WCRP Grand Challenge:

Regional Sea Level Change and Coastal Impacts

Science and Implementation Plan

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and

The GC Sea Level Steering Team

Version 1.0

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Executive Summary

To meet urgent societal needs for useful information on Sea Level (SL), WCRP has focused on the theme of "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 Sea Level is 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.

The structure of the GC Sea Level effort consists of a GC executive team and working groups (WG) underneath, focusing on individual subjects. Working groups consist of the following six overarching themes:

- *(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*
- *(vi)* *Global sea level change*

In each of these working groups, an integrated approach is envisioned, led by up to three co-chairs representing different core disciplines and involving theoretical concepts, observations and models. Over the next 10 years, 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 to 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.

Jointly with three co-chairs, the WG leadership makes up the GC Sea Level executive membership. The expertise of the GC Sea Level chairs involves both natural and coastal sciences. Membership within each WG involves 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.

This document is the science and implementation plan for this effort, Version 1.0, put together by the Science Steering Team. Throughout this document we 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 GC Sea Level Initiative

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.

Coastal SL rise is among the most severe societal consequences of anthropogenic climate change. 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.

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.

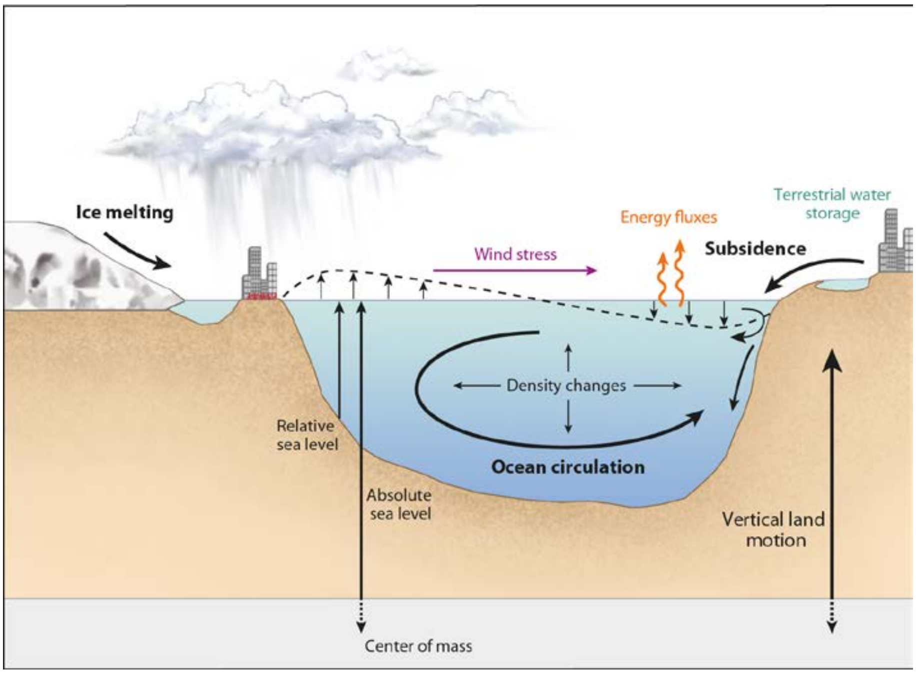

Figure 1: *Processes that influence regional and coastal/local sea level. Global-scale changes in sea level are related to net changes in the total mass (freshwater content) and/or volume (primarily heat content) of the oceans, as well as geometric deformations of the seafloor. On regional scales, mean 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.*

Background

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.

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 six parallel but interacting work packages (WP).

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

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 will 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 coastlines. 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.

Global Issues:

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.

Governance, coordination and implementation

The structure of the GC Sea Level effort consists 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 involve natural and coastal sciences. Membership within each WG 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

Table 2:* *Multi-disciplinary Membership of GC Sea Level Executive 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	Co-Chair
	Tony Payne	U. Bristol, UK	CliC
	Bette Otto-Bliesner	NCAR, USA	PAGES
Regional processes, Reconstrcutions Climate modes Climate modeling	David Holland	Courant, USA	CliC
	Rui Ponte	AER, USA	
	Detlef Stammer	CEN, Germany	CLIVAR, Co-Chair
	Catia Domingues	U. Tasmania, Australia	CLIVAR
	Benoit Meyssignac	LEGOS, France	
	Jianjun Yin	U. Arizona, USA	
	Jonathan Gregory	U. Reading, UK	
Global balances	Anny Cazenave	???	WCRP JSC
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	Co-Chair
	Pietro Teatini	U. Padova, Italy	

The Executive team coordinates and monitors 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.

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

WCRP Grand Challenge *Regional Sea-Level Change and Coastal 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.

Work Package Implementation

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

Leads: Natalya Gomez, Roderik van de Wal, Mark Tamisiea

Supporting team: TBC

Past sea-level changes and glacial isostatic adjustment (GIA) influence our understanding of present-day changes. GIA impacts every observation we make of sea-level changes, including relative sea level (tide gauges, ocean bottom pressure recorders, geological records), altimetry, gravity measurements (GRACE) and crustal motion (GPS). The effects of GIA vary spatially and temporally. While generally considered to produce constant rates of change at present, the impacts of GIA can vary even over decades to hundreds of years, depending upon recent ice mass changes and the local Earth structure.

Classically, understanding millennial- and centennial-scale ice sheet and sea level variations has been approached by two different methods: The ice dynamical approach where individual dynamical ice flow models respond to the changing climate and the development of Glacial Isostatic Adjustment (GIA) models, which infer ice sheet extent, volume and timing of changes by comparing predictions to geologic sea level indicators.
The next major step is to join these two approaches and develop coupled ice sheet – sea level models. This coupled approach explicitly 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. Several groups have recently developed coupled models (e.g. Gomez et al., 2013; de Boer et al., 2014; Conrad, 2013), and these represent a new tool to apply to self-consistently modeling ice sheet and sea-level changes and comparing to available ice age datasets. This way forward will allow us to address several major research challenges that need to be solved in order 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 account for ongoing contributions to the aforementioned observations. It should be noted, however, that as the development of these coupled models is still new, a great deal of research is needed to understand their best application, and where ongoing advances with the classical approaches may be more appropriate.

Scientific challenges that can be addressed by model development:
- 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.
- Understanding ice and sea level histories over Holocene

Needed development:
- Implications of global versus regional Earth and sea-level models
- Assessing the effects of a lateral variations in Earth structure and non-Maxwell rheologies
- Understanding the impacts of model resolution on the predictions and comparisons to observations
- Assessing the optimal times scales for coupling models given the modelling assumptions, e.g. mantle rheology and conditions at the ice-bed interface.

Approach and Next Steps:

Coordination of and communication between the diverse, international communities listed below will facilitate an integrated sea-level approach. Advances will be made through 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. As the development of these coupled models is new, the first step is a meeting of research groups currently driving the research. The purpose of the meeting will be to gather information on the questions listed above regarding the best application of the models. This background will guide further development and create a community necessary for further interaction with WP2 and other international efforts such as MISOMIP+.

Deliverables:

- Improved GIA models and their uncertainties
- Self-consistent ice and sea level histories

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

Leads: Tony Payne, David Holland, Roderik van de Wal, Bette Otto-Bliesner.

Supporting team: Sophie Nowicki, Olga Sargienko, Patrick Heimback/Fiamma Straneo, Heiko Goelzer, Xylar Asay-Davis, Ben Galton-Fenzi, Regine Hock/Ben Marzeion.

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 (GRISO led).
- Improve global glacier and ice cap modeling, and establish coordinated approaches to making future projections of global glacier mass balance (GlacierMIP led).
- 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 (MISOMIP led).
- 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 (ISMIP6 led).
- Characterize the high-magnitude, low-probability end of future global mean sea level's probability density function by using an ensemble-based extension to the above inter-comparison (ISMIP6 led).
- Stimulate the inclusion of ice sheets in global coupled climate models (ISMIP6 led).

Approach:

Advances in this area draw on the work of many different scientific initiatives, however an activity that 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 (Glacier MIP), 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. Coupled ice-ocean models will be developed and validated through the MISOMIP exercise. 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.

Next steps:

- Organize inter comparison of grounding of ice sheet grounding line treatments (MISMIP+).

- Organize inter comparison of ocean circulation in ice-shelf cavities (ISOMIP+).
- Organize inter comparison of ice sheet – bedrock coupling (SE-ISMIP, solid Earth ice sheet MIP in cooperation with WP1).
- Organize inter comparison of ocean – ice sheet model (MISOMIP+).
- Design coupled climate ice sheet CMIP experiment for Greenland (ISMIP6).
- Design standalone Greenland and Antarctic ice sheet inter comparisons with emphasis on initial states (ISMIP6).
- Design CMIP experiment for global glaciers (glacierMIP).
- Liaise with GRISO on development of iceberg calving models.
- Liaise with CliC on creation of activity aimed at process understanding of continental shelf ocean (including ice shelf cavities) dynamics (e.g., SOOS).
- Liaise with CORDEX and CLIVAR on regional simulations of atmospheric and oceanic climate above and around the ice sheets of Greenland and Antarctica.
- Encourage the creation of suitable international funding opportunities.

Linkages: Explicit linkage with WPs 1 and 4 in this programme. Work will leverage links with planned activities from other WCRP programs (CliC, CORDEX) and various working groups (CLIVAR global and regional panels), and international associations (ISMASS and SCAR), among others.

WP 3: Causes for contemporary regional sea level variability and change

Leads: Rui Ponte, Benoit Meyssignac, Catia Domingues, Detlef Stammer

Supporting team: TBC

Work within this WP is focused on the contemporary period (i.e., coincident with the instrumental tide gauge record) and organized in five subtopics described in detail below.

1) Understanding and reducing uncertainties in mass and steric contributions to contemporary sea level budgets at global, regional and local spatial scales.

Challenges to be addressed:
Contemporary global mean sea level (GMSL) is rising and will continue to rise, posing a threat to low-lying coastal and island communities (Church et al. 2013). Important uncertainties, however, remain: whether there is a current acceleration in GMSL rise, what is the associated spatial variability at regional and local scales and what is the associated uncertainty.

A proper account of variability/change for the different components of the sea level budget and an understanding of the underlying physical processes involved are crucial to increase confidence in the detection and attribution and in predictions/projections of sea level rise. In this context, challenges to be addressed from global to regional and local scales are: (1) To quantify and reduce uncertainties in observational estimates of sea level and its different components; (2) To assess the closure of the sea level budget, from interannual to centennial timescales and from global to regional scales (Note that here, for the global sea level budget we focus on the period before satellite altimetry. The question of the global sea level budget over the altimetry era is associated to the monitoring process of sea level and its components. It needs a special focus and it is the object of a dedicated WP, see WP6). ; (3) To assess sea level estimates from climate/ocean models and reanalyses, improve understanding on physical processes and identify important model and/or observational biases and errors.

General Approach:
Internationally coordinated efforts to compare observational estimates of *in situ* ocean temperature and salinity (steric sea level), ocean mass (from space gravimetry), ice sheet mass loss (from space gravimetry, laser and radar altimetry), glaciers mass loss (from satellite imagery, space gravimetry and in situ measurements) and sea level (from satellite altimetry and tide gauge records) are needed to improve the accuracy of estimates, assess the associated uncertainty and test the closure of the sea level budget for different temporal and spatial scales. Sea level reconstructions based on statistical interpolations, ocean reanalyses, forced ocean models and climate models can provide extensive diagnostics necessary to understand the causes and the processes responsible for sea level change. They can also provide insight on missing contributors to sea level change over periods with limited observations. The ability of these sea level reconstructions to reproduce contemporary sea level signals need to be assessed accurately by comparisons and validation against available observations to identify shortcomings and biases in both models and observations.

2) Determining the role of climate modes (e.g., ENSO, IOD, PDO, SAM, NAO, AMO) and internal variability in general on sea level.

Challenges to be addressed:
Internal/natural climate variability contributes measurably to regional sea level variability (e.g., Palanisamy et al. 2015) and can also affect global mean sea level (e.g., Boening et al. 2012,

Cazenave et al. 2014), at timescales ranging from months to decades. Climate modes (ENSO, PDO, NAO, AMO, etc.) are a substantial part of such variability, and a variety of mechanisms can be at work, from a forced response to the atmosphere, to coupled ocean-atmosphere interactions, to intrinsically nonlinear and eddy-driven processes (e.g., Qiu et al. 2015). Aside from being a major source of "noise" masking anthropogenic signals, natural variability can modulate the impact of extreme coastal events. The extent to which natural variability can be affected by climate change itself (e.g., are ENSO events changing in a warming climate?) is also an important issue.

Improved sea level predictions/projections, particularly over the next decades, are critically dependent on understanding observed natural variability, accurately reproducing it in models, and mapping its future behavior under climate change. To move towards this goal, one needs dedicated efforts to: (1) quantify internal/natural variability on a global basis using models and observations, over the period 1860-present; (2) diagnose causal mechanisms (forced, coupled, intrinsic) responsible for such variability as function of timescale and region; (3) assess realism of climate models in simulating natural sea level variability and identify respective model deficiencies (forcing, parameterizations, etc.); and (4) investigate possible dependences of natural sea level variability on the climate state, including under expected future changes.

General Approach:
Joint analyses of observations and coupled/ocean models are needed to assess the ability of models in properly simulating climate modes of variability and their imprint on regional sea level. Tide gauges provide a precise record of variability at the coast dating back more than a century in many regions. Altimetry, reconstructions, and "reanalyses" provide useful global extensions of the tide gauge data over different periods. Natural variability in these fields, in terms of major climate modes, needs to be assessed in detail; treatment of residuals should not be overlooked, particularly if representing non-negligible variance. Similar efforts need to be applied to coupled climate model output, particularly under CMIP5/6, as well as output from ocean models, as in CORE-II. Detailed comparisons between models and observations should serve as a test of model realism and help identify respective shortcomings. Assessing stationarity under climate change may benefit from examination of longer (paleo) records.

Models can provide extensive diagnostics to address causal mechanisms; models with adjoint code capabilities are particularly well adapted to this task. For proper model diagnostics, closed budgets of heat, salt, momentum and other quantities need to be ensured at the grid scale, in terms of surface forcing and interior advective and diffusive fluxes. Various experimental approaches can be useful (many models with same forcing, single model with different forcing, single model with different parameterizations, etc.), both in historical and projection mode. Models that have been fit to available data provide a solid basis for investigation. Different resolutions need to be employed to assess the potential role of eddies and nonlinearities in affecting low frequency sea level variability. The ultimate goal of these analyses is to improve ability to represent and predict natural sea level variability in climate models.

3) Understanding the role of coastal and ocean interior processes (e.g., shelf sea dynamics, ocean mixing, freshwater input, etc.) on local sea level.

Challenges to be addressed:
Sea level variability right at the coast can differ substantially from that in nearby shallow/deep coastal regions, over a range of timescales (e.g., Vinogradov and Ponte 2011; Hughes and William 2010). Aside from geodetic effects such as local subsidence, numerous

dynamical factors can introduce short scale structures in the coastal zone, from strong boundary trapping of upwelling systems and propagating waves to sharp spatial gradients in forcing functions (winds, river runoff). Most current climate simulations do not resolve the coastal zone well enough to capture all the relevant spatial scales. Connecting simulated fields to local variability at the coast is a difficult task, given the complex mixture of oceanographic and geodetic processes affecting the data and not represented in the models.

We need to improve current understanding of the structure of sea level variability across the coastal zone to be able to properly assess models against data, determine model deficiencies, as well as advance the physical interpretation of the coastal sea level records. A good starting point is to pursue a detailed characterization of the spatio-temporal structure of sea level variability in the coastal zone, relating signals seen at tide gauge level to the broader variability as a function of timescale. Careful examination of physical processes affecting the spatial structure of coastal sea level will need to be considered, with analyses specifically tailored to each region of interest. This knowledge can be used to guide the comparisons of data and models, facilitate interpretation of data, and spur model development.

General approach:
Available coastal sea level data can be used to assess spatial structure of variability, although resolution is limited. Until systems like SWOT are flown, developments in coastal along-track altimetry retrievals (e.g., COASTALT efforts) present the best prospects. Value of other data types (e.g., velocities from coastal radar, bottom pressure recorders) should be considered where possible. Data findings should elucidate and guide needed model developments. However, given data limitations, direct exploration of models of different resolutions offers a useful alternative. Experimental high resolution climate model runs (e.g., Griffies et al. 2015) would be most useful. In addition, available "operational" products (e.g., HYCOM, MyOcean) and focused regional modeling efforts (e.g., in the California Current system) should be surveyed and used to the extent possible. In particular, nested/downscaling modeling efforts for the coastal zone can provide major insight into the finest scales, not accessible with global setups typically run on ~0.1° grids. These efforts should involve extensive sensitivity experiments and model comparisons, which are powerful tools to assess the role of physical processes (shelf dynamics, wind setup, mixing, etc.), different forcing (winds, pressure, runoff), resolution, bathymetry and other factors in determining spatial structure of coastal variability. Detailed comparisons of models and data can be used to determine shortcomings in climate models and guide implementation of needed improvements for better representation of sea level variability at the coast.

4) Attribution of regional sea level change to natural (e.g., solar, volcanic) and anthropogenic (e.g., tropospheric aerosols, greenhouse gases) radiative forcing agents.

Challenges to be addressed:
All projections based on coupled climate models involved in CMIP5/6 indicate that sea level will rise higher and faster everywhere during the 21st century than during the 20th century. However, the spread in projections is substantial among models: more than ±50% of the ensemble mean sea level rise projection in 2080-2100 (Church et al. 2013). A significant part of this large uncertainty arises from inappropriate (or sometimes missing) model representations of some physical processes that affect sea level and needs to be reduced for more accurate sea level projections. A promising way to make progress is to compare and validate model simulations against sea level observations. However, this is not straightforward because sea level changes can be due to both anthropogenic or natural (volcanic and solar) forcing and internal climate variability. The internal climate variability is chaotic (i.e., sensitive to initial conditions) and therefore cannot be reproduced by models

with the same phasing as in observations while models can faithfully reproduce the forced signal. By detecting the forced signal above the internal variability "noise", D&A studies open the way to future assessment of model simulations against sea level observations. In addition, by attributing this forced signal to the different forcing agents, D&A studies should be able to unravel the contemporary sea level response to greenhouse gas (GHG) emissions from that to other forcing agents of natural (solar, volcanic) or anthropogenic (e.g., aerosols, land use) origin. A major challenge is to move from global to regional D&A efforts to improve our understanding of sea level response to contemporary GHG emissions and also refine sea level projections in 2100 and beyond when the GHG radiative forcing will largely dominate over the radiative forcing of aerosols and other agents.

General Approach:
To address these challenges, uncertainties in all steps of D&A studies need to be accurately quantified and reduced when possible (Ribes et al. 2016). This includes uncertainties in sea level observations, which should be precisely quantified and reduced following the recommendations in #1, #5, and uncertainties in the internal climate variability, which masks the forced signal at interannual to multicentennial time scales (see #2). Uncertainties in the forced signal at interannual to multicentennial time scales also need study. So far, the only tools that can help in quantifying the latter source of uncertainty are climate models. Unfortunately only a relatively small number (a few tens) of forced simulations are available from CMIP5/6. Thus reliable error covariance matrices can only be estimated for a few variables at the same time, which limits the resolution in regional or in multivariate D&A studies. To overcome this issue, large ensemble of climate model simulations with perturbed physics are needed.

Sea level is a variable that represents integration of many processes involving various fundamental variables of the climate system such as ocean density, surface wind speed and stress, cryosphere mass changes (and others) that vary at different spatial and temporal scales. For this reason, the development of consistent and efficient multivariate D&A methods are needed to address properly the problem of detection and attribution of sea level rise.

5) Requirements for an optimal and integrated (satellite and ground-based) sea level observing system.

Challenges to be addressed:
There is a need to consistently monitor contemporary sea level (and its various components) to reduce our current uncertainty about its rate of rise/acceleration, response to natural and anthropogenic climate change, and to better constrain predictions/projections of future changes, from global to local coastal scales. The challenges involved are: (1) To sustain the current integrated observational monitoring system (space and ground-based), to reduce systematic errors in their measurements via timely development and application of increasingly refined calibration/validation and quality control procedures, and also attachment of more proper uncertainty estimates; (2) To develop and test new measurement techniques/experimental designs that will facilitate the implementation of an optimally integrated (satellite and ground-based) sea level monitoring system to allow the investigation of key sea level questions that are currently poorly constrained. Key questions include: deep/abyssal ocean steric contributions, changes in coastal/marginal seas, including areas under sea-ice and near ice sheets.

General Approach:
The production of long-term consistent quasi-global records of sea level change and its components is possible only through high-quality continuous observations and proper

uncertainties attached. To ensure this continuity, the core instruments of the current observing system, which are nadir satellite altimetry (Topex/Jason, Sentinel), space gravimetry (GRACE) and ocean autonomous profilers (Argo) need to be maintained and replaced before their end of life. To ensure the long-term stability and accuracy, intercalibration of new core instruments against older ones needs to be taken into account in instrumental design. For observations based on multi-instruments such as satellite altimetry, the continuity of a highly accurate and stable reference mission such as the Topex/Jason series is essential to calibrate less accurate missions and achieve higher spatio-temporal resolutions.

Better sea level records close to the coast would involve improvements in 1) the geophysical corrections (in particular the wet tropospheric correction using enhanced geophysical models or alternative measures from GPS) to correct for biases and errors in the coastal region and 2) the radar measurement with new techniques such as SAR altimetry. In ice-covered regions, new retracking forms need to be developed to retrieve the radar signal that is echoed in the leads.

Other ongoing efforts (e.g., development of deep Argo floats; GRACE follow-on and new gravity mission concepts; improvement of the tide gauge network collocated with GPS measurements; development of new coastal *in situ* measurements from radars, visible cameras, GPS reflectometry, and lidars; advanced experimental designs for specific coastal regions) need to continue over the next decade.

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.

Next Steps:

- Contact community members for the formation of a wider working group, with experts in all aspects of WP3.
- Refine WP3 plans with the help of wider working group
- Initiate a WP3 bibliography (2015-...)
- Promote WP3 agenda through meetings and research calls of opportunity

Linkages and Resources:

Work package will involve researchers in the fields of oceanography, terrestrial hydrology, glaciology, geodesy and atmospheric science, among others. Work will leverage resources allocated to related activities across these communities and 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.

For example, for subtopic #2, substantial resources are currently devoted to climate modeling and data analysis, and sea level remains a strong focus. Data efforts (subtopic #1) and high resolution modeling (subtopic #3), as well as those under WP4, can also be leveraged here. Important for the focus of subtopic #2 is to maintain links between data and modeling groups, and to coordinate with modeling efforts to ensure availability of proper fields for relevant diagnostics. Close links should be established with relevant MIP groups endorsed by CMIP6 (e.g., OMIP, ENSOMIP, DCPP, FAFMIP; see full list at https://www.dropbox.com/s/7qgs52hyloib8ol/ApplicationSummary_CMIP6-EndorsedMIPs_141203_Sent.pdf?dl=0) and numerical modeling efforts under CLIVAR.

Work on subtopic #3 is closely related to climate modeling activities being planned as part of CMIP6 and can make use of those efforts and related MIPs (e.g. HighResMIP). Similarly, work can leverage strong investment in observations, modeling and data assimilation systems for many coastal regions, which is being made at the international level. Close interaction with the coastal modeling community, including those working on operational systems (e.g. Coastal Ocean and Shelf Seas Task Team/GODAE OceanView), would be useful. Data efforts (subtopic #1 and #4) and other modeling developments, such as those under WP4, can also be leveraged here.

Important for the focus subtopic #4 is to maintain links between the sea level and the IDAG community (D&A community).

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WP 4: Predictability of regional sea level

Leads: Jonathan Gregory, Jianjun Yin, Tony Payne, Detlef Stammer

Supporting team: FAFMIP, ISMIP6 and GlacierMIP teams, Aimée Slangen and Yoshihide Wada

Improving the capability to make confident predictions and projections of regional sea level change is central to the Grand Challenge. At present this capability mainly relies on atmosphere-ocean general circulation models (AOGCMs) and stand-alone models of land ice. The latter class comprises ice-dynamical models of glaciers and ice sheets with prescribed or simple schemes for computing ice-sheet surface mass balance (SMB), and regional climate models for ice-sheets with more detailed representations of SMB but without ice dynamics. The results of these two classes of models are used to predict 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). Improving the predictive capability firstly requires improved representation of relevant processes in AOGCMs (e.g., land-ice SMB, heat uptake in high-latitude oceans, interaction of ocean and ice-sheets) with sufficient resolution (e.g., for ice-shelf/ocean coupling and of regional features in sea level associated with coasts and currents). Secondly, a larger goal of this effort is to merge these classes of models into Earth system models, so that comprehensive self-consistent model projections of regional sea-level change can be produced as diagnostics and compared among models and with observations, just as has been possible and routine for many years with other aspects of climate change (e.g., surface air temperature, precipitation, sea-ice, ocean circulation).

Challenges that need to be addressed:

- Determine limits of predictability of sea level as function of space and time scale and the role of changing climate modes for sea level predictions.
- Understand and reduce regional inter-model spread in predicted sea level change due to change in ocean properties (temperature, salinity, circulation, mass distribution).
- Incorporate processes relevant for regional sea level change into Earth system models based on AOGCMs, where there are significant interactions with climate. This applies in particular to ice-sheets, because of their interaction with atmosphere and ocean climate change and the solid Earth.
- Make consistent projections of the various contributions to sea level change in a unified framework.
- Provide reliable uncertainties for sea level predictions and projections, including those for the contributions from ice sheets and glaciers, with particular attention to the upper ends of the distribution of predictions.
- Increase the confidence in estimates of the sea level contribution from anthropogenic intervention in terrestrial hydrology.
- Reduce the uncertainty in the thresholds of climate change beyond which the Greenland and Antarctic ice-sheets would be partially or largely eliminated, and in whether the ice-sheet mass loss would be irreversible on the long term. These are potentially important “tipping points”, because global mean sea level could rise eventually by several meters.

Approach:

- To investigate the cause for the existing model spread in regional sea level projections and related aspects of ocean climate change (e.g., heat uptake, AMOC), we have proposed a model intercomparison project (FAFMIP, which can be seen as an ocean analogue of the CFMIP2 patterned-SST experiment included in CMIP5 and CMIP6), in which AOGCMs and OGCMs are forced by a common experimental protocol.

- Regional ocean processes leading to sea level change should be analyzed in CMIP historical simulations, and 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 internal variability (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 subgrid scale variation in topography, and the evolution of topography in order to simulate the elevation feedback on SMB) 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. ISMIP6 will encourage this development. It is also a necessary step for studying the threshold warming for viability of the Greenland and Antarctic ice sheets.
- Coupling of ice-shelf and ocean processes should be considered in the framework of AOGCMs, including sub-ice-shelf circulation and grounding-line migration, which present technical challenges. ISMIP6 will promote the development of coupled models. The AOGCMs provide projections of ocean warming adjacent to ice-shelves, needed to project ice-shelf basal melting. The Ice-shelf models provide projections of sub-surface cold freshwater injection, which may affect sea-ice and ocean circulation.

Deliverables: The outcome of this WP should be the establishment of methods for the peer-reviewed publication of global and regional sea level projections, for particular emissions scenarios, including all contribution and uncertainties. These scientific results should be achieved in time to provide a basis for future IPCC assessments, so that the lead authors can rely more directly on the literature and have less need to devise their own methods for combining what is available.

Next steps:

- Promote research on the decadal predictability of regional sea level change.
- Produce a paper on FAFMIP experimental design and preliminary results. Encourage groups to participate with ocean-only models as well as CMIP6 AOGCMs.
- Complete the design of ISMIP6 experiments and seek to engage AOGCM groups in the development and coupling of their ice-sheet components.
- Begin a discussion on working towards sea-level projections for IPCC AR6.
- Initiate discussions with WP5 and the wider community on the limitations and uncertainties of sea level projections, and how to interpret these in a policy-relevant way.

Linkages: This WP is interdisciplinary in scope, involving the scientific communities engaged in ocean, atmosphere-ocean and Earth-system modelling, terrestrial hydrology, glaciology and geodesy. It relates particularly to WP2 in view of the importance of ice-sheets as a contribution to sea-level rise and their uncertainty.

WP 5: Sea level science for coastal zone management

Leads: Robert Nicholls, Goneri Le Cozannet, Kathy McInnes

Supporting team: S. Unnikrishnan, Kevin Horsburgh, Pietro Teatini; Jochen Hinkel, Kate White, **additional members being invited**)

In the coming years, the previous WGs 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 local coastal communities, at national scales (e.g., informing national priorities), and at international scales (e.g., informing adaptation funding) **more applied and appropriate sea level and related information is needed**. This includes supporting the growing activity in adaptation assessments described in the IPCC AR5. Such advanced SL information needs 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 present and future return-periods of extreme waves and water levels. This implies considering future relative sea level rise, and the implications 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 locally significant (up to one order of magnitude larger than SL) in many deltas and co-located 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 and/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 and appropriate for coastal management
- Downscaling sea level variability and uncertainties from regional to local coastal scales,
- Probabilistic information and return-period from combined effects of sea level rise and changes in extremes (e.g., storm surges).
- Information on how sea level variability on different time and space scales combine to produce local extremes

- Pilot studies for mega city, delta, island state, etc. settings using the improved sea level products from working groups 1-4.

Approach and Deliverables:

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, geology, geomorphology, coastal oceanography, social, environmental and economic sciences, coastal engineers, atmospheric scientists.

Linkages with EUCC, GEOSS Coastal Community of Practice…

WP 6: Global sea level budget

Leads: Anny Cazenave and Benoit Meyssignac

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Scientific Challenges:

Accurate assessment of present-day global mean sea level variations and its components (ocean thermal expansion, ice sheet mass loss, glaciers mass change, changes in land water storage and atmospheric water vapour content, etc.) is important for many reasons. The global mean sea level is an integrator of changes occurring in the Earth's climate system in response to unforced climate variability as well as natural and anthropogenic forcing factors. The evolution of global mean sea level provides information on climate and non-climate driven processes, e.g., net contribution of ocean warming, land ice melt, changes in water storage in continental river basins and glacial isostatic adjustment (GIA). Temporal changes (e.g. acceleration of rise) of one or more components will be reflected in the global mean sea level curve. Study of the sea level budget provides constraints on missing or poorly known contributions, e.g., the deep ocean not yet sampled by current observing systems or changes in water storage on land due to human activities (e.g. ground water depletion of aquifers), still highly uncertain. Global mean sea level corrected for ocean mass change allows independent estimate of temporal changes in ocean heat content, from which the Earth's energy imbalance can be deduced. The sea level and/or ocean mass budget approach can be in principle also used to constrain GIA models. The GIA phenomenon has great impact on the interpretation of GRACE-based space gravimetry data over the oceans (for ocean mass change) and over Antarctica (for ice sheet mass balance). The GIA signal is about the same order of magnitude as the climate signals in these regions. However, there is still no consensus on best estimates, a result of uncertainties in deglaciation models and mantle viscosity structure. Recent GIA models assuming lateral variations in mantle viscosity suggest significant differences with uniform viscosity models as far as the GIA correction over the oceans is concerned. Finally, observed changes of the global mean sea level and its components are fundamental for validating climate models used for projections.

This WP has for objective to assess the various data sets used to estimate components of the sea level budget. These data sets are based on the combination of a broad range of space-based and *in situ* observations, model estimates and algorithms. Evaluating their quality, quantifying uncertainties and identifying sources of discrepancies would be extremely useful for the community worldwide.
The WP will focus on the high-precision altimetry era (since the early 1990s), including the Argo and GRACE period (since early 2000s). Closure of the sea level budget will be assessed, and regular updates, e.g. at yearly intervals, will be provided. Constraints on missing and poorly known contributions to sea level will be regularly revisited.

Effort developed around the sea level budget could be also the opportunity to set up an international project of climate data intercomparison (called CDIP -for Climate Data Intercomparison Project-) within WCRP, similar to the Climate Model Intercomparison Project (CMIP). Such a CDIP initiative should be open to groups outside WCRP, raising the profile of observational assessment efforts.

Approach and communities involved:

This WP will assess products for sea level and its components provided by different groups worldwide and on-going international projects (e.g. the European Space Agency/ESA Climate Change Initiative/CCI Sea Level Budget Closure Project -SLBC_cci-). It will also regularly examine closure of the sea level budget.

In addition to the team members listed above, the international community involved in the various aspects of present-day sea level changes and interpretation is welcome to participate. Coordination among the diverse international communities will facilitate an integrated sea-level budget approach.

It is proposed that the global sea level budget assessment be published on a yearly basis in “Earth System Science Data”.

Products assessed in the CDIP should be freely available to the community worldwide. Coordination with the WCRP Data Advisory Council (WDAC) will be established.

Linkages:

There is obvious linkage with the satellite altimetry, GRACE and Argo communities, as well as with a number of on-going international projects such as the ESA SLBC_cci, IMBIE 2, etc. More generally, considering the interdisciplinary aspect of the global sea level budget topic, contributions from geodesists, remote sensing experts, oceanographers, glaciologists, hydrologists and geophysicists are to be expected.

Together with ocean heat content and the Earth’s energy imbalance, the global mean sea level is one of the best indicators of on-going climate change. The proposed WP should be an opportunity for further inclusion of the global mean sea level among the climate variables considered by the future of the UNFCCC global stocktake.

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.

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 (e.g. 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)