Climate and Ocean – Variability, Predictability and Change

Science Plan
And
Implementation Strategy

April 2018
Draft

Outline:

Executive Summary

This second-generation CLIVAR Science Plan builds on the important legacy of CLIVAR emerging since its inception in 1992 and redirects the CLIVAR goals and priorities for the coming decade after consultation with scientists and stakeholders throughout the climate community.

Being one of four core projects of the WCRP, CLIVAR's mission is to understand the dynamics, the interaction, and the predictability of the climate system with emphasis on ocean-atmosphere interactions. In the future CLIVAR will critically contribute to new challenges of WCRP climate science by covering the following overarching topics:

- Understanding the ocean's role in climate variability, change, and transient sensitivity;
- Understanding the ocean's role in shaping the hydrological cycle and distribution of precipitation at global and regional scales;
- Understanding the drivers of regional climate phenomena that provide predictability on different time scales;
- Provision of coordinated observations, analyses and predictions of variability and change in the Earth's climate system;
- Detection, attribution and quantification of climate variability and change;
- Development and evaluation of climate simulations and predictive capabilities.

To this end, CLIVAR coordinates the 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 individual nation. It facilitates observations, analysis, predictions and projections of variability and 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. Through its Panels, Research Foci, workshops, summer schools and conferences, CLIVAR continues to bring together researchers from all over the world. In doing so, CLIVAR develops a strong, multidisciplinary international community of scientists at all stages of their career who coordinate efforts required to measure, simulate, and understand coupled ocean-atmosphere dynamics, and to identify processes responsible for climate variability, change and predictability.

CLIVAR's new science and coordination activities speaks directly to new strategic WCRP goals and contributes to initiatives of all three WCRP sponsors, the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and the International Science Council (ISC).

Central to future climate science strategies needs to be the development of reliable regional climate change information to be provided on time scales from seasonal to centuries for the benefit of humanity and life on Earth. CLIVAR through its work contributes directly to reaching those goals. It is anticipated that in a 5 to 10 year timeframe much progress will be achieved in expanding theoretical process understanding, in improving the representation of important climate processes in numerical climate models, and in improving regional climate predictions and associated climate information. Such progress will build firmly on the global climate observing system and on the efforts required to improve and sustain it.

Chapter 1. Introduction

CLIVAR was established in 1995 as a World Climate Research Programme (WCRP) Core Project, building on the success of the Tropical Ocean Global Atmosphere (TOGA) project and the World Ocean Circulation Experiment (WOCE), both of which advanced scientific understanding of the ocean circulation and the atmosphere-ocean interactions.

CLIVAR published its initial Science Plan in 1995 (WCRP-89, WMO/TD No. 690). This second-generation Science Plan builds on the important legacy of CLIVAR emerging since its inception and subsequent developments that took place at UNFCCC level. The new Science Plan redirects the CLIVAR goals and priorities for the coming decade after consultation with scientists and stakeholders throughout the climate community.

The newly defined goals have emerged from several important processes:

- The involvement of the International Climate Community assembled during the CLIVAR Open Science Conference, held in Qingdao on September 2016.
- Input from IOC, IMBER, SOLAS, PAGES.
- The development of the new WCRP Strategic Plan, which will cover a 10-year time horizon (2019-2029) and will be released marking the occasion of WCRP's 40-year anniversary.
- The Review of WCRP carried out by its co-sponsors, ICSU-WMO-IOC.

1.1 The WCRP Mission

WCRP develops, shares and applies climate knowledge that contributes to societal well-being by supporting and facilitating the coordination of the international climate scientific research. The Programme, working in a tight partnership with other international initiatives, ensures the implementation of a climate research strategy on the observation, analysis and prediction of the Earth system variability and change on time scales ranging from a week to centuries and from local to global spatial scales.

The overarching objectives of WCRP are:

- Understanding the climate system and its variability.
- Determining predictability on weekly to decadal time scales.
- Determining projectability on decadal to centennial time scales.
- Connecting climate science to policy and decision making.

In support of those objectives, the main foci of WCRP research are:

- The synthesis of current understanding of global energy sources, reservoirs and fluxes with a systematic error analysis of particular constituents;
- The production of extended climate datasets, reanalyses and data integration systems, with high levels of interoperability;
- Advancing the science required to develop coupled data assimilation and initialization systems, using a broader range of climatic data sources;
- The quantification of sources of projectability and emergent constraints from specific components of the Earth system - such as ocean, land, cryosphere, and stratosphere;
- Advancing the understanding needed to couple climate system and socio-economic models in support of improved integrated assessment.

1.2 CLIVAR's role within WCRP

CLIVAR is one of four core projects of the WCRP. CLIVAR's mission is to understand the dynamics, the interaction, and the predictability of the climate system with emphasis on ocean-atmosphere interactions. To this end it facilitates observations, analysis, predictions and projections of variability and 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.

CLIVAR has contributed to many advances in the field of climate and ocean research. Through this work, CLIVAR contributes to initiatives of all three WCRP sponsors, the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and the International Science Council (ISC), that resulted from the merging of the International Council for Science (ICSU) and the International Social Science Council (ISSC) in 2017.

Within WCRP, 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 modelling working groups (WGCM and WGSIP) and Working Group on Regional Climate (WGRC). The WCRP Modelling and Data and Analysis Councils (WMAC and WDAC) serve to coordinate high-level aspects of modelling and data across WCRP, integrating CLIVAR efforts with those of the other WCRP activities and other partners such as WWRP and Future Earth.

CLIVAR's previous research has provided fundamental knowledge about the drivers of variability and predictability in the coupled climate system with emphasis on the ocean, the key subsystem that regulates the Earth climate. For instance, CLIVAR initiatives have been instrumental in the development of ENSO seasonal prediction systems and pioneered decadal predictions. Originally as part of CLIVAR, the developments of coupled models contributed significantly - through the development of coupled climate modelling 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. Largely in part to CLIVAR's efforts during the past two decades, we now have unique, new observing, modelling and reanalysis capabilities that support scientific investigations into ocean dynamics and variability. In addition, CLIVAR embraces and often formally endorses 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 are regularly assessed by the Intergovernmental Panel on Climate Change (IPCC) and that must underpin the provision of operational climate services.

The CLIVAR legacy includes the implementation and development of major multinational and multi-platform observing networks in all the ocean basins, the development of climate models with realistic ocean components and the development of ocean reanalyses. These bridge observations and modelling through data assimilation. *In-situ* elements of established observing systems include global deployment of surface drifters and profiling Argo floats, ocean gliders, arrays of moorings in both tropical and extra-tropical locations, full-depth sampling of the water column from ships of the repeat hydrography program, etc. Since the late 1970s, satellite observations of the ocean have become a crucial part of the global observing system. CLIVAR works closely with GCOS and GOOS, which utilize the "Framework for Ocean Observing" to guide its implementation of an integrated and sustained ocean observing system.

As WCRP moves into a new Strategic planning and implementation phase, CLIVAR's new objective is to describe, understand and model the dynamics of the coupled climate system emphasizing ocean-atmosphere interactions and to identify processes responsible for climate variability, change and predictability on subseasonal-to-seasonal, interannual, decadal, and centennial time scales. In detail, CLIVAR will critically contribute to the new WCRP strategy by covering the following important topics:

- Understanding the ocean's role in climate variability, change, and transient sensitivity;
- Understanding the ocean's role in shaping the hydrological cycle and distribution of precipitation at global and regional scales;
- Understanding the drivers of regional climate phenomena that provide predictability on different time scales;

- Provision of coordinated observations, analyses and predictions of variability and change in the Earth's climate system;
- Detection, attribution and quantification of climate variability and change;
- Development and evaluation of climate simulations and predictive capabilities.

To this end, CLIVAR coordinates the 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 individual nation. It facilitates observations, analysis, predictions and projections of variability and 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. Through its Panels, Research Foci, workshops, summer schools and conferences, CLIVAR continues to bring together researchers from all over the world. In doing so, CLIVAR develops a strong, multidisciplinary international community of scientists at all stages of their career who coordinate efforts required to measure, simulate, and understand coupled ocean-atmosphere dynamics, and to identify processes responsible for climate variability, change and predictability.

CLIVAR's new science and coordination activities speaks directly to new strategic WCRP goals and contributes to initiatives of all three WCRP sponsors, the World Meteorological Organization (WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

Central to future climate science strategies needs to be the development of reliable regional climate change information that can be provided on time scales from seasonal to centuries and beyond to the benefit of humanity and life on Earth. CLIVAR through its work contributes directly to reaching those goals. It is anticipated that in a 5 to 10 year timeframe much progress will be achieved in expanding theoretical process understanding, in improving climate models through improved representation of important climate processes in numerical models and in improving regional climate predictions and associated climate information on time scale from seasonal to decadal. This will build firmly on efforts required to improve and sustain the global climate observing system.

Chapter 2. The Science basis and open questions

Over the next decade CLIVAR will target the following scientific priorities:

1. **Mechanisms of climate variability and change** that require further investigation with the ultimatee goal of better constraining the fluxes of energy and carbon in the climate system;
2. **Ocean processes** that modulate climate variability and change for which open questions remain;
3. C**limate predictability** challenges that exist over a broad range of space and time scales.

2.1 Mechanisms of climate variability, climate change and transient climate sensitivity

The ocean regulates and modulates climate variability, climate change, and transient climate sensitivity. It does so through its massive storage capacity of heat, freshwater and carbon, and the transport of these properties by the ocean currents. Consequently, the ocean contributes to climate variability through its circulation pathways and strength, internal/intrinsic variability, and its interactions with the atmosphere, cryosphere, and land, all of which span a wide range of space and time scales. These processes lead the ocean to respond to natural and anthropogenic forcings that in turn feedback upon the atmosphere, cryosphere, land, and biosphere.

Much progress has been made in recent years in observing, modelling, understanding, and predicting aspects of the climate system. However, many open questions remain concerning the origin of ocean anomalies, the role of air-sea exchanges, the predictability of climate variability, the interactions between natural and forced variations, the sensitivity of ocean processes to natural and anthropogenic forcing, and the space-time scales whereby the ocean influences transient climate sensitivity.

To make further progress on these fundamental areas of climate science, respective CLIVAR activities will be framed around the following science questions:

- What is the ocean's role in determining or modulating natural modes of climate variability? How are these modes and the ocean's role altered by external forcing, particularly those arising from anthropogenic sources?
- What are the oceanic constraints on transient climate sensitivity, including air-sea exchange, ocean heat uptake and transport, and the Earth's energy budget?
- What are the regional and coastal impacts of a changing climate upon sea level, ocean heat content, ocean-cryosphere interactions and the water cycle?
- What is the ocean's role in the Earth's carbon-climate link at both global and regional scales?

In the remainder of this section we outline various climate phenomena and concepts, and we offer a suite of research questions to be addressed through CLIVAR activities over the years to come. In particular we will articulate how CLIVAR forms a central role in furthering the scientific understanding and predictive capabilities surrounding the central questions of climate variability, climate change, and transient climate sensitivity.

2.1.1 The ocean's role in climate variability and change

To further improve our understanding of ocean dynamics, the mechanisms governing it, and the ocean's role in climate variability and change, CLIVAR will provide improved quantitative characterization and physical understanding of (1) internal (i.e., unforced) climate variability and (2) the impact of external forcing (e.g., volcanic, anthropogenic) on internal climate variability. Understanding the ocean's role in setting and modulating climate variability and change requires an understanding of mechanisms driving variability. Key examples include the El Niño Southern Oscillation (ENSO), the Pacific Decadal Variability (PDV), often quantified through the Pacific Decadal Oscillation (PDO) index, and the Atlantic Multidecadal Variability (AMV). A fundamental question concerns how such modes interact through both atmospheric and oceanic teleconnections.

An example is the Atlantic component of the oceanic Meridional Overturning Circulation (AMOC). It is a key driver of AMV, which in turn impacts 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 thermal energy transport in the ocean, but anti-correlated with transport in the tropical atmosphere. However, regional dynamical feedbacks are largely unknown. While coupling between the atmosphere and ocean on interannual time scales has been extensively studied, less is known about how the atmosphere and ocean interact on decadal time scales.

Another fundamental challenge for CLIVAR is the assessment of the interplay between large-scale ocean variability and the regional-scale climate impacts. This includes research on a broad range of time scales and extends from the tropics to the polar regions. Additionally, understanding of the ocean's role in climate variability requires understanding of intrinsic atmospheric variability and its interactions with the upper-ocean boundary layer.

Internal modes of climate variability

There is a plethora of internally-generated modes of atmospheric, oceanic and coupled variability across a broad range of space and time scales. Even a fundamental mode such as ENSO exhibits a variety of flavours (e.g. Capotondi et al. 2015), which depend, among other factors, on the basic climate state, nonlinearities, and the character of the external forcing. Basic questions remain concerning the role of high frequency atmospheric fluctuations and associated coupled feedbacks in setting the characteristics of intra-seasonal variability such as the Madden-Julian Oscillation (MJO) or the Boreal Summer Intraseasonal Oscillation (BSISO). These generally high-frequency climate fluctuations not only yield significant societal impacts themselves, but have also implications for lower-frequency phenomena through rectification or cascade processes.

New CLIVAR coordinated research will emerge concerned with the characterization of different modes of variability considering the diversity of their impacts, ranging from regional sea level, ocean biological 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 state and its modulation on multi-decadal timescales will be given attention. For example, investigations are underway to establish the role that background SST gradients play in the formation of various ENSO flavours and their teleconnections. More research is needed to establish how basin width, baroclinicity, strength and nonlinearity of ocean-atmosphere coupling, and oceanic heat content can influence such climate modes.

Externally forced variability

CLIVAR research will contribute to understanding how external forcing can modify modes of internal climate variability and their atmospheric teleconnections, and possibly create new modes of variability. This task implies understanding the mechanisms whereby forced climate change modifies the mean state that in turn can impact variability. In this context, external forcing embraces trace gases (notably greenhouse gases (GHG) and natural and anthropogenic aerosols), volcanic eruptions, solar insolation, and land use/land cover.

One example is GHG-induced polar amplification and associated sea-ice melting and ice-albedo feedback. These processes lead to changes in oceanic and atmospheric circulations in addition to effects on ocean stratification, with impacts on mixed layer depth and air-sea interactions. In the tropics, externally forced changes in mean-state patterns of tropical SST can lead to changes in teleconnections arising from ENSO and other coupled ocean-atmosphere variability modes such as the Indian Ocean Dipole (IOD), causing dramatic societal impacts. It is also noteworthy that oceanic and coupled processes can extend the lifetime of impacts from a volcanic eruption to nearly a decade, although full understanding of the governing mechanisms is lacking. Finally, the effect of solar variability on past ocean circulation states remains elusive (e.g. the Holocene Bond cycle) and so requires further studies.

In conceptually framing questions surrounding climate variability and the impacts of external forcing, it is useful to formulate null hypotheses against which to test the impact of external forcing on characteristics of internal variability. One such null hypothesis is that stochastic processes generate internal climate variability (Hasselmann 1976). The impacts of external forcing on phenomena such as ENSO, PDV and AMV must be benchmarked against this null hypothesis, recognizing that climate records are generally relatively short and so do not allow to reject the null hypothesis with high confidence. This situation is further complicated since the contemporary period, for which we have the best observational record, is influenced by external anthropogenic forcing, thus complicating the characterization of internal modes of variability (England et al. 2014).

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

A central question of climate science concerns how climate will move to a new equilibrium in response to enhanced greenhouse gas forcing, and what that equilibrium state will look like. Many investigations have attempted to quantify the Earth's equilibrium climate sensitivity to anthropogenic climate forcing, with equilibrium typically requiring many hundreds to thousands of years to realize. However, humans experience climate as a transient adjustment of the Earth system to both natural and anthropogenic forces. Understanding processes and mechanisms influencing the trajectory of the Earth's climate system as it adjusts to anthropogenic forcing is a central focus of CLIVAR science. To address the associated questions of transient climate sensitivity requires furthering our understanding of how the ocean works. The apportioning of energy in the atmosphere, ocean, land, and cryosphere, and the energy exchanges among these components on various time scales, are at the foundation 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 the surface of the Earth (including the atmosphere, ocean, cryosphere and land), where most solar heating takes place, and in the subsurface ocean layers, where the majority of thermal energy is stored. These activities will complement the GEWEX focus on the top of the atmosphere (TOA), where solar radiation enters the system and infrared thermal radiation leaves. At each level, the amount of incoming and outgoing energy must, on average, be equal for the climate to be in equilibrium. Under climate-change conditions (IPCC, 2013), the composition of the atmosphere is altered and excess solar energy is trapped in the Earth system thus precluding equilibrium. This Earth energy imbalance (EEI) (Hansen et al., 2011, von Schuckmann et al., 2016) results in planetary heating, and modifies 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), making them key drivers of transient climate sensitivity (Fig. 1). The remaining excess heat from planetary warming goes into melting both terrestrial and sea ice and warming the atmosphere and land (Hansen et al., 2011; Church et al., 2013; Trenberth et al., 2014).

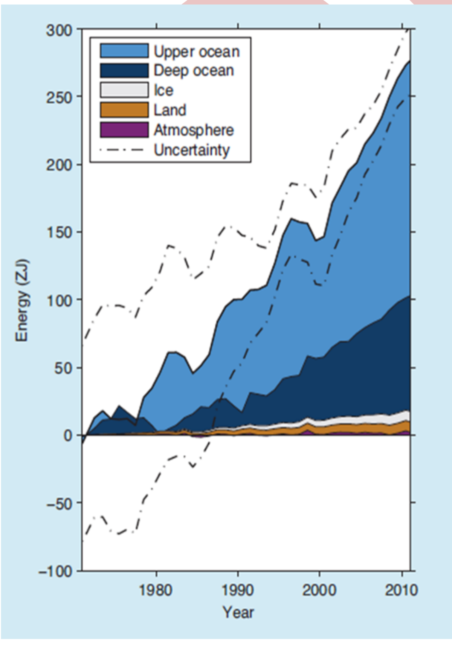

Figure 1 *The largest amount of energy accumulated in the climate system is stored in the ocean (~ 93%). The rest goes into the melting of land and sea ice (~ 4%) and warming of the atmosphere and land (~ 3%). The prevailing increase of stored energy in the ocean (blue shadings) as measured by Global Ocean Heat Content (see Abraham et al., 2013 for a review on observed GOHC) is a clear indicator for a warming climate. (from IPCC, 2013).*

CLIVAR will use observations from the climate observing systems (remote sensing and in situ) along with climate modelling and synthesis tools (e.g., ocean and atmospheric reanalyses) to monitor and analyse where the additional energy is accumulating, and to determine the prospects for future climate change. Ocean constraints on climate regulation, sensitivity, air-sea exchange and the Earth energy imbalance are applied 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., 2014, 2015). The following provides specific points for how CLIVAR will make use of ocean constraints to address questions concerning transient climate sensitivity, air-sea exchange of energy, and the Earth's energy budget.

Constraint of planetary energy imbalance

On a global annual scale, the change in top of the atmosphere net radiation and rate of ocean heat storage should be in phase and of the same magnitude (Loeb et al., 2012). This phase relation arises since all other forms of heat storage in the Earth system are at least 10 times smaller than ocean heat storage (Levitus et al., 2001). Research based on this approach will predominantly focus on the ocean's role in the Earth energy imbalance (Cheng et al., 2017; Dieng et al., 2017), tracking ocean heat content (e.g. Abraham et al., 2013), thermos-steric sea level linked to sea level rise, and tackles methods based on in-situ and satellite observing systems, ocean or coupled reanalyses and climate modelling.

Constraint of air-sea exchange

At longer time scales and at global scale, the amount of incoming and outgoing energy, on average, must be equal at the surface of the Earth and at the TOA (top of the atmosphere), and is in phase with the heat stored in the oceans (see constraint on energy imbalance). At regional scale, information of atmospheric or oceanic energy divergence needs to be additionally considered to address the energy transfer in a given study area. For example, TOA radiation can be combined with atmospheric reanalyses to estimate surface heat fluxes and combined with vertically integrated ocean heat content to then obtain ocean heat transport divergence as a residual (Trenberth and Fasullo, 2017).

Studies using this approach will focus on energy flows through the climate system, as well as assessments of climate data and tools. 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) are fundamental to constraint the estimates of global or regional net air-sea heat flux (Bretherton et al., 1982; Yu et al., 2013; ICPO, 2013).

Constraints from the global sea level budget

Global mean sea level changes due to changes in seawater density (steric) and mass (e.g., land ice melt and continental water inflow). Studies of global sea level have constrained the budget through the use of Argo floats (for density), satellite altimetry (for sea level) and satellite gravity measurements (for mass) (e.g., Church et al. 2011). The self-consistency of these global sea level measures allows for the methods to be used also as an 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 Earth energy imbalance (Llovel et al., 2014).

2.1.3 Regional impacts of climate change

Climate variability and change exist both globally and regionally. Understanding and predicting the broad spectrum of regional patterns of change touch on questions of regional climate impacts that offers useful information to the stakeholder communities (e.g., government, business).

We offer examples where such regional impacts form a societal mandate for much of the science coordinated by CLIVAR.

Regional/coastal sea level rise

Sea level rise has severe societal consequences, including the permanent displacement of huge numbers of humanity. Indeed, roughly 80% of megacities (actual and projected) are in coastal areas subjected to sea level changes. Despite considerable progress during recent years, major gaps remain in our understanding of past and contemporary sea level changes and their causes, particularly at regional scales. Of particular concern is building an understanding of how natural variability masks long-term trends in global and regional sea level (e.g., Cazenave et al., 2014). Knowledge gaps impact our ability to predict/project sea level on regional and local scales, as well as to quantify the role of extreme events (magnitude and return frequency). Uncertainties in sea level science arise from limitations in conceptual understanding of relevant physical processes, deficiencies in observing and monitoring systems, and inaccuracies in statistical and numerical modelling approaches to simulate and forecast sea level.

Understanding and predicting regional and coastal sea level involve quantifying the composite of global mean sea level change and contributions from regional and local processes. These processes include: exchanges of mass between the land, the cryosphere and the ocean; dynamics of the ocean and associated water mass transformation and/or redistribution; regional air-sea-land interactions; impacts from waves and storm surges; and "isostatic" processes associated with deformation of the solid Earth, resulting in seafloor movement along with gravitational and rotational effects.

Patterns of heat uptake and storage

Changes in regional ocean heat storage affect vertical stratification, ocean currents, thermal memory (Hansen et al., 2011), ice melt (Polyakov et al., 2017), climate adjustments such as Earth's surface temperature (Dieng et al., 2017), air-sea interactions as well as marine ecosystems and human livelihoods (Doney et al., 2012; Moore et al., 2018). There are uncertainties in determining the relative importance of under-sampled regions of ocean heat content and related volume changes (ice-covered ocean, marginal seas and deep ocean), and in how and where heat is transferred vertically (von Schuckmann et al., 2016). We need to evaluate how regional patterns change in time and if regional ocean heat content tendency patterns can be used to constrain ocean heat storage. For model simulations, it is important to use appropriate horizontal and vertical resolution for representing processes fundamental to climate on various spatial and time scales; to formulate improved parameterizations of key unresolved processes; and to offer accurate error bounds on reanalysis products that estimate ocean heat content and storage.

Beyond global estimates, it is desirable to determine energy imbalances locally and as a function of time. So called "CAGE" experiments (Bretherton et al., 1982; Yu et al., 2013; ICPO, 2013) provide a useful conceptual framing to conduct the associated budget analyses. These experiments were designed to compare three independent budget estimates in a single ocean basin, aiming to establish the random and systematic errors associated with each approach. Specifically, estimates of heat transport are achieved directly through ocean temperature and velocity observations, inferred through air–sea heat fluxes, as well as from the net radiation at the top of the atmosphere coupled with the atmospheric flux divergence. The design of the CAGE experiments emphasized the importance of redistribution of heat regulating the Earth's climate and the need to obtain an accurate estimate of the mean state of the global climate and of the ocean's role in maintaining that state. See Section 2.1.2 for further regional budget constraints.

2.1.4 Constraining Ocean Carbon Uptake and Storage

While the mean decadal "steady state" of ocean uptake of CO_2 is well constrained (2.6 ±0.5PgCy^{-1}) (Le Queré et al., 2017), the science challenge for the coming decade is two-fold: (1) to understand and constrain the variability (intraseasonal - decadal) and trends of the ocean's uptake and storage of carbon. This is required in support of model bias analysis and for the assessment of the changing global carbon budget; (2) to predict the emergence of physical (wind stress and stratification), biogeochemical and carbonate buffer factor feedbacks and tipping points that are likely to shift ocean CO_2 net uptake and storage to a non-steady state in future decades (McNeil and Matear, 2013; Conrad and Lovenduski, 2015; Hauck and Volker, 2015; McKinley et al., 2016; Roobaert et al., 2018; Landschutzer et al., 2018; Laufkotter and Gruber, 2018). Here we set out these broad challenges and indicate how the CLIVAR community could work with its partners to address them.

The most recent global carbon budget highlights the variability in unaccounted carbon in the Earth system (Fig. 2) (Le Queré et al., 2017). A key question concerns the contribution from interannual to decadal variability in ocean fluxes, particularly in the Southern Ocean (Fig. 2b) (Landschutzer et al., 2015; De Vries et al., 2017; Gregor et al., 2017). How much carbon the ocean will continue to take up in the future is a topic of critical climatic concern, particularly as the feedback mechanisms and sensitivity of vulnerable reservoirs are not well understood (Friedlingstein and Ilyina, 2017; Tanhua et al., 2016; Wang et al., 2016; DeVries et al., 2017). Improved understanding of regional characteristics of the temporal patterns of ocean carbon uptake and its variability is central to understanding the future trajectory of the climate system.

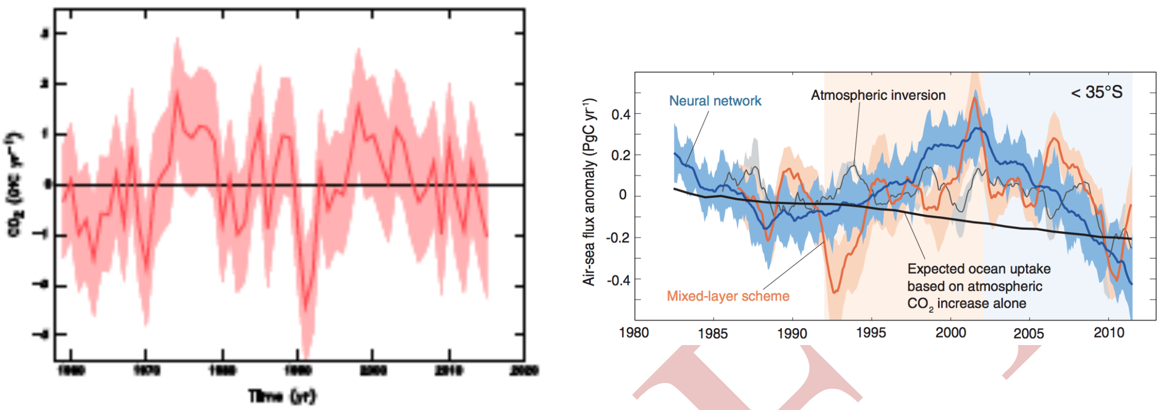

Figure 2: (a) – Decadal variability in the unaccounted carbon of the global carbon budget, including terrestrial, ocean and atmospheric domains (Le Queré et al., 2017). (b) – The decadal variability of air – sea CO_2 fluxes in the Southern Ocean comparing the decadal modes from empirical models and the steady state trend (Landschutzer et al., 2015).

We outline three main areas where the CLIVAR research community intends to contribute to improving the prediction capacity of the carbon – climate system in collaboration with international partner projects and programmes.

Improving the global ocean constraints for CO_2 variability and trends

Improving the temporal and spatial constraints of ocean CO_2 is critical for identifying and addressing biases in ocean and coupled Earth system models as well as assessing their effectiveness in simulating and predicting the non-steady state evolution of ocean carbon fluxes and storage.

Global ocean CO_2 observations are now well coordinated through the global community action of Surface Ocean CO_2 Atlas (SOCAT) for surface ocean fluxes and Global Data Analysis Project (GLODAP) for decadal scale changes in storage in the ocean interior (Bakker et al., 2016; Sabine and Tanhua, 2014). These data are mostly reliant on a network of repeat voluntary observing ships (VOS) as well as dedicated ocean basin transects (GO-SHIP). Carbon enabled moorings, floats and gliders are beginning to contribute towards more scale sensitive observations (Sutton et al., 2014; Monteiro et al., 2015; Williams et al., 2017) In the case of highly variable surface CO_2 fluxes, observed data in themselves are not sufficient to resolve the seasonal cycle, which is now considered the minimum requirement to reduce uncertainty in the interannual variability estimates (Munro et al., 2015; McNeil and Sasse, 2016; Gregor et al., 2017; Landschützer et al., 2018).

The use of linear and non-linear empirical models and remotely-sensed proxy variables to derive a weighted CO_2 estimate has made significant advances towards closing the observational gaps in space and time (Rodenbeck et al., 2015, Landschutzer et al., 2014; 2015; Gregor et al., 2017) and constraining emerging changes to the characteristics of variability (Landschutzer et al., 2018; Sasse et al., 2015). Uncertainties linked to wind and heat fluxes products (Swart et al., 2014; Roobaert et al., 2018), to the choice of empirical model as well as data sparseness remain major limiting factors, especially at high latitudes (Ritter et al., 2017).

Addressing carbon cycling biases in ocean and Earth system models

One of the challenges facing the ocean physics - carbon community is addressing biases in ocean-biogeochemical and Earth system models, particularly with respect to the seasonal cycle of air – sea fluxes of CO_2 (Lenton et al., 2013; Anav et al., 2015; Kessler and Tjiputra, 2016; Mongwe et al., 2016; 2017). Improved finer scale observational constraints are needed to better identify biases and to examine how they are linked to model resolution and process parameterization. In the presence of climate and biogeochemical variability, enhancing the reliability of model projections for future climate trajectories requires improvements to the physical representation of ocean mixing, ventilation and its sensitivity to climate-forcing variability and change, along with an improved understanding and representation of regional biogeochemical processes.

Mechanisms driving future feedbacks in the ocean carbon system

The community starts to recognize that much of the sensitivity of climate to the feedbacks of both CO_2 uptake and storage lies in the fine scale dynamics of the upper ocean. Mesoscale and submesoscale circulations play a major role both intrinsically and in relation to their interaction with the atmosphere, particularly under storms (Lévy et al., 2012; Mahadevan, 2016, McGillicuddy, 2016, Whitt et al., 2017). The relevance of fine-scale ocean dynamics can be large but regionally specific, and perhaps greatest in the Southern Ocean and sub-polar regions (Byrne et al., 2015). How to understand and to incorporate these dynamical scales into global earth system models present a significant research challenge to the CLIVAR community and its partners, and requires linking the changing physics to the biogeochemical responses. On a larger scale, changes to carbonate buffering (Hauck and Volker, 2016) and changes to the overturning circulation are likely major drivers of the evolution and variability of the coupled carbon-climate system (Ito et al., 2015; Lavergne et al., 2014; DeVries et al., 2017)

CLIVAR will continue to play a leading role in identifying and exploring mechanisms by which changes in carbon fluxes and biogeochemical cycles feedback on climate through a diverse array of research enterprises including sustained field and autonomous observational networks, synthesis, theory and modeling. The Southern Ocean offers a compelling regional focus for a CLIVAR – ocean carbon community collaboration. This focus is motivated by current estimates indicating that the Southern Ocean takes up roughly 75% of the added heat to the ocean from anthropogenic effects and roughly 50% of the anthropogenic CO_2 absorbed by the ocean (Frolicher et al., 2015). Central to our understanding of the Southern Ocean is the role of wind forcing on variability and trends of CO_2 fluxes and storage (Swart et al., 2014).

2.2 Fundamental ocean processes influencing climate

Improved knowledge of the processes central to climate is essential for understanding the numerous ways in which the ocean affects the Earth's climate over different space and time scales. Such processes include, among many others: ocean mixing and stirring; heat and freshwater fluxes at the interface of the ocean with the atmosphere; sea-ice and ice-shelf impacts on buoyancy fluctuations, especially along continental shelves; upwelling and shelf interactions in boundary currents; cross-equatorial transports of heat and moisture in the tropics; and tropical-extratropical interactions. These fine-scale processes have global impacts that extend to the coupling mechanisms between the wind-driven and the buoyancy-driven circulations; and to linkages between shortwave radiative fluxes and biological processes in the upper oceans.

In this framework, CLIVAR research will be organized around the following guiding questions.

- Which fine-scale processes control ocean mixing and the ocean mechanical and thermal energy budgets? What is their relative contribution and impacts on the global ocean circulation?
- What processes control coastal dynamics and upwelling systems? How will upwelling systems change with a changing climate?
- What oceanic or ocean-atmosphere coupled processes influence regional climate variability and how they impact the global Earth's system?

In this section we identify areas where CLIVAR leadership will play a role in furthering scientific understanding of how fundamental processes affect the climate system, including climate variations, climate changes, and transient climate sensitivity.

2.2.1 Ocean energetics and mixing

The ocean is a forced-dissipative fluid dynamical system, with mechanical energy input mostly at the large scales and dissipation at the small scales (see Fig. 3). Understanding and quantifying how mechanical energy moves through the ocean is a longstanding problem of physical oceanography. Research addressing this problem deepens scientific understanding of how the climate system works and offers a robust conceptual framework for testing numerical models and developing subgrid scale parameterizations to improve global ocean models and Earth system predictions.

Mechanical forces of atmospheric, cryospheric, solid-earth and astronomical origin, as well as buoyant forces through heat, salt, and water boundary fluxes, determine distributions of the ocean's kinetic and available potential energies (APE). Large-scale APE reservoirs are converted to kinetic energy at the mesoscale (10-200 km scale: the dominant scale of ocean kinetic energy) through transient eddies and their associated fronts (Wunsch and Ferrari, 2004). At the mesoscale, the ratio between inertial and Coriolis forces (i.e., the Rossby number, Ro) is generally far less than unity so that the dynamics are to a first approximation quasi-geostrophic. In quasi-geostrophic flows mesoscale eddies generally cascade kinetic energy to the large scales through an inverse cascade reminiscent of two-dimensional turbulence (Charney 1971). The inverse cascade offers a framework for formulating eddy parameterizations needed in models only partially resolving mesoscale circulations.

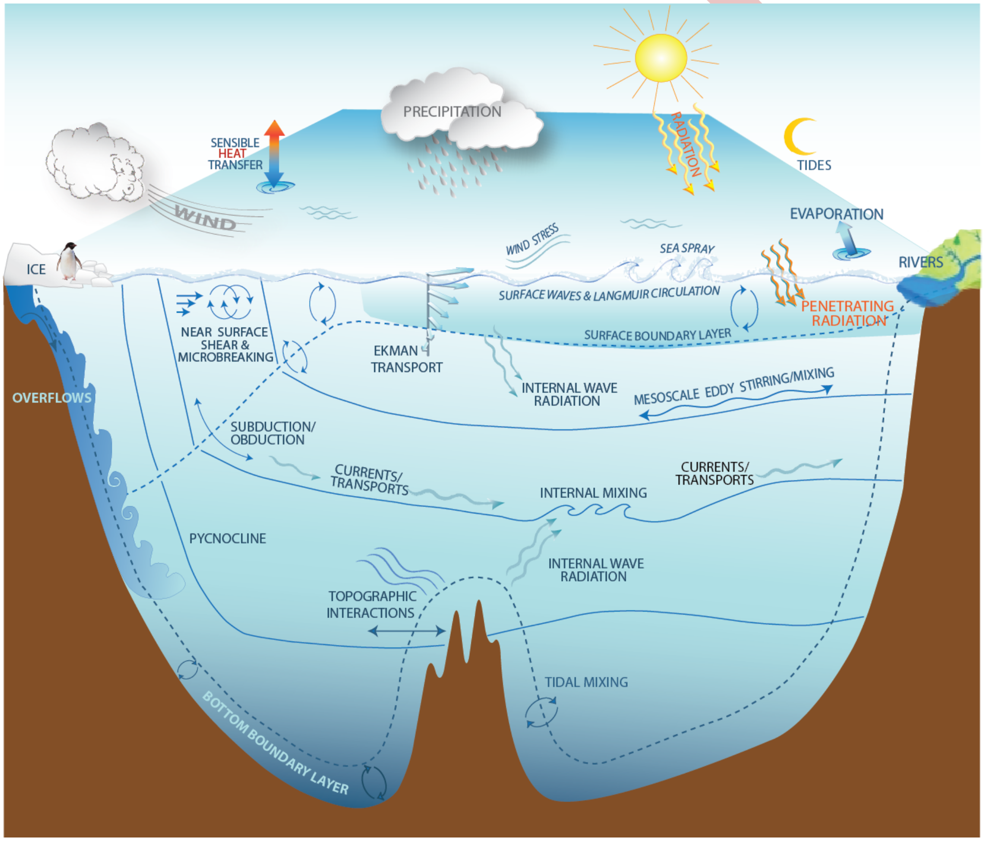

***Figure 3**: Schematic of ocean physical processes that participate in the cascade of mechanical energy from the forcing scales to the dissipation scales. From Griffies and Treguier (2013).*

Near the ocean boundaries (top and bottom) the geostrophic balance between the pressure-gradient and Coriolis forces breaks down when approaching the submesoscale (0.1-10km; McWilliams 2016). Throughout the ocean, lateral density gradients generated by mesoscale eddies and fronts, or by freshwater fluxes from rivers, ice melt and rainfall are enhanced through unbalanced (Ro >> 1) instabilities. Submesoscale dynamics (characterized by Ro ~ 1) further support a direct kinetic energy cascade to smaller unbalanced gravity wave motions. Gravity waves also arise through astronomical tides converted to internal tides via interactions with solid-earth boundaries (Munk and Wunsch, 1998), while geostrophic currents interacting with solid boundaries give rise to leewaves. The breaking of gravity waves and leewaves provides a fundamental, not yet fully quantified, avenue for energy dissipation (MacKinnon et al. 2013).

Over the next decade, CLIVAR will foster research to build both conceptual and quantitative measures of how buoyant and mechanical forces are transferred through boundaries into the ocean interior, thus fostering an understanding and quantification of the ocean mixing geography. In doing so, CLIVAR will directly support improved modeling of the oceanic uptake of heat, carbon and other trace properties and their transport in the ocean interior. Relevant questions concern the parameterization of bulk formula that translate the atmospheric and oceanic state into boundary fluxes, and the role of surface gravity waves, submesoscale turbulence, Langmuir turbulence, and swell waves (Cavaleri et al., 2012). At the ocean bottom, overflow processes provide conduits for dense shelf waters moving in the high latitude abyss and feed the deep waters of the ocean (Legg et al., 2009). Related questions concern modifications to vertical stratification and meridional overturning circulation arising from changes in freshwater fluxes anticipated from enhanced cryospheric melt and modifications to the hydrological cycle (Rahmstorf et al. 2015; Boening et al. 2016; Luo et al., 2016).

2.2.2 Coastal processes and large upwelling systems

There are emerging physical oceanographic issues that concern connections between large-scale and small-scale motions, with these issues at the root of why fundamental physical oceanographic research is relevant for climate. In addition, there is an increasing recognition that many questions previously regarded as regional now require a global perspective. This recognition is of particular importance within the coastal areas embedded in energetic boundary currents. Coastal areas are also affected by intense dynamical interactions between processes at different scales and by complex physical and biogeochemical connections at the land-shelf, ice-shelf, and shelf-open ocean interfaces. With half of the world population living less than 100 km from the seashore, coastal systems are of paramount importance for local resources, national economies and sustainability.

A better understanding of physical processes governing dynamics in large upwelling systems is essential to make progress on this research area, with particular attention given to Eastern Boundary Upwelling Systems (EBUS) and the Southern Ocean Upwelling System (SOUS). In these regions, subsurface (from depths of a few hundred to a few thousand meters) ocean cold waters are forced, by the action of the wind stress curl, to the surface and powerfully shape the regional marine ecosystems and air-sea interactions. Astonishingly, EBUS account for less than 3% of the world ocean surface yet provides the largest single contribution to ocean biological productivity, with up to 40% of the global fish catch (Capone and Hutchins, 2013). Likewise, SOUS exerts a disproportionately large influence with respect to its size on the Earth's heat balance, the oxygen and carbon cycles, and marine life (e.g., Morrison et al. 2015).

These regional ocean systems are both key contributors to physical and biogeochemical fluxes and extremely sensitive to anthropogenic changes. Here, climate variability and change are crucial to shaping marine ecosystem characteristics (Harley et al., 2006). A combination of interdisciplinary observational and modeling efforts is necessary to improve scientific understanding of variability in the coastal ocean and in the large upwelling systems, their responses to climate change, and implications of these regional scale changes for global climate. Two key aspects of CLIVAR research include identifying common biases in their representation in coupled and ocean models, and understanding their variability and trends in a changing climate.

Climate model biases in upwelling systems

Model simulations have large biases in the representation of upwelling systems (Fig. 4). For EBUS, one cause of the biases is the underestimation of the upwelled waters due to coarse resolution of coastal ocean and atmospheric processes, also augmented by a poor representation of deep water characteristics. The resulting air-sea temperature contrast between the upwelled and off-shore waters is thus weaker than observed, implying a diffuse air temperature inversion zone (e.g. Wyant et al., 2010) that prevents the formation of low-level clouds. The role of air-sea processes in modulating 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 ~ 1000 km to submesoscale ~1 km). Additionally, the radiative budget at the air-sea interface is not well understood, and the associated heat budget may involve zonal heat transfer from the coast to the open ocean by mesoscale eddies (Colas et al., 2012; Toniazzo et al., 2010). Observational analyses are required to better understand and quantify the role of eddy activity on the stability of coastal current systems (Dewitte et al., 2012; Combes et al., 2015). Implications range from improving the potential for prediction of regional climate to better understanding of factors influencing primary biological productivity, oxygen and carbon fluxes.

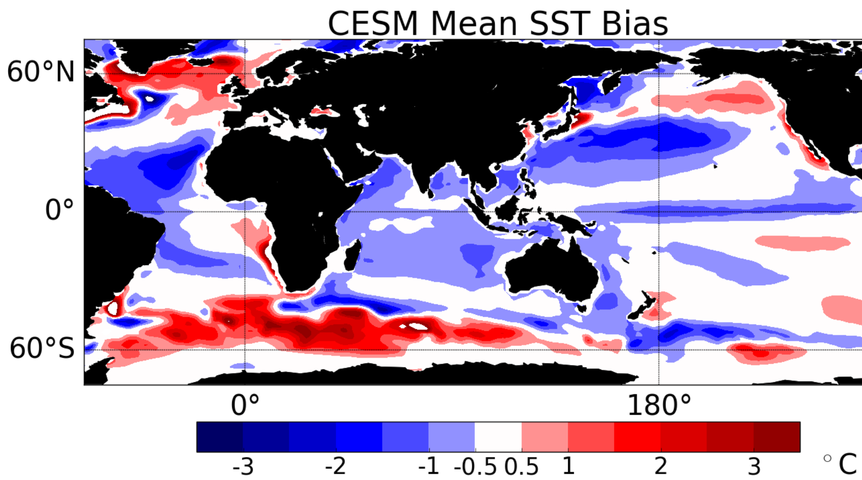

Figure 4: Mean SST bias in the Community Earth System Model (CESM) Large Enseble: Difference in annual-mean SST between an ensemble of 30 members of CESM (historical experiment) and the COBEv2 reanalysis (Hirahara et al., 2014)

The SOUS, driven by vigorous westerly winds circulating around the Southern Ocean, starts close to the Antarctic continent and extends north to about 50° S. This circulation system moves lighter surface water northward and draws large amounts of deep, dense water to the surface in the south (e.g. Marshall and Speer 2012; Rintoul et al., 2013). Here the warm SST bias of about 2°-3°C in the CMIP5 multi-model mean (Figure 4) is commonly attributed to 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 (Ceppi et al., 2012; Hwang and Frierson, 2013).

There are additional hypotheses related to the role of ocean mixing induced by surface waves (Langmuir turbulence). CLIVAR is coordinating investigations into these questions as part of the Coordinated Ocean-ice Reference Experiments (CORE-II) activities (Farneti et al., 2015) as well as the Ocean Model Intercomparison Project (OMIP).

Climate variability and trends in upwelling systems

There is an ongoing debate as to whether eastern boundary upwelling will increase or decrease under climate change. Similar uncertainties apply to the Southern Ocean, where relatively little warming has been observed in 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. The net result is that heat in the Southern Ocean is preferentially stored where surface waters are subducted to the north (Armour et al., 2016; Morrison et al., 2016). Model simulations also suggest that increased Southern Ocean wind stress resulting from global warming and the expansion of the ozone hole will continue to increase northward Ekman transport and upwelling (Lovenduski et al., 2008). However, the extent to which mesoscale eddy fluxes compensate for Ekman transport in the mixed layer is unknown (Farneti et al., 2015). There are basic questions related to the balance between increased carbon uptake and outgassing resulting from increased upwelling.

There are many regional peculiarities of upwelling systems in both environmental forcing, coastline geometry and topography, and sea-ice in the Southern Ocean (Purich et al., 2016). There are also contrasting results of regional oceanic downscaling experiments, coupled or uncoupled, in different upwelling systems (Echevin et al., 2012; Curchister et al., 2015). Consequently, CLIVAR-coordinated research on upwelling will focus on establishing a conceptual and modeling framework for understanding processes key to EBUS and SOUS. In particular, this work will evaluate the sensitivity of both global and regional climate models to climate change with targeted experiments.

2.2.3 Climate dynamics, feedbacks and regional modes of coupled variability

Much research on climate dynamics has focused on statistical descriptions of variability and change in terms of climate modes. These descriptions offer compact ways to describe climate variability and its impacts through local responses and atmospheric teleconnections. However, they do not generally offer a useful lens for insight into dynamical mechanisms and physical processes associated with variability.

As a complementary path, CLIVAR will focus on the following three areas, aiming towards a predictive understanding of these phenomena with a focus on the role of atmosphere-ocean interactions. These areas present challenges for observations, models and theories, alike.

Storm tracks, jet streams, & weather systems associated with extra-tropical air-sea coupling

Mid-latitude ocean circulation, especially western boundary currents, can influence various atmospheric phenomena (e.g., Hewitt et al., 2017). Local impacts are evident on near-surface and vertical winds, precipitation, and clouds, thus providing diabatic sources of heat and moisture to the troposphere (Minobe et al., 2008). Furthermore, an emerging body of atmospheric model experiments show that extratropical air-sea interactions, especially those in the western boundary current regions, influence storm tracks (Small et al., 2014), jet streams (O'Reilly et al., 2017), weather systems such as blocking (Scaife et al., 2011; O'Reilly et al. 2016), and atmospheric circulation anomalies (Smirnov et al., 2015).

Under climate change conditions there are competing influences on the Northern Hemisphere storm tracks, with differing responses to warming of the pole-to-equator temperature gradients in the lower and upper troposphere. Consequently, models tend to predict only modest changes in storms. However, while thermodynamic aspects of storms and storm tracks are relatively robust across models, there is little confidence in their projected dynamical changes (Collins et al., 2013). Furthermore, large-scale extratropical atmosphere-ocean interactions lead to the damping of surface turbulent heat fluxes, so that atmospheric anomalies may persist longer. Atmospheric and oceanic models capable of resolving ocean mesoscale fronts are required to represent this influence. The development of relevant experimental methodologies has proven valuable (Kosaka and Xie, 2013) and needs to be further refined. These processes are being investigated by CLIVAR to better understand mid-latitude coupling.

The tropics and monsoon systems

The Intertropical Convergence Zone (ITCZ) can be viewed as a manifestation of the global monsoon (e.g. Wang et al., 2013) with oceanic modes of climate variability driving coherent variations in the various monsoon regions in concert. Alternatively, the monsoons can be viewed as extended excursions of the ITCZ over land (Bordoni and Schneider, 2008). Understanding variability and change of the monsoons at global and regional scales through climate model simulations is hampered by systematic model biases. These biases include global-scale errors relating to cross-equatorial transports of heat and moisture that affect the position of the ITCZ and thus give rise to rainfall deficiencies in the northern hemisphere monsoon regions (Haywood et al., 2016; Hawcroft et al., 2017). Key observations that could help constrain model outputs, such as observations of the vertical structure of the ITCZ (Huaman and Takahashi, 2016; Huaman and Schumacher 2018), are lacking. There is also a significant dry bias in the Asian monsoon, likely related to deficiencies in modeling tropical convection processes (Sperber et al., 2013). Understanding how monsoons respond to modes of climate variability, and how these responses will change in the future, is a problem requiring the assessment of ocean-atmosphere and land-atmosphere interactions, with this work aided through the use of global models with minimal systematic biases. This is an activity that naturally bridges the gap between CLIVAR and GEWEX scientific interests and requires efforts in observational and process-modelling research.

Tropical-extratropical interactions

The tropical sourced ENSO teleconnections are generally not fully captured by climate model simulations. This model deficiency is highlighted by noting that most CMIP5 models exhibit different relations between ENSO and the Pacific Decadal Oscillation (PDO) in the North Pacific (Newman et al., 2016). The opposite direction of interaction, i.e., mid-latitude influence on the tropics, also plays an important role in climate variability.

For example, SST anomalies excited by atmospheric circulation variability in the mid-latitude North Pacific propagate to the tropics and are associated with wind-evaporation-SST feedbacks that can lead to ENSO occurrences (Vimont et al., 2003). Similar propagating signals and resultant excitations of ENSO-like variability have more recently been reported by Zhang et al. (2014). Furthermore, interactions can occur across basins; it is suggested that decadal Atlantic variability influences the tropical Pacific via trade winds. This inter-basin teleconnection is one cause of the PDO/Interdecadal Pacific Oscillation (PDO/IPO) in recent decades (Li et al., 2017), which is closely related to the global warming hiatus in the first decade of the 21st century (Kosaka and Xie, 2013).

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

Weather and climate span a continuum of time scales. Providing skillful forecast information at different lead times is relevant to a variety of stakeholders, such as governments, agriculture, and businesses. The subseasonal-to-seasonal scale is of special interest as it bridges applications at the much shorter, weather related (hourly through weekly) scales and much longer, climate related (seasonal through decadal) scales in which considerable societal and economic research has been conducted. Climate also exhibits variability on decadal-to-multidecadal timescales often large enough to overshadow regional and global anthropogenic trends. Any improvement of decadal projections has relevance for guiding decisions about future adaptation investments.

While the production of forecasts belongs to operational agencies, WCRP investigates climate system predictability in support of scientific understanding of the underlying mechanisms. This research facilitates actionable forecast information of use worldwide, including developing economies. The ocean acts as a pacemaker of intraseasonal to decadal variability. Consequently, the ocean affects predictability across different time scales as it interacts with the atmosphere, land, and cryosphere.

CLIVAR activities on these topics are organized around the following guiding questions:

- What is the predictability limit at subseasonal-to-seasonal time scales? What about seasonal-to-multidecadal time scales?
- Which deterministic oceanic processes contribute to predictability?
- How do changes in the climate mean state perturb teleconnections and affect predictability?
- Is it possible to attribute changes on decadal-to-multidecadal timescales to specific natural and anthropogenic forcings?
- What properties of extremes are changing under global warming and how does their predictive skill change?

The first question above is addressed at each time scale in the subsections below. The remaining questions span several time scales and are discussed where appropriate. Both observations and model studies are needed to achieve robust answers to these questions and analysis will tackle case studies not only over the instrumental or future periods, but also using paleoclimate information where appropriate.

2.3.1 Subseasonal to interannual variability, predictability and prediction

The subseasonal time scale is key for many activities of societal relevance - for example in the timing of crop sowing and irrigation practices in agriculture - yet it lies between traditional weather forecasts and the emerging use of coupled, initialized seasonal forecasts. It bridges the gap between traditional WCRP and WWRP activities such as in the WMO's subseasonal-to-seasonal (S2S) prediction project. Subseasonal predictions benefit from both atmospheric initial conditions and factors external to the atmosphere, such as the state of the ocean, land, and cryosphere, and require a close collaboration across all core projects of WCRP. Processes internal to the atmosphere including the Madden-Julian Oscillation (MJO), the Boreal Summer Intraseasonal Oscillation (BSISO, with its northward propagations in the monsoons) and low-frequency atmospheric patterns of variability contribute significantly to predictability at these scales. Significant skill of these modes is suggested at more than two-week lead times.

Not all processes and interactions are resolved in numerical models, particularly at the scales of tropical convection and of ocean-atmosphere coupling. There are reasons to hypothesize that these missing processes and interactions represent untapped sources of predictability. Likewise, the role of the land-surface in modulating and enhancing modes of intraseasonal variability as they propagate (for example the MJO across the Maritime Continent) is unclear. CLIVAR will facilitate research into new directions to investigate how skill scores improve with improved representations of the diurnal cycle, high frequency coupling processes, model physics and resolution, as well as the possible change in prediction skill in a changing climate. This predictability research also includes determining contributions from the MJO to the forecast skill of surface air temperature and precipitation in extratropical regions as implied by studies such as Cassou (2008). It will also, more broadly, study how modes of tropical intraseasonal variability can lend predictability to the extratropics, and whether the associated global teleconnections are simulated adequately in models.

Beyond the subseasonal time scales, interannual variations such as ENSO help to set the seasonal rainfall such as in monsoon regions. This interaction can be considered as the influence of the slowly varying lower boundary on the atmosphere (where slow means evolving less rapidly than the seasonal cycle), which lends predictability to the interannual variations of tropical rainfall (Charney and Shukla, 1981). Chiefly, ENSO has clear impact on the various regional monsoons and the global monsoon, while more locally, further predictability can be obtained from the Indian Ocean Dipole, or from the interannual modes of variability in the tropical Atlantic. How interannual modes of tropical variability such as ENSO aid prediction in the extratropics is a continuing area of research. Furthermore, how ENSO affects subseasonal modes such as the MJO remains unclear.

Overall, model uncertainty prevents a reliable estimate of subseasonal predictability. Errors that manifest quickly in tropical convection and affect forecasts on subseasonal time scales have strong similarity to systematic errors on climate time scales in the tropics. While uncertainty due to model formulation can be improved by multi-model methodologies, targeted work is needed using observations to support development of model parameterizations and to reduce systematic model biases. Doing so will facilitate full use of potential predictability across the intraseasonal to interannual time scales.

2.3.2 Seasonal-to-Decadal predictability and prediction

For seasonal to interannual climate predictions, ENSO is the dominant source of predictability for the global climate system. The predictability of ENSO is seasonally dependent, being highest in winter and lowest in spring and summer (Kumar et al., 2017). However, ENSO's predictability limit remains unclear; that is, up to what lead-time can skillful ENSO predictions be made? While some authors argue that ENSO is predictable up to two years (e.g. Chen et al., 2004; Luo et al., 2008), others are less optimistic because of the spring predictability barrier (Newman and Sardeshmukh, 2017), that results in operational forecast skill extending no more than one year (Barnston et al. 2012).

These differences in ENSO predictability arise from model limitations in their representation of the predictable signals as well as the unpredictable noise. Additionally, ENSO can no longer be regarded as an oscillation localized to the east Pacific. Namely, the diversity of ENSO behaviour in terms of its longitudinal position determines how teleconnections are excited through interaction of the oscillation with the background mean state that varies across the Pacific. The predictability of ENSO diversity remains to be assessed as well as the impacts of ENSO teleconnections on regional and coastal systems.

SST prediction skill is consistently high over the central-eastern equatorial Pacific while it is noticeably lower over the Indian and Atlantic Oceans (e.g. Kumar et al. 2011). For instance, skillful predictions of the Indian Ocean Dipole can only be made one season ahead, with predictability being larger for stronger events (e.g. Liu et al., 2017). Beyond the tropical oceans, there are other sources of seasonal predictability arising from soil moisture, snow cover and sea-ice over land. These predictability sources call for an improved understanding and representation of coupled processes. The role of systematic model biases on climate predictability also needs to be further assessed through the multi-model ensemble approach, and by perturbing model parameters or stochastic parameterizations (Doblas-Reyes et al. 2013).

The ocean is the primary driver of decadal and multidecadal climate variability (e.g. Gulev et al. 2013). However, many questions remain about decadal variability, including its character, the processes that generate it, the scope of its predictability, and hence the level of predictive skill. Because of the scarcity of historic observations, global coupled climate models are critical for exploring the predictability of decadal variability (Smith et al., 2013). The Indian Ocean stands out as the region with the highest predictability worldwide in decadal climate prediction studies. This skill is largely attributed to anthropogenic forcing trends, which have larger amplitude than the natural decadal climate variability in the Indian Ocean (Guémas et al., 2013).

Some studies have shown potential decadal predictability when oceanic decadal anomalies can be traced back to a specific oceanic source, typically a subsurface record indicative of past air-sea interactions. This subsurface connection may contribute to a larger predictability over the North Atlantic, where changes in the AMO have been associated with AMOC variability (e.g. Srokosz et al., 2012), the latter possibly having interannual to decadal predictability (Teng et al., 2011). Recently, however, the AMO-AMOC link has been challenged based of model results (Clement et al., 2015). Predictive skill in the Pacific is less compared to the Atlantic and Indian Oceans. The reason is that the Pacific is more sensitive to initial state uncertainty (Branstator and Teng, 2012) and because the mechanisms generating the natural decadal variability in the Pacific are not well established. For instance, the predictability of the ENSO-like pattern of tropical Pacific decadal variability is currently debated: some argue that it is a residual pattern resulting from ENSO spatial asymmetries and skewness, while others argue that specific mechanisms give rise to the tropical Pacific decadal variability that in turn influence decadal ENSO characteristics and teleconnections (Power et al., 1999; Meehl et al., 2014). Given the PDO's relationship with ENSO, PDO forecast skill strongly depends on ENSO forecast skill, especially for forecast leads of up to 1-2 years (Newman et al., 2016). The absence of predictability for ENSO events at longer lead times could result in poor decadal PDV and PDO forecast skill. Recent studies established multi-year predictability of the Kuroshio extension speed (Nonaka et al., 2012) that may lead to PDO related predictability in the western North Pacific.

Many outstanding practical issues must be addressed before decadal predictability can be fully realized in coupled prediction models (Cassou et al., 2017). What are the mechanisms giving rise to decadal climate variability in the different ocean basins? 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 Attribution of decadal-to-multidecadal changes

While the long-term change in global mean surface temperature (GMST) is increasingly dominated by the anthropogenic greenhouse effect, the recent slowdown of GMST increase (the global warming "hiatus" in surface temperatures registered between 1998 and 2012), illustrates that internal variability can modulate the forced trend considerably over periods of a decade and longer (Fyfe et al., 2016). This slowdown has indeed been largely attributed to the negative phase transition of tropical Pacific decadal variability (TPDV) (England et al., 2014). That is, the ocean sequestered heat that otherwise sits in the atmosphere. When that heat was released in 2014-2016, mostly within the tropical Pacific, global surface temperatures sharply rose (Yin et al., 2018).

At the regional scale, this natural variability during the hiatus also resulted in an equatorial Pacific cooling, an intensification of the Pacific Walker circulation and sea-level rise over the western Pacific region. Spatial variations in ocean-surface warming are important for regional changes in rainfall and tropical cyclones, and in ENSO amplitude and ENSO teleconnections. Similarly, the increased warming rate and rapid sea-ice loss of Arctic region warming may be paced by the internal variability of climate modes such as the PDO and AMO (Screen and Francis, 2016; Tokinaga et al., 2017). Hence, at least for some processes (e.g., precipitation), it is expected that natural decadal climate variations will alias the anthropogenic signal over multi-decadal time horizons. At decadal-to-multidecadal scales, a key challenge is to identify the main characteristics and mechanisms of natural decadal climate modes and to 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).

Anthropogenic changes in aerosols are important in explaining historical trends. The aerosol forcing induces a pronounced cross-equatorial Hadley circulation (Ming and Ramaswamy, 2011; Wang et al., 2016) and a weakening of the northern hemisphere monsoons (Polson et al., 2014; Guo et al., 2015), contributing to the long drought of the African Sahel from the 1950s to 1980s. The climate effects thus follow the trend of reversal. Volcanic aerosols (Wigley et al., 2005) and the eleven-year solar cycle (Meehl et al., 2009; Thiéblemont et al., 2015) also modulate decadal trends to various degrees.

Many of the observed regional changes are poorly resolved by observations. Careful synergetic analyses between observations, reanalyses and climate models are necessary to characterize and interpret historical changes in key parameters of the climate system (temperature, winds, rainfall, sea level etc.). Ocean/atmosphere reanalyses prove useful in studying interannual-to-decadal variability but their utility in studying multi-decadal trends remains to be tested because of errors in the boundary conditions and changes in the amount and types of assimilated data.

Regarding climate models, care needs to be taken as common model errors may give rise to robust yet spurious projections, such as in the case of regional changes over the tropical Indian Ocean (Li et al., 2016). Improving models and advancing predictive dynamical understanding of radiatively forced climate change and internal variability are crucial to make robust progress (Xie et al., 2015). CLIVAR leadership in numerous model intercomparisons projects endorsed by and associated with CMIP6, such as the Global Monsoons MIP, Highres-MIP, VolMIP, OMIP, FAFMIP, and the DCPP will enable a more careful attribution of regional temperature, sea level, wind and precipitation changes on decadal-to-multidecadal time scales to anthropogenic forcing (GHG, aerosols, ozone), natural external forcing (volcanoes, solar cycle) or internal modes of the climate system (TPDV, PDV, AMO).

2.3.4 Weather, climate and ocean extremes

Weather and climate extremes have enormous impacts on society and environment, and they occur at different spatial and temporal scales. Examples include continental-scale multi-year drought, large-scale heat-waves that last days to several weeks; localized short duration events such as heavy precipitation on timescales from hours to days; coastal sea-level surges and extreme ocean waves due to short-lived tropical and extratropical storms. Both the science questions and the data require attention to identify factors and mechanisms that determine the location, intensity, and frequency of extreme events. Doing so will help mitigate societal and ecosystem risks and for effective adaptation planning on the long-term. The possibility that climate change could make present day extreme events more commonplace or more intense underlines the critical importance of understanding and predicting extremes.

These problems are at the heart of the WCRP Grand Challenge on Weather and Climate Extremes. Both CLIVAR and GEWEX sponsors science panels that contribute to the science underlying this Grand Challenge. CLIVAR in particular focuses on the role of the ocean, climate variability, and climate change in modulating the characteristics of these extreme events. The ocean impacts climate extremes primarily through its control of cyclogenesis and the large-scale atmospheric circulation. In this regard, the various climate modes discussed in this document have a strong influence on modulating extremes. However, this relationship has only been intensively explored for some types of extremes (e.g., precipitation and drought) and needs to be extended to others.

Tropical cyclone dynamics have been the subject of considerable research and prediction efforts, and existing models can reproduce many aspects of their movement and distribution. However, how their properties change under global warming depends on multiple factors that can either enhance or suppress cyclogenesis. These factors and their interplay need to be better characterized before reliable predictions on occurrence of extreme values of winds and storm surge can be made. Precipitation extremes are known to occur in association with and modulated by synoptic storms, tropical cyclones, and organized heavy convection. More recently, a link has been shown to exist between short-term precipitation extremes and longer time-scale modes of variability such as the MJO or BSISO and to some modes of ocean-related variability including ENSO and modes of Pacific decadal variability. This link suggests the possibility of long-lead prediction. An overall assessment of the key causes of, and large-scale influences on, extreme short-term precipitation, has to be made.

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 circulation dynamics and physical processes is not yet clear. Furthermore, the specific mechanisms by which the large-scale circulation anomalies associated with oceanic forcing modulate continental precipitation remain a subject of ongoing research.

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 fluctuations 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 patterns as well as important local processes are not captured. Furthermore, the amount of variability may be correct for the wrong reasons (Grotjahn, 2013).

In addition to exploration of the underlying mechanisms, several outstanding questions, overarching the WCRP Grand Challenge must be addressed to better understand and predict these weather and climate extremes. Are existing observations sufficient to underpin the assessment of extremes? What are the relative roles of large-scale, regional and local scale processes, as well as their interactions, for the formation of extremes? Are models able to reliably simulate extremes and their changes, and how can this be evaluated and improved? To what extent can detected changes in extremes be attributed to forcing external to the climate system and/or to internal factors such as modes of variability?

Chapter 3. Implementation Strategy for CLIVAR Science

Over the years CLIVAR's structure has evolved to meet emerging science challenges. The organizational structure of CLIVAR consists of standing Panels that advance science and carry out organizational tasks from global to basin scale; and community-driven research foci, that address specific science questions through a limited-lifetime working group format, involving and integrating various CLIVAR panels. Work is coordinated and directed by the Scientific Steering Group (SSG) and supported by the International CLIVAR Project Office (ICPO). SSG's members are appointed by the WCRP Joint Scientific Committee (JSC) and they provide overall guidance for CLIVAR activities, in concert with the goals of WCRP. The SSG establishes CLIVAR Panels and Research Foci and their terms of reference.

The resulting CLIVAR structure is illustrated in Fig. 5. In the future, the implementation structure and strategy will evolve further to better coordinate its science internationally and to accommodate the changing nature of the scientific questions it tackles and the international community it serves.

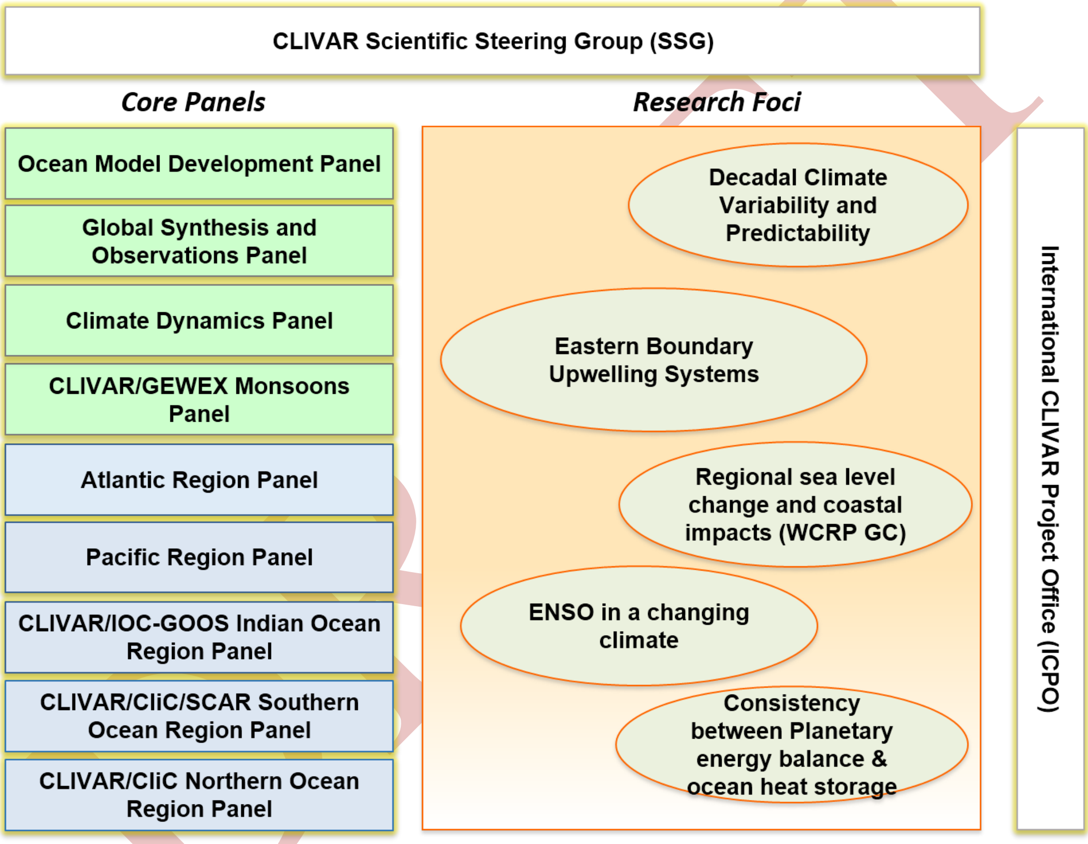

Figure 5: The CLIVAR organizational structure

Below we summarize the strategy for regional to global scale research panels. In the next chapter we describe the international coordination that enables capabilities involving models, observations as well as education and capacity building.

3.1 Standing Panels

3.1.1 Global Panels:

The following four panels advance CLIVAR's science that is global or integrating in nature:

a) Climate Dynamics Panel (CDP): The aim of CDP 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. Current activities are organized around three areas: (i) the organization and impacts of storms, blocking patterns 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. A longer-term focus is to improve understanding of the evolution of natural climate modes (existing and new) in a changing world. 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 (iii) sensitivity or so-called "pacemaker" experiments, where SSTs in ocean basin are relaxed towards observed values and the response of the coupled climate system outside that region is assessed (e.g. Hoskins and Karoly, 1981). These numerical investigations are coordinated by CLIVAR as part of Modeling Intercomparison Projects (MIPs) within the CMIP6 framework.

b) Monsoons Panel (MP): 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. Recognizing the role of the oceans, ocean-atmosphere interaction, processes in atmospheric convection and land-atmosphere interaction, the MP necessarily covers scientific areas of expertise of the GEWEX and CLIVAR core programmes of the WCRP, and is thus a joint Panel. The MP pursues activities both at the level of the global monsoon and for the various regions. At the global monsoon scale, the means by which changes in the regional monsoons vary in a coherent manner under external forcing or due to decadal ocean modes of variability are considered in coordinated activities such as the Global Monsoons MIP contribution to CMIP6. At the regional scale, the MP has established Working Groups covering the three major monsoon regions of the Americas, Africa and Asia-Australia. These WG bring together international and local experts focusing on the particular scientific and societal needs of the different regions. The MP serves to highlight and promote scientific activity common to the regions, including focusing on process-based understanding of model systematic bias and of understanding the implications of climate change through CMIP6, and their translation to climate services for society. A key emerging focus, at the interface between weather and climate time scales, is to understand variability and predictability on subseasonal-to-seasonal scales, and exploit this for improved prediction in monsoon regions. The MP also seeks promotion and exploitation of the outputs of field observation campaigns in the monsoon regions, and contributes to the development and design of oceanic field campaigns such as the Years of Maritime Continent.

c) Ocean Model Development Panel (OMDP): The OMDP leads, coordinates, and/or facilitates the development of global and regional ocean models for research in climate and related fields. A major panel activity in recent years has been the establishment of protocols and provision of forcing data sets for performing Coordinated Ocean-ice Reference Experiments (CORE), providing a mean for evaluation of the ocean and sea-ice components of coupled climate models. This effort forms the basis of the CMIP6 Ocean Model Inter-comparison Project (OMIP; Griffies et al., 2016). Through such coordinated efforts, meetings, and workshops, OMDP leads and encourages developments of ocean model algorithms and physically-based parameterizations, particularly to address persistent model biases; nurtures investigations of the effects of model formulations on the results of the ocean models; promotes interaction among the ocean modelling community and between this and other communities; publicizes developments in ocean models; and encourages use of data produced by CMIP simulations. As the only ocean-modelling panel in WCRP, OMDP regularly collaborates and interacts with other CLIVAR and WCRP panels as well as CLIVAR RFs and WCRP GCs, discussing emerging ocean modelling needs and related issues and providing advice.

d) Global Synthesis and Observations Panel (GSOP): The 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. CLIVAR, through GSOP, pioneers and organizes at the international level the generation and use of ocean syntheses, often referred to as ocean reanalyses. State-of-the-art ocean syntheses now cover 60 years and beyond and are used to study ocean transport, variability and change, as well as the interaction of the ocean with the overlaying atmosphere. A specific use of those ocean syntheses remains the initialization of coupled forecast efforts (e.g., Pohlmann et al., 2013; Belluci et al., 2013; Polhmann et al., 2014; Polkova et al., 2014).

Highlight activities of the panel include: (i) leadership of the ocean reanalysis intercomparison project (ORA-IP), and (ii) leadership of the 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 Regional Ocean Basin Panels (Atlantic, Pacific, Indian, Southern Ocean and Northern 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 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 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. Their expertise and interests span observations, models, experiments and process studies. The Regional 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. As specific examples, the Pacific Region Panel has been involved in the evaluation of the tropical Pacific observing system that is being done by TPOS2020. Similarly, the CLIVAR/CliC/SCAR Southern Ocean Region Panel is involved in the discussions of the Southern Ocean Observing System (SOOS) initiative. The Atlantic Region Panel and the CLIVAR/IOC-GOOS Indian Ocean Region Panel are leading the review of the tropical Atlantic observing system, and of the Indian Ocean Observing System (IndOOS), respectively. Panels also promote data sharing and work with relevant agencies on the standardization, distribution and archiving of observations.

3.2 Research Foci

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 (1) with high potential for significant progress in a 3-5 year time-scale, and (2) that would benefit from enhanced international coordination. RF have proven to be effective means 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, while also providing opportunities to entrain new scientists into CLIVAR.

In the past five years the following topics have been covered: ENSO in a changing climate; Consistency between planetary energy balance and ocean heat storage (CONCEPT-HEAT); Decadal Climate Variability and Predictability (DCVP); Eastern Boundary Upwelling Systems (EBUS). Three of these activities will sunset as RF at the end of 2018, after successfully reaching their goals: DCVP will become part of a pan-WCRP effort, CONCEPT-HEAT will evolve into a pan-WCRP activity and the ENSO Research Focus will move into PRP. EBUS will continue its activities to the end of 2019.

New research foci will be established continuously in a bottom-up process through proposals from members of the CLIVAR and WCRP-at-large community.

Chapter 4. International Coordination as Enabling Capabilities

CLIVAR's research relies fundamentally on enabling capabilities organized through CLIVAR's and WCRP's international coordination. These enabling capabilities include: (1) coordination and cooperation within WCRP and with other programs; (2) organization of sustained observations and their synthesis; (3) improvement of ocean models; and (4) capacity building and knowledge exchange.

4.1 Coordination and Cooperation

Within CLIVAR:
CLIVAR cross-panel activities are always promoted, e.g. collaboration between global and regional ocean panels, and between panels and RF. National and multi-national activities are where CLIVAR science is implemented. National projects, agencies and institutions that fund and support CLIVAR research are too numerous to be listed here. A key example is the U.S. CLIVAR program, which has co-evolved in the context of a mutually beneficial collaboration with CLIVAR. The complementarity of CLIVAR and U.S. CLIVAR - and other national programs - science plans is a testimony of this ongoing dialogue and cooperation.

Within the World Climate Research Programme:
CLIVAR interacts frequently with the other core projects, for example, the MP advances its science mission through a collaborative partnership between CLIVAR and GEWEX. In particular, the GEWEX programme offers advances in process understanding relevant to tropical convection and land-atmosphere interaction (e.g. through GASS and GLASS activities), as well as through initiatives understanding global-scale cross-equatorial fluxes of heat and moisture. Relevant case studies address cross-GEWEX/CLIVAR issues in the monsoon regions and between monsoon regions and are especially valuable to helping understand and reduce model systematic biases. Another example is the cooperation with CliC for the implementation of SORP and NORP scientific objectives. Furthermore, CLIVAR contributes key expertise to various WCRP Grand Science Challenges (e.g. those on Carbon and Decadal Variability and Predictability) and is responsible for the organization of the GC on Regional sea level change and coastal impacts.

Outside WCRP:
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 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, SOLAS and PICES. CLIVAR activities and scientists contribute and will continue to contribute to Future Earth towards the objectives of developing the knowledge needed to effectively respond to the risks and opportunities of global environmental change, and in support of transformations towards global sustainability goals in the coming decades.

Collaboration with 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. Particularly in the monsoon regions, often located in developing nations, translation of climate information to climate services could prove beneficial to society and to reaching development goals.

Cooperation across timescales, e.g. with World Weather Research Programme
Several CLIVAR groups have strong interaction with the World Weather Research Programme (WWRP). For example the MP has been involved in the quadrennial WMO/WWRP International Workshop on Monsoons, suggesting new directions for the programme, and contributing invited

review talks, and ultimately chapters to the published hardcover book that benefits regional Met. Services. As mentioned in previous sections, subseasonal to interannual variability, predictability and prediction is an important focus of CLIVAR, and bridges the gap between traditional WCRP and WWRP activities such as in the WMO's subseasonal-to-seasonal (S2S) prediction project.

4.2 Sustained Ocean Observations and their Synthesis

In the past the world ocean has not been adequately observed in space and time to address many of the key aspects of its role in climate variability and change. For example, only in the last few years have temperature and salinity been systematically observed in the ice-free upper ocean; ocean reanalysis efforts suggest that the historical data base may not be sufficient even to constrain upper ocean heat content trend over recent decades; at present it is challenging to reconcile the trends of the past 15 years of global sea-level rise with those of global upper ocean heat content; there is insufficient information to determine the extent to which ocean circulation is affecting the recent extreme Arctic summer sea ice reductions.

Improvements in measuring trends and variability of ocean heat and fresh water storage through the lengthening global time series of the Argo array of floats contribute improved weather and climate prediction, as well as new understanding of the processes and mechanisms by which the ocean exchanges heat and gases with the atmosphere, land and cryosphere. The expansion of the Argo array to include Biogeochemical Argo promises to also transform the measurement and understanding of the trend, variability and feedbacks in ocean carbon storage. When combined with robust efforts in ocean data assimilation, including biogeochemical data, the prospects for improved ocean reanalysis, decadal prediction and global carbon reanalysis are imminent.

Considerable progress has been made within the past ten years in implementing an initial global ocean observing system for climate (i.e. GOOS and GCOS), following recommendations developed primarily by the international climate research community. This system is intended to support, among other things, development of overturning circulations as well as oceanic transports of heat, freshwater and carbon, and to provide reference information about air-sea fluxes at a few key locations. It is critical for the success of CLIVAR that this system be sustained. Moreover, it needs to evolve according to what we are learning about the sampling requirements from its observations and the analyses and reanalyses done with the data collected from it as well as from the earlier historical record. A major open issue to be addressed in this context is the lack of enough observations near ocean boundaries, where major currents flow and ocean eddies develop. Argo floats only sample up to the 1500 isobath and coastal observations, such as fish stocks assessment cruises and gliders, are not filling the gap.

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. CLIVAR and WCRP must continue to show significant leadership in this direction. Future ocean syntheses for climate research must be sustained in support of climate research and climate services and should contain prior as well as a posteriori error information. Ultimately the community should compile ocean syntheses from multi-model, multi-approach ensemble estimates that are generally of better quality than any estimate alone.

Through the initiative of CLIVAR and WCRP, initialized decadal forecasts have been a firm part of the last CMIP5 effort and will continue to play a substantial role in climate research. Like seasonal forecasting, the skill of decadal forecasts fundamentally depends on the proper initialization procedure of a coupled forecast system by the best possible estimates of the present-day climate state. Because the ocean carries a major fraction of the climate memory, it is especially important to initialize those models to the present ocean state.

4.3 Global, regionally enhanced and process models

CLIVAR, through its Ocean Model Development Panel (OMDP) led the articulation of the scientific rationale for saving a suite of physical ocean fields for CMIP5 (Griffies et al., 2009) and CMIP6 (Griffies et al., 2016). The perspective taken has been that of ocean scientists aiming to enhance the scientific utility of model simulations contributing to the CMIP process. The level of diagnostics requested by OMDP for CMIP5 and CMIP6 was far larger than the CMIP3 ocean diagnostics.

After working through many challenges to realize the normal year CORE-I, OMDP has more recently focused on the interannual CORE-II protocol. CORE-II makes use of the atmospheric state from Large and Yeager (2009), which extends over the period 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. 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, similarly 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 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 2014-2016.

4.4 Capacity Development and Knowledge Exchange

The goals of the scientific frontiers and imperatives listed in Section 2 require a global network of scientists with detailed understanding of major climate issues. Thus, the role of CLIVAR, and more widely WCRP, is also to identify needs and advocate the importance of raising the capacity/capability to undertake climate research, prediction and services.

Two different categories of requirements must be satisfied. There must be qualified people in both developed and developing world, and institutional capability in developing nations. Particular attention should be directed at developing the scientific capacity in climate science fundamentals, model development, computational science and climate services in order to meet societal needs from global to regional and 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 are 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. Furthermore, CLIVAR will offer a regular Series of Summer Courses; on even years in collaboration with the First Institute of Oceanography (China), and on odd years together with the International Centre for Theoretical Physics (Italy).

- 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 early career 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 adaptation, mitigation, resilience, 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.

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LIST OF ACRONYMS

AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AMV	Atlantic Multidecadal Variability
APE	Available Potential Energy
BSISO	Boreal Summer Intraseasonal Oscillation
CDP	Climate Dynamics Panel
CESM	Community Earth System Model
CGCM	Coupled General Circulation Model
CliC	Climate and the Cryosphere
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CMIP	Coupled Model Intercomparison Project
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
COBE	Cosmic Background Explorer
CORE	Coordinated Ocean-Ice Reference Experiments
DCPP	Decadal Climate Prediction Project
DCVP	Decadal Climate Variability and Predictability
EBUS	Eastern Boundary Upwelling Systems
EEI	Earth Energy Imbalance
ENSO	El Niño Southern Oscillation
FAFMIP	Flux-Anomaly-Forced Model Intercomparison Project
FOO	Framework for Ocean Observing
GASS	Global Atmospheric System Studies
GC	Grand Challenge
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Exchanges
GFCS	Global Framework for Climate Services
GHG	Greenhouse Gas
GLASS	Global Land/Atmosphere System Study
GLODAP	Global Ocean Data Analysis Project
GMMIP	Global Monsoons Model Intercomparison Project
GMSL	Global Mean Sea Level
GMST	Global Mean Surface Temperature
GOHC	Global Ocean Heat Content

GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-Based Hydrographic Investigation Program
GSOP	Global Synthesis and Observation Panel
HighResMIP	High Resolution Model Intercomparison Project
ICPO	International CLIVAR Project Office
ICSU	International Council for Science
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IndOOS	Indian Ocean Observing System
IOC	Intergovernmental Oceanographic Commission
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
IQuOD	International Quality Controlled Ocean Database
ISC	International Science Council
ISSC	International Social Science Council
ITCZ	Intertropical Convergence Zone
JSC	Joint Scientific Committee
MIP	Model Intercomparison Project
MJO	Madden-Julian Oscillation
MP	Monsoons Panel
NORP	Northern Ocean Region Panel
OMDP	Ocean Model Development Panel
OMIP	Ocean Model Intercomparison Project
OOPC	Ocean Observations Panel for Climate
ORA-IP	Ocean ReAnalysis Intercomparison Project
PAGES	Past Global Changes
PDO	Pacific Decadal Oscillation
PDV	Pacific Decadal Variability
PICES	North Pacific Marine Science Organization
PRP	Pacific Region Panel
RF	Research Foci
SCAR	Scientific Committee on Antarctic Research
SOCAT	Surface Ocean CO_2 Atlas
SOLAS	Surface Ocean Lower Atmosphere Study
SOOS	Southern Ocean Observing System
SORP	Southern Ocean Region Panel

SOUS	Southern Ocean Upwelling System
SSG	Scientific Steering Group
SST	Sea Surface Temperature
S2S	Subseasonal to Seasonal
TOA	Top of Atmosphere
TOGA	Tropical Ocean Global Atmosphere
TPDV	Tropical Pacific Decadal Variability
TPOS	Tropical Pacific Observing System
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VolMIP	Volcanic Forcing Model Intercomparison Project
VOS	Voluntary Observing Ships
WCRP	World Climate Research Programme
WDAC	WCRP Data Advisory Council
WG	Working Groups
WGCM	Working Group on Coupled Modeling
WGRC	Working Group on Regional Climate
WGSIP	Working Group on Subseasonal to Interdecadal Prediction
WMAC	WCRP Modelling Advisory Council
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WWRP	World Weather Research Programme