

Title:

Towards strategic observatories for regional ocean-atmosphere interactions in the Eastern Boundary Upwelling Systems

Acronym: cOCtEAU (OCEan Atmosphere Upwelling)

Summary/Abstract

Eastern Boundary Upwelling Systems (EBUS) (California, Peru-Chile, Benguela and Canary Current, Sumatra-Java System) are characterized by complex dynamical processes spanning a wide range of spatio-temporal variability due to the strong coupling between atmosphere, ocean and land. They are the most productive marine ecosystems in the world supporting some of the world's major fisheries, being key socio-economic sectors for southern countries and supply of marine products worldwide. At the eastern boundaries of ocean basins, trade winds blowing equatorward produce coastal upwelling, which uplifts cold and nutrient-rich waters toward the surface, where favorable light conditions sustain phytoplankton growth. The air-sea-land processes in these regions also span a wide range of characteristics and nature, and their role in modulating the upwelling dynamics and productivity is presently unclear. Moreover, remote forcing can influence upwelling at timescales from intraseasonal to interdecadal and longer. Below the surface ocean, intense Oxygen Minimum Zones develop due to high organic matter export leading to production and release of climatically-active gases (CO₂, N₂O) and trace gases to the atmosphere. EBUS are also characterized by strong submeso- and mesoscale variability that links the coastal system to the open ocean. This SCOR WG is aimed at increasing the scientific understanding of the interactive processes between land, ocean and atmosphere and their impacts on the marine biogeochemistry and ecosystems at the regional scale. It will focus on the integration of existing knowledge from *in situ* and satellite observations and modeling approaches and formulate a **strategic recommendation white paper** for setting up observational programs/platforms (i.e. OceanSITES) that will fill in the gaps in our understanding of physical and biogeochemical ocean-atmosphere interactions in these regions.

Scientific Background and Rationale

The Eastern Boundary Upwelling Systems (EBUS) are widely known to be the most productive areas of the world's oceans (Pauly and Christensen, 1995), supporting large populations of commercially important fish species (Bakun et al., 2015). This is mainly driven by the air-sea interaction which is triggered when the equatorward alongshore wind displaces the surface layers of the ocean and, by mass conservation, cold, nutrient-rich deeper waters outcrop to re-establish the geostrophic equilibrium in eastern boundaries, developing the so-called Coastal Upwelling Systems. These areas (California, Peru-Chile, Benguela and Canary Current, Sumatra-Java Systems) are characterized by alongshore boundary currents, filaments, squirts, mesoscale eddies and internal waves, which are also driven, triggered and modulated by the local-to-regional wind response (e.g., Chelton et al., 2007). These processes interact at different timescales, thus enriching the coastal upwelling dynamics and defining the oceanography of these regions. The combination of sluggish

circulation and high biological productivity in the surface layer drives elevated rates of organic matter decomposition and dissolved oxygen consumption, resulting in the development of the Oxygen Minimum Zones (OMZs). Low-oxygen areas are important for macroorganisms that cannot survive in oxygen-poor conditions. Extreme anoxic events can have serious impacts either through the habitat structuration or reduction (for instance the Humboldt with a shallow habitable layer which has consequences on catchability) or on mortality (rock-lobster walkouts in the Benguela are well documented). Peculiar biogeochemical processes also occur at low oxygen concentrations that influence global ocean nutrient cycles as well as production of greenhouse gases (e.g. Stramma et al., 2010). The impact of oceanic trace gases on atmospheric chemistry is also yet to be determined.

The basic forcing mechanisms are similar across the different EBUS and establish similarities in essential physical dynamics and ecosystem structure, and progress has been achieved in understanding the EBUS dynamics from an integrative and comparative perspective (e.g., Pegliasco et al., 2015; Capet et al., 2014; Lackar and Gruber, 2012; Gruber et al. 2011; Chavez and Messié, 2009; Capet et al., 2008; Carr and Kearns, 2003). However, many questions still remain regarding specific processes associated with individual EBUS (e.g. the strength of the equatorial teleconnection) and their sensitivity to climate change (e.g. Wang et al., 2015; Bakun et al., 2015; Mackas et al., 2006). For instance, the Peruvian sector of the Humboldt system is one of the most productive EBUS, yet it experiences the largest fluctuations at interannual timescales (i.e., El Niño) compared to the other EBUS systems. The EBUS in the Indian Ocean, the Sumatra-Java upwelling system is relatively less studied, although it plays an important role in the development of the Indian Ocean Dipole (Saji et al., 1999). The difference in their latitudinal positions (Figure 1) implies that some EBUS or EBUS sub-components are more wind-driven (those at high-latitudes) while others experience more tropical oceanic teleconnections, although the Benguela EBUS is also influenced by the Agulhas leakage. Therefore while commonalities in the nature of the forcing have suggested that a common theory of the circulation and its role on biogeochemical properties (e.g. OMZs) could be drawn, the current characteristics of the forcing (amplitude, frequency, persistence, asymmetry) linked to inherent non-linearities of the systems call for revisiting this paradigm. Progress in regional modeling has shed light on potentially important processes that were only inferred until recently (e.g. effect of the wind-drop off on upwelling dynamics (e.g. Capet et al., 2004); current-wind coupling (Chelton et al., 2007); eddies-induced transport (Bettencourt et al., 2015; Gruber et al., 2011; Rossi et al., 2008)) and that are difficult to tackle only with observations. While most modeling studies have been process-oriented, some long-term regional hindcast simulations are becoming available, allowing investigation of low-frequency time scales and estimations of the importance of different regional feedbacks within a climate framework. It is also of interest to contrast the EBUS with the weak upwelling/less productive eastern boundary current systems such as the Iberian Current and Leeuwin Current systems, so as to better understand possible evolution of the EBUS under the future climate change.

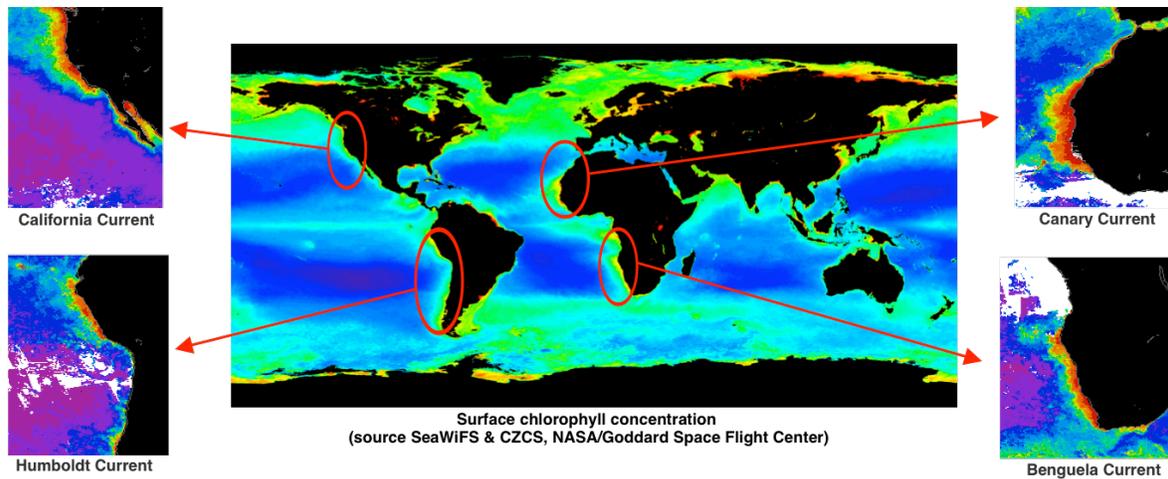


Figure 1. Distribution of Eastern Boundary Upwelling Systems and global satellite-derived annual average chlorophyll-a concentration.

This has spurred in recent years a number of individual efforts to understand the EBUS dynamics from an observational perspective, e.g., the international CLIVAR program VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study) implemented to develop and promote scientific activities leading to an improved understanding of the South Eastern Pacific coupled ocean-atmosphere-land system on diurnal to interannual timescales. The transdisciplinary AMOP (Activities of research dedicated to the Minimum of Oxygen in the eastern Pacific) project was launched to investigate the mechanisms leading to the formation of the OMZ existence off Peru and its variability from hourly to centennial timescales. The German initiative SFB754 ‘Climate-Biogeochemistry Interactions in the tropical Ocean’ addressed the relatively newly recognized threat of ocean deoxygenation, its possible impact on tropical OMZs and implications for the global climate-biogeochemistry system. However, the problem of undersampling, the inadequacy of our current mode of ocean observations to cover the relevant spatial and temporal scales, is still significant despite progress in both observational platforms (gliders, wavegliders, ARGO floats, AUVs, aerial drones) and autonomous physical and biogeochemical sensors, as well as remote sensing. Likewise, the available global models, while useful to document climate variability and its sensitivity to mean state change, still exhibit severe biases at regional scales, in particular in EBUS (in Sea Surface Temperature, Richter, 2015) and OMZs structure (Cabr e et al., 2015). Thus, regional models have been used showing an adequate reproduction of the known aspects of the regional dynamics and are useful to elucidate key questions, e.g., the dynamical relationship between the ocean circulation and OMZs (Montes et al., 2014) that, certainly due to scarce spatial and temporal data distribution, would have been difficult to detect with observations. However, most published modeling work addressing EBUS variability comprises process-studies at short or climatological timescales.

In brief, there are a number of regional processes in EBUS that modelling studies suggest are important but that have been undocumented by observations. This calls for more quantitative evaluations of the role of such processes in EBUS dynamics from integrated modeling platforms, i.e., that take into account the complex feedbacks and scale interactions, and operate within a climate perspective, i.e., from long-term (multidecadal)

simulations. The socio-economic importance of EBUS (1% of global ocean area that sustains 20% of the world's fish catch) further motivates to investigate the role of these regional air-sea interactions onto the biogeochemistry of the OMZs in order to improve our predictive capabilities of the evolution of the marine ecosystems in these key economic regions. This will require efficient observing systems, and via this proposed working group we aim to provide guidance for the design of observational strategy that will specifically improve our process understanding of the dynamical EBUS regions.

The cOCtEAU WG will address the knowledge gaps outlined above by making recommendations as to how better and more cost-efficiently observe these regions in both the ocean and atmosphere *simultaneously*. It will first provide a comprehensive evaluation of current knowledge regarding control mechanisms, impacts on biogeochemical cycles and feedbacks derived from all published observational and modeling approaches, and will then develop a strategical recommendation white paper to fill the gaps. To achieve this goal, a unique mixed group of early career scientists - with an appropriate gender balance - and more senior scientists, all experts in different EBUS of the world ocean, from observational and modelling perspectives, and originating from various developed and developing countries and disciplines, has been invited to participate in this working group.

Terms of Reference

1. **Synthesize** the existing knowledge about the different physical and biogeochemical mechanisms occurring over different time scales (i.e., intradaily, intraseasonal, interannual, decadal, multidecadal) and their influence on water column properties, biogeochemical cycles, biodiversity/ecosystem structure and functioning and regional climate, to identify the key feedback processes and establish the knowledge gaps. The **first workshop** will focus on organizing the **peer-reviewed publication** of this synthesis to be published in an open-access journal.
2. **Develop a compendium** containing a compilation of regional observational systems (e.g., available period, papers published, associated database) and numerical simulations (e.g., including configurations details, scientific production, responsible scientists and their contacts); being prepared as online newsletter for the oceanic and atmospheric science community (especially PhD students and early career scientists).
3. **Produce a** comparative analysis from modelling validated/published results, presented as a **high impact factor review paper**. Terms of References 2-3 will be the target of a **workshop**, followed by a **summer school** organized either in Senegal or Peru involving PhD students and early career scientists mostly from Africa and South America.
4. **Provide a strategic recommendation white paper** for setting up regional observational systems to monitor and understand physical and biogeochemical ocean-atmosphere interactions. These observational systems will be instrumental in improving the performance and reliability of climate models in these socio-

economically relevant regions of the world ocean. Additionally, a **conference** with decision makers, stakeholders and the scientific community will be organized to present the main findings, suggest priority topics and offer alternatives to approach solutions.

Working plan

Year 1

- **cOCtEAU First Workshop.** Objective ‘Organize the structure of the peer-reviewed publication synthesizing the existing knowledge on EBUS’. Full and associate members will attend together with their PhD students (at least one each). This workshop will be held potentially in combination with the AGU Fall Meeting.
- **Submit the peer-reviewed publication** wherein a synthesis of the existing knowledge (physical and biogeochemical ocean and atmosphere components and ocean-atmosphere interactions) on EBUS is presented.

Year 2

- **One day cOCtEAU Second Workshop.** Objective: ‘Organize the **compendium** and the **high impact factor review paper**’. The **compendium** will provide a detailed list of regional observational systems and numerical simulations both in the ocean and atmosphere and, this will serve as material to produce the **high impact factor review paper** that will provide a comparative analysis from modelling results. Full and associate members will attend. This workshop will be held potentially in conjunction with AGU Fall Meeting.
- **Release the compendium** of the compilation of regional observational systems and numerical simulations.
- **cOCtEAU Summer School.** Objective: ‘Present an overview of the main EBUS processes, teach the necessary topics required to understand ocean-atmosphere interactions, combine lectures and hands-on sessions, practical lessons’. All experts and younger scientists will participate by giving lectures and tutorials.
- **Submit the high impact factor review paper compiling modelling results** as a comparison to establish strengths and weaknesses of regional modelling simulations. This will help to point out considerations/actions to be taken in global models as well as observational platforms for better understanding of EBUS dynamics.

Year 3

- **cOCtEAU Open Science Conference**
Day 1: Objective ‘Organize the strategical recommendation brief to be presented as a short paper to the Executive Panel’.
Days 2-3: Objective ‘Bring together all interdisciplinary and multidisciplinary ocean and atmospheric science communities involving modelers and observationalists studying EBUS and related topics’.
Day 4: Executive Panel. Objective ‘Bring together decision makers, stakeholders and the scientific community to present and highlight the main findings, suggest first priority topics, offer suitable and cost-effective alternatives to approach

solutions to further understand the EBUS dynamics'. It will be developed just after **cOCTEAU Open Science Conference**.

- **Submit the white paper** wherein the strategic recommendation brief is presented.
- **Final Report** of the whole SCOR WG.

Deliverables

Deliverable 1. A peer-reviewed publication, wherein the existing knowledge about the different physical and biogeochemical mechanisms developed over different time scales on EBUS is synthesized. This paper will cover three aspects: (1) a theoretical aspect, in terms of theoretical processes, synthesizing past studies, (2) a practical aspect with new results, linking *in situ* and remotely sensed observations and modeling outputs from current studies, (3) a recommendation and perspective for the next decade.

Deliverable 2. A compendium, where regional observational systems and numerical simulations are compiled. This compendium will include detailed information about available data in EBUS mainly to answer where to find the observational and numerical data, their characteristics, identify their owners as well as scientific production or published papers.

Deliverable 3. A high impact factor review paper (e.g., BAMS), wherein a comparative analysis based on modelling results from both the ocean and atmosphere is presented.

Deliverable 4. A short recommendation paper, for stakeholders and policy makers wherein a strategic recommendation will be made on how to more cost effectively design and improve regional observational systems with the overarching goal of improving the performance and reliability of global climate models.

Capacity Building

The cOCTEAU WG is planning to hold an international summer school focused on PhD students and young post-docs mainly (but not exclusively) from Africa and South America and other developing countries. The objective will be to provide the young scientists with an integrative view of the land-atmosphere-ocean continuum in their modelling coupled physical/biogeochemical components. The basics of atmospheric physics and chemistry and associated coupler and modelling platforms will be presented. An introduction to regional weather and climate systems off the EBUS will be given, as well as basic concepts in physical oceanography and biogeochemistry and hands-on practicals with the ROMS-WRF-BIOEBUS modelling platform. Statistics applied to climatology and challenges of regional climate downscaling for performing regional climatic projections will be taught. We will try to explore a new, innovative capacity-building concept: the Network of Early Career Scientists (NECS). This will combine traditional capacity-building of individual early career scientists with a new level of institutional networking. The ultimate goal is to build long lasting capacity through training and by interconnecting the next generation of scientists, and to develop enduring institutional interactions that will help address the scientific challenges facing the EBUS.

We will also encourage and facilitate other training and professional development workshops and programmes, such as those funded by the Marie Skłodowska Curie Innovative Training Network. Funding for sustaining our NECS will be sought from a range of sources and stakeholders supporting training and networking measures worldwide. We will collaborate with START, IAI, POGO and APN, so that their fellowship schemes and other mechanisms can be used for capacity development.

It has to be noticed that some scientists involved in the consortium supervise students from southern countries which ocean science community is very small, therefore this WG proposal will also serve as a platform to increase the critical mass of researchers hence reinforcing capacity in oceanic sciences in these developing countries. The Chair of cOCtEAU Working Group being a woman early career scientist originating from a developing country guarantees the very close attention to be given to capacity building.

Additionally, the compendium will be the key material for students and local researchers from the developing countries which have restricted access to peer-review publications due to their limited resources to pay journals subscriptions. In this sense, since the compendium will provide the complete information from observational and numerical data as well as their respective owners and associated scientific production, students and local researchers would be in direct contact with the ocean science community allowing thus to reinforce their capacity building on these topics and at the same time open and expand their international collaborations.

Working Group composition

Full Members

Name	Gender	Place of work	Expertise relevant to proposal
1. Curtis Deutsch (USA)	Male	School of Oceanography, University of Washington, USA	Chemical oceanography, biogeochemistry and climate
2. Ming Feng (Australia)	Male	CSIRO Marine and Atmospheric Research	Physical oceanographer specialised in the Leeuwin Current dynamics
3. Sara Fawcett (South Africa)	Female	Department of Oceanography, University of Cape Town, South Africa	Biogeochemical Oceanographer, California and Benguela Upwelling Systems
4. Serena Illg (France)	Female	IRD – University of Cape Town, South Africa	Coupled ocean-atmospheric modelling, Upwelling system dynamics
5. Eric Machu (France)	Male	IRD – LPAO-SF, ESP, Université Cheikh Anta Diop, Dakar Sénégal	Oceanographer, structuration of plankton communities from coupled approaches

			(observation & modeling)
6. Baye Cheikh Mbaye (Senegal)	Male	Laboratoire de Physique de l'Atmosphere et de l'Ocean Simeon Fongang (LPAOSF), University Cheikh Anta Diop of Dakar (UCAD)	Physical/biological Oceanography – Senegalese- Mauritanian coastal upwelling within the Canary upwelling system off North-West Africa
7. Ivonne Montes (Peru) Chair of SCOR WG cOCEAU	Female	Instituto Geofísico del Perú (IGP)	Physical Oceanographer, biogeochemical coupled modelling and dynamics of the Peru/Chile System
8. Andreas Oschlies (Germany)	Male	Helmholtz-Zentrum für Ozeanforschung Kiel (GEOMAR)	Physical Oceanography, Marine Biogeochemical Modelling
9. Parv Suntharalingam (UK)	Female	University of East Anglia (UEA)	Oceanographer, biogeochemical modelling
10. Beatriz Yanicelli (Chile)	Female	Centro de Estudios Avanzados en Zonas Aridas (CEAZA)	Oceanographer, Chile Coastal Upwelling System

Associate Members

Name	Gender	Place of work	Expertise relevant to proposal
1. Xavier Capet (France)	Male	CNRS-LOCEAN, Paris	Physical Oceanographer - EBUS dynamics, modeller
2. Boris Dewitte (France)	Male	IRD-LEGOS, Toulouse	Physical Oceanographer, Air-sea interactions and climate variability
3. Iris Kriest (Germany)	Female	Helmholtz-Zentrum für Ozeanforschung Kiel(GEOMAR)	Biogeochemical modeller
4. Ryan Rykaczewski (USA)	Male	University of Southern California	Biological Oceanography of EBUS – California System
5. Marcello Vichi (South Africa)	Male	University of Cape Town	Coupled Physical/Biogeochemical Modelling, Earth System Modelling, Process Studies of Biogeochemical Dynamics in the Regional and Global Ocean
6. Siny Ndoye (Senegal)	Male	Cheikh Anta Diop	Physical Oceanographer

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Working Group contributions

All members involved in this SCOR WG will participate in all activities, they have been invited due to their field of expertise and past works, coming from various countries and disciplines; these are:

Dr. Curtis Deutsch is an expert on chemical oceanography, biogeochemistry and climate currently dedicated to contribute to a coherent understanding of the interactions between biogeochemical cycles and the climate system, based on modeling connections between ocean biogeochemistry and climate from human to geological time scales.

Dr. Sarah Fawcett works on understanding the complex relationships between biogeochemical fluxes (particularly nitrogen) and primary productivity in the ocean, with implications for past and future climate, ecosystem structure and function, ocean fertility, and global biogeochemical cycles. Current focus regions include the Southern Ocean and the southern Benguela upwelling system off the west coast of South Africa, which supports high levels of marine biodiversity and human subsistence.

Dr. Ming Feng is specialised in the Leeuwin Current dynamics, impacts of climate variability on the marine environment, and interactions between physical and biological processes in the ocean boundary current and eddies. He has been leading projects in the Western Australian Marine Science Institution on regional projections of climate change impacts and, an Integrated Marine Observing System project to monitor the long term changes in the Leeuwin Current.

Dr. Serena Illg is focussed on the phenology of the EBUS along the coasts of Peru and Chile in the Humboldt Current System and along the coasts of Angola and Namibia in the northern Benguela Upwelling System. She is specialized on the connexion with the linear equatorial dynamics, and on the air-sea interactions at regional and basin scales. Her approaches are based on an inter-comparative analysis of observations, and a combination of simple and complex models.

Dr. Eric Machu is focussed on understanding the role of small scale processes in structuring plankton communities, the energy transfer through the microbial loop and the environmental control of small pelagic fish which dominate these ecosystems. In terms of methodology, both coupled modeling and observations are used to apprehend the underlying processes. He is the Leader of WP3 in the IRD-BMBF AWA project and member of the steering committee of the international joint laboratory ECLAIRS, two projects gathering numerous partners from North-West Africa.

Dr. Baye Cheikh Mbaye is specialised in the Senegalese-Mauritanian coastal upwelling within the Canary upwelling system off North-West Africa. He analyzes how both environmental physical and biological factors affect the survival of fish early life stage (eggs and larvae), and how this ecological understanding could help to make good policies

for marine conservation and fisheries management in EBUS, based on both modelling and observations.

Dr. Ivonne Montes is specialized on coupled physical-biogeochemical modelling applied to Eastern boundary current system (Guinea Gulf, Mexico and Peru/Chile) to study the role of the ocean in Climate, investigate the processes maintaining the OMZ off Peru, and the impact of remote and local air-sea interactions in upwelling systems.

Dr. Andreas Oschlies is an expert in Marine Biogeochemical Modelling dedicated to study the physical, biogeochemical, and ecological constraints on the oceanic carbon uptake and its climate sensitivity. He is also interested in mixing processes and their representation in numerical models. He is the coordinator of the collaborative research centre SFB754 “Climate-biogeochemistry interactions in the tropical ocean” at Kiel University and GEOMAR in Germany.

Dr. Parv Suntharalingam is focussed on biogeochemical cycles of climatically important species in the atmosphere and ocean.

Dr. Beatriz Yanicelli has been combining modeling, observational and empirical experimental approaches to understand the relationship between physical and biogeochemical aspects of EBUS with the ecophysiology and dynamics of marine exploited populations.

Relationship to other international programs and SCOR Working groups

This EBUS theme is one of the Mid-Term Strategy Initiative of the SOLAS international Program¹ and is an integral part of the Integrated topics in the new SOLAS Science Plan 2015-2025². Moreover, CLIVAR and IMBER have a joint Research Focus on Upwelling systems, recently joined by SOLAS. Within Future Earth, the new research initiative on global environmental change and global sustainability, there is a strong willingness to build a Knowledge Action Network on Oceans and the EBUS hold a very favourable position to be selected as one of the focus topics and a proposal to the Belmont Forum on this topic is foreseen for fall 2016. In addition, there is a strong link between this SCOR WG proposal and the new initiative from IOC-UNESCO called GO₂NE (Global Ocean Oxygen NETWORK), an interdisciplinary network with particular concerns about the low oxygen concentrations in both the open ocean and coastal areas. This working group is also timely since it fits with concerns of the program TPOS2020 that is aimed at designing the future of the observing system in the Pacific (<http://tpos2020.org/>). Interactions with the Task Team “Eastern Boundary” of the TPOS2020 program will be encouraged during the

¹<http://www.solas-int.org/about/mid-term-strategy.html>

²http://www.solas-int.org/files/solas-int/content/downloads/About/Future%20SOLAS/Revised_SOLAS%20Science%20Plan.pdf

*By inversions we mean inversions to obtain information on the properties of materials in the ocean and the atmosphere (gas, particles, dissolved materials, drops etc') as well as at the interface (waves, bubbles). By properties we mean concentration, composition, size and shape, lifetime, optical properties.

course of the SCOR group. This SCOR WG will also have tight links with the SCOR Working Group 144 on Microbial Community Responses to Ocean Deoxygenation which runs between 2014 and 2017. The cOCtEAU WG will interact with WG 144 since one of its objectives is to disseminate standards, data sets and comparative analysis of the oxygen deficient systems in the world ocean to the wider oceanographic and Earth system science communities and the public.

This SCOR WG will also strive to integrate in its synthesis outcomes of relevant regional modeling and observational projects (e.g. CORDEX) through collaborations of its members.

SOLAS is holding a workshop on concurrent remote-sensing inversions of ocean and atmosphere in June 2016 in Frascati, Italy, sponsored by ESA and IGBP funds. It is intended to investigate the benefits and drawbacks of having sensors focused on the ocean and atmosphere (or both) on the same platform/constellation and inverting* ocean atmosphere and clouds together. This will constitute a breakthrough in studying ocean-atmosphere interactions. The cOCtEAU WG will establish contacts with the remote sensing and SOLAS scientists involved in this initiative.

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Appendix

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