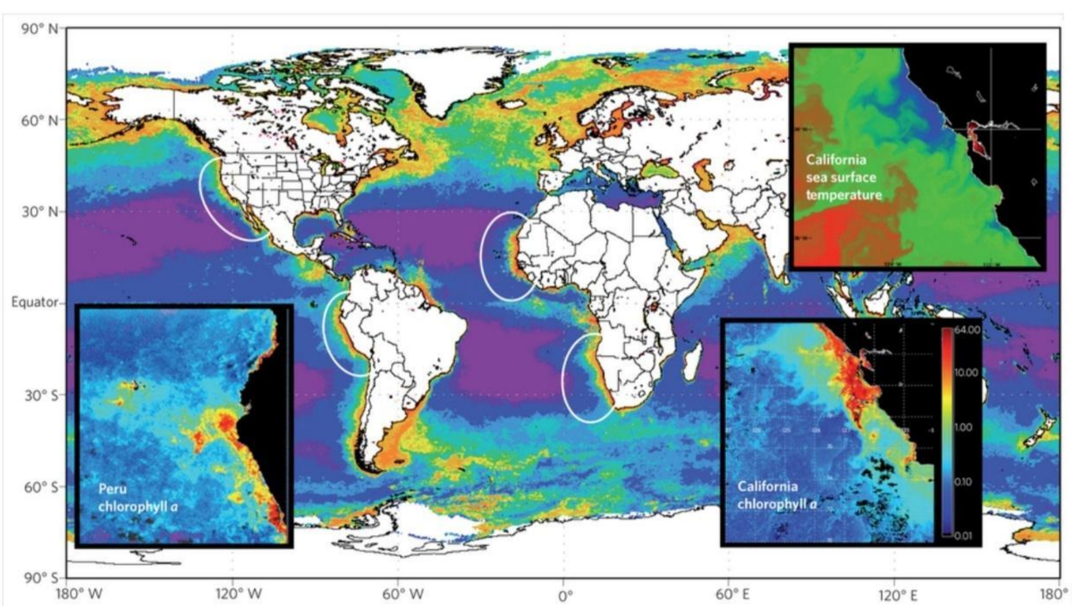
Prospectus for CLIVAR Research Focus on

Eastern Boundary Upwelling Systems (RF-EBUS)



A global false-color 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.

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Revised, June 2018

The following document is revised from the April 2016 EBUS prospectus. Changes to the leadership and membership of the group necessitated shifts in the focus of the efforts. Contributors to the original prospectus include Jack Barth, Antonio Bode, Annalisa Bracco, Nico Caltabiano, Enrique Curchitser, Gokhan Danabasoglu, Reuben Escribano, Riccardo Farneti, Alban Lazar, Art Miller, Colleen Moloney, Ryan Rykaczewski, Thomas Toniazzo, Carl Van der Lingen, and Paquita Zuidema. Additional individuals who have contributed to the revised document include Vincent Echevin, Marisol Garcia-Reyes, Michael Jacox, and Jennifer Veitch.

Background: Why EBUS?

Eastern boundary upwelling systems (EBUS) cover less than 3% of the world ocean surface, yet they play a significant role in the climate system (Large and Danabasoglu 2006). They are home to highly productive ecosystems, with up to 40% of the reported global fish catch (Pauly and Christensen 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 the sensitivity of fish populations to climate processes 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). 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 CO_2 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 highlighted in the literature, their role as either a source or sink of CO_2 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_2O) fluxes and nitrification (Capone and Hutchins, 2013).

Finally, many coupled climate models are characterized by 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) (Toniazzo and Woolnough 2013; 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) with feedbacks to the large-scale climate system (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 significantly improves 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 southern 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 (Harlass et al., 2018), but resolution alone is not enough to remove the bias (Curchitser et al. 2011).

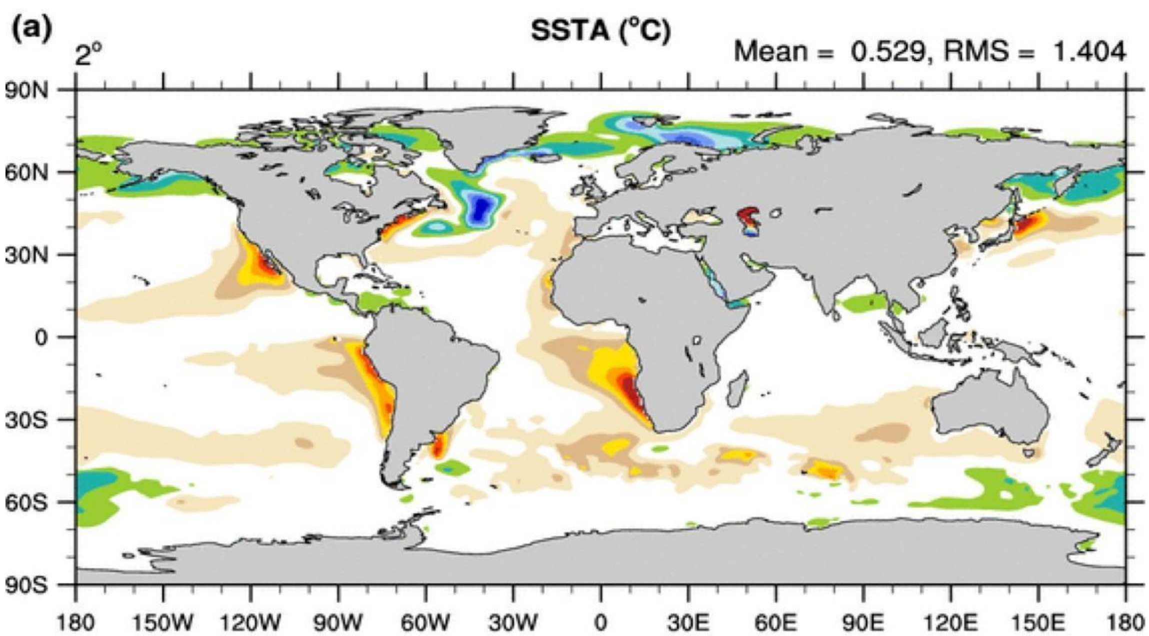

Figure 1: Sea surface temperature anomalies between an NCAR-CESM simulation and WOA data.

Improving the EBUS biases in climate models requires a more realistic representation of the physics of the eastern boundary regions. Their dynamics encompass a range of scales and ocean and atmosphere phenomena, from basin-scale advection (e.g., Rykaczewski and Dunne, 2010) to instabilities in meso- and sub-mesoscale flows (e.g., Capet et al. 2008) and poorly understood air-sea interactions (e.g., Small et al. 2015).

The importance of EBUS regions to the physical climate and the marine ecosystem coupled with improving modeling capabilities and increased observations make this topic relevant for a CLIVAR research focus group. Additionally, the lead authors of the IPCC Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) plan to include a section on EBUS. The Scientific Committee on Oceanic Research (SCOR) and Integrated Marine Biosphere Research (IMBER) also have EBUS working groups, further highlighting the interest of the global community in understanding the EBUS. Below, we set the scientific underpinnings for the work and outline proposed activities.

Atmospheric processes

Ocean currents and the associated upwelling in the EBUS of interest are driven largely by surface wind stress, and variability in ecological productivity in these regions has long been associated with changes in atmospheric conditions. 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 EBUS. The two local drivers of upwelling are 1) the alongshore 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 alongshore currents; and 2) 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 general circulation models (GCMs) currently in use will over-represent upwelling generated by the wind-stress curl and dissipate the wave-induced, near-coastal dynamical component.

The cross-shore structure of the wind-stress field (i.e., the intensity and distance of the offshore wind-stress maximum and its decline near the coast) is important for understanding the nature and intensity of coastal upwelling and the associated meridional currents. 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. Perhaps equally important to the physical and ecological dynamics, a broad area of cyclonic wind-stress curl between the coast and an alongshore wind stress maximum induces poleward surface flow, which typically acts to warm and stabilize the EBUS, weakening the effects of upwelling on mixed-layer temperatures and nutrients (Fennel et al. 2012). Additional modulations to wind-driven upwelling at regional scales may be associated with the large-scale gyre circulation and associated seasonal adjustments of the pressure field (Jacox et al. 2014).

A look at the four main EBUS (Figure 2) highlights three conspicuous features. First, alongshore wind stress has a fairly well-defined maximum in the offshore direction; second, its intensity increases with decreasing distance from the coast; 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 alongshore wind-stress maximum characterizes much of the wind-stress forcing in the EBUS. Dynamically, the along-shore jet is understood to be sensitive to the influence of synoptic-scale mid-latitude depressions (Munoz and Garreaud 2005; Toniazzo et al. 2011), to coastal sub-synoptic circulations such as coastal lows (Garreaud et al. 2002), and a vigorous diurnal cycle (Munoz 2008;

Toniazzo et al. 2013). The Peruvian sector of the Humboldt system appears to be a special case, with a poorly defined surface alongshore 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 EBUS, and, like the Angola upwelling north of the Benguela, strongly influenced by equatorial wave activity.

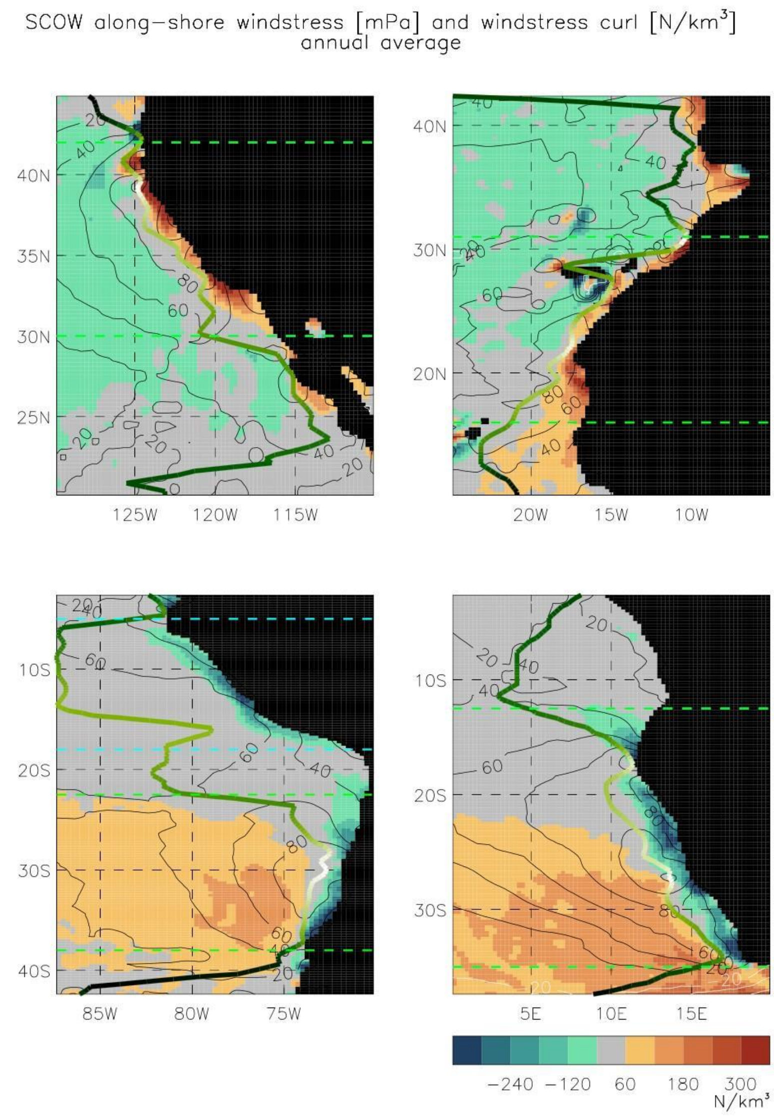

Figure 2: Wind-stress curl (color maps), surface alongshore wind stress (line contours), and the location and intensity of the maximum alongshore wind stress (green/white crosses) according to the SCOW climatology. Figure courtesy of T. Toniazzo.

The seasonal evolution of the low-level jet is represented in Figure 3. The two EBUS in the northern hemisphere generally exhibit a maximum in wind stress between April and September (i.e., in boreal spring and summer). Similarly, the alongshore wind stress in the two southern hemisphere EBUS generally peaks between September and March (i.e., in austral spring and summer). However, a notable distinction is visible at low-latitudes where the strengthening of the wind occurs earlier, during the respective hemispheric winter, with a somewhat weaker maximum.

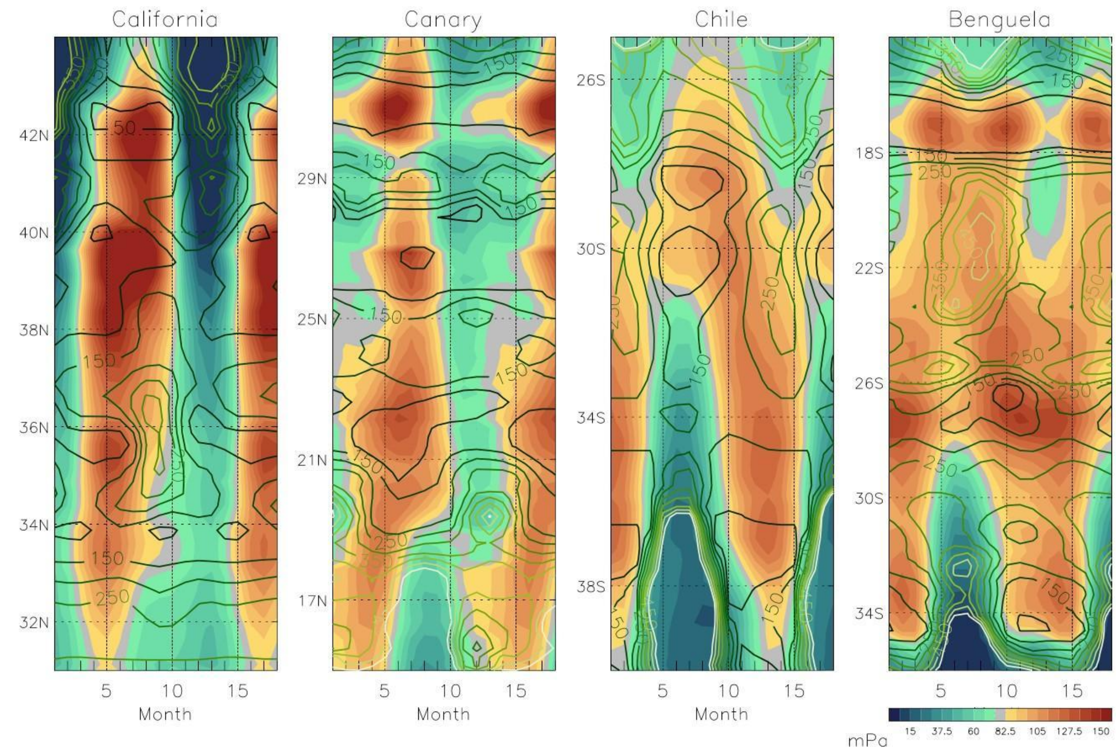

Figure 3: Alongshore surface atmospheric jet strength (as wind stress in mPa, color scale on the bottom right) and its distance from the coast (green contour lines, contour interval 50 km) as a function of latitude and time of the year (month 1 = January) for the four semi-permanent EBUS off the California, 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 wind-driven EBUS have very similar spatio-temporal patterns of wind stresses at seasonal timescales. These climatological wind patterns drive current systems that are also very similar in spite of otherwise significant hydrographic and bathymetric differences. **Such similarity appears to call for a refinement of current theoretical understanding of the regional atmospheric circulation in the EBUS.**

Observations and theory of the current dynamics of EBUS may justify an expectation for a similar evolution in the future. At the same time, the specificity of each EBUS should also be better understood and qualified. Variability in wind forcing in EBUS regions at interannual to centennial timescales and their sensitivities to large-scale climate change remains an area of active investigation. In order to understand EBUS responses to future climate change, it is necessary to gain a deeper insight into the mechanisms that generate the observed relationships between upwelling and the hydrographic and current structure of the ocean basin, the large-scale atmospheric properties and circulation, and the characteristics of coastal orography, and the regional spatio-temporal distribution of surface winds and land and sea surface temperatures.

Oceanographic and biogeochemical processes

Comparisons of the oceanic responses to atmospheric forcing outlined above are challenged by the relative scarcity of observational data in the ocean realm. However, common hydrographic and biogeochemical characteristics are shared among systems, including equatorward surface flow, poleward undercurrents at several hundred meters depth, relatively abundant inorganic nutrient concentrations, and low concentrations of dissolved oxygen. Different oceanographic mechanisms for upwelling (e.g. Ekman, coastal waves) tap into different water reservoirs. **The relatively small scale of these current systems and the steep spatial gradients in physical and biogeochemical properties means that accurate representations of the sources and destinations of upwelled waters are important. Such representation remains a significant challenge for ocean models.** EBUS are also regions of significant meso- and submesoscale activity which act to link the boundary currents with the basin- scale gyre circulation. This further motivates the need to use coupled atmosphere-ocean models for progress in understanding the dynamics of EBUS.

The rate, duration, and frequency of upwelling influence the amount of biological production, hypoxia, and pH levels in EBUS. Upwelling rate can influence the phytoplankton cell size (Van der Lingen et al. 2009); small phytoplankton dominate when the upwelling rate is weak or extremely intense, 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 prey upon plankton of different sizes (van der Lingen et al. 2006, Rykaczewski 2018).

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. Despite species-specific life-history traits and differences in the patterns of exploitation, many of the most significant ecological shifts in EBUS—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 2002, Black et al. 2014). Therefore, those shifts appear to be independent, to a large degree, from the precise representation of upwelling dynamics and species-specific characteristics. (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 EBUS 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 – to represent large-scale/EBUS climate interactions may provide important and useful information for studying ecological changes.

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 EBUS (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 O_2 and CO_2 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. Understanding the implications of different wind reanalyses can help attaching uncertainties to such estimations

With recognition that coastal upwelling in EBUS 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 atmospheric properties and hydrographic 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 necessary step for assessing the utility of applying global models to inform more specific ecosystem questions.

Activities for the CLIVAR Eastern Boundary Upwelling System 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 modeling 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 RF-EBUS:

A. On the physics of eastern boundary upwelling systems and linkages to large scale climate:
i. How is coastal upwelling and the associated ocean circulation in EBUS represented in current numerical circulation models?
ii. What is the structure of atmospheric circulation in EBUS, and how is it represented in current numerical circulation models?
iii. What are the dynamical mechanisms linking EBUS with large-scale climate patterns?
iv. What are the effects of upwelling on the large scale climate?
v. How does a more accurate representation of coastal upwelling in climate simulations improve existing regional and global biases such as in SST and precipitation?
vi. What are the sources, transformations, and destinations of upwelled waters?

vii. How can the temporal and spatial variability of upwelled waters be described?

B. On the role of coastal eastern boundary upwelling systems in regulating biogeochemical processes:
i. What are key physical processes controlling air-sea CO_2 flux and carbon export in the eastern boundary upwelling systems?
ii. What is the sensitivity of the oxygen minimum zones in EBUS to climate variability and to future global warming scenarios?

Additional questions that will be pursued in cooperation with SCOR WG-155 on EBUS

C. On the interaction between biological processes and climate in EBUS
i. 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?
ii. How will the natural and anthropogenic factors change the carbon cycle and ocean acidity in the eastern boundary upwelling regions?
iii. How do changes in the sources of upwelled waters and their nutrient composition influence biological processes in EBUS?
iv. How do mixing and stratification influence the size structure and composition of the plankton community?
v. What physical processes affect the survival of fish larvae?

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Expertise of Members

Members in the CLIVAR EBUS RF were nominated in an effort to balance geographic diversity and discipline. The three tables below display the expertise required and the experience of the current members.

Questions considered:

		Expertise required							
		regional oceanography	regional atmospheric processes	large-scale oceanography	large-scale atmospheric processes	biogeochemistry and/or ecology	regional numerical models	global numerical models	observations
A.	On the physics of eastern boundary upwelling systems and linkages to large scale climate:								
i.	How is coastal upwelling and the associated ocean circulation in EBUS represented in current numerical circulation models?						x	x	
ii.	What is the structure of atmospheric circulation in EBUS, and how is it represented in current numerical circulation models?		x				x	x	x
iii.	What are the dynamical mechanisms linking EBUS with large-scale climate patterns?	x	x	x	x				
iv.	What are the effects of upwelling on the large-scale climate?	x		x	x		x	x	x
v.	How does a more accurate representation of coastal upwelling in climate simulations improve existing regional and global biases such as in SST and precipitation?			x	x			x	x
vi.	What are the sources, transformations, and destinations of upwelled waters?	x					x	x	x

vii.	How can the temporal and spatial variability of upwelled waters be described?	**x**					**x**	**x**	**x**
B.	On the role of coastal eastern boundary upwelling systems in regulating biogeochemical processes:								
i.	What are key physical processes controlling air-sea CO_2 flux and carbon export in the eastern boundary upwelling systems?	**x**				**x**			**x**
ii.	What is the sensitivity of the oxygen minimum zones in EBUS to climate variability and to future global warming scenarios?	**x**				**x**			**x**
Additional questions that will be pursued in cooperation with SCOR WG-155 on EBUS									
C. On the interaction between biological processes and climate in EBUS									
i.	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?	**x**		**x**		**x**		**x**	**x**
ii.	How will the natural and anthropogenic factors change the carbon cycle and ocean acidity in the eastern boundary upwelling regions?	**x**		**x**		**x**		**x**	**x**
iii.	How do changes in the sources of upwelled waters and their nutrient composition influence biological processes in EBUS?	**x**		**x**		**x**		**x**	**x**
iv.	How do mixing and stratification influence the size structure and composition of the plankton community?	**x**				**x**	**x**		
v.	What physical processes affect the survival of fish larvae?					**x**	**x**		

Members:

1	Alban Lazar
2	Annalisa Bracco
3	Antonio Bode
4	Art Miller
5	Jenny Veitch
6	Marisol García-Reyes
7	Martin Schmidt
8	Mathieu Rouault
9	Michael Jacox

10	Moussa Diakhaté
11	Paquita Zuidema
12	Rene Garreaud
13	Ryan Rykaczewski
14	Thomas Toniazzo
15	Uwe Send
16	Veronique Garcon
17	Vincent Echevin

Members' expertise:

		Region of greatest expertise			
		Benguela	California	Canary	Humboldt
Broad topic of expertise	regional oceanography	**2, 5, 7, 8**	**2, 9, 13**	**1, 2, 3, 10**	**2, 17**
	regional atmospheric processes	**5, 11, 14**	**6, 11**	**10, 17**	**11, 12, 14, 17**
	large-scale oceanography	**7, 8**	**4**	**1**	**17**
	large-scale atmospheric processes	**14**	**4, 6**	**10**	**12, 14**
	biogeochemistry and/or ecology	**7, 16**	**6, 13**	**3, 17**	**17**
	regional numerical models	**5**	**7,9**	**1**	**12**
	global numerical models	**2, 14**	**2, 13**	**2**	**2, 14**
	observations	**11, 14**	**15**	**1, 3, 17**	**11, 12, 17**