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Exchanges Special Issue: Sustained Ocean Observing and Information in Support of Ocean and Climate Research

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CLIVAR Ocean and Climate: Variability, Predictability and Change is the World Climate Research Programme's (WCRP) core project on the Ocean-Atmosphere System

Editorial

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CLIVAR is celebrating 20 years of progress since the publication of its first Science Plan in August 1995. The overarching goals of the project continue - to improve understanding and prediction of the ocean-atmosphere system and its influence on climate variability and change, to the benefit of society and the environment, but CLIVAR's structure has evolved to meet the changing nature of the science and the community it serves. There are now four global Panels: the Ocean Model Development Panel, the Global Synthesis and Observations Panel, the Climate Dynamics Panel, and the joint CLIVAR-GEWEX Monsoons Panel. The regional ocean basin Panels (Atlantic, Pacific, Indian and Southern Ocean) promote and provide advice on the implementation of multi-national observational systems and process studies in support of research on climate and ocean variability and predictability. All Panels report to the CLIVAR Scientific Steering Group.

The regional ocean basin panels have developed through the years strong partnerships with groups that also work on the implementation of the ocean observing system, like the CLIVAR/IOC-GOOS Indian Ocean Region Panel links with IIOE-2 activities (see Hood and Yu's article in this issue) and the CLIVAR/CliC/SCAR Southern Ocean Region Panel's links with SOOS (Wahlin et al, this issue). More recently, the Atlantic Region Panel and the Pacific Region Panel are involved with AtlantOS (Visbeck et al., this issue) and TPOS2020 (Smith et al, this issue), respectively. CLIVAR contributes to initiatives such as these that respond to the needs of users from several sectors, while improving the efficiency of the observing system.

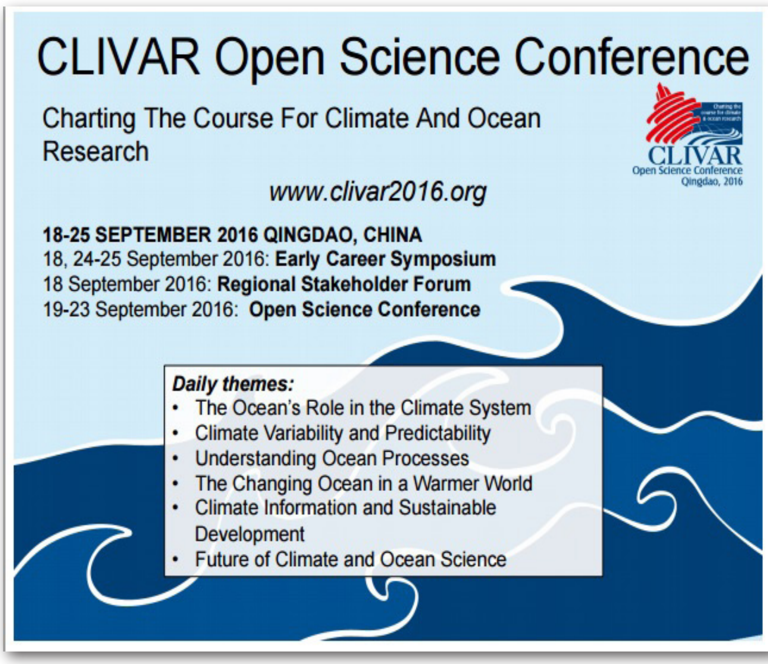
The first meeting of the Climate Dynamics Panel was held at the University of Exeter, UK, 2-4 July 2015. The panel will foster and coordinate international research efforts to increase understanding of the dynamical processes that control circulation variability and change in the atmosphere and ocean on synoptic to centennial time scales. The focus is on large-scale phenomena, processes, and mechanisms of coupled climate variability/modes, teleconnnections and change on seasonal to centennial time-scales, in particular i) storm tracks, jet streams and weather systems, ii) tropical-extratropical interactions, and iii) long-term coupled atmosphere-ocean circulation.

Recognizing the need for the CLIVAR project to be flexible and responsive to new ideas and challenges, the CLIVAR SSG has initiated the concept of Research Foci (RF, http://www.clivar.org/about/research-foci). These are focused research topics identified by members of the CLIVAR community as being ripe for progress in the next 5-10 years and that would significantly benefit from enhanced international coordination. The RF have already demonstrated to be an effective means for CLIVAR to initiate activities and invigorate progress in areas that go beyond the traditional areas addressed by the Panels, fostering cross-panel, cross-community collaboration, and an opportunity to bring young scientists into CLIVAR. Four RF have presented their plans to the SSG and been endorsed to organize meetings and workshops this year to further define their science focus and implementation plans for the coming years: ENSO in a Changing Climate, Decadal Climate Variability and Predictability, Sea Level Rise and Regional Impacts (also a WCRP Grand Challenge) and Planetary Heat Balance and Ocean Heat Storage (CONCEPT HEAT).

Most recently, the Research Focus on ENSO in a Changing Climate led the organization of the 4th CLIVAR workshop on the evaluation of El Niño / Southern Oscillation (ENSO) processes in climate models that was held at Sorbonne-Universités in Paris in July 2015, in conjunction with the UNESCO "Our Common Future Under Climate Change" conference. The workshop was hosted by IPSL and attended by fifty experts, including twelve early-career scientists. The workshop built upon a February 2015 workshop in Sydney, Australia, that focused on ENSO diversity and extremes. It also entrained members of the US CLIVAR Working Group on ENSO Diversity, that has focused attention on understanding the substantial inter-event differences in ENSO mechanisms and impacts. Presentations at the Paris workshop highlighted ENSO mechanisms, the role of intraseasonal variability, climate change and decadal variability, modelling and prediction, and historical and paleo observations. Discussion sessions focused on model evaluation and metrics, and on recommendations for observations that could be realized as part of the Tropical Pacific Observing System 2020 (TPOS 2020) initiative.

This special issue of Exchanges provides an overview of CLIVAR's role in the development of a sustained ocean observing system, in terms of research and advances in understanding. The issue also highlights the importance of CLIVAR's international and regional partnerships in the development, implementation and delivery of ocean observations for climate research. We thank Eric Lindstrom and Martin Visbeck for joining us as Guest Editors and all the authors for their contributions that give the broader CLIVAR community a view of the breadth of on-going and future directions of research and the development related to the ocean observing system.

We look forward to the CLIVAR2016 Open Science Conference (www.clivar2016.org) where we hope many of you will join us to discuss these issues and others related to the future of CLIVAR science.



Sustained Ocean Observing and Information in Support of Ocean and Climate Research

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Introduction

It is with great pleasure that we introduce this Special Issue of Exchanges on the contribution of CLIVAR to sustained ocean observing. The Special Issue coincides with the recognition of the importance to forge close interactions and synergy between the Global Climate Observing Systems (GCOS) community and World Climate Research Programmes (WCRP) climate research community and focuses on sustained ocean observing and information that supports ocean and climate research of direct relevance to CLIVAR. It reflects the fact that a great part of the ocean observing community that has built and is sustaining the global-scale ocean observing system comes from the world of climate research, and that ocean and climate researchers are key users of ocean data and information. Climate research, projections, and the development of climate services crucially depend on a research infrastructure of sustained ocean observations, adequately covering the ocean phenomena that are essential to observe.

Since the launch of the WCRP core project CLIVAR almost 20 years ago there has always been a close interaction between and tight collaboration with the ocean observing community (Gould et al 2013). Sustained in-situ ocean observations were less organized and coordinated when compared to atmospheric observations and the space based capabilities. However, the CLIVAR and WOCE community have established important sustained ocean observing programmes such as the tropical moored buoy arrays (TAO/TRITON, PIRATA and RAMA), global repeat hydrographic surveys (now called GO-SHIP), the profiling float array (Argo) just to name a few that are also a key contribution to the Global Ocean Observing System (GOOS).

In recognition of those tremendous successes and the need to sustain and grow those activities CLIVAR and GOOS/GCOS sponsored the first OceanObs conference in 1999 to draw up plans for networks of sustained ocean observing for the next decade. At the second OceanObs09 conference in 2009 the community came together again and reviewed 10 years of progress in sustained ocean observing and came to the recognition that more integration across disciplines (i.e. fully including the marine chemistry and ecology communities) and a more systematic and strategic approach to ocean observing would be beneficial. A group of experts was convened and the produced a document outlining the "Framework for Ocean Observing" as the proposed strategy for the future (FOO, www.oceanobs09.net/foo), Fischer et al (this issue). The FOO is responsive to societal drivers and the demands these generate for ocean observations and include:

- The need to document ocean change (measuring the responses to climate change, overfishing and pollution);
- Initializing ocean models for climate predictions (e.g. El Niño, Tropical Atlantic Variability, Indian Ocean Dipole and their respective impacts on monsoon systems and decadal predictability);
- Initializing short-term ocean forecasts for marine operations (e.g. oil spill and pollution tracking, search-and-rescue);
- Regulatory matters of coastal states (e.g. Climate Change Convention, Convention of Biodiversity, Marine Spatial Planning and associated demands).

The Framework proposed to guide the ocean observing community around a set of "Essential Ocean Variables (EOVs); an approach shown by GCOS to brake down barriers to cooperation amongst funding agencies and observing networks. Implementation would be guided by the level of "readiness" with immediate implementation of components that have already reached maturity while encouraging innovation and capacity building for less mature observation streams and methods.

By taking a systems engineering approach, the FOO input requirements will be identified as the information needed to address a specific scientific problem or societal issue. The societal issues span from short-timescale needs such as hazard warning to such long-timescale needs as knowledge of ecosystem limits appropriate to the sustainable exploitation of ocean resources. It includes the needs of the science community, such as that from CLIVAR but goes beyond. The mechanisms to deliver these observation elements will then be identified in terms of technologies and observing networks (such as GO-SHIP for repeat hydrography, OceanSite for moored systems and Argo for profiling floats). The outputs (data and information products) will consist of the most appropriate syntheses of ocean in-situ and remotely sensed observation streams to provide services, address scientific problems or permit informed decisions on societal issues.

The vastness, remoteness, and harshness of the oceans means that collecting any in situ observations is expensive. As a consequence, observing systems have been and will continue to be designed to measure as many variables as possible so as to take full advantage of the limited number of observing platforms. These multiple sensors place demands on energy and thus a focus for FOO will be the avoidance of duplication between observing platforms and networks. However, the complementarity of observing networks (for instance between Argo and ship-based CTD observations) has enormous benefits in allowing inter-calibration and eliminating systematic bias. Common standards for data collection and dissemination of EOV data will be adopted so as to maximize the utility of data.

The Framework approach will be used to encourage partnerships between the research (such as WCRP CLIVAR) and operational communities so as to assess and improve the readiness levels of observation elements and data systems appropriate for each EOV. Similar partnerships will refine requirements. The Framework should also enhance collaboration between developed and developing regions and promote the use of common standards and best practices.

In summary the Framework will promote a more consistent and integrated approach to the assessment of readiness, implementation and setting standards for information sharing among the varied and largely autonomous observing elements. It should also lead to a well-defined set of requirements and goals, facilitate coordination between observing system elements, streamline implementation of sustained global-scale observations by applying a systems engineering approach and identifying best practices. Successful implementation will depend on the continuous involvement of the research community as innovators, users and warrants for the best possible quality of the observations and the information products.

The following articles in this special issue give an excellent perspective on the various dimensions of this productive area of science.

Gould, J.; Sloyan, B.; Visbeck, M., 2013: In Situ ocean observations: a brief history, present status and future directions. In: Siedler, G.; Griffies, S.; Gould, J.; Church, J., (eds.) Ocean Circulation and Climate: A 21st Century Perspective. 2nd Ed. Oxford, Academic Press, 59-82.

Fischer, A., 2015: A Framework for Ocean Observing. CLIVAR Exchanges, this issue.

A Framework for Ocean Observing

Albert Fischer

IOC UNESCO, France

Introduction

Nearly six years ago, the ocean observing community gathered at the OceanObs'09 conference (21-25 September 2009, Venice, Italy, oceanobs09.net) to reflect on a decade of progress in sustained ocean observations, and to look at the challenges and tremendous opportunities in the coming decade through to 2019. In a conference declaration, the community called for a framework for planning and moving forward with an enhanced global sustained ocean observing system over the next decade, integrating new physical, biogeochemical, and biological observations while sustaining the present system.

A team that was named in partnership by all the major international ocean research and observing initiatives, including the WCRP, developed the Framework for Ocean Observing (doi:10.5270/OceanObs09-FOO), published in 2012. The team drew from the best practices of networks and observing systems that have successfully been sustained over the long term.

The intent of the Framework is to guide the observing community as a whole to sustain and expand the capabilities of the ocean observing system. It provides a structure to promote collaborative alignment of independent groups, communities, and networks, building on existing structures as much as possible. It will provide a basis for integrating sustained observations of the biogeochemistry and biology of the oceans along with existing and future physical and climate observations. Through this provision of a common language, the communication within the observing community and to an outside audience of users and funders can be streamlined, and integration can be fostered across disciplines, platforms and institutions. The set of sustained ocean observations is a complex system, made up of both research and operational effort, in situ and satellite observing networks measuring different variables, new technological developments, data streams, and products. The team applied some systems thinking to help grapple with the problems of coordinating and managing the complexity. The Framework for Ocean Observing breaks down the artificial barrier between operational and research observations.

The Framework's simple model of the ocean observing system has an input in the form of requirements driven at the highest level by societal benefit, a process in the form of coordinated observing networks, and an output in the data and products, as shown in Figure 1. This output generates scientific or societal benefit, the source of the requirements, and evaluation and management of the system should aim to ensure that the output is fit for its purpose.

Expanding on the ideas of this simple model, the team drew from the best practices of the present sustained ocean observing system for climate, which is encapsulated in reports by the Global Climate Observing System (GCOS) to the UN Framework Convention on Climate Change (UNFCCC). Climate observing requirements at the highest level are expressed as requirements on Essential Climate Variables, which from a scientific point of view are essential to monitor on a sustained high quality basis in order to meet societal needs for climate information resulting from research, monitoring, and projections.

Generalizing, the requirements from society for sustained ocean observations to support climate research and services, real-time services, and sustainably manage ocean health, can be distilled scientifically into requirements to measure Essential Ocean Variables (EOVs). Any single EOV may be measured by multiple observing networks and technologies, satellite or in situ, in independent observing elements that need to be coordinated (Figure 2). These observing elements are independently governed and managed, but to participate in a global system have responsibility to adopt standards and best practices for both observational methods and data streams. For example, temperature is observed from ships with very high accuracy, by Argo profiling floats with high vertical resolution and broad space and time resolution, by satellite at the surface, by expendable bathythermographs (XBTs) across lines with high horizontal resolution, and by many other elements including surface drifters, moorings, and gliders. Some of these elements, such as ship-based repeat hydrography, measure a large number of EOVs, and other such as XBTs only measure one. Some observing elements are coordinated globally, and others on a regional or national level. To be used for research and the development of useful information products, individual observing element data streams must be combined with coordinated metadata and arrangements to produce the useful outputs of an observing system.

The Framework seeks to support self-funding and self-managing observing elements. Overall the Framework provides a common language and consistent handling of requirements, observing technologies, and information flow among different, largely autonomous, observing elements.

In order to deliver on its requirements, the observing system needs processes for regular oversight, coordination, and evaluation, which create two feedback loops: one inner loop examining whether the requirements to observe EOVs are being fulfilled by the observing elements and data management arrangements in place, and a larger outer loop that evaluates whether the outputs of the observing system are having the desired scientific and societal impacts stated at the outset, including whether ocean information is having an impact on decision-making and policy – whether they are fit for purpose.

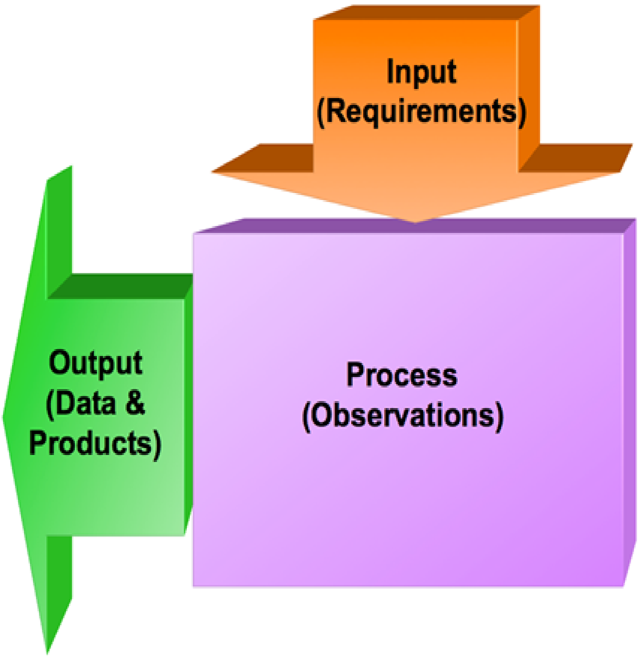

Figure 1: Framework model

Essential Ocean Variables and building Readiness

A key idea in the Framework is the definition of Essential Ocean Variables (EOVs), which have some overlap with other types of essential variables that have been defined, such as Essential Climate Variables (ECVs) of GCOS (which also cover the atmosphere and terrestrial domains), the original Essential Variables defined by the World Meteorological Organization as being essential for weather forecasting, and Essential Biodiversity Variables that are being defined by Group on Earth Observation Biodiversity Observing Network.

A central tenet of the Framework is that for the key societal and scientific drivers of sustained ocean observations, we cannot measure everything—nor do we need to. Essential Ocean Variables should respond to these high-level drivers, related to climate, to understanding and managing ecosystem services, to conserving biodiversity, to managing living marine resources, to safety and protection of life and property at sea and on the coasts.

Aligning the coordination processes of the observing system on variables, rather than by platforms or observing techniques, stays truer to the natural system which we are trying to observe, while allowing for innovation of observing techniques over time as technology and capability develop.

The definition of an EOV must be driven by these requirements, but be rooted in reality: its measurement must be feasible. The truly Essential variables will have a high impact on scientific questions and to address societal issues, and high feasibility for global sustained observation (Figure 3).

We may not be ready to measure all EOVs, but assessing and encouraging the development of readiness is also a Framework concept, shown in Figure 4. Readiness levels are in fact an idea that has been part of the developing sustained ocean observing system for a several decades. In the early 1990s, building on ocean research observation techniques that had

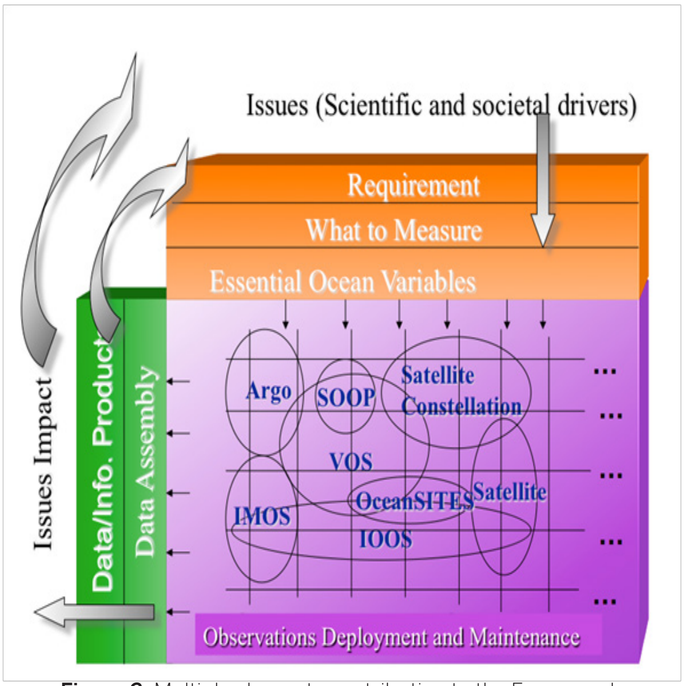

Figure 2: Multiple elements contributing to the Framework

developed rapidly, an Ocean Observing System Development Panel was established, chaired by Neville Smith of Australia, under the auspices of the WCRP, the Intergovernmental Oceanographic Commission (IOC) of UNESCO and ICSU's Scientific Committee for Oceanic Research (SCOR). This panel used concepts of readiness to recommend the observing elements that should be developed into a permanent ocean observing system for climate, and helped lead to the establishment of the Global Ocean Observing System (GOOS) in 1997.

The concept of readiness in the Framework (Figure 4) reminds us of the contribution of research to a sustained ocean observing system, and of the importance of regular evaluation and innovation in the system.

As we as an ocean observing community build readiness—with refined requirements of what is most essential to measure for multiple goals, with improved observing techniques and platforms, and with improved data management arrangements, data streams and information products—we help to build additional advocates for the observing system, and to help drive an integration across disciplines and especially the data products that will help build a system that is more than a sum of its individual parts.

The nations of the world who fund sustained ocean observations cannot afford multiple ocean observing systems, each responding to different expressed requirements. One integrated system that responds to many different requirements will be far more sustainable and fruitful.

The Framework in this case was developed to be applied globally, but is equally applicable for the open ocean and the coast; and for global, regional, or national priorities.

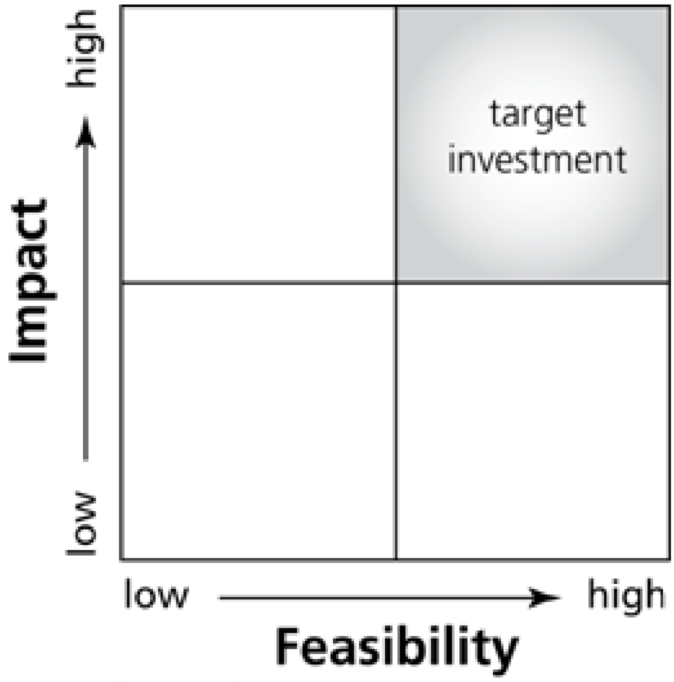

Figure 3: Essential Ocean Variables by feasibility and impact

The Global Ocean Observing System and the Framework

In practice, the Framework for Ocean Observing has been adopted as a core guiding document by the Global Ocean Observing System (GOOS).

GOOS as a programme is formally sponsored by three UN organizations, the Intergovernmental Oceanographic Commission of UNESCO which hosts its main office, the World Meteorological Organization (WMO), and the United Nations Environment Programme (UNEP); as well as the International Council for Science (ICSU). Its program activities are also supported by staff and activities provided by donations from a number of countries. GOOS the observing system is a voluntary collaborative system of an even larger number of participating countries, organizations, and observing elements. It leverages a sustained ocean observing system that is a multi-billion US dollar investment yearly.

GOOS at the global level as a program deliver strategic oversight, coordination, and evaluation of the sustained ocean observing system for these three themes: climate, services, and ocean health. The program is helping to coordinate a wide range of efforts by national and regional research and operational agencies, entraining a wide range of voluntary effort.

At the top level of coordination, the GOOS Steering Committee is responsible for advocacy for an integrated and sustained GOOS, ensuring that the necessary structures are in place to manage Framework processes, and negotiating with all of the interested parties. The Steering Committee is presently co-chaired by John Gunn (AIMS, Australia) and Eric Lindstrom (NASA, USA).

GOOS is covering this space with three panels under the Steering Committee. The physics panel is shared with GCOS and WCRP, and chaired presently by Mark Bourassa (USA) and Toshio Suga (Japan), with secretariat support from Katy Hill at the GCOS office in Geneva. The biogeochemistry panel is being led by the SCOR-IOC International Ocean Carbon Coordination Project with additional funding, and is chaired by Toste Tanhua (Germany) with Maciej Telszewski (Poland) serving as the secretariat. The relaunched biology and ecosystems panel is being co-chaired by Nic Bax (Australia) and Samantha Simmons (USA), with secretariat support from Patricia Miloslavich (Venezuela, now based in Australia) and Ward Appeltans of the IOC secretariat. The biology and ecosystems panel is beginning a substantive activity to identify the already ongoing activities, their essential parts for greatest impact, geographic gaps, and building an understanding of how these observations will serve universal needs to monitor

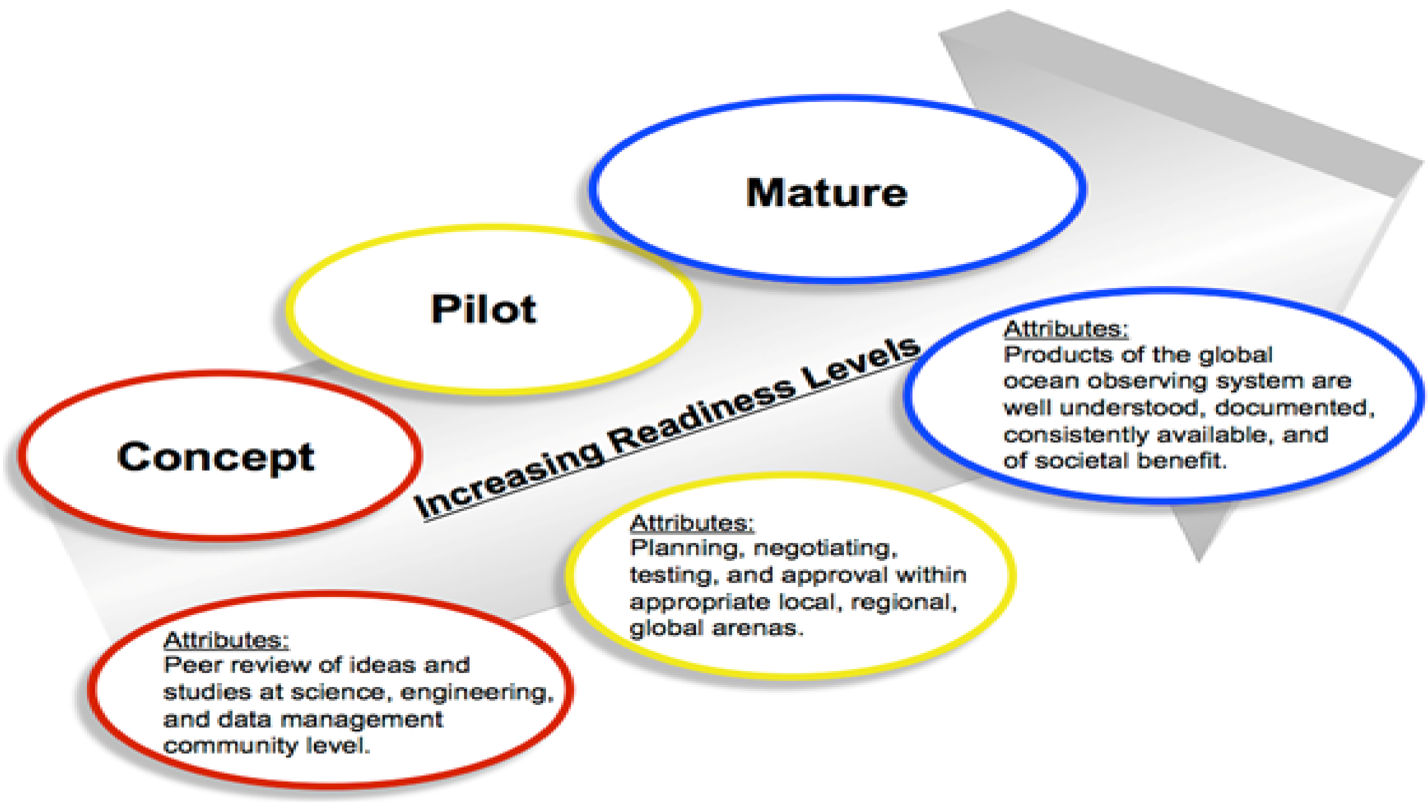

Figure 4: The concept of readiness in the Framework

ecosystem health. A large number of the in situ observing networks coordinate through the Joint IOC-WMO Technical Commission for Oceanography and Marine Meteorology's Observations Coordination Group (JCOMM OCG), chaired by David Legler (USA), and have built a common technical coordination at JCOMM's Observing Program Support Centre (JCOMMOPS) in Brest, France.

At the core of the ocean observing system are technical advisory and coordination groups, that naturally form around particular observing networks, or the generation of products, often focused on a particular variable, pulling all available data together. Many CLIVAR scientists are deeply involved in these groups, as well as the larger GOOS structures described above. At the regional level, the GOOS Regional Alliances in the past few years have been active in mapping their own priorities and capabilities, sharing experiences, and in the past year have embarked in an extensive review of their modeling needs and capacities.

GOOS Strategic Mapping and Projects

This activity will allow us to improve a Strategic Mapping of GOOS that is a basic tool for mapping out the links in the Framework for Ocean Observing. This Strategic Mapping is shown in Figure 6 linking the three major societal drivers of GOOS: climate, services, and ocean health; with the societal benefits informed by sustained ocean data; the scientific issue, application, or product needed; the Essential Ocean Variable we need to capture; and the type of observing element contributing to the measure of these variables.

We can track how any particular observing platform measures a number of variables, feeding products and applications that deliver societal benefit. Behind each of the nodes in this mapping is a specification sheet with additional information on the global groups and standards and best practices information.

A major message from this complicated diagram is that there are many interconnections. Many observations have multiple lifetimes – multiple uses. With growing sensor capability we are increasingly building an integrated observing system. And there is a tremendous need for the coordination activities that make this system as efficient and effective as possible.

Elements of GOOS are fragile, and require constant maintenance. In 2013 the tropical moored array in the Pacific maintained by NOAA suffered from a dramatic drop in data return, due to logistical and funding problems. Due to a renewed commitment, this is largely back to normal. However, the far western part of the array, TRITON, which has been maintained for more than 15 years by JAMSTEC, is now at 50% and is scheduled to be reduced to 4 moorings by 2017.

GOOS along with many partners has launched the Tropical Pacific Observing System in 2020 project to address these issues with sustainability (www.tpos2020.org), see Smith et al. (this issue). The project will evaluate, and where necessary change, all elements that contribute to the Tropical Pacific Observing System based on a modern understanding of tropical Pacific science. The project aims for enhanced effectiveness for all stakeholders, informed by the development and requirements of the operational prediction models that are primary users of TPOS data. The project embraces the integration of diverse sampling technologies, with a deliberate focus on robustness and sustainability, and will deliver a legacy of improved governance, coordination and supporting arrangements contributing to GOOS.

The TPOS 2020 project is funded and managed independently of GOOS, but reporting to the GOOS Steering Committee to ensure integration of its legacy of GOOS. It is a model for other development projects that are extending the reach of the ideas of the Framework for Ocean Observing and energizing and expanding the capabilities of GOOS. We will be launching a Deep Ocean Observing Strategy project, and GOOS is working closely with other large-scale development projects such as the European Commission AtlantOS project, and the Global Ocean Acidification Observing Network GOA-ON; as well as being involved in the Second International Indian Ocean Expedition (IIOE-2).

GOOS and CLIVAR

We are using the knowledge gained from the success of building up physical and climate observations, and taking advantage of the growing readiness of sensors and platforms to make the leap forward in the identification and coordination of essential biogeochemical and biological/ecosystems

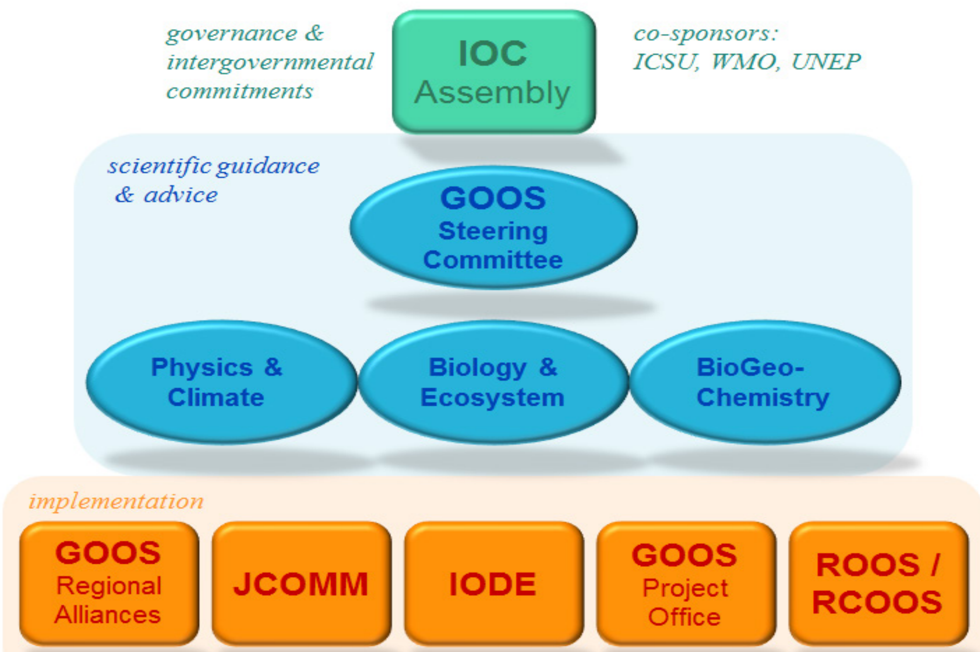

Figure 5: Structure of the Global Ocean Observing System (GOOS)

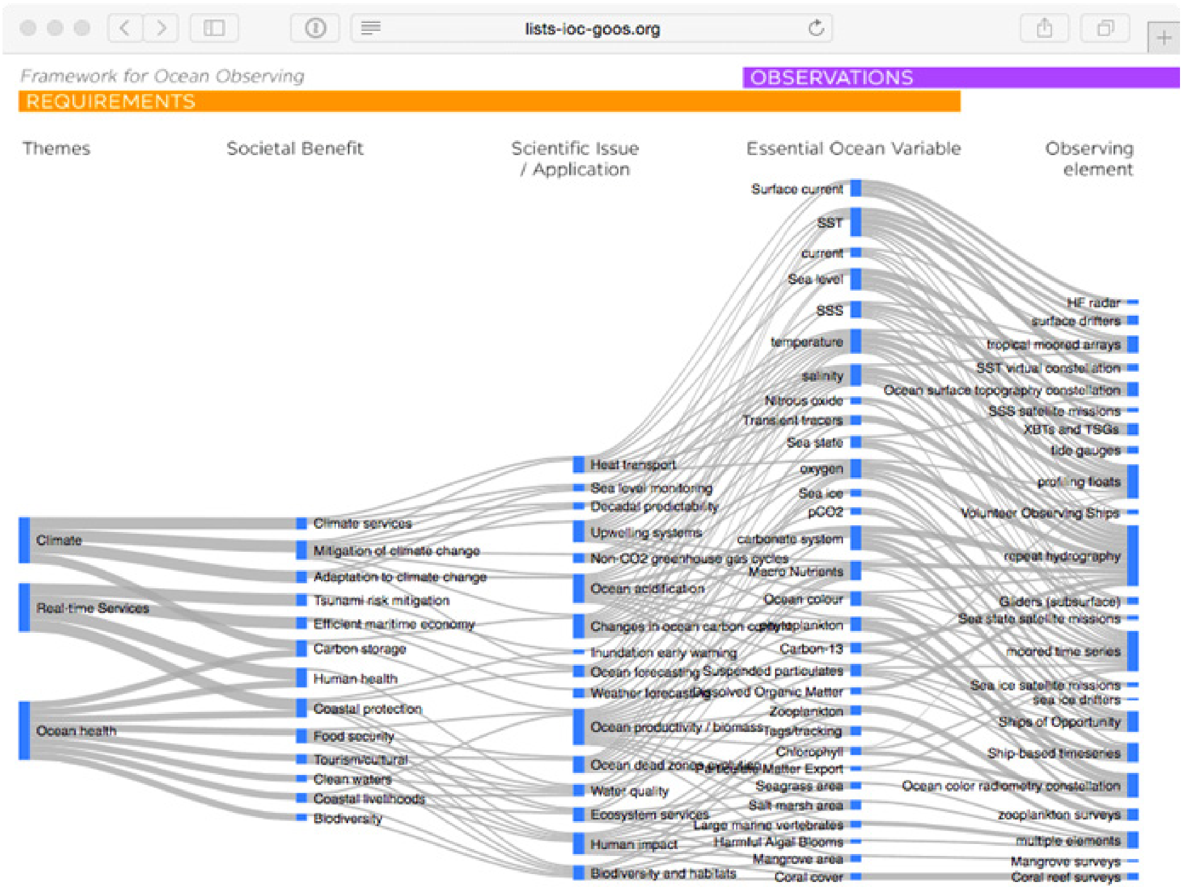

Figure 6: GOOS Strategic Mapping [live interactive version linked from ioc-goos.org/Strategic-Mapping]

variable observations. Increasingly to deliver the needed climate information for adaptation and mitigation, we need information about the physical, biogeochemical, and biological state of the ocean. In turn, the objectives and research foci of CLIVAR critically depend not only on a sustained research infrastructure of physical ocean observations, but increasingly on complementary biogeochemical and biological data as well.

This issue presents more detail about GOOS-related projects and closely related activities that add value for CLIVAR research through a sustained ocean observing system. They include links with the data management and modeling and synthesis communities that help to create value from ocean observations.

CLIVAR is an important partner for GOOS in the Framework for Ocean Observing, particularly in creating value and knowledge out of sustained observations, helping to evaluate the observing system, and innovating in observing system design with new methods and techniques. Research has always been central to sustained ocean observing, and will continue to do so in the future.

To keep abreast of GOOS news and webinars, please join our mailing list at ioc-goos.org/join or follow us on Twitter @ GOOSocean.

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CLIVAR and the Second International Indian Ocean Expedition (IIOE-2)

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Introduction

The end of 2015 will mark the 50th Anniversary of the completion of the International Indian Ocean Expedition (IIOE). SCOR[1] , IOC[2] and CLIVAR[3]/IOGOOS[4] are working to stimulate a new phase of coordinated international research focused on the Indian Ocean for a 5-year period beginning in late 2015 and continuing through 2020. The goal is to help to organize ongoing research and stimulate new initiatives in the 2015-2020 time frame as part of a larger expedition. These activities will serve as a core for a new Indian Ocean research focus, which has been termed "IIOE-2." Indeed, through the Indian Ocean Region Panel (IOP), CLIVAR has played a central role in motivating the IIOE-2 and defining its research priorities. The motivation, coordination and integration of Indian Ocean research through IIOE-2 will advance CLIVAR science by increasing knowledge and scientific capacity, and enabling international collaboration in an under-sampled, poorly understood, yet important region.

Motivation

Although there have been significant advances in our ability to describe and model the Earth System, our understanding of geologic, oceanic and atmospheric processes in the Indian Ocean is still rudimentary in many respects. This is largely because the Indian Ocean remains under-sampled in both space and time, especially compared to the Atlantic and Pacific. The situation is compounded by the Indian Ocean being a dynamically complex and highly variable system under monsoonal influence. Many uncertainties remain in terms of how geologic, oceanic and atmospheric processes affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations in and around the Indian Ocean. There are also growing concerns about food security in the context of global warming and of anthropogenic impacts on coastal environments and fisheries sustainability. These impacts include sea level rise, which leads to coastal erosion, loss of mangroves, and loss of biodiversity. There is a pressing need for ecosystem preservation in the Indian Ocean for both tourism and fisheries.

More than 50 years ago SCOR and IOC of UNESCO motivated one of the greatest oceanographic expedition of all time: IIOE (Figure 1).

In the 50 years since the IIOE, fundamental changes have taken place in geological, ocean and atmospheric science. These have revolutionized our ability to measure, model, and understand the Earth System. Thanks to these technological developments we can now study how the ocean changes across a wide range of spatial and temporal scales, and how these fluctuations are coupled to the atmosphere and topography. Moreover, compared to the IIOE era, which relied almost exclusively on ship-based observations, new technologies, in combination with targeted and well-coordinated field programs provide the capacity for a much more integrated picture of Indian Ocean variability. In addition, improved communication through the World Wide Web allows much broader engagement of the global scientific community.

SCOR, IOC and CLIVAR/IOGOOS are working to stimulate a new phase of coordinated international research focused on the Indian Ocean for a 5-year period beginning in late 2015 and continuing through 2020. The goal is to help organize ongoing research and stimulate new initiatives in this time frame as part of a larger expedition. International programs that have research ongoing or planned in the Indian Ocean during this time include not only CLIVAR and IOGOOS, but also many others (for example, the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, the Bay of Bengal Large Marine Ecosystem (BOBLME) Project, the Strategic Action Programme Policy Harmonization and Institutional Reforms (SAPPHIRE) Project, the EAF-Nansen project (Strengthening the Knowledge Base for and Implementing an Ecosystem Approach to Marine Fisheries in Developing Countries), GEOTRACES (a program to improve the understanding of biogeochemical cycles and large-scale distribution of trace elements and their isotopes in the marine environment), the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), the International Ocean Discovery Program (IODP), InterRidge (an international organization that promotes interdisciplinary, international studies of oceanic spreading centers) and others). Many countries, including Australia, China, Germany, India, Indonesia, Japan, Norway, the United Kingdom, South Africa and the United States, are planning cruises and other activities in this time frame, and new regional research programs in the Indian Ocean are under development. These programs and national cruises will serve as a core for the new Indian Ocean "IIOE-2" research focus.

The overarching goal of IIOE-2 is to advance our understanding of interactions between geologic, oceanic and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region, and determine how those dynamics affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations. This understanding is required to predict the impacts of climate change, pollution, and increased fish harvesting on the Indian Ocean and its nations, as well as the influence of the Indian Ocean on other components of the Earth System. New understanding is also fundamental to policy makers for the development of sustainable coastal zone, ecosystem, and fisheries management strategies for the Indian Ocean. Other goals of IIOE-2 include helping to build research capacity and improving availability and accessibility of oceanographic data from the region.

IIOE-2 Science is structured around six scientific themes (Hood et al., 2014, 2015). Each of these include a set of questions that need to be addressed in order to improve our understanding of the physical forcing that drives variability in marine biogeochemical cycles, ecosystems and fisheries in the Indian Ocean and develop the capacity to predict how this

[1] SCOR: Scientific Committee on Ocean Research
[2] IOC: Intergovernmental Oceanographic Commission
[3] CLIVAR: Climate and Ocean: Variability, Predictability and Change
[4] IOGOOS: Indian Ocean Global Ocean Observing System

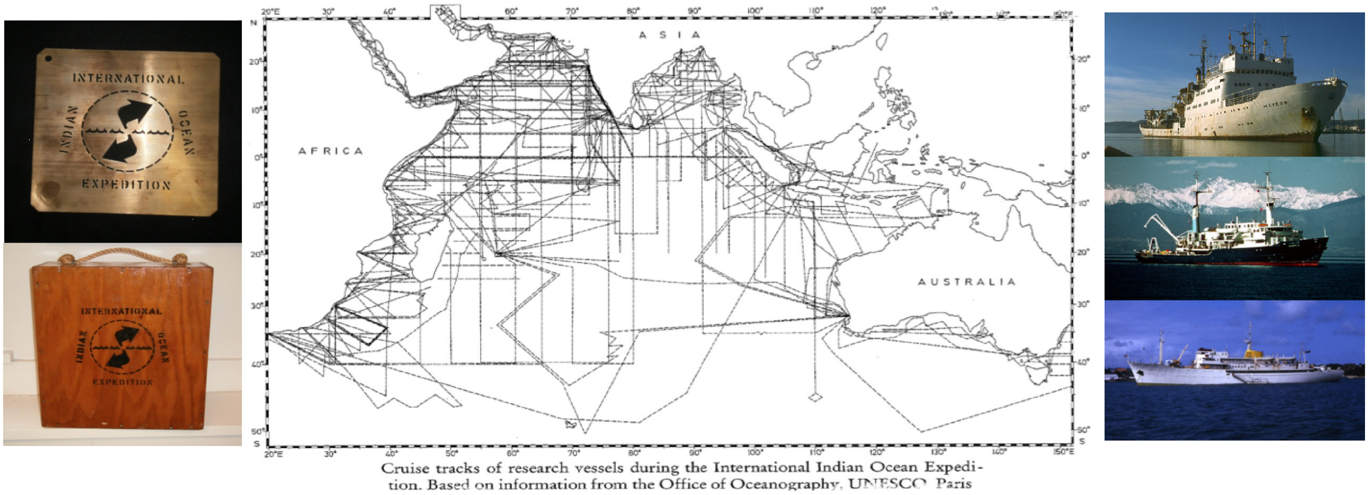

Figure 1: Center: Map of the Indian Ocean showing the cruise tracks of research vessels during the International Indian Ocean Expedition. Left: Logo and field instrument case from the IIOE. Right: Three oceanographic research vessels that participated in the IIOE, from Germany (Meteor II, top), the US (Atlantis II, middle) and the UK (Discovery, bottom).

variability will impact human populations in the future. All of these themes are relevant to CLIVAR's Research Foci and the WCRP's Grand Challenges.

Theme 1: Human Impacts
(How are human-induced ocean stressors impacting the biogeochemistry and ecology of the Indian Ocean? How, in turn, are these impacts affecting human populations?)

Theme 2: Boundary current dynamics, upwelling variability and ecosystem impacts
(How are marine biogeochemical cycles, ecosystem processes and fisheries in the Indian Ocean influenced by boundary currents, eddies and upwelling? How does the interaction between local and remote forcing influence these currents and upwelling variability in the Indian Ocean? How have these processes and their influence on local weather and climate changed in the past and how will they change in the future?)

Theme 3: Monsoon Variability and Ecosystem Response
(What factors control present, past and future monsoon variability? How does this variability impact ocean physics, chemistry and biogeochemistry in the Indian Ocean? What are the effects on ecosystem response, fisheries and human populations?)

Theme 4: Circulation, climate variability and change
(How has the atmospheric and oceanic circulation of the Indian Ocean changed in the past and how will it change in the future? How do these changes relate to topography and connectivity with the Pacific, Atlantic and Southern oceans? What impact does this have on biological productivity and fisheries?)

Theme 5: Extreme events and their impacts on ecosystems and human populations
(How do extreme events in the Indian Ocean impact coastal and open ocean ecosystems? How will climate change impact the frequency and/or severity of extreme weather and oceanic events, such as tropical cyclones and tsunamis in the Indian Ocean? What are the threats of extreme weather events, volcanic eruptions, tsunamis, combined with sea level rise, to human populations in low-lying coastal zones and small island nations of the Indian Ocean region?)

Theme 6: Unique geological, physical, biogeochemical, and ecological features of the Indian Ocean
(What processes control the present, past, and future carbon and oxygen dynamics of the Indian Ocean and how do they impact biogeochemical cycles and ecosystem dynamics? How do the physical characteristics of the southern Indian Ocean gyre system influence the biogeochemistry and ecology of the Indian Ocean? How do the complex tectonic and geologic processes, and topography of the Indian Ocean influence circulation, mixing and chemistry and therefore also biogeochemical and ecological processes?)

The Role of CLIVAR and the Indian Ocean Region Panel

CLIVAR has a number of panels and working groups based on the study of climate variability and predictability of different components of the global climate system. CLIVAR's regional panels focus on specific aspects of the climate system. Since the different regions of the ocean are qualitatively different, and given the important role of the oceans in controlling climate over the interannual, decadal, and centennial timescales considered by CLIVAR, the subdivision into panels is largely based on regions of the ocean system. The CLIVAR regional panel that is focused on the Indian Ocean is the Indian Ocean is the Indian Ocean Region Panel (IOP, see: http://www.clivar.org/clivar-panels/indian). The CLIVAR IOP provides scientific and technical oversight for implementation of the sustained Indian Ocean Observing System (IndOOS) and coordinates research on the role of the Indian Ocean on the climate system.

Through the IOP, CLIVAR has played a central role in motivating the IIOE-2 and defining its research priorities. Indeed, the IOP was a key participant in a seminal meeting that was convened in Cape Town, South Africa in October, 2012 (see: http://www.clivar.org/panels-and-working-groups/indian/events/clivar-goos-9) that led to the initiation of IIOE-2 planning, and the IOP has participated fully in all of the subsequent planning efforts, which include four IOC sponsored planning workshops (see: http://iocperth.org/IOCPerth/).

The CLIVAR/IOGOOS Indian Ocean Observing System

Long-term in situ observing and monitoring efforts are ongoing in several coastal and open ocean locations in the Indian Ocean. Studies motivated as a part of IIOE-2 will target and build upon this existing research infrastructure.

For example, the CLIVAR IOP and the IOGOOS programs have developed the IndOOS (International CLIVAR Project Office, 2006), that is centered around the deployment of a mooring array (the Research moored Array for African-Asian-Australian Monsoon Analysis and Prediction or RAMA, McPhaden et al., 2009) along with repeated XBT lines, tide gauges, surface drifters, Argo and ship-based hydrography through GO-SHIP (Figure 2).

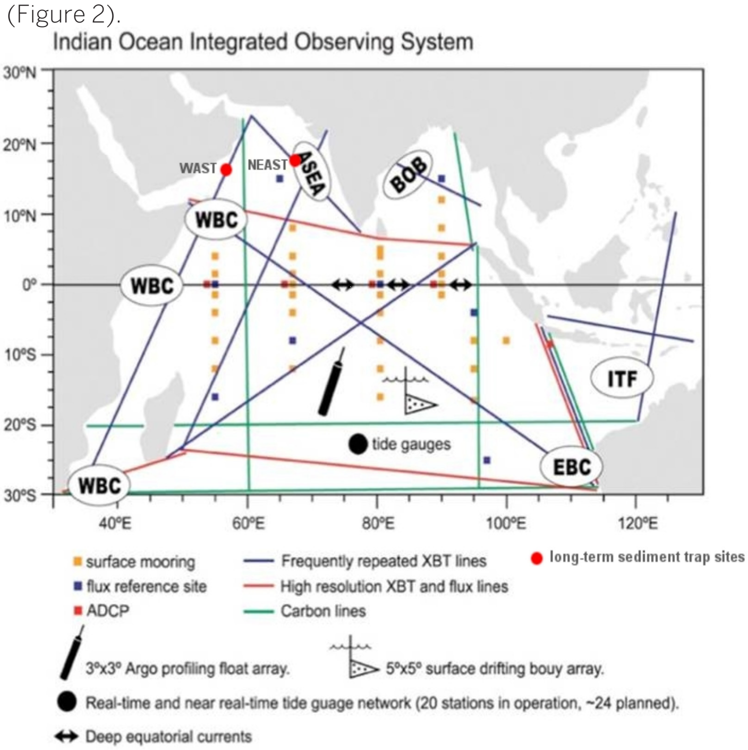

Figure 2: The integrated observing system, with basin-scale observations by moorings, Argo floats, XBT lines, surface-drifters and tide-gauges; as well as boundary arrays to observe boundary currents off Africa (WBC), in the Arabian Sea (ASEA) and Bay of Bengal (BOB), the Indonesian Throughflow (ITF), off Australia (EBC) and deep equatorial currents.

The RAMA moorings are capable of measuring key variables needed to describe, understand and predict large-scale ocean dynamics, ocean-atmosphere interactions and the Indian Ocean's role in global and regional climate. Efforts have also been undertaken to deploy biogeochemical sensors on the RAMA moorings (e.g., Strutton et al., 2015). Indeed, the mooring-based measurements can provide an excellent atmospheric and physical oceanographic observational foundation for carrying out a wide variety of biogeochemical and ecological studies.

The RAMA mooring array is intended to cover the major regions of ocean-atmosphere interaction in the tropical Indian Ocean, namely the Arabian Sea, the Bay of Bengal, the equatorial waveguide, where wind-forced intraseasonal and semi-annual current variations are prominent, the eastern and western index regions of the Indian Ocean SST dipole mode (10°N-10°S, 50-70°E; 0-10°S, 90-110°E), the thermocline ridge between 5°S and 12°S in the southwestern tropical Indian Ocean, where wind-induced upwelling and Rossby waves in the thermocline affect SST and cyclone formation (Xie et al., 2002). The bulk of the array is concentrated in the area 15°N-16°S, 55-90°E (Figure 2). Thus, the RAMA mooring array is ideally situated to study the physical, biogeochemical and ecological impacts of phenomena such as the Indian Ocean Dipole (IOD), Madden Julian Oscillation (MJO) and Wyrtki Jets.

However, due to piracy issues in the northwestern Indian Ocean and constraints on ship availability, the RAMA array has been only partially implemented, occupying 34 of the designed 46 locations (74% completion) up to June 2015. The IIOE-2 presents an important opportunity to complete the array and also motivate the deployment of additional biogeochemical and ecological sensors. The IIOE-2 will help garner additional resources to complete, enhance and maintain IndOOS and many aspects of IIOE-2 research will be critically dependent on it.

IIOE-2 Research Initiatives

In addition to coordinating ongoing research, the IIOE-2 is working to initiate new geologic, oceanic and atmospheric research projects and programs that are designed to address the core IIOE-2 research themes. These will include both national and international efforts. For example, international planning is underway to initiate upwelling research initiatives in the both the eastern and western Indian Ocean: The Eastern Indian Ocean Upwelling Research Initiative (EIOURI) and the Western Indian Ocean Upwelling Research Initiative (WIOURI). These new initiatives, which are aligned with CLIVAR's interdisciplinary upwelling Research Focus, will address understanding the interacting forces that drive upwelling variability in the Indian Ocean and the resulting biogeochemical and ecological responses.

Upwelling, used here in the general sense to imply the vertical movement of water and not necessarily outcropping, is an important mechanism in ocean dynamics that strongly influences coastal and open ocean regions. Although limited to a vertical movement of less than a few hundred meters, it underpins physical, atmospheric and biological processes in and above the ocean as well as in adjacent landmasses. Not only is upwelling a key process that regulates ocean ecosystem functioning (i.e., through facilitation of the vertical flux of nutrients and biogeochemical tracers into the euphotic zone), but it also effects the depth of the mixed layer and at times sea surface temperature (SST), which both influence climate variability, and ultimately rainfall and drought over land. Upwelling also influences higher trophic level productivity and marine biodiversity and in many cases recruitment of species through its influence on food supply and through advection of eggs and larvae. Consequently fisheries are strongly related to upwelling. The ultimate dependence of upwelling on wind and wind-driven currents implies that upwelling will be affected by global climate change with obvious socio-economic consequences.

The Eastern Indian Ocean Upwelling Research Initiative (EIOURI)

EIOURI, which has been motivated and led by members of CLIVAR's IOP, is highlighted here. Planning for an EIOURI is already in an advanced stage. The main focus of this initiative will be on the upwelling regions that develop seasonally off Java, Sumatra, and northwestern Australia (Figure 3). However, the broader area of interest also includes upwelling in the eastern equatorial Indian Ocean, the Sri Lanka Dome and upwelling associated with boundary currents in the Bay of Bengal and Andaman Sea, and off western Australia associated with Leeuwin Current and the eddies it generates (Figure 3).

The physical oceanography and atmospheric science drivers for this initiative include understanding the combined influences of local versus remote forcing on upwelling variability and also coastal-open ocean interactions. The study of local versus remote forcing includes consideration of ocean-atmosphere interaction, seasonal development and decay and intra-seasonal, and inter-annual variability in upwelling. This theme also covers the impacts of equatorial wave dynamic processes and local wind forcing, and the influence of the ITF on upwelling. The study of coastal-open ocean interaction in EIOURI includes consideration of the impacts of eddies and jets on onshore-offshore transport and also the broader influence of eastern Indian Ocean general circulation.

The biogeochemical and ecological science drivers for EIOURI include the need to understand the impact of the unique regional physical forcing in the eastern Indian Ocean upwelling regions on nutrient concentrations and stoichiometry related, for example, to the influence of the ITF, atmospheric inputs, nitrogen fixation and denitrification, and also how phytoplankton productivity and community composition responds to these nutrient inputs. What is the fate of this productivity response (recycling, transfer to larger consumers, aggregate export, transport offshore in filaments and eddies)? What are the impacts of upwelling on eastern Indian Ocean fishery resources, especially in the unique region between south Java and northwest Australia, the only known spawning ground for southern bluefin tuna? Are there differences in trophic transfer efficiency in eastern Indian Ocean upwelling regions compared to other eastern boundary upwelling centers, related, for example to differences in the food web dynamics? In addition, what are the biogeochemical and ecological impacts of lower oxygen and pH in upwelled water? Is this water advected onto the shelf in these upwelling regions? What are the potential human consequences? All of these science drivers and questions are relevant to CLIVAR science priorities.

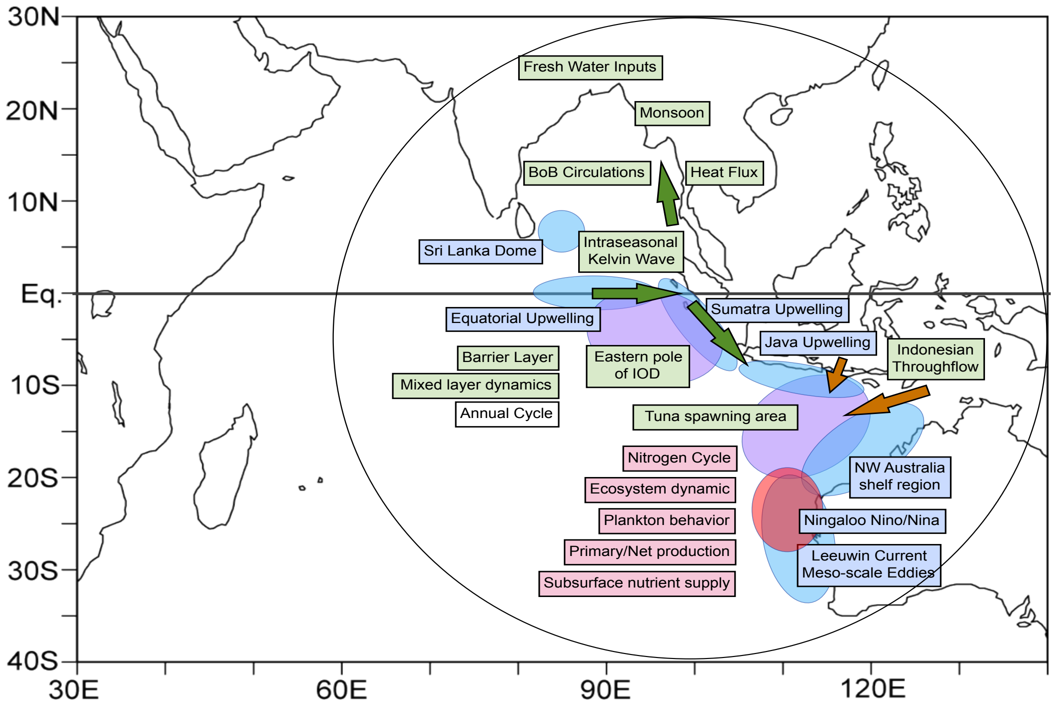

Figure 3: Regions and processes of interest in the Eastern Indian Ocean Upwelling Research Initiative.in the IIOE, from Germany (Meteor II, top), the US (Atlantis II, middle) and the UK (Discovery, bottom).

IOE-2: Advancing CLIVAR Science

The motivation, coordination and integration of Indian Ocean research through IIOE-2 will advance CLIVAR science by increasing knowledge and scientific capacity, and enabling international collaboration in an under-sampled, poorly understood, yet important region. IIOE-2 will promote awareness of the significance of Indian Ocean processes and enable a major contribution to their understanding, including the impact of Indian Ocean variability and change on regional ecosystems, human populations, and global climate. These are all high priority areas in CLIVAR. The legacy of IIOE-2 willbe to establish a firmer foundation of knowledge on which future research can build and on which policy makers can make better-informed decisions for sustainable management of Indian Ocean ecosystems and mitigation of risk to Indian Ocean rim populations. IIOE-2 will leverage and strengthen SCOR, IOC, CLIVAR/IOGOOS by promoting coordinated international, multidisciplinary research among both developed and developing nations, hence increasing scientific capacity and infrastructure within the Indian Ocean rim and neighboring nations.The success of IIOE-2 will be gauged not just by how much it advances our understanding of the complex and dynamic Indian Ocean system, but also by how it contributes to sustainable development of marine resources, environmental stewardship, ocean and climate forecasting, and training of the next generation of ocean scientists from the region. If this vision of success is realized, IIOE-2 will advance CLIVAR science and leave a legacy at least as rich as the original expedition.

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The Tropical Pacific Observing System 2020 Project: The Role of Research and Innovation

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Introduction

In January 2014, NOAA and JAMSTEC, in collaboration with the Ocean Observations Panel for Climate (OOPC) convened a Review of the Tropical Pacific Observing System (TPOS), through a Workshop and associated White Papers (TPOS 2020, 2014). The Review was in direct response to the deterioration of the mooring array elements (TAO) of the network during 2012-2014 (Figure 1) and consecutive decreasing number of deployed buoy of TRITON since 2011 (fifteen buoys to eight buoys in the western Pacific), and highlighted the risks to a system that underpins the capability for seasonal forecasting around the globe. The Review considered immediate actions to address the deterioration in the observing system, but more importantly proposed a number of activities and provided recommendations to change to a more robust and sustainable system.The major outcome was initiation of a TPOS 2020 Project to achieve this change (Smith et al, 2015).

The TPOS 2020 Project will evaluate, and where necessary change, all elements that contribute to the Tropical Pacific Ob serving System based on the current understanding of tropical Pacific science (see McPhaden et al 1998 for a description of the original TOGA observing system). The project aims for enhanced effectiveness for all stakeholders, including research, and requirements of the operational climate prediction systems that are primary users of TPOS data. TPOS 2020 embraces the integration of diverse sampling technologies, with a deliberate focus on robustness and sustainability. TPOS 2020 is a focused, finite term project, beginning in 2014 and completing in 2020, with its primary outcome being an internationally-coordinated and supported sustainable observing system for the Tropical Pacific Ocean.

This note focuses on the role of research and innovation in the evolution of the TPOS. To achieve change, the Project will draw on the scientific evidence available today and, as appropriate, facilitate research and technical development to guide the redesign of the TPOS to meet the requirements of 2020 and beyond.

Initial themes of work

Under the guidance of the TPOS 2020 Project Steering Committee (see http://TPOS2020.org/), a number of initial tasks were agreed, some with relatively short time horizons, others with longer. Given that TPOS 2020 has a finite lifetime and that some of these tasks may endure beyond 2020, it is important that TPOS 2020 engages early with international research groups and intergovernmental organizations that have enduring mandates.

The specific areas for action include:

i. Re-evaluation of the backbone of the TPOS, including broad-scale aspects. The backbone of the TPOS is a legacy of the Tropical Oceans-Global Atmosphere Experiment (TOGA, the forerunner of CLIVAR; McPhaden et al 1998) and the following TAO/TRITON array with salinity time series in the western Pacific region, but a number of different remote and in situ platforms have emerged over the last two decades and it is timely to revisit and, as appropriate, adjust the design.

ii. Elaboration of the scientific need and feasibility of observing the planetary atmosphere-ocean boundary layer. TPOS 2020 sees this as a potential area for innovation. Coupling between the atmosphere and ocean occurs on a range of scales. Research is showing that inclusion of near-surface processes on diurnal time scales may lead to improvements in weather and climate models (Tseng et al., 2015, Woolnough et al. 2007). Thus for example, capturing the diurnal cycle associated with the Madden Julian Oscillation may help improve intermediate time scale forecasts.

iii. Evaluation of observational approaches for the eastern and western boundary regions. Despite the many scientific advances over the last 30 years, these regions continue to represent knowledge gaps and sources of errors on time-scales of weather prediction to climate change.

iv. Development of rationales, requirements and strategy for biogeochemical observations. The ENSO Observing System and its modern manifestation TPOS were focused on physical climate. It is timely and appropriate to extend the design to biogeochemical requirements and, in time, to biological observations.

v.Consideration of approaches to improve modelling, data assimilation and synthesis, and use of models and their requirements for informing the design and evolution of TPOS. One of the barriers to success for TPOS is the inefficient use of ocean data by models. Model bias (see Figure 2) reduces the efficiency of the observed data during assimilation, and therefore, limits the effectiveness of the

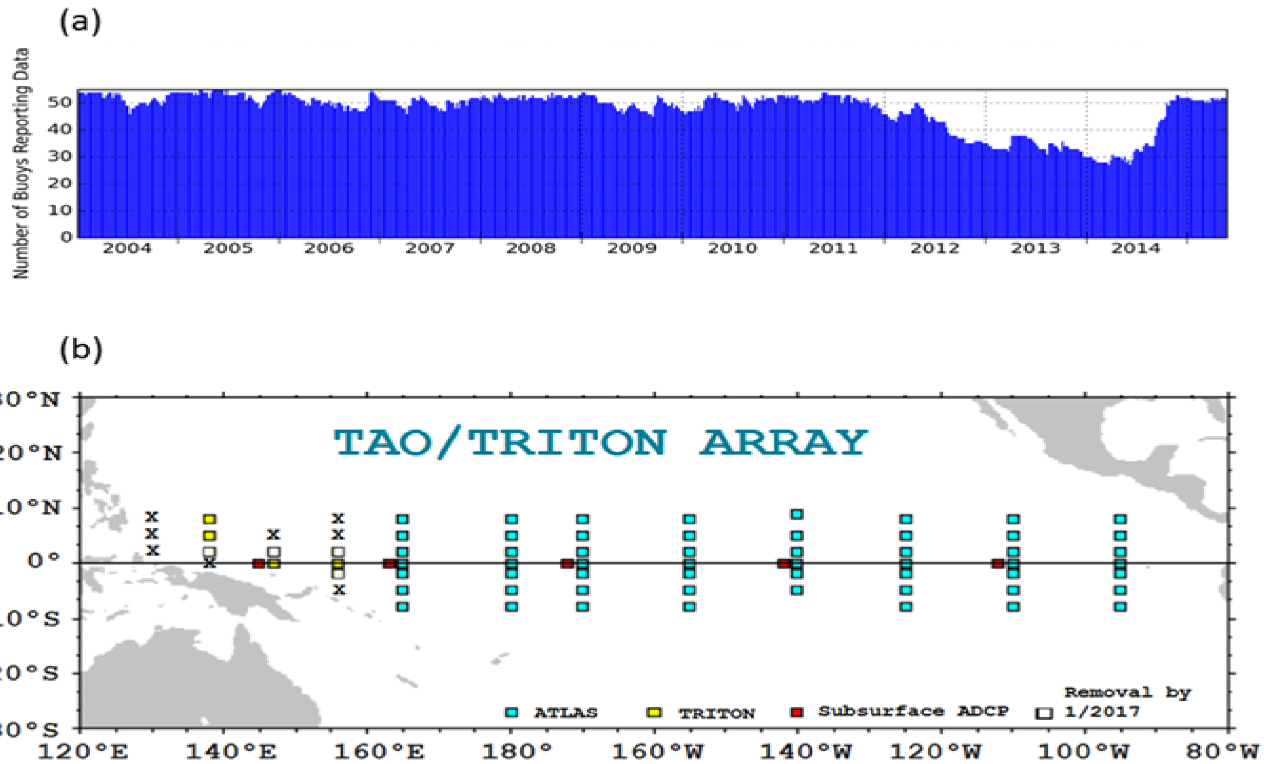

Figure 1: (a) Number of TAO moorings returning data 2003-2015 (courtesy PMEL). (b) The TAO/TRITON array in the western Pacific. Sites where operation has ceased are marked with a cross. Locations that are planned to cease in early 2017 are shown in yellow (latest information provided by JAMSTEC).

observing system for monitoring and predicting climate variability.While the next section will provide further elaboration, a number of other aspects are worth noting:

- The observing system should be considered as an integrated whole, including satellites, modeling, data management and the range of modern and robust in situ technologies. Thus the project will articulate the strengths of a multi-platform approach appropriate to the multi-scale variability of the tropical Pacific.
- There should be the explicit assessment of risks to the observing system as part of TPOS 2020, taking into account system requirements such as necessary redundancy, sensor diversity, etc. Identifying and managing risks to the long-term climate records will be a priority.
- It is critical that the TPOS 2020 re-energize the associated research community. In the past two decades, models have continued to improve but the improvement has slowed (see for example, FAQ 9.1, in Flato et al, 2013) and the research community dedicated to climate model prediction improvements has seemingly plateaued, perhaps even shrunk. In the meantime, more questions about the diversity of ENSO and its hiatus have been raised.
- Initiate discussions with interested organizations to broaden support for the TPOS, including all-important research vessel/ship support and participation in coordinated joint process and modelling studies. For example, WCRP and CLIVAR support a number of Panels and Working Groups that either coordinate specific aspects of model development and modeling activities (e.g. the CLIVAR Ocean Model Development Panel (OMDP)) or include modelling in their mandate (e.g. the CLIVAR regional basin panels). Relevant activities include the Coordinated Ocean-ice Reference Experiments, particularly CORE-II, a suite of hindcast experiments coordinated by OMDP, and a new project being developed within the WCRP Working Group on Seasonal to Interannual Prediction (WGSIP) on assessing the impact of model drift/initial shock on performance within the first month of forecasts. Likewise, while the U.S. and Japan have been the primary sponsors for the existing TPOS, in the future, other nations may play increasingly important roles.

Elaboration of research requirements

Backbone Observing System

TPOS 2020 refers to the basic sustained sampling network as the “backbone” (formerly called “broadscale”) of the system. This terminology emphasizes that the backbone anchors and underlies all other pieces of the observing system, some of which may be experimental or implemented for a limited time. The backbone will be designed to maintain consistent and well-understood sampling rates and scales that allow for the detection of climate variability and climate trends and maintenance and extension of the climate record. The backbone observing system will observe and quantify the state of the ocean, on time scales from weekly to interannual/decadal, and provide data for forecasting systems. It will also support integration of satellite measurements into the system, including for calibration and validation.

Scientific evidence and research will elucidate the unique capabilities of the ‘legacy’ (eg, McPhaden et al 1998) and existing observing system elements (Roemmich and Cravatte, 2014) as a contribution to the backbone of TPOS beyond 2020, including consideration of efficiency, effectiveness and scientific utility. Based on current requirements for essential ocean and climate variables, enhancements and/or modifications to these efforts will be studied, taking account of available synthesis approaches. The use of models and data assimilation tools to aid the objective design of the future backbone of TPOS and for the assessment of an integrated ocean observing system is the more straightforward approach. However, given the presence of systematic errors

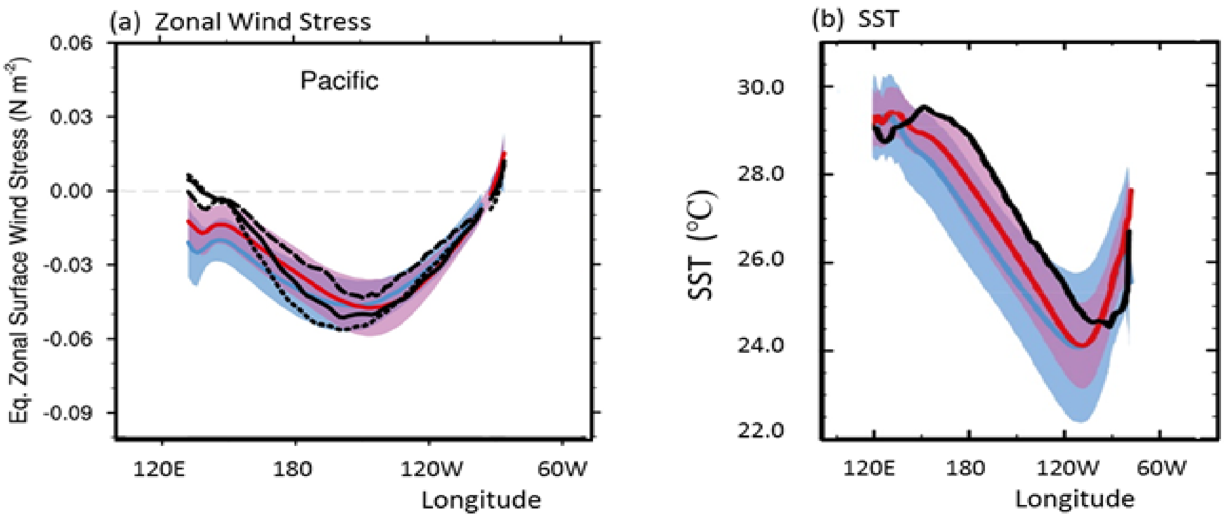

Figure 2: [Adapted from Flato et al 2013] (a) Equatorial (2°S to 2°N averaged) zonal wind stress for the Pacific in multi-model mean comparison with CMIP3. Shown is the time-mean of the period 1970-1999 from the historical simulations. The black solid, dashed, and dotted curves represent ERA-Interim (Dee et al., 2011), National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis I (Kalnay et al., 1996) and QuikSCAT satellite measurements (Risien and Chelton, 2008), respectively. Shading indicates the inter-model standard deviation. (b) Equatorial multi-model mean SST in CMIP5 (red curve), CMIP3 (blue curve) together with inter-model standard deviation (shading) and observations (black). Model climatologies are derived from the 1979-1999 mean of the historical simulations. The Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Rayner et al., 2003) for observations.

in the modelling and assimilating tools, such guidance needs to be used with caution. Specific studies will assess the strengths and weaknesses of individual components of the observing system, their capabilities to represent specific individual components of the observing system, their capabilities to represent specific physical processes, and explore different sampling strategies (e.g. Gasparin et al. 2015, submitted). As stated above, the observing system should be considered as an integrated whole, and studies will also be carried out to combine the different components of the observing system (satellite data, in situ Lagrangian and in situ Eulerian data platforms) in the most efficient way. Tools such as ARMOR-3D (Guinehut et al., 2012) and DFS (Oke et al., 2009) may help in assessing the contribution, redundancy and content of information of each part of the observing system. As these tools rely on the assumed decorrelation scales, results will depend on the processes we aim at resolving, and experiments should be performed to cover the different space/time scales of phenomena that are to be resolved by the backbone observing system.

We need to anticipate the future evolution of prediction systems and draw on research advice, for example to determine the initial strategy for backbone biogeochemical observations.

Western Pacific and Eastern Pacific Boundary Regions

The boundary regions of the Western and Eastern Pacific remain regions of high scientific interest due to their fundamental role in variability and predictability of the coupled climate system as well as their direct socio-economic benefits (for example, Harrison et al 2014; Takahashi et al 2014). Several large regional observing activities or finite-lifetime process studies already exist or are planned in the Western Pacific (eg, Ganachaud 2013; Ganachaud et al 2008; Hu et al 2011), and TPOS 2020 has compiled a report on these activities of operational and research agencies in a relevant region. (Ando, K., in preparation).

A number of NE Asian agencies are contemplating significant research in the western Pacific, motivated by interest in the Western Pacific ocean circulation including Indonesian Through Flow, the East Asia monsoon, typhoons and ENSO. The CLIVAR Pacific Region Panel can foster coordination so that the whole can be more than the sum of the individual pieces; there would be benefit to all by joining these activities together as an integrated research initiative, including connecting up the science rationale. Such integration may raise opportunities for greater research collaboration, and lead to discussions about what a sustained regional observing system for the Western Pacific could look like post 2020.

For the Eastern Pacific, there is strong potential to strengthen regional collaboration by bringing together a core group of researchers across regional agencies. Persistent serious errors in climate models are particularly obvious in the eastern tropical Pacific, including a warm bias off South America; a double Inter-Tropical Convergence Zone (ITCZ) with excessive precipitation in the Southern Hemisphere; an excessively strong seasonal cycle in SST and winds and a spurious semi-annual cycle; and weak cloudiness in the marine boundary layer (Flato et al. 2013). Additionally, climate forecasts at up to three months lead time in advance for western South America depend critically on the propagation of equatorial Kelvin waves (Takahashi et al., 2014; Figure 3), which can interact strongly with the mean thermocline structure in the eastern Pacific (e.g. Mosquera-Vásquez et al., 2014), while long-range forecast skill is low in this region, particularly during strong El Niño events (Takahashi et al., 2014). This makes the region an obvious focus for TPOS 2020. Although mooring arrays in the region have typically had low data returns due to high levels of vandalism, Argo floats and new technologies such as gliders and wave-gliders may make observing the ocean in this region more achievable in future.

Additionally, regional observational and data exchange initiatives exist, such as the CPPS Regional Cruise and the GOOS Regional Alliance for the South-East Pacific region (GRASP), respectively, that can serve as a basis and provide important input to the TPOS in this region. As with other regional activities, any focused regional work around the far eastern Pacific boundary will inform requirements and options for the backbone TPOS. Priority is being attached to engaging regional experts and institutions and capacity building to improve sustained observing capability; the development of a regional research project may facilitate improved guidance for a sustained observing system.

Modelling and data assimilation

Much of the use and benefit of TPOS observations will be realized through their use in model assimilation systems that provide initial conditions for coupled model climate forecasts and are used for process studies. However, model biases degrade the value of the observations because models rapidly drift towards their own climate once a forecast commences (see for example Figure 2). The model and data assimilation development community and operational prediction centers are key research partners in the success of TPOS. TPOS 2020 efforts, including embedded process studies, will be designed to address phenomena that are leading candidates for causes of systematic errors in models, and where detailed observations are needed to guide diagnostics of model errors (Fujii et al, 2015; Guilyardi 2009; Guilyardi, 2015). Examples of potential studies include those geared toward a greater understanding of the relationship of ocean near-surface conditions and convective rainfall in the tropics, and the mechanisms that communicate surface fluxes into the subsurface ocean (see following sub-section).

The initial focus is on identifying research pathways that will contribute to improved understanding of systematic errors and, hopefully, to subsequent model improvements, especially the avenues to be explored. Improved understanding and prediction of sub-seasonal climate variability has also been identified as a priority.

Surface Boundary Layers

The ocean and atmospheric boundary layers represent one of the main knowledge gaps for the tropical Pacific Ocean and dependent forecast systems (Cronin et al 2014; Josey et al 2014). TPOS 2020 aims to formulate a practical observing strategy and technical sampling requirement for oceanic and atmospheric boundary layer measurements. There is increasing appreciation of the role of diurnal variability of air-sea fluxes and boundary-layer properties in affecting large-scale, lower-frequency variability such as the Madden-Julian Oscillation (Zhang, 2005; Woolnough et al., 2007), and TPOS 2020 aims to identify a set of key ocean and climate regimes for which high-frequency measurements (hourly or better resolution) of the air-sea fluxes of heat, moisture, and momentum are needed. Likewise, because these ocean and atmosphere exchanges are moderated by and impact the planetary boundary layer, observations within the planetary boundary layer need to be made at a significantly higher resolution than needed for observations of thermocline variability associated with equatorial waves. TPOS may thus

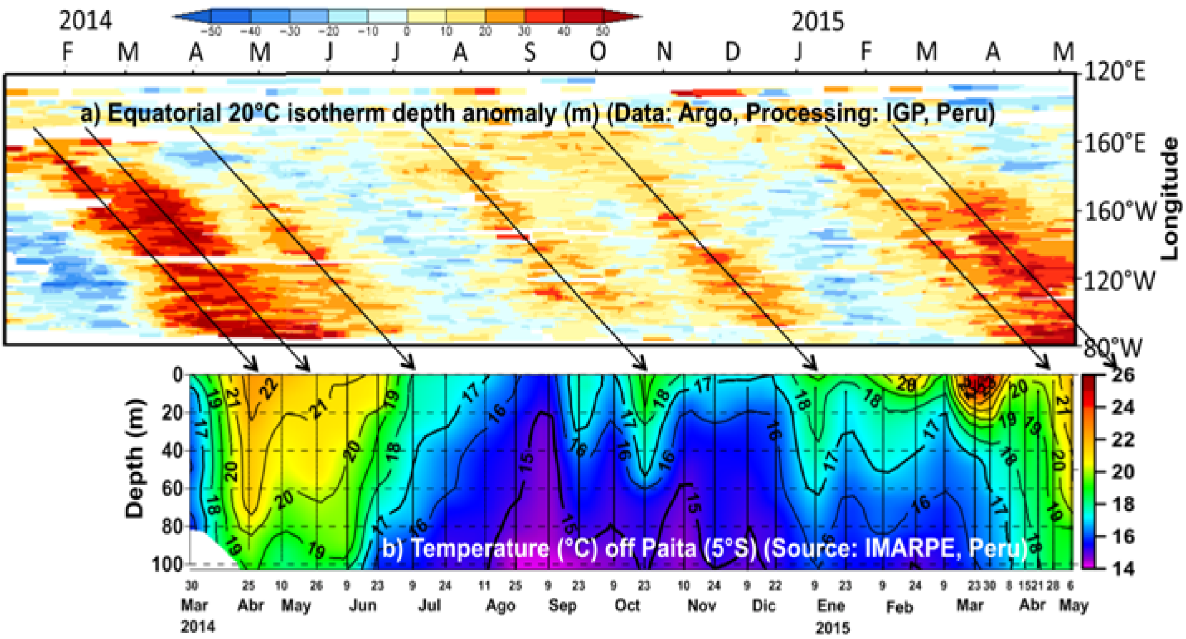

Figure 3: Example of propagation of Kelvin waves (with Argo data) and their impact on ocean temperature at the Peruvian coast (Peruvian data).

through promotion of joint activities with other bodies such as WCRP and CLIVAR that have mandates to improve models. In an ideal world, observational system studies using assimilation systems would be central to designing and planning the future TPOS observing systems, but the aforementioned systematic errors limit their efficacy and conclusions have to be used with caution (Fujii et al 2015). Another avenue for advancing the outcome of TPOS is development of data assimilation systems that can take advantage of the full suite of TPOS observations (e.g., salinity, ocean currents).

There are numerous possible pathways into the research modelling community, and TPOS 2020 does need to be judicious and efficient in such engagements. The WCRP/GEWEX Grand Challenge on Clouds, Circulation and Climate Sensitivity (Bony et al 2015), the various WCRP and CLIVAR groups (e.g., on seasonal prediction, ocean and coupled model development, global synthesis and observations), the emerging Year of the Maritime Continent initiative, and the various Task Teams under GODAE/OceanView are some of refocus surface mooring platforms for observing the planetary boundary layer variability, and rely upon other platforms for monitoring slower ocean deeper ocean variability.

The mix of sustained versus campaign network elements is to be determined. Further studies are required on the most efficient way to meet existing and developing ocean satellite and modelling requirements. One consideration for possible innovation is a subset of regimes where direct eddy-correlation approaches might be tested for feasibility and scientific value. This area provides research opportunities with the biogeochemical and ecosystem community to ensure the needs of key gas exchange calculations are met as well as to improve the all-important mixed layer representation.

New technology

The community is demanding ever more sophisticated services derived in whole or in part from the TPOS (for example, as manifested in the Global Framework for Climate Services; http://www.wmo.int/gfcs/), but the basis of such services has a number of risks. The underlying observations are under resource pressures and the evolution of the prediction systems is not keeping pace with expectation in terms of accuracy and reliability. This represents an opportunity for scientists, technologists/engineers, and operational climate services to re-engage to achieve major change, change that will have profound benefits for future generations.

We believe technology has much to contribute to this change, through improved and more efficient observations and models, and through novel approaches to the challenges of observing ENSO. The recent two pilot satellite missions dedicated to sea surface salinity measurements (Halpern et al., 2015) and the glider application in monitoring the South-western Pacific boundary current (Davis et al., 2012) are excellent demonstrations of the promise and value of new technology. In the next decade there will be some exciting advancement in technology, autonomy and platforms that the observing and prediction community can take advantage of (Figure 4).

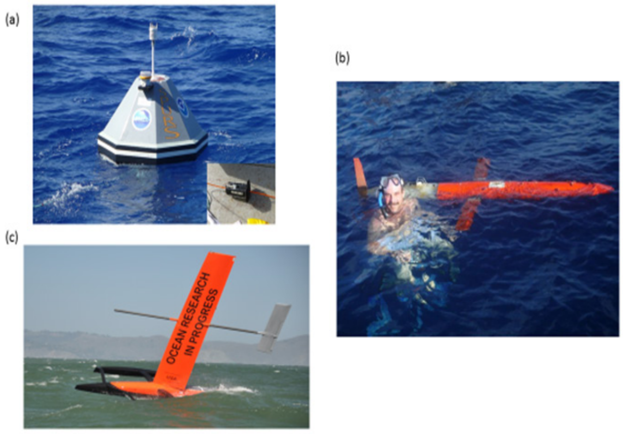

Figure 4: Examples of new technology. (a) Wave-powered moored ocean profilers and PRAWLER (inset; courtesy John Shanley (@ NOAA, (b) sea gliders that can be directed to undertake observations in a certain pattern or for a specific region (photo by Lionel Gourdeau, LEGOS), and (c) observing platforms that are deployed and recovered from shore [courtesy C Meinig, PMEL]

Conclusions

The TPOS 2020 Project was initiated by research and operational agencies to develop a more robust sustained observing system for beyond 2020. At its heart, it is a Project of change and will be informed by accumulated scientific knowledge and, as appropriate, specific studies and projects where knowledge gaps exist. TPOS 2020 will deliver a refreshed and more effective design for the TPOS, promoting sustainability, and making full and appropriate use of new and emerging technologies.

TPOS 2020 will endeavour to enhance cooperation and coordination among the TPOS international sponsors and contributors, including research, to deliver improved efficiency, reduced risk and greater robustness. Facilitation of experiments and studies in process parameterisation and modelling will guide improvements in climate prediction and associated applications, a core interest of CLIVAR. There will be a comprehensive assessment of climate scales and signatures and their dependency on the backbone observing system in order to safeguard and enhance the climate record. Innovations include the integration of biogeochemical and biological sampling into the TPOS design and implementation and potentially new approaches to sampling at diurnal and subseasonal scales and in the ocean boundary layers.

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More Integrated and More Sustainable Atlantic Ocean Observing (AtlantOS)

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Introduction

Many nations need information on the Atlantic Ocean. Several of them already share the burden of supporting scientific observations as well as maritime operations. While space-based observations are better coordinated, the in-situ observing networks are still somewhat fragmented. More effective international coordination on requirements, observing system design, implementation, data management arrangements, and information products delivery, hold significant potential to increase efficiency. Some existing in-situ observing networks are built on internationally coordinated strategic scientific requirements, design and implementation plans, while others are voluntary communities of practice that promote common standards and best practice.

The newly launched Horizon 2020 AtlantOS project (http://www.atlantos-h2020.eu) brings together scientists, stakeholders and industry from around the Atlantic to provide a multinational framework for more and better-coordinated efforts in observing, understanding and predicting the Atlantic Ocean. The overarching objective of AtlantOS is to achieve a transition from a loosely coordinated set of existing ocean observing activities producing fragmented, often mono-disciplinary data, towards a sustainable, efficient, and fit-for-purpose integrated Atlantic Ocean Observing System. To this end, the project builds on complementary observing systems that have emerged to meet the needs of particular research disciplines (physical, chemical, biological) and stakeholders; specifically, the existing elements of the Global Ocean Observing System (GOOS) and in support of the GEO Blue Planet Initiative. AtlantOS takes strategic guidance from the "Framework of Ocean Observing" (FOO; see Lindstrom and Visbeck, in this special issue of CLIVAR Exchanges). The vision of AtlantOS is to create a more systematic, cost effective, user-driven and international coordinated Atlantic observing system. This requires a better identification of key requirements as well as the identification and filling of targeted gaps in the in-situ observing system networks. Data accessibility and data usability, including standard formatting, storage and exploration services, are key aspects of AtlantOS. Thus, the scope of the existing Atlantic observing networks will be extended to more fully include underrepresented disciplines such as ocean biogeochemistry and biology. The integration of in-situ and remotely sensed Earth observations will produce information products supporting a wide range of sectors.

Areas of Action

AtlantOS employs an integrative approach in providing a refined observing system design that meets the requirement of a large range of societal benefit areas (e.g. Climate, Fisheries, Ecosystem Services, Maritime Services, Conservation, Ocean Assessments and Scientific Discovery).The project adopts the principles outlined in the FOO. The FOO has been from the OceanObs09 conference held in September 2009 in Venice, Italy. It provides a guideline for the ocean observing community to establish integrated and sustained ocean observing and includes defining observing requirements for science and society, identifying related Essential Ocean Variables (EOV), providing an overview of observation systems (including profiling floats, surface drifters, deep ocean and coastal moorings, gliders, ships, deep hydrographic surveys, plankton recorders, fishing surveys) and their capabilities in EOV sampling. Moreover, data assembly, data management and data dissemination strategies are outlined - connecting the data and data derived products to users which provide feedback to eventually revising the ocean observing requirements.

The areas of action of AtlantOS are organized according to this FOO loop principle (see Figure 1) and are summarized below.

Observing system requirements and design studies

The identification of sustained ocean observing requirements and the application of the FOO's systems design process will guide the development of an integrated Atlantic Observing system. The evaluation of gaps and the assessment of costs will be addressed internationally, on a pan-Atlantic level, combining scientific and operational needs. The methodologies that will be used are based on state-of-the art concepts namely the refinement of EOVs and the methodology of "Observing Systems Simulation Experiments" (OSSEs) to direct the design and implementation of a system of systems against selected observing targets and in close coordination with Global Ocean Data Assimilation Experiment (GODAE).

Enhancement of ship-based and autonomous observing networks studies

Ship-based and autonomous platforms complement each other in the acquisition of cost-effective EOVs. The overall ambition is to advance the development, cohesion and implementation of a finite number of complimentary observing networks that rely on the use of existing capacities in various ship-based (including GO-SHIP, Ships Of Opportunity Program SOOP, Continuous Plankton Recorder CPR, fisheries and zooplankton observations in the context of ICES, and deep seafloor mapping) and robotic platforms (including Argo, OceanSITES biogeochemistry and transport, Glider EGO, tropical moored array PIRATA, surface drifter network, animal telemetry network) and their sensor systems. AtlantOS will advance the network performance with respect to the quantity (increasing spatial and temporal resolution of data acquisition), quality (new quality control procedures) and diversity (new EOV) of data that will be shared and delivered in a timely fashion. This will be undertaken in cooperation of with international partners, not only in Europe but also in North America and especially South America where partnerships have been established in expanding ship-board monitoring in the South Atlantic. While each network will have its own organization with respect to operations at sea there is a common ambition to develop the sharing of good practices for data quality control and distribution.

Interfaces with coastal ocean observing systems

Interfacing the project's activities with initiatives in coastal ocean observing will constitute a first attempt in closing gaps and improving the coordination between continental shelf and deep ocean observing networks, while exploring the feasibility of optimizing shelf sampling. The state of the art in coastal ocean observing is a large number of systems that deliver broadly-fit-for-purpose products and services to identified users. These systems can unequivocally benefit from integration, where best practice is shared and synergies are sought in maintaining and deploying marine platforms, with data shared openly and freely to common standards for all Atlantic observations. Autonomous operating high resolution multi-parameter sampling systems, such as gliders, will be connected with existing fixed-point high resolution measurements in order to derive a 4-dimensional picture of the open ocean/costal transition zone.

Integrated regional observing systems

Full integration of physical, chemical and biological observing to benefit both climate and fisheries research has never been done on a basin scale. The power of integrated international trans-Atlantic observing to provide information necessary to cope with global challenges will be shown in two particular regions of the Atlantic Ocean: the Sub-polar North Atlantic and the sub-tropical South Atlantic. These regions were chosen to demonstrate how integration among observing networks and different research fields can provide new and integrated ocean information that will enable advances in understanding the climate-fisheries nexus. This integration aims to consider current international Atlantic observing efforts such as RAPID/MOCHA, OSNAP, SAMOC, OTN in connection with activities under the auspices of the International Council for the Exploration of the Sea (ICES), activities in European Union projects such as NACLIM and PREFACE, and the various national initiatives (e.g. OVIDE, RACE, LOCO, VITALS).

Cross-cutting issues and emerging networks

Developing new technologies and observing system practices with an emphasis on sensors and instrumentation will enable multiple observing networks to produce more data (in particular widespread biogeochemical and biological observations) that are better targeted at stakeholder, user and customer requirements whilst reducing overall cost. These new developments span the cutting edge of observing approaches, and incorporate amongst other things, the development of (meta)-genomic techniques for phytoplankton and zooplankton community structure.

Data flow and data integration

Data management activity will be oriented towards an enhanced data management capacity in coherence with existing European and International data infrastructure. The data sets collected in AtlantOS will be made readily and freely available to the wider, international ocean science community and other stakeholders in this field. This will be achieved by harmonizing workflow, data processing and distribution, by integrating observations in existing data infrastructures, by improving modeling outputs and by implementing existing, international standards as well as innovative methods. A close connection with each of the ship-based and autonomous observing network is ensured.

Social benefits from observing/ information systems

The value of an integrated Atlantic Observing system will be demonstrated by developing a suite of products that are targeted at issues of societal concern across the Atlantic community in five key GEOSS societal benefit areas. These products will support enhanced safety of coastal communities and promote economic development in key and/or emerging marine and maritime sectors through better decision support tools (flooding, maritime safety, HAB) and resource assessment (offshore aquaculture).

System evaluation and sustainability

Procedures will be established to monitor and evaluate the performance of the current and enhanced in-situ Atlantic observing system. How many platforms are operational today or will be in the future? Have we maximized use of these platforms among existing observing networks? Are all the data reaching the repositories in a timely fashion? How well are the EOVs determined and where are the gaps? Where are the roadblocks for growth and sustainability of a truly multinational integrated Atlantic Observing system?

Outlook

The AtlantOS project has the ambition to deliver an advanced framework for the development of an integrated Atlantic Observing system that goes beyond the state-of-the art, and leaves a legacy of sustainability after the life of the project. The project will strive to strengthen trans-Atlantic collaboration through close interaction between Europe, Canada and the United States as well as Brazil, South Africa, Argentina, and other nations of the Atlantic region. As one example, the Canadian partnerss (Wallace et al. 2014) are working on the development of the Canadian component of an integrated Atlantic Observing system in recognition of "an urgent need for coordination and planning of ocean observations." AtlantOS will aim to link up with the greater part of related international and national projects / initiatives such as the Southern Ocean Observing System (SOOS), Tropical Pacific Observing system (TPOS2020), or Arctic Observing systems initiatives. A close partnership with industry will be established in order to gain inclusiveness and cross-fertilization. Developing an outcome-oriented dialogue with key stakeholders communities will enable a meaningful exchange between the products and services that integrated Atlantic Observing can deliver and the demands and needs of the stakeholder communities.

The aim is to ensure that an Atlantic Ocean observatory network is firmly embedded in broader economic and societal value chains. This includes making sure that data and information contribute to sustainable economic activities as well as to environmental protection measures in the oceans. Finally, establishing a structured dialogue with funding bodies, including the European Commission, European nations, USA, Canada, Brazil, South Africa, Argentina and other countries bordering the Atlantic, or with particular interests in the Atlantic Ocean, is foreseen to pave the way for a sustainable and emergent integrated Atlantic Observing system.

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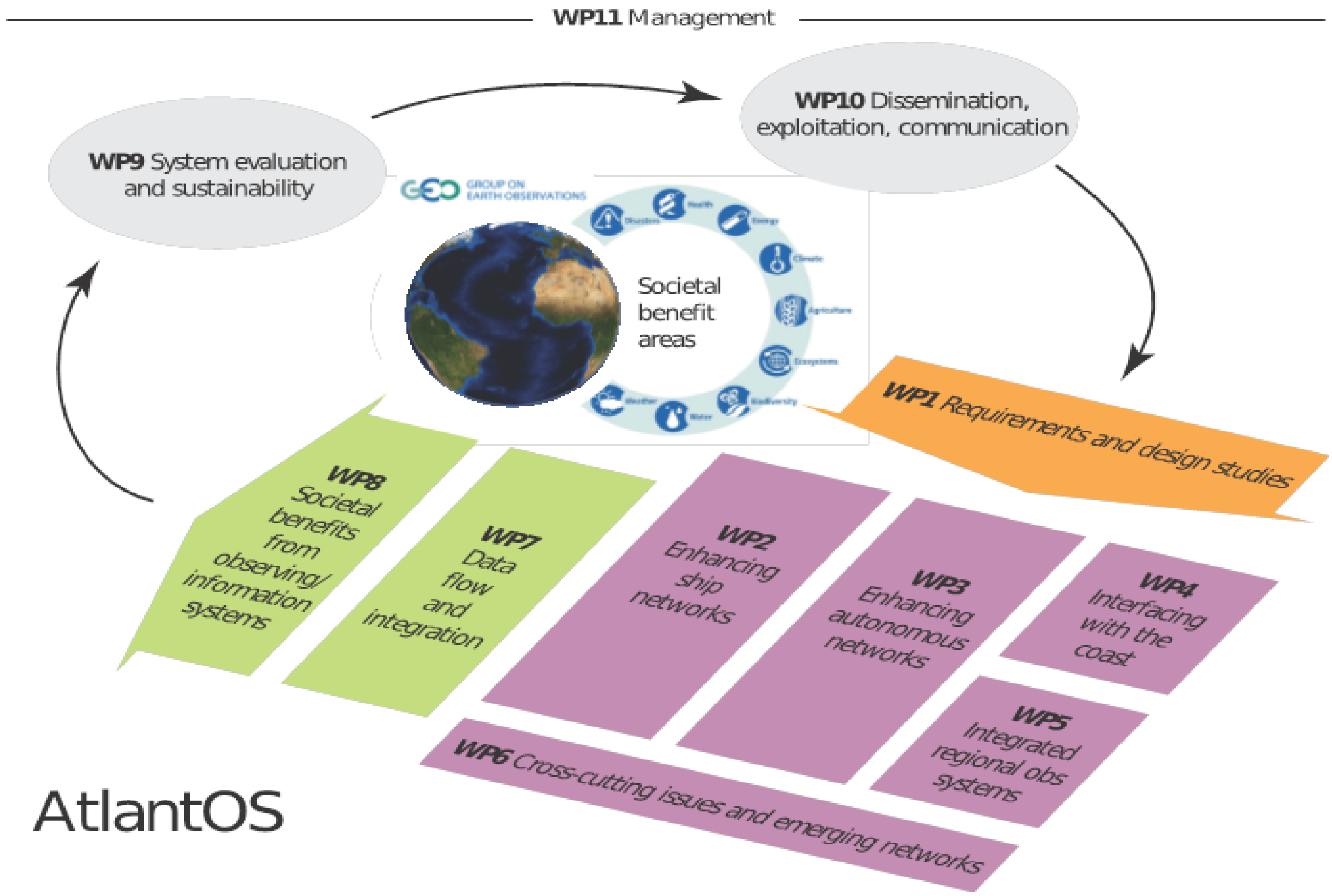

Figure 1: The AtlantOS preparatory project organigram based on FOO report (Figure 4 in report)

Towards an integrated Southern Ocean Observing System

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Introduction

The importance of the Southern Ocean in the global climate and biogeochemical system has been well articulated in a number of key publications over the last few years (IPCC, 2014; Kennicutt, 2014; Heywood et al, 2014; Paolo et al, 2015; Schmidtko et al, 2015; Meredith et al, 2013). Furthermore, many recent publications highlight observed changes in Southern Ocean systems - a cause for global concern (Constable et al, 2014). The Southern Ocean is warming more rapidly, and to greater depth, than the global ocean average (Boning et al, 2008; Schmidtko et al, 2014). The floating glaciers along the coast are melting at an accelerating rate (Paoblo et al, 2015) and the upper layers have freshened while widespread warming of the Antarctic Bottom Water has been observed (Schmidtko et al, 2014). Sea-ice extent is showing strong regional trends (Stammerjohn et al, 2012; Massom et al, 2013), and the uptake of CO2 by the ocean is changing the chemical balance (e.g. Hauk et al., 2013; Fay et al, 2014; Wanninkhof et al., 2013). These changes in the physical and climate systems are already impacting Antarctic ecosystems (e.g., Saba et al., 2014; Clucas et al, 2014). Improved understanding of the links between Southern Ocean processes, global climate, biogeochemical cycles and marine productivity is needed to inform an effective response to the challenges of climate change, sea-level rise, ocean acidification and the sustainable use of marine resources. Our ability to achieve this is severely limited by a lack of long time series of observations undertaken at the correct time and space scales to observe key variability and change.

Challenges

There are a number of key challenges that must be addressed for a Southern Ocean observing system to be successful; long time series (>10 years) needed to understand the interaction between the Southern Ocean and the climate are almost non-existent. Lack of continuous funding for sustained observations poses a major challenge for measuring and understanding change in Southern Ocean and for documenting its role in climate and sea level rise. No nation can do this alone and finding the mechanisms for sustained funding within national programs is very important. Moreover, improved communication between nations, programs and disciplines on activities and requirements are extremely important to streamline effort and leverage investments for greater results. At present, this remains to be achieved. As a consequence, there are substantial observational gaps in time and space.

There are similar hurdles to overcome in the maintenance and storage of data. Presently many data are stored in unconnected, and single discipline formats and repositories. This makes accessing the data a difficult challenge, along with a large variation in national/institutional data management arrangements. Many data remain to be appropriately archived and are inaccessible, which may be overcome with improved data sharing and funding to work on platform interoperability. As a result, access to multidisciplinary, quality-controlled, observational data from the Southern Ocean is difficult and time consuming to obtain.

The Southern Ocean Observing System (SOOS; www.soos.aq) is an international initiative of SCAR and SCOR, and was launched at the end of 2011 to address these challenges. The SOOS mission, recently redefined, is to facilitate the collection and delivery of essential observations on dynamics and change of Southern Ocean systems to all international stakeholders, through the design, advocacy, and implementation of cost-effective observing and data delivery systems.

Progress

In 2012, SOOS members published in CLIVAR Exchanges, highlighting the key building blocks for SOOS, and outlining the potential way forward (Newman et al., 2012). Since then, SOOS has worked hard to clearly define its mission and key objectives, and identify the precise actions required to achieve them. Much progress has been made on building a community, developing a community-level understanding of the SOOS mission, and putting in place a governance and implementation structure that will support the defined way forward.

The Southern Ocean community have been actively working to fill the gaps in Southern Ocean observations. International observational programmes and multi/national field campaigns form the bedrock of SOOS. National funding in support of these initiatives make a significant contribution to the coverage of data required in an observing system. These coordination programmes and field projects also make an enormous contribution to quality control and management of data, as well as ensuring the continuation and enhancement of funding for these observational activities. They are imperative to the success of SOOS. Although significant gaps exist in Southern Ocean data, it is important to recognize the ongoing activities that continue to deliver data streams to the community.

The global Argo program, for example, has greatly enhanced our understanding of the physical state of the Southern Ocean, with over 260,000 profiles collected south of 40oS since 2000. Although previously restricted to waters north of 60oS, ice-capable Argo floats (e.g. Klatt et al, 2007) are now further enhancing collection of data from the sea-ice zone - a region of key importance but traditionally too difficult to observe. Potential changes to funding of key Argo nations may result in a significant reduction in floats deployed in the Southern Ocean over the next few years. The community needs to ensure the imperative remains strongly vocalized for not only a continuation of current levels of funding, but an extension of the existing array into the sea-ice zone.

A major challenge for ice-capable Argos is under ice positioning, and progress has been made in this field with acoustic beacons aiding profiling floats when they are under sea ice (e.g. Boebel and Fahrbach, 2003; Sagan et al, 2007). Presently arrays of beacons are installed in the Weddell Sea and it is of high priority to expand this technology into more regions in the sea-ice zone of the Southern Ocean.

The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), is a globally coordinated network of sustained hydrographic sections, providing the highest possible quality CTD and hydrographic data to the international community. GO-SHIP data is available from CCHDO (www.cchdo.ucsd.edu).

The global continuous plankton recorder program (GACS) is an international organization with goal to understand changes in plankton biodiversity at ocean basin scales through a global alliance of CPR surveys. GACS brings together the expertise of approximately 50 plankton specialists, scientists, technicians and administrators from 12 laboratories around the world, towing a common and consistent sampling tool, the CPR, from about 50 vessels. Working together, pooling data and resources, is essential in order to understand the effects of environmental changes on plankton biodiversity at a global level.

The international organization MEOP (Marine Mammals Exploring the Oceans Pole to Pole, see Weise and Fedak, this issue) is coordinating and facilitating the collection of data from sensors carried by marine mammals, in particular seals. The sensors measure position and hydrographic properties of the environment the mammal is moving through. In many ice-covered regions in the Southern Ocean this is the only way to obtain wintertime measurements in the upper water column, and the mammals provide a unique platform since they can find breathing holes in the sea ice cover in which satellite transmission is possible. To date there are 329665 profiles available, a large portion of which are in the ice covered regions of the Southern Ocean.

The SOOS-endorsed NECKLACE project (K. Nicholls, British Antarctic Survey), uses newly developed technology to collect year-round time-series data on ice-shelf melt. The instrument (developed by the University College London and the British Antarctic Survey), is a lightweight, low power and low cost, ground-based downward-looking radar that measures changes in ice-shelf thickness to millimetre precision. The aim of NECKLACE is to use the circumpolar reach of Antarctic research nations to deploy instruments on all major ice shelves for an extended period during 2015 - 2020. Four instruments were deployed in 2013/2014 as a proof-of-concept on Pine Island Glacier (UK) and on the Ross Ice Shelf (Coulman High, NZ). These have been recording ice-shelf melt data over the last year and will be collected this coming season. Building on the success of the initial deployments, activities during the coming two field seasons (2014/2015 and 2015/2016) will greatly enhance the network. About 30-35 new instruments will be deployed on different ice shelves around Antarctica by several nations including UK, Australia, Belgium, Sweden, Korea and Norway (Figure 1).

Many mooring arrays are currently maintained in the Southern Ocean (Figure. 1). The majority of these are short-term, with a deployment length of maximum 2 years. A few examples of longer term deployments with plans for continuation exist in the Weddell Sea, in the Ross Sea, in Prydz Bay and in the Amundsen Sea. Most of them require heavy icebreakers to service and redeploy the moorings and rely on national research council funding support. International collaboration is hence required in order to maintain these longer-term

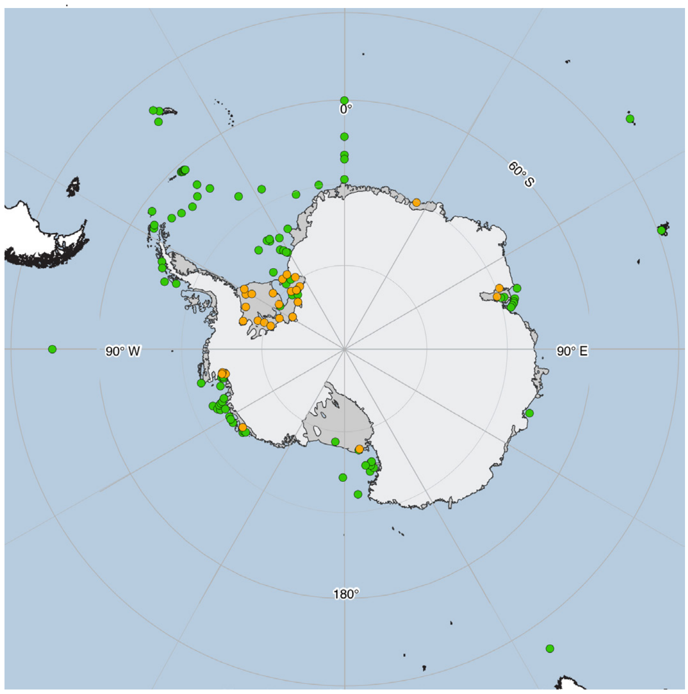

Figure 1: Green circles indicate approximate location of moorings around Antarctica currently in the water, or funded for deployment in the field season 2015/2016. Orange circles indicate existing and planned (funded) location of NECKLACE radars. This map illustrates the potential for individual national efforts to be combined to form a comprehensive circumpolar effort.

The way forward

The challenges posed in the Southern Ocean can only be partially met with existing technology. Although a number of sensors and platforms exist that provide data in near real-time, such as Argo floats, satellite remote sensing and the tagging of marine mammals, these data streams are the exception, with most observations collected through short-term, regionally-specific projects that are sparse in space and have a delay in data delivery of months to years. Most of the existing autonomous platforms are not capable of operating in sea ice conditions or under floating glaciers, leaving the marine environment under ice as an essentially blind spot in the observing system of the Southern Ocean (Rintoul et al, 2015). Figure 2 shows a summary of existing platforms that can be used to build the observing system. If we divide the Southern Ocean into the four regions sketched in Figure 2, it is only half of the first region that is anywhere near to having sustained and integrated multi-disciplinary observations performed. Even if the current level of investment by the nations involved in Southern Ocean research is maintained, the logistical demands and costs associated with traditional methods of collecting observations from research vessels or ships-of-opportunity will likely prohibit collection at the spatial and temporal resolutions required. The long-term solution is automation of data collection, with a much greater use of technologies that can be operated remotely or completely autonomously, development of new platforms suitable for observations under ice, and development of new sensors in particular for the biogeochemical and biological variables.

The observing system has to be aligned with a data management system that delivers the data in real-time and a cyberinfrastructure that enables the implementation of an effective adaptive sampling strategy. Key to achieving the SOOS goal is enhanced discoverability and delivery of SOOS data. One of the challenges in the Southern Ocean is the lack of a unified data access. The broader scientific goals of SOOS cannot be realized without a strong understanding of what data already exist, and better coordination of data collection activities. The SOOS Data Management Sub-Committee (DMSC) is a multinational team of experts working directly on linking various data sets of interest into the SOOS information web.

A searchable metadata portal within NASA's Global Change Master Directory has been created and is currently being populated with records describing key SOOS datasets. These metadata records will lead the user to the associated data located in areas that intersect with the SOOS region and are related to any of the candidate Essential Ocean Variables (EOVs) identified by the SOOS Scientific Steering Committee. In addition, the GCMD provides web services that will allow other interfaces to be implemented in the future. A data rescue effort has been launched and is focused on historical data by making their metadata discoverable through the SOOS GCMD domain. The DMSC is also tracking down orphan datasets so that they can be documented and housed in easily-accessible data repositories and linked into the portal. An orphan dataset is one that is not publicly documented and available, often because the responsible researchers have been unaware of potential repositories for housing their data. The SOOS DMSC also encourages researchers to work through their national data centers to ensure that their data are safely stored and made accessible. Where this is not possible, we are identifying alternative data repositories and working with researchers to find appropriate homes for their data.

The DMSC is also developing tools for visual data exploration, and will populate it with representative samples of the datasets available through the metadata portal. SOOS is also designing a platform for researchers to easily share their field work plans. This platform, a GIS based tool providing classes of information provided by researchers before their field seasons start, is intended to facilitate collaborative activities such as offering and taking advantage of ships-of-opportunity, moorings-of-opportunity, adding sensors to packages, deploying instruments or sharing calibration information.

The SOOS data effort thus far has been limited by a lack of dedicated personnel, but recently gained support through the Australian Research Council's Special Research Initiative for Antarctic Gateway Partnership (Project ID SR140300001) and hired a Data Officer in April 2015 for 2 years.

SOOS Implementation Activities

In 2015, SOOS developed a 5-Year Strategic Plan that builds on the Initial Science and Implementation Strategy (Rintoul et al., 2012), and more clearly identifies the key objectives, the precise actions required to achieve them, and the measures of progress and success. In June 2015, SOOS held its 4th annual Scientific Steering Committee meeting and the Strategic Plan was discussed in detail. The plan will go through a review process before being finalized, but in the short-term, SOOS implementation will be based on the following 6 objectives, which follow a logical sequence from design of the system, through implementation, to delivery of the data:

1. Facilitate the design and implementation of a comprehensive and multi-disciplinary observing system for the Southern Ocean
2. Advocate and guide the development of new observation technologies
3. Compile and encourage use of existing international standards and methodologies, and facilitate the development of new standards where required
4. Unify and enhance current observation efforts and leverage further resources across disciplines, and between nations and programmes
5. Facilitate linking of sustained long-term observations to provide a system of enhanced data discovery and delivery, utilising existing data centres and programmatic efforts combined with, as needed, purpose-built data management and storage systems.
6. Provide services to communicate, coordinate, advocate and facilitate SOOS objectives and activities

SOOS has already made progress against these objectives. A comprehensive overview of SOOS milestones can be found in the recently published 3-Year Progress Report (www.soos.aq).

Implementation of SOOS will ultimately be done regionally as it fundamentally depends on the involvement of nations that have traditional regions of focus. SOOS is therefore developing Regional Working Groups that will coordinate and implement the observing system in their defined region, including facilitating improved readiness and ability where needed. Regional Working Group membership will be open, and will have solid representation from all nations working in the region, and expertise across all disciplines.The development and implementation of technologies, improvement in observational design, efficiency and coverage, and the development of information management and dissemination will be managed by Capability Working Groups. The existing national and international projects and programs that contribute to SOOS will be identified and recognised as contributing regionally and/or to enhancing capabilities. Examples of activities undertaken in this category is the development of an international under ice strategy (co-sponsored by CSIRO Wealth from Oceans Flagship, CliC, POGO, Antarctica New Zealand) in 2014 (Rintoul et al, 2015), identification of observational and science gaps in the Ross Sea region (Williams et al, 2015) and a report of community needs for Southern Ocean satellite data which is in preparation (sponsored by SCAR, SOOS, CliC).

In June 2015, SOOS held its first international planning workshop Implementation of a Southern Ocean Observing System, hosted by the Institute for Marine and Antarctic Studies at the University of Tasmania. This workshop brought together 70 international Southern Ocean researchers to identify the regions for Regional Working Groups and distil the capabilities of highest priority for development through Capability Working Groups.Five priority regions were identified: The Weddell Sea, the Indian Sector, the Ross Sea, the Amundsen and Bellingshausen Indian Sector, the Ross Sea, the Amundsen and Bellingshausen Seas, and the West Antarctic Peninsula. Two of these already have already submitted Working Group proposals to the Steering

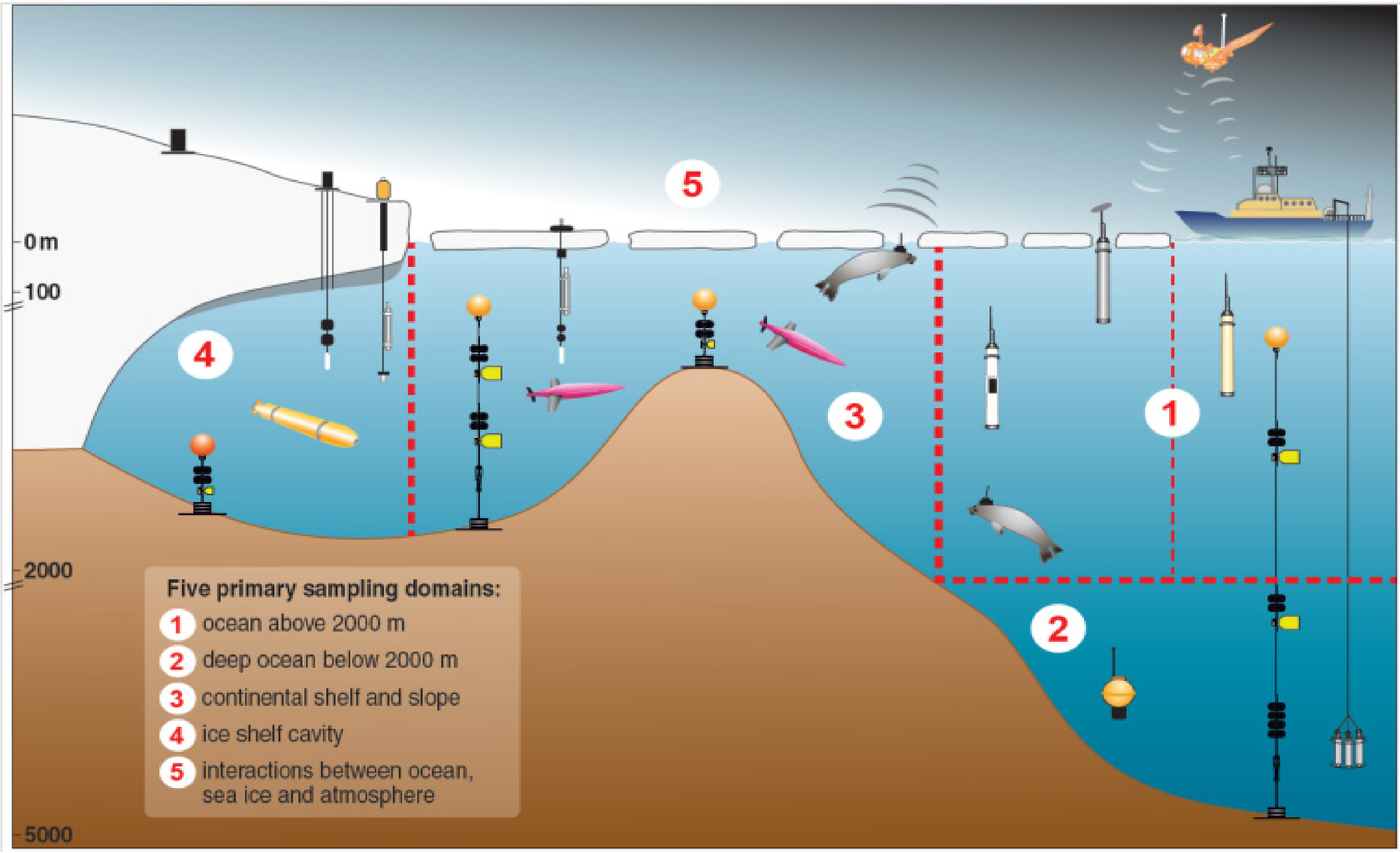

Figure 2: The high latitude Southern Ocean and Antarctic margin includes several physical environments, each with distinct characteristics that mean a different mix of platforms is appropriate in each case. (1) Ocean basin, 0-800 m water column (ice covered and ice free), (2) Ocean basin, deep water >800 m depth, (3) Continental shelf region, (4) Under ice shelf. From Rintoul et al (2015)

Committee, and the community is encouraged to register interest in creating other Working Groups or becoming involved in the existing applications. Furthermore, a number of key observing system capabilities were highlighted for development: Underwater acoustics (passive, active, communication), satellites (algorithms, specific communities, cal/val upcoming missions) , air-sea fluxes (impact on models, sensor gaps, quantification of fluxes in many regions), System Design (OSSE simulations, sampling strategies), Ecosystem (eEOVs, products to support management, models), sensor development (in particular low cost, small, operable on autonomous platforms), ships of opportunity (including tourist vessels and fishing vessels), under ice capabilities (under ice argo, technology, ice cavities, sensors, fluxes). The community is asked to register interest in these capabilities, or other ones that were not highlighted here.

Summary

Despite being one of the climatologically most important regions on Earth, Southern Ocean observations are sparse, difficult and expensive to obtain, and are often limited in space, time, quality and variables measured. The Southern Ocean faces a number of almost complete data gaps in important areas, e.g. climatological-scale time series (i.e. >10 years), wintertime measurements, and under ice measurements. This is mainly a result of the lack of coordination and the challenges posed by the physical environment. By gathering the research community in this joint effort to unify and promote sustained, integrated measurements in the Southern Ocean we see a path forward to address this great challenge that we face

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Past, Present and Future of Satellite Altimetry for the Oceans, Cryosphere and Hydrosphere

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Introduction

Satellite altimetry has existed on and off for over 40 years and consecutively for almost 25 years. Data from these unique observing platforms have helped redefine our understanding of ocean dynamics on global scales. These missions have facilitated significant advances in our understanding of global sea level rise, El Niño and La Niña, ushered in a new era of near-real-time monitoring of currents with scales greater than 100 km, and provided a new tool for observing lake and river levels, wind and wave height, and ice cover. Early missions proved the feasibility of satellite altimetry beginning with Skylab in 1973, GEOS-3 in 1975, Seasat in 1978 and GEOSAT in 1985. Data from these missions allowed scientists to track eddies, improve bathymetric measurements, tide models and much more. Their success led to the development of precise and continuous satellite altimetric observations starting in 1991 with ERS-1 and TOPEX/Poseidon (T/P) in 1992, which laid the foundation for modern missions. The importance of these observations is demonstrated by the commitment to future missions with Jason-3, Sentinel-3, Jason-CS and SWOT. These missions will continue the long time series of ocean observations and add new capabilities in the measurement of the cryosphere and hydrology and small scale oceanographic signals.

Past Missions

Before the current constellation of satellite altimeters was designed and launched, several previous missions demonstrated the feasibility and utility of satellite altimetry. The first space born altimeter, S-193, was installed on the Skylab space station to measure the geoid. From May 1973 to February 1974 it was operated only sporadically, since the crew had to be on board to operate the station and instruments. S-193 proved that the geoid and the sea surface height could be measured remotely from space by resolving a clear signal in the ocean's surface when it traversed the Puerto Rico Trench (Pierson 2004). Only very large features could be seen since the altimeter had an accuracy of only 90 cm (Evans et al. 2005). GEOS-3 was a dedicated geodetic mission that operated from 1975 to 1979. Despite large errors in its orbital position, GEOS-3 data achieved an accuracy of 20-50 cm by averaging and using crossovers. This made it accurate enough to detect some larger oceanic signals such as large eddies (Mather et al. 1980) and to calculate the Mean Sea Surface (MSS) (Marsh et al. 1992), but not to study basin scale ocean dynamics. This changed with Seasat, NASA's first dedicated oceanographic satellite mission. It was launched in July 1978, though stopped operating in October 1978 after a power Sea Anomalies (SSHA) with an accuracy of 10 cm (Tapley et al. 1982, Evans et al. 2005), assuming that the data were averaged and filtered, and that significant wave height was <5m. It enabled studies of eddy kinetic energy (Menard 1983), western boundary currents, MSS (Marsh and Martin 1982), sea level change, and regional studies. This was possible because of the spatial coverage it provided and the focus on orbit determination, atmospheric corrections, and tidal corrections. This mission also helped demonstrate the importance of sea state bias correction. The development of these corrections and algorithms were the basis for the various corrections in TOPEX/Poseidon and Jason-1, which contributed to the sub-cm SSHA accuracy that is now achievable (G. H. Born, personal communication). It also showed the importance of having a dedicated altimetric mission and the need for a dual frequency altimeter to correct for path delay due to propagation of the signal through the ionosphere.

The next mission to advance satellite altimetry was Geosat, originally a geodetic mission launched by the US Navy. In 1986 it was maneuvered into a 17-day near repeat orbit to facilitate the measure of sea surface height variability. This move allowed the data to be declassified and made available to the science community. Geosat provided a more accurate (5 cm) (Evans et al. 2005) and longer time series of SSHA than Seasat. SSHA was now at an accuracy that global circulation models could be evaluated using altimeter data (Nerem et al. 1990). Studies of ocean variability in key regions were improved due to the longer time series available, including estimates of eddy kinetic energy (Shum et al 1990), Agulhas ring shedding (Fu and Zlotnicki 1989) and Gulf Stream transport (Kelly and Gille 1990), to name only a few. The accuracy and duration of the time series also meant that El Niño and La Niña events and the associated Kelvin waves could now be observed in altimetric satellite data (Miller et al. 1988). Geosat provided further support for of the inclusion of a dual-frequency altimeter (to correct for path delay through the ionosphere) and onboard radiometer (to correct for path delay due to water in the atmosphere).

Present Missions

Prior to the early 1990s, satellite altimeters proved that measuring sea surface height from space is feasible, and they provided very valuable information for studying ocean dynamics and climate signals. However, in 1991 and 1992, satellite altimetry was revolutionized again. Today, the majority of satellite altimetric data comes from one of two series: NASA and CNES TOPEX/Poseidon (T/P), Jason-1&2 (TPJ12) or ESA ERS-1&2 and Envisat (EEE). These two series have provided global altimetric data for almost 25 years and plans are in place to continue them for at least another decade and a half. These series provide dependable global water heights in the ocean and on land due to the well quantified operation of the altimeters and precise orbit determination.

The joint NASA and CNES TOPEX/Poseidon(T/P) mission (September 1992- October 2005) was the first satellite mission to be designed, built and launched cooperatively by both agencies. There was a strong emphasis on corrections and orbit accuracy, both important factors to be able to undertake oceanographic and climate studies. It was launched into a non-Sun synchronous orbit so that tides (although aliased) could be accurately resolved with a long enough time series. In addition, a dedicated calibration/validation (cal/val) site was created by installing a tide gauge on the Harvest oil rig platform, located off the southern coast of California and falling directly under an open ocean ground track. This proved so successful that additional, dedicated cal/val sites were developed around the globe to improve the accuracyof ongoing missions (Le

Tra on 2013). This level of accuracy was needed so that T/P could perform its main objective, measuring changes in ocean circulation on spatial scales from 100 km to the size of entire ocean basins. It captured the large El Niño event in 1997, along with other climatological signals over its 13 years of operation. Indeed, the overall accuracy of T/P was so good, that this mission was the first to demonstrate the feasibility of measuring globally averaged sea level rise using satellite altimeters (Nerem et al., 1995). In addition to the main T/P mission, hydrological measurements were also extracted. Using the waveform data, allowing for the removal of land contamination, measuring lake and river heights were possible (Birkett 1995).T/P was so successful that there was a follow-on mission, Jason-1 (December 2001-June 2013). To ensure the quality of Jason-1 data, T/P flew in tandem for 210 days to quantify the instrument bias between the two satellites. When the tandem mission was complete, the interleaved mission commenced so that the satellites flew on adjacent ground tracks, doubling the spatial resolution. Jason-1 continued observing the ocean and lakes, but also furthered the operational capabilities of altimetry. Jason-1 carried a mission requirement to make operational data available no later than 5 hours after it was collected. This opened the door for near real time applications, such as navigation and meteorological forecasts. T/P and Jason-1 proved that altimetric satellites could serve both operational and scientific communities.

Jason-1's successor, the Ocean Surface Topography Mission (OSTM)/Jason-2 (June 2008-present) was developed as an operational mission and included NOAA and EUMETSAT as partners. When Jason-2 launched, another tandem mission intercomparison was carried out between Jason-1 and Jason-2. After 180 days Jason-1 was again moved to an interleaved orbit, but this time with a 5-day lag between occupation of adjacent tracks, improving temporal resolution as well as spatial resolution. As Jason-1 began to age, a decision was made to move it to a third orbit to avoid the possibility of a collision with the now defunct T/P, which remains in an orbit close to the interleaved orbit. In May 2012, Jason 1 was moved into a geodetic orbit, at a lower altitude, where it remained until it was decommissioned in July 2013. The geodetic mission mapped many tectonic and bathymetric features that were previously undetected by shipboard or other satellite measurements (Sandwell et al. 2014).The combined time series of TPJ12 provide a globally averaged record of sea level change back to late 1992 with a trend of about 3 mm per year (Nerem et al. 2010, Beckley et al. 2013) and regional trends as shown in Figure 1 (Nerem et al. 2010). This altimetric series has also provided lake and river levels for the same time periods, producing useful information on the hydrology of both well populated and remote areas. The next satellite in the series is Jason-3, which will launch this summer. It will continue to provide information on the global ocean, meteorology and hydrology.

The European Space Agency (ESA) has its own rich history of satellite altimeter missions. ERS-1 (July 1991-March 2000) was ESA's first sun synchronous, polar-orbiting satellite with an inclination of 98.5°, covering most of the polar seas. The sun synchronous orbit meant that tides could not be easily resolved. More care was needed to remove the effects of tidal aliasing. Its successors were ERS-2 (April 1995-July 2011) and Envisat (March 2002-April 2012). These satellites contained additional instruments to measure other aspects of the Earth, such as a Synthetic Aperture Radar (SAR) and a radiometer that could measure sea surface temperature. Like T/P and the Jason mission, the EEE missions facilitated important advances in ocean science and hydrology. Its higher inclination angle allows for the measurement of Arctic sea level changes, which differ from lower latitude

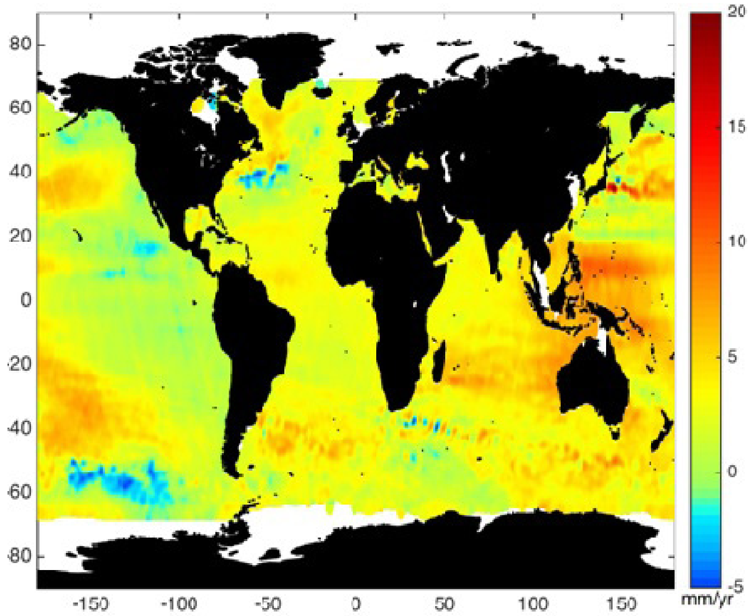

Figure 1: Sea level trends calculated from the TOPEX/Poseidon, Jason-1 and OSTM/Jason-2 series. The global sea level trend from this series is 3.3 +0.4 mm/yr (Nerem et al. 2010).

regions because the cold temperatures and the importance of salinity for determining ocean circulation through the addition of fresh meltwater. Envisat showed that the regional sea level rise in the Arctic has a trend of 1.7 mm/yr (Cheng et al. 2015). While there is currently no proposed follow-on for Envisat there is another altimetric mission SARAL/AltiKa (February 2013 - present) that is in the same orbit. SARAL is a satellite developed and built by the Indian space agency (ISRO). AltiKa is a Ka-band altimeter built by CNES, which operates onboard SARAL. Previous altimetric missions operated on Ku and/or C-band. Ka-band is a higher frequency that provides better resolution for coastal areas, and is nearly insensitive to ionospheric path delays (Desai and Haines 2013). SARAL/AltiKa continues the measurements on the same path as EEE, including the Artic Ocean. It has also demonstrated that Ka-band altimeters are a viable option for future altimeters. Several other altimetric satellite missions have been launched in addition to the TPJ12 or EEE series, including Geosat Follow-On, CryoSat-2 and HY2A. These missions each had a different orbit and thus offered increased spatial and temporal resolution when merged with the TPJ12 and EEE series allowing for improved studies of ocean dynamics on smaller scales. The US Navy's second altimetric mission was Geosat Follow-On (GFO, February 1998- October 2008). Its prime mission was to measure the geoid, similar to Geosat. However, it also provided measurements for the oceans, climate and ice sheets.

CryoSat-2 (April 2010 - present), operated by the European Space Operations Centre (ESOC), is Europe's first mission to monitor variations in the extent and thickness of polar ice through the use of a satellite in low Earth orbit. It is in a highly inclined polar orbit, reaching latitudes of 88° north and south, to maximize its coverage of the poles. Its main instrument is a Synthetic Aperture Interferometric Radar Altimeter (SIRAL) and the main mission is to measure ice thickness. The information provided about the behavior of coastal glaciers that drain thinning ice sheets will be key to improving predictions of future sea level rise. SIRAL can operate in a low resolution mode that can also extract sea surface height, similar to the typical altimeters found on TPJ12 or EEE. Not only does Cryosat-2 provide scientific measurements, but it demonstrates that a SAR can be used to measure sea surface height when merged with other altimetric missions for better coverage (Dibarboure et al. 2012). This is significant for the development of future altimetric missions, discussed below.The China Academy of Space Technology has been developing a series of ocean observing satellites, one including an altimeter, HY-2A (August 2011-present). It was calibrated by comparison with Jason-2 at crossover points (Bao et al. 2015). Despite biases with Jason-2, it has been demonstrated to provide useful oceanographic observations as well. It has a different orbit than the EEE and TPJ12 series and therefore enhances the spatial coverage of the globe.

Future Missions

Over the past quarter century, satellite altimetry has become indispensable to scientist who study oceanography, climate, hydrology, geodesy and the cryosphere; forecasters who provide marine weather and navigational forecasts; and the public and policymakers who monitor global sea level rise as an indicator of climate change. As a result, future missions are being designed to ensure that the time series continues. ESA will contribute to the Copernicus program, headed by the European Commission, building and launching the Sentinel series of satellites. Sentinel 3, planned to launch at the end of 2015, will measure various properties of the ocean and continue the EEE series. It will have the same SAR based altimeter as Cryosat-2 operating on Ku and C band frequencies.Jason-3 will launch this summer to continue the TPJ12 series, and Jason-CS is expected to launch in 2020. Jason-CS will differ from the rest of the series by carrying a SAR altimeter similar to that of Cryosat-2 and Sentinel-3. Jason-CS will provide continuity of the reference ocean surface topography time series used to determine ocean circulation and sea level rise. This data will also continue to be used in operational applications including El Niño and hurricane forecasting, safe navigation, and offshore operations.

Given the complications of removing land contamination from the altimeter signal in order to measure lake and river levels, the next generation of satellite altimeters will carry an interferometer to observe an across-track swath with very high resolution. The SWOT (Surface Water Ocean Topography) mission will measure both sea surface height and lake and river levels, making SWOT the first hydrology mission for NASA and CNES. The altimeter for this mission is KaRIN, a Ka band interferometer SAR. The higher frequency of Ka band and the SAR component of this new altimeter will allow for a higher spatial resolution of data that the combined series of present and past altimetric missions are not able to provide. The spatial resolution proposed within the swath is 1 km for the ocean and 500 m for coastal and hydrology. The ocean resolution will enable the study of submesoscale as well as mesoscale features. The high resolution in coastal regions and over lakes and rivers allows for better removal of land contamination, which is the largest contributor of error for these regions.

Conclusion

Satellite altimeters have pioneered a rich history of scientific advancement, revolutionizing oceanography, hydrology and the study of the cryosphere. Society benefits from the use of altimeter data in operational forecasts and climate monitoring. From the first altimeter on Skylab to the promise of SWOT, radar altimeters have proven time and again to be one of our most powerful space-borne tools for looking back at the Earth to better understand it. Given our radically changing climate, we need tools like these now more than ever.

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Ocean Reanalyses in the context of GODAE OceanView

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Introduction

Ocean reanalyses involve the combination of ocean observations with numerical models to yield an estimate of the three-dimensional, time-varying ocean circulation. Facilitated by progress in ocean modelling and data assimilation methods, increased supercomputing capacity and, most importantly, enhanced, routine and sustained in-situ and remotely-sensed ocean observations, the last 15 years saw the development and operational implementation of mesoscale ("eddy-resolving") short-range ocean forecasting and reanalysis capabilities in an increasing number of oceanographic centres. Building and maintaining operational[1] ocean forecasting systems requires extensive expertise. Founded as an experiment in the late 1990s as the Global Ocean Data Assimilation Experiment (GODAE), its successor GODAE OceanView (GOV) coordinates multi-agency efforts to coordinate the research, development and operational implementation of physical and biogeochemical ocean forecasting and reanalyses systems through its science team (www.godae-oceanview.org). GOV continues the legacy of GODAE (GOV Science Team, 2014) with its collaborators from more than 50 academic and national agencies world-wide with a research focus to improve short- to medium-range (days to weeks) operational ocean forecasting systems, and to enhance and sustain their development and routine operations.

The forecast and reanalyses systems provide timely information about the marine environment including ocean physical and biological states. This information benefits marine, ecosystem, cryosphere and numerical weather prediction and associated applications such as marine industries (e.g. commercial fishing, shipping, oil and gas, renewable energy, tourism), governments (e.g. search and rescue, defence, coastal management, environmental protection) and other stakeholders (recreation, artisanal and sport fishing, yacht racing).

The objectives of the GOV Science Team are aligned with those of the World Weather Research Program (WWRP), the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), the Committee on Earth Observation Satellites (CEOS) and the

[1] "operational" is used here "whenever the processing is done in a routine pre-determined systematic approach with consistent accuracy and constant monitoring. With this terminology, regular re-analyses may be considered as operational systems, as well as organized analyses and assessment of climate data".

Blue Planet initiative of the intergovernmental Group on Earth Observations (GEO). In this context, GOV contributes to the prioritisation, advocacy, implementation and exploitation of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). Akin to numerical weather prediction, GOV operational ocean forecasting systems must be sustained, as well as evolve and improve, to remain relevant and have broad utility. This necessitates an ongoing, coordinated research activity. The core ocean forecasting disciplines of ocean modelling, data assimilation, forecast verification and observing system evaluation are routinely applied to associated reanalyses systems. These systems often underpin operational forecasting systems and assimilate quality-controlled in-situ and remotely-sensed observations. Consequently, reanalyses represent the "best case scenario" in terms of skill to be expected from an operational forecast system that have the additional challenge of near-real-time quality control of observations (due to the short time window from data sampling to data assimilation) and forecast surface fluxes (compared to reanalysed surface fluxes for reanalyses).

There exists a diverse range of four-dimensional reanalyses of the ocean state at global to regional scales - based on the common modelling and assimilation infrastructure used for ocean forecasting. Horizontal grid resolution of ocean models has been steadily increasing over the last two decades accompanied by increases in forecast skill (Tonani et. al., 2015) with horizontal spatial resolutions for global systems of typically 1/4° to 1/12°. Similarly, ocean data assimilation systems used in operational ocean forecasting and reanalyses use ensemble optimal interpolation (EnOI) (e.g. Oke et al., 2008; Ferry et al., 2010), adjoint tools (e.g. Lee et al., 2009) and Ensemble Kalman Filter (EnKF) methods (e.g. Sakov et al., 2012).

The GOV reanalysis systems are similar (in some cases, identical) to those used by the climate community (e.g. CLIVAR GSOP – Global Ocean Synthesis Panel, see Caltabiano et al, this issue) with the exception that operational considerations have been taken into account in the design of the reanalyses modelling and data assimilation systems (Schiller et al., 2013). The term "reanalyses" is used here to denote retrospective analyses that combine observed and modelled fields to reconstruct the ocean state. As our observing systems, data assimilation, and modelling capabilities improve over time it is often useful to repeat reanalyses with enhanced observations, thus providing improved model-based estimates of the ocean circulation.

GOV Reanalysis Systems: Applications for Climate Research

Even though high-resolution reanalysis systems have been originally developed to improve the analytical and forecasting capabilities for shorter time scales (days to weeks), the results of studies based on these systems improve our understanding of regional dynamics that is also important in climate research. The ocean is turbulent and dominated by mesoscale variability (Chelton et al., 2011). Hence, high-resolution ocean reanalyses can provide important first-order insights into basin-scale ocean current systems (e.g., Maximenko et al., 2008; Divakaran and Brassington, 2011). Furthermore, reanalysis products associated with operational forecast systems can contribute to better understanding of ocean dynamics at mesoscale resolution and can lead to new scientific findings in climate research. There is an increasing synergy between ocean reanalyses, championed by GODAE OceanView, and and those championed by CLIVAR - particularly as high-resolution reanalyses performed under GOV are performed to cover longer periods ("1990's to present reanalyses are typical, and provide consistent performance; however reanalyses back to the 1950's and 1970's are emerging). Some short-term ocean forecast and seasonal-to-decadal assimilation systems now share much of the data assimilation methodology and infrastructure. For example, the ongoing French Global Ocean Reanalysis and Simulation (GLORYS) project adopted the assimilation scheme developed for the French Mercator Océan forecasting system (Ferry et al., 2010). Similarly, the data assimilation component of the Australian seasonal prediction system POAMA (Yin et al., 2011) is based on the same data assimilation system used for short-range prediction (Oke et al. 2005; 2008; 2013). The relatively high-resolution nature of the ocean analysis and forecasting systems benefits studies of regional ocean dynamics and climate (including regional sea level change). Some examples are described below.

The goals of the Australian BLUElink effort include the development of eddy-permitting, data-assimilating, ocean forecast and reanalysis systems. The post-1991 assimilation product of BLUElink has been shown to realistically reproduce the mesoscale circulation in the Asian-Australian region (Schiller et al., 2008). Accurate representation of mesoscale eddy and circulation behaviour provides important information needed to realistically estimate mass and heat transport and to elucidate processes associated with water mass formation in conjunction with climate variability. For instance, Schiller et al. (2010) demonstrated the utility of the Bluelink assimilation product to represent the observations collected by the INSTANT program and to study the dynamics of intraseasonal variability associated with the complicated pathways of the Indonesian throughflow. More recently, Divakaran and Brassington (2011) have discovered ocean zonal mean currents in the southeast Indian Ocean by using similar BLUElink products.

In parallel to the development of the Global Ocean forecasting system, supported by the European MyOcean project, the Mercator Océan Agency has produce different versions of GLORYS spanning the 1992–2013 time period. Based on the NEMO Ocean and Sea Ice model, with the use of ERA-Interim air sea fluxes and a data assimilation system based on Ensemble Optimal Interpolation (sometimes referred to as an extended Kalman Filter, based on the SEEK approach), altimetry, SST, in-situ (e.g. Argo, XBT, TAO, sea-mammals) and sea ice concentration data are assimilated to provide a deterministic estimate of the ocean state (Figure 1; Lellouche et al, 2013). This reanalysis provides boundary conditions to regional ocean reanalyses all along the European shelves at higher resolution and to produce long-term simulation of the PISCES biological model (Aumont et al., 2015).

In the context of the European Copernicus programme (2015-2021), Mercator Océan will become the leader of the Marine Service and will update the operational global ocean forecasting system as well as reanalysis by improving the NEMO ocean / sea-ice model, increasing the resolution of the deterministic simulation (1/12°, 1/24°) and to develop an ensemble-based data assimilation system at lower resolution (300 members, 1/4°).

The Norwegian TOPAZ4 forecasting and reanalysis system is a coupled ocean-sea ice data assimilation system for the North Atlantic Ocean and Arctic (Sakov et al., 2012). It is currently the only operational, large-scale ocean data assimilation system that uses the EnKF (specifically, the Deterministic EnKF; Sakov and Oke 2008). TOPAZ4 therefore features a time-evolving, state-dependent estimate of the background error covariance and includes covariances between ocean

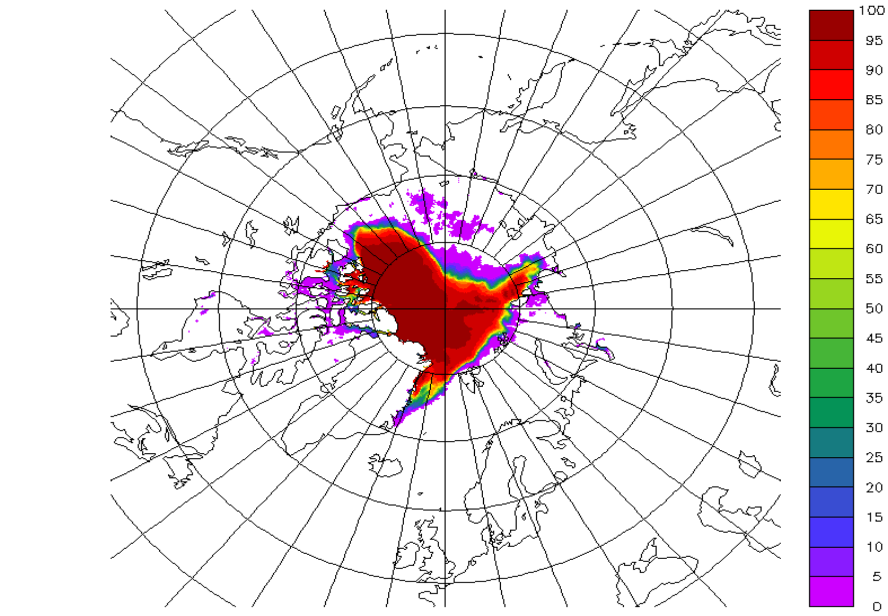

Figure 1: Monthly sea ice concentration based on GLORYS reanalysis for September 2007, showing the percentage of coverage.

variables and sea-ice variables, through the ensemble statistics – that is unique to ensemble-based data assimilation systems. TOPAZ4 produces a realistic estimate of the ocean circulation in the North Atlantic and the sea-ice variability in the Arctic.

The US Naval Research Laboratory (NRL) has run a 32-layer 1/12° global HYbrid Coordinate Ocean Model (HYCOM) ocean reanalysis that is the same basic configuration as the US Navy's operational Global Ocean Forecast System 3.0 (Metzger et al., 2014). It assimilates surface and subsurface observations using the Navy Coupled Ocean Data Assimilation system (Cummings and Smedstad, 2013) and is forced with National Centers for Environmental Prediction 1-hourly Climate Forecast System Reanalysis products (Saha et al., 2010). The time period spans October 1992 to December 2012. The ocean output have been interpolated to a constant 0.08° latitude/longitude grid (HYCOM's native grid is on a tri-pole configuration) and have been remapped in the vertical to 40 z-levels. A snapshot of sea surface height is shown in Figure 2. These output are served at: http://hycom.org/dataserver/glb-reanalysis.

Outlook

The development of data assimilation methods, mesoscale-resolving ocean reanalyses and their application to a wider range of problems will likely proceed as a result of their proven utility in ocean climate research. Data assimilation for oceanic biogeochemical and ecological modeling is of interest because of the possible application of such models to sustainable management of marine resources. However, there are many issues to be addressed in data assimilation for such complex systems. In particular, there remains uncertainty in a variety of oceanic biogeochemical and ecosystem model parameters, largely due to inaccurate 3-dimensional advection as one of the key processes determining the distributions of nutrients and plankton (e.g., Anderson and Robinson, 2001). At present, ocean color measurement from satellites seems to be the most suitable observation type to constrain biogeochemical and ecosystem models. However, the expansion of oxygen sensors on Argo floats promises to offer an important compliment to satellite observations.

A suite of ocean synthesis products have been produced in the past decade for various purposes. Few products provide uncertainty estimates for inferred quantities (e.g., global ocean heat content and sea level change). There is an increasing need to understand the consistency and uncertainty of these products. This is a very challenging task because of the large number of factors that can contribute to the differences among these products. Among these factors are the differences in model (including the configuration, parameterization, resolution, etc.), in forcing, in assimilation or estimation methods (including the way they are implemented; e.g. the treatment of error estimates), and in the observational data being assimilated (e.g., data types, data sources). Decadal and longer variability and temporal inhomogneity of observations could also contribute to the differences among different products. These challenges are not unique to ocean products, and are also known in atmospsheric analysis and reanalysis products.

Understanding the consistency and uncertainty of ocean synthesis products requires international coordination among ocean synthesis groups such as the ongoing evaluation effort coordinated by CLIVAR GSOP and GOV. A close collaboration among the ocean reanalyses, modeling, and observational communities becomes increasingly important. Moreover, the ocean and atmopsheric reanalysis communities need to work together to tackle over-arching issues such as the estimation of air-sea fluxes. Similarly, as capabilities in biogeochemical modelling improve, the community needs to consider methods for coupling the physics and biology for mutual benefit. As new capabilities in ocean forecasting emerge with countries like Canada, Brazil, India and China, it is likely that researchers in these countries, and elsewhere, will soon contribute to the international efforts in ocean reanalyses.

An important future challenge is the development of seamless systems that will enable scientists to fully investigate multi-scale interactions (i.e., between short- and long-term, between small- and large-scale phenomena, and across interfaces, such as ocean-atmosphere). This development is important because high-frequency and small-scale features may rectify low-frequency and large-scale phenomena, and large-scale climate signals may compound with synoptic variability (e.g., storm surge) to affect regional changes (e.g., for regional sea level).In this context it will be important to provide analyses of the coastal zone to better understand land-ocean exchange processes that are relevant to climate change, for instance, in conjunction with the distribution and fluxes of freshwater. However, application of the data assimilation approach to coastal oceanography involves many complications (e.g., De Mey et al., 2009). High-resolution models are required to represent nearshore phenomena on relatively fine temporal and spatial scales. Such models often produce strong currents that reduce controllability during the assimilation procedure because of inherent nonlinearities (Köhl and Willebrand, 2002). Further development of data assimilation techniques and improved model implementations will inevitably require sustained observations of the finer structure of water properties and precise topographic information to improve model representations of near-shore phenomena.

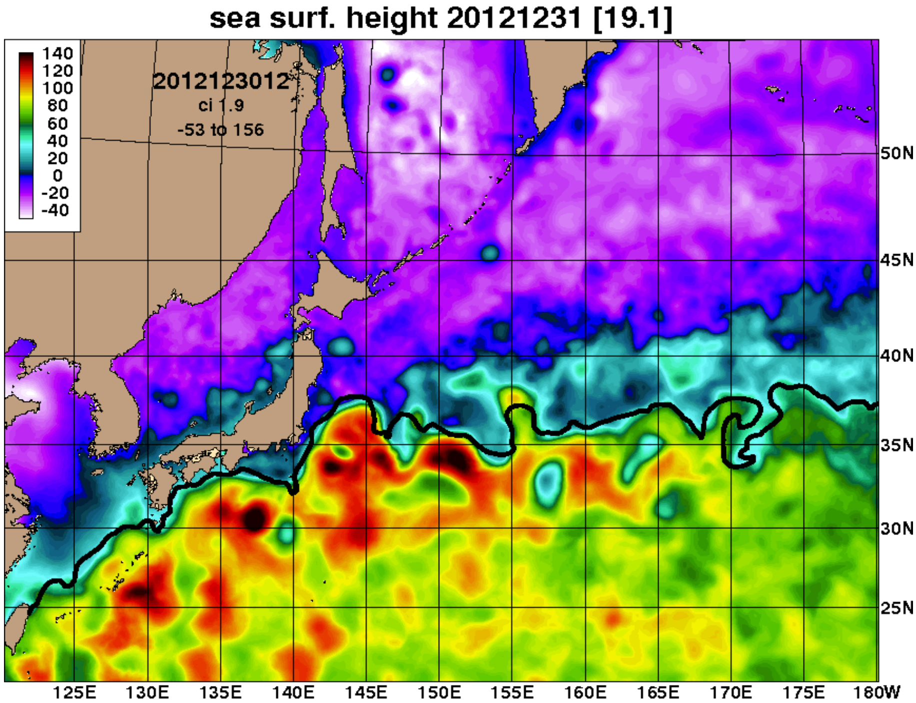

Figure 2: Snapshot (31 December 2012) of sea surface height in the Kuroshio Extension region from the HYCOM reanalysis. Units of the colour bar are in cm and the black line denotes an independent infrared frontal analysis that depicts the north wall of the Kuroshio.

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Animal-Borne Platforms for Ocean Observing

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Introduction

Marine vertebrates play important roles in ocean ecosystems, and as such, are an ideal platform for sampling the ocean environment. Because direct observation of these animals is difficult, and because of the rapid advances in low energy electronics and computation it is hardly surprising that the use of telemetry and autonomous data loggers to study them has rapidly increased. The combination of new positioning technologies, small, low power sensors and the variety of data recovery options provide a tremendous capacity to investigate how aquatic animals use their three-dimensional world, and to quantify important physical and biological aspects of their environments. The benefit of improvements to our understanding of animal movement and behavior can be seen in a wide range of applications, including those providing scientific information for marine fisheries and protected species management, and for evaluating the potential effects of anthropogenic disturbances. The data the animals have collected has also been used for improving coupled ocean-atmosphere observation and forecasting models.

Biological applications

Tag data can be used to inform and improve population censuses and stock assessment activities. For example, tag-derived movement data helped to improve management of Atlantic bluefin tuna through delineation of stock structure and demonstration of movement patterns (Taylor et al. 2011). Leatherback sea turtles have been observed to use corridors shaped by persistent oceanographic features such as the southern edge of the Costa Rica Dome and the highly energetic currents of the equatorial Pacific (Shillinger et al. 2008), and these findings led to an International Union for Conservation of Nature resolution to conserve leatherback sea turtles in the open seas. Habitat utilization patterns of marine mammals revealed by animal telemetry have helped identify, avoid or mitigate conflicts with oil, gas and alternative energy development, dredging and military activities (Tyack et al. 2011). By establishing times when tagged animals are not in close proximity to proposed human development operational windows for construction, dredging, pile driving, and military activities have been delineated, avoiding or minimizing disturbance. Distribution and migration data from a variety of taxa have been overlaid on oceanographic data to develop predictive mapping tools that help Central Pacific longline fishers minimize bycatch of protected loggerhead sea turtles (Howell et al. 2008). From the perspective of biological study of the animals themselves, most often these technologies have been usedto answer basic questions about the animals' behaviour and physiological state. Simple questions about their geographical movements, diving behaviour and foraging success require answers if we are to understand how conditions and human activities at sea influence their reproductive success and its population consequences. Because of the dynamic quality of the ocean environment and the complex lag between physical oceanographic conditions, primary production and trophic interactions, the importance of in-situ observations at the immediate position and scale of the animal has been only gradually recognized. We need to know not just where animals go, where and how they find food but also what oceanographic conditions are associated with their success.

Oceanographic applications

It is only in the last decade that the instruments attached to the animals have included physical and ocean sensors that provide data of the quality oceanographers expect. Few would disagree that the Argo Program has revolutionized ocean observation. Nearly 4,000 floats are currently active and well over one million profiles have been provided over the last decade. Efforts continue to improve global coverage but some gaps remain. These are often in Polar Regions, over continental shelves, near shore and in seasonal ice cover. But many species of animals exploit data poor areas of ocean or areas where data is only available in limited time windows. In this case, the animals themselves can also be an important source of data that compliments existing sources for oceanographic forecasting and models. This is particularly true for high latitude areas where ice cover and other logistic issues have constrained observations from ships, buoys and gliders but where large diverse populations of marine mammals thrive and travel with ease. Since 2003, close to a half-million CTD profiles from animal-borne CTD tags have been collected.

The use of these "animal-borne platforms" has led to a valuable synergy between biologists and oceanographers. The collection of oceanographic data from the animals themselves can play an important role in understanding their immediate habitat requirements and how they might respond to environmental change. If for example, we can identify the water mass properties where individual animals do well in terms of gathering resources, we can potentially get some idea of geographic options available to the population as a whole, in a way that is less open to bias caused by the particular sample of animals that were tracked. This was the approach taken by Buiw et al. (2007) where they identified the particular water mass properties where elephant seals gained mass. This approach could even be used to examine how changes in patterns of ocean circulation in the future might impact localized populations, a clear case of where oceanographic models can have biological implications.

Tag Platform Technology

The animal telemetry community, working together with engineers, has built a range of tags with high precision sensors that permit dynamic measurements of moving animals in ocean environs. Animal tracking can be conducted in real-time with radio, acoustic and satellite telemetry or in 'archival' mode where information is reconstructed from time-series data that are either transmitted on a time-delayed basis via satellites, or analysed when the animal is recaptured and the tag physically recovered. Satellite relay of data provides the opportunity of getting data back in near real time. If this requirement is not a priority, other data collection and relay approaches have been developed that relax or change the nature of some of these constraints. Currently, about ten standard tag types exist with distinct position and sensor capabilities. Fishes, marine mamm-als, turtles and seabirds have been tagged routinely with sophisticated instruments that sample animal behaviours (e.g. diving, orientation, acceleration and feeding), oceanographic variables (pressure, light, temperature, salinity), position (GPS, ARGOS, Geolocation), acoustics (e.g. animal vocal behavior, tail-beats, respirations, environmental sounds), and physiology (e.g. body temperature, heart rate, blood or tissue oxygen saturation). Location data enable assessment of animal foraging "hotspots," ecological interactions, migration routes and habitat utilization patterns.

It was fortunate that physical oceanographers got involved at an early stage in the development of such instruments because this fostered a synergistic relationship between the disciplines that has since provided not only biological insight but also created this additional and cost effective route to obtain oceanographic data from logistically challenging locations and times. The first deployment of such instruments developed from a collaboration between oceanographers interested in ocean conditions under ice in Svalbard (Lydersen et al 2002). Further development of the instrumentation was supported by a National Oceanographic Partnership Program grant from the Office of Naval Research to the Census of Marine Life - Tagging of Pacific Pelagics (TOPP)[1] project which led to the development by Sea Mammal Research Unit (SMRU) Instrumentation[2] of ocean profilers, so called CTD-Satellite Relay Data Logger (SRDL)[3] that could be attached to marine animals which could collect and store data and relay it via the Argos System[4] of satellites. The challenges in developing effective animal-borne platforms relate not to just the harsh physical conditions subjected to them by the animals on land and at great depths but also to the interrelated constraints of size, sampling frequency, bandwidth, and the duration of deployments. Energy is the currency linking these constraints because batteries are often the largest and most size limiting components because of the demands of the sensors and transmission of data. Further constraints, but not additive ones are imposed by the limited time animals are at the surface and limitations of the transmission systems, such as Argos System itself. These combined bandwidth limitations require that the animal borne tags be particularly parsimonious and selective in which data they send. For example, CTD profiles are often relayed in two or more 248 bit message packets consisting of a total of 20 temperature salinity depth points selected by complex criteria determined by the particular demands of the deployment (see Fedak et al 2002 for a general (SRDL) discussion of the various strategies used to reduce bandwidth). Because sensors, memory and processing are increasingly relatively cheap in terms of space and energy, doing more on-board analysis and processing (by so-called smart tags) can help overcome these limitations, making it possible to describe fine scale information without needing broadband transmission of data.

Archival data loggers that store data for subsequent collection when animals are recaptured or that float when detached from the animals avoid the energy costs associated with data transmission. Because of the rapid decrease in size, cost and power requirements of non-volatile memory, bandwidth constraints are relaxed but issues related to location accuracy and bias in the data recovered remain related to the nature of any recovery. Some loggers are now collecting acoustic data, over a period of hours or days, and a variety of other behavioural data at high rate (e.g. acoustic data at 193 Hz and accelerometer data at up to 50 Hz) and have up to 128 Gb of memory on-board (Johnson & Tyack 2003; Burgess

1 http:/www.coml.org/projects/tagging-pacific-predators-topp
2 http://www.smru.st-andrews.ac.uk/Instrumentation/Overview/
3 http://www.smru.st-andrews.ac.uk/Instrumentation/CTD/
4 http://www.argos-system.org/?nocache=0.04490273636220865

et al. 1998).Acoustic tags are available that send messages on tag identity over relatively short ranges (<400m) to either fixed receivers on the sea bed or, less commonly, receivers on other animals. In many cases, these "identity" tags are smaller than the previously described satellite and archival tags.

This is particularly useful for studying small species (e.g. smolts of salmon) that are incapable of carrying relatively large satellite tags, and aquatic species that do not surface often or long enough to make radio transmission of data useful to employ. Acoustic tag technology provides a cable-free underwater network for recording animal observations. The decreasing size, longer life spans of batteries and increasing sophistication of acoustic transmitters provides a mechanism for monitoring the behaviour of a wide range of species across great distances, using networks of underwater receivers that span multi-national boundaries. The emerging use of satellite enabled acoustic receivers and unmanned mobile gliders or mobile marine mammals fitted with acoustic receivers that together provides a "wired ocean" potential, complements these networks. Although still in its infancy, this new approach to animal telemetry involves tags that can communicate with each other. For example Vemco VMT receiver tags have been attached to seals also carrying a second tag, either Argos or GSM phone tags that collect information from the Vemco acoustic receiver via a blue-tooth link. The Argos or GSM tags store the information and the time it was received and then later relay the acoustic detections when the animals are at the surface or hauled-out on land within GSM reception. By combining the acoustic and radio data links, this approach provides a direct way to get information on trophic interactions, which are critical for establishing potential consequences of environmental exploitation, regulation and change.

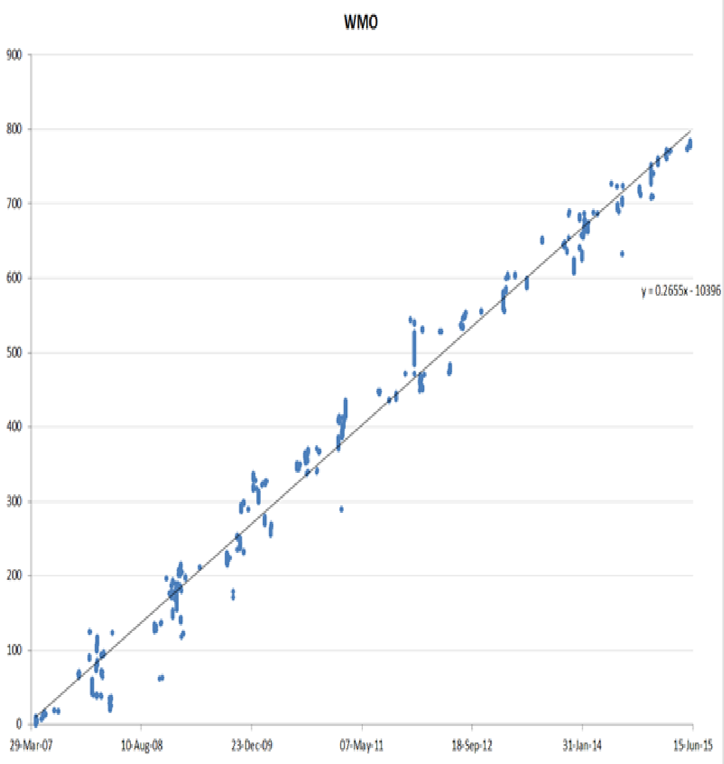

Figure 1 a): Increase in total number of WMO indexed CTD-SRDLs tags since 2006

Integration of Ocean Observations from Animals with other Sources

Given that animal telemetry technology could now be considered mature and operational, these data are ready to be integrated in Ocean Observing Systems. Over the last decade animal-borne tags have integrated oceanographic sensors capable of providing high-accuracy sea-surface and vertical temperature, salinity and fluorometry profiles throughout the water columns visited by the animals, in some cases (elephant seals) deeper than 2000 m. The first large scale deployments of tags like the current CTD-SRDLs began in 2004 with the SEaOS Project (Fedak, 2013). The TOPP program from 2000-2014 deployed over 6,000 electronic tags on 24 pelagic species, a portion of which were CTD-SRDLs (Block et al. 2011). This was followed by the larger Marine Mammals Exploring the Oceans Pole-to-Pole (MEOP) Project[5] , an International Polar Year project involving 10 countries coordinated by the Norwegian Polar Institute. Other deployments have continued on an ad-hoc, project-by-project basis when funding has become available, both in Polar Regions and elsewhere. Almost all projects applying CTD-SRDLs tags have agreed to make the near real-time CTD profiles freely available for operational use. Nearly 800 tags have been assigned WMO numbers, and since 2004 CTD-SRDLs tags have delivered 477,182 raw (i.e. no quality control or post-processing) CTD casts to the British Oceanographic Data Centre (BODC)[6] (Figure 1a) for broadcast via the Global Telecommunication System (GTS)[7]. The majority of the profiles obtained in SEaOS and MEOP are from high latitudes (Figure 1b) and it is in polar regions where the animal

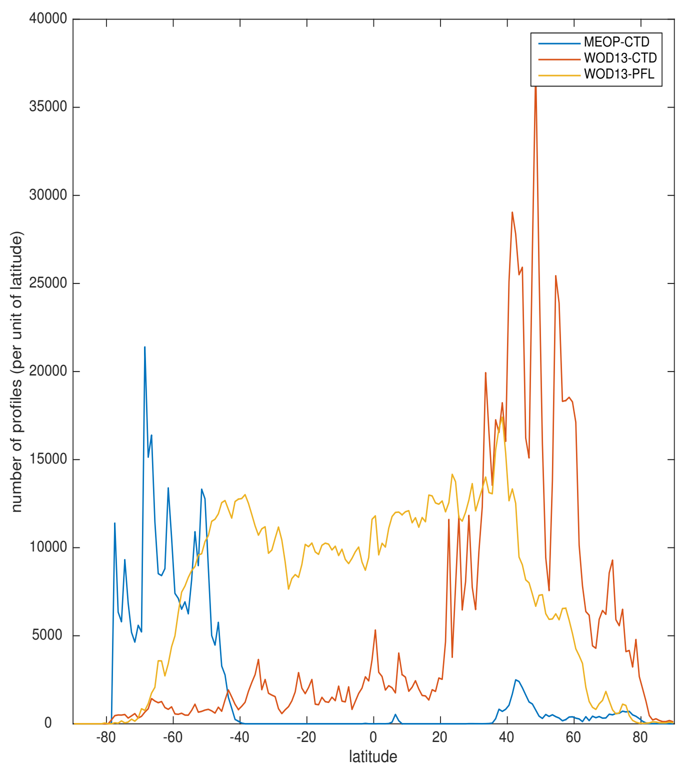

Figure 1 b): Comparison of the number of hydrographic profiles per degree of latitude, between the MEOP-CTD database and the World Ocean Database (WOD13-CTD: ship-borne CTDs, and WOD13-PFL: profiling floats).

5 http://www.meop.net/meop-portal/
6 http://www.bodc.ac.uk/about/news_and_events/seal_data_to_gts.html
7 https://www.wmo.int/pages/prog/www/TEM/GTS/index_en.html

platform data has had the greatest influence because of the long-term deployments and frequency of sampling made possible by the tags (Figure 2). The delivery varies by season because of the life history patterns of the animals but tag retention usually covers the winter months when data availability in Polar Regions is most limited.

Maximizing Data Value and Return

To get the most value from the animal platform data, efforts have been made to make the data freely available in available in standardized formats, after it has been quality-controlled and post-processed, and modelled similar to that used with Argo profiling floats. Two systems have been developing in parallel which overlap to some degree.

1. MEOP.net

This web site at http://www.meop.net/ is operational. It was created with the particular efforts of Fabien Roquet and Phil Lovell and the other MEOP Partners to make all the data from deployments of CTD-SRDLs freely available. The portal has been developed to handle the relatively conventional profile data delivered by tags used on large diving animals, so far, largely seals. All of this has been developed for CTD-SRDLs built by SMRU but the site is able to handle data from other tags as they develop and provide data with similar characteristics to those provided by Argo floats.

The data have been subjected to various levels of post-processing, details of which are given at http://www.meop.net/meop-portal/ctd-data.html. A range of cross-comparisons with other calibrated devices or known stable water masses are used to improve and confirm data quality. For example, when possible, instruments are attached to a standard ship-borne CTD frame for direct comparison, prior to deployment. It is also often possible to also use standard ship's instruments to get profiles in the immediate area of the deployment to get direct comparisons. Cross-comparison with other instruments that are opportunistically in the area (e.g. Argo floats, gliders moorings etc.) are often possible, along with comparisons between tags on different seals. Comparison with climatic information from deep, stable water masses, and temperature corrections when seals enter freezing water with known freezing point can be used to validate or correct temperature. The CTD data distributed via the MEOP portal thus has an accuracy level that can vary depending on the availability of cross-comparisons and on the relevant instrumentation technology or the water mass types visited during the deployment. Overall, once adjusted and validated, a minimal data accuracy of 0.03°C and 0.05 PSU can be assumed for data presented on the site, although some will exceed this level. All data on the site has been subjected to this consistent post-processing and set into standardized netCDF files format to make it easy to access and use. The intention is that, as more data from animal platforms are collected, that owners of the data will make it available through this portal within a year of collection or once they feel it can be open source. The data available there has already been utilized in the production of a growing number of publications listed on the MEOP site.

The portal is currently being operated without dedicated external funding and is dependent on data from the independent projects, which originally funded the deployments, and also for associated metadata on procedures and conditions surrounding deployment. The operators of the site carry out post-processing on a voluntary basis. Beyond the obvious

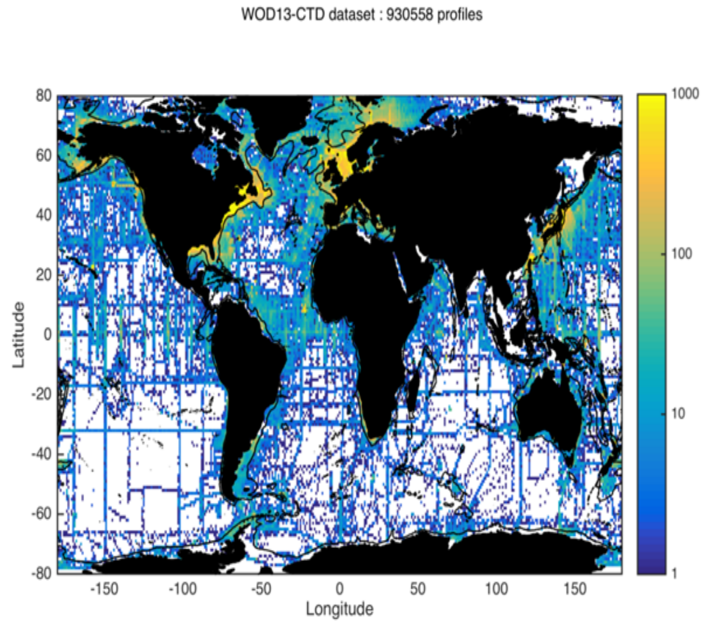

Figure 2 a): animal-based MEOP CTD-SRDLs -MEOP-CTD

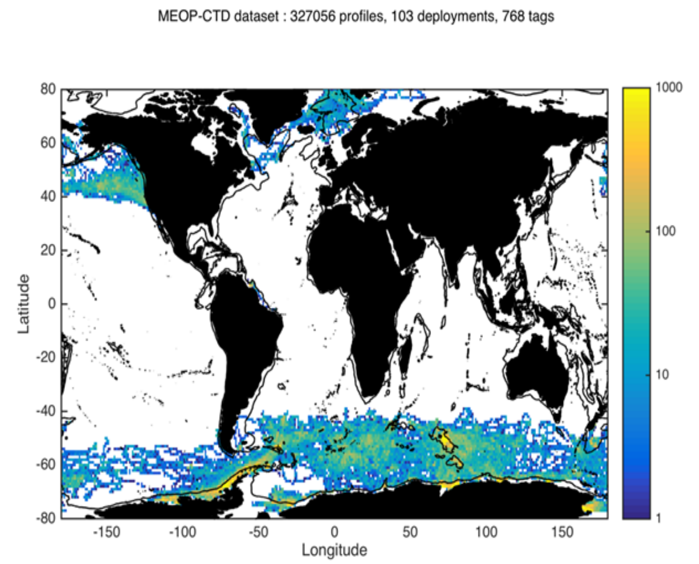

Figure 2 b): ship-borne CTDs - WOD13-CTD

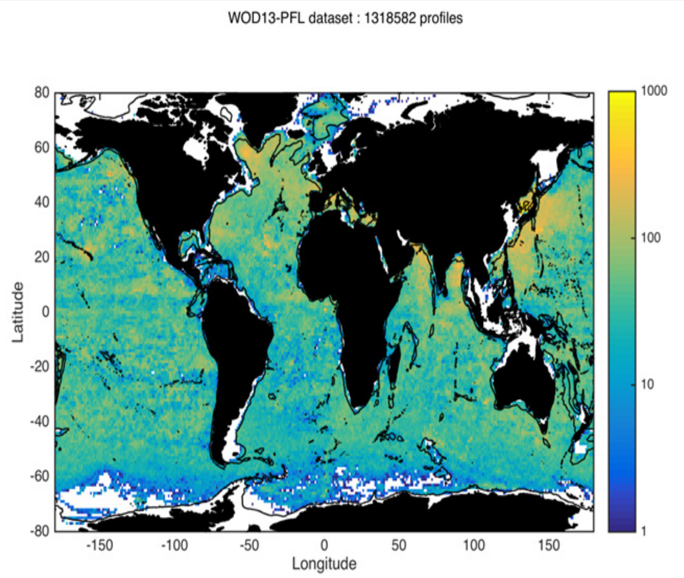

Figure 2 c): conventional profiling floats - WOD13-PFL. The contribution of marine mammals is particularly crucial South of 60oS, where other few other observations exist.

desirability of making the data available for general use, an important advantage in submitting data to the site is the intervention of oceanographers experienced in the post processing of animal-platform data. It also provides the opportunity to make direct comparisons with other data sets and is meant to encourage data to be made available as quickly as possible. In any case, many publications require data to be deposited in open databases at the time of publication, and an increasing number of funding agencies and instruments have open data policies. The MEOP site fulfils these requirements.

2. U.S. Animal Telemetry Network

The United States Animal Telemetry Network (ATN) through the auspices of the U.S. Integrated Ocean Observing System (IOOS) will provide a mechanism to create an alliance among federal and non-federal entities conducting animal tagging efforts. The ATN data management approach involves receiving, handling and distributing diverse data types from archival, satellite, and acoustic tag platforms that originate from a variety of individual researchers and large programs using consistent metadata standards and best practices. The core of the ATN data management system will be a quasi-centralized national ATN Data Assembly Center (DAC), which will receive and distribute data and data products to U.S. IOOS Regional Associations and other partner organizations.

The ATN DAC will aggregate the real-time data into collections or deployments, and then displayed on the ATN DAC user web interface (http://oceanview.pfeg.noaa.gov/ATN/). The DAC web display and interface was made possible by leveraging prior developments for tag data management (e.g. TOPP, Global TOPP, GulfTOPP) into a single system with an intuitive front end, capable of delivering and visualizing U.S. telemetry data streamed from multiple animal and platform types.

The ATN DAC in its current version provides access to four data streams: 1) "live" data from the animal borne platforms that report automatically from Argos satellites via codes that directly download from the CLS to ATN servers and then display location and data sets to the DAC in near real time, 2) Acoustic data collected by receivers and via automated Iridium satellite-linked acoustic receivers mounted on stationary buoys or mobile platforms, 3) Pop-up satellite linked tags that report data throughout the year, and then take approximately 20 days to download as the tag floats at the surface and transmits data to the DAC. The DAC servers collect oceanographic, position and behavioural data archived on the tag and rapidly display the information, and 4) the archival-based data drawn from the thousands of animal tracking deployments and datasets collected by various tagging programs using implantable archival tags and pop-up archival tags (already deployed and recovered).

The ATN will provide routine animal telemetry data and data products via the ATN DAC web interface to meet the requirements of U.S. federal and non-federal entities. For all tag types (satellite, archival, and acoustic), tag deployment and recovery metadata will be available on the ATN DAC website. Some satellite tags provide near-real time access to location-only; whereas, other satellite-linked time-depth recorders will provide near-real time access to location, temperature, salinity, fluorometry, and depth data, which are transmitted via the GTS and archived in the World Oceanographic Data Centre (WODC). Raw unfiltered datasets will be available on the website, and state-space modelled animal tracks are displayed on the web interface, including confidence intervals around individual daily Argos or Fastloc locations.

The Future of Animal Platform Data in Global Ocean Observations

Over the last decade data loggers and telemetry devices mounted on marine animals have provided critical information to understand their biology, while simultaneously providing a rich flow of oceanographic data. So far, this has happened in a rather ad-hoc way, owing more to opportunistic funding of individual projects, often from groups in many different countries, than a unified strategy. The fact that many of these groups have opted to work cooperatively and form larger integrated projects has added to the value of the information and the efficacy of the projects. The impact of the all-season observations from the Southern Ocean and Arctic areas has been particularly great. But there is a clear argument for developing a more strategic, coordinated international approach to animal-borne ocean observations in the future (Rintoul et al 2009). Data from the animal platforms has clearly demonstrated that broadening the geographic scope of routine ocean observations to include the out-of the way places the animals go, will improve our prediction of the oceans behaviour in terms its effect on weather, climate and ice (Roquet et al., 2013). Combining animal platforms in a ongoing, consistent source of these data that complement those provided by other methodologies in an extremely cost effective way. And these observations come with an additional bonus of delivering biological observations that elucidate animal behavioural patterns, inform aquatic species stock assessments, and identifying essential or critical habitat for marine species management. This combination facilitates a more ecological perspective on the observation of oceans that will be increasingly important in a changing climate and with increasing ocean exploitation.

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See www.meop.net for more information.
Courtesy of Fabien Roquet (Department of Meteorology of the Stockholm University, Sweden).

The IQuOD initiative: towards an International Quality controlled Ocean Database

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Introduction

Long-term high quality ocean observations are essential to understanding our changing climate, predicting future changes and underpinning more effective mitigation and adaptation strategies. Driven by the present demand from both the observational and modeling user communities, a new initiative – the International Quality Controlled Ocean Database (IQuOD; www.iquod.org) – aims to create a "climate quality" reference database for historical ocean profiles, by coordinating worldwide expertise and resources into a single best practices community effort.

Due to the ocean's slow modes of propagation and the enormous capacity to store and transport heat and freshwater, high quality subsurface observations are essential to support a wide range of Earth system science and services for societal benefit. In particular, long-term high quality ocean temperature and salinity records are needed:

- To accurately assess contemporary changes in the context of past changes (e.g., mean trends, variability and extremes);
- To improve our understanding of ocean variability, water cycle, sea level and climate change processes;
- To increase confidence in the attribution of natural and anthropogenic drivers;
- To facilitate the development of more accurate observational constraints on future climate and sea level change;
- To promote advancements in the evaluation and development of ocean, climate and Earth system models;
- To provide the best possible initial conditions and hindcast skill assessment for seasonal-to-decadal prediction systems;
- To enable refinements to data assimilation schemes (through comprehensive uncertainty estimates) for operational ocean and coupled reanalyses.

Understanding climate change is the most demanding application of our historical ocean profile observations, requiring long-term records with the best data quality, the most complete metadata and comprehensive uncertainty estimates. However, a large fraction of the ocean profiles were not collected with these stringent requirements in mind. Rather, the historical data were often collected as part of

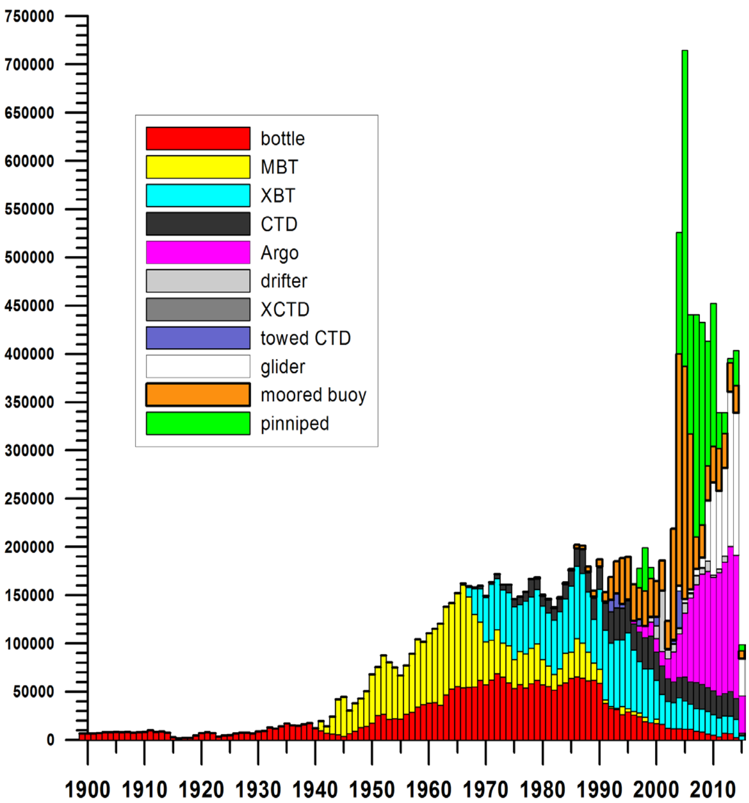
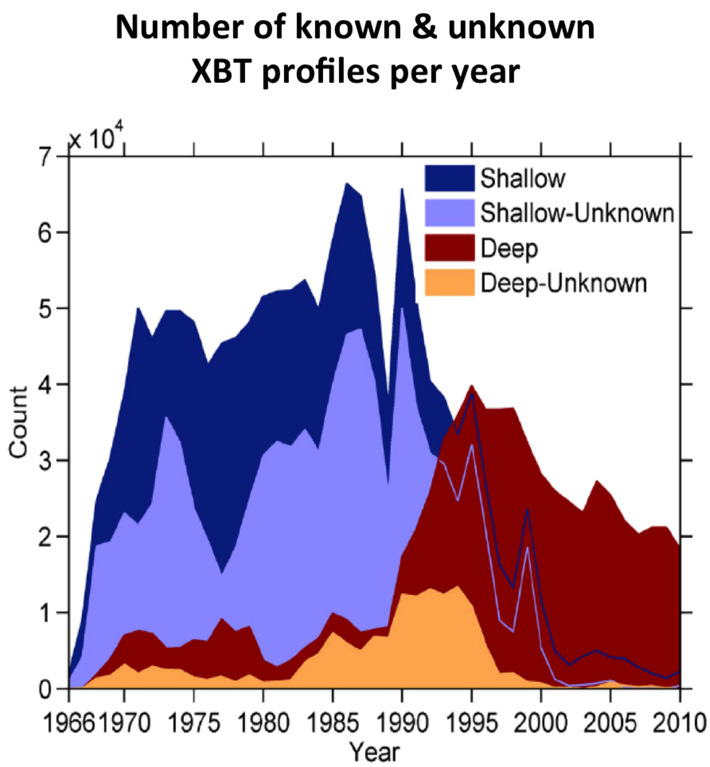


Figure 1: Number of oceanographic casts by instrument for each year 1900-2015 (first quarter) in the World Ocean Database.A cast is a one or more co-located depth/variable profiles.

independent projects with different goals, and by an evolving mix of instrument technologies (Figure 1), with various precisions and biases (Abraham et al., 2013).

Historical profiles were also, in several instances, only made public with reduced vertical resolution and incomplete metadata, partly due to limitations in computational and storage resources at the time.

In 1994, the US National Oceanographic Data Center (NODC) released the first and most comprehensive global ocean profile database - the World Ocean Database (WOD) - a project that was established by the International Oceanography Commission, under the leadership of Sydney Levitus. NODC has continued to provide the World Ocean Atlas gridded climatology products alongside the WOD and these data products have been very widely used in a range of ocean and climate studies. The legacy of the WOD and WOA products is highlighted by more than 6,000 citations in the scientific literature, to date. The Global Oceanography Data Archaeology and Rescue (GODAR) program has been fundamental to the discovery, digitization and inclusion of 9 million temperature stations in the WOD. GODAR has also been essential to the rescue of ocean profile data in electronic format at the risk of media degradation and permanent loss (www.nodc.noaa.gov/General/NODC-dataexch/NODC-godar.html).



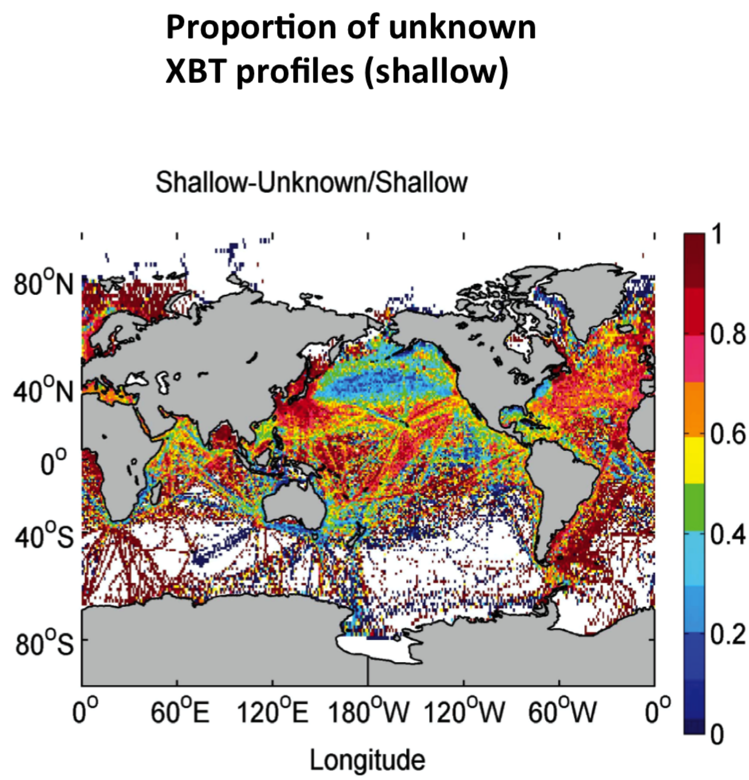


Figure 2: (left) Number of XBT profiles recorded each month separated by sampling depth. (right) Number of "shallow" XBT profiles of unknown type divided by the number of profiles that include probe type in available metadata. Figure reproduced from Abraham et al. (2013).

Currently, our irreplaceable collection of tens of millions of historical ocean temperature (and salinity) profiles - collected at a cost of billions of dollars and dating back as far as 1772 (Figure 1) - still contains a substantial fraction of biased, duplicated and substandard quality observations that can confound ocean and climate change science (e.g., Gronell and Wijffels, 2008), despite a number of quality control efforts by independent research groups. Proper identification of instrumental biases, causes, and development of correction schemes (Abraham et al., 2013) also depend on the quality and completeness of the historical profile data and metadata.

Historical observations from expendable bathythermographs (XBTs) comprise the largest fraction of ocean temperature profiles in the WOD over the period 1967-2004 (Figure 1). Numerous correction schemes (Cheng et al., 2015) have been proposed after Gouretski and Koltermann (2007) revealed time-dependent biases in XBT profiles. XBT bias corrections represent a leading order uncertainty in estimates of global upper-ocean heat content (and sea level) change over multidecadal timescales (e.g. Lyman et al., 2010; Abraham et al., 2013). About 50% of these XBT profiles have incomplete metadata (e.g., probe type, manufacturer, logging system, etc), especially for the shallow XBT probes that sample the upper few hundred meters (Figure 2).

The addition of full vertical resolution data and more complete metadata for XBTs and other instrument profiles would greatly help to reduce uncertainties in bias corrections and promote a more homogeneous long-term ocean record critical for climate change research, data assimilation and modeling efforts.

IQuOD is the first globally coordinated effort with the goal of producing the most complete, consistent and high quality global database for historical ocean profiles - with comprehensive uncertainty and metadata information - to promote advances in a range of ocean, climate and Earth system research and services. To achieve this goal, IQuOD is bringing together the widest possible pool of international expertise and resources into a single best practices community effort. This global community effort will establish and implement an internationally agreed framework. Coordination of a range of expertise and resources is essential to complete IQuOD's goal in an effective and timely manner. Currently, the IQuOD community is represented by experts and users from 17 nations: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Japan, Mexico, Norway, Russia, Senegal, Spain, South Africa, UK, and USA.The oceanography community (including ex- and current CLIVAR GSOP and US CLIVAR members) is leading the IQuOD effort, along with experts in data quality and management (e.g., from IOC/IODE), and in close consultation with end users (e.g., observational, modeling and broader-related climate communities). Although the initial focus in on producing a "climate quality" global database for historical ocean temperature profiles, later IQuOD plans to expands its effort to include salinity, oxygen, nutrients and other tracers.

The global IQuOD database will be maintained at the National Centers for Environmental Information (former NODC) alongside the World Ocean Database. There is also a large demand for added-value products, such as gridded datasets with comprehensive uncertainty estimates, in addition to the profile database.All data, documentation and processing algorithms will be placed in the public domain to ensure maximum utility for the wider research community, including climate modelers, through collaboration with PCMDI. The IQuOD database will draw on and preserve knowledge and skills from a range of experts, such as in ocean instrumentation, quality control metthods, data homogenization techniques, and regional oceanography. Knowledge transfer will be facilitated through international workshops but we expect to achieve longevity through fostering a new community of ocean scientists, particularly from developing nations. Guidance on best practices and open-access documentation (including software tools) will ensure that the progress made by the IQuOD community also leaves a long lasting legacy.

Over the next 3-5 years, the main objectives for IQuOD are to deliver:

- Development and application of algorithms for inclusion of "intelligent" metadata;
- Development, implementation and dissemination of best practice (automated and expert) quality control procedures;
- Development and inclusion of uncertainty estimates;
- Global IQuOD database assembly and open distribution;
- Production of downstream added-value (gridded) products.

In addition to capacity building in developing and developed nations, expected outcomes from the IQuOD effort will support a number of major international community activities. These include:

- CLIVAR Research Foci and Ocean Climate Indicators
- US CLIVAR science plan
- IODE related projects
- GODAE ocean view
- SOOS
- IPCC assessments (WCRP CMIP)
- WCRP Grand Challenges

The IQuOD is a vibrant and growing community of oceanographers, data analysts and climate researchers, working very much with an "open door" policy for those who are interested in getting involved in any aspect of the project. For further information and updates, please see the IQuOD website: http://www.iquod.org/.

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Estimating the Circulation and Climate of the Ocean (ECCO): Advancing CLIVAR Science

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Origins and Motivation

The Consortium for "Estimating the Circulation and Climate of the Ocean" (ECCO) has its origin in the early 1990s, following the World Ocean Circulation Experiment (WOCE) and the advent of satellite altimetry (TOPEX/Poseidon). While these programs provided data of unprecedented scope and volume, making the most of these observations posed a challenge due to their irregular and incomplete sampling with respect to the ocean's inherent scales of variability. ECCO was formed against this backdrop with the goal of synthesizing such diverse observations into complete and coherent descriptions of the ocean that can readily be used to study the ocean and its role in climate (Stammer et al. 2002).

ECCO's synthesis evolved as a natural progression from classical steady-state geostrophic inverse calculations (e.g., Ganachaud and Wunsch 2000). In comparison to geostrophic inversions, and as envisioned by Munk and Wunsch (1982), the ECCO synthesis employs practically all extant observations to estimate the time-varying state of the ocean, in addition to its time-mean, using the complete physics embodied in ocean general circulation models. Mathematically, the synthesis problem belongs to that of optimal estimation and control.

Since its inception, a series of estimation methods and infrastructure have been advanced and a succession of corresponding estimates has been derived that integrate new observing systems (e.g., Argo, GRACE). The latest such estimate is the global bidecadal (1992-2011) solution referred to as ECCO Version 4 (hereafter "ECCO v4") developed in part to support CLIVAR science (Forget et al. 2015a). Here, we briefly recall some of the salient features of the ECCO approach (Section 2) followed by an overview of the ECCO v4 solution (Section 3). Applications of ECCO products for ocean and climate studies are illustrated in Section 4. We conclude with an outlook to future requirements and developments in Section 5.

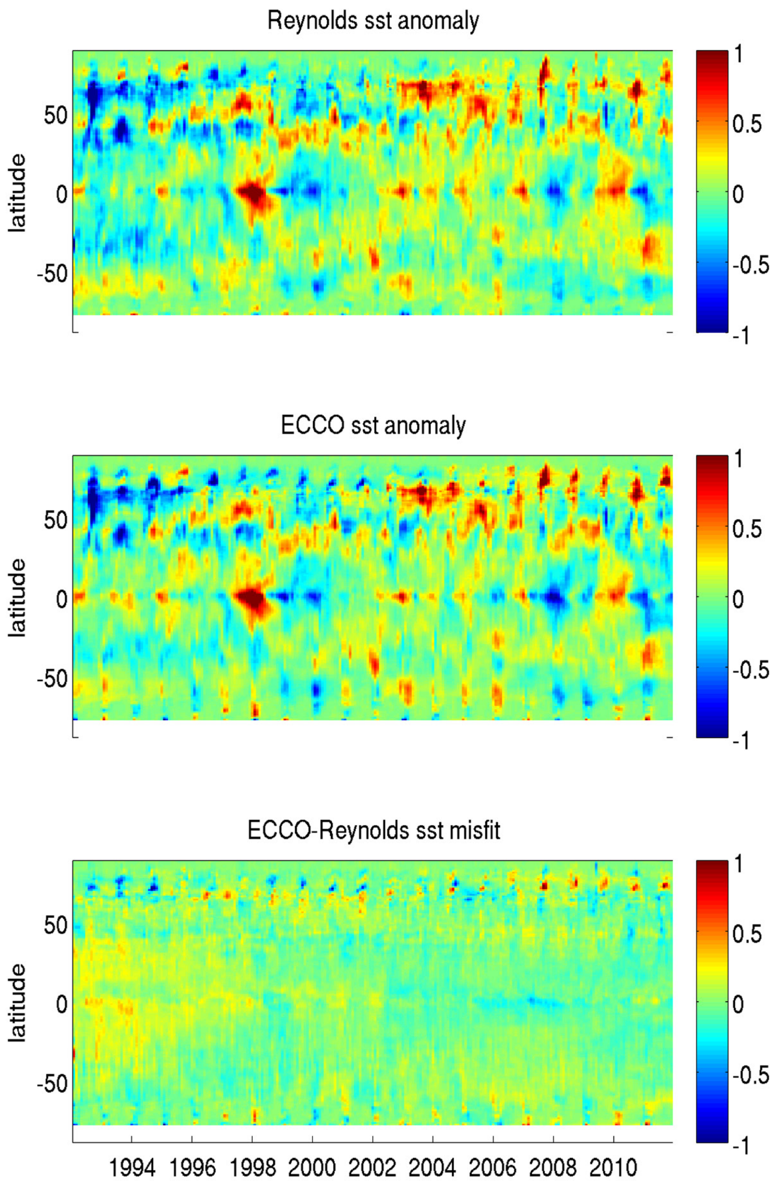

Figure 1: Monthly anomalies in zonal mean Reynolds (top) and ECCO v4 (middle) sea surface temperature, computed by subtracting the respective mean monthly seasonal cycle. Bottom: residual difference between the two products. This plot is one of currently 148 diagnostics depicted in the gcmfaces standard analysis (Forget et al. 2015a, supplementary material) that documents the ECCO v4 state estimate.

ECCO approach and infrastructure

ECCO's approach to model-data synthesis differs from that of many other syntheses owing to the Consortium's particular goal in understanding ocean circulation. Most syntheses are rooted in methods originally developed for numerical weather forecasting, a.k.a. data assimilation, in which models are initialized with coincident data so as to optimize the skill of the model's subsequent forecast. Owing to such periodic "data updates", the temporal evolution from one instant to another is not explicitly accounted for by physical processes (e.g., Bromwich et al. 2011). In contrast, ECCO uses the data to correct inaccuracies in the model physics per se (e.g., errors in surface forcing and mixing parameters). As a result, the temporal evolution of ECCO's estimates is described entirely by these processes, allowing unambiguous analyses of mechanisms underlying the ocean state (Wunsch et al., 2009).

A central element of ECCO's infrastructure is its models' adjoint. Adjoints provide computationally efficient means to evaluate gradients of a model quantity with respect to all other variables across space and time. The adjoint method of estimation employed in most ECCO products, including ECCO v4, utilizes such gradients to minimize model-data differences using an iterative optimization algorithm. As a measure of model sensitivity, the adjoint gradients also provide insight into the ocean's controlling mechanism and processes and are effective tools for studying the ocean by themselves.

Examples in Section 4 illustrate the merits of such approach and infrastructure. The utility of the adjoint in both estimation and process studies also highlight the significance of automatic (algorithmic) differentiation (AD) tools that are critical in deriving the model adjoint. The examples likewise demonstrate the efficacy of the Massachusetts Institute of Technology general circulation model (MITgcm; Marshall et al, 1997), a state-of-the-art general circulation model employed by ECCO, for which adjoint versions can readily be derived.

ECCO Version 4

The ECCO v4 model setup and state estimate are presented in detail in Forget et al (2015a). Unlike the previous versions of ECCO, the model setup is subjected to daily regression tests to ensure that it remains compatible with the up-to-date numerical core. ECCO v4 started with an extensive revisit of model settings, the inclusion of air-sea real freshwater fluxes, and treatment of the Arctic. Variants of the ECCO v4 model setup are also used in un-optimized modeling studies (Danabasoglu et al., 2014; Marshall et al., 2015).

The bidecadal state estimate and its variability over the 1992-2011 period are documented by a number of topical papers (examples in section 4), as well as by the "gcmfaces" standard analysis (Forget et al. 2015a, supplementary material), and through the Ocean ReAnalysis Intercomparison

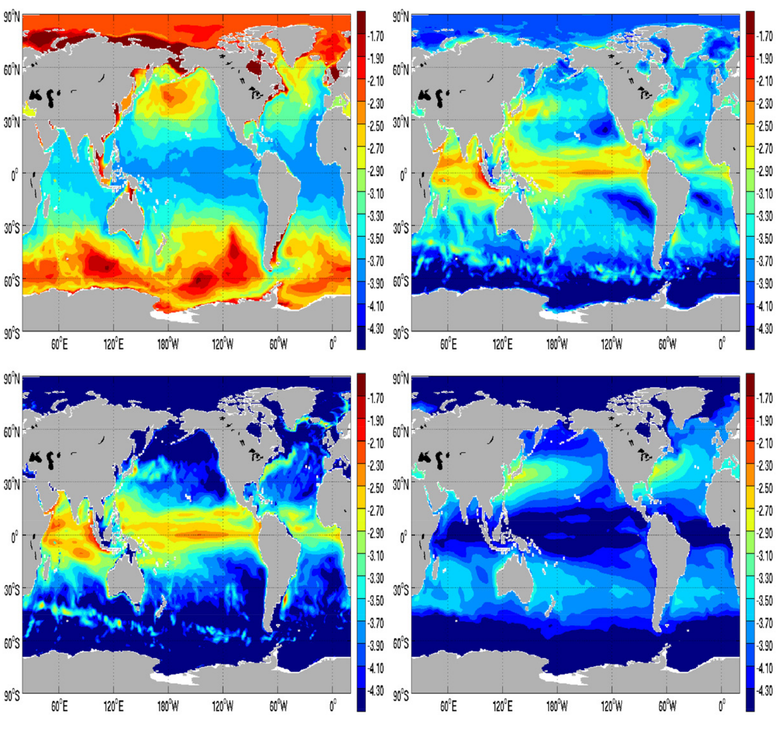

Figure 2: Budget of monthly sea level variability according to the ECCO v4 state estimate (Forget and Ponte, 2015). Panels show the log10 of the variance (units of m2) for (top left) bottom pressure, (top right) steric height, (bottom left) steric height due to heat advection, (bottom right) steric height due to surface heat fluxes.

Project (Balmaseda et al. 2015). A full suite of model-data comparisons (such as the one shown in Figure 1 for SST) and ocean state diagnostics are readily available as part of the standard analysis. The state estimate output further includes a complete set of fields required to perform accurate offline budget calculations, in accordance with recommendations by

the CLIVAR Working Group on Ocean Model Development (OMDP).Because it is a pure and maintained forward model solution, the ECCO v4 state estimate is relatively easy to reproduce by any interested user (as compared with, for instance, atmospheric reanalyses).

Arguably the most important improvement in the ECCO v4 solution, as compared with earlier versions, lies in its better agreement with Argo and other in-situ data. While earlier ECCO versions only adjusted initial conditions and time-varying surface boundary conditions, ECCO v4 also adjusts time-mean, three-dimensional fields of diapycnal diffusivity, isopycnal diffusivity and parameterized eddy-induced advection. The adjustment of these uncertain parameters targets model error in the ocean interior and was instrumental in reducing misfits to the observed hydrography. The estimated parameter adjustments generally are physically plausible, guided by Argo observations of ocean stratification, and yield a marked reduction in artificial model drift (Forget et al. 2015b).

The difficulty of obtaining accurate estimates of small-scale high-frequency oceanic variability directly from the available sparse spatio-temporal data sampling has motivated attempts at deriving empirical frequency-wavenumber spectra based upon the ECCO solutions (Wortham and Wunsch, 2014). Such spectra are powerful tools for estimating background noise of mesoscale and macro-turbulence against which trend detection is performed, and in the context of quantitative observing system design (Wunsch, 2010). In the context of estimating the large-scale oceanic state they serve to quantify representation error statistics of variations that the model cannot resolve. Previously, Forget and Wunsch (2007) presented a first map of subsurface hydrographic variance based upon Argo in-situ profiles. It revealed the geography, magnitude, and vertical structure of mesoscale variability, complementing inferences made from satellite sea surface height measurements and is a crucial ingredient in the ECCO estimation problem. ECCO v4 targets large-scale misfits in order to better separate large-scale climate variability from macro-turbulence (Forget and Ponte 2015).

Applications of ECCO Products and Infrastructure

The products and infrastructure of ECCO offer powerful diagnostic tools and new physical insights in studies of the ocean's variability and its role in climate. ECCO has permeated many CLIVAR activities, contributing to a number of CLIVAR's central Research Foci (http://www.clivar.org/about/research-foci). In the following we present examples of such application in studies of ocean circulation, climate, and marine biogeophysical interactions. The synthesis and analysis of global and regional sea level and mass variability is a particular focus of current climate research. Forget and Ponte (2015) take advantage of the full ocean state provided by ECCO v4 to assess the main modes and local/remote forcing mechanisms of regional sea level variability over the global ocean. Precise budgets of hydrostatic pressure variability (steric and mass contributions shown in Figure 2) and other diagnostic tools are used to gain insights into observed altimetric and gravimetric variability (Piecuch and Ponte, 2011), the dynamical effects of buoyancy forcing in the tropical oceans (Piecuch and Ponte, 2013), and the combined effects of stratification and

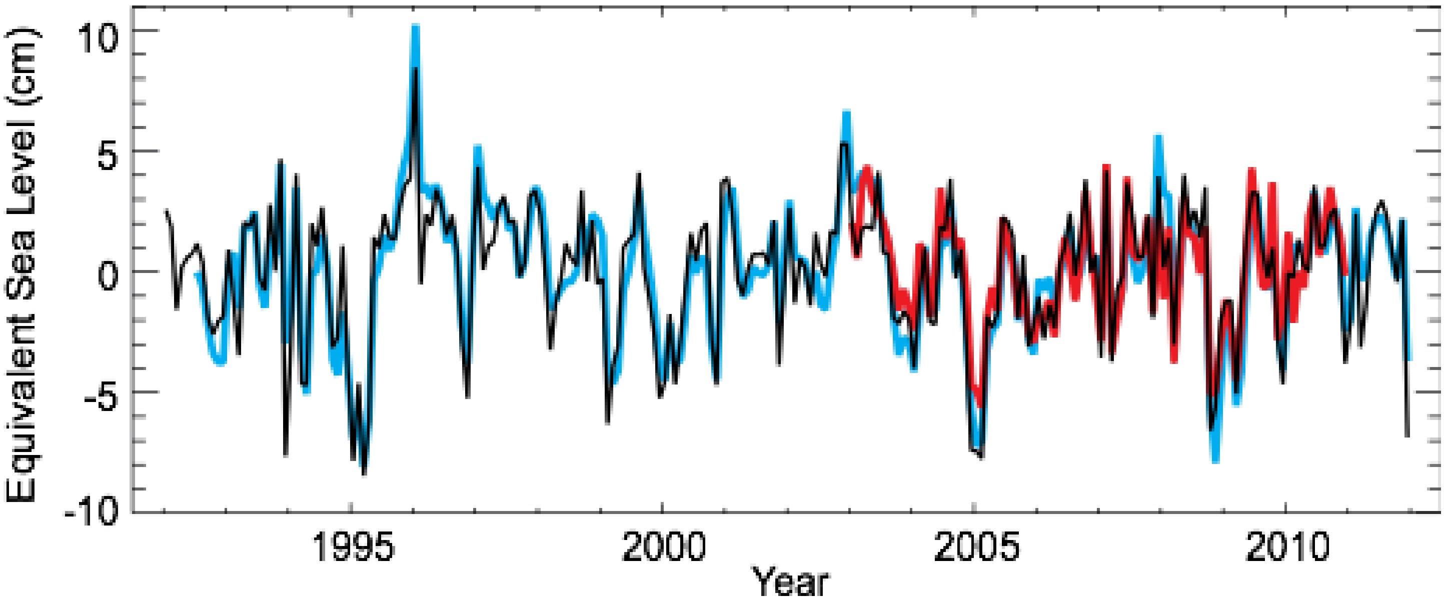

Figure 3: Time-series of mean ocean bottom pressure across the Arctic Ocean from ECCO v4 (black), GRACE (red), and a reconstruction based on a convolution of winds with corresponding adjoint gradients (blue). Similarity among the three illustrates the skill of the model and the efficacy of the model adjoint expansion. The dominant terms in the expansion are found to be associated with coastally trapped waves (Fukumori et al., 2015).

topography in vorticity dynamics of the Southern Ocean (Ponte and Piecuch, 2014).

Studies of air-sea interactions, heat storage in the mixed layer, mode water formation and related topics are facilitated by the consistency between air-sea fluxes and internal ocean processes provided by ECCO estimates. In the North Atlantic Forget et al. (2011) show that combining Argo profiles and atmospheric re-analysis data within ocean state estimation leads to improved estimates of seasonal heat storage and water mass transformation. Maze et al. (2009) further reveal the geography of water mass transformation driven by air-sea heat flux. Buckley et al. (2014) highlight the interplay of surface heat flux, diffusion, and advection by Ekman and geostrophic flows in controlling low-frequency SST and upper-ocean heat content variability in the North Atlantic. Halkides et al. (2015) examine all processes controlling intraseasonal mixed-layer variability in the tropical Indian Ocean, including the relevance of barrier layers. Vinogradova and Ponte (2013) find that the large impact of ocean advection and diffusion make it difficult to infer surface freshwater fluxes from only knowledge of mixed layer salinity. The inclusion of ocean-sea ice coupled dynamics in ECCO estimates is exploited by Fenty and Heimbach (2013), Nguyen et al. (2012), and Roquet et al. (2013) to investigate the interaction between upper ocean water masses, the atmosphere and sea ice, respectively, in the North Atlantic, Arctic Ocean, and Southern Ocean.

On a global scale, ocean heat uptake and its three-dimensional redistribution within the ocean interior is a subject of active research. Using the complete three-dimensional coverage afforded by ECCO estimates, Wunsch and Heimbach (2014) infer a 10% contribution of the abyssal ocean to global heat content changes over the period 1992-2011, but call attention to the significant background variability and the need for improved observational sampling. A more detailed investigation of the vertical redistribution of heat over that period reveals a net upward heat transport in the deep ocean, implying net abyssal cooling over the past two decades and the need to account for long-memory effects in oceanic property redistribution (Liang et al., 2015). Decadal variability and predictability in the Atlantic Meridional Overturning Circulation (AMOC) has been investigated by Wunsch and Heimbach (2013) in the wider context of North Atlantic circulation dynamics and variability (Buckley et al. 2014).

In addition to its state, ECCO's model adjoint itself is utilized in a number of studies to investigate oceanic processes and causal mechanisms. For instance, detailed analysis of dynamical pathways afforded by the adjoint provides insight in observing system design (Mazloff, 2012). Zanna et al. (2012) employed the adjoint and tangent-linear model to investigate non-normal transient amplification of the AMOC, and drew inferences on decadal climate predictability. Adjoints can also be employed to analyze the origin and pathway of water masses, taking full account of the effects of advection and mixing, including convective processes (Gao et al., 2011). Notably, adjoints can be used to expand modeled quantities in terms of their forcing and deduce causal mechanisms. Fukumori et al. (2015) utilized such expansion to identify remotely forced waves causing a basin-wide fluctuation of the Arctic Ocean (Figure 3). Ocean tracer transport studies are another important application of ECCO products that are, for example, particularly well suited to drive models of ocean biogeochemistry and ecology (see Follows and Dutkiewicz, 2011 for a review). Reducing errors in the physical ocean state and circulation indeed benefits tracer simulations as highlighted by Forget et al. (2015b) for biogeochemistry. In the Ocean Carbon-cycle Model Intercomparison Project (OCMIP), ECCO solutions reproduce observed CFC-11 distributions with high skill as compared to unconstrained ocean circulation models (Fletcher et al., 2006). As an example of the insights gained by this approach, the result of driving an ecosystem model with a global eddy-permitting ECCO circulation estimate is shown in Figure 4, which reveals complex relationships among marine microbial communities that play a key role in the global carbon cycle and are especially diverse in regions of energetic currents. As another example Gierach et al. (2012) used forward and adjoint passive tracer simulations with an ECCO estimate to study biophysical interactions in the tropical Pacific Ocean and revealed the relative impacts of horizontal advection and vertical processes (upwelling and vertical mixing) on interannual changes of chlorophyll concentration associated with different types of El Niño events.

Future Development

In response to a growing demand on the fidelity and scope of ocean state estimation, further ECCO advancements are climate

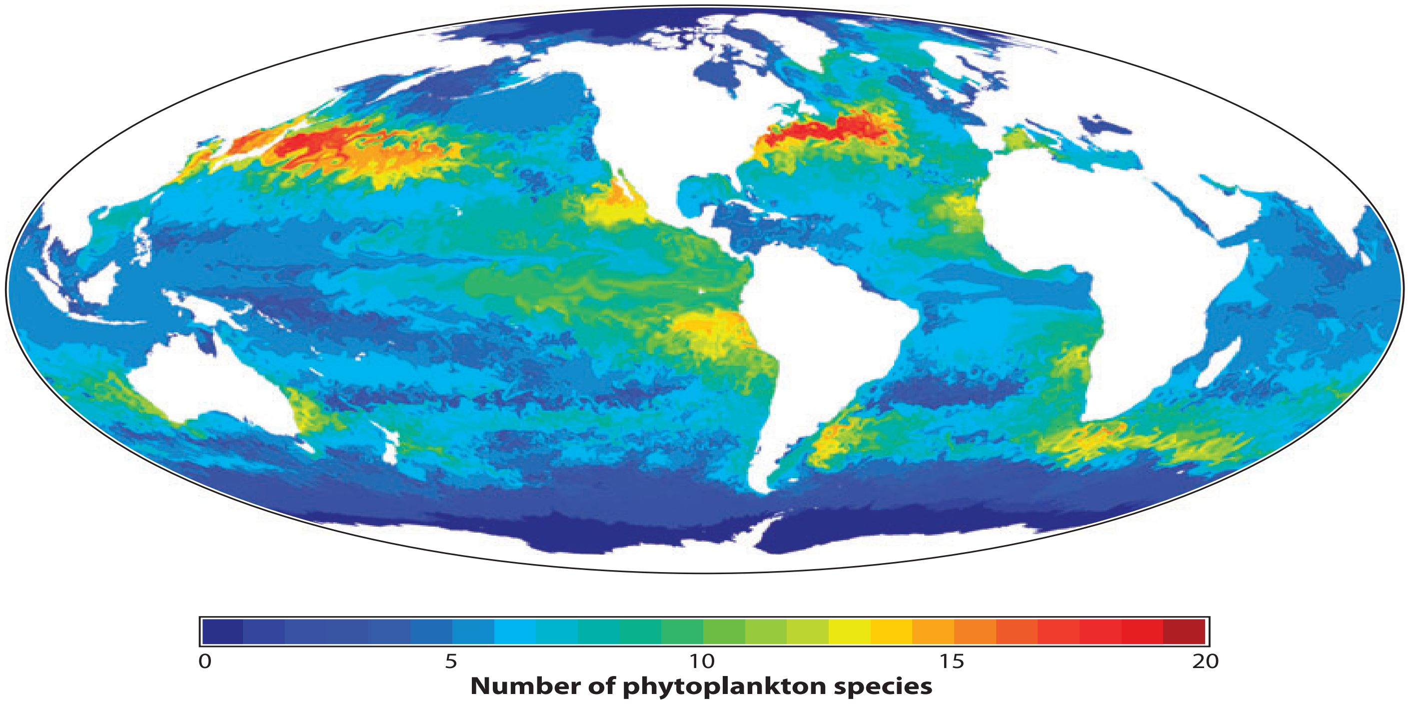

Figure 4: Simulated diversity of phytoplankton in terms of numbers of species with biomass above a certain threshold value (Follows and Dutkiewicz 2011). The ecosystem model was driven by physical circulation fields from an ECCO solution. Figure credit: Oliver Jahn, MIT.

variability and to foster a broader utilization of its estimates and modeling system (Forget et al. 2015a). Of particular scientific interest is the understanding and prediction of global sea level rise, which embodies numerous intersecting topics in Earth system science. ECCO's comprehensive synthesis of observations, mathematical and statistical rigor, and physical consistency provide a unique framework to address this scientific and societally relevant problem. Simultaneously, the advancements aim to improve the usability of ECCO's estimation system as a facility for ocean state analysis in support of the broader climate change science community.

One of such advancement concerns the estimate's representation of the cryosphere. In particular we have added capability for coupled ocean and sea-ice estimation (Heimbach et al., 2010), a key element for improving ocean-sea ice interactions and the ocean's radiation budget. Improving the coupled ocean-sea ice state in the Arctic may help, in turn, improve near-surface properties of atmospheric reanalysis products in this region where direct observations are limited. We have also added the capability for coupled-ocean and thermodynamic ice sheet estimation (Heimbach and Losch, 2012). The ice sheets' mass loss is a significant element underlying the ongoing global mean sea level rise and is expected to become its dominant component in the coming decades. Growing evidence in Greenland (Straneo et al., 2013) and Antarctica (Schodlok et al., 2012) suggests that ocean warming is a controlling factor in accelerating this mass loss.

The ECCO estimates are being periodically extended in time to the present to support investigations of processes underlying recent ocean climate variability. New observational data streams are being incorporated as they become available, a recent example being sea surface salinity observations from the Aquarius satellite mission (Vinogradova et al., 2014). A comprehensive suite of model diagnostics is available with the estimates, such as quality-controlled observations employed in the calculation, the estimation's control adjustments (e.g., corrected model forcings), and various components of the fluxes necessary for budget analyses and process studies. The underlying model and its adjoint are also available for further studies by the community. The increased use of ECCO products calls for future workshops to support these interests, to entrain a wider user community in their applications, and to foster user involvement in shaping future product development. We invite participation and contribution to these endeavors and encourage further exploration and utilization of the ECCO estimates and tools.

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Using models to design and evaluate Ocean Observing Systems

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Introduction

The use of ocean models and data assimilation tools to contribute to the design and assessment of the Global Ocean Observing System (GOOS) has a long history. GODAE OceanView (www.godae-oceanview.org; GOV Science Team, 2014), the successor to the Global Ocean Data Assimilation Experiment (GODAE; www.godae.org) together with the CLIVAR Global Ocean Synthesis Panel (CLIVAR-GSOP; www.clivar-gsop.org), have committed substantial resources to assessing the GOOS for its suitability to constrain and initialize ocean forecasts on time-scales of days to months. This has included a series of international workshops (see www.godae-oceanview.org/outreach/meetings-workshops/), providing a forum for members of the GOV Observing System Evaluation Task Team (OSEval-TT), members of the CLIVAR GSOP, and the broader community to work together on OSEval-related research. By organizing their efforts in this way, the GOV OSEval-TT together with the CLIVAR GSOP, are committed to providing evidence-based recommendations to decision-makers on issues relating to the maintenance and enhancement of the GOOS. To this end, this community has undertaken many projects that address different aspects of observing system design. These studies use various models and data assimilation tools and have resulted in a series of community papers that describe OSEval-related studies and recommendations (e.g., Balmaseda et al. 2015, Oke et al. 2015a,b).

OSEval studies exploit methods that range from simple, practical approaches that utilize readily available information to understand length-scales, time-scales, variability, and co-variability - to sophisticated approaches that exploit advanced metrics and diagnostics derived from data assimilation tools. It is increasingly recognized that conclusions drawn from OSEval studies depend, to some extent, on the details of the underpinning model and data assimilation system. This recognition has led to the adoption of more rigorous experimental designs (e.g., Halliwell et al. 2015) and an increasing number of multi-system studies (e.g., Fujii et al. 2015a).

Recently performed OSEval studies have demonstrated the importance of data from the Tropical Ocean Atmosphere(TAO) mooring array and the Argo float array for seasonal predictionsystems (Fujii et al. 2015a,b), the importance of satellite altimetry, eXpendable BathyThermograph (XBT) data, and satellite sea surface temperature on short-range ocean forecasts (e.g., Lea et al. 2012, 2013). In addition to these assessments of the conventional elements of the GOOS, there is also an increasing number of studies that evaluate complimentary and less conventional data types, such as HF radar, ocean gliders and instrumented marine mammals (see examples in Oke et al. 2015b).

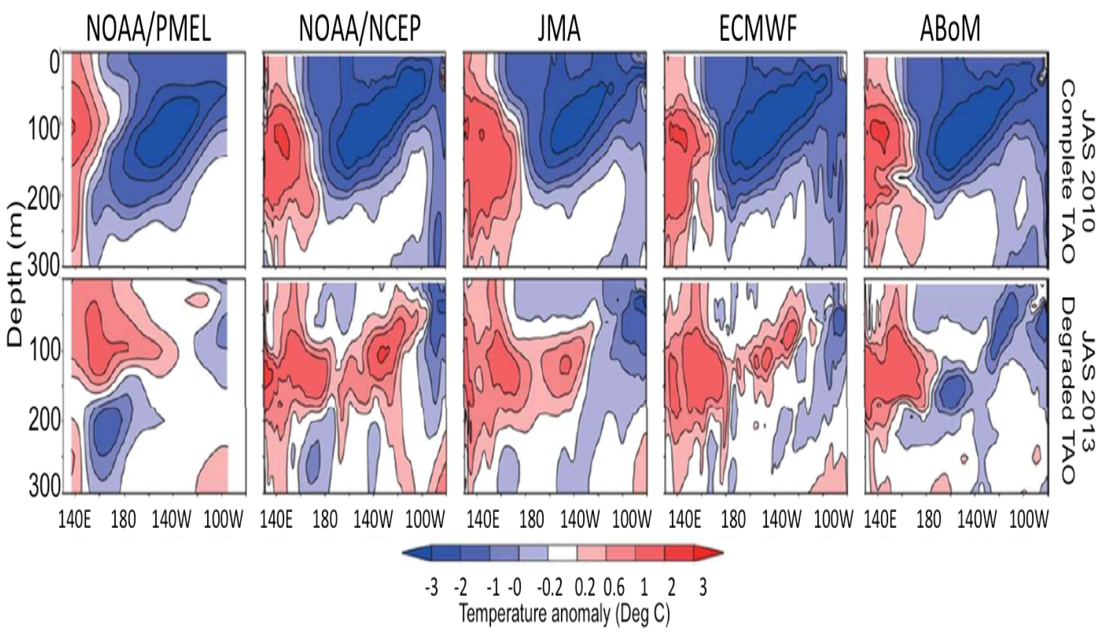

Figure 1: Analysis of temperature anomaly distribution averaged in July-September 2010 (top row) and 2013 (bottom row) in the equatorial from the TAO/TRITON data produced by PMEL and the operational DA results of NCEP, JMA, ECMWF, ABoM (left-to-right). Figure adapted from Fujii et al. (2015)

This paper provides an overview of the current and future developments in ocean observing system evaluation, and the impact of this work on advancing CLIVAR science. This paper presents a summary of current activities in this area of research, followed by an overview of future activities under GOV and CLIVAR GSOP.

Current Activities

Commonly used approaches to OSEval studies include analyses of time- and length-scales, performance of Observing System Experiments (OSEs), Observing System Simulation Experiments (OSSEs), and analyses of metrics derived from data assimilation systems. These methodologies are described below, with reference to recently performed studies.

Historically, the most basic approach to observing system assessment is the computation of length-scales and signal-to-noise ratios (e.g., Schiller et al. 2004), using both models and observations (e.g., Oke and Sakov, 2009). More recently, model intercomparisons have been analyzed to assess observing systems - drawing on readily available data to demonstrate the adequacy (or otherwise) of an observing system to constrain different models. For example, Figure 1 shows a comparison of temperature anomaly along the equatorial Pacific Ocean from five different seasonal prediction systems at two different times. The first example (Figure 1, top row) shows results when the TAO array was delivering data from about 50 buoys, with 80% data-return. During this period, gridded analyses based on TAO data alone, using different objective analysis and data assimilation systems, show good agreement. This demonstrates that the tropical mooring array at that time was suitable for monitoring the properties of the equatorial ocean.

By contrast, the second example (Figure 1, bottom row) shows analyses when the TAO array was delivering data from only about 35 buoys, with 40% data-return. During this period, the analyses show considerable disagreement, indicating that the tropical mooring array at that time was inadequate for initializing and constraining seasonal prediction systems. These intercomparisons were incredibly timely - coming at a time when it was being suggested that the TAO array was unnecessary in light of the proliferation of the Argo array. Fujii et al.'s (2015) study provided a clear demonstration of the value of the TAO data, strongly supporting the case for its ongoing maintenance.

The most common method for evaluating contemporary, or historical, observation types is still OSEs. OSEs involve a series of data-assimilating experiments that systematically withhold different sub-sets of observations to quantify their impact. It is typical to perform an experiment that assimilates all observations, and no observations, representing the best and worst case respectively for forecast of reanalysis system. OSEs provide a faithful assessment of observation impact, but they are expensive to perform and analyze, and are only suitable for assessing the impact of available observations - not future, or planned missions.

An example of results from a series of OSEs to quantify the impact of Argo observations on the ECMWF's ocean reanalysis system (ORAS4; Balmaseda et al, 2013) is presented in Figure 2 that shows the root-mean-squared difference between upper ocean temperature in OSE that assimilates no data and all data; and between OSEs that assimilate all data except Argo, and all data. The OSEs presented here span the period 2001-2009. The results indicate that the neglect of all observations (panel

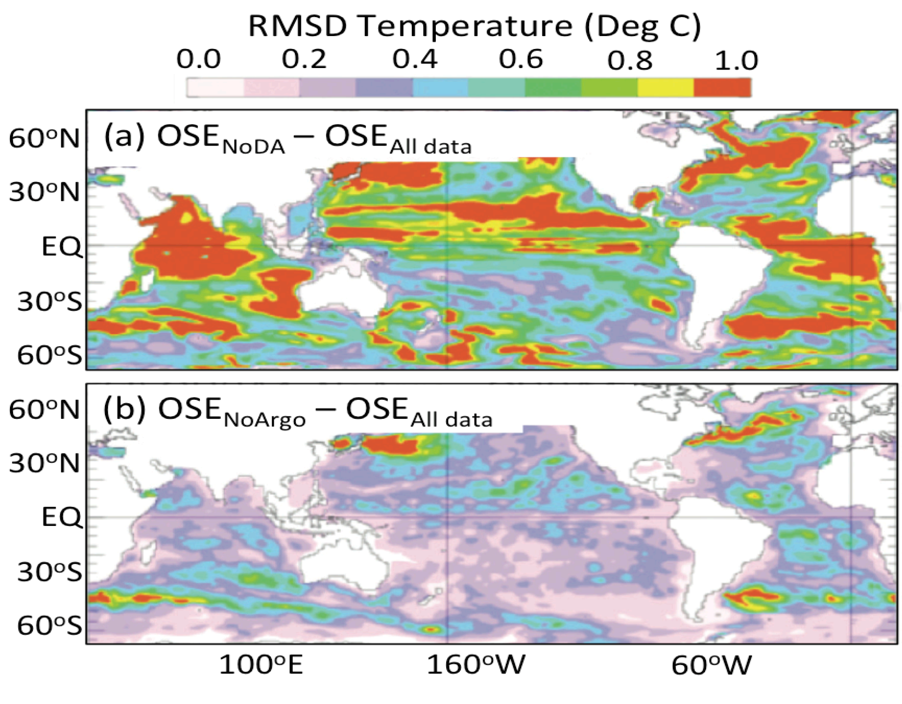

Figure 2: Maps of the root-mean-squared difference of temperature, averaged over the top 100 m depth, between OSEs that assimilate (a) no observations (OSENoDA) and all observations (OSEAll data; assimilating altimetry, Argo, mooring, and satellite SST observations); and (b) all observations, except Argo data (OSENoArgo), and OSEAll data. Figure adapted from Oke et al. (2015a)

a) impacts the upper ocean temperature by over 1^{oC} over much of the ocean, and that the neglect of Argo observations (panel b) impacts the upper ocean temperature by 0.5-1$^{oC.}$ The study described by Balmaseda et al. (2013) provides a good demonstration of the value of data from Argo floats to intermediate-resolution ocean reanalyzes that use ocean models that underpin seasonal forecasts.

The ocean reanalysis intercomparison project (ORA-IP, Balmaseda et al., 2015) represents a coordinated effort between the CLIVAR GSOP and GODAE OceanView communities to carry out a comprehensive comparison of more than 20 ocean state estimates. Comparison of ocean reanalyses provides useful insights into the ability of the historical ocean observations, in combination with sate-of-the-art data assimilation systems, to constrain various aspects of ocean variability and climate change. Using an ensemble approach often results in a combined state estimate that is more skillful that any individual analysis. In addition, the ensemble spread provides a useful way to gauge the level of uncertainty, both geographically and for different time periods. Areas of largest spread among analyses are indicative of where more observations are required in order to promote better initial conditions for forecast systems.

The most commonly employed method for assessing future observation arrays is OSSEs. OSSEs typically use two models: one to be treated as the "truth" - and sampled in a manner that reflects the planned, or proposed observational array, generating "synthetic observations"; and a second used to assimilate these "synthetic observations". The results of the assimilating system are compared to the "truth" to assess the impact of the proposed observational array. OSSEs are an incredibly powerful tool for observing system design - providing a systematic method for quantitatively assessing different options for observing systems, at a minimal cost. However, the limitation of OSSEs is that the results are often overly optimistic. It is due to the fact that the models used as the "truth" and for the assimilation are typically too similar, with common numerics, methods, resolution, forcing fields etc., and therefore with similar biases and errors.

The developments of advanced data assimilation systems, such as 4dVar and the Ensemble Kalman Filter, have led to the analysis of data assimilation metrics, such as forecast sensitivities (Langland and Baker 2004; Cummings et al. 2014), Degrees of Freedom of Signal, and Spread Reduction Factor (Sakov et al. 2012). These tools are increasingly being used for adaptive sampling - to identify gaps in the GOOS; and for attribution of forecast skill - to identify which observations are the most important for improving skill of a particular forecast. The challenge for the application of these methods is their complexity. That is, they are not always easy to interpret. The data assimilation community continues to work on ways to effectively deliver this information to the broader community in a meaningful way. These efforts are further described below.

Future Plans

There are several planned activities under GOV and the CLIVAR GSOP that have the potential to advance CLIVAR science. These include plans to perform annual community OSEs using GOV systems, the developments of Observation Impact Statements (OISs), and the intercomparison of results from climate model output to assess the characteristics of the deep ocean circulation. These initiatives are summarized below.

Community OSEs are intended to be a series of OSEs performed using multiple forecast/analysis systems that include systems from groups all over the world. As outlined in the previous section, OSEs are incredibly powerful tools for assessing observation impacts. They do have, however, limitations. Results from a particular OSE using a single forecast or reanalysis system is only truly valid for the system that underpins it. Results depend upon the details of the model configuration, the data assimilation system, and the assumed error background and observation errors. Consequently, the OSE results may not be universally true. The idea of community OSEs, is to perform equivalent OSEs with multiple systems. Output from such a set of experiments can then be analyzed, with the most robust results identified. Community OSEs are therefore likely to provide more meaningful, more relevant, and more robust recommendations than a set of OSEs performed with a single system. The GOV OSEval-TT is coordinating a series of community OSEs every year - focusing on quantifying the impact of different observation types (e.g., Argo, satellite altimetry etc.) each year. It is anticipated that community OSEs will provide up-to-date demonstrations of observation impacts to policy- and decision-makers - providing evidence-based recommendations relating to the maintenance and enhancement of the GOOS.

OISs are a new initiative that is being developed by the GOV OSEval-TT. A demonstration of the feasibility and benefit of OISs was performed by Lea (2012) using FOAM (Blockley et al. 2012), a global 1/4^{o} resolution short-range ocean forecast system. OISs are intended to be short communiqués - produced by multiple organizations, based on different forecast systems - to quantify the impact of assimilated observations on ocean analyses and forecasts. OISs will include basic information, such as what observations are assimilated, and simple metrics that quantify observation impacts. One of the motivations of OISs is to routinely provide up-to-date information of the value of observations on operational systems. The motivation for OISs being produced by multiple organizations is to identify the most robust results. Additionally, OISs are intended to be performed routinely (perhaps quarterly, or monthly), providing up-to-date information of the impact of observations on operational ocean forecasts that are relevant for the current period of time. Moreover, it is envisaged that OISs can provide information that is relevant to operational decisions that relate to the maintenance of some element(s) of the GOOS (e.g., decisions to continue processing data from a satellite altimeter that might be becoming unreliable; or even decisions to deploy additional resources in regions of poor data coverage).

In addition to OSEs carried out using ocean forecast/assimilation systems there is a need to assess the ability of the historical and future observing systems for constraining key aspects of ocean climate change, such as the global energy and sea level budgets (Church et al. 2011). Despite significant progress in recent years, there is still considerable spread in historical estimates of ocean heat content change for the upper 700m (Abraham et al. 2013) with important implications for our ability to constrain the planetary energy imbalance and therefore the rate of global climate change (Loeb et al. 2012; Palmer and McNeall 2014; von Schuckmann et al. 2014). A planned initiative under CLIVAR will generate "synthetic profiles" from both climate model and high-resolution ocean models to assess the mapping procedures used to estimate global and regional historical ocean heat content and sea level change. The same approach will also be used to help inform the requirements for a deep ocean observing system. The climate model simulations provide an estimate of the emergent signal of ocean climate change and representation of the large-scale climate variability. High-resolution ocean models offer insights into the robustness of mapping methods to the presence of eddies and other mesocale "noise". As well as providing information on the strengths/weaknesses of different mapping approaches, this work will provide new estimates of uncertainties and help identify any systematic sampling biases (e.g., Cheng and Zhu 2014).

There are many issues that are currently being addressed by the OSEval community. These include questions relating to the design of:

- Deep Argo – a plan by the Argo community to deploy and maintain a subset of Argo floats that can profile to depths of up to 6000 m (e.g., www.argo.ucsd.edu/AcDeep_Argo_Workshop.html);
- BioArgo – a plan by the Argo community to include biogeochemical sensors on Argo floats;
- the ongoing maintenance of the TAO array - in response to the increasing density of Argo floats along the equator;
- the role of deep water gliders in the GOOS, particularly in regions where Argo floats "struggle" to occupy;
- the maintenance and importance of XBT data, in light of the proliferation of the Argo array;
- the impact of satellite sea surface salinity (SSS) observations - including studies to fully exploit SSS data that may have larger than expected errors; and
- the refinement of the satellite altimeter programs - to help determine the most optimal constellation to monitor the many dependent fields of research, ranging from sea-level change, to short-range ocean prediction and operational oceanography.

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Coriolis 2014-2020: an integrated in-situ ocean observation infrastructure for operational oceanography and ocean/climate research

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Introduction

The Coriolis (www.coriolis.eu.org) structure gathers efforts of seven French institutes (CNES, CNRS, IFREMER, IPEV, IRD, Météo-France, SHOM) to organize the in-situ component of the French operational oceanography infrastructure. The objective is to organize the data acquisition and real-time/delayed mode data processing of in-situ measurements required for operational oceanography and ocean/climate research. Coriolis is focused on a limited number of physical and biogeochemical parameters that are acquired systematically and in real time or slightly delayed mode. Coriolis follows a fully open data policy.

The collaboration framework for Coriolis was renewed in 2014 and now covers the time period of 2014 up to 2020. By signing this new agreement, the Directors of the seven French institutes have clearly stated their willingness to sustain and consolidate further the Coriolis in-situ infrastructure. The new framework agreement strengthens the links between research and operational oceanography. The scope is also extended to integrate the main French contributions to the global and regional in-situ observing systems: Argo, gliders, research vessels, ship of opportunities, drifting buoys, marine mammals, tidal networks and high frequency coastal observatories (see Figure 1). The new Coriolis 2014-2020 framework agreement provides a better integration of the French contributions to the Global Ocean Observing System (GOOS/JCOMM). It also confirms and extends the European mission of Coriolis, in particular, in the framework of the Euro-Argo ERIC, EuroGOOS, Emodnet and the Copernicus Marine Environment Monitoring Service.

The different networks contributing to Coriolis 2014-2020 are organized by one or several institutes or laboratories with a pooling of resources for at sea operation, data processing and data dissemination and R&D activities (transverse components) (see Figure 2). The at sea component facilitates the functioning of the entities for the at sea operation activities and ensures that data are transmitted in real time to Coriolis data centers. The data center component consists of distributed data centers operated by the different partner institutes and the Coriolis data portal providing a single access point to all data sets both in real time and in delayed mode. The R&D component relies on laboratories in charge of networks and dedicated personnel working on cross-cutting issues (e.g. consistency between networks). The objective is to improve real time/delayed mode quality control methods and prepare long term delayed mode quality control data sets and associated products (e.g. Cora).

The networks are often labelled as Service d'Observation (SO). French Argo is also labelled as a TGIR (very large research infrastructure) as it is associated with a long term commitment from French Ministry of Research to the Euro-Argo research infrastructure (Euro-Argo ERIC). French Argo coordinates all French activities contributing to the international Argo program and the Euro-Argo ERIC: preparation and deployment of floats, preparing the new phase of Argo with an extension to Deep Argo and Bio-Argo, improving QC methods, real-time and delayed processing of floats and operation of one of the two Argo global data centers. The Sea Surface Salinity (SSS) network coordinates all activities contributing to the international GOSUD program: monitoring and implementation of thermosalinographs (and measurement systems such as pCO2 / DIC) on the French SO SSS vessel network. The research vessels network organizes the acquisition of CTD data, thermosalinographs and current profiles from Ship-ADCP mounted under French research vessels and ensures that data are processed, validated and transmitted in real time and delayed mode to Coriolis data centers. The glider network is in charge of the operation of the French glider fleet including real time and delayed mode data processing. It also includes the links and contribution to international (e.g. EGO) and European activities and initiatives (GROOM, EuroGOOS). The marine mammal MEMO network (SO) organizes the acquisition, quality-control and distribution of oceanographic (T/S) and biological (oxygen, fluorescence) data from French Marine Mammals observatories. It also works with European and international partners to consolidate global data sets (MEOP). The surface drifter network is the French contribution to the Data Buoy Cooperation Panel (DBCP). It focuses its activities on the deployment of surface drifters in the North Atlantic and Indian Ocean and real time data transmission. It is also in charge of the preparation of a global near real time surface current data set derived from surface drifter trajectories. The PIRATA network (SO) is the French contribution to the PIRATA tropical mooring array. It contributes to the maintenance of the array and its evolution. The tidal network includes the operation of the French RONIM tidal network that aims at setting up and maintaining a modern tide gauge network in France and its overseas territories. The high frequency coastal network operates several coastal networks: coastal moorings, HF radars, vessel observations (FerryBoxes, Recopesca), coastal profilers and organizes the real time and delayed data processing.

Coriolis 2014-2020 also features a strengthened organization and governance. A Steering Committee (co-chaired by S. Pouliquen and R. Reverdin) with representatives of all networks and of the three transverse components (at sea operation, data center, R&D) is in charge of the scientific and technical management. It reports to a Governing Board (directors of institutes). A Scientific Council (shared with Mercator Ocean) provides the required scientific guidance, in particular, for issues related to the integration with modelling and data assimilation.

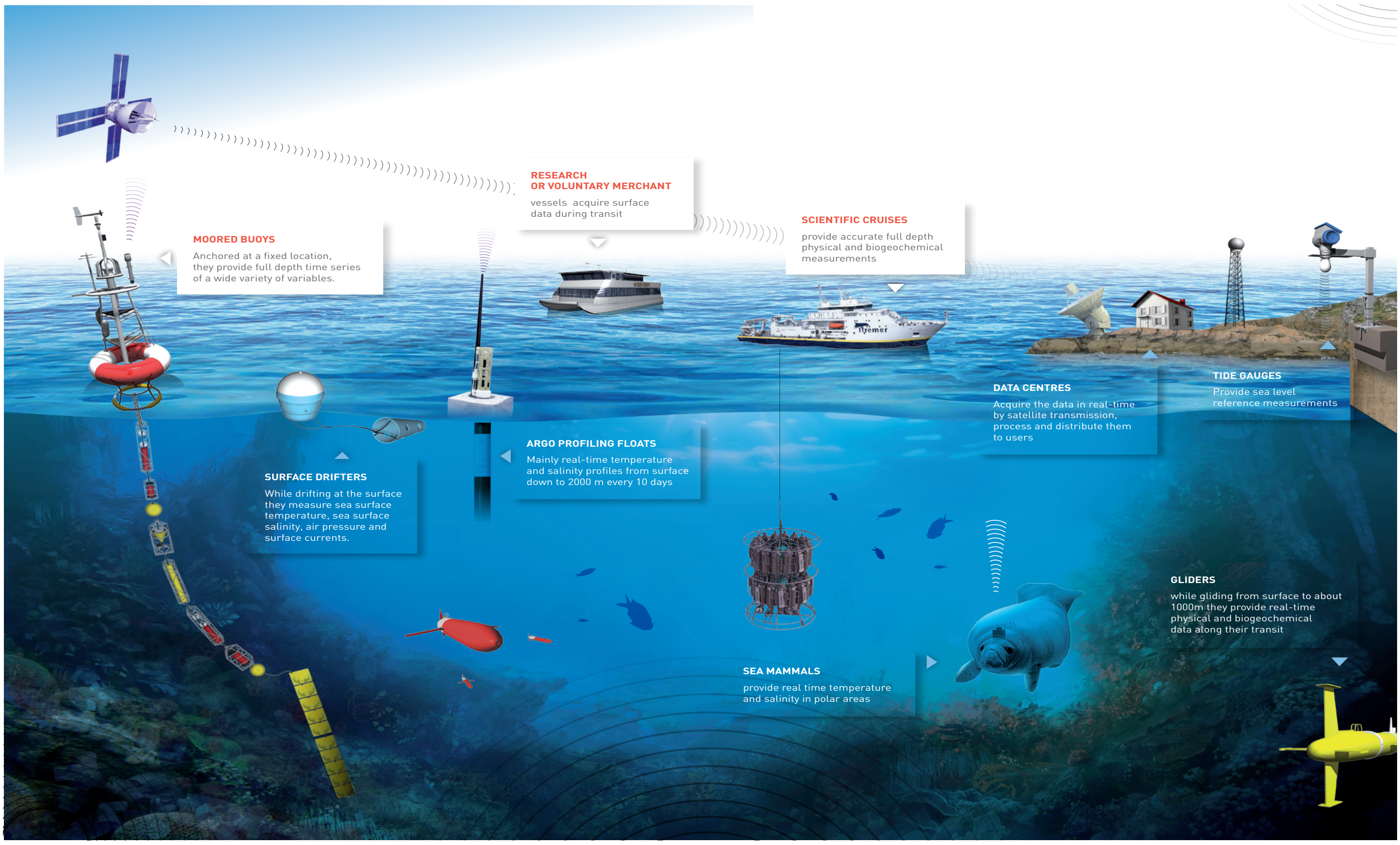

Figure 1: Global and regional in-situ observing systems: Argo, gliders, research vessels, ship of opportunities, drifting buoys, marine mammals, tidal networks and high frequency coastal observatories

Figure 2: The different networks contributing to Coriolis 2014-2020, organized by one or several institutes or laboratories with a pooling of resources for at sea operation, data processing and data dissemination and R&D activities (transverse components)

The CLIVAR Global Synthesis and Observations Panel (GSOP): Coordination Partnerships on Ocean Observations and Synthesis

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Introduction

The CLIVAR Global Synthesis and Observations Panel initially grew out of an earlier panel, the CLIVAR Upper Ocean Panel (UOP), builing its accomplishments. The UOP was central to the transition from the TOGA/WOCE observing system of the early 1990s, and (along with the Global Ocean Data Assimilation Experiment - GODAE) to the creation of systematic global ocean observing systems, including the Argo Program. The UOP and Ocean Observations Panel for Climate (OOPC) convened the OceanObs99 Conference to garner the community's knowledge and to establish a strategy for global ocean observations. In particular, the OceanSITES program originated from this conference. Ten years later, the status of the ocean observing system and community recommendations for its enhancement were reviewed at the OceanObs'09 Conference, organized by GSOP and OOPC, together with the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Project, and several other partners. Participants reached a strong consensus that observations must be continuous in order to meet the requirements for climate research. Moreover, it showed the opportunities and benefits to extend the system to include integrated observations, data sharing, analysis and forecasting of the biogeochemical state of the ocean and the status of marine biodiversity and ecosystems (Fischer et al., 2010).

GSOP has continued in the role of advocate for sustaining and enhancing the global ocean observing system. In particular, GSOP has been fostering synthesis activities (including statistical analyses and data assimilation using ocean models) to evaluate and demonstrate the impacts of the evolving observing system. These activities include assessment of the utility of data that are directly synthesized/assimilated as well as independent non-assimilated data for posteriori validation/evaluation of the synthesis products. GSOP, along with OOPC, have provided and will continue to provide scientific steer among the international research community to help inform maintenance and further development of the ocean observing system.

The Global Ocean Observing System

Much progress has been made over the last decade in the global ocean observing system. The core Argo mission of 3,000 active floats was achieved in 2007 and continues to deliver data in the open and ice free oceans; the global expendable bathythermograph (XBT) network transitioned from broad-scale monitoring (taken over by Argo) to circulation monitoring via frequently repeated (FRX) and high-resolution (HDX) XBT lines with a global design. Sustained satellite measurements of ocean surface topography, sea surface temperature, and ocean vector wind, and the recent advent of satellite remote sensing of surface salinity, have enabled a space-borne view of the ocean from different perspectives based on these measured parameters.

To further facilitate climate research, the following enhancements of the global ocean observing system and integration across elements are necessary:

- The sampling domain of autonomous platforms can become truly global through extensions to higher latitudes, into marginal seas and the deep ocean, and through higher resolution observations in boundary current regions. Further technology development, which is well underway, and the definition of new sampling requirements, are needed for these extensions.
- The global network measuring the physical state of the oceans provides a platform for multi-disciplinary observations of biogeochemical and ecosystem impacts of climate change. Key requirements are further developments in low-power sensor accuracy and stability, and effective integration between autonomous and shipboard observational networks (e.g. definition of core variables; ensuring a sufficient quantity of reference-quality data for quality assurance of autonomous sensors).
- Improvements in the observation of the ocean surface layer and of air-sea exchanges require enhanced utilization of research vessels and commercial shipping, improvements to automated measurement systems, better coordination across networks, and a review of sampling requirements for marine meteorology and ocean surface velocity.
- Strong commitment to preserve, and in some cases repair, the continuity of satellite measurements of the air-sea momentum flux from scatterometers, and variations in the ocean mass field from gravity satellites. The principal challenge remains to advocate, plan and finance, and press for executing the transition of the critical satellite sensors to sustained status, through international and national commitments.

Deep Ocean Observations

The implementation of GO-SHIP as an internationally coordinated program has been a major success, contributing to a global view of how the ocean is changing from the sea surface to the ocean floor, including geochemical variables. Recent observational and modeling studies have identified the importance of the deep ocean in ocean heat storage variability and changes on decadal and longer time scales. This has significant implications for global heat, freshwater and sea level budgets and climate change research. The current Argo system has revolutionized the observation network in the upper 2km of the ocean, but sampling must be extended from 2km to the seafloor in order to close the global energy and sea level budgets. Technological advances during the past few years have made float prototypes available that could probe the deep ocean down to 4km or 6km. It is now feasible to make use of these technologies and a preparatory phase of abyssal Argo measurements within the Atlantic Ocean is underway (French NAOS project, European E-AIMS project). This preparatory phase needs to demonstrate that the floats are capable of making the required measurements and to perform a study for the optimal design of the abyssal ocean observing system. OceanSITES currently identifies 50 moored locations that have deep T/S sensors, but with uneven distribution and data quality control. OceanSITES is facing the challenge of adding additional sites in order to provide more uniform global coverage. These observations will be monitored and analysed in collaboration with the assimilation community who require the available measurements of the deep ocean in order to develop improved ocean state estimate products. In addition, multi-decadal ocean warming and acidification have impacts on marine ecosystems with severe socio-economic consequences. Given the value of ocean ecosystems to human health and welfare, it is important to understand the links between ocean and climate variability, marine chemical processes and their impact on marine ecosystems. Thus, there is an urgent need to fully integrate biogeochemical and biological observations into the ocean observing system, particularly during the development of the deep ocean observing system. The Global Ocean Observing System (GOOS) is leading these discussions, and GSOP will play an integral role.

Ocean Climate Indicators

Climate variability and change have significant societal implications. The oceans, with their vast capacity to store and transport heat and freshwater, play important roles in regulating climate variability and change. Ocean indicators or indices are being developed that reflect key elements of climate variability and change have great societal relevance, in the same sense as the so-called "Keeling Curve", is used as an indicator of CO2 concentration in the Earth's atmosphere. Currently, the ocean and climate research community compute various indices of the ocean climate using resources for individual research projects, often in an uncoordinated way. A systematic and sustained effort to establish and compute ocean climate indices would benefit not only the ocean and climate research community at large, but also the general public, by bringing a broader and more timely awareness of the ocean's role in climate variability and change.

Much of the existing effort on ocean climate indices has focused on global indices such as upper-ocean heat content and global sea level. However, regional variability and change are often substantially larger than global averages and usually more relevant in terms of associated impacts. Moreover, regional changes may not be coherent with global averages and are less easily attributable to climatic drivers. Well-known examples of these include sea level change in the western tropical Pacific in the past two decades, and upper ocean heat content in the South Indian Ocean. Given the above rationale, there is an important need to devise and compute regional ocean indices that reflect user-relevant climate variability and change information in a systematic coordinated manner using a sustainable approach. GSOP intends to form an Ocean Climate Indicator Task Force to create a key list of ocean climate indicators (1) that are important to monitor and understand the variability and change of the physical aspects of the ocean as related to climate, (2) that have important societal relevance, (3) that can be used to evaluate climate models not explicitly constrained by observations, and (4) that can be used to advocate for sustaining and enhancing the observing systems.

Coupled Synthesis

The production of ocean reanalyses, or ocean state estimates, is now an established activity in several research and operational centres. An initial review of the state of the art on ocean reanalysis produced was undertaken by Stammer et al (2010) and Lee et al. (2009). A new generation of products has recently been produced and a coordinated community effort on the Intercomparison of those ocean reanalyses has been undertaken addressing a variety of aspects. These include: i) quantifying uncertainty; ii) measuring progress in the quality of the reanalyses; and iii) defining indices for ocean monitoring. These are the motivations for the current Ocean Reanalyses Intercomparison Project (ORA-IP), which was jointly developed by GSOP and GODAE Ocean View (CLIVAR Exchanges, 2014; Balmaseda et al., 2015, and with a special issue of Climate Dynamics almost complete).

A new phase of research will focus on further development and comparison of coupled synthesis products. Coupled reanalysis systems are being developed at a number of operational centers with the aim of building integrated data assimilation systems suitable for all timescales of forecasting, from numerical weather prediction (NWP) to decadal predictions. Coupled data assimilation is also planned for the next generation of reanalyzes. Weakly coupled methods, using the coupled model for forward integration in outer loops, along with separate ocean or atmospheric increment analysis for the inner loops, is becoming a common approach. For example at ECMWF the CERA (Coupled ECMWF Reanalysis) uses 4Dvar for the atmospheric inner loop and 3Dvar (NEMOvar) for the ocean inner loop, both with a 24hour window, with the atmospheric step applied twice to allow the atmosphere to adjust to the new ocean observations. This has similarities to the coupled DA introduced in Saha et al (2011) at NCEP. Weakly coupled DA should reduce initialization shocks (Mulholland et al; 2015) since the forecasting model is always coupled, but the increments themselves will not necessarily be well adjusted, which may require the development and use of coupled co variances. At ECMWF a first weakly coupled reanalysis product is expected to be available within ~1 year. GSOP will provide leadership to coordinate international activities on coupled synthesis.

Data quality control

A major effort is needed to ensure that data quality is maximized, that data access is simplified (including for data types extending across multiple observational networks), and that data products are useful and available in a timely manner. The ocean observing system is heterogeneous, and data volumes are growing rapidly year on year. For maximum value, system interoperability is required in data formats, metadata protocols, and modes of data delivery. The synthesis and delivery of high quality data and products are major undertakings that have historically been under-resourced. Each individual component of the observing system collects data and applies quality assurance, flagging, and data adjustments before archival of data and metadata that are required for documentation and to direct steps in processing. Many of these streams include both near real-time (operational) and delayed-mode (research- quality) versions. The availability of complementary observations from multiple observing systems is becoming increasingly important with each data source having distinctive issues of quality and processing. There is a need for integrated datasets, unified access to distributed datasets, and archiving at world data centres to ensure long-term preservation. Over the last few years, GSOP has supported the IQuOD (International Quality Controlled Ocean Database; Dominguez et al, this issue) initiative, which will produce and freely distribute a community best practice" quality controlled ocean profile database with the most comprehensive meta-data and uncertainty information, along with some downstream added-value products.

There is also a need for data products, for example gridded reanalysed datasets, to be provided with uncertainty estimates. The documentation and characterization of products and datasets is essential along with guidance on suitability of datasets for a range of applications. Revolutionary new instruments will only fulfil their promise for global observation if there is an efficient means of deployment and an effective system for delivering their data, and the best derived data products, to users. It is critical that the infrastructure of the observing system, including both physical and organizational elements, should evolve and be maintained in harmony with instrumental technologies and user requirements. A major factor in the success of the observing system will be the effective utilization of all available means of access to the oceans: research vessels (including both dedicated cruises and opportunistic use of transiting RVs), commercial ships, navy ships, Antarctic supply ships, and even aircraft. Improved information delivery, careful planning, and coordination are needed for this function at both national and international levels.

Continuing Development of the Observing System

GSOP has been working closely with GODAE and its follow-on GODAE OceanView (GOV) to demonstrate the value of ocean observing systems (both satellite and in-situ) in ocean state estimation and in initializing seasonal-to-interannual forecasts, through use of Observing System Experiments (OSE) and Observing System Simulation Experiments (OSSE). The most recent activity was the contribution to TPOS2020 (Smith et al., this issue). The GODAE/OceanView OSEVal Task Team (Oke et al., this issue), together with GSOP, will be assessing further opportunities and needs for the use of these tools.

GSOP has been working closely with OOPC to define observational requirements for Essential Ocean Variables (EOVs) for the Global Climate Observing System (GCOS) and has provided valuable input to the Global Climate Observing System (GCOS) in terms of spatial and temporal sampling and accuracy requirements for phenomena on different climate time scales for temperature and salinity. These contributions will be used for the upcoming update of observational requirements and observing strategy by GCOS, in 2016.

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CLIVAR Exchanges No. 64, Vol. 19, No.1, February 2014

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CONTENTS

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