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Capabilities of Global Ocean Programmes to Inform Climate Services

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Abstract

Climate services are identified as a means of providing the information that is needed to support decision makers in assessing the impacts of climate change on the oceans. We discuss the current observation programs to support these services, and their capacity to provide the information needed to monitor and address key science questions. An analysis of the current oceanographic observation programs is shown to be under-subscribed from their original plans. There are vulnerabilities in the current observing programs, particularly in relation to satellite measurements. The interaction of climate services with the research community, with policy makers and stakeholders and operational centres is outlined and leads to four recommendations. The key recommendations are for the more pervasisve development of climate services and for a modest increment in the observing program informed by the recommendations of the OceanObs'09 conference.

Keywords: Oceanography, climate change, ocean observing system, climate services, adaptation, policymakers

1. Introduction: assessing the changing ocean state

The ocean is a critical element of the whole climate system. The oceans have stored more than 80 per cent of the energy content change of the earth system since 1955 [2]. The oceans have become more acidic at a rate 0.02 pH units per decade over the last 20 years [3]. Sea level is rising at a rate that is now higher in the last 50 years compared with the first 50 years of the twentieth century [2]. All of these changes are projected to continue and accelerate through to 2100 [4]. Even with stabilization of the concentration of greenhouse gases in the atmosphere the ocean state will continue to evolve over the next millennia, albeit at a decelerating rate.

These global-scale changes are already having, and are projected to have, a profound impact on the circulation of the oceans, on the coastal regions by rising sea level, on ocean and coastal ecosystems and through the changing biochemistry of the oceans. While the broad global details of the changing ocean state have been established with moderate levels of confidence in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report [5], much remains uncertain for detailed projection and predictions into the twenty-first century, and on finer spatial scales. The IPCC Fourth Assessment Report concluded that the "limitations in ocean sampling imply that decadal variability in global heat content, salinity and sea level changes can only be evaluated with moderate confidence" and "there is low confidence in observations of trends in the meridional overturning circulation" [5]. Our knowledge of global sea level is also incomplete with "Global average sea level rise from 1961 to 2003 appear[ing] to be larger than can be explained by thermal expansion and land ice melting", although significant progress has been made to increase understanding of the various contributions to the sea-level budget [6].

These uncertainties in the ocean state become even more relevant to understanding climate change in the ocean, particularly for understanding the joint relationships between atmospheres and oceans, and for understanding future projections of the ocean state in the context of the regional change and with short time horizons. It is quite likely, given the spatial distribution of ocean state

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variables (for example the distribution of aragonite isocline) that some regions are going to exceed critical thresholds earlier than would be expected from simpler analyses of the global state [7]. Similarly, we can expect that natural variations on seasonal, interannual, decadal and longer timescales in ocean state variables will push some large areas of the ocean across similar thresholds (albeit for short periods) earlier than expected from global averages as reported in the IPCC Fourth Assessment Report. An example of the impact of decadal variations is the response to climate and the natural Pacific Decadal Oscillation on eastern Pacific island states.

Adapting to the climate change at the regional and local scales frequently requires a better knowledge of where and when regions are likely to become vulnerable to the changing state of oceans. It is this information that allows planning for the adapting to the impacts of climate change and is the tactical knowledge that is required in planning a response to climate change. The provision of this information to the wider community in a timely way is central to successful adaptation. The climate and oceans community is increasingly recognizing the importance of creating climate information systems to increase the relevance of climate change science [8].

Knowing where and when to adapt in response to climate change will be important to decision-makers in order to have a response that enables cost-effective solutions at the right time, and that balances both economic resources and safety imperatives. The challenge to the oceanographic community is to be able to progressively provide the oceanographic information that is relevant to decision-makers for adapting. While the four IPCC assessment reports for climate change have had an enormous impact on the wider policy, industry, general and research communities in establishing the importance of climate change, these reports appear every five or six years and describe a restricted set of scenarios, limiting their applicability to specific requirements for regional adaptation. They include emission scenario projections but not predictions. The need to provide oceanographic services for the wider climate and policy community has increasingly become recognized as being central to shaping the adaptation responses to the evolving state of the ocean.

There are significant international observational, modelling and data assimilation projects (World Climate Research Programme [WCRP] and Global Climate Observing System [GCOS]) that provide the framework for building these general ocean services that allow progressive assessments of the current ocean state and the forecast of the future ocean state on seasonal, interannual, decadal and longer timescales. These frameworks, along with the underpinning observational programs need to be augmented and integrated in the same way as the operational and research activities that occur in the weather forecasting communities with well established products and services that can be used by end-users in their decision systems (see Section 5).

This paper addresses the needs of the wider community to provide the overall oceanographic services of the climate system that are needed for end-users and decision-makers, and the research improvements and integration that are required so that these oceanographic information services can be provided. The emphasis of this white paper is on the “bluewater” or “open ocean” capabilities and needs as distinct from coastal areas. A companion paper focuses on the information systems for coastal needs [9]. Section 2 covers the capacity of current research systems to deliver a synthesis, attribution and predictions of the ocean state variables. Sections 3–6 cover the needs of the oceanographic community to deliver these climate services and to create a system that enables integration and construction of services relevant to users for understanding the ocean state.

2. Capacity to assess and monitor ocean state

Existing observations have shown that changes in the ocean in response to changes in its surface forcing, and assessed over the last years and decades, appear to cover the entire water column. This is especially obvious in high latitudes, where the window of the deep ocean to the atmosphere and cryosphere is most direct through air–sea interaction (or ice–sea interactions) and respective formation of dense water that sinks down to levels between 2 000 and 4 000 m depths. However, air–sea interactions also affect all other parts of the world ocean and play a significant role in forcing the atmosphere by the ocean, especially in low latitudes. Changes identified over the last 50 years are summarized in Figure 1; those changes are associated with changes in heat content and in freshwater, affecting the ocean circulation and causing sea level to change. But changes also affect sea-ice cover and other processes impacting deep water mass formation rates. Moreover, identified changes also correlate to geochemical changes, such as changes in the CO_2 content and thus in the pH of sea water, as well as changes in oxygen. Understanding the impact of a changing climate in the ocean is getting urgent, especially with respect to geochemistry and ecosystems.

Assessing all changes occurring presently in the ocean requires a global observing system that provides information not only about the physical and geochemical state of the ocean over a long time and over the full depth of the ocean, but also about its ecosystem and its health. Those observations are needed to address questions about changes in the oceans’ heat and freshwater content and anthropogenic carbon content as well as changes in pH and oxygen concentration, and to use that information for projections of ongoing changes into the future. Given that the ocean is a major reservoir for heat and for anthropogenic carbon, a careful monitoring of all climate-relevant variables must take place and must continue over a long time to come. However, this has not been the case until recently, and even today the ocean observing state is still evolving toward a more complete state sufficient to answer urgent questions that with past measurements cannot be addressed.

As an example, assessing sea-level changes globally and regionally requires a detailed description of the changes in heat and freshwater content over the entire water column and over many decades, as well as changes in the mass of the ocean. All of these measurements became feasible only recently, since the advent of altimetry satellites and through Argo profiling floats and satellite gravity measurements such as GRACE. Prior to these new ocean observations much of the ocean was hardly ever observed, and in some areas had only been observed once over the last 100 years. Providing answers to questions about global sea-level changes over the last 50 years is therefore presently not possible with great confidence but will require a continuation of satellite altimetry, and top-to-bottom Argo-like profile measurements of temperature and salinity, with global coverage including regions under sea-ice cover. In addition, regional changes in sea level are much larger than global numbers, implying that one needs a local tide gauge network on top of global estimates to answer urgent questions about sea-level change and coastal security. Figure 1 demonstrates that to properly assess changes in the ocean and attribute them to natural variability or anthropogenic causes, we need to gather information on changes of the external forcing by the atmosphere, cryosphere and other components of the Earth system (for example, run-off and river discharge). Attribution of these forcings is fundamentally about the science of climate predictability, including for climate variability (for example, El Niño–Southern Oscillation [ENSO], seasonal variability, and other factors), as well as long-term climate change. Indeed, understanding and attributing what has just happened is a prerequisite to making the next climate prediction.

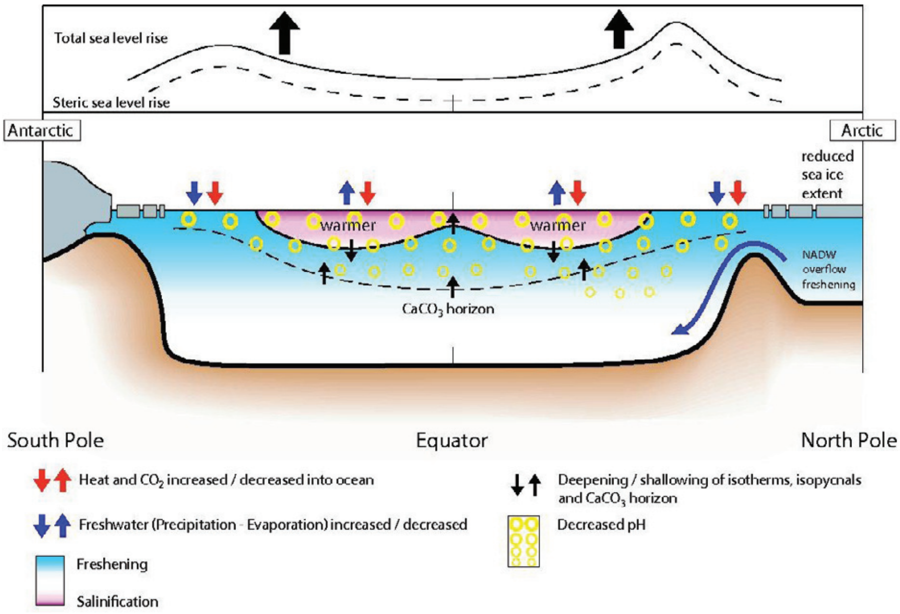

Figure 1. Summary of the assessed changes in the ocean state from the 1950s–1960s to the 1990s–2000s in the global oceans based on observations of the ocean state from research and operational observing systems (Source: IPCC [5], Figure 5.18)
Note the steric changes are spatially non-uniform while the ocean mass changes are uniformly distributed.

Presently such ocean information is used to compute important climate indices, such as heat content of the ocean, and to start attributing changes to various sources. An example of a recent estimate of the change in the oceans heat content is shown in the left panel of Figure 2 as it follows from ocean information alone. The figure reveals that the oceans' heat content is varying substantially on interannual to multi-decadal timescales. The impact of an insufficient observing system in the past is reflected by substantially enhanced error bars during the 1950s and 1960s, and it is obvious that even under present conditions uncertainties still loom large. The figure also indicates the effects on atmospheric aerosols of volcanic eruptions on the oceans' heat content (as on sea level and surface temperature) rendering prediction of those quantities in great detail over several decades to centuries difficult due to the unpredictable nature of volcanic eruptions.

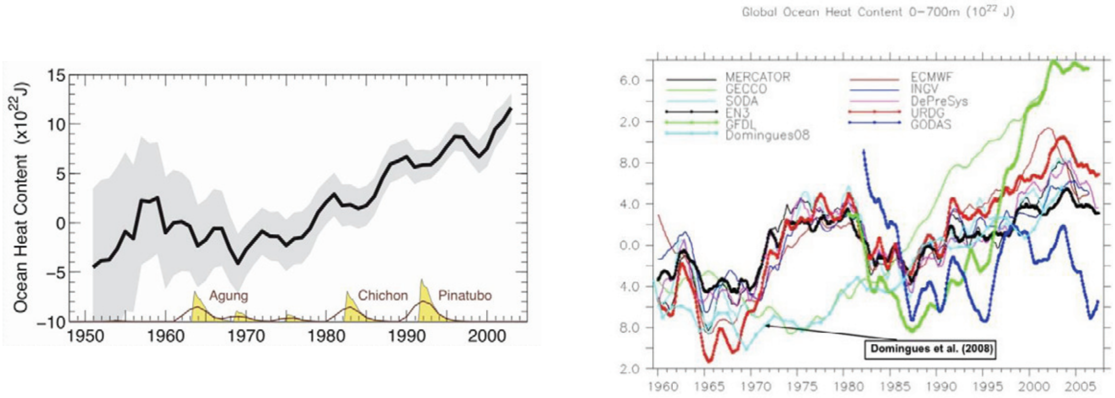

Figure 2. Heat content changes (left), estimates of heat content changes from ocean syntheses (right) (Sources: Domingues et al. [10]; Stammer et al. [11])

Given the deficits of the observing system over the last decades in providing information about basin-scale or global changes, we have to bring all ocean information together in a way much more efficiently than can be done by individual analyses by also taking into account our knowledge of ocean dynamics, as is being done in ocean syntheses. Several ocean syntheses have been produced and compared. A wide spread of results is obvious (Figure 2, right panel) and the need for specifying proper uncertainties for model and data errors and for estimation results in the ocean and atmosphere is critical. A significant effort is required to understand uncertainties in estimates of climate indices and how they depend on the underlying method. An ultimate application of ocean syntheses is to use information to initialize the ocean in coupled climate forecast models. This is done for seasonal-to-interannual forecasts, but we are now at the forefront to expand the prediction window to cover decadal and longer timescales. While very encouraging results are available from atmosphere and ocean reanalyses, which already serve many purposes, climate is a coupled problem and ultimately we need to address a coupled synthesis embracing not just atmosphere and ocean, but also land and sea ice. A central goal of ocean and atmospheric reanalyses is to document and understand observed climate variability and change and the causes, including the uncertainties, and to be able to: (a) determine what parts of the observed change is short-term ocean variability versus longer-term change; (b) use this understanding to improve model realism and forecast skill; (c) provide climate and ocean predictions; and (d) communicate this knowledge and understanding to users and the public in general.

Dealing with the coupled system does allow us to understand where the most prominent impacts of climate change occur. Figure 3 shows such an assessment in terms of heat content in the climate system, and reveals that it is especially the ocean that takes up almost all of the increased heat content in the climate system. Without the ocean, changes over land would be enormous if not catastrophic. However, the figure also suggests that if one wished to detect changes in the climate state one should be observing the ocean, again underlying the importance of a complete climate observing system in the ocean. The figure clearly demonstrates that it is the ocean that has the largest reservoir of heat and that therefore needs to be monitored in great detail to understand its role in climate change, how it is being affected by changes in the atmosphere, but also how both together affect quantities like sea level, global rainfall patterns and wind fields on regional and global scales.

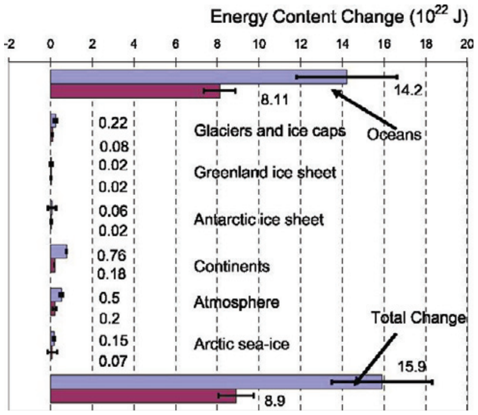

Figure 3. The assessed trends in energy content change of the Earth System Components 1961–2003 (blue bars) and 1993–2003 (burgundy bars) (Source: IPCC [5], Figure 5.4)

Projecting the ocean state over the next decade or even centuries requires running a coupled climate forecast system and information about the initial/present climate state as well as boundary conditions for the ocean, that is, forcing fields representing the feedback between the ocean and other components of the climate system. Indeed one of the goals for an ocean observing and synthesis system is to provide proper initial conditions for ocean and climate forecasts on seasonal to decadal timescales beyond the typical IPCC assessment efforts. The related activities are to improve and initialize climate models and make seamless ensemble climate predictions for the oceans for the time horizons of up to at least 30 years. Such climate predictions are essential to understanding the consequences of climate change on the oceans, and in the future we should aspire for such predictions to seamlessly expand from days and weeks of weather-casting to seasonal and interannual predictions (including ENSO) to decadal predictions.

Climate predictions are at present in their infancy. Our knowledge of the predictable elements of the ocean state, for example, sea level and ocean heat content, is still immature. Some indications exist that at least some elements (such as the meridional overturning circulation) of the ocean state are predictable for a few decades [12]. However, much has to be learned about predictable elements and also about our approach to predicting them. As in seasonal forecasts, the quality of the coupled models used for the predictions have a substantial impact on the quality of the predictions. Likewise the approach to initialize imperfect coupled models with incomplete and imperfect observations does have a substantial impact on the results. Both of the problems of initialization and prediction call for the development of coupled assimilation and forecast systems that make full use of ocean data to determine initial conditions and at the same time make use of the of observations over land and the cryosphere. Information is also required about the accumulated impacts to date of anthropogenic radiative forcing. Demands will therefore be made on observations not only to describe the state of the system but also to provide the optimal observations for climate predictions.

3. Capacity to provide relevant temporal and spatial scales for decision-making

There is great desire for regional information about the expected magnitude and impact of climate variability and change on all timescales for decision-making. However, information for decision-making encompasses a huge range of space and timescales. A few examples to illustrate this range from (a) accurate predictions of tropical and extra-tropical storm size, intensity, rainfall and track; (b) accurate predictions of heating or cooling degree-days (or extent of drought) in the coming season or two; (c) changes in the probability of storms likely to bring threshold levels of damage (including flooding) to particular areas in particular seasons; (d) the rate of sea-level rise or of ecosystem health events in locally important coastal regions; to (e) the likelihood of significant changes in commercially important marine biomass in coming decades.

Information from the ocean (both surface and ocean interior) is important for all of these problems, even when not obvious. This is because of the fundamentally coupled nature of the earth–atmosphere–ocean system. Examples exist of observed oceanic effects for each of the above examples of societally important information. However, research is needed to estimate specific observational needs from the oceanic observing system for each impact of concern, and to harness this research, as discussed in Section 5.

The global oceanic observing system has been progressed to serve needs of all nations for large-scale climate information through coupled model forecasts and projections. In addition to the general climate variability and change information needs of all nations, there are nation-specific needs for coastal ocean observations and coastal ocean information for decision-making. It is very important that each nation identify its priority coastal ocean information needs so that these can be aggregated internationally, and efforts to address these needs can be addressed and coordinated.

The extent to which needs for coastal ocean information can be addressed with existing ocean observing, ocean synthesis and forecasting systems needs additional attention. (See Malone et al. [9]) In general it appears that enhanced coastal observing and forecasting efforts are needed and supported through international programs and national efforts. Useful coastal forecasting depends upon accurate local coastal and bottom topographic information and accurate high spatial resolution wind and rainfall forecasts.

4. An ocean observing system for climate change assessment

Systematic, long-term and high quality observations of the global ocean are necessary to monitor the three-dimensional climatic large-scale ocean variability patterns and their coupling with the atmosphere. Such a global ocean observing system is an essential prerequisite to a better understanding of the fundamental role of the ocean on the earth climate and to the development of decadal to long-term forecasts of the earth climate.

An initial design of a permanent, global and real-time observing system comprising both in situ and remote sensing components was proposed in the OceanObs 1999 St. Raphael conference and endorsed by the Global Ocean Observing System (GOOS), GCOS and the Joint World Meteorological Organization/Intergovernmental Oceanographic Commission Technical Commission for Oceanography and Marine Meteorology (JCOMM) [13][14]. Satellite data include altimeter (sea level and surface currents), sea-surface temperature, ocean colour, sea ice and scatterometer (wind) data. The main in situ data include Argo, multidisciplinary moorings, data from research vessels and ships of opportunity, surface drifters and tide gauges.

The main objectives of the global ocean climate observing system are to detect climate variability on seasonal to decadal timescales and to provide data that are necessary to initialize and constrain climate models through data assimilation and thereby allow the attribution of the observed changes to the underlying change and variations in the climate system [15]. The objectives are to measure and monitor:

(a) Ocean heat and fresh water content and transports;

(b) Sea level variations;

(c) Ocean carbon content;

(d) Sea-surface temperature and surface currents;

(e) Air–sea exchanges of heat, momentum and fresh water;

(f) Sea ice extent, concentrations and thickness.

An overview of the global ocean observing system is given below. More details can be found in Clark et al. [16]. The global in situ observing system includes:

Argo profiling floats. This array was developed as a Global Ocean Data Assimilation Experiment (GODAE) and Climate Variability and Predictability (CLIVAR) observing system initiative to understand upper (0–2 000 m) ocean temperature and salinity variability. Argo achieved its initial implementation goal of 3 000 operating floats in November 2007. Although it has not yet reached its desired geographical coverage of a float per 3° x 3° region, the array is providing for the first time a nearly global picture of the world's oceans every ten days. (See Freeland et al. [17])

Global Tropical Moored Array. In the tropical Pacific, the Tropical Atmosphere Ocean/ Triangle Trans-Ocean Buoy Network (TAO/TRITON) array was fully deployed by 1999, while in the Atlantic, the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) has expanded to nearly double in size from 10 moorings in 1999 to the current 20. The Indian Ocean Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA), started more recently, is about 50 per cent complete.

OceanSITES. A global network of ocean reference station moored buoys is being implemented to provide the most accurate long-term climate data records of oceanic and near-surface atmospheric variables in key ocean regimes. OceanSITES has plans to deploy and maintain 89 ocean reference stations. There are currently 43 reference stations.

Global sea level observing system. Tide gauges are necessary for accurately measuring long-term trends in sea-level change and for calibration and validation of the measurements from satellite altimeters.

Repeat hydrographic surveys. The global repeat hydrographic survey is an essential observing system element for understanding the controls and distribution of natural and anthropogenic carbon, circulation tracers and a large suite of biogeochemical measurements in the ocean interior, including nutrients and oxygen. The surveys also remain critical for documenting ocean changes below 2 000 m.

Surface drifting buoys. This array provides accurate bulk sea-surface temperature (SST) observations, and surface current and surface pressure observations. It reached its initial number goal of 1 250 drifters in 2005, but has not yet achieved the desired geographical coverage of a drifter per 5° x 5° area of the ice-free ocean.

International Arctic buoys. This network is used to monitor synoptic-scale fields of sea-level pressure, surface air temperature and ice motion throughout the Arctic Ocean. The Arctic ocean observing buoys have more than doubled over the past 10 years (24 in 1999 and 54 in 2008).

Ships of Opportunity. The primary sensors employed by Ships of Opportunity are expendable bathythermographs (XBT), ThermoSalinoGraphs (TSG) and sensors equipped to measure the partial pressure of carbon dioxide (pCO_2).

Thanks to major advances achieved in the past two decades, satellites now have a demonstrated capability to measure a series of essential climate variables for the ocean. Main satellite oceanography missions include:

Ocean surface topography. Precision altimetry was initiated by the United States National Aeronautics and Space Administration (NASA) and France's National Centre for Space Studies (CNES) with the launch of their TOPEX/Poseidon in 1992; it is being continued by Jason-1 and Jason-2 (launched in 2008). The National Oceanic and Atmospheric Administration (NOAA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) are now proposing a Jason-3 for launch in 2013. Gravimetry (GRACE and Gravity field and steady-state Ocean Circulation Explore [GOCE]) satellites are needed to get absolute topography and surface currents and to monitor large-scale ocean mass variations.

Sea-surface temperature. For a couple of decades, continuing observations of sea-surface temperature, to varying degrees of accuracy, have been provided by infrared radiometry (IR). Microwave radiometry (MR) now offers an all-weather, but relatively coarse resolution. Donlon et al. [18] provide a detailed overview on how the Global High-Resolution SST Project combines the best attributes of IR and MR to develop improved SST products.

Ocean surface vector winds. For more than a decade and a half, satellite scatterometry has provided observations of the surface vector wind field over the oceans. The longest-running with the broadest coverage, NASA's QuikSCAT, was launched in 1999 and is still operating today; the first fully operational scatterometer, Advanced SCATterometer (ASCAT) on EUMETSAT's MetOp-A, was launched in 2006 with units on MetOp-B and -C to follow.

Sea ice cover and ice drift. Passive microwave data is still the backbone of sea ice observations. Improved resolution and more detailed ice edge estimates are obtained by use of scatterometer data. Ice drift information is derived from successive satellite passages from these instruments. Ice thickness measurements should be provided by the advanced altimeter on CryoSat-II.

Ocean colour. Over the last decade, satellite-derived ocean colour data have provided invaluable observations of the large-scale variations of chlorophyll-a. This is a unique means to assess the coupling between biology and climate change.

Sea-surface salinity. Microwave radiometry will be used to demonstrate the feasibility of observing sea surface salinity from space from the end of 2009 (Soil Moisture and Ocean Salinity [SMOS], Aquarius).

The in situ and remote sensing components have been jointly developed and are strongly complementary. In situ data are needed to calibrate or validate the satellite observations and provide observations of the ocean interior. There are strong synergies between the two components. Argo, Jason altimeter datasets and GRACE gravimetry observations need, for example, to be analysed together to understand the global mean sea-level variations and the contributions of ocean warming (volume variations) and continental ice melting (mass variations).

There has been major progress over the past 10 years in implementing the initial system. (See Figure 4.) The main challenge today is to complete the initial design and to ensure its long-term sustainability. This is critical for climate change assessment which requires long time series (several decades) of observations. An adequate data processing and re-processing infrastructure is also required to make sure that long time series of inter-calibrated, validated and high quality datasets are delivered.

Further developments are also needed. The OceanObs'09 conference in Venice (September 2009) has developed a process for building consensus for sustaining and evolving systematic and global ocean observations over the next 10 years in support of societal benefits. The ocean observations have also been augmented with new technologies such as autonomous gliders [19] and with enhancements of current technologies. For example, several improvements and possible future expansion of the Argo array (Freeland et al. [17]) are, in particular, important to better assess climate change variations. These include extension of the Argo core mission to higher latitudes under sea ice and to greater depth (>3 000 m) and a progressive extension of Argo measurement capabilities to include biogeochemical observations (for example, oxygen sensors).

While much has been achieved in the creation of the overall observing system and in sustaining the system in the long term many of these systems are vulnerable to gaps in coverage or inadequate coverage of the global ocean. This is particularly true of the some of the satellite-based observing systems (Figure 5) but also for the other observing networks. For some satellite systems the follow-on missions are only in the design phase and frequently are based on a single satellite and therefore vulnerable to failure of the satellite.

In terms of climate change, continuity of the records with overlapping periods are critical for calibration, bias correction and the overall quality of the climate date record (Section 5).

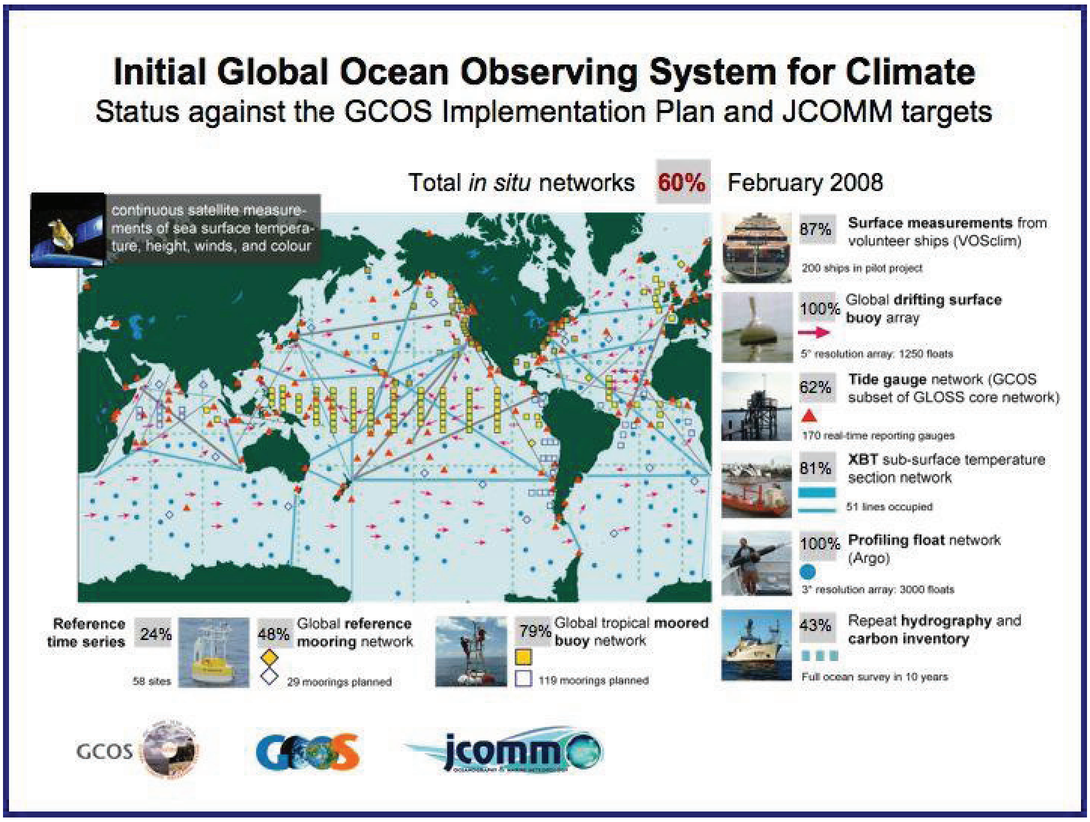

Figure 4. Status of the in situ Global Ocean Observing System against targets defined by the GCOS Implementation Plan and accepted by JCOMM

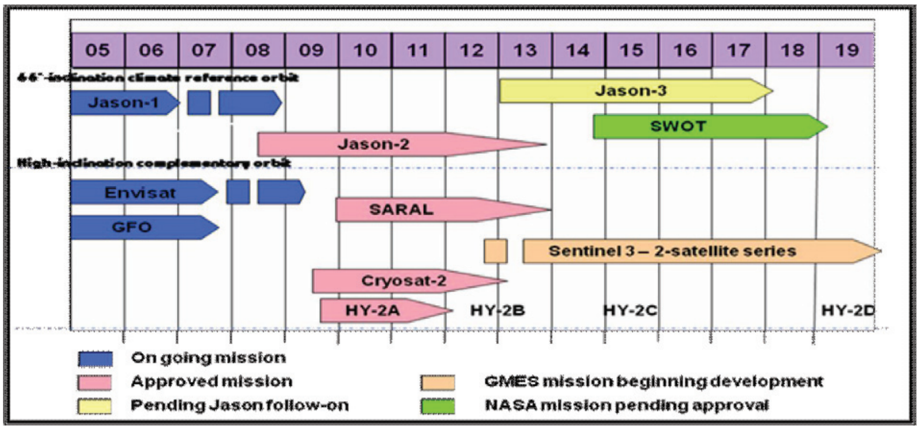

Figure 5. The timelines for a suite of satellites systems for observing the oceans state
Note that some systems have limited redundancy and limited periods of overlap and are consequently vulnerable to gaps.

5. Requirements for ocean–climate infrastructure and meeting information needs

The capacity of society to adapt, respond to, and mitigate the impacts of climate change in the ocean and marine environment places significant demands on the current infrastructure, both in terms of the capacity to observe the oceans and in simulating the oceans. An imperative and essential step is to build a climate information system [20][21] that informs decision-makers about what is happening and why, and what the immediate prospects are (Figure 6). This information system is envisaged as a continuum of systems with the ocean observing systems at it base, operational modelling and assimilation leading to a range of ocean products that are delivered to users along with high-level assessments for policymakers. At the same time, these systems must recognize and respond to the needs of society and users. The research community works with the data, modelling, assimilation and predictive components of the system to improve the processes and information about the ocean climate, and consequently in creating climate services informing all levels of the system, including users and policymakers.

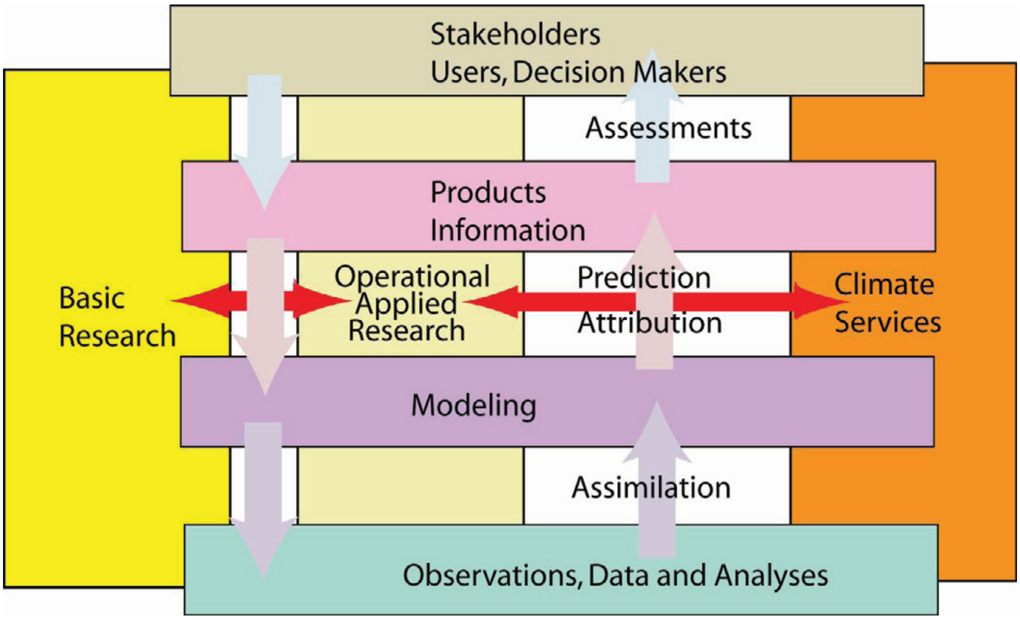

Figure 6. A schematic of the flow of the information (shown by red arrows) of an ocean information system (Adapted from Trenberth, 2008 [21])

Basic research feeds into applied and operational research leading to better data, modelling and products, which then leads to the development of climate services. The system is built on the ocean observing system that includes the analysis and assimilation of data using models to produce analyses and fields for initializing models, and the use of models for attribution and prediction. After all the information is assessed and assembled into products and information, it is disseminated to users. The users in turn provide feedback on their needs and on how to improve information.

The global ocean observing system (Section 4) is the foundation of an ocean climate information system. An ongoing challenge is to create climate data records of the ocean from the observations that can be re-used multiple times for both operational and research purposes. Overall what is required is that the observations satisfy the climate observing principles; a performance tracking system; the ingest, archival and stewardship of data; access to data, including data management and integration; the analysis and reanalysis of the observations and derivation of products, especially Climate Data Records (CDRs) [22]; assessment of what has happened and why (attribution), including likely impacts on human and eco-systems; prediction of near-term ocean change over several decades; and responsiveness to decision-makers and users. While absolute accuracy and calibration are desirable, the most important attributes of CDRs is that they must be homogeneous and continuous over periods of decades – characteristics that are essential to enable changes to be discerned.

Much more work is needed to take advantage of the existing observations to better establish the observed changes in the ocean state. A key part of the overall strategy in creating climate data records is the need to have a vibrant program of reprocessing of past data [14], for example, applying the corrections for instrumental defects [23] and the application of new techniques and methods creating new global products and atlases of the changes in ocean heat content and sea level [10][24]. The IPCC report (2007) relies on multiple analyses of the ocean state rather than any single analysis for key state variables such as sea level or global heat content. This report and later papers demonstrate shortcomings of the ocean records, particularly from instrumental biases and errors in calibration. Research has also demonstrated the potential for improvements in these records as progress is made on algorithm development and solutions are found to problems such as heterogeneities in the records from the use of different instruments types or satellites.

Coordination among the major observing programs and satellite observations is highly desirable in order to reach agreements on algorithms and calibration procedures with in situ measurements and between variables where possible. The fields would include temperatures, sea-surface temperatures, sea ice, snow cover, winds and tropical storms and hurricanes. This coordination between agencies and in situ oceanographic observing systems requires substantial resources to develop the adjusted and calibrated products with their associated metadata and documentation [25].

Global oceanographic analyses are then produced in real time operationally for a range of variables (including sea level and ocean temperature and salinity). As these assimilating models are used to analyse the observations there is a tendency for further improvements in the observations. Reanalysis is the name given to the reprocessing of all these and other observations with a state-of-the-art system that is held constant in time, thereby improving the continuity of the resulting climate record. In the meteorological community, successive generations of atmospheric reanalyses have led to continual improvement of the basic atmospheric dataset, and we can expect a similar result for ocean reanalyses.

A further challenge is dealing with the changing observing system [21]. The assimilation system for the oceans (Figure 6) should result in a more coherent description of the changing ocean (and atmosphere, land surface and other climate components). In addition, the assimilated products include derived fields not directly observed and which can be utilized by the many users of the climate products created from the reanalyses. This includes the testing of model predictions in hindcast mode. Reanalysis thus contributes to the capacity-building objectives of programmes such as GOOS, GODAE and Global Earth Observation System of Systems (GEOSS), and should be considered an essential component of an ocean observing system.

The related follow-on activities are to improve and initialize climate models and make seamless ensemble climate predictions for the next 30 years or so. Climate predictions are essential and will seamlessly expand from the days and weeks of weather-casting to seasonal and interannual predictions (including ENSO) to decadal predictions. Climate system predictions of natural and forced change require initialization of coupled general circulation models with the best estimates of the current observed state of the oceans (atmosphere, cryosphere and land surface), a state influenced both by the current phases of modes of natural variability and by the accumulated impacts to date of anthropogenic radiative forcing. Demands will therefore be made on observations not only to describe the state of the system but also to provide the optimal observations for climate predictions.

The development of the climate information system potentially takes on, in a more operational and coordinated framework, a key part of what is currently being undertaken by the research organizations as part of the assessment done by the IPCC. There are many research questions on how to develop the system, and what the system should include to make it viable. Building a climate information system should integrate research and underlying data streams from WCRP, the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), Diversitas and GOOS (GCOS) and feed them into the National Meteorological and Hydrological Services, and national oceanographic services [26]. Basic research feeds into applied and operational research, including technological transfer, that in turn develops climate products and services. Many aspects require research on assembling observations, analysis and assimilation; attribution studies; establishing relationships among physical and environmental impact variables; running models and coping with model biases; predictions and projections; downscaling and regionalizing results; and developing information systems and ways of interacting with users.

6. Climate services to the benefit of facilitating decision-making and adaptation

The impacts of climate change and the plausible adaptation responses to mitigate these changes is really only effective if undertaken at the local scale where the impacts are felt [7]. Ocean climate services have an important role in this process through the provision of the information to support this decision-making. By their nature, ocean services are stable, reliable operations that deliver on an ongoing basis ocean information from a continuum of products. These services (as described in Section 5) have typically been developed in the research environment and made operational through the interaction with ocean service providers. In addition to the standard products, ocean services also have the capacity to deliver ocean data and information in selected streams in response to the requests from users of the information.

Services, by definition, cannot be developed in isolation of the users. The whole world presently demands information about climate. The customers include government bureaucrats charged with creating adaptation strategies for their communities, journalists trying to figure out what's going on, decision-makers trying to create mitigation policies, scientists in fields responding to climate change, IPCC, Earth system scientists trying to improve the climate models or formally attribute changes to physical phenomena, and last but not least, the general public, who are concerned and want to be kept informed.

A key aspect of the development of these products delivered through these services is that they must result from a dialogue with users (ranging from users in research and the wider community to policymakers). This dialogue is a critical element of creating the infrastructure that delivers this information, since this infrastructure requires significant investments from national governments and organizations. Further, ocean climate services are characterized by a wide set of end-users and policymakers who are situated outside the normal range of communities often encountered by researchers. A consequence of this diversity of external end-user and policymakers means that ocean climate services must be flexible, responsive and adroit in engaging with these external communities.

The dialogue to create these ocean climate services as part of the overall infrastructure in the context of climate change is illustrated below (Figure 7). For example, a key vulnerability might be identified (through a variety of processes) for a particular timescale and area or sector. The IPCC is an example of such dialogue between governments and scientists during the scoping process for each of its assessment reports. This scoping process identifies areas of vulnerability that then determine the science issues that need to be addressed to improve the knowledge of vulnerability, and to improve predictive capacity. This scientific research is subsequently reflected back into improved ocean climate services and as advice informing the analysis for policymakers of the impacts and strategies for mitigating vulnerability.

The process of dialogue leads to refinements that are retained by the services and the research community, and that can be then be updated on a sustained basis in response to external user requirements. Central to decision-making is information provided by the ocean climate services.

7. Conclusions and recommendations

The oceans are changing in response to climate change and these changes are likely to affect the capacity of the ocean to store carbon and heat, to cause sea-level rise and to alter sea-level extremes. The global freshwater cycle will change, and new evidence is emerging about the changing ocean stratification, de-oxygenation of the ocean and weakening over-turning circulation in both hemispheres. These changes and observed poleward movement of marine ecosystems in some regions are projected to further displace marine ecosystems poleward and impact on their functioning [1]. While the some of the impacts of change are becoming increasingly apparent and reflected in policies, the specific near- and long-term consequences of these changes for society, policy and adaptation responses is often unclear. Such specific consequences form the basis of urgent science questions that need to be addressed to inform decision-makers who can respond through adaptation or mitigation of the impacts on these systems. Thus, there is an urgent need to build the capacity of global ocean observing systems and to build ocean information services that can respond to the policy and science questions so that we are better informed to respond and adapt to the Earth's changing climate.

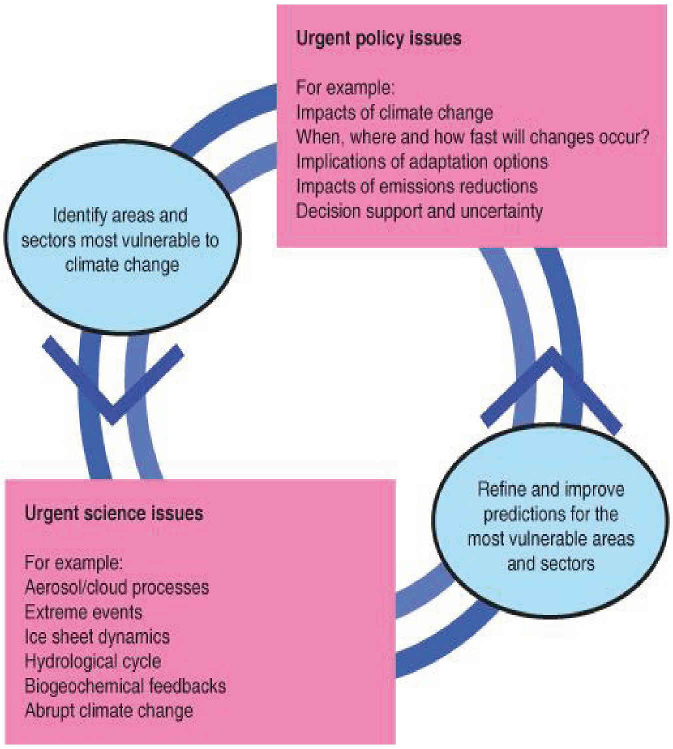

Figure 7. The Science–Policy Dialogue
This figure shows that areas identified to have risk are frequently associated with urgent science issues, and that resolution of these science issues increases our capacity to improve predictions for these vulnerabilities [8].

We recommend that:

(a) Ocean information services be developed and extended to allow the timely delivery of ocean and related climate data to the all sectors of the communities involved in analysis, synthesis and interpretation, planning and policy and management.

(b) Pathways be created for the oceanographic community to engage with policymakers to address the urgent science issues and to improve our projections and predictions of their consequences for the oceans and marine environment.

(c) Sustained observations in the oceans and from space be maintained with sufficient quality to be used for ocean climate monitoring and initialization of climate prediction models. We recognize that some key components of the global ocean observing system are vulnerable to dislocation and funding shortfalls and it is essential that these be avoided.

(d) Modest expansion of the initial ocean observing system be implemented to meet the new requirements including support for the new innovations that are occurring in the oceanographic observing systems (across physical, bio-geochemical and carbon). This expansion should be informed by the recommendations from the OceanObs'09 conference.

Greater engagement of the global oceanographic communities including researchers, users and policymakers be encouraged in all aspects of the design and operation of ocean observing, ocean information and ocean climate services.

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