocean models. EBUS are also regions of significant meso- and submeso-scale activity, which act to link the boundary current with the basin-scale gyres. This leads to the suggestion that coupled atmosphere-ocean models are necessary for progress on the dynamics of EBUS.

**Biogeochemical and ecological considerations**

For the biogeochemistry, the rate and duration of upwelling influence the amount of biological production, hypoxia and pH levels. Upwelling rate determines the phytoplankton cell size (Van der Lingen et al., 2011); small phytoplankton dominate when the upwelling rate is extreme, resulting in extra trophic levels between the algae and fish, which reduces fish production. In contrast, large-sized phytoplankton dominate under moderate upwelling and production can be transferred more efficiently to fish via large zooplankton grazers. Further, upwelling rate may determine the plankton and fish community structure, given that different fish species are better suited to preying upon plankton of different sizes (van der Lingen et al., 2006).

Atmosphere-ocean GCMs (AOGCMs) are important tools for exploring the changing dynamics of the climate system, both during the historical period and under conditions representative of future climates. As mentioned, in the EBUS AOGCM simulations exhibit prominent positive SST biases. Despite these local biases, however, AOGCMs have been shown to provide useful information to improve our understanding of the dynamics of upwelling ecosystems. Marine ecologists frequently find appreciation for detailed descriptions of relationships among organisms and their environments; species-specific, life-history-dependent, or regionally explicit processes are often important in describing why populations vary in response to environmental changes. But many of the most significant shifts in these systems—particularly in the Pacific—have been attributed to large-scale, ocean-atmosphere processes (e.g., changes associated with ENSO, PDO, and the timing of seasonal shifts to upwelling-favorable conditions) (Brodeur et al., 1996, Peterson and Schwing, 2003, Mackas et al., 2004, Roesler et al., 1987, Rebstock, Black et al., 2002). Those
shifts appear therefore to be independent, to a larger degree, from the precise representation of upwelling dynamics. (We note that observed ecosystem changes off southern Africa have been difficult to attribute to specific causes, but this is likely because of a paucity of appropriate long-term data - Blamey et al., 2012, Jarre et al., 2015, Moloney et al., 2013). Many unanswered questions in marine ecology would benefit from an improved understanding of the temporal and spatial response of the EBUSs to the large-scale climate variability. Even if the representation of the mean magnitude of the physical properties (e.g., SST or upwelling rate) may be biased in AOGCMs, their ability – if quantified and understood – of representing large-scale/EBUSs climate interactions may provide important and useful information for studying ecological changes.

With recognition that coastal upwelling along eastern boundary currents is poorly resolved in the current generation of AOGCMs and that the number of models that include coupled biogeochemical components (such as oxygen, nutrients, and plankton) are limited, we suggest that focusing on large-scale relationships between physical properties and ecosystem structure should be prioritized. **We hypothesize that observed decadal scale changes in ecosystem structure are forced by large-scale, physical changes in ocean processes resolved by the current generation of global ocean models.** Testing this hypothesis (through investigation of relationships between ecosystem structure and large-scale physical fields) is a necessity step for assessing the utility of applying global models to inform ecosystem questions.

Basic ecological characteristics of lower-trophic-level communities that influence the productivity and distribution of living marine resources include plankton size structure and composition (Moloney et al., 1991, van der Lingen et al, 2009, Hooff et al., 2006, Rykaczewski and Checkley, 2008). While local nutrient availability, water-column stratification, and mixing influence these ecological characteristics, relationships between plankton composition and large-scale water-mass properties (including origin and ventilation history) have also been identified (Fisher et al., 2015, McGowan et al., 1996, Escribano et al., 2000, Pages et al., 2001, Varela et al., 1991, Bode et al., 2011). Variability in circulation may be a first-order determinant of the composition of plankton assemblages, and estimation of historical variability in water masses supplied to EBUSs (including variability in the source and ventilation of those water masses) would facilitate systematic investigation of the relationships between water masses and plankton structure. Additionally, knowledge of the variability in boundary-current transports (both the equatorward currents and poleward countercurrents) and hydrographic properties (T, S, mixed-layer depth and O₂ and CO₂ solubilities) of those currents will provide basic descriptions of conditions associated with changes in characteristics of lower-trophic-level communities. We recommend that a suite of reanalysis forced ocean models (with or without ocean data assimilation) be used to provide estimates of
historical variability in the boundary-current transports and water masses supplied to upwelling zones. Such data would also be valuable to set boundary conditions for regional circulation and ecosystem simulations. Archived observational records of plankton abundance and community composition are available in each EBUS (with durations of these observations ranging from about two to six decades), and variability in the plankton can be compared to large-scale water-mass properties in each region. Comparing the sensitivities of plankton characteristics to water-mass properties across regions will also help to elucidate the relative importance of different physical-biological mechanisms among the four systems. A systematic evaluation of the past relationships between water masses and variability in plankton composition in EBUSs, has the potential to greatly enhance the appreciation for the climate models’ ability to provide information regarding future changes in ecosystem characteristics.

Activities for the CLIVAR Eastern Boundary Upwelling Research Focus

Given recent advances in atmosphere, ocean and biogeochemical models and observations, it is timely to re-visit the physical and biological science of EBUS, to develop research recommendations for synergistic activities between the modelling and observational communities, and to improve the quantification of potential impacts of climate change on the marine ecosystem and the consequences on their dependent societies. The approach builds on the recognition that progress will be made with a unified consideration of the coupled atmosphere-ocean-biogeochemical system. The following are recommendations for topics the research focus group can address. Addressing these topics will lead to recommendation for further research and observational needs.

Questions to be considered by the RF-EBUS

1. On the physics of eastern boundary upwelling systems and linkages to large-scale climate:
   i. What is the structure of atmospheric circulation in EBUS and how is it represented in current global and regional models
   ii. What are the dynamical mechanisms linking the upwelling regions with the large-scale climate patterns.
   iii. What are the effects of upwelling on the regional and global air temperatures, precipitation and wind patterns.
   iv. How does a more accurate representation of coastal upwelling in climate simulations improve existing regional and global biases such as in SST and precipitation.
   v. Source, transformation and destination of upwelled waters
   vi. Temporal and spatial variability of upwelled waters
   vii. Representation of undercurrents in GCMs.
2. On the role of coastal eastern boundary upwelling systems in regulating biogeochemical processes:
   i. What are key physical and biological processes controlling air-sea CO2 flux and carbon export in the eastern boundary upwelling systems.
   ii. What are the relative contributions of regional biological productivity and basin-wide circulation to the extent and intensity of oxygen minimum zones in these systems.
   iii. How will the natural and anthropogenic factors change the carbon cycle and ocean acidity in the eastern boundary upwelling regions.
   iv. What is the sensitivity of the oxygen minimum zones in EBUSs to climate variability and to future global warming scenarios.

3. On the climate and fisheries connection leading to fluctuations of fish populations:
   i. What is the source of upwelled waters and nutrients.
   ii. Mixing rates versus stratification (related to the size of particles eaten by fish).
   iii. What physical processes affects the survival of fish eggs.

*Initial activities for RF-EBUS*

In order to address the research questions the specific activities of the RF-EBUS will be:

1. Analysis of existing ocean reanalysis products and climate- and downscaled-climate models in the eastern boundary regions. The proposed group has expertise in the four major EBUS and a concurrent analysis of the representation of the four systems will highlight similarities, differences and deficiencies of current models. Where possible, the group will analyze downscaled or high-resolution models to contrast with the coarser resolution climate models. Issues to be addressed are:
   i. Sensitivity of key upwelling metrics to horizontal and vertical resolution as simulated by coupled models at seasonal to interannual scales.
   ii. Design a series of upwelling metrics such as: a) vertical volume transport throughout each EBUS; b) cross-shore trends in vertical velocity; c) depth of maximum vertical velocity; d) magnitude and cross-shore trends in upwelling favorable winds and wind-stress curl; e) physical properties (including transport, velocity, depth, and variability) of poleward undercurrents in each system.
   iii. Identify processes that are well represented or poorly represented across models. Workshop participants will also
recommend key physical measurements and datasets to be used for comparison between models and data and common across EBUS.

2. Summary of existing physical, biogeochemical and fisheries data in each EBUS. The ultimate goal here is to write a prospectus/white paper that will highlight observational priorities of future observations in these regions. A significant aspect of this activity will be to define each EBUS based on physical and dynamical considerations (North/South/West extent). Describe the temporal scales of variability in oxygen concentrations in each EBUS given available observations. Attempt to attribute variability to local changes in water-column structure or/and remote changes forced by basin-scale variability. The resulting product will be a synthesis paper describing the timescales and drivers of oxygen variability in EBUS. EBUS are areas of naturally high CO2 concentrations due to the supply of deep, poorly ventilated waters. Additionally, the high levels of primary productivity and organic matter remineralization stimulate sharp spatial and temporal gradients in ocean carbonate properties. Synthesize current understanding of the carbonate system in upwelling regions to promote a more balanced understanding of ocean acidification in these regions, the relative importance of natural and anthropogenic processes at various time scales, and the potential impact of these changes on ecosystem processes.

3. Design a series of numerical experiments with existing climate models to address specific mechanisms important in these regions. In light of recent literature, these experiments can address, among other considerations, both the representation of coastal winds and potential feedbacks to the large scale.

4. Analyze the relative importance of different sources of new nutrients (e.g., surface mixing, riverine input, curl-driven upwelling, coastal upwelling) to structuring the composition (e.g., species, size) of planktonic communities. The resulting product will be a synthesis of the oceanographic processes that affect planktonic communities that nourish small pelagic fish in EBUS.

5. Explore the variability in the source waters (and their nutrient concentrations), which has been poorly resolved in historical observations. Given the growing recognition of the importance of such changes in EBUS, the RF-EBUS will draft suggestions of necessary field measurements to quantify variability in source-water properties as seasonal-to-interannual time scales, and this document will be distributed to EBUS survey programs.
6. Common practices for field and laboratory studies of ichthyoplankton survival will be drafted. Common biological experiments to be conducted across EBUS will be suggested to better understand the relative amounts of biological (e.g., food limitation; plankton composition) vs physical (e.g., turbulence) control in inhibiting the growth and survival of small pelagic fishes across the ecosystems. We hope that such guidelines will serve a key components of proposals for extramural funding in each EBUS.
Table 1: Potential members for RF-EBUS:

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<th>Name</th>
<th>Country</th>
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