Agenda Item: 2.4

Report of CLIVAR Research Foci Development Team on Sea Level

CLIVAR SSG 21

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Executive Summary

To meet urgent societal needs for useful information on Sea Level (SL), WCRP has implemented the theme "Sea Level Rise and Regional Impacts", as one of its cross-cutting science questions, or Grand Challenges (GC), involving most core-projects and working groups. The overarching goal of this WCRP research effort, led by CLIVAR, is to establish a quantitative understanding of the natural and anthropogenic mechanisms of regional to local sea level variability; to promote advances in observing systems required for an integrated SL monitoring; and to foster the development of SL predictions and projections that are of increasing benefit for coastal zone management.

To meet this challenge, the GC scoping team on Sea Level has developed an integrated interdisciplinary program on SL research reaching from the global to the regional and coastal scales. In particular, the program aims for close interaction with relevant coastal stakeholders to make sure that results of the proposed scientific research are most useful for coastal zone management, and impacts and adaptation efforts.

During a 10-year period, the program will address the following imperatives, which will be approached in five parallel, but interconnected, working groups:

- *(i)* An integrated approach to historic sea level estimates (paleo time scale)
- *(ii)* Quantifying the contribution of land ice to near-future sea level rise
- *(iii)* Contemporary regional sea level variability and change
- *(iv)* Predictability of regional sea level
- *(v)* Sea level science for coastal zone management

In each working group, led by up to three co-chairs representing different core disciplines, an integrated approach is envisioned, involving theoretical concepts, observations and models. The GC team will provide an assessment of the state of affairs of sea level research every two years and will use the resulting information to make adjustments of its science plan and recommendations for international sea level research efforts. It is also planned that the GC team will write summaries on data and modeling issues, bringing together information and recommendations from all working groups.

The structure of the GC Sea Level effort will consist of a GC executive team and working groups (WG) underneath, focusing on individual subjects. Jointly with three co-chairs, the WG leadership would make up the GC Sea Level executive membership. GC Sea Level chairs will involve natural and coastal sciences.

Membership within each WG will involve members from joint CLIVAR/CLIC/GEWEX/SPARC, modeling groups, but also from other relevant programs (e.g, PAGES, IAG). GC Sea level co-chairs will report to the WCRP JSC and the CLIVAR SSG.

Background

Coastal SL rise is among the most severe societal consequences of anthropogenic climate change. Contemporary global mean sea level rise will continue over many centuries as a consequence of anthropogenic climate warming, with the detailed pace and final amount of rise depending substantially on future greenhouse gas emissions.

Over the coming decades, regional sea level changes and variability will significantly deviate from global mean values. The detailed sea level change along coastlines can therefore potentially be far more substantial than the global mean rise and will depend on many processes involving the ocean, the atmosphere, the geosphere and the cryosphere (see Church et al., 2013 and the literature cited therein). Societal concerns about sea level rise originate from the potential impact of regional and coastal sea level change and associated changes in extremes on coastlines around the world, including potential shoreline recession, loss of coastal infrastructure, natural resources and biodiversity, and in the worst case, displacement of communities and migration of environmental refugees.

Local sea level rise and extreme events can have significant impacts on coastal zones. On subsiding coasts, the impacts of resulting sea level rise are already demonstrable in some coastal cities and deltas. However, there is a lack of evidence to attribute rising climate-induced sea level to coastal impacts (IPCC WGII AR5 Chapter 18, section 3.3), by the end of the 21st century, it is very likely that a large fraction of the world's coasts will be affected by climate-induced sea level rise (Church et al., 2013). Detailed impacts, however, will vary strongly from region to region and coast to coast and therefore cannot be easily generalized, as changing mean and extreme coastal water levels depend on a combination of near shore and offshore processes, related to climatic but also non-climatic anthropogenic factors, such as natural land movement arising from tectonics, volcanism or compaction; land subsidence due to anthropogenic extraction of underground resources; and changes in coastal morphology resulting from sediment transport induced by natural and/or anthropogenic factors.

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

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

This document is a draft science and implementation plan for this effort, put together by an interim scoping team, whose members are listed in Table 1. The WCRP JSC as well as the CLIVAR SSG will review the document.

Throughout this document we will refer to **regional sea level changes** as those occurring on basin and sub-basin scale. In contrast, **coastal/local sea level changes** describe changes occurring at the coastlines, taking into account local settings (e.g. subsidence, local coastal and estuarine hydrodynamics).

The science plan has been discussed at the pan-CLIVAR meeting in Le Hague in July 2014 and at the WCRP "Lessons Learned" meeting in Bern during September 2014. It is envisioned that in November 2014 the GC "Sea Level" science plan will have been approved by the CLIVAR SSG and the implementation of the work will start.

Table 1: GC Sea Level Scoping Team

Expertise	Name	Country	Partner Organization
Geodesy/ Geophysics	Natalya Gomez	Harvard, USA	
	Mark Tamisiea	NOC, UK	
Glaciology/ Ice sheets	Roderik van de Wal	U. Utrecht, The Netherlands	
	Tony Payne	U. Bristol, UK	CliC
Regional processes,	Edward Hanna	U. Sheffiled, UK	CliC, ISMASS
	David Holland	Courant, USA	CliC
	Rui Ponte	AER, USA	
	Detlef Stammer	CEN, Germany	SL scoping co-chair CLIVAR
	Catia Domingues	ACE CRC/IMAS/U. Tasmania, Australia	SL scoping co-chair, CLIVAR
Reconstructions	Benoit Meyssignac	LEGOS, France	
Climate modes	Axel Timmermann	IPRC, USA	
	Jianjun Yin	U. Arizona, USA	
Climate modeling	Stephen Griffies	GFDL, USA	CLIVAR
	Jonathan Gregory	U. Reading, UK	
Satellite observations/Terrestrial hydrology	Anny Cazenave	ISSI, Switzerland	WCRP JSC
Extremes, storm surges, waves and coastal impacts	A.S. Unnikrishnan	NIO, India	
	Gonéri Le Cozannet	BRGM, France	

The GC Sea Level Initiative

Despite considerable progress during the last decade, major gaps remain in our understanding of past and contemporary sea level change and their causes, particularly for prediction/projection of sea level rise on regional and local scales, and superimposed extreme events (magnitude and return frequency). These uncertainties arise from limitations in our current conceptual understanding of relevant physical processes, deficiencies in our observing and monitoring systems, and inaccuracies in statistical and numerical modeling approaches to simulate or forecast sea level.

Understanding and predicting regional and coastal sea level require the quantification of the composite of global mean sea level (GMSL) change and regional and local processes (Figure 1). These contributions can include: exchanges of mass between the land, the cryosphere and the ocean; dynamics of the ocean and associated water mass transformation and/or redistribution; static processes associated with deformation of the solid Earth, resulting in seafloor movement along with gravitational and rotational effects.

In the most general terms, sea level represents the mean height of the ocean surface, as measured either with respect to the Earth's center of mass (**absolute sea level,** as measured by satellite altimetry) or, alternatively, relative to the crust or seafloor (**relative sea level,** as measured by tide gauges). Most relevant for coastal implications are relative sea level changes. We will refer to **sea level** as a mean level averaged over a period of one year. In contrast, **water level** is the sea level averaged over a few minutes, which must be evaluated for impact assessment of extreme events.

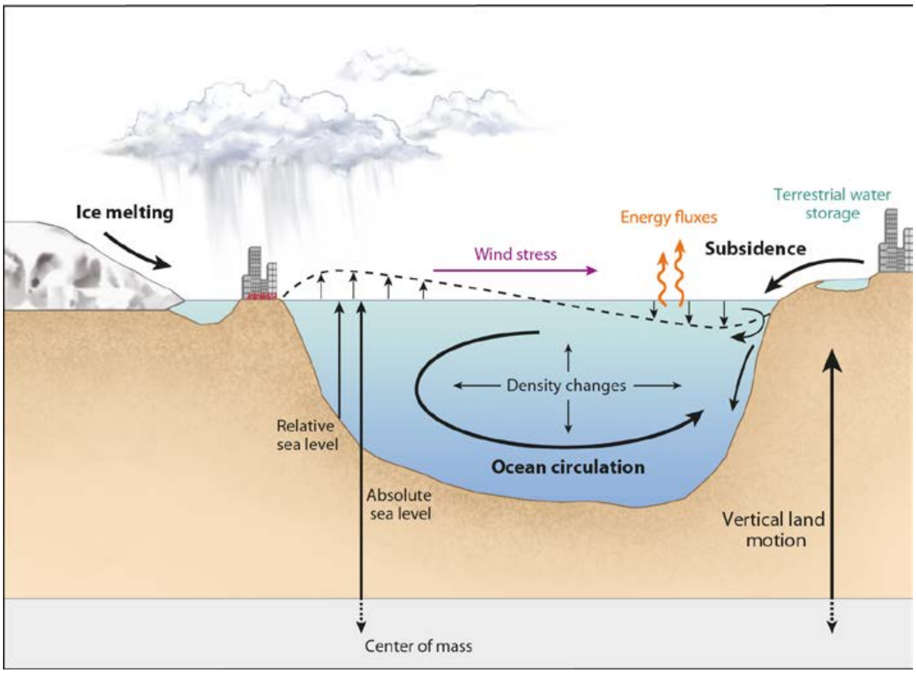

***Figure 1:** Processes that influence regional and coastal/local sea level. Global-scale changes in sea level are related to net changes in the total mass (freshwater content) and/or volume (primarily heat content) of the oceans, as well as geometric deformations of the seafloor. On regional scales, mean sea level can also be affected by changes in the atmospheric and oceanic circulations (hereafter referred to as dynamic changes) and by solid Earth processes, i.e., large-scale deformations of ocean basins and variations in Earth's gravity field (due in particular to changes in ice sheet mass distributions) plus uplift and subsidence (hereafter referred to as static changes). On the coastal-local scales, additional processes must be taken into account to evaluate sea level changes and their impacts: these are related to coastal hydrodynamical processes, biogeomorphological changes, and many other human influences not associated with climate change. During storm events, the water level can rise above the predicted tide due to reduced atmospheric pressures, strong winds and wave setup. In addition, the instantaneous sea level caused by waves (swash) must be taken into account for accurate coastal flooding assessment.*

Current Limiting Factors

Over the last few years, insight into global mean sea level has improved substantially. It also has become feasible to address regional SL variability and change in some detail. To meet urgent societal needs for useful information on SL rise for coastal planning purposes, improved sea level predictions/projections and useful probabilistic error information is needed, particularly on regional and local scales, which can be used subsequently for impact assessments and the development of adaptation plans.

To meet these goals, many remaining challenges need to be overcome before regional to local SL changes can be predicted with the accuracy necessary to benefit impact assessments for coastal planning purposes. In an attempt to enhance the utilization of future climate related sea level information by coastal communities, the GC Sea Level effort will strive to overcome those challenges outlined below.

Simultaneous to dealing with future sea level changes, it is also imperative to improve our understanding of past and contemporary changes in regional SL, since we need to learn from past sea level changes to understand processes participating in future changes. In particular, the development of short-term predictions and long-term projections require a quantification of global, regional and local processes underlying sea level changes, the determination of how these contributions vary with time, and the understanding of their causes (natural or anthropogenic attribution) and sources of uncertainty. Nevertheless, large uncertainties remain in reconstructing past SL changes and in monitoring contemporary SL within an integrated framework.

Climate models are just beginning to simulate sea level variations on basin scales, but have many deficiencies in simulating sea level changes on local/coastal scales. Particularly lacking is a proper understanding of the relation of basin scale sea level changes with those happening on the shelves and along coastlines. Some local effects (e.g., shelf dynamics, tectonics, land subsidence due to groundwater extraction) may additionally complicate or obscure such a relationship between coastal and offshore sea level change. Increasing ice sheet mass losses will also contribute to regional patterns of SL change through a dynamical adjustment of the ocean because of the effect of freshwater flux on ocean salinity, which alters density and causes an ocean dynamical response.

Large uncertainties in SL projections also arise from a significant spread in climate model projections for any given greenhouse gas emission scenario, i.e., from model uncertainties. Part of the spread of regional sea level predictions has been related to the differences in the Earth System Models (ESMs) simulations of surface climate and air-sea fluxes, especially changes in wind stress in the Southern Ocean and buoyancy fluxes in the North Atlantic. However, these differences do not explain all the diversity of projections, part of which is attributable to differences in ocean model formulations and response to climate forcing. Advances in our understanding of future regional SL changes involve the quantification of changes resulting from modes of intrinsic climate variability (e.g., ENSO, NAO, IOD, SAM, PDO, AMO, etc), and strongly depends upon the ability of climate models to properly simulate present and future climate modes.

For precise projections of regional SL pattern we need to better understand where in detail ice masses are being lost as a function of time and which exact sea level finger print results. To this end projections for the future contributions from ice sheets need to improve, especially those resulting from ice sheet dynamics, all processes that are not even part of existing climate models. Geological sea level records and uplift data depend on the location and timing of ice mass changes and need to be interpreted in an integrated way. Without this step we will not be able to improve our understanding of GIA processes, which will continue to act also in the future.

Studies related to detailed impact assessments and the development of adaptation plans will not be performed as part of this WCRP GC on SL. Instead the GC effort will focus on all the components of global to local sea level changes and will consider the necessary analyses on global and regional climate change data and simulations, extreme events and potential impacts, including the evaluation of sea level rise impacts for coastal zones. There is presently a lack of attributional evidence regarding the role of contemporary sea level rise in observed impacts such as coastal erosion and saline intrusions in aquifers, reflecting the multiple drivers operating in the coastal zone (IPCC WG2 Ch. 5 and 18). Several analyses of global data repositories indicate that changes in extreme water levels have increased due to the secular sea level rise. However, the actual impacts of mean sea level rise on extreme marine flooding events in specific locations remains difficult to establish (IPCC WG2 Ch. 5 and 18), although on the US East Coast, for example, such links are now being made. More research on attribution of sea-level rise and the components of sea-level rise would be useful to communicate the impacts that are already occurring and reinforce concerns about future impacts. Actual extreme water levels at the coast also depend on regional to local coastal factors that may evolve over weeks, years and decades, including tides, surges, wave breaking and wave setup. To better evaluate the recent or future impacts of sea level rise for extreme coastal flooding events, must be developed that evaluate each component of extreme water levels at the coast (mean sea level changes, tides, atmospheric and waves effects) and their potential interactions under different nearshore and inland geomorphic and anthropogenic coastal changes. These will applied locally in selected pilot studies in work package 5 to demonstrate these methods.

This issue deserves attention as coastal storms can have major physical and human impacts at present, as demonstrated by recent events. Still, whatever the specific coastal change considered, regional to local information regarding sea level change will be required. The WCRP Grand Challenge "Sea level rise and regional impacts" strives to provide such information to exposed coastal communities.

GC Sea Level Work Program

From the challenges summarized above, imperatives follow which will form the basis for the GC work structured in the following 5 parallel but interacting work packages (WP).

- ***(i)*** An integrated approach to paleo time scale sea level estimates
- ***(ii)*** Process understanding of fast ice sheet dynamics (contemporary)
- ***(iii)*** Causes for contemporary regional sea level variability and change
- ***(iv)*** Predictability of regional sea level
- ***(v)*** Sea level science for coastal zone management

Among those challenges, scientific understanding of paleo-time scale and recent sea level change are the subjects of WP (i) and (iii). Fast ice-sheet dynamics is presently the largest uncertainty in projections, and is therefore also the subject of a separate WP (ii). Outcome from all three WPs are important ingredients in the evaluation of the models and their improvements used to make projections, a task central to WP (iv). Finally WP (v) is concerned with impacts of sea level change on coastal systems.

The subject of the latter WP is important for the GC and it relates most directly to the practical needs of coastal planners building on input from all the other WPs. It is expected that a wider coastal impacts group will be brought together after an initial community consultation. The initial consultation will address the following questions: What sea level products are needed for coastal impact assessment and coastal management? How to use them in adaptation practices? Can we demonstrate their use in practice? The interaction with the coastal communities early on during the process is important to understand questions and needs.

The GC team plans to provide an assessment of the state of affairs of sea level research every 2 years and to use the resulting information to make adjustments to its science plan and recommendations for international sea level research efforts. In each working group an integrated approach is envisioned, relating theoretical concepts, observations and models. To be most useful for planning purposes, the GC team will write summaries on data and modeling issues, bringing together information and recommendations from all working groups.

The work program for the GC project needs to address:

Process Issues: Recent results suggest that changing winds and the associated changes in the flow field and transports are a major cause for observed changes in short term regional (steric) SL changes. This mechanism might also be one of the important drivers for regional SL variability on decadal and longer time scales, particularly in connection with future changes in coupled atmosphere-ocean modes of variability. A major methodological challenge remains in evaluating the consequences of different sea level rise scenarios for coastal zones (i.e. coastal and estuarine flooding, coastal erosion, saline intrusion in coastal aquifers, and the consequences for the environment and human activities). To proceed in this field, a detailed assessment of the uncertainties of coastal impacts models is needed. In addition, a detailed understanding of the relationship between regional deep-ocean changes and coastal sea level change is missing. Separating the contribution of the loss of land elevation due to natural and/or anthropogenic land subsidence from the cumulative SL changes is also an open issue. Finally, understanding the controlling adjustment processes in coastal regions under various sea level scenarios will be important.

Data issues: Further improvements in our understanding of SL variability and trends on multi-decadal timescales requires continuing improvements of the SL observing system including its tide-gauge network, full-depth in situ hydrography, satellite sea level observations, gravimetry satellite missions and many additional ancillary systems providing information on land ice mass and discharge, river runoff, bottom pressure, air-sea fluxes and other crucial parameters. For the analysis of past SL, a variety of existing proxy sources need to be exploited. Newly available data sets in ice-free areas of the open ocean in the upper 2000 m allow partitioning of the steric SL change contribution into thermosteric and halosteric effects, revealing that salinity changes do matter for regional SL – this type of information was lacking in the past in most parts of the world. The TG data is critical for assessing both extreme events and past long-term behavior near coast lines. The existing effort in processing the data needs to be exploited in coastal assessments.

Modeling Issues: Requirements for coupled WCRP model developments include all relevant processes that can lead to regional and coastal sea level changes, involving the ability to use hydrological and cryospheric models in sea level modeling studies. This work also involves the integration of modeling and observations to investigate science questions, and ultimately will require coupled reanalysis. Additionally, there is a need to couple ocean models to ice sheet models, with moving grounding lines, basal melt and calving physics as well as wetting/drying algorithms for both the ocean and land models. Projections on multi-decadal timescales by ocean and ice sheet models currently exhibit substantial uncertainty. A reduction in this uncertainty is dependent on improved representation of physical processes in numerical models. Finally we need to improve CMIP output (i.e., availability of diagnostics) and model information to make it more useful for the sea level (including cryosphere) community.

Coastal Issues: An important step in the GC will be to provide coastal communities with regional to local sea level scenarios, which is a necessary but not sufficient condition to meet the complex and often unformulated needs of those communities. Here, there is the need to better identify which type of advanced coastal information is needed to support adaptation planning. For example, advanced sea level information could be expert elicitation of model outcomes, probabilistic or high-end scenarios at different time horizons (e.g. 2030, 2070, 2100 or possibly beyond for some critical activities or coastal areas). In addition, there is the need to demonstrate how each type of sea level product can be used appropriately in actual coastal management and adaptation practices, which implies considering a wide range of complex natural and anthropogenic processes taking place at multiple time and space scales in coastal zones. This requires a two-way dialog between sea-level scientists and coastal managers so that the most appropriate and useful information is provided. This interaction involves the communication of uncertainties and better efforts to define the high end tail of the distribution of possible sea-level rise in ways that managers can use. These efforts are expected to stimulate new cooperation/synergies between sea level science and coastal communities in later stages of the GC implementation plan.

Because SL is affected by almost all climate components, improving our understanding of all processes contributing to regional SL variability and change and improving the representation of these processes in climate models requires the involvement of many communities within WCRP and outside. There are also significant contributions to SL change not related to climate, especially in coastal regions. Thus, effective uptake of research outcomes requires cooperation with other science communities, including social sciences.

Linkages with other programs and communities

The sea-level challenge is truly interdisciplinary and requires input from many research communities associated with WCRP and outside of it. The WCRP core project CLIVAR has the leading role in organizing their input and coordinating corresponding research activities. In addition to that, CLIVAR will provide a basis for research on all oceanographic aspects of SL variability and change. CLIVAR will pursue a number of relevant global and regional research initiatives focusing on ocean heat storage, ENSO in a changing climate, decadal variability and predictability, and prediction and attribution of extreme events. The CLIVAR Working Group on Ocean Model Development (WGOMD) will continue international coordination of ocean model intercomparisons. The Climate and Cryosphere core WCRP project (CliC) will help to mobilize research on cryospheric contributions to SL rise. Water storage on land will be addressed with the assistance of the Global Energy and Water Exchanges (GEWEX) project. The Working Group on Coupled Modelling (WGCM) coordinates a number of highly relevant numerical experiments, and, above all, the Couple Model Intercomparison experiment (CMIP). Its sixth phase (CMIP6) will contain a set of experiment of prime importance for SL research. Observational requirements for ocean and terrestrial essential climate variables that are of relevance for SL will be conveyed to the Ocean Observations Panel for Climate (OOPC) and Terrestrial Observations Panel for Climate (TOPC), which are cosponsored by WCRP. The observation al activities will be conducted under the leading ocean observational systems such as JCOMM, GOOS, and its SL component, GLOSS. Space agencies will strongly contribute to SL and related observations. The uptake of the results in the domain of the coastal zone management will require strong engagement of the coastal management communities associated with IOC and the GEOSS coastal communities of practice and other relevant communities, e.g. Geohazards Supersites scoping teams.

The Regional SL Grand Challenge will be a strong contributor to the WCRP Grand Challenge on climate extremes in all aspects related to coastal SL hazards. The Water Availability Grand Challenge will be instrumental for the SL research through an advancement of water balance studies. The Cryosphere Grand Challenge will help to translate advances in modeling and prediction of cryosphere and in improvement of understanding of polar climate predictability into assessments of cryospheric contribution of SL rise. Advances in understanding of regional climate and of the role of clouds and circulation in climate sensitivity to CO_2 will also have a positive impact on conclusions related to future SL variability and change.

WP I: An integrated approach to paleo time scale sea level estimates

(Potential leads: Natalya Gomez, Roderik van de Wal, Mark Tamisiea)

Classically, understanding millennial- and centennial-scale sheet and sea level variations has been approached by two different methods: The ice dynamical approach where (single) ice flow models respond to the changing climate or development of Glacial Isostatic Adjustment (GIA) models, which inferred ice sheet extent, volume and timing of changes by comparing to geologic sea level indicators. The next major step forward is to solve this coupled problem based on forward dynamic simulations of all ice on Earth coupled to the solution of the sea level equation, which accounts for the redistribution of the mass in the ocean, validated against all available data. This coupled approach implicitly accounts for the possible feedbacks between sea level changes, solid earth deformation and ice sheet evolution, some of which are addressed in more detail in WP 2. This way forward will allow us to address several major research challenges, which we need to solve to explain regional sea level changes over a wide range of time scales. By addressing these challenges, we will also generate better GIA models, needed to correct for ongoing contributions to present-day observation, i.e. tide gauges, Global Navigation Satellite System (GNSS), and gravity data.

Challenges that need to be addressed:

- Generating a consistent sea level budget for different time periods:
  - Last Glacial Maximum – far-field sea level indicators in agreement with total ice volume
  - The Eemian interglacial and other warm periods (e.g. Late-Pliocene) in the past, when temperatures were only slightly higher than today but sea levels were much higher
  - The 20th century and recent budgets considered in WP 3.
- Self-consistent interaction between the models of ice, land, ocean, and atmosphere
- Understanding ice and sea level histories over Holocene
- Assessing the effects of a lateral variations in earth structure and non-Maxwell rheologies
- Supplementing geologic sea level indicators with geodetic data, while accounting for other contributors to these observations
- Identifying weaknesses in the observational data set of paleo sea level change

Approach and Deliverables:

The proposed integrated sea level approach, working with the communities listed below, will facilitate the development of coupled models and data assimilation techniques to capture relevant feedbacks and the integration of geodetic data and information about Earth structure into modeling efforts.

Deliverables of this working group include:

- Improved GIA models and their uncertainties
- Self-consistent ice and sea level histories
- Identification of locations and times where sea level indicators reduce uncertainties in sea level histories
- Further constraints on sea level budgets: LGM, LIG, Holocene and present day

Communities involved: To achieve this improved understanding of long-term sea level changes we need to engage: geodesists, glaciologists, geophysicists, geologists and geomorphologists.

Linkages with the GRACE community, GGOS and IAG with respect to geodetic data, PALSEA related to geologic data. Plismip and PMIP activities are clearly also highly relevant for this WP. In addition a clear link exists with the model development, which is foreseen in WP2 on process understanding of fast ice sheet dynamics.

WP 2: Quantifying the contribution of land ice to near-future sea level rise

(Potential leads: Tony Payne, David Holland, Roderik van de Wal, Ayako Abe-Ouchi)

The contribution of land-based ice masses (glaciers and ice caps, as well as the Antarctic and Greenland ice sheets) to contemporary and future sea level is highly uncertain. This uncertainty has many sources including a lack of process-understanding, the poorly constrained nature of regional climate (both atmospheric and oceanic) in the vicinity of ice masses, and the computationally challenging nature of ice-flow. A unique element of land ice is the potential for high-magnitude contributions whose probability is important to many end-user communities but is extremely difficult to quantify.

Challenges that need to be addressed:

- Liaise with other initiatives aimed at improving understanding of key processes, such as iceberg calving and ice-ocean interactions around Antarctica, in particular to focus on how these processes can be incorporated in to the numerical models used for projection.
- Improve global glacier and ice cap modeling, and establish coordinated approaches to making future projections of global glacier mass balance.
- Test the numerical basis of the new generation of ice sheet models in a range of idealized test cases, in particular related to processes affecting the Marine Ice Sheet Instability.
- Validate CMIP climate simulations of atmospheric and oceanic climate above and around the ice sheets of Greenland and Antarctica.
- Conduct a range of model inter-comparison exercises for the both the Greenland and Antarctic ice sheets employing climate forcing from CMIP and validating against observational time series where available.
- Characterize the high-magnitude, low-probability end of future sea-level's probability density function by using an ensemble-based extension to the above inter-comparison.
- Stimulate the inclusion of ice sheets in global coupled climate models.
- Tipping points for Greenland and western Antarctica ice sheets (CliC).

Approach:

Advances in this area draw on the work of many different scientific initiatives, however an activity which links all of these various elements together in order to make robust projections of land-ice change is currently lacking. The aim is to create an ice-sheet model inter-comparison effort (ISMIP6) that will link process-understanding and observational developments to the CMIP climate modeling activity. A complementary project will bring together global glacier modelers, and those involved in observationally-based glacier inventories, to evaluate mass balance estimation for the historical period and to provide an ensemble of projections for future glacier change. These projects will bring projections of the land-ice contribution to sea level change to the same level as other components of the Earth system. The project will build on community efforts like SEARISE and ices2sea initiatives.

Deliverables:

Producing probabilistic projections of the land ice contribution to future sea level change that account for all of the relevant sources of uncertainty.

Communities involved: glaciologists, ocean and atmospheric sciences, CMIP.

Linkages: The activity will be one of coordination and model inter-comparison, which will complement CLIC's targeted activities in calving and fjord processes (GRISO), ice-ocean interaction (WAGOM) and global glacier modeling, as well as the ISMASS expert group on ice sheet mass budget. Other linkages include CORDEX Arctic and Antarctic (as well as other glaciated regions), CLIVAR Atlantic and Southern Ocean panels, as well as the IMBIE initiative on satellite observations.

WP 3: Contemporary regional sea level variability, change and extremes

(Potential leads: Rui Ponte, Catia Domingues, Benoit Meyssignac, Kevin Horsburgh, Detlef Stammer)

Understanding of contemporary (1860-present) regional sea level requires quantification of the contributions from all relevant climatic and non-climatic processes, operating at global, regional and local levels, and identification of their natural or anthropogenic causes. Such knowledge is crucial for development of short-term predictions and plausible long-term projections for impact and risk analyses, as well for the understanding of other relevant aspects of the climate system, such as the Earth's energy balance and hydrological cycle.

Challenges that need to be addressed:

- Understanding and reducing uncertainties in mass and steric contributions to contemporary sea level budgets at global, regional and local spatial scales.
- Determining the role of climate modes (e.g., ENSO, IOD, PDO, SAM, NAO, AMO) and internal variability in general on sea level.
- Understanding the role of coastal and ocean interior processes (e.g., shelf sea dynamics, ocean mixing, freshwater input, etc) on local sea level.
- Attribution of regional sea level change to natural (e.g., solar, volcanic) and anthropogenic (e.g., tropospheric aerosols, greenhouse gases) radiative forcing agents.
- Requirements for an optimal and integrated (satellite and ground-based) sea level observing system.
- Understanding contemporary subsidence and extremes.

Approach:

To address the above challenges, work will involve improvements to the quality, consistency and completeness of relevant observational (in situ and satellite) data sets to reduce uncertainties from individual contributions to sea level budgets, over different spatial and timescales. Work will also involve improvements to conceptual understanding and numerical/statistical model formulations (in conjunction with WP1, 2 and 4). Joint analyses of observations and coupled/ocean models will be undertaken to assess the ability of models in properly simulating climate modes of variability and their imprint on the regional distribution of sea level. Sensitivity experiments and model intercomparisons will be one of the tools to assess the role of physical processes (shelf dynamics, mixing, freshwater forcing, etc). Observational estimates and model simulations will be used in detection and attribution studies to identify natural and anthropogenic causes of regional sea level change. Process studies and analyses of various contributions to regional sea level at different locations will be used to identify the most important gaps in observing systems and possible ways to fill them, including potential need to develop new observing technology.

Deliverables:

- Improved data sets and models for sea level analyses and predictions/projections.
- Improved understanding of global, regional and local sea level budgets.
- Improved knowledge of physical processes and the nature of their causes at global, regional and local scales, and over different timescales.
- Improved integrated monitoring system for sea level variability and change.
- Baseline information about extremes.

Communities involved: Oceanography, terrestrial hydrology, glaciology, geodesy, atmospheric science, among others.

Linkages: Work will leverage links with planned activities from other WCRP programs (GEWEX, CliC) and various working groups (CLIVAR global and regional panels, WGOMD, modeling and data assimilation), and international associations (IAG, IAMAS), among others.

WP 4: Predictability of regional sea level

(leads: Jonathan Gregory, Jianjun Yin, Tony Payne, Detlef Stammer)

Improving the capability to make confident predictions and projections of regional sea level change is central to the Grand Challenge. This capability mainly relies on improved atmosphere-ocean general circulation models (AOGCMs) with improved representation of relevant processes (e.g., water cycle), detailed structures (e.g., resolution), and off-line models of land ice (glaciers and ice sheets, partly in connection with WP 2). At present time these models are used to predict both global mean sea level change (through thermal expansion and addition of mass to the ocean) and its geographical distribution (due to change in ocean density and circulation and to change in the geoid and lithosphere caused by mass redistribution). A goal of this effort is to merge these separate efforts into one coupled projection procedure.

Challenges that need to be addressed:

- Determining limits of predictability of sea level as function of space and time scale and the role of changing climate modes for sea level predictions.
- Understanding and reducing regional inter-model sea level spread in predicted sea level due to change in ocean properties (temperature, salinity, circulation, mass distribution).
- Provide reliable uncertainties for sea level predictions and projections, including those for ice sheets and glacier projections.
- Incorporate processes relevant for regional sea level change in AOGCMs, especially glaciers, ice-sheets. Including ice-sheets will place a focus on a better representation of polar regions in climate models.
- Provide reliable estimates of terrestrial hydrology.

Approach and Deliverables:

To investigate the cause for the existing model spread in regional sea level projections, we propose a model intercomparison project (FAFMIP, which can be seen as an ocean analogue of the CFMIP2 patterned-SST experiment included in CMIP5), in which AOGCMs and OGCMs are forced by a common experimental protocol. Regional ocean processes leading to sea level change will be analyzed in CMIP historical simulations, which can be compared with observations, using detection and attribution methodology. Attribution of sea level change can be made either to forcing agents (e.g. greenhouse gases, anthropogenic tropospheric aerosol, stratospheric aerosol from volcanic eruptions) or to physical phenomena (e.g. PDO, change in SAM or AMOC). In either case, the aim is to use the observed past to refine or set constraints on future projections. The representation of land ice surface mass balance (in particular regarding albedo, refreezing and the effect of subgridscale variation in topography) should be improved in AOGCMs. This will benefit the regional simulation and climate feedbacks in AOGCMs, and enable AOGCMs to project the glacier and ice-sheet surface mass balance contribution to sea level change. It is also a necessary step for studying the threshold warming for viability of the Greenland and West Antarctic ice sheets, which are potentially important tipping points, because the elimination of either ice sheets would eventually raise global mean sea level by several meters.

Communities involved: ocean, terrestrial hydrology, glaciology, geodesy, atmosphere, climate

Linkages with other WCRP, and other communities of climate and ice-sheet modelers working on the development of Earth system models which incorporate AOGCMs and ice-sheets, both surface mass balance and dynamics, interactively simulated. A fully coupled treatment with moving grounding lines and wetting/drying capabilities is necessary because fast ice-sheet dynamics and ice-shelf melting affect and are affected by regional ocean changes.

WP 5: Sea level science for coastal zone management

(Potential leads: Robert Nicholls, Goneri Le Cozannet, S. Unnikrishnan, Kathy McInnes, Kevin Horsburgh, Pietro Teatini)

In the coming years, the previous research foci will provide the fundamental research background needed to better evaluate future sea level rise and the associated uncertainties. However, to ensure that this research is beneficial for impact, adaptation and planning assessments in coastal communities, **more applied coastal information is needed**. This includes supporting the growing activity in adaptation assessments described in the IPCC AR5. Such advanced SL information need to include a good baseline and probabilistic and high-end scenarios of future sea level rise tuned to coastal manager's needs. In addition, coastal users need future return-periods of extreme waves and water levels, which implies taking into account not only future relative sea level rise, but also the impacts of climate change on winds, waves and storm surges and the relevant interactions between processes (e.g. tides and sea level rise; river water discharge and coastal hydrodynamic processes). A clear distinction is needed to understand the relative contribution of climatic (including changes in the hydrological cycle) versus other anthropogenic and natural processes on coastal evolution, including the role of subsidence which is significant (up to one order of magnitude larger than SL) in many deltas and coastal cities, for example.

Research is needed here to better understand and represent the physics of coastal hydrodynamic processes, from regional to local scales, but also to elaborate new sea level information (e.g., separating the contribution of land subsidence from the cumulative SL change) that has utility for end-users. Progress is expected to occur by focusing on exemplary case studies, where advanced sea level and related information across the dimensions defined above will be delivered bridging the gap between the coastal communities and sea level research. This can be done by improved regional atmospheric modeling (CORDEX, etc.) and application of other downscaling techniques, providing accurate projections of near-surface atmospheric wind fields (10 m) and MSLP and application of regional models to be used for storm surges and waves. A specific working group bringing together sea level and coastal scientists is needed to address this important societal challenge: presently, many densely populated coastal and estuarine areas in the world are vulnerable to flooding, coastal erosion or saltwater intrusion into surface waters and coastal aquifers. Future climate change and sea level rise represent an additional threat for coastal systems already affected by drastic human activities and environmental changes. In the coming ten years, this WG is expected to stimulate new approaches and methods, as well as effective two-way communication, to better inform coastal management and adaptation. The potential issues to consider are numerous and will need to be carefully selected to maintain focus and scope. Possible issues include attribution of impacts to climate-induced sea-level rise and the likelihood of less frequent but larger coastal flood disasters as coastal cities grow and adapt and sea levels rise.

Challenges that need to be addressed:

- Sea level information useful for coastal management
- Downscaling sea level variability and uncertainties from regional to local coastal scale,
- Probabilistic information and return-period from combined effects of sea level rise and changes in extremes (e.g., storm surges).
- Pilot studies for mega city, delta, island state, etc. using accurate sea level products from working groups 1-4.

<u>Approach and Deliverables:</u>

The scope of this Working Group is intentionally limited to the development of advanced sea level information with coastal users. Key deliverables are:

- Requirements Report (Workshops, literature and users surveys)

- Scientific information needed to facilitate the development of future coastal climate services, covering regional to local scales and watershed to the coast
- Roadmap to enhance synergies with coastal community (after 1st delivery of validated sea level rise scenarios)
- Impact of future subsidence and extremes.
- Uncertainty estimates and communication of coastal sea level change

Communities involved: geodesy, geophysics, geologist, geomorphologists, coastal oceanography, social, environments and economic sciences, coastal engineers, atmospheric scientists.

Linkages with EUCC, GEOSS Coastal Community of Practice…

Governance, coordination and implementation

The structure of the GC Sea Level effort will consist of a GC executive team and working groups (WG) underneath, focusing on individual subjects. In addition, each WG could introduce short-term task teams to deal with special targeted problems, e.g., related to local processes. Jointly with two co-chairs, the WG leadership would make up the GC Sea Level executive membership.

GC Sea Level chairs will involve natural and coastal sciences. Membership within each WG will involve members from joint CLIVAR/CLIC/GEWEX/SPARC, modeling groups, but also from relevant other programs (e.g, PAGES, IAG). GC Sea level co-chairs will report to the WCRP JSC and the CLIVAR SSG

The Executive team will coordinate and monitor activities within WPs and will revise science strategies according to repeated assessment of sea level science and funded projects (every 2 years). GC Executive team meets once a year, with video conferencing in between. WGs have their own agenda. The GC Executive team will stimulate interaction with other GCs through participation of invited representatives at annual meetings. It will also interact with funding agencies to stimulate funding of activities.

It is anticipated that the GC Sea Level effort will start implementing a 10-year activity in fall 2014 and plans for first GC meeting for November/December time frame. It will produce repeated progress reports using the following measures of success:

1) Deliverables
2) New (inter-comparison) projects spawned
3) Amount of community integrations
4) Entraining new countries or young scientist
5) New, improved and historic observations, impact on space agencies
6) Improvement of models
7) Impact in coastal community

GC Output

It is envisioned that the output from the GC effort includes the following:

- Document outlining a multidisciplinary long-term program of SL research in support of coastal community.
- Coastal Community Requirements Report
- Bi-annual Progress Report: Update on state-of-understanding (SREX style) and future SL estimates.
- Database of climate quality observational data set including uncertainties (paleo to present)

- Model intercomparison analyses on sea level variability and change
- Data requirement document
- Improved GIA models and uncertainties
- Participation in CMIP6.
- Integration of interdisciplinary sea level community from developed and developing countries
- Making sure to identify all factors involved and communities concerned
- Generating provocative discussion in the community including through high visibility papers
- Benefitting where possible from other existing initiatives such as Year of Polar Prediction in 2017-2018 and corresponding observations
- Targeted model intercomparison studies (eg ocean-ice shelf-ice sheet interactions, Greenland melt)
- Metrics recommendations for outputs
- Observing System requirements for monitoring, model development, model evaluation/validation, initialization – both satellite and in-situ
- Effective communication of research outcomes

Milestones for a 10-year period

- White paper
- Set-up of Sea level relevant data "clearing house"
- Workshop with coastal communities.
- 2016 Sea Level Symposium
- 2021 Sea Level Conference
- 2015 Summer School (building on Delft 2014, every 2 years)

Outreach and Capacity Building:
The GC effort will include significant outreach and capacity building activities and that will benefit developing countries potentially affected by sea level rise in Latin America, Africa and Southern Asia.

The following activities are envisioned:

- WEB Outreach through WCRP
- Sea level relevant data "clearing house"
- Local data recovery and quality control activities (e.g., tide gauge data meta data) in coordination with Global Sea Level Observing System (GLOSS).
- Establishment of regional actions plans with WMO Regional Climate Centers, and in coordination with the GC on Regional Climate Information, to promote and sustain regional sea level activities with developing countries.
- Regional workshops with coastal communities in developing countries to foster data sharing, co-production of knowledge and to encourage local community and government involvement.
- Training courses on sea level data management in developing countries, in coordination with GLOSS.
- Participation in coastal workshops
- 2016 Sea Level Symposium (possibly in NY)
- 2021 Sea Level Conference in Developing Country
- 2015 Summer School, building on Delft (2014) (every 2 years)

Proposed multi-disciplinary Membership of GC Sea Level Team

CLiC and GEWEX need to be involved in identifying community representatives.

Table 2: Potential GC Sea Level Team

Expertise	Name	Country	Partner Organization
Geodesy/ Geophysics	Natalya Gomez	Harvard, USA	
	Mark Tamisiea	NOC, UK	
Glaciology/ Ice sheets	Roderik van de Wal	U. Utrecht, The Netherlands	Suggested co-Chair
	Tony Payne	U. Bristol, UK	CliC
	Ayako Abe-Ouchi	Japan	PAGES
Regional processes, Reconstrcutions Climate modes Climate modeling	David Holland	Courant, USA	CliC
	Rui Ponte	AER, USA	
	Detlef Stammer	CEN, Germany	CLIVAR Suggested co-Chair
	Catia Domingues	U. Tasmania, Australia	CLIVAR
	Benoit Meyssignac	LEGOS, France	
	Jianjun Yin	U. Arizona, USA	
	Jonathan Gregory	U. Reading, UK	
Subsidence, Extremes, storm surges, waves and coastal impacts and adaptation.	A.S. Unnikrishnan	NIO, India	
	Gonéri Le Cozannet	BRGM, France	
	Kathy McInnes	CSIRO, AU	
	Kevin Horsburgh	NOC	IOC/WMO JCOMM
	R. Nicholls	U. Southampton, UK	Suggested co-Chair
	Pietro Teatini	U. Padova, Italy	

List of Abbreviations

Terms of Reference for Execution Phase (January 2015-December 2024)

WCRP Grand Challenge *Sea Level Rise and Regional Impacts*

The GC Sea Level group will address issues relevant to global, regional and local sea-level change and variability and to regional sea level impacts. The overarching goal of this WCRP research effort, lead by CLIVAR, is to establish a quantitative understanding of the natural and anthropogenic mechanisms of regional to local sea level variability; to promote advances in observing systems required for an integrated SL monitoring; and to foster the development of SL predictions and projections that are of increasing benefit for coastal zone management.

Specifically, the Group will:

- Periodically review the state of knowledge and corresponding research on regional sea–level rise, identify gaps and research needs across WCRP, other Programs and relevant parties;
- Foster the improvement of the observing system and development of modeling techniques necessary to properly observe and simulate sea level variations and changes.
- Advise on the development of in-situ and satellite observing systems required to improve our understanding and projections of sea-level rise.
- Promoting interdisciplinarity, across science fields (cryo, hydro, geo, etc.) but also methodologies (data, models, state estimation), and advocating for appropriate funding resources and support at national and international levels.
- Foster the development for the scientific understanding necessary to assess and predict regional sea-level evolution;
- Facilitate development of a basis for quantification of future regional extreme sea levels due to superposition of mean sea-level rise, high tides and storm surges;
- Facilitate the use of improved observations, understanding and projections of sea level rise by various groups assessing the impacts of sea-level rise and the associated risks.

The group will have annual face-to-face meetings. The group may convene broader community workshops. The GC team is expected to report annually to WCRP at meetings of JSC and to the CLIVAR SSG.

Funding opportunities for Sea Level Studies

Several funding opportunities exist or are spinning up on national and international level related to sea level research. Here we list several of those funding opportunities.

Germany:
DFG-SPP "Regional Sea Level and ", to be submitted October 2014.

UK: Several active relevant Research Council UK (RCUK) funded research projects, and future funding is consistent with RCUK priorities.

Holland:
Existing 10-year program with paleo sea level included.
Polar program with sea level as part of that

France:
The yearly generic calls for the French national agency for research include challenges on climate change studies, on climate services and on coastal territories. A project on assessing Sea level rise impacts for extreme storm surges and submersion submitted to the French National Agency for Research (ANR, April 2014)

EU:
Presently no calls exits that specifically address the GC topic. This is probably an action to undertake to ensure that this challenge is well considered in H2020. However, there will be one call, may be more relevant for the impacts aspects (they support a project and a coordination and support action) http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/1074-drs-09-2014.html SLR/Regional impacts at this stage of implementation ? Another opportunity could come through JPI Climate, where it seems a call on "climate services" is scheduled.

JPI-Oceans open a call on regional sea level rise.

US:
Various different efforts by NASA, NOAA, NSF, DOE. NASA has recently appointed a Sea Level Change Team (N-SLCT) with funding from various different NASA programs, and future NASA support for sea level research seems likely. Various NSF programs, including ones with a strong interdisciplinary focus such as Frontiers in Earth System Dynamics, and the Climate Program Office of NOAA have regular calls related to climate and various aspects of sea level research. The U.S. DOE has traditionally supported CMIP-related work and could be another funding source. Concerted, larger efforts could be commended by the National Oceanographic Partnership Program.

Belmont call on sea level:
There is one call on the topic of: http://igfagcr.org/cra-2014-arctic-observing-and-research-sustainability

Australian Research Council:
Discovery Projects (3-year grant): http://www.arc.gov.au/ncgp/dp/dp_default.htm