ESA Climate Change Initiative (CCI)

Sea Level Budget Closure (SLBC_cci)

Science Requirements Document D1.1
ESA_SLBC_cci_D1.1
Version v1.2, issued 25 Aug 2017

Report at initial point of project

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To be cited as:

Novotny, K.; Horwath, M.; Cazenave, A.; Palanisamy, H.; Marzeion, B.; Paul, F.; Le Bris, R.; Döll, P.; Caceres, D.; Hogg, A.; Shepherd, A.; Forsberg, R.; Sørensen, L.; Andersen, O.B.; Johannessen, J.; Nilsen, J.E.; Gutknecht, B.D.; Merchant, Ch.J.; Macintosh, C.R.: *ESA Climate Change Initiative (CCI) Sea Level Budget Closure (SLBC_cci). Science Requirements Document D1.1, Report at initial point of project. Version 1.2, 25 August 2017*

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Change Log

Issue	Author, Org.	Affected Section	Reason/Description	Status
1.0	M. Horwath / TUDr ...	All	Document Creation	Released to ESA 2017-06-30
1.1	K. Novotny / TUDr	All	New generation of PDF file	Released to ESA 2017-06-30
1.2	K. Novotny, M. Horwath / TUDr	All	Document revision after review by ESA	Released to ESA 2017-08-25

Distribution List

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Acronyms and Abbreviations

Acronym	Explanation
Argo	global array of temperature/salinity profiling floats
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CCI	Climate Change Initiative
CCI SST	CCI Steric Sea Level Project
CLS	Collecte Localisation Satellites
CPOM	Centre for Polar Observation and Modelling
CSIRO	Australia's Commonwealth Scientific and Industrial Research Organisation
CSR	Center for Space Research (University of Texas at Austin)
DEM	Digital Elevation Model
DTU	Danmarks Tekniske Universitet
ECHAM	Max Planck Institute for Meteorology atmospheric general circulation model
ECV	Essential Climate Variables
EN4	version 4 of the Met Office Hadley Centre ‘‘EN’’ series of data sets of global quality controlled ocean temperature and salinity profiles
Envisat	ENVIronment SATellite
EO	Earth Observation
ERA	Earth system ReAnalysis
ERS-1/2	European Remote Sensing Satellite -1/2
ESA	European Space Agency
ESA STSE	ESA Support to Science Element
ESRIN	European Space Research Institute
GCOS	Global Climate Observing System
GIA	Glacial Isostatic Adjustment
GLL	Grounding Line Location
GMB	Gravimetric Mass Balance
GMSL	Global Mean Sea Level
GPS / GNSS	Global Positioning System / Global Navigation Satellite System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
HIRHAM	RCM based on a subset of the HIRLAM and ECHAM models
HIRLAM	High Resolution Limited Area Mode
HYOGA	Japanese, means glacier
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise
IPCC	International Panel on Climate Change
IPCC AR	IPCC Assessment Report

IV	Ice Velocity
LEGOS	Laboratoire d’Etudes en Géophysique et Océanographie Spatiales
LWS	Land Water Storage
MAR	Modèle Atmosphérique Régional
MDT	Mean Dynamic Topography
MOG2D	Modèle d'Onde de Gravité à 2 Dimensions
MSS	Mean Sea Surface
NOAA	National Oceanic and Atmospheric Administration
NorCMP	Norwegian Climate Model Prediction
NorESM	Norwegian Earth System Model
OGGM	Open Global Glacier Model
OMC	Ocean Mass Balance
ORAP-5	Ocean ReAnalysis Pilot 5
ORAS4	Ocean Reanalysis System 4
PSMSL	Permanent Service for Mean Sea Level
RACMO	Regional Atmospheric Climate Model
RCM	Regional atmospheric Climate Model
RGI	Randolph Glacier Inventory
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SL	Sea Level
SL CCI	CCI Seal Level Project
SLBC	Sea Level Budget Closure
SSL	Steric Sea Level
SSL4SLBC	Steric Sea Level for Sea Level Budget Closure
SST	Sea Surface Temperature
TWS	Total Water Storage
WGHM	WaterGAP Global Hydrology Model

1 Introduction

1.1 Purpose and Scope

This document reviews the state of the art of sea level budget closure investigations, the open scientific questions and the approaches to address them, as envisaged by the SLBC_cci project at the beginning of this project. The document results from the discussion of the entire SLBC_cci consortium in the course of the preparation of the project, from a review of developments during the last months and from the discussion at, and in the context of, the scientific kick-off meeting of the SLBC_cci project in March 2017.

1.2 Document Structure

Section 2 reviews the state of the art of sea level budget closure. Section 3 reviews the state of the art and the challenges related to the estimation of the individual sea level budget components and the approaches to address these challenges. Section 4 discusses overarching requirements related to sea level budget assessments. Section 5 draws the conclusions for the SLBC_cci project.

2 Current status of sea level budget closure

Sea level is one of the best indicators of climate change. In effect, sea level integrates changes of several components of the climate system in response to anthropogenic forcing as well as natural forcing factors related to natural sources and internal climate variability. The Earth is currently in a state of thermal imbalance because of anthropogenic greenhouse gas emissions. 93% of this heat excess is accumulated in the ocean, the remaining 7% being used to warm the atmosphere and continents, and melt sea and land ice (von Schuckmann et al., 2016). Global mean seal level (GMSL) rise is a direct consequence of this process. To our best knowledge, GMSL is been rising since the beginning of the 20th century at a mean rate of 1.7 ± 0.3 mm/yr, as recorded by in situ tide gauges (e.g., Church et al., 2013; Church and White, 2011). Since the early 1990s, sea level variations are routinely measured by high-precision satellite altimetry. Satellites indicate that in terms of the global mean, sea level is rising at a rate of 3.2 ± 0.4 mm/yr, i.e., twice as fast as during the previous decades, suggesting an acceleration of the phenomenon (e.g., Ablain et al., 2016). Present-day GMSL rise primarily reflects ocean warming (through thermal expansion of sea waters) and land ice melt, two processes resulting from anthropogenic global warming (Church et al., 2013). Anthropogenic changes in land water storage constitute an additional contribution (Cazenave et al., 2014, Dieng et al., 2015a) arguably modulated by effects of climate variability (Reager et al., 2016).

Precisely monitoring these climate variables is crucial to understand processes at work under current climate change and to validate the climate models used for future projections. In recent years, the Global Climate Observing System (GCOS) has defined a set of 50 Essential Climate Variables (ECVs) that should be monitored on the long term to improve our understanding of the changing climate. Among these ECVs, 26 are observable from space. Since 2010, ESA developed the Climate Change Initiative (CCI) programme in order to produce consistent and continuous space-based records for a first series of 13 ECVs. Sea level as well as glaciers and the two ice sheets are part of them. Figure 1 shows the global mean sea level record from the CCI-Sea Level project, over January 1993-December 2014. In Figure 2 the CCI global mean sea level over 2005-2014 as well as the steric and mass components based on Argo and GRACE are shown.

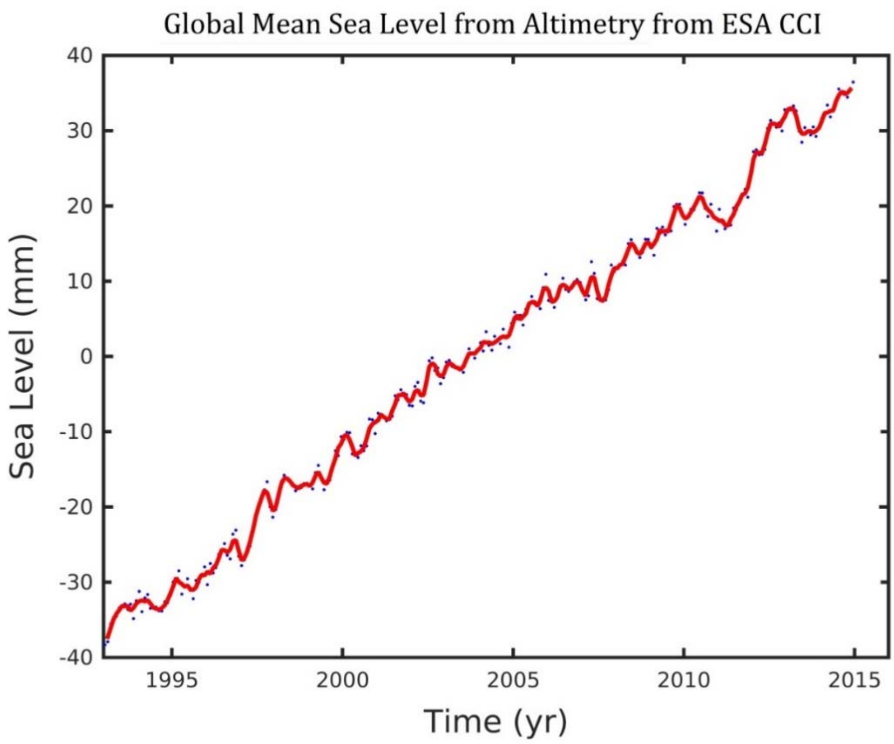

Figure 1: The CCI GMSL record (update from Ablain et al., 2016)

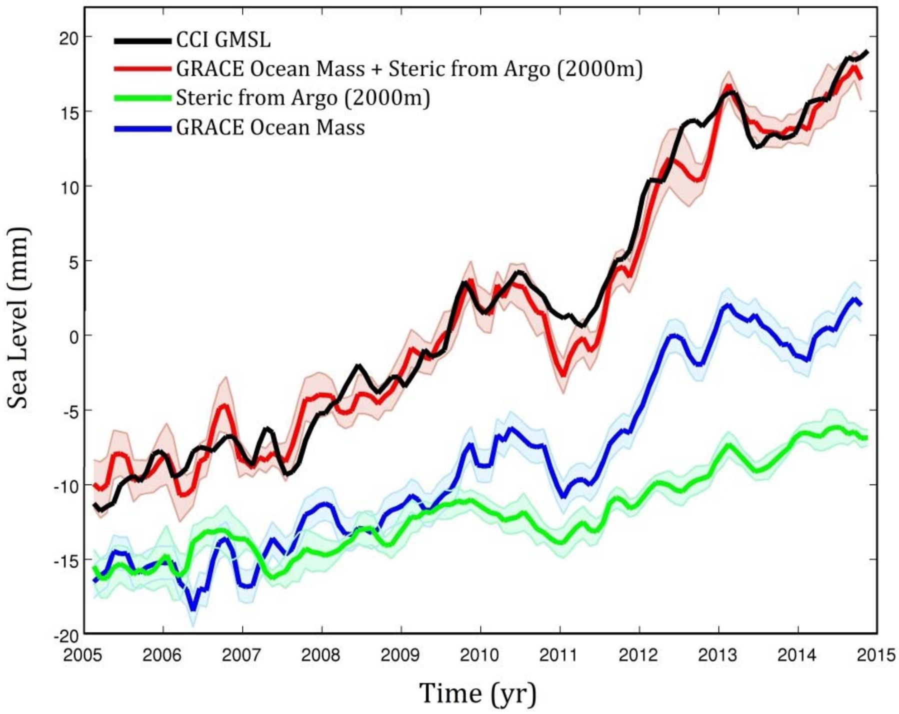

Figure 2: The CCI global mean sea level over January 2005-December 2014 and the steric and mass components. The steric/ocean mass components (green/blue curves) are based on averages of four Argo and three GRACE products respectively. The red curve is the sum of the steric and mass components. Updated from Dieng et al., 2015b.

For processes as complex as sea level change it is of utmost importance to regularly assess the accuracy and reliability of our knowledge about this process and its causes. Assessments of the sea level budget are an indispensable means for such assessments.

Closure of the sea level budget implies that we have:

$$\Delta SL(t) = \Delta M_{Ocean}(t) + \Delta SSL(t), \qquad (1)$$

where Δ means change of a given variable with time t; ΔSL(t) is time-variable sea level, ΔMOcean(t) and ΔSSL(t) are time variable ocean mass and steric sea level components (SSL(t) being the effect of the depth integrated change in sea water density due to ocean temperature and salinity variations).

Water mass conservation in the climate system implies closure of the ocean mass budget:

$$\Delta M_{Ocean}(t) = -[\Delta M_{Glaciers}(t) + \Delta M_{ice\ sheets}(t) + \Delta M_{LWS}(t) + \Delta M_{Atm}(t) + \text{missing mass terms}], \quad (2)$$

where the ΔM(t) terms in the right hand side refer to glacier and ice sheet mass balances, changes in land water storage (LWS, including seasonal snow cover), and atmospheric water vapor.

Over the course of its five assessments, the IPCC has reported a significant improvement in our understanding of the sources and impacts of global sea level rise. Today, the sea level budget is often considered closed, within measurement uncertainties (Church et al. 2013), and confidence in projections of future sea level rise has increased, thanks to improved physical understanding, considerably improved global input datasets, and to closer agreement between the models and observations required to perform complete assessments. However, significant challenges remain. For example, IPCC AR5 identified a 0.4 mm/yr difference between the observed GMSL rate and sum of contributions over the 1993-2010 time span (IPCC, 2013). Moreover, uncertainties of sea level rise on the one hand and the sum of components on the other hand, were very large, in the order of 0.8 mm/yr and 1.1 mm/yr, respectively. Recent assessments of various aspects of the sea level budget since the IPCC AR5 include the studies by Dieng et al. 2015b,c, Chambers et al. 2017, and Piecuch et al. 2016.

Such large differences have several causes. For example, the potential contribution to sea level due to mass losses from the polar ice sheets is least certain, because past changes have been too small to judge the performance of ice sheet models, and because physical processes with the potential to effect considerable ice losses – such as ice shelf collapse – are poorly understood. Another important contribution to sea level rise comes from glaciers. Glacier mass balance estimates come from in-situ measurements over a limited number (about 300) of glaciers with an often unknown representative-ness for the larger mountain range. However, the number of the world glaciers is estimated to be 200,000 (Pfeffer et al., 2014) and glaciers measured in the field are often much smaller. Hence, it is legitimate to further improve the current estimates of the glacier component (Huss and Hock, 2015). Another issue concerns the land water contribution due to human activities (e.g., ground water depletion and dam building), a factor very difficult to quantify due to lack of global data. A last example concerns the effects on sea level due to solid Earth deformations to changing ice loads (i.e., visco/elastic deformations of the solid Earth and associated self-gravitation due to Glacial Isostatic Adjustment – GIA – and present-day land ice melt) (e.g., Stammer et al., 2013, Chambers et al. 2010).

The atmospheric water vapor component has little impact on the trend of the sea level budget (order of magnitude of 0.05 mm/yr) over the last 2 decades but is important in terms or interannual variability of the GMSL. Because GMSL interannual variability is highly correlated with ocean mass changes during El Nino/La Nina events, mostly driven by land water storage changes and atmospheric water vapour content, it is important to take water vapour into account using atmospheric reanalyses data (e.g., ERA Interim) (cf. Dieng et al., 2015b).

The climate data records developed within the ESA CCI programme present a timely and unique opportunity to investigate in a coherent way the closure of the sea level budget (accounting for the ocean thermal expansion component), thus allowing us to assess the quality of these variables, and constrain remaining unknown or poorly known components (e.g., deep ocean heat uptake, land water storage changes due to human activities, snow and permafrost melting, etc.; e.g., Dieng et al., 2015a,b,c).

3 Requirements for improved assessments of individual components

3.1 Sea Level

For this work package, CCI Sea Level (SL_cci) project products form the main base of data. These products benefit from a quality control that includes internal validation, consistency check and comparison with in-situ data (see Ablain et al., 2016). An additional scientific quality assessment by internal validation is intended within this project. Based on comparisons with good quality tide gauge records (covering the entire interval January 1993-December 2015) at sites with collocated GPS/GNSS receivers for correcting vertical crustal motions an internal validation of the sea level data will be provided.

Although the project is mainly devoted to using CCI products, we cannot avoid comparing the CCI data to other GMSL products (from AVISO, NOAA, Univ. Colorado, GSFC and CSIRO). In effect, based on our previous studies, we noticed that the GMSL products fall into two categories (with significant differences in terms of short-term trends): CCI, AVISO, NOAA and CSIRO on one hand, and Univ. Colorado and GSFC, on the other hand (see Figure 3). The GMSL assessment task will include identification and reduction of the main sources of difference coming either from the instrumental and geophysical corrections applied to the satellite altimetry data, or from gridding methods (e.g., Masters et al., 2012; Henry et al., 2014, Ablain et al., 2015, Dieng et al., 2015a,b).

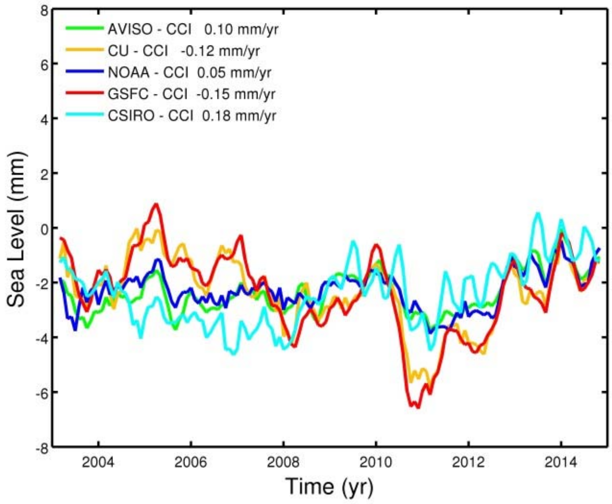

Figure 3: Global mean sea level differences for 5 satellite altimetry-based products and the CCI sea level data over 2003-2014 (data versions from February 2016) (Source: LEGOS).

Furthermore, an international comparison exercise will be set up involving the 5 groups processing altimetry data, following a well-defined protocol, to identify the main sources of discrepancies between the different GMSL products. This inter-comparison shall also confirm that the corrections and methodologies developed in the course of the CCI SL project are superior.

3.2 Steric component

The sum of steric thickness changes integrated from (nominally) the ocean floor to the sea surface estimates the steric contribution to sea level (sea surface height) change (relative to the baseline). For conciseness, such estimates will hereafter be referred to as "steric changes".

CCI SST will produce monthly steric change data on a horizontal grid resolution that projects conveniently onto the monthly altimetry products of sea level from SL CCI (0.25 degrees latitude-longitude, monthly). The real feature resolution of sub-surface steric change information is estimated to be 5^o by 5^o, a resolution that is compatible with the feature resolution of gravity-based mass change estimates, and therefore a sound basis grid for regional-to-global budget closure assessment. A number of products have been generated for steric change at 1^o by 1^o, although scientifically it must be recognized that such a grid is completed primarily by interpolation of real observations. For the integrated sea level assessment compared to altimetry and other products on a finer grid, a version of the data nominally at 1° by 1° can be obtained, if required, by interpolating the 5° by 5° product from SSL4SLBC_CCI in a way that preserves the volume effect implied by the 5° by 5° grid. The steric change products from SSL4SLBC_CCI will be built on standard, publicly available data sets: initially sourcing data from Coriolis and EN4 (Good et al., 2013) including Argo profiles. Similar techniques to existing products (von Schuckmann and Le Traon, 2011) will be used for steric change estimation. Two aspects of added value will be exploitation of CCI data on sea surface temperature (SST) as a means of adding improved spatial co-variance information to the knowledge of the upper ocean mixed layer; this may be capable of introducing some real feature resolution for steric change at 1° by 1° for those (limited) spatio-temporal domains where vertical covariance is high over a sterically significant depth: this will be assessed as part of the project and may support a 1° by 1° version of the product that has a somewhat improved feature resolution compared to 5° by 5°. The time intervals focussed on will be (1) the "golden" era (2005 to present, with both GRACE and significant Argo deployments), and (2) the "altimetry" era (1993 to present), matching the total period of the sea level CCI products.

Within WP210, additional steric products (including ocean reanalyses, e.g., ORAS4, ORAP-5) already available at LEGOS will be compared to the steric products from SSL4SLBC_cci, and all steric products will be evaluated as a preparation for the sea level budget assessments.

3.3 Ocean Mass component

GRACE inferences of ocean mass change may either build on time series of Level-2 global spherical-harmonic solutions of the Earth's gravity field or on mascon solutions that a few processing centers generate directly from the Level-1 GRACE observation data.

Most analyses based on spherical harmonic solutions have used the 'direct' (or 'regional integration') approach (Swenson and Wahr, 2002, Horwath and Dietrich, 2009). Basically, GRACE gravity field variations are converted into variations of surface mass density (mass per area, or height of an equivalent water layer). The total mass change over an area (e.g. the global ocean) is then derived by spatial integration with an appropriate weight function or by an equivalent linear functional in the spherical harmonic domain. The challenge consists in the vanishing sensitivity of GRACE to small spatial scales. This requires smoothing of the GRACE-based mass changes (or, as a matter of perspective, smoothing of the integration kernel) to a spatial resolution as coarse as 300-500km. This causes leakage effects: Mass changes in coastal regions cannot be uniquely assigned to either the land side or the ocean side. Since hydrological (or glaciological) changes on the land side tend to have larger amplitudes than oceanic mass changes on the ocean side, a buffer zone of a few hundred kilometers is typically masked out from the ocean integration kernel. Methodological choices related to the integration kernel, as well as to the used release of GRACE Level-2 gravity field solutions and to the filtering of these solutions for noise suppression all contribute to uncertainties and to some divergence between different GRACE-based OMC results.

Other challenges include: the insensitivity of GRACE to surface mass displacements of spherical harmonic degree one (hemispherical patterns) (Swenson et al. 2008); the reduced accuracy of GRACE-based changes of C_20 (the Earth's flattening term) (Cheng and Ries 2017); and the separation of mass displacements in the Earth interior due to glacial isostatic adjustment (GIA) (Shepherd et al. 2012; Ivins et al. 2013; Martín-Español et al. 2016).

For the analysis of spherical harmonic solutions, an alternative to the 'direct' approach consists in the 'inverse', or 'forward modeling' approach (e.g., Rietbroek et al., 2012, Chen et al., 2013, Horwath and Dietrich 2009, Kusche et al. 2016). This approach prescribes a set of patterns of mass change and estimates scaling factors to these patterns in a least-squares adjustment to GRACE results. Even if OMC is the target parameter, the patterns usually prescribe continental water or ice mass changes, completed by the 'fingerprints' of passive (gravitationally consistent) oceanic reaction. The 'inverse' approach may incorporate co-estimation of degree-one mass redistributions (or even GIA). It may be favorable for suppressing GRACE solution noise. However, the prescribed set of patterns is generally incomplete, and it is challenging to assess how this incompleteness biases the results. Conceptually, the effect of this incompleteness is analogous to leakage known for the direct approach (Horwath and Dietrich, 2009).

The available Level-1-based mascon solutions (Luthcke et al. 2013, Watkins et al. 2015, Save et al. 2016) follow a similar approach as the 'inverse' or 'forward modeling' approach discussed above, with the difference of using the original Level-1 data instead of the Level-2 spherical harmonic solutions. The SLBC_cci project will consider available mascon solutions of this type. The generation of these mascon solutions by the processing centers implies methodological choices as discussed above, which cannot be controlled or altered by the users of these solutions. In particular, mascon solutions also need to solve the problem of assigning mass changes to either the land side or the ocean side of coastlines. For this purpose, some mascon solutions (CSR, GSFC) assign every mascon to either ocean or land. (This is the approach that will be also followed by the spherical-harmonic-based solutions developed within SLBC_cci – see next paragraph.) The JPL mascon solutions start with coarse 3° x 3° equal-area mascons and subsequently implement a so-called coastline resolution improvement filter. The SLBC_cci D2.1.2 Product Description Document shows comparisons between mascon solutions and illustrates the significance of the mentioned methodological choices.

In the frame of the ESA Antarctic and Greenland CCI projects (and the earlier ESA STSE Antarctic Peninsula Mass Balance project) TU Dresden has developed a framework that unifies the 'direct' and 'inverse' approaches of analyzing spherical harmonic solutions (Groh and Horwath 2016, Horwath and Groh 2016). So far, the focus was put on the ice sheets. However, assessing mass changes of land ice (and continental hydrology) and assessing changes in ocean masses are just two different perspectives on water mass exchanges between continents and oceans.

Within the project, the WP 220 will further elaborate algorithms to estimate mass changes of ocean water, land water and ice, having complete control on the methodological choices of this analysis. While the focus is on changes in ocean mass, our approach will consistently co-estimate the sources of ocean mass change on land, namely changes in continental ice and water masses.

3.4 Glaciers contribution

Meltwater from glaciers is currently contributing about one third to GMSL and is thus a key component of sea level rise (Vaughan et al., 2013). The main problem in accurately estimating their contribution is related to their large number (200 000) of which only a few hundred are annually measured in terms of their mass changes (Zemp et al., 2015). Moreover, the representativeness of those measured glaciers for the mass changes of the surrounding larger mountain region is only known for a few regions, is probably variable in time, and simple extrapolation schemes fail due to the diverse nature of glaciers. Figure 4 demonstrates this complexity for the glaciers around Bara Shiri Glacier in the Indian Himalaya.

Current best estimates of their global mass change are thus based on a combination of field and remote sensing based observations (e.g. Gardner et al., 2013). As these are temporally restricted to the measurement period of the satellites and their sampling is spatially incomplete as well, numerical models help to bridge gaps of the spatio-temporal coverage by extending the time periods back and forward in time (Marzeion et al., 2012, Radić et al., 2014, Huss and Hock 2015). Only one of these models (Open Global Glacier Model (OGGM), Marzeion et al., 2012) is able to extend time-series backwards in time while also considering glacier geometry change. All models require three key datasets as an input to determine global glacier mass changes: (a) a globally complete dataset of glacier outlines from a known point in time, (b) a digital elevation model (DEM) to derive their area-elevation distribution, and (c) global meteorological datasets covering the intended modelling period. Moreover, independent calibration and validation datasets are required to achieve a good quality and to quantify systematic and random errors. The error estimate for glaciers will be based on out-of-sample cross validation of the model, using either multi-temporal glacier outlines, or observed mass changes (both geodetic and glaciological), depending on availability.

The validation of all glacier models currently under development (e.g., considering more processes, optimizing code, etc.) indicate that their limiting factor lies in the

Figure 4: The highly debris-covered Bara Shiri Glacier (upper centre) in the Indian Himalaya with its numerous tributaries and the - often also debris-covered - surrounding glaciers demonstrates the diversity of their appearance and challenges to model them. The impact of debris on ablation is not yet included in global-scale glacier evolution models. Black outlines are taken from the RGI 5.0 and were compiled within the framework of the ESA project GlobGlacier (Frey et al., 2012).

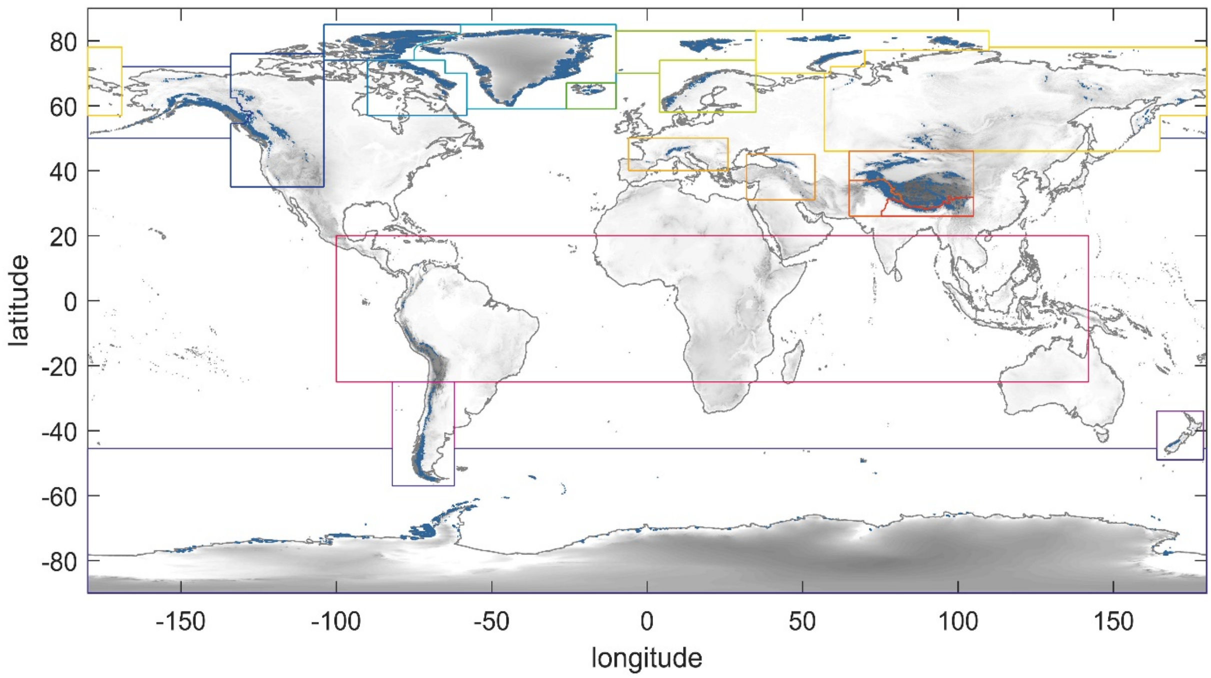

Figure 5: Global distribution of glaciers (blue areas) according to the RGI (Pfeffer et al., 2014). Colored boxes indicate the extent of the 19 RGI regions.

initial and boundary conditions. Major future improvements can thus be expected to be related to dataset (a), the quality of the glacier outlines in the global inventory. The only currently available global dataset of glacier outlines is the Randolph Glacier Inventory (RGI) shown in Figure 5, which has been compiled by an ad-hoc community effort for IPCC AR5 (Pfeffer et al., 2014). It still contains regional shortcomings in quality (e.g. seasonal snow mapped as glaciers), while constantly being improved by the community as well as the Glaciers_cci project.

Within the SLBC_cci project, the glacier WP will thus focus on two key components to further improve upon current best estimates of their sea level contribution: (i) improvements of the model used to determine a global value, mostly based on re-calibration using additional observational data, and (ii) improvements of the quality and consistency (in a temporal sense) of the glacier inventory used for initialization.

3.5 Ice Sheets contribution

The melting of the Greenland and Antarctica ice sheets presents the greatest threat for future global sea level rise. However, the total meltdown of the ice sheets would take millennia. Of more urgent concern is current decade-scale mass loss, with an equivalent GMSL rise of 0.59 +/- 0.20 mm/yr over the period 1992 to 2011 (Shepherd

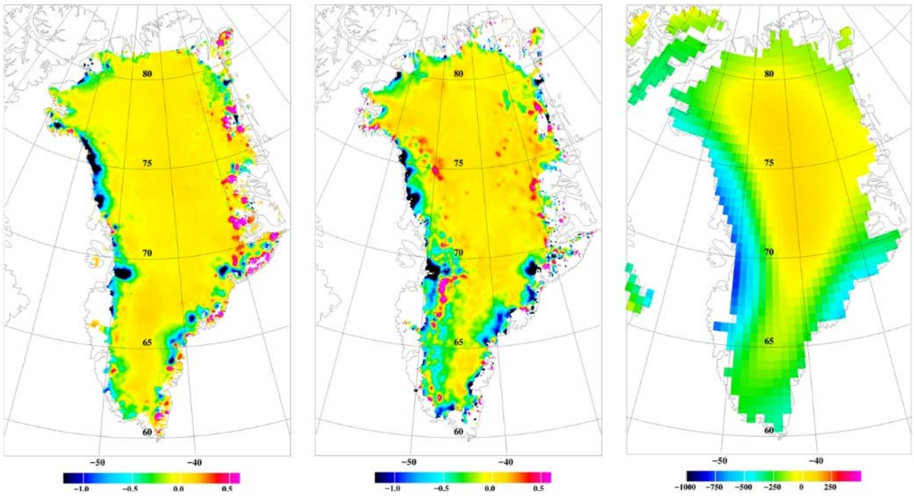

Figure 6: Elevation changes of the Greenland ice sheet from Envisat 2002–2010 (left), CryoSat 2010–2015(centre), and GRACE 2010–2015 (right). Units: m/year for height changes, and mm/year water equivalent for GRACE (from Forsberg et al., 2017)

et al., 2012). Both the Greenland and Antarctic Ice Sheets are losing ice mass at accelerating rates (e.g. McMillan et al., 2014; Rignot et al., 2011) in response to atmospheric (van den Broeke et al., 2009) and oceanic forcing (Joughin et al., 2012). While Greenland is currently losing mass at three times the rate of the Antarctic Ice sheet (Shepherd et al., 2012), its losses are primarily meteorological in origin (van den Broeke et al., 2009). Conversely, the principal Antarctic ice sheet mass losses are oceanographic in origin (Shepherd et al., 2004), even though they modulated by variations in snowfall (Lenaerts et al., 2013, Horwath et al., 2012).

To monitor the ice sheet changes satellite data from satellite altimetry, gravimetry (GRACE), and ice flow velocities from SAR interferometry/feature tracking are key space observations to understand the acceleration in ice sheet melt (Figure 6). The Antarctic and Greenland CCI projects are making full use of archived and future EO datasets for generating the four main ECV products of surface elevation change (SEC) (McMillan et al., 2014), ice velocity (IV) (Nagler et al., 2015), grounding line location (GLL) (Hogg et al., 2016), and gravimetry mass balance (GMB) (Horwath et al., 2012), with a primary focus on datasets acquired by ESA missions.

Satellite altimetry elevation changes, together with GRACE estimates, provide the most reliable estimation of overall current mass loss of the ice sheets. The EO datasets used to generate the EC Antarctic and Greenland Ice Sheet cci product (cf. Figure 7) dates back to the early 1990's, providing the longest continuous 26 year long record of ice

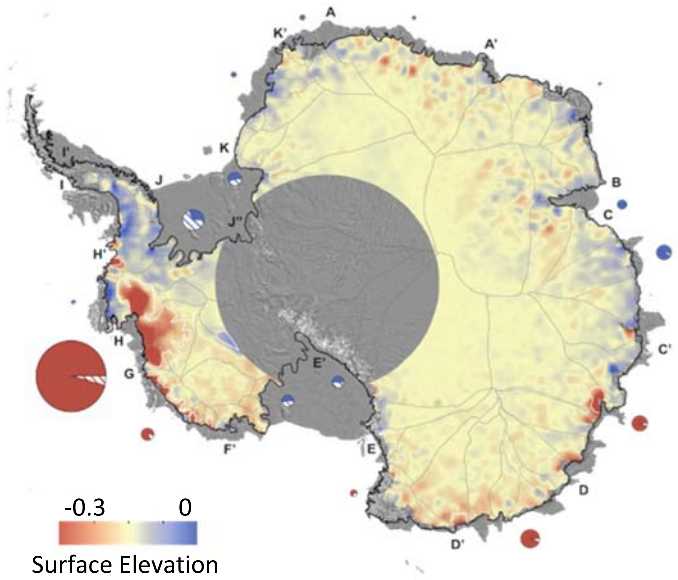

Figure 7: Surface elevation change for Antarctica generated from a long time series of Radar altimetry data (CPOM).

sheet changes (Shepherd et al., 2012). While the Antarctic and Greenland Ice Sheet CCI projects provide GRACE-based mass balance products (ranging from 2002 to present), they do not exploit, so far, the satellite altimetry products for an estimation of ice *mass* changes. An additional challenge to be addressed is the conversion of ice elevation height (or volume) changes to mass changes. This requires the incorporation of additional information, or additional assumptions, on the question to what extent the observed SEC is related to changes in the firn structure and to what extent the SEC is related to changes in the ice column (McMillan et al., 2016). By exploitation of these satellite data, mass variations starting from 1993 will be studied in this project.

The Greenland and the Antarctic Ice sheet will be addressed by two different partners (DTU Geodynamics and Univ. of Leeds), who will make choices for the volume-to-mass conversion method accounting for the different meteorological conditions and the different evidences in the literature. The methodological choices that will be considered for the volume-to-mass conversion range from applying, in different ways, firn densification models (driven by atmospheric climate models, such as HIRHAM and RACMO (Noël et al., 2015), MAR for Greenland) to applying density masks based on robust assumptions on the dominance of firn processes or ice flow dynamic processes as causes for SEC (Shepherd et al., 2002).

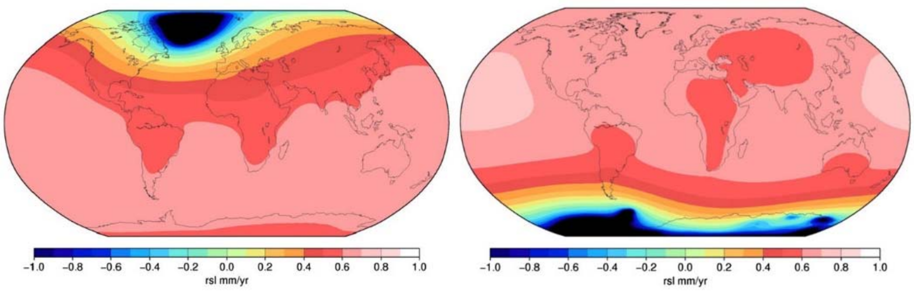

Figure 8: Relative sea level rise (sea level fingerprint) due to Greenland melt (left) and Antarctica melt (right) for IceSat period 2003–2008, unit mm/year. The sea level fingerprint accounts for the solid Earth load deformation and the gravitationally consistent ocean mass redistribution.Figures courtesy of V. Barletta (DTU Space) produced as part of EU Ice2Sea project, taken from Forsberg et al., 2017.

In SEC-based time series of mass changes hence derived will be combined in an additional effort with the GRACE-based mass change time series. In this way, reconciled mass change time series for the two ice sheets and their large drainage basins will be derived.

It is also important to note that ice sheet mass fluctuations cause non uniform variations in sea-level due to their changing gravitational attraction (Tamisiea et al., 2003). A consequence of this effect is that mass losses from ice sheets lead to local sea level falls and sea level rises in the opposite hemisphere. Consequently, changes in the Antarctic ice sheet are of greater importance for Northern hemisphere sea level rise, providing a strong impetus for European nations to study Antarctica. As a third task, the current mass change signal will be “fingerprinted” on a global scale, solving the global sea level equation with regional input from the ice sheet melt (Figure 8). In this way, the consequent global redistribution in ocean level coming from the redistribution of ice mass and GIA will be calculated.

3.6 Land Water contribution

Variations of total water mass on the continents can be conceptualized as water storage variations in the compartments canopy, soil, snow, glaciers, groundwater, surface water bodies (distinguishing rivers, wetlands, lakes and man-made reservoirs). Mass variations in these compartments are mainly driven by climate, human water abstractions and reservoir construction. Multi-decadal trends of continental water mass are dominated by decreases due to glacier mass loss and groundwater depletion and by increases due to the construction of new reservoirs. Interannual variations are mainly driven by climate variations (IPCC, 2013, Döll et al., 2014, Dieng et al., 2015a).

In its standard version, the global hydrological model WaterGAP 2.2 computes water storage variations in all these compartments except glaciers and simulates monthly time series of total water storage (TWS) variations with a spatial resolution of 0.5° x 0.5° for all continent areas of the globe except Greenland and Antarctica (Müller Schmied et al., 2014). Model outputs strongly depend on climate data and assumptions about irrigation water use. In a non-standard version, daily output time series of the global glacier model HYOGA2 (glacier area, glacier mass, glacier runoff; Hirabayashi et al., 2013, 2010) have been integrated into WaterGAP 2.2 to better simulate river discharge downstream of glaciers. WaterGAP simulates groundwater abstraction and surface water abstractions separately and can thus compute the impact of human water use on groundwater and surface water storage, including groundwater depletion (Döll et al., 2014).

Within the current project the model version WaterGAP 2.2b shall be further developed and improved for these effects:

- *reservoir construction on continental water storage*

  An algorithm for simulating the effect of reservoir construction and reservoir filling will be developed and included into WaterGAP for the approximately 1000 largest reservoirs. For product evaluation, observations of reservoir filling for selected reservoirs need to be found and analyzed, and river discharge as computed by WaterGAP with and without simulating reservoir construction will be compared to observed river discharge downstream of reservoirs.

- *groundwater depletion*

  The impact of different climate data sets and parameters for the computation of groundwater recharge will be analyzed, and the resulting groundwater depletion will be compared to the validation data of Döll et al. (2014) to improve the model and to determine whether the conclusion of Döll et al. (2014), that in groundwater depletion areas farmers irrigate at approx. 70% of the optimal rate, is still valid with the most recent WaterGAP 2.2 version and the state-of-the-art-climate data sets.

- *glacier mass variations*

  Glacier mass variations have to be assessed by comparing HYOGA2 output to OGGM output (Marzeion et al., 2012) with respect to glacier mass and area as well as to observed glacier mass balances at interannual and multi-decadal time scales.

In a second step, daily output of the glacier model HYOGA 2 is integrated into WaterGAP 2.2b. Annual glacier mass changes derived from the OGGM will be used alternatively in WaterGAP by scaling daily HYOGA2 glacier mass changes and runoff such that annual glacier mass changes of the OGGM are implemented.

Running the updated WaterGAP 2.2b model with various global climate data sets and possibly various plausible water use estimates, an ensemble of equally plausible TWS variations for the time period since 1992 will be computed. Based on this, the ensemble mean and uncertainty range of continental mass variations will be determined. This will be the first time that an ensemble approach is used for studying TWS variations.

Finally, best estimates of continental water mass variations including uncertainty ranges from 2003 onward will be derived by synthesizing the modeled TWS ensemble with GRACE-based TWS estimates. The synthesis will also be used to adjust model-based estimates for the time period 1992-2002.

3.7 Arctic Ocean sea level budget components

During recent decades, the Arctic region has warmed at a rate about twice the rest of the globe (Rhein et al., 2013). This primarily results from human-induced climate change, with strong amplification of anthropogenic warming in this region. Previous studies of high latitude and Arctic Ocean sea level changes have mostly focused on the use of tide gauge data along the Russian and Norwegian coastlines (Proshutinsky et al., 2011a,b, Henry et al., 2012), as the presence of sea ice has limited the use of altimetry. However, recently Cheng et al., (2015) developed a dedicated reprocessed along-track ERS-1/2 and Envisat altimetry data with coverage up to 82°N. A major improvement in data coverage was thus obtained. In the meantime a new sea level product over the Arctic Ocean has been obtained from a joint effort between CLS (Collecte Localisation Satellites) and PML (Plymouth Laboratory, UK) (Valladeau et al., 2015). Over the frozen ocean surfaces, areas with open water such as leads and polynias have been identified. In these areas, a specific waveform retracking and post-processing have been developed to optimize and improve the sea-level estimation. These new altimetry data sets now allow an investigation of the Arctic sea level budget over the period 2003 to present since the steric sea level can be estimated using ocean reanalyses (there are almost no Argo measurements in the Arctic) and the mass component can be derived from GRACE.

In general, the ocean circulation in the high latitude seas and the Arctic Ocean is characterized by four regional circulation regimes and their cross-regional exchanges and volume transports, namely the Northeast Atlantic including the Sub-Polar Gyre, the Labrador Sea and Canadian archipelago, the Nordic and Barents Seas and the Arctic Ocean (Johannessen et al., 2014). At scales of about 100 km and more the connection between these mean circulation regimes and the mean sea surface (MSS) height is determined by the mean dynamic topography (MDT) referenced to a geoid (G) (e.g. MDT = MSS - G). Under the assumption that the geoid is time invariant the changes in the sea level will thus be balanced by a change in the MDT. As such, the mean sea surface changes will also impact the large-scale ocean circulation and hence the heat and freshwater transports.

The work will focus on the assessment of inter-annual to decadal sea level variability for the high latitude seas and Arctic Ocean north of 66°N both for the time period 2003 to 2014 (GRACE compliant) and the altimetric period 1993 to 2014. If possible, the seasonal cycles are also assessed. In doing so the main contributing components and their uncertainties to the sea level variations, notably from mass changes, changes in atmospheric pressure, changes in steric height and tides and effect of polar gaps will be examined.

Due to the limited availability of observation data (limited performance of altimetry over sea-ice covered ocean, limited drifter data), observations will be combined with modeling results to provide the individual sea level budget components.

Overall, the work will build on the following input data:

- The ESA Sea Level CCI products
- The NorESM fields
- The Norwegian Climate Model Prediction (NorCMP) reanalyses fields
- ocean mass variations in WP220, contributions from the glaciers in WP230, the ice sheets in WP240, and the land water in WP250
- Regional/global models from DTU (DTU15MSS, DTU15MDT, DTU10BAT)
- Sea level pressure from MOG2d; Hadley Center; Univ Washington
- Arctic Ocean in situ data (i.e. bottom pressure data, tide gauge data (PSMSL), possible Year of Polar Prediction Campaign data).

4 Overarching requirements for budget closure assessments

The core task of budget closure assessments is to assess to what extent the budget Equation 1 for the Sea level budget and Equation 2 for the ocean mass budget (cf. Section 2) are fulfilled by the considered datasets on individual budget components.

The assessment will address the global mean values of the individual components as well as the regional variability in sea level and sea surface temperature, and investigate the relative contributions of the natural/internal climate variability and anthropogenic forcing (detection/attribution) to associated spatial trend patterns. The Arctic Ocean is chosen as the study region for this regional analysis.

Integrative context

Sea level budget closure assessments should be carried out in an integrated context. This implies to bring together expertise from a large range of disciplines. It further implies to establish a coordinated, iterative working scheme consisting of (1) the provision and further development of datasets on individual budget components, (2) the assessment of the budget closure, and (3) feedback to the improved development of budget component estimates and to improved methods of budget closure assessment.

Consistent framework

The assessments have to be done in a consistent framework in many aspects:

The definition of data products, their spatial coverage, spatial resolution, temporal coverage and temporal resolution, as well as related data formats need to be well-defined and consistent. In this context, CCI presents a unique basis, because the programme provides a common, rigorous scientific framework and can support frequently updated assessments.

In view of the availability of observation-based datasets, the study time span should cover the precise altimetry era (starting in 1993). A special focus should be given to the period 2003/2005 to present, coinciding with the availability of GRACE space gravimetry data (informing on changes in ocean mass, glaciers, ice sheets and land water storage components), and Argo data (providing the steric component for the 0-2000m ocean depth, with almost complete 3-D coverage of the oceans).

The establishment of a common framework should include discussion and agreement about the way how long-term trends are derived from time series.

Even more crucially, the common framework should include a clear communication and a best-possible consistency in the way how uncertainties of datasets are defined, and determined. This is challenging because different disciplines have different approaches and different possibilities in this context (in particular observation-oriented approaches versus modeling-oriented approaches). The Guide to the Expression of Uncertainty in Measurement (GUM) by the Joint Committee for Guides in Metrology (JCGM, 2008) provides an established reference, at least for the measurement-based datasets.

Further matters of exchange and feedback within the consortium

The consistency of geophysical corrections applied to different datasets needs to be investigated and sought for. In particular this concerns the correction for GIA in the GRACE-based ocean mass change products, in the altimetry-based sea level products and in the ice sheet contribution products. In this context the conclusions from the GIA-related discussion within the IMBIE-2 project should be taken into account.

The correction for effects of atmospheric pressure variations is another example where consistency between altimetry products on sea level and GRACE products on ocean mass change needs to be considered.

The consistency of, or differences between, climate models used in the generation of the individual budget components need to be discussed. Generally, due to specific requirements of the individual approaches, a diversity of used climate models will need to be retained. This implies the need for a clear documentation of climate models used in the individual assessments.

River runoff, as modelled by WGHM may be incorporated into the analysis of the Arctic Ocean sea level budget. Likewise, possibly available Earth Observation related to river runoff may be used to support hydrological modeling.

Mass changes of peripheral glaciers in Greenland and Antarctica must not be double-counted with their contribution to ocean mass change. They need to be included either in the ice sheet contribution part or in the glacier contribution part. However, prior assessments of peripheral glacier mass balance by both WP230 and WP240 may aid the evaluation of respective mass balance results.

5 Summary of science requirements and conclusions for SLBC_cci

In summary, estimates of the individual sea level budget components have to be improved beyond the state of the art, tackling the major challenges specific to the individual components and specified in Section 3. Based on the recent estimates of the individual components, the closure of the sea level budget and the ocean mass budget has to be assessed in an integrative context and under a common framework.

Specifically, the SLBC_cci project will concentrate on datasets obtained by the ESA CCI programme or generated by using ESA CCI products. In addition, datasets from other sources will be considered for comparison. In this way, SLBC_cci will also assess the quality of the CCI products involved in the sea level budget and evaluate the ongoing evolution of the quality of products.

As a primary CCI objective was to reduce current uncertainties of sea level change and its individual components, better closure of the sea level budget should be possible based on the CCI products. This will improve our understanding of processes involved in causing global mean sea level rise and its regional variability. This will further help to improve models used for projections of future climate changes.

Studying the sea level budget with accurate climate records promises major scientific benefits – adding confidence to satellite-based assessments of climate change, shedding light on missing or poorly known processes such as land hydrology that remain a challenge for Earth Observation, or heat uptake by the deep ocean and its role in the current 'hiatus' (von Schuckmann et al., 2016). This will allow the key processes affecting sea level rise to be precisely quantified, leading to more informed model projections. Together with extreme events like storm surges and tropical cyclones, regional/local sea level changes represent a major threat in low-lying, highly populated coastal regions of the world, each of which affects coastal planning (Cazenave and Le Cozannet, 2014). The project is therefore a timely opportunity to add societal value and visibility to the CCI, allowing it to form the backbone of a milestone contribution to climate science.

6 References

Ablain M., Cazenave A., et al. (2015): Improved sea level record over the satellite altimetry era (1993-2010) from the Climate Change Initiative Project, *Ocean Sciences*,11, 2029-2071, doi:10.5194/osd-11-2029-2014.

Ablain M., Legeais J.F., Prandi P., Fenoglio-Marc L., Marcos M., Benveniste J., and Cazenave A. (2016): Altimetry-based sea level, global and regional, in review, *Surveys in Geophysics*.

Cazenave A. and Le Cozannet G. (2014): Sea level rise and coastal impacts, *Earth's Future*, vol2, issue2, 15-34, doi :10.1002/2013EF000188.

Cazenave A., Dieng H., Meyssignac B., von Schuckmann K., Decharme B. and Berthier E. (2014): The rate of sea level rise, *Nature Climate Change*, vol 4, 358-361, doi:10.1038/NCLIMATE2159.

Chambers, D.P., Cazenave, A., Champollion D., Dieng, H., Llovel, W., Forsberg, R. von Schuckmann, K., Wada, Y. (2017): Evaluation of the Global Mean Sea Level Budgetbetween 1993 and 2014. *Surv Geophys* (2017) 38:309–327, DOI 10.1007/s10712-016-9381-3.

Chambers D., Wahr J., Tamisiea M., and Nerem, R. (2010): Ocean mass from GRACE and glacial isostatic adjustment. *Journal of Geophysical Research: Solid Earth* (1978–2012), 115(B11).

Chen J. L., Wilson C. R., and Tapley B. D. (2013): Contribution of ice sheet and mountain glacier melt to recent sea level rise. *Nature Geoscience*, 6(7), 549-552.

Cheng Y., Andersen O. B. and Knudsen P. (2015): An improved 20-Year Arctic Ocean Altimetric Sea Level Data Record, *Mar Geod*, 38:2, 146-162, doi:10.1080/01490419.2014.954087.

Cheng, M., and Ries, J. (2017). The unexpected signal in GRACE estimates of C_{20}. *Journal of Geodesy*, 1-18.

Church, J. A., and N.J. White (2011): Sea-level rise from the late 19th to the early 21st Century, *Surveys in Geophysics* 32(4-5), 585-602, doi:10.1007/s10712-011-9119-1.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan (2013): Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dieng H. B., Cazenave A., von Schuckmann K., Ablain M., and Meyssignac B. (2015c): Sea level budget over 2005-2013: missing contributions and data errors. *Ocean Science*, 11(5), 789.

Dieng H., Champollion N., Cazenave A., Wada Y., Schrama E., and Meyssignac B (2015a): Total land water storage change over 2003-2013 estimated from a global mass budget approach, *Environmental Research Letters*, 10, 124010, doi:10.1088/1748-9326/10/12/124010.

Dieng H., Palanisamy H., Cazenave A., Meyssignac B., and von Schuckmann K. (2015b): The sea level budget since 2003: inference on the deep ocean heat content, *Surveys in Geophysics*, 36, 1, doi:10.1007/s10712-015-9314-6.

Döll P., Müller Schmied H., Schuh C., Portmann F., and Eicker A. (2014): Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resour. Res.*, 50, 5698–5720, doi: 10.1002/2014WR015595.

Frey H., Paul F., and Strozzi T. (2012): Compilation of a glacier inventory for the western Himalayas from satellite data: Methods, challenges and results. *Remote Sensing of Environment*, 124, 832-843.

Forsberg, R., Sørensen, L., and Simonsen, S. (2017): Greenland and Antarctica Ice Sheet Mass Changes and Effects on Global Sea Level. *Surv Geophys* 38: 89. doi:10.1007/s10712-016-9398-7.

Gardner A.S., Moholdt G., Cogley J.G., Wouters B., Arendt A.A., Wahr J., Berthier E., Hock R., Pfeffer W.T., Kaser G., Ligtenberg S.R.M., Bolch T., Sharp M.J., Hagen J.O., van den Broecke M.R., and Paul F. (2013): A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, 340 (6134), 852-857.

Good S. A., Martin M. J., and Rayner N. A. (2013): EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates, *Journal of Geophysical Research: Oceans*, 118, 6704-6716, doi:10.1002/2013JC009067.

Groh A., and Horwath M. (2016): The method of tailored sensitivity kernels for GRACE mass change estimates. *Geophysical Research Abstracts*, 18, EGU2016-12065. Slides available under http://presentations.copernicus.org/EGU2016-12065_presentation.pdf.

Henry O., Ablain M., Meyssignac B., Cazenave A., Masters D., Nerem S., Leuliette E., and Garric G. (2014): Investigating and reducing differences between the satellite altimetry-based global mean sea level time series provided by different processing groups, *J. of Geodesy*, 88:351–361, doi: 10.1007/s00190-013-0687-3.

Henry O., Prandi P., Llovel W., Cazenave A., Jevrejeva S., Stammer D. , Meyssignac B., and Koldunov N. (2012): Tide gauge-based sea level variations since 1950 along the Norwegian and Russian coasts of the Arctic Ocean: Contribution of the steric and mass components. *J. Geophys. Res.* 117 (C6), doi:10.1029/2011JC007706.

Hirabayashi Y., Döll P., and Kana, S. (2010): Global-scale modelling of glacier mass balances for water resources assessments: Glacier mass changes between 1948 and 2006. *J. Hydrol.*, 390, 245-256.

Hirabayashi Y., Zang Y., Watanabe S., Koirala S., and Kanae S. (2013): Projection of glacier mass changes under a high-emission climate scenario using the global glacier model HYOGA2. *Hydrol. Res. Letters*, 7, 6-11. doi: 10.3178/HRL.7.6

Hogg, A. E., A. Shepherd, N. Gourmelen, M. Engdahl (2016): Grounding Line migration from 1991 to 2011 on Petermann Glacier, North West Greenland, *Journal of Glaciology*, 62, 236, 1104 – 1114, doi: 10.1017/jog.2016.83.

Horwath M., and Dietrich R. (2009): Signal and error in mass change inferences from GRACE: The case of Antarctica. *Geophys. J. Int.* 177(3): 849-864, doi: 10.1111/j.1365-246X.2009.04139.x.

Horwath, M., and Groh, A. (2016): The GRACE mass change estimators developed for ESA's CCI ice sheet mass balance products. Proc. GRACE Science Team Meeting 2016, Potsdam, 5-7 November 2016. http://www.gfz-potsdam.de/en/section/global-geomonitoring-and-gravity-field/topics/development-operation-and-analysis-of-gravity-field-satellite-missions/grace/gstm/gstm-2016/proceedings/.

Horwath M., Legrésy B., Rémy F., Blarel F., and Lemoine J. M. (2012): Consistent patterns of Antarctic ice sheet interannual variations from ENVISAT radar altimetry and GRACE satellite gravimetry. *Geophysical Journal International*, 189(2), 863-876.

Huss M. and Hock, R. (2015): A new model for global glacier change and sea-level rise. *Frontiers in Earth Science*, 3, 1-22. dx.doi.org/10.3389/feart.2015.00054.

IPCC (2013): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, doi: 10.1017/CBO9781107415324.

Ivins, E. R., James, T. S., Wahr, J., Schrama, O., Ernst, J., Landerer, F. W., and Simon, K. M. (2013): Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth*, 118(6), 3126-3141.

Johannessen, J.A., R. P. Raj, J. E. Ø. Nilsen, T. Pripp, P. Knudsen, F. Counillon, D. Stammer, L. Bertino, O. B. Andersen, N. Serra, N. Koldunov (2014): Toward Improved Estimation of the Dynamic Topography and Ocean Circulation in the High Latitude and Arctic Ocean: The Importance of GOCE. *Survey of Geophysics*, doi: 10.1007/s10712-013-9270-y.

Joughin, I., Alley, R. B., & Holland, D. M. (2012) : Ice-sheet response to oceanic forcing. *Science*, 338(6111), 1172-1176.

Kusche J., Uebbing B., Rietbroek R., Shum C. K., and Khan Z. H. (2016): Sea level budget in the Bay of Bengal (2002–2014) from GRACE and altimetry. *J. Geophys. Res. Oceans* 121(2), doi: 10.1002/2015JC011471.

Lenaerts, J., Meijgaard, E., Broeke, M. R., Ligtenberg, S. R., Horwath, M., & Isaksson, E. (2013). Recent snowfall anomalies in Dronning Maud Land, East Antarctica, in a historical and future climate perspective. Geophysical Research Letters, 40(11), 2684-2688.

Luthcke, S. B., Sabaka, T. J., Loomis, B. D., Arendt, A. A., McCarthy, J. J., & Camp, J. (2013). Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution. *J. Glac.*, 59(216), 613–631. doi:10.3189/2013JoG12J147.

Martín-Español, A., King, M. A., Zammit-Mangion, A., Andrews, S. B., Moore, P., and Bamber, J. L. (2016): An assessment of forward and inverse GIA solutions for Antarctica. *Journal of Geophysical Research: Solid Earth*, 121(9), 6947-6965.

Masters D., Nerem R. S., Choe C., Leuliette E., Beckley B., White N., and Ablain M. (2012): Comparison of global mean sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2, *Mar. Geod.*, 35, 20–41.

Marzeion B., Jarosch A. H., and Hofer M. (2012): Past and future sea-level change from the surface mass balance of glaciers, *The Cryosphere*, 6, 1295-1322.

McMillan, M., A. Leeson, A. Shepherd, K. Briggs, T. W. K. Armitage, A. Hogg, P. Kuipers Munneke, M. v. d. Broeke, B. Noel, W. J. v. d. Berg, S. Ligtenberg, M. Horwath, A. Groh, A. Muir, L. Gilbert (2016). A high-resolution record of Greenalnd Mass Balance, *Geophysical Research Letters*, 43, 7002–7010, doi:10.1002/2016GL069666.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., HOgg, A., and Wingham, D. (2014). Increased ice losses from Antarctica detected by CryoSat-2. *Geophys. Res. Lett.*, 41(11), 3899-3905.

Müller Schmied H., Eisner S., Franz D., Wattenbach M., Portmann F.T., Flörke M., and Döll P. (2014): Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrol. Earth Syst. Sci.*, 18, 3511-3538, doi: 10.5194/hess-18-3511-2014.

Nagler, T., H. Rott, M. Hetzenecker, J. Wuite, P. Potin (2015): The Sentinel-1 Mission: New Opprotunities for Ice Sheet Observations, *Journal of Remote Sensing*, 7, 9371 – 9389, doi:10.3390/rs70709371.

Noël, B., W. J. van de Berg, E. van Meijgaard, P. Kuipers Munneke, R. S. W. van de Wal, and M. R. van den Broeke (2015): Evaluation of the updated regional climate model RACMO2.3: Summer snowfall impact on the Greenland Ice Sheet, *Cryosphere*, 9(5), 1831–1844, doi:10.5194/tc-9-1831-2015.

Pfeffer W.T., Arendt A.A., Bliss A., Bolch T., Cogley J.G., Gardner A.S., Hagen J.-O., Hock R., Kaser G., Kienholz C., Miles E.S., Moholdt G., Mölg N., Paul F., Radić V., Rastner P., Raup B.H., Rich J., Sharp M.J., and the Randolph Consortium (2014): The Randolph Glacier Inventory: a globally complete inventory of glaciers. *Journal of Glaciology*, 60 (221), 537-552, dx.doi.org/10.3189/2014JoG13J176.

Piecuch, C. G., and Quinn, K. J. (2016): El Niño, La Niña, and the global sea level budget. *Ocean Science*, 12(6), 1165.

Proshutinsky, A., Y. Aksenov, J. Clement Kinney, R. Gerdes, E. Golubeva, D. Holland, G. Holloway, A. Jahn, M. Johnson, E. Popova, M. Steele, and E. Watanabe (2011a): Recent advances in Arctic ocean studies employing models from the Arctic Ocean Model Intercomparison Project. *Oceanography* 24(3):102–113, http://dx.doi.org/10.5670/oceanog.2011.61.

Proshutinsky, A., Timmermans M. L., Ashik I., Beszcynska-Moeller A., Carmack E., Eert J., Frolov I., Itoh M., Kikuchi T., Krishfield R., McLaughlin F., Rabe B., Schauer U., Shimada K., Sokolov V., Steele M., Toole J., Williams W., Woodgate R., Zimmermann S. (2011b) : The Arctic Ocean, *Bull. Am. Meteorol. Soc.*, 92(6), supplement, S145–S148.

Radić V., Bliss A., Beedlow A. C., Hock R., Miles E., and Cogley J. G. (2014). Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics*, 42(1-2), 37-58.

Reager J. T., Gardner A. S., Famiglietti J. S., Wiese D. N., Eicker,A., and Lo M. H. (2016): A decade of sea level rise slowed by climate-driven hydrology. *Science*, 351(6274), 699-703.

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang (2013): Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 255–316, doi:10.1017/CBO9781107415324.010.

Rietbroek R., Brunnabend S.E., Kusche J., and Schröter J. (2012): Resolving sea level contributions by identifying fingerprints in time-variable gravity and altimetry. *J. Geodyn.* 59-60:72-81.

Rignot, E., Velicogna, I., Van den Broeke, M. R., Monaghan, A., & Lenaerts, J. T. M. (2011): Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, 38(5).

Save, H., Bettadpur, S., and Tapley, B. D. (2016): High resolution CSR GRACE RL05 mascons. *J. Geophys. Res. Solid Earth*, doi:10.1002/2016JB013007.

Shepherd, A., Ivins, E. R., A, Geruo, Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sandberg Sorensen, L., Scambos, T. A., Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V., van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., Zwally, H. J. (2012): A Reconciled Estimate of Ice-Sheet Mass Balance. *Science*, 338(6111):1183-1189, doi: 10.1126/science.1228102.

Shepherd, A., D. Wingham, J. A. D. Mansley (2002): Inland thinning of the Amundsen Sea sector, West Antarctica, *Geophys. Res. Lett.*, 29, (10), 1364, 10.1029/2001GL014183.

Shepherd, A., Wingham, D., and Rignot, E. (2004). Warm ocean is eroding West Antarctic ice sheet. *Geophysical Research Letters*, 31(23).

Stammer D., Cazenave A., Ponte R., and Tamisiea M. (2013): Contemporary regional sea level changes, *Annual Review Marine Sciences*, 5, 21–46.

Swenson, S., Chambers, D., and Wahr, J. (2008): Estimating geocenter variations from a combination of GRACE and ocean model output. *Journal of Geophysical Research: Solid Earth*, 113(B8).

Swenson S., and Wahr, J. (2002): Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research: Solid Earth*, 107(B9).

Tamisiea, M. E., Mitrovica, J. X., Davis, J. L., & Milne, G. A. (2003): Long wavelength sea level and solid surface perturbations driven by polar ice mass variations: fingerprinting Greenland and Antarctic ice sheet flux. In *Earth Gravity Field from Space—From Sensors to Earth Sciences* (pp. 81-93). Springer Netherlands.

Valladeau G., Thibaut P., Picard B., Poisson J.C., Tran N., Picot N. and Guillot A., (2015): Using SARAL/AltiKa to improve Ka-band altimeter measurements for coastal zones, hydrology and ice: the PEACHI prototype. *Marine Geodesy*, 38 (S1): 124-142, doi:10.1080/01490419.2015.1020176.

van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., and Wouters, B. (2009): Partitioning recent Greenland mass loss. *Science*, 326(5955), 984-986.

Vaughan D.G., Comiso J. C., Allison I., Carrasco J., Kaser G., Kwok R., Mote P., Murray T., Paul F., Ren J., Rignot E., Solomina O., Steffen K., and Zhang T. (2013): Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the IPCC. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317-382.

von Schuckmann, K. and Le Traon, P.-Y.(2011): How well can we derive Global Ocean Indicators from Argo data?, *Ocean Sci.*, 7, 783-791, doi:10.5194/os-7-783-2011, 2011.

von Schuckmann K., Palmer M.D., Trenberth K.E., Cazenave A., Chambers D., Champollion N., et al. (2016): Earth's energy imbalance: an imperative for monitoring, *Nature Climate Change*, 26, 138-144.

Watkins M. M., Wiese D. N., Yuan D. - N., Boening C., and Landerer F. W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons: Improved Gravity Observations from GRACE. *J. Geophys. Res. Solid Earth*, 120(4), 2648–2671.

Zemp M., et al. (2015): Historically unprecedented global glacier changes in the early 21st century. *Journal of Glaciology*, 61 (228),745-762.