Sea Level Research Workshop

"Sea-Level Change: Earth System Feedbacks"

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Antonio Bonaduce[1], Johnny A. Johannessen[1], Kristin Richter[2,4], Roshin P. Raj[1], Andreas Born[3]

[1] Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway

[2] Norwegian Research Centre (NORCE), Bergen, Norway

[3] University of Bergen (UiB), Bergen, Norway

Purpose of the Workshop

The Nansen Center will organize a workshop on "*Sea-Level Change: Earth System Feedbacks*" to **foster the collaboration** between the different partners of the Bjerknes Centre for Climate Research (BCCR[1]) on sea-level research and to set-up a **Sea-level Research Group (SLRG)**.

Sea-level variability is **characterized** by multiple **interacting components of the Earth system** (i.e. atmosphere, hydrosphere, lithosphere) that act over a wide spectrum of temporal and spatial scales (Annex 1). Therefore, **sea-level research** must follow a **multidisciplinary** approach as it requires **multiple skills** to capture the cascade of processes characterizing the **global and regional sea-level** variability and trends.

The accurate estimate of the components contributing to the **global sea-level** and their **role/impact at the regional scales** is recognized by the World Climate Research Programme (WCRP) and the Intergovernmental Panel on Climate Change (IPCC) as one of the **priorities for climate research** during the next decades, with a large **societal benefit and impact**. Sea level is an essential climate variable (ECV) and considered a **key climate indicator** and at the same time represents one of the largest **societal concerns about climate change**, because of the potential impacts of sea-level rise on the large human population inhabiting the coastal regions and the loss of natural resources.

Research on sea-level change is challenging and requires cross-disciplinary skills to **account for the unresolved feedbacks** of the Earth system at the broad range of temporal and spatial scales. The **BCCR**

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[1] Bjerknes Centre for Climate: https://bjerknes.uib.no/en.
Partners: NORCE (https://www.norceresearch.no/en/); University of Bergen (https://www.uib.no/en); Institute of Marine Research (https://www.hi.no/en); NERSC (https://www.nersc.no/).

and its partners **offer the scientific framework** to meet such a challenge. In order to define and implement such a framework for sea-level research, a dedicated workshop is planned during the autumn of 2020.

Workshop Objectives

The overall objective of the workshop is to gather ideas from the BCCR partners and other participants to design the framework that could guide our activities towards: (i) **sea-level research** "actions" during the **next decade** (2021 – 2030); (ii) tackling the **unresolved feedbacks and large uncertainties** which are still existing at present in sea-level science.

More specifically, the workshop aims to provide an overview of ongoing activities and possible synergies among them to explore the **dominant and sub-dominant processes and interactions** influencing the global and regional **sea-level variability**. Important discussion points are:

- **Observations-based studies**, including in-situ measurements, remote-sensing, and reconstructions from geological archives, as well as methods to merge the different sources of information.
- **Modeling-based studies**, including global and regional studies (e.g. the Arctic Ocean) and coupling of different Earth System's components (incl. NorESM).
- **The synergy between observations and models**, including Cal/Val activities, reanalysis, experiments for existing and forthcoming observing systems.
- **Processes-oriented studies**, including studies that aim to identify the different contributions to the sea-level budget at global and regional scales.
- **Sea-level future projections** based on climate scenarios, with a focus on the leading sources of uncertainties.
- **Innovative methods** (e.g. based on artificial intelligence) to tackle knowledge gaps combining heterogeneous datasets, optimizing the existing methods of sea-level estimation, extract unrevealed patterns/feedbacks, and formulate new research questions.

Workshop Outputs

The Workshop will identify **priorities** to realize **cross-disciplinary research** about the contributions of the Earth system components to sea-level change and result in the following main outputs:

- The launch of the Bjerknes **"Sea-Level Research Group"** to define and implement sea-level research during the next decade (2021 – 2030).
- Identify the **skills, expertise** and knowledge **gaps** in the SLRG with respect to leading processes, uncertainties and gaps which characterize the global and regional (e.g. in the Nordic Seas and Arctic Ocean) sea-level response to Earth system feedbacks, such as:
  - Ocean density: thermosteric, halosteric and steric contributions.
  - Mass induced sea-level changes (e.g. ice-sheets, glaciers, land water).
  - Heat, salt, and water mass transports (redistribution).
  - Sea-state contributions (ocean wave-induced processes).

- Vertical land movements (e.g. Glacio-Isostatic Adjustment).
- Atmospheric variability and patterns.
- Changes in extreme sea level.

- Identify possible strategic **partnerships** (national and international).

The SLRG will be entrusted with the action to deliver a workshop report. Moreover, in order to launch a comprehensive research and development project on sea-level change and earth system feedbacks in the coming decade the SLRG will also be tasked to deliver a **strategy** and **implementation plan** for short- and medium- term **research activities**.

Annex 1

Background

Sea level is considered as a key indicator of climate variability and change (e.g. IPCC, 2019), as it integrates the response of different components of the Earth's system (e.g. Storto et al., 2019a) and has been used to monitor the Earth`s energy imbalance (e.g. von Schuckmann et al., 2016, 2018).

The processes contributing to sea-level changes act on various temporal and spatial scales. Over time scales ranging from centuries to millennia, a leading role is played by very slow and continuous processes such as lithospheric and mantle deformation following and persisting after the melting of ice sheets. This process of glacio-isostatic adjustment (GIA) contributes to global as well as regional sea-level changes (e.g. Peltier, 2004; Spada et al., 2006). At the multi-decadal to centennial time scales, other non-negligible factors for sea-level changes are the perturbations in the Earth's rotation (Munk, 2002) and the effect of geothermal fluxes (Piecuch et al., 2015).

Sea-level changes at decadal and interannual time scales are dominated by density and water-mass distribution variations in the ocean, driven by wind, atmospheric pressure changes, heat and freshwater fluxes and barystatic sea-level changes through water mass exchange between the land and the ocean. Wind stress and atmospheric pressure produce, through mechanical stress, a displacement of the water mass resulting in sea-level variations. Variations of temperature and salinity due to heat and water fluxes modify the density structure of the water column (steric effect; e.g. Mellor and Ezer, 1995; Storto et al., 2019a), thereby changing the height of the water column.

At the global scale, sea-level change is mostly related to: - the expansion of water masses due to density variations (mostly thermosteric component) ; - the increase of water masses due to ice-sheet and glacier melting; - and the redistribution of water between different Earth system components related to the water cycle.

At the regional scales, changes in oceanic transport of heat, salt, and water masses have a leading effect on sea-level variability, adding complexity to sea-level dynamics and making regional mean sea-level changes substantially different from the global estimates (Stammer et al., 2013; Pinardi et al. 2014). In addition, changes in the gravitational field induced by changes in the mass distribution on Earth's surface (e.g. melting land ice) alter regional sea level (e.g. Riva et al., 2010).

Ocean waves can affect sea level (e.g. Staneva et al., 2017) through changes to the ocean surface stress, mixing and circulation (e.g. Wu et al., 2019), and wave-induced processes (Breivik et al., 2015) have a major contribution during sea-level extremes (e.g. Staneva et al., 2015). Recent studies underlined that the effect of waves on sea-level rise along the coasts of the World's ocean was probably underestimated (Melet et al., 2018) and that optimal and integrated coastal sea-level observing systems should consider wave-induced processes (Ponte et al., 2019).

The most recent estimates of sea-level rise during the altimetry period (1993–2017) consider the trend of the global mean sea level (GMSL) to be equal to 3.35 ± 0.4 mm year−1, with a statistically significant acceleration over such a period equal to 0.12 ± 0.07 mm year−2 (Ablain et al., 2019).

Sea level rise (SLR) during the 21st century is expected to be larger than during the 20th century (e.g. Suzuki et al., 2011; Church et al. 2011) even if greenhouse gas emissions stopped now (Hu and Bates, 2018). In this sense, the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) of the Intergovernmental Panel on Climate Change underlined the influence of ice-sheets on Greenland and Antarctica, which contain most of the freshwater on the Earth`s surface, on sea-level change (Oppenheimer et al., 2019; Meredith et al., 2019). SLR of the 21st century might be higher than inferred from earlier projections: experts recently concluded that potential contributions from ice sheets to SLR are larger than estimated before (Bamber et al., 2019), even though large uncertainties are associated with mass-induced sea-level changes mainly given by Antarctica and Greenland ice-sheets (Nowicki and Seroussi, 2018). At the regional scale, sea-level changes can intensify (e.g. Terada and Minobe, 2018), e.g. due to weakening of the thermohaline circulation (Pardeans et al., 2011), and contribute to unprecedented flooding risks in coastal areas (Vousdoukas et al., 2018).

The accurate estimate of sea-level rise is one of the most important scientific issues that climate change poses, with a large impact for human population (e.g. Lichter et al., 2011; Bonaduce et al., 2016; Storto et al., 2019a) as it was recognized as the main driver for changes in sea level extremes (e.g. Menéndez and Woodworth, 2010; Feng and Tsimplis, 2014).

In this respect, the World Climate Research Project (WCRP) considers the sea-level rise and regional impacts as one of the major challenges of climate research (e.g. Eyring et al., 2016) to reduce the uncertainty associated to future sea-level projections (e.g. Gregory et al., 2016).

It is therefore necessary to continuously assess and monitor sea-level changes using all the tools at our disposal (Storto et al., 2019) and develop innovative methods to account for the unresolved feedbacks of the Earth System to sea-level change and the associated uncertainties (MacIntosh et al., 2017).

Methods of estimation of sea-level

Several methods exist nowadays to measure and obtain estimates of total sea level change as well as the different components contributing to sea-level variability and trends.

Tide-gauge measurements provide valuable information about sea-level variability along the coasts and have been fundamental in highlighting the trend in the rise in sea levels in the last century (e.g. Holgate et al., 2013; Church et al., 2013).

Satellite altimetry provides data, for more than 25 years, which are essential for the understanding of the ocean mesoscale dynamics (e.g. Le Traon et al., 2015) and to obtain homogeneous climate records of sea level anomalies by cross-calibrating the different satellite missions launched in the last decades (e.g. Legeais et al.,2018).

Sea-level reconstructions (Church and White, 2011; Carson et al., 2017) aim to reproduce the multi-decadal sea-level variability over a continuous spatial domain, combining the spatial and the temporal information from remote-sensing and in-situ measurements, respectively.

Gravimetry missions launched during the 2000s, provide estimates of the mass-induced sea level variations at ~ 500 km spatial resolution with good accuracy except in coastal regions.

Direct estimations of global steric sea-level change rely on in-situ profiles (XBTs, CTDs, and Argo floats; e.g. Church et al., 2010).

Combining in-situ ocean profiles with altimetry and gravimetry data has recently allowed: - the sea-level budget to be closed at both global and regional scales (Leuliette et al., 2009; Garcia et al., 2010; Kleinherenbrink et al., 2016; Raj et al., 2019; Howarth et al., 2020; Cazenave et al., 2019); - the validation of the ocean model-based steric sea level estimates (Storto et al., 2017, 2019); - the estimates of the ocean circulation and transport (e.g. Johannessen et al., 2014, Raj et al., 2018), which represent the main driver of sea-level variability at the regional scale.

The combination of different data sources represents a valuable approach also to the estimate of the contribution of glaciers and polar ice-sheets to SLR.

The contributions of glaciers, the second largest contribution in the 20th century, is estimated by in-situ measurements of length and mass changes, remote sensing methods as well as mass balance modelling driven by climate observations (Marzeion et al., 2017), the latter being facilitated by the advent of a global inventory of glacier outlines in the form of the Randolph Glacier Inventory (Pfeffer et al., 2014).

The total contribution of the polar ice sheets to SLR has been estimated using a combination of in-situ and remote-sensing observations (Shepherd et al., 2019, IMBIE Team 2019). Mass changes are measured directly using gravity field measurements. Ice volume changes are inferred from direct measurements of height changes from satellite altimetry (since 1992), and measurements of ice flow velocities and surface mass balance provide estimates of total mass change through the input-output or mass-budget method. Through this method, Greenland and Antarctic mass loss have been estimated back to 1972 (Mouginot et al., 2019) and 1979 (Rignot et al., 2019), respectively.

The continuous improvement of the representation of physical processes considered by state-of-the-science ocean general circulation models (OGCMs; e.g. Madec, 2016) allows nowadays to obtain reliable information about sea-level variability at the different spatial scales considering both long-term trends (e.g. Storto et al., 2019a) and extreme events (e.g. Staneva et al., 2016, 2017).

Ocean models are proven effective in reproducing regional modes of sea-level variability (Kuhlbrodt and Gregory, 2012; Lombard et al., 2009), and helpful for understanding the causes of sea-level rise. Earth system modelling relies on coupled global and regional models which are essential tools in climate science, e.g. to provide sea-level projections for the 21st century (e.g. Yin et al., 2010).

Ocean syntheses, which merge observation-based products and OGCMs through multivariate data assimilation methods, have shown increasing reliability over the last decade (Storto et al., 2019b). They are currently used to capture the sea-level variability (e.g. Chepurin et al., 2014), trends and to obtain estimates of the different components of the sea-level budget (e.g. Balmaseda et al., 2015; Storto et al., 2019a,).

Observing system experiments (e.g. Oke and Schiller, 2007; Halliwell et al., 2017) are rigorous methods for demonstrating the impacts of observations to resolving the ocean circulation and, once applied to sea-level measurements (e.g. altimeters constellation, Argo floats), can represent a valuable source of information to assess new deployment strategies and sampling characteristics for existing systems, and to the design of new observing systems required to overcome the gaps in our understanding of sea-level processes at the different scales of variability.

The effective use of all these different approaches to minimize the uncertainty associated with each component of sea-level variability, and to achieve new insights about unresolved feedbacks of the Earth`s system to sea-level change, could lead to design the future of sea-level research during the next decades.

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