Projecting Sea-Level Rise: from Ice Sheets to Local Implications - PROTECT

1. Excellence

Coastal zones (less than 10 m above sea level) are ecologically rich, diverse and productive but highly sensitive to changes in sea level [Wong et al., 2015]. They are also home to more than 600 million people, of which 270 million live in flood-prone areas. Coastal zones are key engines of the global economy, containing 65% of the world's large cities, most of which are still expanding rapidly. If current trends continue, the coastal population will roughly double by 2060 [Neuman et al., 2015], while the coastal economy will increase even more – plausibly by an order of magnitude – which greatly increases the exposure of humans, infrastructure and ecosystems to hazards caused by sea-level rise (SLR).

SLR is highly variable in space and time, as it results from a combination of many processes working at different temporal and spatial scales. In the 20th century, SLR was mainly caused by oceanic thermal expansion and the mass loss of mountain glaciers [Stocker et al., 2013]. In recent decades, however, the two ice sheets of Antarctica and Greenland have increasingly contributed [e.g. Bamber et al., 2018]. As highlighted in the last two Intergovernmental Panel on Climate Change (IPCC) assessment reports [Solomon et al., 2007; Stocker et al., 2013], the main *uncertainty* in projections of *future* SLR is our limited ability to model the dynamics of the Antarctic and Greenland ice sheets and robustly predict the potential emergence and rate of their collapse. Part of this uncertainty stems from the absence of atmosphere/ice-sheet/ocean feedbacks in model projections, which results in poor connections between atmospheric forcing and ice-sheet surface changes, and between ocean warming and changing ice shelf basal melt rates. Although the relative contribution of ice sheet mass loss to SLR will increase over the 21st Century, glaciers will continue to make a significant SLR contribution that must also be better quantified [Stocker et al., 2013]. Moreover, local SLR is different from the global-mean change, so it is important to better understand and quantify the regional coastal implications in order to support relevant mitigation and adaptation strategies. The project **Projecting Sea-Level Rise: from Ice Sheets to Local Implications (PROTECT)** aims to address all of these issues.

The PROTECT consortium is highly interdisciplinary and brings together world-leading European experts in modelling and observations of (i) meteorology and surface mass balance of ice sheets, (ii) oceanography and ice shelf basal melting, (iii) ice sheet processes (including calving) and dynamics, (iv) the coupling of these components, (v) mass balance of mountain glaciers, (vi) regional sea-level changes, and (vii) coastal and societal impacts. The consortium has strong links with major international scientific research programs and stakeholders, ensuring efficient collaboration and optimal sharing of knowledge and resources. Our direct involvement in the World Climate Research Programme (WCRP) "Regional Sea-level Change & Coastal Impacts" Grand Challenge, all three Working Groups of the IPCC, and our close connections with coastal adaptation stakeholders (including partnerships with indigenous Arctic institutions and low-lying island states), will ensure efficient delivery of the project outcomes. By delivering improved SLR projections, PROTECT will help achieve the Sustainable Development Goals (SDGs) of the United Nations and supports the European Union Adaptation Strategy, the adaptation strategy of the UNFCCC Paris Agreement, and the EU Arctic strategy, as well as other frameworks aiming at increasing resilience to climate change (e.g., the Sendai Framework for disaster risk reduction).

1.1. Objectives

The overarching scientific objective of PROTECT is to assess and project changes in the land-based cryosphere with quantified uncertainties, to produce robust global, regional and local projections of SLR on a wide range of timescales (Figure 1). The project will place particular emphasis on the *low-probability, high impact* scenarios of greatest interest to coastal planning stakeholders. A novelty in PROTECT is the strong interaction between these stakeholders and the sea-level scientists (ranging from glaciologists to coastal impact specialists) to identify relevant risks and opportunities from global to local scales and enhance European competitiveness in the provision of climate services.

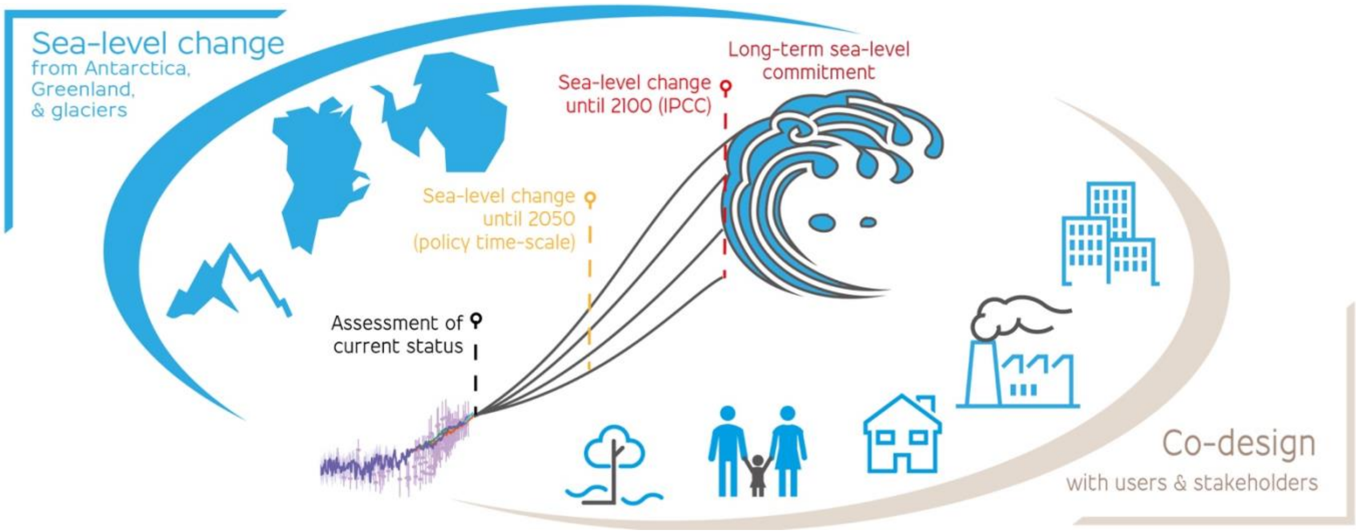

Figure 1: PROTECT will produce sea-level projections and their associated uncertainties on a range of time scales, to support coastal adaptation planning and mitigation policy.

The comprehensive spectrum of expertise allows PROTECT to cover, for the first time, all spatial and temporal scales that are relevant for future SLR. PROTECT will achieve the following specific objectives:

1. Assess the **contemporary mass balance** of ice sheets and glaciers, quantify the relative importance of anthropogenic forcing and internal climate variability to ice sheet and glacier changes, and use remote-sensing observations to evaluate and improve the models used for ice sheet and glacier projections. To meet this objective, PROTECT will use and develop data products from the ESA Earth Observation Programme and Copernicus climate data.
2. Use the improved understanding of short-term variability in glacier and ice-sheet mass balance to make projections until **2050, the timescale of relevance to many of today's coastal management decisions**. This mainly concerns the melting of mountain glaciers and key areas of significant contemporary ice sheet mass loss in West Antarctica (Amundsen Sea embayment and Antarctic Peninsula) and the ablation zone and major outlet glaciers of the Greenland ice sheet (e.g. Jakobshavn Isbrae).
3. Use a range of newly-developed, coupled climate-ice sheet models to project SLR as a result of glacier and ice sheet mass change until **2100, the IPCC timescale that is relevant for critical long-term infrastructure**. Improved understanding and modelling of critical processes and feedbacks will better characterise the probability of high-end SLR under plausible climate change trajectories.
4. Assess the irreversibility of glacier and ice-sheet mass loss and the associated sea-level rise commitment to **2500 and beyond, the timescale relevant to the long-term viability of coastal cities, small islands and low-lying states**. This requires understanding of the conditions needed for glacier and ice-sheet regrowth and their likelihood under strong mitigation of anthropogenic greenhouse gas emissions.

1.2. Relation to the work programme

PROTECT has been carefully designed to respond to H2020-LC-CLA-07-2019: The changing cryosphere: uncertainties, risks and opportunities, action (a): Sea-level changes. The table below shows (in the right column) how PROTECT matches the specific challenges and scope of the call (in the left column). The PROTECT work packages (WP1-7) are described in Section 1.3.

Specific challenge: Globally, glaciers and the large ice sheets of Antarctica and Greenland are vulnerable to climate change, risking a significant future increase in sea level. At present, significant uncertainties, e.g. relating to their stability, prevent an accurate assessment of their vulnerability.	PROTECT quantifies contemporary and future contributions to SLR from ice masses in Antarctica (WP4), Greenland (WP5) and mountain glaciers and ice caps globally (WP6). We will produce global, regional and local SLR projections (WP7), including constrained high-end contributions from potentially unstable sectors of the ice sheets, with a focus on ice-sheet processes (WP3) and ice sheet-climate feedbacks (WP4-5).

Scope: actions should aim at developing innovative approaches to address [...] sea level changes	PROTECT has an innovative project structure and scientific approach using newly-developed methods to quantify cryospheric contributions to SLR, with improved process understanding (WP3) and ocean-atmosphere-ice sheet coupling (WP4-5) on three key time scales: (i) relevant for today's policy makers (2050); (ii) relevant for the objectives of the Paris Climate agreement and the IPCC (2100); and (iii) long-term SLR commitments (2500). A core principle of PROTECT is co-design and close interaction with stakeholders to ensure efficient knowledge exchange.
Actions should assess the processes controlling changes to global ice mass balance - including ice dynamics such as ice shelf-ocean and sea-ice interactions, surface components, effects of crustal de-loading (Glacial Isostatic Adjustments) on relative sea-level changes and/or gravitational effects of ice mass changes on the spatial patterns of sea-level changes.	PROTECT will improve representations of key processes including (i) snowpack processes and runoff, and the potential for ice shelf hydrofracture (WP3-5); (ii) sub-ice shelf melt in state-of-the-art coupled and standalone ice sheet and ocean/sea ice models (WP3-4); (iii) ice sheet basal sliding and hydrology (WP3); (iv) ice shelf damage and calving (WP3); (v) rapid Glacial Isostatic Adjustment in West Antarctica and effects on grounding-line migration (WP4); (vi) impacts of debris cover on glacier mass balance (WP6); (vii) gravitational effects and fingerprinting of regional SLR projections (WP7).
Actions should assess the status of ice sheets and glaciers, report on how their changes are likely to affect future sea-levels, and increase confidence in predicting changes in the cryosphere including through better representation of poorly represented processes.	PROTECT assesses contemporary mass balance of Earth's ice sheets and glaciers, combining models and observations (including remote-sensing data from the ESA Earth Observation Programme), to assess the relative importance of natural climate variability and anthropogenic warming (WP4-6) to recent historical changes. WP3 tests and improves model representation of key ice-sheet processes such as calving, marine ice-cliff instability, firn processes and runoff, and ice-ocean interactions. WPs4-5 apply this new understanding to ice sheet SLR projections.
Actions should [...] analyse low-probability high-impact scenarios including those associated with the collapse of ice sheets (sea-level fingerprints).	PROTECT targets instabilities associated with ice sheets that may lead to high-end SLR scenarios (WP4-5) to produce regional SLR projections (fingerprints, WP7). Key areas vulnerable to rapid change (Amundsen Sea, Antarctica and Jakobshavn Isbrae, Greenland) will be simulated in more detail with coupled models (WP4-5).
Actions may be focused on specific issues which substantially contribute to sea-level changes and to the assessment of the associated major risks to and impacts on coastal communities, coastal ecosystems and critical infrastructure across the globe.	PROTECT WP2 co-designs sea level and impact studies with users, using stakeholder knowledge to ensure relevant project outcomes, including targeted case studies that address vulnerable coastal ecosystems, communities and infrastructures in Europe (France and the Netherlands), Greenland and the Maldives. Finally, WP7 assesses the global coastal impacts of SLR on critical infrastructures.
Clustering with relevant projects funded by the ESA Earth Observation Programme is encouraged.	The PROTECT consortium includes the groups leading the cryosphere elements of the ESA Climate Change Initiative (CCI) and the Copernicus Climate Change Services (C3S).

1.3. Concept and methodology

1.3.(a). Concept

1.3.(a).(i) Overall concept

The cryospheric contribution to SLR needs to be better constrained to produce useful projections, with reduced uncertainties, so that practical adaptation options can be explored. PROTECT will address this urgent need to improve our understanding of the processes governing ice sheet and glacier mass loss. To do so, PROTECT will **bring together the leading European experts in remote-sensing and modelling of polar and glacier environments**. This consortium clusters and coordinates various initiatives, including process understanding, ice sheet modelling and coupling ice sheet with ocean and atmosphere models, which are all necessary to better assess the state of land-based ice masses and anticipate their forthcoming short- and long-term changes. Furthermore, this gives the PROTECT consortium the opportunity to access **a large suite of stand-alone and coupled models of various complexities, allowing a multi-model ensemble approach**. Multi-model ensembles are a well recognized approach in climate science to constrain structural uncertainties, but remain in their infancy in cryospheric sciences; PROTECT will boost the development and take-up of this approach, including calibration and validation with remote-sensing data.

SLR is highly non-uniform in space and time. To design relevant adaptation and mitigation strategies it is crucial to translate global projections into regional [Slangen et al., 2014] and local [Hinkel et al. 2014] projections. PROTECT will link the various spatial scales and propagate uncertainties from global to regional and local impacts**. By uniting cryospheric, sea-level and coastal impact experts, the PROTECT consortium has been specifically built to meet this considerable interdisciplinary challenge.**

Recognizing that developing climate services for coastal adaptation is an iterative and two-way process, **PROTECT will significantly improve upon existing mechanisms for interactions between scientists and stakeholders**. The project will address the needs of stakeholders who require sea-level information (WP7), but also examine local case studies to maximize the use of the sea-level information produced during the project (WP2). In order to address the different preferences of adaptation practitioners and varying levels of risk aversion, we will consider several frameworks (best estimates, likely and high-end scenarios, probabilistic and extra-probabilistic projections). Finally, using the knowledge from stakeholders, PROTECT will ensure that it provides salient information to support **current and future climate policies over a broad range of time horizons**:

- **2050**: Can we expect a significant acceleration in the contribution of glaciers and ice sheets to SLR at this time horizon, causing a major failure of current adaptation practices? To answer this question, PROTECT will provide better understanding of oceanic and atmospheric forcing of glaciers and ice sheets, feedbacks between ice sheet change and the climate system, and improved initialization of ice-sheet models.
- **2100**: How to produce relevant sea-level information for users with a variety of risk aversion levels, including best estimates and high- and low-end scenarios? Responding to these questions, PROTECT will generate better understanding of glacier and ice sheet contributions to extreme SLR, such as an evaluation of Marine Ice Cliff Instability (MICI, DeConto and Pollard [2016]) and related calving processes, and feedbacks between atmosphere, ocean and ice sheets.
- **2500 and beyond**: How will the long term viability of coastal cities, island states, and cultural sites be affected by the trajectories of ice sheet evolution? Using global coupled climate/ice sheet models, PROTECT will better constrain long-term SLR commitment.

1.3.(a).(ii). Numerical models

PROTECT benefits from the contrasting strengths of a wide range of models brought together in carefully designed model intercomparison and ensemble experiments, extending innovative methodologies developed within the consortium [Ritz et al., 2015; Edwards et al. 2019].

- Dynamical ice sheet models: BISICLES (U. Bristol/U. Swansea), Elmer/Ice (CNRS), f.ETISh (ULB), GISM (VUB), IMAUICE and CISM (UU), ISSM (AWI), PISM (PIK, AWI), Ùa (U. Northumbria), WAVI (BAS). All these models solve the ice-flow momentum equations on various horizontal grids, with different levels of complexity (from “full-Stokes” to “shallow” approximations) and various sliding laws. Some are suitable for multi-millennium simulations and large ensembles while others are more suitable for century-scale simulations, with a fine representation of grounding line dynamics and initialisation from assimilated remote-sensing data. The modelling groups have a long history of productive collaboration, most recently in ISMIP6 for Greenland and Antarctica.

- Surface mass balance models: Dynamic bias correction will be applied to CMIP6 projections, providing boundary conditions for leading regional climate models (RCMs) that are specifically adjusted for polar regions: HIRHAM (DMI), MAR (U. Liège, CNRS) and RACMO2 (UU). They all include sophisticated representations of snow and firn processes essential for computing accurate surface mass budget over ice sheets. The use of an RCM ensemble allows PROTECT to assess model uncertainty, enhance understanding of atmosphere-ice sheet interactions at the surface, and derive the best possible driving fields for ice sheet dynamical models.

- Ocean models: FESOM (AWI), MITgcm (BAS, U. Northumbria) and NEMO (CNRS, BAS). These models simulate the ocean circulation in ice-shelf cavities and the thermodynamic interactions with the ice (melting and freezing). They have all been coupled to ice-sheet models, i.e. they can represent sub-ice oceanography and melting in the presence of an evolving ice-sheet geometry. They also include dynamic/thermodynamic sea ice components. NEMO and MITgcm have structured horizontal grids and will be run as global and regional models (with lateral conditions imposed from climate models and ocean reanalysis products), while FESOM has an unstructured grid, enabling it to run globally but with greatly refined resolution along the ice-sheet margins.

- Glacier models: Using state-of-the-art global climate model output from CMIP6, three models will further compute mountain glacier mass change. GloGEM (ETHZ) and OGGM (U. Bremen) include realistic glacier geometries and take into account frontal ablation of tidewater glaciers; OGGM also calculates glacier geometry change based on explicit ice dynamics. A third model (U. Bremen) will also be used, which is highly parameterized (no realistic geometry, no separation between surface mass balance and frontal ablation), but has been shown to produce particularly robust results with respect to parameter choices.

- Earth System Models: Output from CMIP6 will be used to compute regional sea level changes and their uncertainties as a result of ocean thermal expansion, ocean dynamics and atmospheric pressure effects. CMIP6 output will be complemented by PROTECT simulations using AWI-CM (AWI) and CESM2.0 (UU), fully coupled Earth system models including one or both ice sheets, in order to study feedbacks between earth system components and reversibility of ice sheet loss over longer timescales.

- Sea-level change and impact models: The response of the solid Earth to past glaciations will be computed (NIOZ) using the ICExG suite of models (Peltier et al, 2015). The changes of the geoid and solid Earth due to ongoing mass redistributions (e.g., ice melt, land water exchange) will be computed using a gravitationally self-consistent sea-level model (NIOZ). The global DIVA (GCF) and local (BRGM) coastal impact models will be used to compute consequences such as flooding and shoreline changes, by combining mean sea level changes with tides, waves, and storm surges.

1.3.(a).(iii) Positioning

The numerical models employed in the project are already fully operational, and most have been assessed in model inter-comparison projects [e.g., Pattyn et al., 2013; Asay-Davis et al., 2016; IMBIE team 2018]. The individual models can therefore be described as 'complete and qualified', i.e. Technology Readiness Level (TRL) 8. The coupling of ice sheet models with ocean and atmosphere models is a more recent development, i.e. at TRL 2-3, the 'technology/experimental proof of concept' stage. Coupled simulations have in some cases already been performed but specific regional applications and full comparison with data remain novel. We expect the project to yield coupled models that reach TRL 5-6 'technology validated/demonstrated in relevant environment'. The models used for the translation of mass contributions to regional sea-level change and impacts, such as the gravitational fingerprinting code and the DIVA model, have been extensively tested and published and are therefore at the TRL 8 level. The CMIP6 climate models, at the root of IPCC projections and assessments, are based on ocean and atmosphere models routinely used in operational environment (TRL9).

There are several satellites currently in orbit collecting Earth Observation (EO) data of the cryosphere, including the CryoSat-2, AltiKa, Sentinel-3, and IceSat-2 altimeters, the Landsat-8, Sentinel-1, and Sentinel-2 optical and radar imagers, and the GRACE-FO gravimeter (TRL 9). The algorithms used to generate records of essential climate variables from EO data, for example changes in land ice thickness, flow, and mass, are fully developed and operational, and have been extensively demonstrated in previous projects (e.g. CCI, C3S). As such they are regarded as TRL 8. Processing methods to combine time series from different satellite missions have been successfully employed, for example within IMBIE, and can be considered at TRL 7-8. Further development is required to incorporate ancillary data (e.g. surface mass balance and glacial isostatic adjustment) and to produce regional assessments. The inclusion of new and future missions is an ongoing requirement, and so this task is at TRL 3-4.

1.3.(a).(iv) Link to national and international initiatives

The PROTECT consortium unites the leading European institutes in the relevant cryospheric, climate, and sea-level science, in full synergy with several ongoing large international and national initiatives. In particular, the PROTECT project will benefit from and support:

- European Earth Observation programs, which produce fundamental climate data records of the cryosphere, are tightly linked to PROTECT. This includes the ESA Climate Change Initiative (CCI) and the Copernicus Climate Change Service (C3S). Specifically, WPs 4-6 involve leaders of the Antarctica (Shepherd), Greenland (Forsberg), and Glaciers (Paul) CCI+ consortia, a WP leader of the Sea Ice CCI+ consortium (Mottram), and the Ice Sheets (Shepherd) and Glaciers (Paul) science leaders of the C3S Land Hydrology and Cryosphere service. PROTECT also benefits from direct involvement in other international activities related to cryosphere EO, including leadership of the ESA-NASA Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE), membership of the WCRP Ice Sheet Mass Balance and Sea Level working group (ISMASS), involvement in the 4DAntarctica consortium, and the provision of scientific advice (Shepherd) and campaign support (Forsberg) to ESA's CryoSat-2 satellite mission.

- International intercomparison initiatives. (i) **ISMIP6** is the dedicated ice sheet model intercomparison embedded in CMIP6, due to be completed in 2020. Ice sheet modellers involved in the PROTECT consortium are leading ISMIP6 (Payne is co-chair) and PROTECT will support the exploitation and dissemination of ISMIP6 results and prepare ISMIP7. (ii) **MISOMIP** is a coupled ice/ocean model intercomparison [Asay-Davis, 2016] focused on simplified geometries and forcings. Its successor MISOMIP2 will prepare the first ocean/ice model intercomparisons on realistic cases. The PROTECT consortium is strongly involved in MISOMIP and MISOMIP2 (Jourdain is co-chair). (iii) **GlacierMIP** coordinates glacier projections by combining all actively developed global glacier models, as well as collecting and disseminating the results to the community. PROTECT will build on the current activities and foster GlacierMIP2 (UBremen). (iv) **Coast-MIP** brings together diverse coastal impact models and the underlying science to better understand and forecast the long-term impacts of climate change on coastal infrastructure and ecosystems (Hinkel is co-lead). PROTECT will provide improved sea-level projections (including high-end) to Coast-MIP.

- Related International funded projects. (i) **NSF/NERC Thwaites programme,** which aims to improve projections of ice loss from Thwaites Glacier in West Antarctica. PROTECT includes partners leading Thwaites projects (BAS and Northumbria) and activities will be built in synergy with the NERC/NSF programme through interaction with its science coordination office (BAS). (ii) **TiPACCs** (Tipping Points in Antarctic Climate Components), a H2020 consortium starting mid-2019, involves several PROTECT partners. The objective of TiPACCs is to determine thresholds for ocean - ice-sheet interactions in the Antarctic region under idealized climate scenarios. TiPACCs will not provide realistic projections related to emission scenarios, but it will feed PROTECT (WP4) by analysing important climate mechanisms and supporting the development of ice/ocean coupled models. (iii) **ERA4CS INSeaPTion project** aims at developing coastal climate services for adaptation, using the latest sea level projections. PROTECT will build upon the co-design initiated within INSeaPTION, and will specifically address high-end scenarios for risk averse users.

- National efforts, related to the impact of the cryosphere on SLR are already funded or emerging (e.g. PARAMOUR in Belgium, PalMod in Germany, Danish National Monitoring of the Greenland Ice Sheet (PROMICE, GNET) and the associated PolarPortal, EarlySea in the Netherlands). The PROTECT consortium includes the principal investigators of these initiatives, ensuring an optimal synergy.

PROTECT will deliver the coordinated, interdisciplinary science necessary to make a major step-change in the quality and utility of real-world SLR projections based on the knowledge of specific processes and regions generated by these existing efforts.

1.3.(b). Methodology

PROTECT comprises 7 tightly-interconnected work packages (WPs), shown schematically in Figure 2.

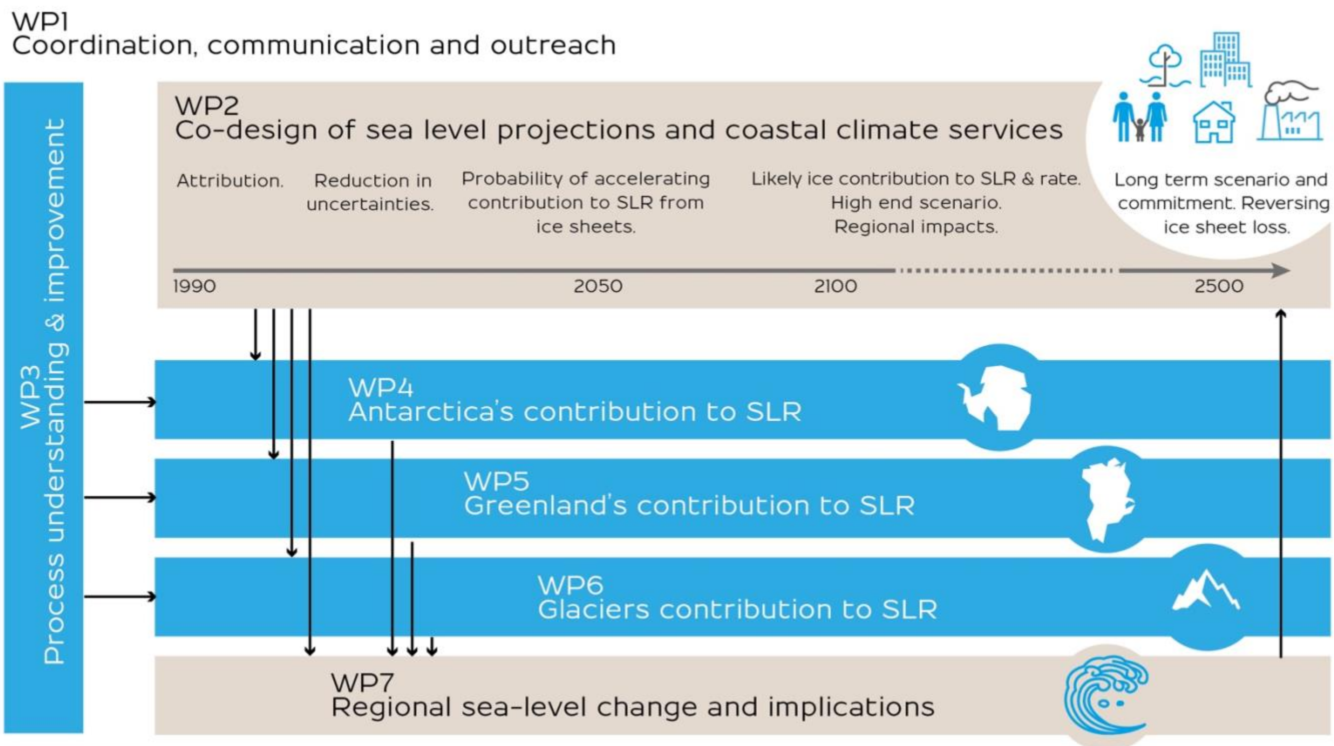

Figure 2: Structure of PROTECT and relations between work packages.

WP1: Coordination, communication and outreach. The coordinator will be supported by a Steering Committee selected to account for gender balance and career-stage balance. This group will ensure an efficient coordination of the scientific activities, develop the capabilities of the next generation of scientists and ensure an optimal dissemination of the results to all audiences. The Steering Committee, responsible for monitoring progress on deliverables to H2020, will be further advised by an international advisory board, with membership chosen specifically to reinforce the link with the most significant non-European SLR initiatives.

WP2: Co-design of sea level projections and coastal climate services. Coastal climate services are widely identified as business opportunities with one of the strongest growth potentials in the area of adaptation to climate change. However, sea level projections remain misaligned with users' needs and do not consider important decision-making contexts, which vary considerably between stakeholders in terms of exposed assets, levels of risk aversion, and ultimate objectives. Furthermore, state-of-the-art sea level projections are difficult to access, which limits the potential for development of coastal climate services such as those within Copernicus and ERA4CS. Within this context, the general objective of WP2 is to co-design, with users, the sea-level projections and innovative climate services that will be fed by the scientific results of WP3-7. Specifically, we will focus on: understanding which mean and extreme sea-level projections are relevant to global and local user needs; identifying combinations of impact model simulations that can be used to provide science-based projections relevant to user needs; improving current coastal climate services with better sea level products and impact projections; advising adaptation and mitigation strategies, including those concerned with regulation policies; contributing to the dissemination of sea level science and impacts. WP2 will build upon four case studies: i) a cultural site threatened by erosion within the context of sea level change in Greenland; and adaptation options under different mean and high-end sea level rise scenarios in ii) the Maldives, iii) France and iv) the Netherlands, with these three regions chosen to represent vulnerable communities, ecosystems and infrastructures respectively.

WP3: Process understanding and improvement. WP3 will improve our current understanding of the boundary conditions and physical processes that control the dynamic behaviour of the Greenland and the Antarctic ice sheets. This will occur through focussed improvements of key ice-dynamical processes. More specifically, WP3 aims to make structural model improvements in areas that control rates of SLR and extreme/high-end SLR uncertainty, including ice-shelf damage, basal processes, and ice-ocean and ice-atmosphere interactions. We will improve model calving mechanisms and propose new calving laws, with a particular focus on processes that influence Marine Ice-Cliff Instability and its representation in models via a targeted model intercomparison on calving processes. We will investigate the use of different sliding laws at the ice bed, and how they can be improved using time-dependent initialization techniques reproducing remote-sensing observations. We will explore different parameterizations for ice sheet-ocean interaction for both stand-alone ice-sheet and coupled ice sheet-ocean models, crucial for deriving future changes in sub-shelf melting from ocean conditions projected by coarse-resolution climate models. Finally, we will improve the representation of processes controlling ice surface mass balance, including firn buildup and demise (thresholds for ice shelf hydrofracturing), precipitation estimates and cloud physics uncertainties.

WP4: Antarctica's contribution to SLR. WP4 will focus on the Antarctic ice sheet, with a particular emphasis on its interaction with other parts of the Earth's climate system. We will begin by assessing the contemporary state of the ice sheet, producing improved estimates of its mass balance during the recent past from spaceborne observations. Then, through dedicated ocean and ice simulations, we will quantify the relative historical contributions of anthropogenic forcing and internal climate variability to these recent ice-sheet changes. These steps are necessary to (i) build confidence in our models by evaluating them against observations and (ii) inform the uncertainty estimates in our future projections, by quantifying internal climate variability, anthropogenic forcing uncertainty, and model structural uncertainty. We will then use these models to produce future projections. We will first build projections to 2050, with special focus on the Amundsen Sea sector, and will then consider projections to 2100 for the entire Antarctic ice sheet. For this, we will build upon existing ice-sheet projections, further extend the ISMIP6 ensemble to new CMIP6 scenarios, and simulate the coupled interactions at the ocean/ice and air/snow/ice interfaces that are missing in current CMIP projections (this will be fed by WP3). The statistical properties of the resulting ensemble will be emulated to estimate probabilities of high-end scenarios at 2100 [Edwards et al., 2019]. The final goal is to focus on the long-term (~2500) contribution to SLR from Antarctica, including the possibility of ice-sheet regrowth under strong mitigation scenarios. For this, we will couple an ice-sheet model to a 3D solid Earth model in order to account for the glacial isostatic adjustment fingerprint on SLR and its feedbacks to the ice-sheet evolution.

WP5: Greenland's contribution to SLR. WP5 will focus on the Greenland ice sheet and its interactions with other parts of the climate system. Ice loss from Greenland is presently dominated by surface melt and runoff, making the ice sheet vulnerable to variability in atmospheric circulation on relatively short (interannual) time scales. By coupling atmospheric and oceanic circulation with ice sheet processes, WP5 will attribute contemporary ice sheet mass loss to anthropogenic climate change as well as natural (internal) variability, following the methodology of WP4. The impact of climate states and modes of variability, including the North Atlantic Oscillation (NAO), Atlantic Multi-decadal Oscillation (AMO) and Arctic Oscillation (AO), and Greenland blocking on the surface mass budget will be assessed with a range of model experiments using dynamical downscaling with RCMs to estimate SLR contributions to 2050. At the same time, parts of the ice sheet are vulnerable to ocean-driven melt and calving collapse, processes related to but distinct from those found in Antarctica that may be important on longer timescales. The role of ice dynamics in mass loss from Greenland up to 2100 will be explored by taking full advantage of the ISMIP6 model ensemble to explore statistical uncertainties. Dedicated ice sheet models will also be used to narrow down the uncertainties introduced by ice sheet model parameterisations of key processes. The interaction with the ocean and the role of fjords will be more closely examined with a case study where we can take advantage of detailed observational data from our Greenlandic partners Asiaq, supplemented by modelling of the fjord glacier system close to Nuuk including the Kangiata Nunata Sermia (KNS) glacier. Together with WP4, we will use a fully coupled Earth System Model to assess how the two ice sheets will evolve over the long term (100-500 years) as well as exploring the possibility of a reversal in ice sheet mass loss.

WP6: Glaciers contribution to SLR. WP6 will improve projections of the contribution of mountain glaciers and ice caps to SLR over decadal to multi-centennial time scales. The emergence of operationally available geodetic observations of glacier volume change for a large fraction of the world's glaciers enables us to follow a new approach to model calibration. To a large degree, we will be able to eliminate spatial interpolation of model parameters for calibration, significantly reducing parameter uncertainty. We will develop modular frameworks (i.e., applicable to different glacier models) for model calibration and cross-validation. Debris cover is known to strongly affect the glacier mass balance in many mountain ranges, but so far has been neglected by all glacier models producing projections on the global scale. We will implement parameterizations of debris cover effects on the surface mass balance, and evaluate their skill using cross-validation based on geodetic mass balance observations.

WP7: Regional sea-level change and implications. WP7 will quantify the implications of ice sheet, ice caps, and mountain glacier changes for coastal communities, coastal ecosystems and critical infrastructure at the global and regional scale. It has two main aims. The first aim is to translate the results of WP3-6 into mutually consistent global and regional sea level scenarios, combining results from PROTECT for land ice mass loss, CMIP6 model output for ocean thermal expansion and ocean dynamical response with land water storage projections from literature. The WP will subsequently compile regional SLR scenarios, accounting for gravitational and rotational effects and including the different components of SLR. The second aim is to assess coastal impacts and adaptation needs, taking into consideration changes in extreme water levels. This starts with detailed modelling of impacts and adaptation implications to 2100 using the global DIVA model. It will further consider indicative long-term impacts and adaptation implications from 2100 to 2500 using new methods developed within the DIVA framework. Hence, these analyses will consider how 21st century climate change may lock-in SLR impacts and adaptation needs in the longer term, informing the mitigation debate. The outcome of WP7 will feed back into the case studies of WP2 and support the development of coastal climate services.

Gender dimensions will be part of the analysis conducted within WP2 and WP7 on global impacts and case studies, with a particular focus on analysing gender and factors intersecting with gender (cultural, socio-economic, age, family configuration); these are especially relevant in the case studies identified in WP2.

1.4. Ambition

PROTECT will push SLR projections beyond the state-of-the-art and have a long standing scientific and societal impact by (i) significantly improving our understanding and the numerical representation of so far poorly constrained but significant glaciological processes (MICI, ice shelf hydrofracture, basal processes, etc.), (ii) providing a step change in modelling the interactions between atmosphere, ocean and ice sheets and the feedbacks between ice sheets and the climate system, (iii) improving the representation of dynamical ice sheets in Earth System Models, (iv) improving the methodology and accuracy of SLR projections with a robust propagation of uncertainties from global to regional scales, (v) assessing the societal implications of high-end SLR scenarios over decades to centuries, (vi) developing and mentoring early career scientists who will be at the heart of PROTECT, with proper consideration of diversity and inclusiveness as a core task across all work packages.

PROTECT will be innovative in developing climate services for coastal adaptation. While the market for climate services in Europe is progressively emerging, further significant opportunities have been identified, in particular in the sector of coastal flood risk [Cavelier et al. 2017]. Through the co-design mechanisms proposed in WP2, PROTECT addresses all the commonly recognised barriers for the early design of climate services [le Cozannet et al., 2017]. It will, in particular, provide improved projections of future SLR, including robust the high-end scenarios required to develop climate services for risk-averse users and for long-term planning and management of critical coastal infrastructure, coastal ecosystems, and cultural coastal heritage. The dedicated case studies in WP2 will provide representative examples of these applications, demonstrating how global knowledge can be applied locally to develop innovative adaptation approaches. This will stimulate these applications and services, enhancing their use around the world.

2. Impact

2.1. Expected impacts

Strengthening European leadership in climate science and coastal impacts. The PROTECT consortium brings together core developers of community numerical climate and coastal impact models, embracing a wide range of research activities in Europe and beyond. Step-changes in the performance of the component- and coupled models are expected, further enhancing European climate-modelling capabilities, interactions and coherence. The strong involvement of PROTECT partners in all major international cryospheric and coastal impact initiatives will ensure an effective uptake of PROTECT developments, rapidly benefitting the international climate research community.

Strengthening European development of coastal climate services. As emphasized in Section 1.4, coastal climate services have a strong growth potential in Europe. PROTECT will develop innovative approaches for adaptation to SLR, stimulating worldwide applications and services. Their uptake will be facilitated through PROTECT partners at the interface of academia and operations (DMI, KNMI, BRGM, GCF, Asiaq), their mission being specifically to enhance innovation and knowledge transfer to public services and private markets.

Support policy makers. PROTECT will go further than simply delivering a new generation of sea-level projections. PROTECT's unique engagement with stakeholders, including their involvement in the project's experimental design (WP2), will enhance the way in which these projections are conceived and delivered. PROTECT deviates from traditional IPCC-style projections through (i) a focus on high-magnitude, low-probability estimates of SLR, (ii) a direct link between changes in land ice mass and regional sea-level implications, and (iii) a focus on policy-relevant timescales shorter than the end of the century, as well as long-term SLR commitment over centuries. PROTECT partners officially advise governments in key EU states that are vulnerable to SLR (DK, NL, UK, FR).

Supporting EU policy on sustainable development. By providing improved knowledge on potential high-end, short-term and long-term (beyond 2100) SLR scenarios and their implications, PROTECT will also serve global agendas such as the United Nations Sustainable Development Goals (SDGs) and the Sendai Framework for Disaster Risk Reduction. Specifically, PROTECT will inform SDG 13 (Climate Action) by providing recommendations for the development of national adaptation plans and the implementation of national and local disaster risk reduction strategies (SDG 13.1 & 13.2). It identifies sea-level priorities for the use of the Green Climate Fund (SDG 13.A) and will support education, awareness-raising and the human and institutional capacity to adapt (SDG 13.3). PROTECT also addresses SDG 6 (Ensure availability and sustainable management of water and sanitation), by informing about salt intrusion in coastal areas, notably deltas and estuaries, SDG 11 (Sustainable cities and communities), as flooding of coastal cities is one of the major concerns associated with SLR, and both SDG 14 (Life below water) and SDG 15 (Life on land) as sea level is a fundamental control on terrestrial and marine life in the coastal zone.

The following table summarizes the specific impacts outlined in the call (left column) and how these impacts are achieved in PROTECT (right column):

...the implementation of the new integrated EU policy for the Arctic...	PROTECT directly contributes to achieving the three main objectives of the integrated EU policy for the Arctic of climate change, sustainable development and international cooperation. PROTECT will assess key climate impacts in the Arctic and will provide input on the status of the Greenland ice sheet and Arctic glaciers to the Arctic Monitoring and Assessment Programme (AMAP), especially its report on snow, water, ice and permafrost in the Arctic (SWIPA). PROTECT also promotes sustainable development in collaboration with indigenous people via partner Asiaq, and will enhance the capabilities, development opportunities and resilience of local communities. Finally, PROTECT contributes to enhancing international cooperation via participation in multinational fora such as the Arctic Circle and WCRP/CliC scientific panels.
...the IPCC assessments and other major regional and global initiatives...	PROTECT involves lead authors and contributing authors to all three IPCC AR6 Working Groups. Furthermore, PROTECT builds on CMIP6 and AR6, and will provide a science cornerstone in preparation of CMIP7 and AR7. The direct involvement of PROTECT partners will allow the project to support:: (i) the activities of the WCRP on climate and cryosphere, regional sea level change and coastal impacts (ISMIP6, GlacierMIP, MISOMIP2, Cordex, CoastMIP, Sea-level Grand Challenge), (ii) the Global Framework for Coastal Services (by expanding the stakeholder engagement

	initiated as part of the climate services research projects supported through ERA4CS and JPI Climate), (iii) the Antarctic Ice Sheet Dynamics and Global Sea Level (AISSL) Programme Planning Group of the Scientific Committee on Antarctic Research (SCAR) (by providing the most up-to-date assessments of Antarctic ice sheet mass balance evolution and related uncertainties), (iv) the current working groups of the International Association of Cryospheric Sciences (IACS).
...enhanced engagement of and the interaction with residents from local communities and indigenous societies...	PROTECT will reinforce interactions with citizens and stakeholders through the co-design and co-development of SLR projections and climate services in WP2 and four dedicated case studies: a cultural site in Greenland, adaptation options in the Maldives, ecosystem impact in France and threatened infrastructure in the Netherlands. By doing so, PROTECT will optimally use local knowledge and strengthen links between European, Greenland and Maldivian researchers, local communities, and adaptation stakeholders.
...support the EU Arctic Research Cluster...	PROTECT will propose to join the EU Arctic Cluster. Multiple partners of PROTECT (DMI, BAS, AWI) are already members, which greatly facilitates joint activities, e.g. joint outreach on Arctic issues to stakeholders; the organisation of summer schools in collaboration with the EU cluster, Blue-Action and WCRP/CLIVAR. Through its dedicated focus on land-ice evolution, the proposed research in PROTECT is highly complementary to ongoing research within the EU Arctic Cluster.

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