CLIVAR Science Plan 2015 – 2025
(35p plus figures)

Version September 19, 2016

Summary

This document is a draft of the new CLIVAR science plan. It will be completed after receiving comments from CLIVAR members, from other organizations within and WCRP. The summary will be completed subsequently along with the rest of the text.

The Science Plan describes CLIVAR's evolution from the past and outlines the major scientific challenges and outstanding research questions pursued by CLIVAR over the next 10 years. It addresses scientist from the broader community with an interest in ocean and climate science, international science organizations, as well as agencies and funders on a national level.

The new CLIVAR Science Plan reflects the move to greater integration of climate science across disciplines. The implementation will include enhanced interactions with other WCRP projects, but also with elements outside WCRP, e.g., those now moving under the FurtureEarth umbrella. The document should motivate senior and early career scientist to get involved in CLIVAR.

Chapter 1. Introduction

To mark CLIVAR's 20th anniversary, its leadership[1] has updated the CLIVAR Science Plan detailing its science goals and priorities for the next 10 years. Of all core-projects of the World Climate Research Program (WCRP), CLIVAR is the core-project on Climate and Ocean, addressing key questions of climate variability, predictability and change. Addressing these questions requires international coordination that takes into account the ongoing changes in the climate system as well as an evolving political framework dealing with these changes.

The new CLIVAR science plan summarizes the challenges CLIVAR will address and the respective research CLIVAR will coordinate and foster over the years to come to the benefit of society, thereby building on emerging climate science challenges and taking into account achievements obtained by the WCRP community to date.

The Science Plan also articulates the necessary implementation activities, including expanding upon CLIVAR's core research to target specific Research Foci that strengthen ties to the broader WCRP science and the relevance to societal impacts.

1.1 The WCRP mission.

The WCRP mission is to facilitate and coordinate international efforts on the analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society. Thereby the two overarching objectives of the WCRP are:

- to determine the predictability of climate; and
- to determine the effect of human activities on climate.

Progress in understanding climate system variability and change makes it possible to address its predictability and to use this predictive knowledge to develop adaptation and mitigation strategies. Such strategies help global communities to respond to the impacts of climate variability and change including those pertaining to food security, energy and transport, environment, health and water resources.

The main foci of WCRP research are:

- Observing changes of the Earth system and in the interaction of its components (atmosphere, oceans, land and cryosphere);
- Improving our knowledge and understanding of global and regional climate variability and change, and of the mechanisms responsible for this change;
- Assessing and attributing significant trends in global and regional climate;
- Developing and improving numerical models that can simulate and assess the climate system on a wide range of space and time scales;
- Investigating the sensitivity of the climate system to natural and human-induced forcing agents and estimating the changes resulting from specific disturbing influences.

CLIVAR works closely with its sister WCRP core projects, in particular in the implementation of the WCRP Grand Science Challenges, and with the WCRP global modeling working groups (WGCM and WGSIP) and Working Group on Regional Climate (WGRC). The WCRP Modeling Council and the Data and Analysis Council (WMAC and WDAC) serve to coordinate high-level aspects of modeling and data across WCRP, and integrate CLIVAR efforts with those of the other WCRP activities and other partners such as WWRP and FutureEarth.

The World Climate Research Programme is sponsored by the World Meteorological Organization (**WMO**), the International Council for Science (**ICSU**) and the Intergovernmental Oceanographic Commission (**IOC**) of UNESCO. CLIVAR also contributes to initiatives of the two other WCRP sponsors, WMO and ICSU.

[1] The CLIVAR leadership consists of members of the Science Steering Committee (SSC) and chairs from all CLIVAR panels and research foci.

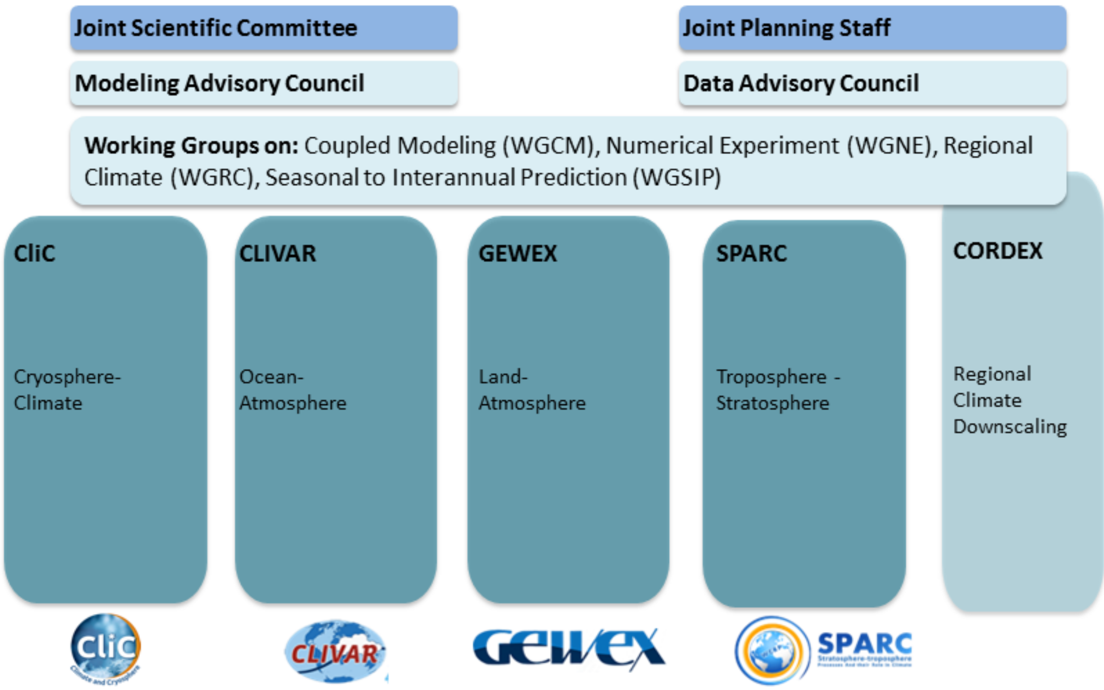

Fig 1: WCRP structure (see http:wcrp-climate.org for details).

1.2 CLIVAR's role within WCRP

CLIVAR is one of four core Projects of the World Climate Research Programme (WCRP). **CLIVAR's mission** is to understand the dynamics, the interaction, and the predictability of the coupled ocean-atmosphere system. To this end it facilitates observations, analysis and predictions of changes in the Earth's climate system, enabling better understanding of climate variability and dynamics, predictability, and change, to the benefit of society and the environment in which we live.

Initiated in 1995, the CLIVAR project built on the successes of the Tropical Ocean – Global Atmosphere Project (TOGA) and the World Ocean Circulation Experiment (WOCE) to further understanding of the oceans and climate. CLIVAR has contributed to many advances in the field of climate and ocean research.

The CLIVAR legacy includes the implementation and development of major multinational observing networks in all the ocean basins; the development of ocean-climate models and the development of ocean reanalyses, bridging observations and modeling through data assimilation. In-situ elements of established observing systems include global deployment of surface drifters and profiling Argo floats, arrays of moorings in the tropics, full depth sampling of the water column from ships of the repeat hydrography program, and moorings collecting time series at key extra-tropical locations. During the last decades satellite observations of the ocean became a firm part of the observing system.

CLIVAR's previous research has provided fundamental knowledge about the characteristics and dynamics of mechanisms of variability in the coupled climate system. CLIVAR scientists have been instrumental in the development of ENSO seasonal prediction systems and pioneered initialized decadal predictions. Originally as part of CLIVAR, the developments of coupled models contributed significantly - through the development of coupled climate modeling capabilities and of climate model intercomparison projects - to the understanding of the response of the climate system to anthropogenic increases in radiatively active gases and changes in aerosols.

CLIVAR, through the advancement of the climate observing systems, process studies and coupled climate models, has greatly advanced our understanding of the processes driving the ocean circulation and its role in the coupled climate system. Through CLIVAR's efforts during the past two decades we now have unique, new observing and modeling capabilities to investigate the variability and dynamics of the ocean.. In addition, CLIVAR embraces many new activities and projects that develop outside the CLIVAR framework but that demonstrate clear relevance to CLIVAR goals and objectives. Topical scientific workshops are organized by CLIVAR aimed at communication, collaboration, education, and furthering the careers of young scientists. CLIVAR science makes fundamental contributions to the knowledge and understanding of the climate system that must underpin the provision of climate services and that is regularly assessed by the Intergovernmental Panel on Climate Change (IPCC).

After restructuring WCRP, CLIVAR's new objective is to describe and understand the dynamics of the coupled ocean-atmosphere system and to identify processes responsible for climate variability, change and predictability on seasonal, interannual, decadal, and centennial time-scales, through the collection and analysis of observations and the development and application of models of the coupled climate system, in cooperation with other relevant climate-research and observing activities.

To this end, CLIVAR coordinates international research in climate and ocean science, facilitating cooperation amongst national and multinational efforts, thereby enabling global climate research beyond regional and institutional capabilities of any involved individual nation. Through its Panels, Research Foci, workshops, summer schools and conferences, the CLIVAR project continues to bring together researchers from all over the world to coordinate efforts required to understand the dynamics of the coupled ocean-atmosphere system and to identify processes responsible for climate variability, change and predictability.

CLIVAR's critical contributions to WCRP will cover the following important topics:

- Understanding the ocean's role in climate variability.
- Understanding the role of the ocean in shaping the hydrological cycle and distribution of precipitation at global and regional scales;
- Understanding the predictive drivers of regional climate phenomena on different time scales;
- Provision of coordinated observations, analysis and predictions of changes in the Earth's climate system;
- Attribution of climate variability and change;
- Development and evaluation of climate simulations and predictive capabilities.

1.3 Structure of Research Plan

The structure of the research plan consists of an outline of CLIVAR's research challenges and outstanding research questions provided in Chapter 2. Chapter 3 summarizes CLIVAR's organizational structure and implementation. The international coordination of enabling capabilities is discussed in Chapter 4. The need for international cooperation in setting up or expanding the enabling infrastructure facilitated by CLIVAR is also be addressed, e.g., in modeling and observations that allow the WCRP' Grand Challenges (GCs) and other climate science efforts to be successfully and efficiently addressed.

The CLIVAR science plan will be updated on a continued basis to take into account newly emerging challenges and demands from the science community and nations, worldwide.

Chapter 2. CLIVAR Science Challenges

CLIVARs research is guided by and organized around three main science challenges.

- Determining mechanisms of climate variability, climate change and climate sensitivity.
- Quantifying fundamental physical processes that need to be properly represented in climate models.
- Identifying the ocean's role in climate predictability with implications for extreme events.

These are long-standing challenges that motivated CLIVAR initially. And while substantial progress has been made important questions remain along with newly emerging ones. They all will be listed below, separately for each subtopic.

One of the expected outcomes of CLIVAR research is the development of improved predictive capability of climate and climate change for the benefit of society.

2.1 Mechanisms of climate variability, climate change and climate sensitivity

In general terms, climate variability arises from intrinsic processes within the atmosphere, the oceans, land and the coupled system. For example, large-scale atmospheric circulation patterns such as the hemispheric Northern and Southern Annular Modes (NAM and SAM, respectively), as well as more regional patterns such as the North Atlantic Oscillation (NAO) and the Pacific-North American (PNA) and Pacific-South American (PSA) patterns, among many others, result from internal dynamics of the extra-tropical atmosphere. These intrinsic atmospheric patterns typically exhibit e-folding time scales of a few weeks or less. This does not mean that they have no variability on long time scales; indeed, their "white noise" spectral character indicates that they fluctuate on all time scales. These intrinsic atmospheric patterns may interact with the underlying ocean to produce spatially-coherent structures of regional and hemispheric SST variability, for example the Atlantic "tripole" and a pattern reminiscent of the "Pacific Decadal Oscillation". Because of the upper ocean's greater thermal inertia, these atmospherically-forced patterns of SST variability exhibit a red-noise character, with typical e-folding time scales of months to years. Internal oceanic processes such as those governing fluctuations of the global thermohaline circulation generally result in lower-frequency phenomena. A prime example is Atlantic Multi-decadal Variability (AMV), whose sub-polar center of action is linked to ocean dynamics. Finally, coupled interactions between the atmosphere and ocean may produce patterns of variability with preferred time scales. A prime example is ENSO, which originates from air-sea interaction in the tropical Pacific. External forcing of natural or anthropogenic origin may influence these intrinsic "modes" of variability. At the same time, they may feed back by influencing Earth's energetics at global, ocean basin, and regional scales.

Relevant key CLIVAR activities are organized around the following guiding questions:

- What is the ocean's role in determining or modulating climate variability and externally forced climate change?
- What are the oceanic constraints on climate sensitivity, air-sea exchange and Earth's energy budget?
- What are the regional impacts of a changing climate upon sea level, ocean heat content, cryosphere and the water cycle?
- What is the ocean's role in the Earth's carbon cycle?

2.1.1 The ocean's role in climate variability

The ocean plays a fundamental role in setting or modulating climate variability through air-sea interactions, internal variability, coupling with sea ice and responding to fresh water inputs from river runoff and ice sheets. It also responds to various natural and anthropogenic forcing factors, which affect the ocean's heat, salt and carbon budgets that feedback upon the atmosphere, sea ice, ice-sheets and biogeochemical cycles.

Progress has been made in observing, modeling, understanding, and predicting aspects of these climate phenomena. However, many open questions remain concerning their origin, predictability, and sensitivity to natural and anthropogenic forcing.

To further improve our understanding of the ocean's role in climate variability, CLIVAR must provide improved quantitative characterization and physical understanding of (1) internal variability and (2) the impact of external forcing on intrinsic modes of variability. Understanding the oceans role in setting and modulating climate variability requires the understanding of mechanisms driving coupled modes of variability, a prime example being ENSO, but also aspects of Pacific Decadal Variability (PDV) and Atlantic Multi-decadal Variability (AMV), and how such modes interact through atmospheric and oceanic teleconnections. Determining the interplay between large-scale ocean variability and regional scale climate and coastal impacts is fundamental to the research foci of the CLIVAR program. Finally, an understanding of the ocean's role in climate variability cannot be accomplished without also taking into account the role of intrinsic atmospheric variability and its thermodynamic interaction with the upper-ocean mixed layer.

In many cases, classical modes of variability do not provide a direct analog for spatial patterns of anthropogenic climate change. The extent to which we can interpret climate change as change in the frequency distribution of internal modes is similarly limited. Yet there is emerging knowledge of the dynamical processes underlying the statistical descriptions of modes of variability. It remains a challenge to translate this dynamical understanding into dynamical understanding of climate change and regional impacts, e.g., on precipitation over land.

The Atlantic Meridional Overturning Circulation (AMOC) is thought to be a key driver of AMV that has impacts on Sahel rainfall, North American and European weather, the South and East Asian Monsoons and Arctic sea ice (e.g., Sutton and Hodson, 2005). Decadal AMOC variability is positively correlated with northward energy transport in the ocean, but anti-correlated with transport in the tropical atmosphere. However, regional dynamical feedbacks are unknown. While coupling between the atmosphere and ocean on interannual time scales has been extensively studied, relatively less is know about how the atmosphere and ocean interact on decadal time scales. It is not possible to assume that the same feedbacks that operate during the interannual ENSO cycle also exist on longer time scales. Under climate change conditions, the locations of tropical rainfall changes over land are highly uncertain; nevertheless large changes are expected and may arrive as early as mid-century (Chadwick, 2015; Xie et al., 2015).

Internal modes of climate variability: Progress is necessary on analyses of internally generated modes of atmospheric, oceanic and coupled variability across a broad range of time scales. This should include the role of high frequency atmospheric fluctuations and associated coupled feedbacks in the generation and development of tropical cyclones, and in setting the characteristics of intra-seasonal variability with possible implications for lower-frequency phenomena.

New foci should emerge on the analyses of the different modes of variability considering the diversity of their impacts including in terms of regional sea level, ocean productivity, and the energy and water cycles. In addition, interactions among modes , their teleconnections, and the extent to which they depend on the characteristics of the background mean state, for example basin width, baroclinicity, strength of ocean-atmosphere coupling, and oceanic heat content merits attention.

Externally forced variability: Progress is necessary on the understanding of how external forcing may modify existing modes of internal climate variability, and possibly create new ones. These include understanding the mechanisms whereby forced climate change modifies the mean state that in turn may impact variability. In this context, external radiative forcing includes changes in trace gasses notably GHG, natural and anthropogenic aerosols, volcanic eruptions, solar insolation related to changes in Earth's orbit, and land use/land cover changes. Examples include GHG-induced effects on polar amplification and sea-ice which in turn leads to changes in oceanic and atmospheric circulations in addition to effects on ocean stratification, with impacts on mixed layer depth and air-sea interactions. Similar considerations apply to the case of anthropogenic aerosol forcing. It is also noteworthy that oceanic and coupled processes may extend the lifetime of impacts from a volcanic eruption to nearly a decade, although additional understanding of the governing mechanisms is still needed. Finally, the effect of solar variability on past ocean circulation states is still elusive (e.g. Holocene Bond cycle) and in need of further study.

> It is imperative to formulate null hypotheses against which to test the impact of external forcing on the characteristics of internal variability. One such null hypothesis is that stochastic processes modulate internal variability. In particular, the impacts of external forcing on phenomena such as ENSO, PDV and AMV must be benchmarked against such a null hypothesis, recognizing that climate records are generally not long enough to reject the null hypothesis with confidence.

2.1.2 Ocean constraints on climate sensitivity, air-sea exchange and Earth's energy budget

The apportioning of energy in the atmosphere, ocean, land, and ice components of the Earth's climate system (Figure XX), and the energy exchanges among these components on various time-scales are at the core of climate dynamics and determine how the climate system evolves.

To understand how the climate system balances the Earth's energy budget, CLIVAR jointly with GEWEX will investigate processes occurring at three levels: the surface of the Earth (including the ocean and land), where most solar heating takes place; the Top of the Atmosphere (TOA), where sunlight enters the system and infrared thermal radiation leaves; and the atmosphere in between.

At each level, the amount of incoming and outgoing energy must, on average, be equal on longer time scales for an equilibrium climate. Under climate change conditions caused by human activities (IPCC, 2013), the composition of the atmosphere is altered and excess solar energy is trapped in the Earth System. This Earth's energy imbalance (EEI) (Hansen et al., 2011) results in planetary heating, and interferes with the natural flow of energy through the climate system (Trenberth et al., 2014).

The global ocean plays a critical role in regulating these energy flows (natural and anthropogenic), being by far the most important heat reservoir due to its enormous heat storage and transport capacity. Over 90% of the anthropogenic excess heat goes into the oceans (IPCC, 2013; Figure XX). The remaining excess heat from planetary warming goes into melting of both terrestrial and sea ice and warming the atmosphere and land (Hansen et al., 2011; Church et al., 2013; Trenberth et al., 2014; Figure XX).

CLVAR uses observations from the climate observing systems (remote sensing and in situ) along with climate modeling and synthesis tools (e.g., ocean and atmospheric reanalyses, climate models) to monitor and analyze where the energy is accumulating and what the prospects are for future climate change. In addition CLIVAR uses physical approaches based on ocean constraints on climate sensitivity, air-sea exchange and Earth's energy budget (CLIVAR research focus CONCEPT-HEAT, section XX, von Schuckmann et al., 2014) to assess uncertainties of existing climate observing systems and tools, as well as to advance climate research through multi-disciplinary synergy approaches (e.g. von Schuckmann et al., 2015).

These different ocean constraint approaches include:

(1) Constraint of planetary energy balance. Under the influence of external and/or internal climate forcing the Earth's energy budget is no longer in balance, and can hence, lead to a temporal positive or negative EEI. On a global annual scale, the change in TOA net radiation and rate of ocean heat storage should be in phase and of the same magnitude (Loeb et al., 2012). This is due to the fact that all other forms of heat storage in the Earth system are factors of 10 or smaller than ocean heat storage (Levitus et al., 2001). The use of this physical constraint in previous analysis has lead to fundamental discussions within the climate science community such as the "missing energy concept" (Trenberth and Fasullo, 2010), or the role of the deep ocean in global ocean warming (Trenberth, 2010; Hansen et al., 2011; Loeb et al., 2012; Levitus et al., 2012).

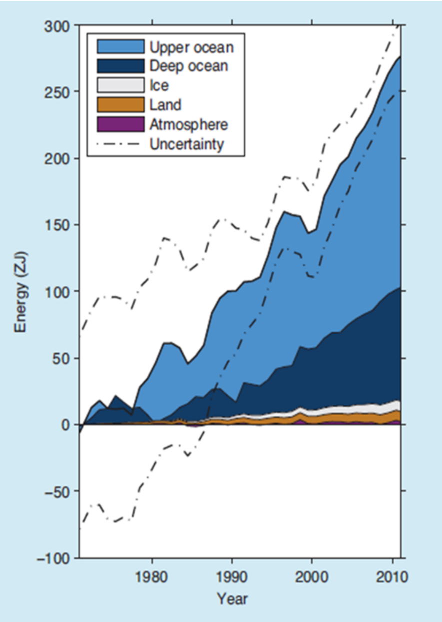

Figure XX (from IPCC, 2013): The largest amount of energy accumulated in the climate system is stored in the global ocean (~ 93%). The rest goes into melting of land and sea ice (~ 4%) and warming of the atmosphere and land (~ 3%). The prevailing increase of stored energy in the global ocean (blue shadings) as measured by Global Ocean Heat Content (see Abraham et al., 2013 for a review on observed GOHC) is a clear indicator for a warming climate.

(2) Constraint of air-sea exchange. Global and regional integrations of net heat fluxes through the air-sea interface lead to mean errors on the order of 20 Wm^{-2} (Josey et al., 2013). Thus, improving our estimates of the global surface energy budget and producing reliable uncertainty estimates remain to be significant challenges to the air-sea/land interaction community. Advances in ocean observing systems (e.g., Argo, the Rapid-MOCHA array) and synthesis efforts (e.g., Ganachaud and Wunsch, 2002, Stammer et al., 2004) have provided an alternative method to constraint the estimates of global or regional net air-sea heat flux (Yu et al., 2013; ICPO, 2013). In the regional context, for example, the heat budget equation can be written as

$$d(OHC)dt = Qnet + Qocean \quad ,$$

where *OHC* is the ocean heat content (storage), Q_{net} is the regional net air-sea heat flux, and Q_{ocean} is regional oceanic heat transport convergence due to advective and diffusive processes. Data from the Argo observing system can provide estimates of on seasonal and longer time scales during the last decade. If a region is chosen strategically such that Q_{ocean} has minimal contribution or can be estimated reliably from observations such as those from the Rapid-MOCHA array or from ocean synthesis products (Balmaseda et al., 2015), then Q_{net} can be effectively constrained by ocean observations and synthesis. This is similar to the CAGE concept envisaged in the early 1980s (Bretherton et al., 1982).

(3) Constraint of global sea level budget. Global sea level change SL_{TOTAL} is related to global steric (density) height (SL_{STERIC}) and ocean mass variability (SL_{MASS}) through

$SL_{TOTAL} = SL_{MASS} + SL_{STERIC} + SL_{RES}$.

SL_{TOTAL} is observed by altimetry since 1993, SL_{MASS} is measured by gravity satellite missions such as GRACE during the last decade (Chambers and Schröter, 2011), and SL_{STERIC} can be integrated globally over the 2000 m from Argo data since 2005 (von Schuckmann et al., 2011) and before over the upper 700m depth from historical ocean hydrographic data (Abraham et al., 2013). The residual of the sea level budget (SL_{RES}) includes deep-ocean steric changes (below integration depth), plus any source of uncertainty in observations and/or data treatment (e.g., quality control, gridding, von Schuckmann et al., 2014). Beside the quantification of the global sea level budget (e.g. Church et al., 2011), examples for application of this physical budget constraint include uncertainty assessment for different independent global observing systems (Willis et al., 2008; von Schuckmann et al., 2011; Dieng et al., 2015a,b), performance assessment of global observing systems (e.g. von Schuckmann et al., 2014), as well as indirect estimates of climate related estimates such as the deep ocean warming and the EEI (Llovel et al., 2014).

2.1.3 Regional impacts of the changing climate: sea level, ocean heat content, cryosphere and water cycle

Climate change does not just manifest itself in terms of global changes, but typically comes with pronounced regional patterns. The impacts of climate change are more complex at a regional scale because natural ocean internal variability and this noise source frequently masks the detection of long-term trends not only at regional scales, but also for global estimates (e.g. Cazenave et al., 2014). In particular and in despite considerable progress during the last decade, major gaps remain in our understanding of past and contemporary sea level changes and their causes, particularly for prediction/projection of sea level rise on regional and local scales, and superimposed extreme events (magnitude and return frequency). These uncertainties arise from limitations in our current conceptual understanding of relevant physical processes, deficiencies in our observing and monitoring systems, and inaccuracies in statistical and numerical modeling approaches to simulate or forecast sea level. The same holds for regional and coastal sea level change. It is especially the coastal sea level rise that is among the most severe societal consequences of anthropogenic climate change.

Understanding and predicting regional and coastal sea level quantifying the composite of global mean sea level (GMSL) change and regional and local processes. These contributions can include: exchanges of mass between the land, the cryosphere and the ocean; dynamics of the ocean and associated water mass transformation and/or redistribution; and static processes associated with deformation of the solid Earth, resulting in seafloor movement along with gravitational and rotational effects.

CLIVAR's efforts on regional scales includes:

- Better understanding of low-frequency variability in terms of heat content, freshwater and sea level and their association with changes of the ocean circulation (MOC and/or wind-driven circulation).
- Investigation of changes of the ocean heat uptake, freshwater changes, and sea level changes on decadal and longer time scales.
- Identification of the processes by which the ocean takes up heat; identification of geographical regions, where excess heat is being taken up and those where this heat is being stored; same for freshwater.
- Assessing the dynamical causes of observed changes and what regional changes can be attributed to human influence?
  Regional and coastal sea-level predictions and projections

Observed climate variations such as the current hiatus or unresolved inconsistencies of climate observations (e.g. "missing energy" in the climate system) underpin the need for fundamental research activities on the regional distribution of TOA, OHC (including vertical distribution) and sea level, as well as their implication for their global estimates. Continued assessment and attribution studies of regional natural climate variability are essential to improve our estimates of global changes. There is also an urgent need to evaluate the relative importance of currently under-sampled regions of ocean heat content change and related volume changes (ice-covered ocean, marginal seas and deep ocean) and to understand how heat is transferred vertically (von Schuckmann et al., 2016). We have to evaluate how regional patterns change in time and if regional OHC tendency patterns can, along with other patterns e.g. regional sea level, be used to test/falsify model hypotheses. We need to further understand the role of resolution of climate models and reanalysis models in resolving natural climate variability and providing accurate error estimates, as well as to understand which are the relevant model physics and parameterizations that need further improvements.

As well as global estimates, it is desirable to have the energy imbalance locally and as a function of time of year. There is a framing for how to do this related to what has previously been called a "CAGE" experiment envisaged in the early 1980s (Bretherton et al., 1982; Yu et al., 2013; ICPO, 2013) and was designed to inter-compare three types of independent estimates in a single basin under favorable circumstances to establish the random and systematic errors associated with each approach. Three approaches for computing meridional heat transport by the oceans are discussed, including using the ocean temperature and velocity observations, air–sea heat fluxes, and the net radiation at the top of the atmosphere coupled with the atmospheric flux divergence. More precisely, the design of the CAGE experiment recognized:

(i) the importance of meridional heat transport in Earth's climate,
(ii) the need for obtaining an accurate estimate of the mean state of the global climate and of the ocean's role in maintaining that state,
(iii) uncertainties in existing surface flux products and ocean observations that preclude realistic assessment of the changes in ocean heat transport and storage.

It is now possible to carry out this approach owing to numerous advances in the global climate observing system and are discussed on the CLIVAR research focus CONCEPT-HEAT (ICPO, 2016).

2.1.4 Carbon uptake and biogeochemical cycles

The ocean is currently responsible for the sequestration of approximately 42% of historical fossil fuel CO_2 emissions, providing an invaluable climate service. Understanding ocean carbon uptake and cycling is critical not just for the characterization of this climate service, but also as a critical inverse constraint on land carbon uptake, which is very difficult to measure directly. How much carbon the ocean will continue to take up in the future is a topic of critical climatic concern. Improving our understanding of the patterns of ocean carbon uptake and its variability is central to understanding the future carbon and climate trajectory of the earth system.

Much of the seeming certainty in ocean carbon uptake estimates derives from our assumption that the ocean biogeochemistry and circulation are in a quasi-steady-state on centennial timescales. Unfortunately, such reductionist assumption comes from a lack of observations to refute it. One effort of CLIVAR is therefore focused on understanding the attributions of changes in carbon uptake on interannual to multi-decadal timescales with the objective of distinguishing between internal variability in the changing carbon system and secular changes on centennial and longer timescales. In order to resolve interannual variability and trends, uncertainties of estimates of CO2 fluxes across the ocean surface need to be less than 10% (Monteiro et al., 2010). The available observations are insufficient in this respect, also because the high latitude oceans, traditionally poorly sampled, are responsible for more than 60% of the ocean carbon uptake. For example two dominant modes of climate variability that significantly impact the ocean carbon budget are the Southern Annular Mode (SAM) (LeQuéré, et al., 2007) and the MOC (McKinley et al., 2011; Ito et al., 2015), but the observational characterization of their variability is limited, their representation in climate models substantially biased, and their evolution under climate warming highly uncertain.

Model-only predictions support weakening ocean CO_2 uptake in the years to come, while empirical-modeling-based predictions based on the assumption of steadiness in circulation and biogeochemical cycling suggest that uptake will continue increasing with emissions. CLIVAR is active in reconciling these differences, in trying to reduce uncertainties in observations-based flux estimates, as well as in addressing questions around regional vs. global scale approaches. Improvements in the physical representation of ocean ventilation and its sensitivity to climate variability and change, along with a more robust understanding and representation of regional biogeochemical processes are critical to improving reliability of future climate trajectories in the face of climate and biogeochemical variability. CLIVAR is particularly active in identifying and reducing regional ocean biases in ocean models: These biases fall into three general categories: (i) surface properties and air-sea exchanges; (ii) subsurface circulation and stratification; and (iii) representation of specific physical and biogeochemical processes.

As an example, model-based estimates of the impact of surface wind changes on ocean carbon uptake are highly dependent on driving surface flux measurements. Unfortunately, uncertainties in reanalysis and observed surface wind stress products, for example, put current model-based estimates of CO_2 uptake changes into question (Swart et al., 2014). Support for advancing the biogeochemical ARGO array and other long-term surface flux observations, and their evaluation and contextualization through synthesis and modeling is key to constraining these estimates.

On decadal timescales, observationally based estimates of ocean carbon uptake are highly reliant on global surveys of anthropogenic carbon distributions derived from synthesis of direct measurements and via biogeochemical proxies. CLIVAR's support for continued efforts such as TPOS and GO-SHIP is key to providing these constraints. On centennial and longer timescales, changes in ocean carbon are thought to be major contributors to past climate variability, and should provide important constraints on the climate sensitivity to anthropogenic CO_2 when other factors such as land ice, sea level, and past circulation changes are taken into account. Research efforts relevant to CLIVAR's mission in this area are ongoing in collaboration with the paleoclimate community.

Overall, CLIVAR continues to play a key role in identifying and exploring the mechanisms by which changes in carbon fluxes and biochemical cycles feedback on climate through a diverse array of research enterprises including sustained field and autonomous observational networks, synthesis, theory and modeling. CLIVAR supports the design and implementation of new process studies to address gaps, improve process parameterizations in models and propose new measurements. The identified processes are related to specific physical phenomena that occur in the ocean and play an important role in carbon and heat uptake. These processes link ocean physics, biology, and biogeochemistry and operate across Earth system boundaries (ocean, land, cryosphere, atmosphere). Examples of such processes include transport by mesoscale eddies at low- and high-latitudes; dynamics of coastal upwelling zones; ocean convection; overflows from marginal seas and shelf, and interior pathways of dense water masses.

An important aspect of CLIVAR's research on the oceans role in anthropogenic carbon uptake is the investigation of the changing role of the Southern Ocean. Current estimates indicate that the SO takes up 80% of the heat and 50% of the CO2. Central to our understanding of the Southern Ocean is the role of wind forcing. A rigorous assessment of the input of wind energy into the ocean and the uncertainties (spatial and seasonal) associated with the observing system is needed, as there are still basic unanswered questions. For example, estimates of satellite- and reanalysis-derived winds are poorly constrained and therefore wind trends uncertain. More direct observations, as well as enhanced validation of satellite products with radiosonde data are needed. The contribution of wind products towards the uncertainty of flux estimates is being increasingly highlighted (Wanninkhof, 2013; Monteiro et al., 2015)

Beyond carbon, indications that changes in biogeochemical fluxes influence climate come from the direct modulation of shortwave penetration by chlorophyll and other seawater impurities, aerosol formation via sulphur cycling, and volatile and particulate organic carbon emissions (REFS). While SOLAS continues to lead the characterization of these biogeochemical contributors, CLIVAR plays a key role in contextualizing these components and their feedbacks within the whole earth system, particularly by supporting climate process teams to bring novel understanding from observations and theory into earth system models.

2.2: Quantifying fundamental processes that need to be properly represented in climate models.

Understanding what processes are critical to climate variability and change is of importance for several reasons. Primary among these is that first-order physical processes need to be correctly represented in climate models to improve simulations of ocean and climate variability.

There are numerous ways in which the oceans affect the Earth's climate over different space and timescales, and improved knowledge of the processes that are critical to climate variability is essential. Such processes include, among many others, ocean mixing; heat and freshwater fluxes at the interface of the ocean with the atmosphere; sea ice control of buoyancy fluctuations, especially along shelves; and upwelling and shelf interactions in boundary currents. At global scales is also imperative to improve our understanding of the coupling mechanisms between the wind-driven and the buoyancy-driven circulations; and linkages between shortwave radiative fluxes and biological processes in the upper oceans. Recent studies have also highlighted that improved understanding of mesoscale and sub-mesoscale ocean variability, of air-sea fluxes over frontal zone and of the diurnal cycle may have a role in the ocean heat transport (ref) and its intraseasonal variability (ref), and in the development of the seasonal cycle (ref). Finally, perturbation of the ocean hydrological cycle can influence the ocean thermohaline circulation with implications over centennial to millennial time-scales, or lead to abrupt transitions such as the Dansgaard-Oeschger (REF) events recorded during glacial times.

CLIVAR activities in this arena are organized around the following guiding questions:

- What processes are critical for global and regional climate variability (e.g., what oceanic or ocean-atmosphere coupled processes do influence regional modes of climate variability and teleconnections, and how)?
- Which processes do control the ocean energy budget and what is their relative contribution?
- What processes do control coastal dynamics and upwelling systems, and what how may the coastal ocean change in a warming climate?

2.1.1 Climate Dynamics, feedbacks and regional modes of coupled variability

In the past, much research on climate dynamics has focused on statistical descriptions of variability and change in terms of climate modes, such as the North Atlantic Oscillation (NAO), the Pacific North American (PNA) pattern, and the Southern and Northern Annular Modes (SAM/NAM). These descriptions offer compact ways of describing climate variability and its impacts. However they are less useful in providing insight into the dynamical and physical processes that drive the variability and will be essential for climate change.

For this purpose CLIVAR seek to understand and predict statistical measures of the behavior of dynamical phenomena, e.g., the average and variability of the position of the jet stream or Inter Tropical Convergence Zone (ITCZ), or the intensity and structural organization of storm tracks and associated strength and frequency of storm events. The importance of predictive understanding of the dynamics of climate is increasing as our planet experiences warming through this century that is unprecedented in human history (Xie et al., 2015). The success of predictions depends on knowing the response of such phenomena to boundary conditions; the ocean, ice and land surface signals and external factors, including anthropogenic influences. A major challenge in climate dynamics is to move beyond qualitative indicators to quantitative descriptions of physical and dynamical feedbacks and processes.

CLIVAR has chosen to focus on five different areas and aims to accelerate our predictive understanding of these phenomena with a focus on the role of atmosphere-ocean interactions. They present challenges for observations, models, and theories, alike.

(1) Storm tracks, jet streams, and weather systems: One view of the NAO that of the seasonal imprint of the position of the North Atlantic's storm track, either being preferentially zonally oriented with storms mostly propagating into western Europe, or having a pronounced SW-NE tilt with storms preferentially propagating towards Scandinavia. Predictable variations in the NAO are hypothesized to be related to Rossby Wave trains emanating in the tropics/subtropics, forced by variations in tropical and subtropical convection (Scaife et al., 2014). While the benefit of predictable capabilities are obvious, the extent to which this linear view of the NAO holds needs to be tested. Under climate change conditions there are competing influences on the Northern Hemisphere storm tracks and, as a consequence, models tend to predict only modest changes in storm in the Northern Hemisphere. While thermodynamic aspects of storms and storm tracks seem relatively robust across models, there is little confidence in their projected changes in dynamical aspects (Collins et al., 2013).

(2) Extra-tropical air-sea coupling: It has become clear that the western extra tropical ocean basins can affect the atmospheric circulation through SST anomalies associated with variations in western boundary currents. Those anomalies can have a significant local influence on atmospheric vertical velocities, providing diabatic sources of heating and moistening of the troposphere (Minobe et al., 2008). While atmospheric models forced by SSTs have long provided evidence for the impact of the ocean on the atmosphere, our understanding of the oceanic forcing of the atmosphere outside the tropics needs to be fostered. Atmosphere-ocean interactions in the extra tropics lead to the damping of surface turbulent heat fluxes, so that atmospheric anomalies may persist longer. The development of respective experiments has been proven valuable (Kosaka and Xie, 2013) and need to be further refined. The extent to which these local influences get 'scaled-up' to affect jet streams and storm tracks is still an open question. High-resolution in both atmosphere and ocean models are required to represent this influence. These processes are investigated by CLIVAR to better understand mid-latitude coupling.

(3) Tropical-extratropical interactions: The Intertropical Convergence Zone (ITCZ) typically is described as a contiguous rain band. However, in the tropics rainfall is associated with tropical convection, whereas towards midlatitudes the rainfall is mostly associated with the equatorward propagation of midlatitude weather systems. Monsoon circulations can be viewed as the excursions of tropical convergence zones over land (Bordoni and Schneider, 2008); however, a rapid monsoon onset is not adequately explained by the classical planetary-scale sea breeze circulation. To what extent stationary waves and local processes (e.g., latent heating and land-atmosphere interaction) influence regional monsoon dynamics in terms of timing and strength is being investigated by CLIVAR.

(4) Long-term coupled atmosphere-ocean circulation: In many cases classical modes of variability do not provide a direct analog for spatial patterns of mean climate change. The extent to which we can interpret climate change as change in the frequency distribution of modes is similarly limited. Yet there is existing and emerging knowledge of the dynamical processes that underlie the statistical descriptions of modes of variability. It represents a challenge to translate this dynamical understanding into dynamical understanding of climate change.

Fundamental physical processes that influence the ocean, in turn, determine the modes of ocean variability on various space and time scales. Among them oceanic eddies and waves dominate this variability on timescales of days to months. Eddies can be thought of as the oceanic counterpart of weather in the atmosphere and are generated through various physical mechanisms – sudden changes in the direction of surface winds and their speed; dynamical instabilities associated with the ocean thermal fronts; and interactions between oceanic flows and bottom topography. However, such mechanisms are not always /everywhere well constrained. Due to their ability to exchange energy with the large-scale oceanic state, mesoscale eddies influence the oceanic circulation and stratification on a variety of timescales. They contribute to the transport heat, salt and biogeochemical tracers (such as carbon and oxygen) and play a key role in the oceanic uptake of heat and carbon. Most climate models do not explicitly resolve ocean eddies and rely on empirically derived parameterization schemes (Mclean et al. 2008). Internal gravity waves breaking in the ocean interior and near rough topography likely plays a critical role in the transformation of water properties through diapycnal mixing, influencing global scale processes such as the Meridional Overturning Circulation (MOC).

The ocean circulation is also very sensitive to the fresh water flux from river runoff, or from Ice-sheet/Ocean Interactions. How the different fresh water fluxes affect the ocean stratification and the stability of the MOC is still poorly understood, and poorly represented in climate models (refs to Ramsforth paper, Boening nat geo 2016, and Luo nat geo 2016). Improved understanding of the role of salinity and fresh water fluxes in triggering ocean variability and changes at multi-decadal to millennium time scale is a prerequisite to understand past and future climate tipping points such as Dansgaard-Oeschger events.

2.2.2 Ocean energetics and mixing

The ocean is a forced-dissipative dynamical system. A longstanding problem of physical oceanography with fundamental implications for the climate system is to understand and quantify how energy moves through the ocean, from the forcing mostly at the large scales to dissipation at the small scales. Addressing the many facets of this problem deepens our scientific understanding of the climate system as a whole, and offers a robust framework for testing numerical models. Here we outline briefly the current understanding of the processes at play, and in so doing we explore areas where CLIVAR leads and can continue to lead coordinated ocean process studies and related numerical model development.

Buoyant forces (imparted by heat and water fluxes at the boundaries) affect the huge store of ocean potential energy by modifying its density. Mechanical forces (from atmospheric, solid-earth and astronomical sources) and buoyant forces affect kinetic and available potential energy (APE) distributions. Large-scale reservoirs of APE are then converted to kinetic energy at the mesoscale (10-500 km scale: the dominant scale of transient ocean kinetic energy) through eddies and frontal features (Wunsch and Ferrari, 2004). When averaged at those scales the ratio between inertial and Coriolis forces (i.e the Rossby number, Ro) is generally less than one and the dynamics are captured by the quasi-geostrophic approximation: mesoscale eddies generally cascade energy upscale (i.e., to the large scales) through an inverse cascade reminiscent of two dimensional turbulence. Near the ocean surface the geostrophic balance between pressure gradient force and Coriolis effect breaks down at smaller scales (so called submesoscales 0.1- 10km) and the lateral density gradients generated by the mesoscale features (eddies and fronts) or by the boundary freshwater fluxes are enhanced through largely unbalanced instabilities (Molemaker et al., 2005; Fox-Kemper et al., 2008; Thomas et al., 2008). Unbalanced submesoscale dynamics (Ro ~ 1) support a direct energy cascade to smaller unbalanced gravity wave motions. Gravity waves also arise through astronomical tides converting to internal tides via interactions with solid-earth boundaries (Munk and Wunsch, 1998), while geostrophic currents again interacting with the ocean solid boundaries give rise to leewaves (Nikurashin and Ferrari, 2010) - see MacKinnon et al. (2013) for a review of these and other gravity wave related processes. The breaking of those waves provides a fundamental, not yet fully quantified, avenue for energy dissipation.

Research over the next ten years will need to explain and quantify how buoyant and mechanic forces are transferred through the boundary layers to the ocean interior. In doing so a better understanding of the oceanic uptake of heat, carbon and oxygen will follow. At the ocean surface, questions arise on the parameterization of bulk formula that translate the atmospheric state (winds, pressure, and temperature) to boundary fluxes, and on the role and importance of surface gravity waves, submesoscale turbulence, Langmuir turbulence and swell waves in the upper ocean boundary layer (Cavaleri et al., 2012; Belcher et al., 2012; McWilliams et al., 2014). At the ocean bottom, relatively small-scale overflow processes provide important conduits for dense shelf waters moving in the high latitude abyss, thus affecting the overturning's deep-limb (Legg et al., 2009).

The energy cascade scenario provides a working hypothesis for how energy transfers from the large- scale forcing, through the boundary layers, to the Kolmogorov scale (mm to cm) where molecular viscosity dissipates it, and offers a framework to investigate fundamental ocean processes. This scenario impacts our basic understanding of the ocean, which in turn has huge practical feedbacks to the formulation and development of high-fidelity numerical ocean climate models. For example, mechanical energy is increasingly being used as a currency that is conservatively transferred between the resolved and parameterized portions of ocean models (Mellor and Yamada, 1982; Gaspar et al., 1990; Eden and Greatbatch, 2008; Marshall and Adcroft, 2010; Jansen and Held, 2014; Mana and Zanna, 2014; Eden et al., 2014).

2.2.3 Boundary currents, coastal processes and upwelling systems

The coastal ocean represents a small fraction of the global ocean, but is significant for the exchange of water mass properties between the surface and the deeper layers. It is also fundamental for air-sea interactions and may play a fundamental role during climate change. In addition it houses a significant proportion of the ocean life. Coastal boundary upwelling systems in particular account for less than 3% of the world ocean surface, but they make the largest single contribution to ocean biological productivity, with up to 40% of the global fish catch (Capone and Hutchins, 2013). The adjacent coastal regions, in addition, host vast human populations, thus playing key biological and socio-economical roles. The Southern Ocean (SO) upwelling system also exert a disproportionally large influence –with respect to its size - on the Earth's heat balance, the carbon cycle, and much of ocean biology.

Two key aspects of on-going CLIVAR research on upwelling systems include identifying common biases in their representation in coupled and ocean models, and understanding their variability and trends in a changing climate.

CGCM biases in upwelling systems: Models show biases in upwelling system which in terms of SST often exceed 3°-10°C. The primary cause of this bias is the underestimation of the upwelled waters due to low resolution, at times augmented by a poor representation of deep water characteristics. The resulting air-sea contrast is thus weaker, implying a diffuse air temperature inversion zone (e.g. Wyant et al., 2010) that often prevents the formation of low-level clouds. These SST biases have remote effects on surface and subsurface temperature and salinity, and on precipitation and hence atmospheric heating and circulation (Collins et al., 2006). The role of air-sea processes in modulating the climate variability and change in the upwelling systems is presently unclear because of the variety of processes and the wide range of space scales involved (from regional to mesoscale). The radiative budget at the air-sea interface is not well understood either and may involve zonal heat transfer from the coast to the open ocean by eddies (Colas et al., 2012; Zheng et al., 2010; Toniazzo et al., 2010), but observational analyses are required (Holte et al., 2013) to understand the role of eddy activity on the stability of coastal current systems (Dewitte et al., 2012; Combes et al., 2015). The SST bias, in turn, causes weaker winds with a positive feedback (Wang et al., 2014).

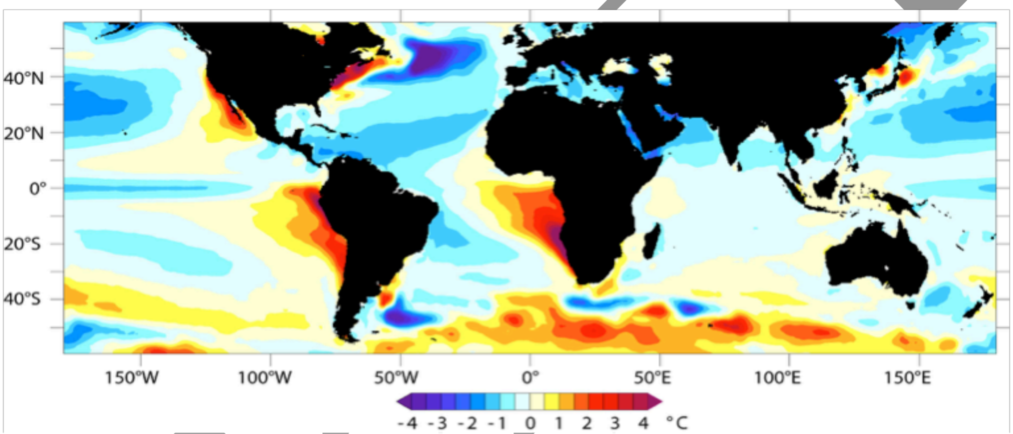

Figure 1: Mean SST bias in the CMIP5 ensemble.

SO upwelling, driven by the westerly vigorous winds, starts close to the Antarctic continent and extends to about 50° S, moving lighter surface water northward and drawing large amounts of deep, dense water to the surface in the south (e.g. Marshall and Speer 2012). Here the warm SST bias, of about 2°-3°C in the CMIP5 multi-model mean is commonly interpreted as result of excessive shortwave radiation absorbed by the southern hemisphere in comparison to the northern counterpart (Trenberth and Fasullo, 2010) due to cloud biases that impact also circulation and precipitation representation (Ceppi et al., 2012; Hwang and Frierson, 2013). A modeling exploration of this issue and of the role of mesoscale eddies in the SO circulation has been recently performed within the second phase of the Coordinated Ocean-ice Reference Experiments (CORE-II), organized by the CLIVAR Ocean Model Development Panel (OMDP). CORE-II uses many different state-of-the-art global ocean-sea ice models forced with the same atmospheric state spanning 1948-2007.

Climate variability and trends in upwelling systems: The state of upwelling regions vary dramatically on interannual and interdecadal time scales and longer. Links between interannual to decadal variability and the state of the upwelling systems are established for some systems (cf. Santos et al., 2005) but the mechanisms by which climate variability connects to them remains unclear, particularly in the South Hemisphere. There is an ongoing a debate on whether upwelling will increase or decrease under climate change. Similar uncertainties are relevant to the SO, where only little warming has been observed in the recent decades and greenhouse gas-induced surface heat uptake appears to be balanced by anomalous northward heat transport associated with the equatorward flow of surface waters, with the end result that heat is preferentially stored where surface waters are subducted to the north (Armour et al.,). Model simulations also suggest that increased wind stress resulting from global warming and the expansion of the ozone hole will continue to increase northward Ekman transport and upwelling (Russell et al., 2006; Le Quéré et al., 2007; Lovenduski et al., 2008). However, the extent to which eddy fluxes may compensate for Ekman transport in the mixed layer is, as already noted, unresolved, as is the balance between increased carbon uptake and outgassing that result from increased upwelling. Difficulties in understanding the long-term evolution of upwelling systems are also related to uncertainties in trends in the atmospheric reanalysis and in the role of the coastal or SO mesoscale atmospheric circulation onto the Ekman dynamics (Capet et al., 2004; Renault et al., 2012; Renault et al., 2015). Given regional peculiarities in both environmental forcing, coastline geometry and topography, sea-ice in the SO case (Purich et al., Nat commn. 2016), and the contrasting results of regional oceanic downscaling experiments in different upwelling systems (Echevin et al., 2012; Curchister et al., 2015), a focus of CLIVAR research is put on evaluating the sensitivity of climate models to climate change and establish a new paradigm.

2.3 How predictable is the climate on different time and space scales?

Weather and climate span a continuum of time scales, and providing forecast information with different lead times is relevant to different sorts of decisions and early warning. The sub-seasonal to seasonal scale is especially interesting as it bridges applications at much shorter (hourly through weekly) and much longer (seasonal through decadal) scales where considerably more societal and economic research has been conducted (e.g. decision and economic valuation studies, climate change impact and adaptation studies). Climate exhibits also variability on decadal (10−20 year) timescales, with important societal consequences. Decadal climate variability is often large enough to overshadow regional and global anthropogenic trends, and hence has relevance for guiding planning decisions about future adaptation investments.

While the provision of forecasts belongs to operational agencies, it is the duty of CLIVAR to investigate the predictability of the climate system and underlying mechanism, to investigate how initialized forecasts or uninitialized projections can be best made and how large uncertainties in respective climate information are. Respective investigates need to address whether seamless predictions can be provided or whether ‘gaps’ in forecasting capabilities exists, for example at the sub-seasonal scale of prediction. After pioneering respective work CLIVAR continues to work at the forefront of climate predictions and projections, now also considering improving the information emerging from such efforts for climate service purposes.

Respective CLIVAR activities are organized around the following guiding questions:

- What limits the predictive skill of seasonal forecasts?
- Which processes lead to decadal variability in the ocean and which of those cause decadal climate predictive skills?
- What are the important dynamical processes that underlie short-term precipitation and temperature extremes?
- How do these short-term processes interact with the larger-scale, slower and potentially-predictable climate fluctuations linked to the ocean?
- Which predictive skills and what properties of extremes are changing under global warming?

2.3.1 Intra-seasonal to Interannual Variability, Predictability and Prediction

From the end-user perspective, the sub-seasonal time scale is a very important one, because it lies between the weather forecasts and the developing use of seasonal forecasts. Many decision making processes, such as in agriculture, require information on the intervening sub-monthly to two-monthly time scale, so the development of more seamless weather-to-climate forecasts promises to be of significant societal value, and will augment the regions/situations where there is actionable forecast information. In principle, advanced notification, on the order of two to several weeks, of tropical storms, severe cold outbreaks, the onset or uncharacteristic behavior of the monsoonal rains, and other potentially high impact events, could yield substantial benefits through reductions in mortality and morbidity and economic efficiencies across a broad range of sectors.

Sub-seasonal predictions benefit from both atmospheric initial conditions and factors external to the atmosphere, such as the state of the ocean, land, and cryosphere. Processes internal to the atmosphere including the Madden-Julian Oscillation (MJO) and low-frequency atmospheric patterns of variability contribute significantly to the predictability (*Nat Acad. Sci. 2010*). Furthermore, in a sub-seasonal forecast, some kind of time average (e.g. weekly or pentad mean) is usually used, which removes part of the weather noise. Therefore, it is reasonable to expect sub-seasonal forecasts i.e. beyond the traditional weather forecast limit of two weeks, to have useful skill. At this time range the forecasts have to be probabilistic.

Model uncertainty prevents one from having a reliable estimate of sub-seasonal predictability. Forecast skill against observations provides a lower bound for predictability, which measures the performance of individual models. The potential predictability resulting from the "perfect model" approach is also highly model-dependent. What can be achieved is unclear. Uncertainty due to model formulation can be improved by multi-model methodologies. Questions that can be explored using a multi-model approach include those related to the upper limit of sub- seasonal predictability and possible skill improvement.

There is still much to learn on sources of predictability. Since not all the processes and interactions are resolved in numerical models, there may still be untapped sources of predictability. It is important to know the relative importance of different sources. Their combination may not be linear, and how the sources interact with each other is not well understood. Other questions related to sources of predictability can also be investigated. For example, it is still unclear how well the models agree on the contribution of the MJO to the forecast skill of surface air temperature and precipitation in extratropical regions. Further studies are needed on models' fidelity in representing global teleconnections and how that influences the forecast skill.

Representation of model uncertainty in atmosphere, ocean, sea ice and land models is expected to be crucial to obtain reliable spread-skill characteristics. While it should be relatively straightforward to apply the multi-model concept in the polar regions extensive research will be necessary to formulate stochastic parameterization schemes, which in the past have focused on the atmosphere in general and convection in particular, for all components of the climate system.

2.3.2 Decadal Variability, Predictability and Prediction (multi-decadal variability and detection/attribution of changes)

Developing a comprehensive dynamical understanding of decadal variability and developing predictive skill based on decadal modes has proven difficult, primarily as a consequence of the scarcity of *in situ* time series that are long enough to resolve it with statistical reliability. Decadal variability is generally described in terms of large-scale modes (Deser et al., 2010). These modes are the dominant patterns of variability, involving both atmospheric and oceanic variables, which reoccur (oscillate) at decadal timescales and are concentrated in specific regions. Several modes can exist within a region. In that case, they tend not to be completely independent, either because they share common dynamics or because similar variables are involved in their definitions. For example, several of the modes describing decadal variability in the Pacific Ocean region are correlated with each other to some degree.

Ongoing challenges are to identify causes and determine if they can be exploited for decadal climate prediction, and to separate natural from anthropogenically-forced variability in the evolution of the climate system (Solomon et al., 2011). Decadal variability is societally important because it directly impacts atmospheric, terrestrial, as well as oceanic conditions.

The time dependence of climate modes typically exhibits a broad peak at decadal frequencies. The lack of a distinct peak is certainly one reason why isolating the basic processes that underlie decadal variability has proven difficult. Decadal-scale variability may also be weak relative to the year-to-year variability. A relatively low signal suggests that the predictability associated with decadal variability is limited (but see below).

Another important consequence of decadal variability is that it obfuscates the climatic trend expected from increasing greenhouse gases, causing global-mean temperatures to rise more rapidly or slowly in some decades (Solomon et al., 2011). For example, the rapidly increasing global mean temperature rise since the 1970s has slowed or even halted since the 1990s (Easterling and Wehner, 2009; Kaufmann et al., 2011, Meehl et al., 2011) and wintertime northern-hemisphere temperatures have cooled during the last 10 years (Cohen et al. 2012a,b). At least for some variables (e.g., precipitation), the trend is not expected to emerge as the dominant climate signal until the middle of the century (Deser et al. 2012b). In the interim, separation of natural (decadal) variability from the anthropogenic signal will be dif- cult, potentially leading either to costly adaptive strategies or to a sentiment of complacency to the need for such actions.

Despite extensive research, the mechanisms that lead to decadal climate variability are not yet well understood. Because of the large thermal inertia of the ocean, it is likely that decadal variability has its origins in coupled ocean-atmosphere interactions, as is known to be the case for the prominent modes of interannual variability (e.g., ENSO in the Pacific, Atlantic Niño, and the Indian Ocean Dipole). In addition, other factors that are not directly linked to ocean-atmosphere coupling are known to impact regional climate variability, and may also be important for decadal variations and feedbacks. They include soil moisture in deeper layers, vegetation, snow cover, changes in anthropogenic aerosols (Kaufmann et al., 2011, Booth et al., 2012), and stratospheric water changes (Solomon et al., 2011).

Many questions remain about decadal variability: its character, the processes that generate it, the scope of its predictability, and hence the level of predictive skill. Scarcity of observations is a severe stumbling block in answering these questions. The use of coupled models therefore becomes a critical tool for scientific advancement. Property-conserving state estimation (data assimilation) is also useful, helping to extract as much information as possible from scarce datasets and to facilitate the improvement of process parameterizations in coupled systems. It is essential to continually evaluate and improve the fidelity of these systems (e.g., Collins et al., 2006; Furtado et al. 2011).

In addition to their ability to improve dynamical understanding, coupled models are beginning to be used to explore the predictability of decadal variability, and experimental prediction efforts have begun (Smith et al., 2013). Some early studies have shown potential decadal predictability when oceanic decadal anomalies can be tracked back to a specific oceanic source, typically a subsurface record indicative of past air-sea interactions. For example, changes in the AMO are associated with AMOC variability (Knight et al., 2005; Zhang, 2008, Hawkins et al., 2011), and the latter has decadal predictability (Teng et al., 2011). On the other hand, the models where these signals are predictable are simple in comparison to the real world, in which strong higher-frequency variability makes predictions at decadal timescales more challenging.

Many outstanding practical issues must be addressed before decadal predictability can be utilized in coupled models to make predictions. They include the following. Given imperfect and incomplete observations and assimilation systems, what is the best method of initialization? What is the added skill in climate predictions with initialization when compared to uninitialized predictions? What is the impact of small ensemble size in the spectrum of decadal means? What predictions should be attempted, and how would they be verified?

2.3.3 Extreme Weather and Climate and Ocean Extremes

Extreme meteorological and oceanographic events can have major impacts on society. Their properties (e.g., strength, duration, and frequency) are often clearly linked to large-scale climate variability and change. In many cases, however, the linkages are so complex that they are not yet adequately understood or even their existence is a matter of debate. Due to the very wide range of possible definitions, the scope is rather vast and underlying physical processes and societal implications can vary considerably based on these definitions, even for the same variable and timescale. They are short-term events with long-term consequences. Climatic factors influencing precipitation extremes are poorly known, in part due to the broad range of dynamical mechanisms involved and to regional differences. The possibility that pending climate change could make extreme events more commonplace or more intense makes the understanding and prediction of extreme events of critical importance.

The ocean impacts climate extremes primarily through its impacts on cyclogenesis and the large-scale atmospheric circulation. In this regard, the various climate modes have a strong influence on modulating extremes. However, this relationship has been better explored for some types of extremes (e.g., precipitation and drought) than for others. The significant gaps existing in our basic understanding of the causes of climate extremes limit our ability to make physically based predictions and projections.

CLIVAR's effort related to extremes are concerned with climate-related extremes, including hurricanes and other intense-wind events; heavy-wave and storm surge events; heavy precipitation on timescales from hours to days, which can lead to flooding on timescales from days to weeks; droughts on timescales from weeks to decades; and cold snaps and heat waves on timescales from hours to weeks.

Hurricane dynamics have been the subject of considerable study, and existing models are able to reproduce many aspects of their movement and distribution. However, how their properties may change under global warming is less certain, depending on multiple factors that can either enhance or suppress cyclogenesis. Additionally, hurricanes are related to the occurrence of extreme values of winds and storm surge, which are important extremes in terms of societal impact.

Precipitation extremes are known to occur in association with synoptic storms, tropical cyclones, and organized heavy convection. A link has been shown between short-term precipitation extremes and some modes of ocean-related variability including ENSO and Pacific decadal variability, suggesting the possibility of long-lead prediction. An overall assessment of the key causes of, and large-scale influences on, extreme short-term precipitation, however, has not yet been made.

Regarding droughts, forcing by Pacific and Atlantic SST anomalies associated with climatic modes (e.g., ENSO and the PDO) appears to have played a prominent role in most major US drought episodes, with additional influence from local factors (soil moisture, temperature-driven evaporation, water availability, vegetation cover and state, etc.). While connections to SSTs in both observations and modeling studies are fairly robust, capturing the magnitude of severe droughts remains difficult. Whether errors result from random noise or imperfect representations of the underlying dynamics is not yet clear. Furthermore, the specific mechanisms by which the large-scale circulation anomalies associated with oceanic forcing modulate continental precipitation are still a current research question.

The causes of temperature extremes (heat waves and cold outbreaks) are not fully understood. Heat waves and cold-air outbreaks are associated with large displacements of air masses into regions where they are not normally found, which in turn are caused by unusually large meridional oscillations in the circulation. Factors that influence heat waves include both local and remote larger-scale factors. Climate models are able to generate large-scale patterns with extreme heat (e.g., Meehl and Tebaldi 2004). However, important details of the large-scale pattern as well as important local processes may be missing; further, the amount of variability may be incorrect or correct for the wrong reasons (Grotjahn, 2013).

Having an adequate observational database is essential for understanding extremes. In this regard, it is important to ensure that records are long lasting and without gaps in order to capture reliable statistics, especially if the statistics are not stationary. Regarding modeling, key questions are: Do current models produce realistic precipitation and temperature extremes for the correct dynamical reasons? Do they adequately represent both large-scale and local processes? Are model parameterizations, which might be tuned for "median conditions," adequate for representing extremes? Are they therefore reliable enough to make long-term projections?

Chapter 3. Organizational Structure and Implementation (5p)

3.1 Concept of Panels

CLIVAR's structure has evolved to meet the challenges described in the previous section. It will further adjust over the years to accommodate the changing nature of the science and the community it serves. The structure of CLIVAR, which consists of standing panels and community-driven, limited-lifetime research foci, is how CLIVAR coordinates its science internationally.

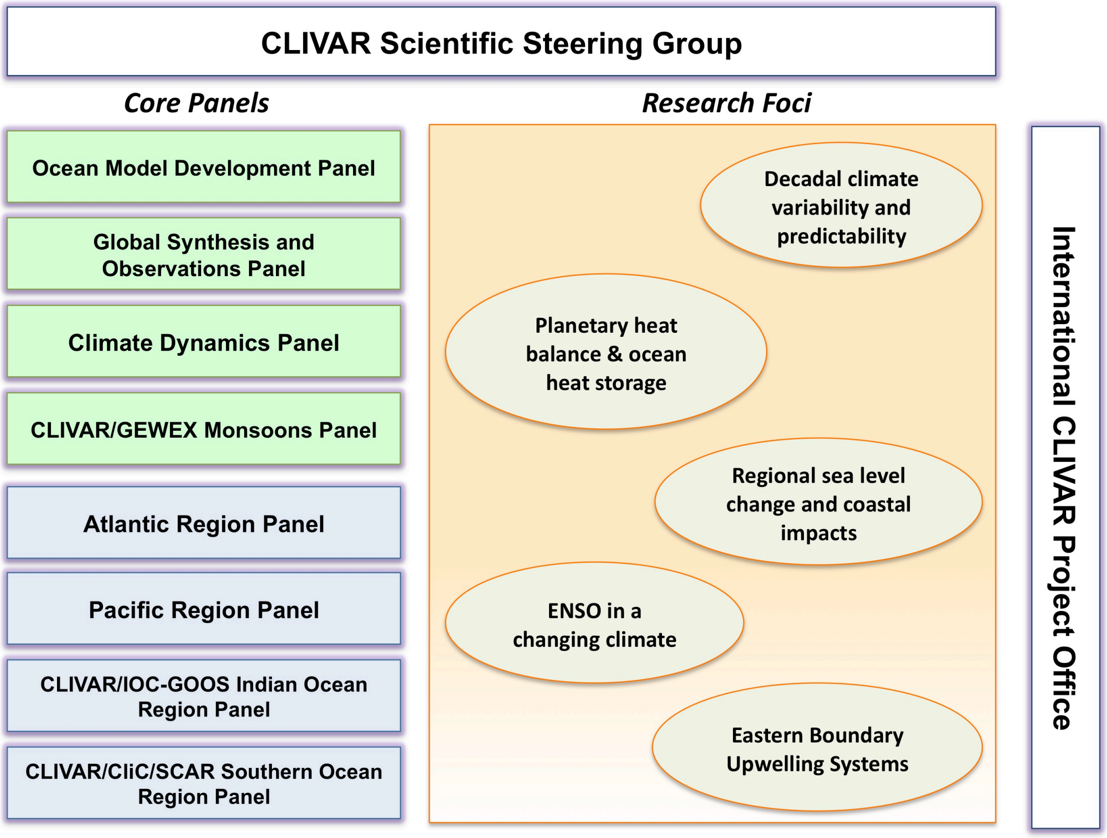

Fig 2: CLIVAR structure (see http:clivar.org for details).

3.1.1 Global Panels:

On the global scale there are four panels: the Climate Dynamics Panel, the Ocean Model Development Panel, the Global Synthesis and Observations Panel, and the joint CLIVAR-GEWEX Monsoons Panel.

Climate Dynamic Panel:

The main aim of the Climate Dynamics Panel is to advance our basic understanding of atmosphere-ocean climate dynamics using observations and models and to determine the role of climate dynamics in shaping climate variability and change on seasonal to centennial time scales. Specific activities will, in the first instance, be organized around three areas; (i) the organisation of storms, blocks and jet streams on seasonal and longer time scales, (ii) ocean basin to ocean basin and tropical-extratropical teleconnections and (iii) the development of predictive theories of climate dynamics involving non-linear interactions between the dynamics and physics of the atmosphere and ocean.

Key methodological approaches employed to address these objectives are (i) high-resolution atmosphere-only and coupled models, (ii) the use of stripped-down or simplified dynamical models of the atmosphere and ocean e.g. aqua-planet configurations with mixed-layer oceans, and (ii) 'pacemaker' type experiments where e.g. SSTs in ocean basin are relaxed towards observed values and the response of the coupled climate system outside that region is assessed.

Monsoons Panel:

Monsoon systems represent the major annual mode of variability in the tropics and affect the lives of billions of people, often in the world's developing and least-developed nations. The Monsoons Panel covers all regional monsoons systems and offers the advantage of bringing together the elements of weather and climate physics that are common to all those systems. These encompass aspects of tropical dynamics, the ITCZ, multi-scale convective physics and understanding the response of the "global monsoon" to common forcing whether from internally generated ocean decadal variability or to anthropogenic forcing. The Monsoons Panel will establish regional working groups with a remit to tackle locally specific scientific problems and, crucially, to foster improved interaction between research and user communities. The Monsoons Panel has a joint membership and operation between WCRP's GEWEX and CLIVAR projects.

OMDP:

CLIVAR is in the process of developing new techniques for accelerating the improvements in models and assessing the impacts of model errors and biases on our understanding of climate variability and change. In addition, we need to improve theories of climate change that arise from basic physical principle governing atmospheric and ocean dynamics, rather than relying on predictions from imperfect model simulations alone. Therefore a new paradigm for model development has been coordinated through CLIVAR, whereby process and observational studies feed directly into high-end models through Climate Process Teams.

In general, these efforts aim to enhance the integrity of numerical tools for science and prediction. In addition CLIVAR leads through the Ocean Model Development Panel (OMDP)'s Coordinated Ocean-ice Reference Experiments (CORE), now part of CMIP6 as the Ocean Model Intercomparison Project (OMIP). Such comparison projects offer opportunities to scrutinize high-end simulations to the climate scientific community. Further work with coordinated fine resolution process studies and global integrations will provide the means to cooperatively interrogate elements of the cascade hypothesis, including the important role of boundary layers, via a hierarchy of simulations resolving a growing portion of the energy spectrum.

GSOP:

The Global Synthesis and Observations Panel (GSOP) plays a vital role in CLIVAR as the main interface between the global observing systems and modelling activities. GSOP is tasked with defining CLIVAR's requirement for globally sustained observations and promoting their optimal use in a variety of research applications, such as ocean state estimation, seasonal-to-decadal forecasting, model evaluation and detection-attribution studies. Highlight activities of the panel include: (i) leadership of the ocean reanalysis intercomparison project (ORA-IP), in collaboration with the Global Ocean Data Assimilation Experiment (GODAE) OceanView community; and (ii) leadership of International Quality Controlled Ocean Database (IQuOD) initiative, which aims to produce the definitive historical subsurface database to support climate science and services.

3.1.2 Regional Panels: The Changing ocean circulation: Causes and processes involved

Regional ocean basin Panels (Atlantic, Pacific, Indian and Southern Ocean) design, promote and oversee the implementation of multi-national observing systems and process studies on ocean and climate variability and predictability.

The CLIVAR regional panels provide a forum for scientists with an interest in a particular basin to come together to discuss new ideas, collaborate on research initiatives and develop joint activities such as multi-national observational arrays and process studies. Over the years, CLIVAR basin panels have been instrumental in establishing important climate and ocean observing networks and in advocating for sustained observations and their funding streams. Many major climate and ocean process studies have been designed and implemented under the auspices of the CLIVAR regional panels. Regional Panels monitor and evaluate progress in climate and ocean research in their respective areas and identify topics requiring further investigation. They are responsible for facilitating progress in the development of tools and methods required to assess climate variability, climate change and climate predictability of the ocean-atmosphere system in each of the ocean basins.

CLIVAR regional panels also identify opportunities and coordinate strategies to implement these tools and methods, spanning observations, models, experiments and process studies. The Panels work closely with other climate and observing systems and networks in their region to provide scientific and technical input and enhance international research coordination. Panels also promote data sharing and work with relevant agencies on the standardization, distribution and archiving of observations. Examples of processes and partnerships are shown below:

Over the past ten years, substantial progress has been made towards realizing the goal of instrumenting a comprehensive AMOC observing system in the subtropical North Atlantic (26N Rapid), subpolar North Atlantic (OSNAP) and the subtropical South Atlantic (SAMOC). A high priority area in the near-term is to fully implement these observing systems, synthesize the in-situ observations and combine them with ocean state estimation models to improve our understanding of the AOMC changes that have been observed. AMOC variability has now linked as a “fingerprint” associated with sea-level, surface and sub-surface temperature anomalies. More effort will be devoted to the use of multi-model analysis and historical data to see if a proxy for AMOC variability in the past can be constructed from historical time series. Modelling studies aimed at understanding and predicting AMOC variability continue to provide model-dependent results. A coordinated and focused set of experiments across a hierarchy of models is needed to develop a common set of metrics for intermodal comparison (e.g. AMOC variability in density space), the determine best practices for model initialization and bias correction. Ongoing intercomparisons and verifications studies of IPCC AR5 decadal prediction experiments can help assess the robustness and model dependency in AMOC predictions.

The Indo-Pacific is home to major modes of climate variability, the El Niño- Southern Oscillation, and the Indian Ocean Dipole. Extreme El Niño events, as occurred in 1982/83 and 1997/98, cause global disruption of weather patterns and affect ecosystems and agriculture through changes in rainfall. The issue of how the frequency of extreme El Niño will change under global warming has challenged scientists worldwide. Extreme El Niños is associated with a dramatic shift of atmospheric convective zone to the eastern equatorial Pacific, leading to large rainfall anomalies. In association, the response of rainfall to sea surface temperature anomalies is nonlinear such that there is positive rainfall skewness in the eastern equatorial Pacific. Thus, these characteristics may be used to benchmark climate models: (1) skewness and (2) ability to produce extreme rainfall response in the eastern equatorial Pacific (Cai et al., 2014a). Similarly, extreme positive Indian Ocean Dipole, as occurred in 1961, 1994 and 1997, causes devastating floods in eastern African but severe drought an bushfires in countries surrounding the eastern Indian Ocean (Cai et al., 2014b, Cai et al., 2013). In the eastern Indian Ocean, cold SST anomalies attain a greater amplitude than the warm ones, indicating that positive Indian Ocean Dipole events tend to be greater than negative Indian Ocean Dipole events. During such positive events, the cool anomalies and the associated subsidence in the eastern Indian Ocean extend westward along the equator, pushing the convergence downstream further west toward the eastern Africa, leading to floods in east African countries. This westward extension is additional to that represented by the conventional Indian Ocean Dipole index. The negative SST skewness in the eastern Indian Ocean and the westward extension of cool and dry anomalies along the equator are features that can be used to select models for studying the response of extreme positive Indian Ocean Dipole events, which is characterized by an increase of a factor of three in the frequency of extreme Indian Ocean Dipole events (Cai et al., 2014b).

In the Indian Ocean, the cross fertilization between members of traditional physical oceanography and biogeochemistry communities has resulted in several joint interdisciplinary research publications. Noteworthy progress in the description of Indian Ocean bio-physical interactions over the last 10 years include: a general description and modelling of the chlorophyll blooms in the Indian Ocean (e.g. Levy et al., 2007; Koné et al., 2009; Marra et al., 2009); advances in our understanding the influence of the IOD and ENSO on biogeochemical and ecological processes (e.g. Wiggert et al., 2009; Currie et al., 2013); and quantification of the influences of advection, mixing and biological oxygen demand in determining the distribution of low oxygen water in the Arabian Sea (e.g. Resplandy et al., 2012; McCreary et al., 2013). Northern Indian Ocean: Efforts have also been undertaken to explore the role of eddies in primary production of the Bay of Bengal and Arabian Sea (Prasanna Kumar et al., 2004,Resplandy et al., 2011); investigate the response of Bay of Bengal productivity to cyclones (e.g. McPhaden, et al., 2009); examine the chlorophyll signature of the MJO in the thermocline ridge region (Resplandy et al., 2009); and analyse results from Bio-Argo floats (Ravichandran et al., 2012; Prakash et al., 2012; Prakash et al., 2013). Important advances have emerged from a detailed study of the biological oceanography of the Leeuwin Current from 22-34°S that has generated a series of papers covering the physical oceanography (Feng et al., 2010; Weller et al., 2011), nutrients (Thompson et al., 2011), primary production (Lourey et al., 2013) and larval fish assemblages (Holliday et al., 2012). Important new findings have also emerged concerning the transport and ecology of the planktonic larval phase of the western rock lobster (Saunders et al., 2012; O'Rorke et al., 2012).

3.2 Concept of RF:

In response to the rapid pace of scientific advances and recognizing the need for the project to be flexible and responsive to new ideas and challenges, CLIVAR has developed the concept of Research Foci (RF). These are focused research activities on topics with high potential for significant progress in the next 3-5 years and that would benefit from enhanced international coordination. This mechanism has proven to be an effective means for the CLIVAR community to initiate in a bottom-up-process new research and invigorate progress in areas that are of high priority to the climate research community, thereby fostering cross panel, cross WCRP community collaboration, at the same time providing an opportunity to entrain new scientists into CLIVAR.

3.2.1 The Future Of ENSO: Evolution of Coupled Modes of Variability

The El Niño–Southern Oscillation (ENSO) phenomenon is a naturally occurring climate fluctuation, which originates in the tropical Pacific region and affects ecosystems, agriculture, freshwater supplies, hurricanes and other severe weather events worldwide (Goddard and Dilley, 2005; McPhaden et al., 2006). Despite considerable progress in our understanding of the impact of climate change on many of the processes that contribute to ENSO variability (e.g., Collins et al., 2010), it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency or character of events will change in the coming decades (Vecchi and Wittenberg, 2010).

This Research Foci have three main goals: 1) better understand processes that control ENSO characteristics in nature and in the models, namely diversity of El Niño events and decadal variations, 2) propose a standard ENSO evaluation protocol for CGCMs and 3) understand how ENSO characteristics might be modified in the next decades, namely under the influence of anthropogenic climate change. Working towards these ambitious goals requires a synthesis of existing ENSO evaluation methods for

CGCMS, including metrics, process based evaluation methods and El Niño Models of Intermediate Complexity (ENMICs). Another step is to identify gaps and duplication in these methods, which observations are essential, and how they can be better used. In particular paleo and last millennium observations (e.g. Emile-Geay et al., 2013ab; McGregor et al., 2013) have a large mostly untapped potential. A next step is to use the proposed rich and coordinated multi-model evaluation in innovative ways to inform society and other stakeholders how ENSO may, or may not, evolve in the next decades. Last but not least, a capacity building component will bringing together an interdisciplinary group and train young scientists. The protocol and methods proposed will be used to document ENSO performance of existing multi-model databases (e.g. CMIP) and contribute to the Metrics Panel set up under WGCM guidance. CLIVAR is the natural place to formalise this cross-cutting Research Foci, as many of its Panels and topical groups should be involved (Pacific and Indian Ocean Panels, WGOMD), Links with WGCM, WGSIP, WGNE, SOLAS and PAGES will also be central. This Research Foci will also make strong contributions to both the model development process (CMIP6 protocol) and the IPCC assessment.

3.2.3 RF heat content evolution

Climate is the result of energy transfer between the different components of the Earth's system. The Earth's Energy Imbalance (EEI) is the fundamental measure of climate variability and the rate of global change (Hansen et al., 2011; von Schuckmann et al., 2015). All the energy that enters or leaves the climate system radiatively at the top of Earth's atmosphere is balanced under an equilibrium climate. Any climate forcing (of natural or anthropogenic origin) can perturb this energy balance and give rise to EEI, i.e. excess of energy – mostly in the form of heat – in the climate system.

There are four approaches that can potentially be used to estimate the absolute value of EEI and its time-evolution (Figure 1, section 2.3.1). An overarching scientific challenge faced by the whole climate science community is related to the fact that each method has its own strengths and weaknesses, however in many ways, the various methods are complementary (von Schuckmann et al., 2015). To face this challenge is the overarching objective of the CLIVAR research focus CONCEPT-HEAT ("Consistency between planetary energy balance and ocean heat storage"). Developing the knowledge, and observational capability, necessary to "track" the energy flows through the climate system is critical for better understanding relationships between climate forcing, response, variability and future changes.

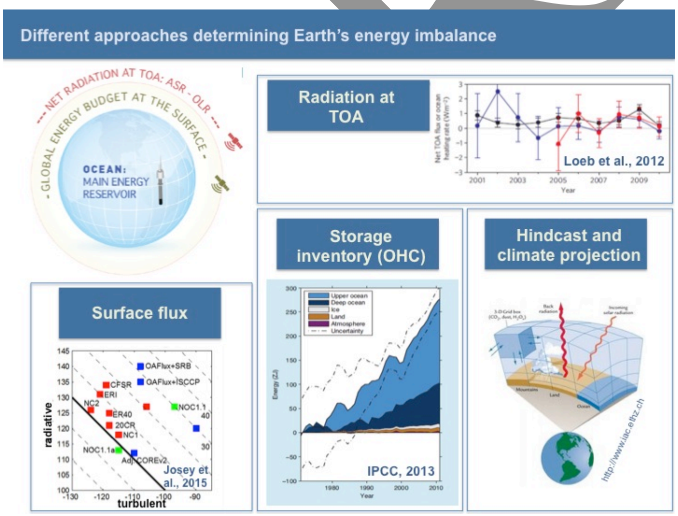

Figure 1: Schematic presentation of different approaches determining the Earth's energy imbalance (EEI). Values of EEI can be derived from: remote sensing at the Top of the Atmosphere (TOA); the mean surface budget as derived from in situ observations, remote sensing data and atmospheric reanalyses; an inventory of heat stored in the climate system (Ocean Heat Content, OHC) – in particular in the global ocean from in situ measurements and ocean reanalyses systems -, as well as from state-of-the-art numerical model approaches.

CONCEPT-HEAT aims to bring together experts from ocean and atmospheric reanalysis, air-sea fluxes, ocean heat content (OHC), climate models, atmospheric radiation and sea level to better synthesize all the information available. Thus, an important goal of our workshop was to foster collaboration between these different communities to expedite progress, and to build up a multi-disciplinary synergy community for climate research aiming to work on two different issues:

I. Quantify Earth's energy imbalance, the ocean heat budget, and atmosphere-ocean turbulent and radiative heat fluxes, their observational uncertainty, and their variability for a range of time and space scales using different observing strategies (e.g., in-situ, satellite), reanalysis systems, and climate models.

II. Analyze the consistency between the satellite-based planetary heat balance and ocean heat storage estimates, using data sets and information products from global observing systems (remote sensing and in situ) and ocean reanalysis. In addition the results can be used to compare to outputs from climate models to facilitate validation.

3.2.4 Sea Level GC: sea level change, ocean and freshwater heat content

To meet the sea level challenge, WCRP has implemented the theme "Sea Level Rise and Regional Impacts", as one of its grand science questions (http://www.wcrp-climate.org/index.php/grand-challenges). This requires an improved and coordinated physical understanding of all contributions to past, contemporary and future sea level, including the quantification of sources of uncertainty (e.g., from model and observational data sets, estimation methods, climate system dynamics, etc). Predicting regional to local sea level changes is an intrinsically multi-disciplinary challenge involving many communities, as changes in regional sea level involve a complex interplay between many contributing processes operating over a broad range of spatial and temporal scales. These contributions can include: change of mass of the ocean (barystatic sea level change) caused by exchanges of mass with the land (e.g., ground water extraction) and the cryosphere and the resulting gravitational and rotational changes; wind-driven and buoyancy-driven dynamics of the ocean and associated water mass transformation and/or redistribution..

The overall goal of this Grand Challenge is to establish, over a 10 year time span, a quantitative understanding of the natural and anthropogenic mechanisms of regional to local sea level variability; to promote advances in observing systems for integrated SL monitoring; and to support development of SL predictions and projections that are of increased benefit and utility for coastal zone management. Achieving these goals requires an integrated interdisciplinary program on SL research covering global, regional, and local aspects of sea level change. The program envisions a close connection to coastal impacts and adaptation communities to ensure that newly emerging scientific results are transferred to coastal zone management studies.

3.2.5 DCVP RF: predictability of decadal ocean and climate changes

The study of Decadal Climate Variability and Predictability (DCVP) is the interdisciplinary endeavor to characterize, understand, attribute, simulate, and predict the slow variations of climate on a global and on regional scales. Whether externally forced or arising from internal interaction between the climate system components, these variations significantly affect the near-term evolution of climate, particularly on regional scales. In the near term, modern society critically depends on decadal climate variability information in planning and adapting to the impact of climate variability and change. In particular, it is important for a broad range of stakeholders and decision makers to know how the mix of the response to anthropogenic forcing and the impact of natural variability will affect the near term evolution of regional climate conditions. The study of DCVP aims to facilitate and improve the provision of such information through research and observation. This goal remains challenging despite years of study, extensive progress in climate system modeling and improvements in the availability and coverage of observation.

CLIVAR is interested in the dynamics and predictability of the ocean-atmosphere interaction, in particular: (*i*) the ability of such interaction to generate sustained long- term predictable variations in sea surface temperature (SST), upper ocean heat content (OHC) and sea surface height (SSH) and the effect of these on the atmosphere in general and importantly over land; and (*ii*) the land and ocean response to external radiative forcing and the subsequent impact on climate. This includes the response to solar variability, to changes in atmospheric aerosol concentrations (from volcanic eruptions and other natural sources and from human activity) and to the increase in atmospheric greenhouse gas (GHG) concentrations.

3.2.6 Eastern Boundary Upwelling Systems

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

The impacts of climate-scale variability on EBUS and consequently on their fish resources have become widely accepted in recent years (e.g., Lehodey et al., 2006; Parrish et al., 2000). One of the most compelling examples of climate- driven fish stock changes is the fluctuations of sardines and anchovies described since the early 1980s, the so-called Regime Problem (Lluch-Belda et al., 1989, 1992; Schwartzlose et al., 1999). Landings of sardines show synchronous variations off California, Peru, and Chile (and Japan), with populations flourishing for 20 to 30 years and then practically disappearing for similar durations. Periods of low sardine abundance have coincided with increases in anchovy populations. Benguela Current sardine and anchovies in the Atlantic Ocean appear to be in synchrony with Pacific stocks, but in opposite phase. As demonstrated through paleo-reconstructions (Baumgartner et al., 1992), and because synchrony takes place despite different fishery management schemes (Schwartzlose et al., 1999), those fluctuations appear to be fishery-independent. Due to the large spatial and coherent temporal scales involved, a single global driver linked to large-scale atmospheric or oceanic forcing has been proposed to explain the variations across different systems (Bakun, 1996).

Finally, and most importantly, many coupled climate models are characterized by very large SST biases in the coastal upwelling regions of the California Current System (CCS), the Humboldt Current system (HCS), the Canary Current System and the Benguela Current System (BCS), where simulated mean SSTs are much warmer than observed (typically in excess of 3^{o}C and as high as 10^{o}C) (Figure 1). Furthermore, these SST biases have significant remote effects on surface and subsurface temperature and salinity, and on precipitation and hence atmospheric heating and circulation (Collins et al. 2006), and affect the large-scale climate system through feedbacks (Large and Danabasoglu, 2006; Curchitser et al., 2011, Small et al., 2015).

In order to address these important issues, the EBUS RF aims to:

- Analyse existing ocean reanalysis products and climate- and downscaled-climate models in the eastern boundary regions.
- Summarise existing physical, biogeochemical and fisheries data in each of the four main EBUS. The ultimate goal here is to write a prospectus/white paper that will highlight observational priorities of future observations in these regions, including field measurements to quantify variability in source-water properties as seasonal-to-interannual time scales.
- Design a series of numerical experiments with existing climate models to address specific mechanisms important in these regions. In light of recent literature, these experiments can address, among other considerations, both the representation of coastal winds and potential feedbacks to the large scale.
- Analyze the relative importance of different sources of new nutrients (e.g., surface mixing, riverine input, curl-driven upwelling, coastal upwelling) to structuring the composition (e.g., species, size) of planktonic communities. The resulting product will be a synthesis of the oceanographic processes that affect planktonic communities that nourish small pelagic fish in EBUS.

Chapter 4. International Coordination as Enabling Capabilities

In this section the need for an international cooperation in setting up or expanding the enabling infrastructure facilitated by CLIVAR needs to be addressed,

- CLIVAR panels provide capabilities enabling science and activities needed to achieve the overall CLIVAR objectives. They underpin all CLIVAR science.

  - Improving ocean system models.
  - Improving ocean-observing systems.
  - Ocean data, synthesis and information systems
  - Knowledge transfer and stakeholder feedback.
  - Education, capacity building and outreach.

4.1 Climate and Ocean Process and Sustained Observations

One of the major research activities supported by the CLIVAR over the past decade is the development of an observing system for the Atlantic Meridional Overturning Circulation (AMOC). A main component of the AMOC observing system is the trans-basin array along 26.5°N established in 2004. Additional AMOC observing networks include time series arrays deployed in a variety of locations such as the Denmark Strait (e.g. Jochumsen et al. 2012), at 35°N (e.g. Toole et al., 2011; Peña-Molino et al., 2012), at 16°N (e.g. Kanzow et al., 2008; Send et al., 2011), and at 35°S (Meinen et al. 2013).

As of April 2014 the RAPID-MOCHA-WBTS program will have completed 10 years of continuous measurement of the AMOC structure and variability at 26.5°N, using satellite winds to derive the Ekman transport, a trans-basin mooring array to monitor the mid-ocean transport, and subsea cable across the Straits of Florida to monitor the Gulf Stream transport (Cunningham et al., 2007). The array also allows continuous estimates of the meridional heat transport across 26.5°N and the respective contributions by the overturning (vertical) and gyre (horizontal) components of the circulation (Johns et al., 2011). Recently updated results for the AMOC at 26.5°N are contained in McCarthy et al. (2012) and Smeed et al. (2014).

OSNAP is a US-led collaboration with UK, Dutch, German, French and Canadian scientists aimed at measuring the flow of heat, mass and freshwater in the subpolar North Atlantic Ocean using moored instrumentation, subsurface floats, gliders and hydrographic surveys. The OSNAP line (Fig. 7) consists of two legs: OSNAP West extends from southern Labrador to southwestern Greenland and OSNAP East from southeast Greenland to the coast of Scotland. The two legs are situated to capitalize on a number of existing or planned long- term observational efforts in the subpolar North Atlantic: the Canadian repeat AR7W program in the Labrador Sea (although the OSNAP West line has been shifted slightly southeastward to capture the export of all LSW from the Labrador Sea); the German Labrador Sea western boundary mooring array at 53°N; the US Global OOI (Ocean Observatories Initiative) node to be placed in the southwest Irminger Sea; the repeat A1E/AR7E and OVIDE (Figure 3) hydrographic sections across the Irminger and Iceland Basins (approximately coincident with OSNAP East); and the Ellett line in the Rockall region.

Recent observing system design studies have suggested that, of the South Atlantic latitudes, 34.5°S would be ideal for capturing MOC variability at the 'mouth' of the Atlantic basin (Perez et al., 2011). This location is also well supported by theoretical analyses that suggest that crucial MOC stability evaluations would be best applied as far from the equator in the South Atlantic as possible (e.g. Dijkstra, 2007; Drijfhout et al., 2011). This location has been therefore selected to implement an array of mooring and ship observations to measure the density structure and the flows in the South Atlantic. This array has been defined as the "South Atlantic MOC Basin- wide Array" (SAMBA). This array together with that along GoodHope and Drake Passage were among the cornerstones for what has become known as the international South Atlantic MOC (SAMOC) initiative. The overall SAMOC Project is intended to study the variability of the Meridional Overturning Circulation in the South Atlantic and its impacts on climate change, from regional to global scales. It is an international effort in which participate institutions from Argentina, Brazil, France, Germany, Russia, South Africa, Spain, and the USA.

The long term SST warming is uneven, both in regions and seasons. In the Ocean, outside of polar regions, accelerated warming is found along two latitudinal bands, roughly 25-40 degree, and peaks in the western boundary current (WBC) regions (Deser et al. 2010, Wu et al. 2012). The post-1900 SST warming rate over the path of WBC is two to three times faster than the global mean surface ocean warming rate and enhanced during winter, suggesting a major role of ocean dynamics in shaping SST warming patterns along WBC, while atmospheric processes make some contributions (Zhang et al. 2010, Yeh and Kim 2010). The accelerated warming is associated with a synchronous poleward shift and/or intensification of global subtropical western boundary currents in conjunction with a systematic change in winds over both hemispheres (Cai et al. 2010, Wu et al. 2012). A dynamical framework that links the western boundary current to global warming has been explored in both hemispheres (Cai et al. 2005, Yang et al. 2013, Sun et al. 2013).

The Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) objective was to understand the southwest Pacific Ocean circulation and the SPCZ, as well as their influence on regional and basin-scale climate. South Pacific thermocline waters are transported in the westward flowing South Equatorial Current (SEC), from the subtropical gyre centre toward the southwest Pacific Ocean, creating a major circulation pathway that redistributes water from the subtropics to the equator and to the Southern Ocean. A major part of SEC waters enters the Southwest Pacific area, with its numerous Islands and straits. This transit in the Coral, Solomon and Tasman Seas is potentially of great importance to the climate system. Changes in either the temperature or the amount of water arriving at the equator have the capability to modulate ENSO, while the southward pathways influence climate and biodiversity in the Tasman Sea. The concept of a coordinated experiment in the Southwest Pacific started during a workshop in 2005 (Cairns, Australia), which led to the development of a science plan and endorsement by CLIVAR in 2008 (on clivar.org). Over the past six years, substantial efforts have been devoted to improve understanding of this region, through in situ oceanic observations, modeling, as well as remote sensing and comprehensive analyses of historical data. Many aspects have been addressed through SPICE-coordinated projects: heat and mass transports; properties and dynamics of the strong boundary currents and jets; water mass transformations and SPCZ behavior. More information and references are on http://spiceclivar.org and in two recent review papers: Ganachaud et al. (2013, 2014). Two hydrographic cruises – Pandora (July 2012) and MoorSPICE (March 2014) – have been undertaken as part of SPICE, that included mooring deployments designed to directly capture the various streams of the WBC that flow through the Solomon Sea toward the equator. A capacity-building workshop focused on practical hands-on training of students was held in Port Moresby, Papua New Guinea, November 2013.

The Northwestern Pacific Ocean circulation and climate (NPOCE) aims at better understanding the WBCs and their relations and impact with the ocean- atmosphere system in this area. After the successful Open Science Symposium on Western Pacific Ocean Circulation and Climate in October 2012 in Qingdao, China, two new 973 projects were approved by the Chinese MOST to study "Processes and mechanisms of multi-scale marine variability in the Northwest Pacific and its predictability" (led by Lixin Wu, 2013-2017) and "Mechanisms of upper ocean response to and modulation on typhoon" (led by Dake Chen, 2013-2017). In 2013, a new project called the Strategic Priority Project of the Chinese Academy of Science was established to study the northwestern Pacific Ocean circulation and climate. The project will deploy scores of subsurface moorings in the key strategic sections of the western boundary currents and the main equatorial currents to measure the seasonal to interannual variations of these currents for better climate predictions. The project has been funded for the period of 2013-2017. The mooring arrays will be deployed in the summer of 2014 to cover the strategic key sections in the western Pacific Ocean and the Indonesian seas. In 2013, the Korean Poseidon project has replaced the moorings in the North Equatorial Current. The Korean GAIA project has deployed subsurface ADCPs on the TAO moorings along the 165oE section at 2°N, 5oN, and 8oN to monitor the subsurface currents. Japan has carried out a cruise in the west Pacific Ocean in early 2013 to conduct measurements along 8oN, and 130oE on its way to maintain the TRITON arrays near the equator.

In the Indian Ocean, the Indian Ocean Observing System (IndOOS) is a multi-platform long-term observing system, which consists of a surface mooring array, Argo floats, surface drifting buoys, tide gauges, Voluntary Observing Ship (VOS) based XBT/XCTD sections and satellite measurements. The system is designed to provide high-frequency, near real-time climate-related observations, serving the needs of climate research, forecasting, and services. The main platform for in situ observations in the tropical IO is the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA, http://www.pmel.noaa.gov/tao/rama/index.html), which is similar to the TAO/TRITON array in the Pacific and PIRATA array in the Atlantic Ocean (McPhaden et al., 2009a). The RAMA array consists of a total of 46 moorings, of which 38 are ATLAS/TRITON-type surface moorings. Eight of these surface moorings are surface flux reference sites, with enhanced flux and subsurface ocean measurements. The surface mooring system can measure temperature and salinity profiles from the surface down to 500 m depth as well as the surface meteorological variables, and the observed data are transmitted in real-time via ARGOS satellites. In addition to these surface buoys, there are four subsurface ADCP moorings along the equator and one near the coast of Java to observe current profiles in the upper ocean, and three deep current-meter moorings with ADCPs in the central and eastern equatorial regions. The RAMA array design was evaluated and supported by observing system simulation experiments (Oke and Schiller, 2007; Vecchi and Harrison, 2007).

CLIMODE (http://www.climode.org) is a process study to investigate the dynamics of Eighteen Degree Water (EDW), the subtropical mode water of the North Atlantic. EDW is a canonical example of subtropical mode waters, which are found in regions of significant air- sea exchange adjacent to strong baroclinic fronts in all the world's oceans. EDW is created in the winter just south of the Gulf Stream, by convection in the presence of strong shear, with competing effects of vertical/lateral mixing and advection/stirring colluding to set its properties. This project stems from two years of CLIVAR planning (with advice and support of both the CLIVAR Atlantic Implementation Panel and US CLIVAR) to develop an experiment to attack key processes that are poorly understood and poorly represented in ocean climate models - i.e. the treatment of convection, eddy and mixing processes in setting properties of subtropical mode waters, the associated air-sea interaction, and the exchange of fluid between the mixed layer and the upper ocean.

Extensive observational campaign (with 107 days at sea including two winter cruises) was conducted in the 5-year period beginning October, 2004 as a collaborative effort among 17 PIs from 9 institutions (The CLIMODE Group 2009). For the subsequent 4 years, the second phase of the CLIMODE was devoted to analyzing various newly obtained observations along with the hierarchy of model simulations. The CLIMODE observations encompassed winters with active EDW formation (Joyce et al. 2009) as well as very weak renewal (Billheimer and Talley 2013). Various researches ranging from revising the COARE air-sea flux algorithm to the assessing realism of the IPCC-class climate models have resulted in improved understanding of the air-sea interaction, ocean dynamics, and numerical modeling associated with formation, circulation, and destruction of EDW. The findings are published in more than 40 journal articles (see the webpage for the list) including the special issue in the Deep-Sea Research II (http://www.sciencedirect.com/science/journal/09670645/91).

4.2 Global, regionally enhanced and process models

CLIVAR, through its Ocean Model Development Panel (OMDP) led in writing a document that articulated a scientific rationale for saving a suite of physical ocean fields for CMIP5 (Griffies et al., 2009) and CMIP6 (Griffies et al., 2015). The perspective taken was that of physical ocean scientists aiming to enhance the scientific utility of model simulations contributing to the CMIP process. As discussed in Griffies and Danabasoglu (2011), the level of diagnostics requested by OMDP was far larger than the CMIP3 ocean diagnostics. However, it is important to note that OMDP provided three levels of priority, with most of the newer variables not at the highest level. Furthermore, new variables related to subgrid scale parameterizations were largely requested only for the final 20 years of the historical simulations.

After working through the many challenges required to realize CORE-I, OMDP has focused more on the interannual CORE-II protocol. CORE-II makes use of the atmospheric state from Large and Yeager

(2009), which extends over years 1948-2007, as well as the river runoff dataset from Dai and Trenberth (2002). Simulations extend over five repeating cycles of the 1948-2007 CORE-II state, with analysis focused on the final few decades of the last cycle. The remainder of the protocol largely follows the CORE-I approach.
Whereas the CORE-I simulations are largely of use for model development, the CORE-II "hindcast" simulations are motivated from both a model development perspective as well as one based on direct comparison to recent observations. Namely, CORE-II simulations provide a venue for the following activities:

- To evaluate, understand, and improve ocean models, in a way similar to CORE-I;
- To investigate mechanisms for seasonal, inter-annual, and decadal variability, and to evaluate the robustness of mechanisms across models;
- To complement data assimilation by bridging observations and modelling;
- To provide ocean initial conditions for climate (decadal) predictions.

CORE-II simulations have garnered a tremendous interest from modellers and analysts. In particular, there are now nearly 20 models having produced simulations that generally follow the CORE-II protocol. Furthermore, these CORE-II simulations have fostered analysis efforts focused on several research areas, with a CORE-II special issue of the journal Ocean Modelling published during 2014-2015.

4.3 Assessment and synthesis

Assessing all changes occurring presently in the ocean requires a global and long-term observing system, capturing the full state of the ocean. 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 those measurements became feasible only recently, essentially since the advent of altimetry and through ARGO and GRACE (before then large parts of the ocean where hardly observed even once over the last 100 years). However, the need is to estimate climate changes in the ocean over the last decades to centuries.

To obtain reliable estimates of long-term variations of climate indices from a limited database, all existing data should be used as best and as carefully as possible. Given the imminent problems associated with anthropogenic climate change, it is essential to learn as much as possible from the past. But using the existing data in the ocean for investigations of decadal and longer term climate variations requires the reprocessing of the entire climate data base to assure that uncertainties from the observations are reduced as best as possible (e.g. remove uncertainties in the XBT fall rate, biases in temperature or salinity profiles).

CLIVAR and WCRP must continue to show significant leadership in this direction. An important step in obtaining the best possible estimates of the changing ocean as part of the climate system is then to analyze climate-quality ocean observations in a holistic approach by using all information available and analyzing it in ways consistent with our dynamical understanding as embedded in ocean and climate models. Such an approach has to take in account uncertainties of observations as well as of models in which data are being assimilated. Future ocean syntheses for climate research must be sustained in support of climate research and climate services. Not every ocean synthesis is useful for this purpose. Results depend on the assimilation approach: some are tailored for mesoscale predictions or for the initialization of SI models. It is essential that ocean syntheses are accompanied by uncertainty measures. Ultimately the community should compile ocean syntheses from multi-model, multi-approach ensemble estimates that are supposed to be of better quality than any estimate alone. However, the science has to go a long way to reach that goal, which as a pre-requisite requires prior as well as a posteriori error information.

A new vintage of ocean reanalyses has recently been generated, which has come about through the availability of new surface forcing fluxes (from new atmospheric reanalyses), improved quality-controlled ocean datasets, including important corrections to the observations (Lymann et al 2010, Wjiffels et al 2009) , as well as the steady improvement in the ocean models and data assimilation methods. There are lower resolution reanalyses (~1 degree horizontal resolution), spanning a long time period (typically 50 years), as well as higher resolution, “eddy permitting”, products (about 1⁄4 of degree), which are available for shorter recor9ds (usually the altimeter period 1993- onwards). The evaluation and exploitation of the most recent ocean reanalyses products is the subject of the current Ocean Reanalyses Intercomparison Project (ORA-IP), a coordinated community effort on the intercomparison of existing ORAs to exploit the existing information for a variety of purposes, namely i) quantifying uncertainty, ii) measuring progress in the quality of the reanalyses and iii) defining indices for ocean monitoring.

Partly through the initiative of CLIVAR, initialized decadal forecasts became firm part of the last CMIP5 effort and will continue to play a substantial role in climate research. Like seasonal forecast, the skill of decadal forecasts fundamentally depend on the proper initialization procedure of a coupled forecast system by the best possible estimate of the present-day climate state. Because the ocean caries a major fraction of the climate memory it is especially important to initialize those models by the present day ocean state. CLIVAR through GSOP pioneered the collection and quality control of required global climate data set. Also through GSOP, CLVAR pioneered and organized on an international level the generation and use of ocean syntheses (often also referred to as ocean reanalyses) which through a combination of all available ocean data with a general circulation model lead to estimates of the changing ocean. Respective ocean synthesis exist now on a routine basis, covering 60 years and beyond and are being used to study the changing ocean and ocean transports as well as the interaction of the ocean with the overlaying atmosphere. A specific use of those ocean syntheses will remain the initialization of coupled forecast efforts.

The GSOP community has been engaging the decadal forecast community to use ocean reanalysis products to initialize decadal prediction. GSOP’s effort has also led to emerging effort to use these products to test the impacts on decadal prediction (e.g., Pohlmann et al. 2009 and 2013, Belluci et al 2013, Polhmann et al 2014, Polkova et al., 2014).

To facilitate the related efforts, an ocean synthesis directory was established in University of Hamburg (http://icdc.zmaw.de/easy_init_ocean.html?&L=1) that contains the description of model configuration, data assimilated, and assimilation methods. The directory also contains some ocean reanalysis products that the decadal prediction community can obtain directly without having to retrieve from individual data servers (some products do not have a dedicated data server).

4.4 Capacity Development and Knowledge Exchanges

To achieve the goals of the previous six scientific frontiers and imperatives requires a global network of scientists with detailed understanding of the major climate issues. Thus the role of CLIVAR, and more widely WCRP, should be to identify needs and advocate the importance of raising the capacity/capability to continue to undertake climate research, prediction and services. Two different categories of requirements must be satisfied. There must be qualified people in the developed world and institutional capacity in developing nations. Particular attention should be directed at developing the scientific capacity in model development, computational science and climate services in order to meet societal needs from regional to local spatial scales.

In developing its capacity-building activities further, CLIVAR will scope various suggested approaches, including the following.:

- Contributing to the education of the next generation of climate scientists with a particular focus on interdisciplinary studies and scientists from developing countries. CLIVAR panels and working groups will be encouraged to organize workshops targeted at graduate students and post-docs that have a high interdisciplinary content and, where practical, involve contact with operational activities.

- Providing global and regional fora for the exchange of ideas and knowledge amongst climate researchers and students. Support will be sought to bring young scientists and those from developing countries to CLIVAR meetings and conferences.
- Encouraging extended visits to research labs through exchange programmes for young scientists.
- Encouraging making research outputs useful and easily accessible to the broader scientific community and to end-users such as adaptation planners, policy makers and decision makers in climate-sensitive sectors such as agriculture, energy and construction. A few targeted workshops to bring together climate scientists and specific sector user communities will provide fora for communication, with a focus on developing a common understanding of uncertainty in climate forecasts.

Chapter 5. Coordination and Cooperation

- Within CLIVAR

National and multi-national activities are where CLIVAR science is implemented. National projects, agencies and institutions funding and supporting CLIVAR research are too numerous to be listed here; specific activities are referred to in the related Panel and Research Foci webpages.

- Within World Climate Research Programme

- Outside WCRP (Climate Services, FutureEarth projects, IOC, …)

CLIVAR depends on the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS), to implement and coordinate observations in support of climate research. CLIVAR representatives are therefore ex-officio members of the GCOS/GOOS/WCRP Ocean Observation Panel for Climate (OOPC) that designs and oversees the implementation of the ocean observing system in support of the Framework for Ocean Observing (FOO), led by the Intergovernmental Oceanographic Commission (IOC), one of the three WCRP sponsoring organizations.

CLIVAR works closely with several other existing projects, in particular PAGES, IMBER and SOLAS.

CLIVAR activities and scientists will contribute to the success of Future Earth, a new 10-year international research initiative that is bringing together three of the major global environmental change programmes (DIVERSITAS, the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP)) to develop the knowledge needed to respond effectively to the risks and opportunities of global environmental change and in support of transformation towards global sustainability in the coming decades.

- Collaboration with research and operational communities that develop and use climate information

The Global Framework for Climate Services (GFCS) is a global partnership of governments and organizations that produce and use climate information and services, guiding the development and application of science-based climate information and services in support of decision-making. The needs identified in climate services is one motivation for climate research, and the knowledge gained and information facilitated through CLIVAR can benefit climate services.

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