ESA Climate Change Initiative (CCI)

Sea Level Budget Closure (SLBC_cci)

Science Requirements Updated and Preliminary Thoughts on Roadmap

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Prime & Science Lead: Martin Horwath

Technische Universität Dresden (TUDr)

Martin.Horwath@tu-dresden.de

Technical Officer: Jérôme Benveniste

ESA ESRIN, Frascati, Italy

Jerome.Benveniste@esa.int

Consortium: Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS)

Universität Bremen (UB)

Universität Zürich (UZH)

University of Leeds (UoL)

Goethe-Universität Frankfurt (GUF)

Danmarks Tekniske Universitet, DTU Space, Geodynamics (DTU-GDK)

Danmarks Tekniske Universitet, DTU Space, Geodesy (DTU-GEK)

Nansen Environmental and Remote Sensing Center (NERSC)

University of Reading (UoR)

Mercator Ocean, Toulouse (MerO)

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Signatures page

Prepared by	Kristin Novotny Project Manager, TUDr Martin Horwath Science Leader, TUDr Anny Cazenave, Hindumathi Palanisamy, LEGOS; Ben Marzeion, UB; Frank Paul, Raymond Le Bris, UZH; Petra Döll, Denise Cáceres, GUF; Anna Hogg, Andrew Shepherd, UOL; Rene Forsberg, Louise Sandberg Sørensen, DTU-GDK; Ole B. Andersen, Heidi Ranndal, DTU-GEK; Johnny Johannessen, Jan Even O. Nilsen, NERSC; Benjamin D. Gutknecht, TUDr; Christopher John Merchant, Claire Rachel MacIntosh, UoR; Karina von Schuckmann, MerO	Date: 2020-06-15 Martin Horwath
Checked by	Martin Horwath Science Leader, TUDr	Date: 2020-06-15 Martin Horwath
Approved by	Jérôme Benveniste Technical Officer, ESA	Date:

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Distribution List

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ESA	Jérôme Benveniste Marco Restano Américo Ambrózio

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Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
BISICLES	Berkeley Ice Sheet Initiative for Climate Extremes
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative (initiated by ESA)
CMUG	Climate Modelling User Group
CNES	Centre National d'Etudes Spatiales
CLS	Collecte, Localisation, Satellites
CSR	Center for Space Research (University of Texas at Austin)
DAC	Dynamic Atmospheric Correction
DEM	Digital Elevation Model
DTU	Danmarks Tekniske Universitet
DTU10BAT	DTU Global Bathymetry 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
ENSO	El Niño Southern Oscillation
EO	Earth Observation
ERA	Earth system ReAnalysis
ESA	European Space Agency
GAA, GAB, GAC, GAD, GSM	Names of data products related to GRACE atmospheric and oceanic background models (refer to section 3.5)
GIA	Glacial Isostatic Adjustment
GMSL	Global Mean Sea Level
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-On
GrIS	Greenland Ice Sheet
GSFC	Goddard Space Flight Center
GT	Gigatons
HYCOM	Hybrid Coordinate Ocean Model
IB	inverse barometric effect
ICE-5G, ICE-6G	models of postglacial relative sea-level history
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise
ISO	International Organization for Standardization
ITSG	Institute of Geodesy, Theoretical Geodesy and Satellite Geodesy (TU Graz)
JPL	Jet Propulsion Laboratory
LTR	Long-term rates of change

LWS	Land Water Storage
MDT	Mean Dynamic Topography
MOG2D	Modèle d'Onde de Gravité à 2 Dimensions
MSS	Mean Sea Surface
NASA	National Aeronautics and Space Administration
NERSC	Nansen Environmental and Remote Sensing Center
OMC	Ocean Mass Change
PCR-GLOBWB	PCRaster GLOBal Water Balance (large-scale hydrological model)
PSMSL	Permanent Service for Mean Sea Level
RMS	Root Mean Square
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SL	Sea Level
SL_cci	ESA CCI_Sea Level Project
SLB	Sea Level Budget
SLBC	Sea Level Budget Closure
SLR	Sea Level Rise
SSL	Steric Sea Level
SST	Sea Surface Temperature
SWOT	Surface Water Ocean Topography
TOPAZ	(Towards) an Operational Prediction system for the North Atlantic European coastal Zones
TOPEX	TOPography EXperiment, part of the TOPEX/Poseidon satellite(joint radar altimetry project, NASA and CNES)
TWSA	Total Water Storage Anomaly
TWS	Total Water Storage
WCRP	World Climate Research Programme
WP	Work Package

1 Introduction

1.1 Purpose and Scope

The Science Requirements Document D1.1 released in August 2017 reviewed 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 its beginning. After reaching the mid-term of the project course, this document gives an update of these science requirements. Numerous discussions about the data and first results within the project led to more specifically open scientific questions and the approaches to address them.

Moreover, first thoughts on a roadmap beyond this project are presented. The roadmap part is kept intentionally short, because the development of a more elaborated roadmap is under way in parallel to preparing this document.

Relevant documents:

SLBC_cci Science Requirements Document D1.1:

> 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.

SLBC_cci Sea Level Budget Closure Assessment Report based on v0 data, D3.1:

> Novotny, K.; Horwath, M.; Cazenave, A.; Palanisamy, H.; Marzeion, B.; Paul, F.; Döll, P.; Cáceres, D.; Hogg, A.; Shepherd, A.; Forsberg, R.; Sørensen, L.; Barletta, V.R.; Andersen, O.B.; Ranndal, H.; Johannessen, J.; Nilsen, J.E.; Gutknecht, B.D.; Merchant, Ch.J.; MacIntosh, C.R., von Schuckmann, K.: *ESA Climate Change Initiative (CCI) Sea Level Budget Closure (SLBC_cci) Sea Level Budget Closure Assessment Report D3.1*. Version 1.0, 25 January 2018

1.2 Document Structure

Section 2 provides an update on the state of sea level budget studies from the literature and from the WCRP sea level budget assessment and summarizes conclusions from the SLBC_cci v0 budget assessment.

Section 3, as the central part of the document, discusses concepts and requirements for budget closure assessment.

Section 4 provides updates on requirements for the assessment of the individual budget components.

Section 5 provides preliminary thoughts on a science roadmap. This section is intentionally brief because the development of a more elaborated roadmap is under way in parallel to the preparation of this document.

2 Update on state of sea level budget closure

2.1 Literature review update

In a recent article, Nerem et al., 2018 account for the internal climate variability (ENSO) and the Pinatubo eruption cooling effect on sea level and components. The impact of decadal variability is to partly mask the climate change driven acceleration. The authors also confirm that accounting for the TOPEX A instrumental drift leads to a global mean sea level curve that shows clear acceleration over the altimetry era (as in Chen et al., 2017 and Dieng et al., 2017). Nerem et al., 2018 estimate the altimetry sea level acceleration of 0.084 mm/yr^2, a value in good agreement with the acceleration deduced from individual components (0.074 mm/yr^2).

This article is interesting in the framework of the ESA SLBC_cci project as it can help in inter-comparisons of the results obtained. The important point to focus on would be the thermosteric contribution to sea level rise as the article has used a specific thermosteric data based on Cheng et al., 2017 that provides a higher estimate of thermosteric contribution to sea level when compared to other steric data sets that have so far been used in this ESA SLBC_cci project.

Chambers et al. (2017) review the GMSL budget over two periods, 1993-2014 and 2005-2014, by using multiple data sets of both total GMSL and the components (mass and steric). They compare both linear trends as well as the level of agreement of the time series. Budget closure is found in terms of the long-term trend but not for year-to-year variations, consistent with other studies. This is due to the lack of sufficient estimates of the amount of natural water mass cycling between the oceans and hydrosphere long-term trend and for month-to-month variations.

Looking at the GrIS, Simonsen and Sørensen (2017) presented an inter-comparison of the Cryosat-2 derived elevation changes with those derived from Operation IceBridge laser data. The study concludes on which waveform parameters should be applied to best correct for changes in volume scattering when using Cryosat-2 ESA L2 data. Using this approach to correct for the scattering properties, a volume loss of −292±38 km^3 yr^{-1} (equivalent to 0.74±0.10 mm yr^{-1} GMSLl equivalent if the density of ice is assumed) is found for the GrIS for the time span November 2010 until November 2014.

Forsberg et al. (2017) analyze 13 years of GRACE data to assess GRACE-derived mass changes for the ice sheets. They find a mass loss during the period 2002–2015 amounting to 265±25 Gt/year for Greenland (including peripheral ice caps), and 95±50 Gt/year for Antarctica, corresponding to 0.72±07 mm/year and 0.26±0.14 mm/year average global sea level change.

High-resolution estimates of Greenland SEC and mass balance were produced by McMillan et al. (2016) using CryoSat-2 radar altimetry data. In this study, the contribution of GrIS to GMSL is estimated to be of 0.74 ± 0.14 mm/yr between 2011 and 2014 showing that GrIS is losing mass at an accelerated rate compared to the previous decade.

Concerning the continental water storage, Scanlon et al. (2018) compare GRACE-derived (two mascon solutions and one spherical harmonics solution) total water storage anomaly (TWSA) trends to TWSA trends of two global hydrological models (WaterGAP and PCR-GLOBWB) and five land surface models in 186 glacier-free river basins between 2002 and 2014. One conclusion is that large decreasing and increasing decadal TWSA trends derived from GRACE are underestimated by all models, which might be caused by insufficient model storage capacity. Moreover, decadal TWSA trends, summed over all basins, are positive for GRACE but negative for models, contributing opposing trends to global mean sea level change.

2.2 International assessment of the global mean sea level budget in the context of the World Climate Research Programme

Several previous studies have addressed the sea level budget over different time spans and using different data sets (e.g., Chambers et al., 2017, Dieng et al., 2017, Chen et al., 2017, Nerem et al., 2018 for the most recent ones). Assessments of the published literature have also been performed in past Intergovernmental Panel on Climate Change reports (e.g., Church et al., 2013).

Recently, in the context of the Grand Challenge entitled "Regional Sea Level and Coastal Impacts" of the World Climate Research Programme (WCRP), an international effort involving the sea level community worldwide has been carried out with the objective of assessing the various data sets used to estimate components of the sea level budget during the altimetry era (1993 to present) (WCRP Sea Level Budget Group, 2018). Here we briefly summarize the main findings of this global mean sea level budget assessment.

Almost all available quality data sets have been used for each component. This resulted in a large number of considered data sets (11 for thermal expansion, 5 for glaciers, 8 for the Greenland ice sheet and 11 for Antarctica). For each component, an ensemble mean has been considered for the budget. Comparing components individually shows that ocean thermal expansion remains the dominant contribution to the GMSL trend over the altimetry era. The mean thermal expansion trend is estimated to 1.3 +/- 0.4 mm/yr over 1993-2015 and 2005-2015. The 0-700 m ocean depth layer contributed by 70% over 1993-2015 and 65% over 2005-2015 (Argo era), indicating that more heat has reached the 700-2000m depth layers. Most recent updated estimates for the glaciers, Greenland and Antarctica mass balances lead to trend contributions of 0.65 +/- 0.10 mm/yr, 0.48 +/- 0.10 m/yr and 0.25 +/- 0.10 mm/yr over 1993-2005 and 0.74 +/- 0.10 mm/yr, 0.76 +/- 0.10 mm/yr and 0.42 +/- 0.10 mm/yr for 2005-2015. For the latter period, Greenland and Antarctica mass balances are essentially based on GRACE. The Greenland ice sheet contribution is larger than the other two, with a significant increase in ice mass loss in the recent years. Overall, the total land ice contribution (sum of glaciers, Greenland and Antarctica) dominates the ocean thermal expansion over the two considered time periods. The terrestrial water component that results from water storage changes on land in response to natural climate variability and direct human intervention (dam building on rivers, groundwater extraction, deforestation, land use, wetland drying, etc.) remains so far the most uncertain contribution to the GMSL. Direct observations of the net land water storage exist since 2002 through the use of GRACE. Most recent GRACE-based estimates (Reager et al., 2016, Scanlon et al., 2018) provide a negative contribution to sea level, in the order of -0.3 mm/yr. On the other hand, estimates from hydrological models tend to give slightly positive contribution. Clearly more work is needed to precisely quantify the land water component and its contribution to the GMSL.

2.3 Conclusions from v0 budget assessment

The process of doing and discussing the v0 budget assessment was extremely important because it has driven the SLBC consortium towards

- better understanding and fulfilling the requirements on dataset consistency
- further development of approaches for budget closure assessment.

This process of exercising and discussing the budget assessment needs to go on in the course of the preparation of the v1 product generation and v1 budget assessment.

Most aspects of the conclusions drawn so far are elaborated in Sections 3 and 4. Here we summarize important aspects.

The budget assessment should, in a first instance, aim at understanding the misclosure, rather than seeking the choice of data products that brings us closest to budget closure. Such a choice might just mask errors.

The v0 budget assessment was done basically on the comparison of trends estimated from the different time series. Interannual variability highly influences trend estimation. Therefore trend values can be compared only for identical periods of time. Moreover, trends from different calculation methods are different. This fact requires good documentation of calculation methods. Simulations with model datasets and cross-checking the time series analysis by two or more groups might be helpful.

As an example on the sensitivity to underlying time intervals, we note that Dieng et al. (2017) estimated the contribution of GrIS and AIS to GMSL between 1993 and 2015 to be of 0.61 ± 0.05 mm/yr and 0.30 ± 0.06 mm/yr respectively while the IMBIE1 project estimated the contribution of both ice sheets to be of 0.59 ± 0.20 mm/yr between 1992 and 2011 (Shepherd et al., 2012). The difference between the two studies can be explained by the fact that Dieng et al. (2017) are extending their study by four additional years and it has been shown that the ice sheets are losing mass at accelerated rates during these additional years compared to the period covered by the IMBIE1 project (e.g. Velicogna et al. 2014). Furthermore, the IMBIE1 project estimate is a reconciled estimate of different techniques (altimetry, gravimetry and input-output method) while Dieng et al. (2017) are using the CCI ice sheet product, which is derived from satellite gravimetry only. The different techniques and time periods used could help explain the discrepancies between these two estimates.

As more fundamental caveat we note that trends calculated from regressions on time series are primarily a means of signal extraction. Their interpretation and their uncertainties depend on the actual existence and separability of physically meaningful long-term signals. A budget assessment, in contrast, can be done, on the basis of time series, that is, based on the actual change of a magnitude within a given time period. Such a time series approach avoids interpretation problems inherent to trends. In return, the time series approach might be less robust against data problems like outliers and data gaps.

In future assessments, the time series approach should be followed. More details are given in Section 3 and in the Appendix.

Concerning the Arctic Ocean budget assessment, the v0 data products have very different coverage in the Arctic. This leaves a full and consistent Arctic budget assessment to the next version. Also, with the existing methodological limitations, it makes no sense to assess uncertainties in this version of the datasets. The apparent discrepancies can be due to several methodological issues, such as lacking inclusion for the areas without data coverage, to issues related to generation of the data sets involved. See for instance the uncovered polar region or the large spread in the ocean mass trends.

3 Concepts and requirements for budget closure assessment

3.1 Concepts for quantifying sea level changes and its individual components at different temporal scales

3.1.1 Concepts of time series

The budget closure assessment is based on time series of changes of sea level and its individual contributions. These time series, together with quantified uncertainties, are provided by the different project partners and by external authors. It is important to specify the content of the time series and their uncertainties as well as the assumptions underlying the time series analysis conducted for the budget assessment.

We consider time series of state parameters, such as sea level, glacier mass, etc., in the form

$$z(t). \qquad (1)$$

Note, that *z(t)* usually does not refer to a single point in space and a single point in time. It rather means the mean value over a time interval (e.g., one calendar month) and an area (e.g., one grid cell, or the global ocean). Somewhat sloppily we identify the time interval (e.g. a month) with a single time *t* where *t* is the interval midpoint.

An alternative way of thinking about temporal changes is by the rates of change

$$\frac{\Delta z}{\Delta t}(t) \qquad (2)$$

In practice the time series is again given in a discrete manner. That is, *t* refers to a time interval with length Δt (e.g. a month or a year) and $\Delta z/\Delta t$ refers to the change of the state parameter *z* during that interval, divided by Δt. Cumulation of $(\Delta z/d\Delta)(t)$ gives *z(t)*:

$$z(t) = \sum_{\tau=t_0}^{t} \frac{\Delta z}{\Delta t}(\tau)\, \Delta t, \qquad (3)$$

where the summation is over the discrete time steps from t_o to *t*.

More precisely speaking, *z(t)* in (1) and (3) does not denote the state parameter (sea level, glacier mass etc.) in an absolute sense. It denotes the *difference* between the state at time *t* and a reference state Z_o. For example, for ice sheet mass contributions, *z(t)* is the difference between the ice sheet mass at time *t* and a reference ice sheet mass Z_o. The reference state Z_o needs to be well defined but it does not need to be quantified explicitly. (Its quantification may be in fact very uncertain.) Typical choices of Z_o include the state at a specific time (e.g. the start of the time series) or the mean state over the time interval covered by the time series. The choice affects plots of *z(t)* by a simple shift along the ordinate axis. However, the choice of the reference state has a more complicated impact on uncertainties of *z(t)* if errors are correlated in time. This fact may cause inconsistencies and misinterpretation of the graphical

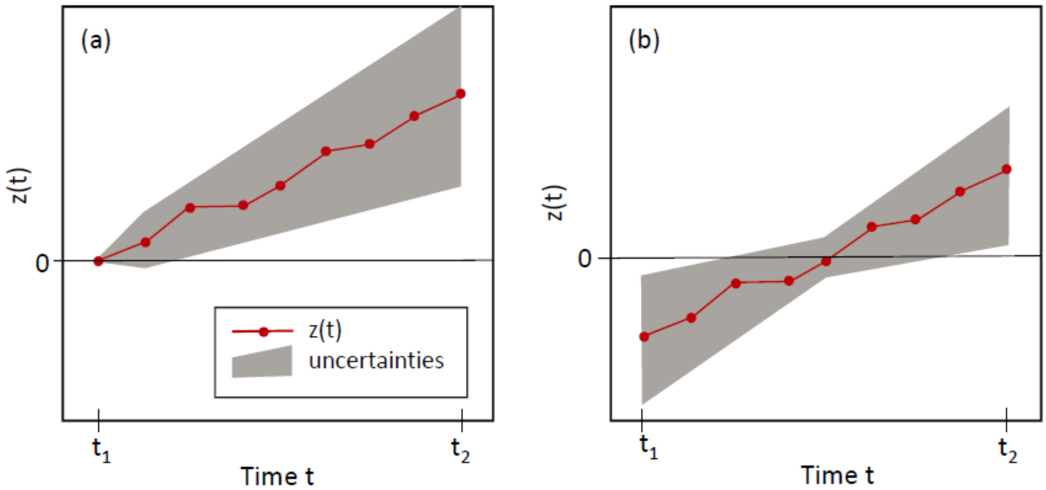

Figure 1: Schematic illustration of the impact of the reference state Z_0 on uncertainties of *z(t)*. The red curves in (a) and (b) are identical except for a vertical shift. They refer to a reference state Z_0 which is (a) the state at time t_1 and (b) the mean state over the interval $[t_1,t_2]$. The uncertainties (grey shading) include an uncertainty in the temporally linear component – hence the wedge-shaped error bounds. They differ due to the different choices of reference state.

representation of uncertainties when time series are compared that refer to different reference states. Figure 1 illustrates the case.

Glaciological modeling and hydrological modeling have $\Delta z/\Delta t$ as their primary product, from which *z(t)* is derived as a secondary product. In contrast, for satellite altimetry and satellite gravimetry *z(t)* is usually considered as their primary product and temporal changes arise as derived products.

3.1.2 Concepts of temporal components

The literature offers a diversity of approaches to analyse time series with the aim of separating components of different temporal characteristics, in particular for determining long-term rates of change and possible temporal variations of rates of change. Visser et al. (2015) provide an illuminating review in the sea level research context. Chen et al. 2017 use a method that extracts time-variable long-term rates of sea level rise that vary monotonically or have one extremum. Didova et al. (2016) propose a sophisticated approach for time-variable rates of change based on state space models and their solution by Kalman filtering. Nerem et al. (2018) add a remarkable contribution on the significance of sea level change acceleration.

Here we discuss the commonly made distinction of seasonal, interannual and long-term signal components, with the aim to converge with a methodology that can be adopted by the SLBC_cci consortium.

Seasonal

By seasonal component we mean the component of z(t) that is periodic with a one-year period. Seasonal signal is not a priority for the global sea level budget assessments within SLBC_cci. It cannot be reliably resolved based on observations for some of the individual component datasets, such as the steric component and the glacier component. However, the consideration of seasonal signal may be of interest to understand the other temporal components and their mis-closure.

Two approaches are common to determine the seasonal signal. The stacking approach basically consists of calculating the average of all January values, the average of all February values, etc. The sequence of the resulting 12 values gives the seasonal signal in a monthly resolution. The harmonic regression approach uses a truncated harmonic decomposition of the periodic signal: The amplitudes of a sine and cosine function with one-year period are estimated in a least-squares adjustment. Harmonic functions with multiples of the once-per-year frequency are sometimes included to better approximate non-sinusoidal seasonal signals. The estimation is usually done in a context where other temporal components (such as a constant and a linear component) are co-estimated.

Interannual variations and long-term rates of change

We discuss interannual components and long-term components together because the discussions on their definition and their determination overlap.

There is no widely accepted precise definition of **interannual variations**. Taken literally, they are variations between the years. They make annual averages vary from year to year. In the frequency domain, interannual variations could be roughly defined as the part of the spectrum with wavelength longer than a year. Interannual variations are sometimes thought to exclude the long-term rates of change, but this is not always clear and depends on the very definition of long-term change.

As an example, Horwath et al. (2012) extract interannual variations from a time series by fitting and removing a linear signal and annual and semiannual sinusoids (which represent the "long-term" component and the seasonal component, respectively) and subsequently low-pass filtering the time series (Gaussian filter with a 2-sigma width = 0.5 yr, effecting a 50% amplitude damping at 1.33 yr wavelength). A low-pass filtering of such kind is useful both to obey the definition of "interannual" and to reduce noise in the observation data or, respectively, to account for its limited temporal resolution.

Concerning **long-term rates of change (LTR)** of $z(t)$ within a chosen multi-year interval $[t_1, t_2]$, two distinct approaches have been discussed within the SLBC_cci consortium.

The **Average Rate Approach** consists in estimating the long-term rate of change as

$$LTR_{average} = (z(t_2) - z(t_1)) / (t_2 - t_1). \qquad (6)$$

Note that a best estimate may involve averaging $z(t)$ in a neighbourhood of t_1 and t_2 rather than evaluating $z(t)$ at the single epochs t_1 and t_2. This may be motivated by dampening observation noise and by excluding high-frequency physical variability.

The **Regression Approach** consists in fitting a functional model to $z(t)$ and quantifying the long-term trend from the fitted model parameters. A common functional model consists of a constant, a temporally linear component, and annual harmonic components:

$$z(t) = a_1 + a_2 t + a_3 \cos(\omega_1 t) + a_4 \sin(\omega_1 t) + \varepsilon(t) \qquad (4)$$

with $\omega_1 = 2\pi$ year^{-1}. The parameters $a_1, \ldots, a_4$ are estimated by minimizing, in a least-squares sense, the residuals $\varepsilon(t)$. The parameter a_2 (the linear trend) is taken as the quantification of the long-term rate of change:

$$LTR_{regression} = a_2. \qquad (5)$$

Information on the variances and covariances of $\varepsilon(t)$ may be incorporated, which may induce, for example, unequal weighting of the observations $z(t)$.

It is interesting to express both approaches in terms $(\Delta z/\Delta t)(t)$. $LTR_{average}$ is simply the average of $(\Delta z/\Delta t)(t)$ over the interval $[t_1, t_2]$, where every $\Delta z/\Delta t$ has the same weight:

$$LTR_{average} = \frac{1}{(t_2 - t_1)} \sum_{\tau=t_1}^{t_2} \frac{\Delta z}{\Delta t}(\tau)\, \Delta t = \sum_{\tau=t_1}^{t_2} \frac{\Delta t}{(t_2 - t_1)} \frac{\Delta z}{\Delta t}(\tau)\, . \qquad (7)$$

$LTR_{regression}$ may be also expressed as a weighted mean of the discrete $\Delta z/\Delta t$,

$$LTR_{regression} = \sum_{\tau=t_1}^{t_2} w(\tau) \frac{\Delta z}{\Delta t}(\tau)\, , \qquad (8)$$

because the sequence of operations leading from $(\Delta z/\Delta t)(t)$ to $LTR_{regression}$ is a sequence of linear operations. However, now the weights $w(\tau)$ are not equal.

Figure 2 illustrates (by the blue and green straight lines) the two concepts. For a discussion on many more details on both approaches, the reader is referred to the Appendix.

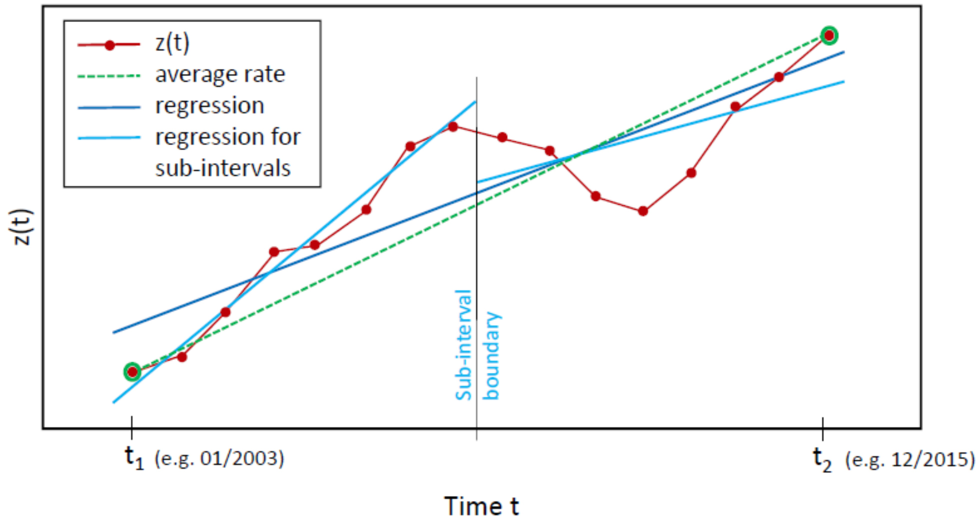

Figure 2: schematic illustration of concepts for long-term rates of change.

Discussion within the SLBC_cci consortium has converged on the understanding that the two approaches serve very different purposes. The Average Rate Approach considers the budget of *z(t)* within a given time interval without assumptions on the nature of the underlying signal. It directly builds on the time series. It does not strictly distinguish long-term changes from interannual changes. The average rate approach (or "time series approach") is preferable for budget assessments. In contrast, the Regression Approach is useful to extract a physically distinct long-term signal under the assumptions that such a signal exists and may be separated from other signals. The Regression Approach is therefore useful to infer and study the underlying physical processes, including, e.g. additional components such as an acceleration (cf. Nerem et al. 2018). At the same time, the interpretation of the related regression rates and their uncertainties rely heavily on the validity of the underlying assumptions. Therefore, while the Regression Approach is important to investigate the physical signal, it is not the preferred approach for budget assessments.

3.2 Concepts for quantifying uncertainties of sea level changes and its individual components at different temporal scales

We refer to the ISO (1995) “Guide to the expression of uncertainty in measurement”. Uncertainties of a measurement (including its corrections) should be quantified in terms of the second moments of a probability distribution that “characterizes the dispersion of the values that could reasonably be attributed to the measurand”. Specifically, the standard uncertainty (i.e. standard deviation) should be always specified.

This quantification of uncertainty is transferable: The uncertainty evaluated for one result can be used as a component in evaluating the uncertainty of another measurement in which the first result is used. The law of uncertainty propagation should be used. For example, in the simple case of a summation of results with uncorrelated errors, the combined standard uncertainty is the root sum square standard uncertainties of the individual components. Error covariances have to be accounted for if errors are correlated.

Following ISO (1995), the probabilistic approach to uncertainties and their quantification in terms of standard uncertainties is recommended irrespective of the question whether the numerical values are evaluated (a) by statistical methods based on the repetition of measurements or (b) by other means.

ISO (1995) further discusses the case (b) in its Appendix E4.4: “It has been argued that, whereas the uncertainties associated with the application of a particular method of measurement are statistical parameters characterizing random variables, there are instances of a “truly systematic effect” whose uncertainty must be treated differently. […] But if the possibility of such an offset is acknowledged to exist and its magnitude is believed to be possibly significant, then it can be described by a probability distribution, however simply constructed, based on the knowledge that led to the conclusion that it could exist and be significant.”

We propose that this ISO (1995) argument should be adopted also for such complicated corrections as the GIA correction. The *concept* of uncertainty quantification should obey to standard uncertainties and the Law of uncertainty propagation, irrespective of the imperfection in the *realisation* of this concept.

Uncertainties refer to the estimation of a well-defined measurand. The elementary measurand in the sea level budget assessment is the time-dependent state parameter $z(t)$ or the time-dependent rate of change $(\Delta z/\Delta t)(t)$. Ideally, standard uncertainty is quantified per epoch. Information on temporal correlations need to be included if applicable. Likewise, information on temporal correlations of monthly errors need to be applied when aggregating monthly values to annual values. The uncertainty of corrections that are linear in time, such as the GIA correction, is an example for such temporal correlations, which can just be stated as an uncertainty on the linear trend.

Discussion within the SLBC_cci consortium concerning the GIA correction relevant to several components of the sea level budget has lead to the conclusion that it is advisable to state GIA corrections and their uncertainties separately. In this way, the application of the GIA corrections to the time series and the combination of GIA uncertainties with other uncertainty components can be done at a late state of the analysis. This facilitates the study of correlations between the GIA correction errors of different components of the sea level budget.

3.3 Criteria for "budget closure"

Previous work has mostly focussed on the budget of trends derived by the regression approach (e.g. Dieng et al. 2017, Chambers et al. 2017). However, as stated in Section 3.1, the regression approach is not the favoured approach for budget assessments for SLBC_cci. Where it is used anyway (e.g. for the sake of comparison to previous work) the calculation of trends from regressions should be done centrally (within WP 300) or following a strictly identical methodology. Aspects of choosing the methodology trends from the regression approach include:

- unbiasedness, consistency, efficiency
- robustness to outliers
- sensitivity to calculation from monthly values versus calculation from annual values
- co-estimation seasonal signal and trend or sequential estimation (and reduction) of seasonal signal and trend
- inclusion of a quadratic "acceleration" component.

Budget closure assessment should concentrate on the budget of changes over time spans (Average Rate Approach) based on time series of the individual components. Closure of the budget means that the absolute value of the misclosure does not exceed the combined uncertainties of the components, accounting for error correlations in time and error correlations between the budget components.

Budget closure analysis will likely not be based on unsmoothed monthly-resolution time series (too noisy for GRACE, virtually impossible for steric), but on temporal resolution of 1 year or three months (see Section 3.4). Inspection of time series (to understand events etc.) may be on a higher temporal resolution than the budget assessment.

The analysis of the variability of misclosure time series and its comparison to the uncertainty envelope will help evaluating the uncertainty assessment and/or inferring information on missing components or misrepresented components. Notably, in the case of agreement of trends, large variability of misclosure time series relative to uncertainty, could be a sign that the trend agreement is just coincidental.

More details on the methods of budget closure analysis cannot be prescribed here, since they will depend on intermediate results and need to be further elaborated by WP3x2 and WP3x3. It is therefore crucial that the input individual component time series and uncertainty characterization are well-documented and consistently derived according to Section 3.1 and 3.2.

3.4 Update on requirements for consistent temporal and spatial coverage and resolution

The conclusion from Section 3.1 to 3.3 that budget assessments should be done primarily on a time series basis underlines the need for a consistent temporal resolution. As a compromise between the desirable and the possible, the following standards are defined:

- annual resolution (calendar years) for all time series
- 3-month averages (January-March, April-June, etc.) for most time series
- 1-month resolution (calendar months) where possible

De-seasoned time series should be included.

The time intervals to be covered by the time series are

- January 1993 - December 2015
- January 2003 - December 2015

Extensions beyond 2015 are useful where they are possible, but related efforts should not distract too many resources from developing the methodologies, which is the focus of the project.

3.5 Update on requirement for consistency between used data sets

GIA

GIA models have not been used consistently for corrections of the individual budget components in the v0 budget assessment. Notably, commonly used GRACE-based Antarctic ice mass changes use regional GIA models which are different from the global GIA models used for GRACE-based ocean mass change estimates. Moreover, correlations between GIA errors intrinsic to different budget components have not been investigated for v0. A more consistent and systematic treatment of GIA could be outlined in the v2 assessment, even though a really comprehensive investigation is beyond the framework of the current project. The extensive modeling study by Caron et al. (2018) can be a starting point for designing a more consistent treatment of the GIA correction.

Inverse barometric effect

The problem:

Atmospheric pressure variations displace ocean water, which is known as the inverse barometric (IB) effect. Sea level variations and ocean mass variations respectively, could be considered by including this effect or by correcting for this effect. How consistently is this effect treated in the different sea level budget components?

The IB effect does not change global ocean volume or global ocean mass, but only the volume and mass distribution, respectively, within the ocean. Therefore, for strictly global assessments of ocean volume change and ocean mass change, the question whether or not IB is corrected would not play a role.

However, it plays a role for regional assessments such as for the Arctic Ocean. Practically, it also plays a role for global assessments from altimetry if they are not truly global by omitting parts of the polar oceans.

Treatment for GRACE:

The releases of GRACE monthly gravity field solutions include, for every month (cf. Flechtner et al. 2015):

- GAA: modelled mean monthly atmospheric anomalies
- GAB: modelled mean monthly oceanic anomalies
- GSM: mean monthly anomalies other than GAA and GAB, as determined from GRACE.

Here, the term 'anomalies' refers to the gravity field effect of the difference between the mass distribution during the month in question and the mass distribution averaged over long-term interval. The ocean model used for GAB includes a dynamic correction for atmospheric pressure variations, while preserving global ocean volume.

In addition, the GRACE Science and Data System provides

- GAD: similar to the sum of GAA and GAB, with a domain restricted to the ocean. This product corresponds to the ocean bottom pressure effect of the modelled oceanic and atmospheric variations used in GAA and GAB.

GRACE analyses for regional ocean mass changes could, in principle, (a) include the IB effect, that is, attempt to represent the ocean mass changes as they really occur, or (b) correct for the IB effect, that is, attempt to represent ocean mass changes as they would occur if the IB effect would not take place. In case (a) we would have to consider the sum of GSM and GAA. In case (b) we would have to consider the sum of GSM and GAD minus the spatial average of GAD over the ocean domain. The latter subtraction reduces the effect of atmospheric mass variations over the ocean domain which would be otherwise interpreted as ocean mass variations. The approach (b) has been more common (cf. Johnson and Chambers 2013).

Treatment for ocean altimetry:

Ocean altimetry analyses commonly correct the IB effect by applying a Dynamic Atmospheric Correction (DAC). For the Arctic Ocean, the effect of the DAC on multi-year trends is significant. The v1 data product will apply the DAC.

Atmospheric water content

The reliability of the long-term trend of the ERA-15-based time series of changes in the atmospheric water content applied to parts of the v0 budget assessments is unclear. It needs to be clarified whether the inclusion of atmospheric water content time series should be referred to future studies and the atmospheric water component included in the uncertainty budget instead.

4 Update on requirements for improved assessment of individual components

4.1 Sea level

In the previous sea level budget closure assessments (v0) for the observed altimetry based sea level component, CCI Sea Level (SL_cci) product was used after having corrected the TOPEX A drift between 1993 and 1998 following Dieng et al. (2017). Instrumental aging of the TOPEX A altimeter impacted significant wave height estimates until TOPEX A was replaced by TOPEX B in early 1999. Dieng et al. (2017) followed a sea level budget approach and quantified the drift rate over 1993 and 1998 as 1.5 mm/yr. This value was therefore used to correct the CCI global mean sea level (GMSL) time series between 1993 and 1998.

In the future SLBC_cci sea level budget assessments, we will also be considering two new GMSL time series, one from CLS and the other based on Beckley et al. (2017) that have adopted different methodologies for the TOPEX A drift correction. The TOPEX A drift correction from CLS involves comparison of the altimetry based sea level time series with tide gauges and filtering out the differences by applying a Lanczos low pass filter. Various issues have been investigated to enable an accurate drift correction estimate of the CLS GMSL time series. Beckley et al. (2017) proposed usage of tide gauges as a validation tool to altimetry based GMSL time series rather than using them for calibration. Further the TOPEX A drift correction of Beckley et al. (2017) involves the removal of cal-mode corrections applied to the original TOPEX data.

A comparative study of GMSL using these two new time series and their associated sea level budget analyses will be performed as the next scientific requirement.

4.2 Steric component

The previous document (D1.1) described challenges of feature resolution given Argo sampling density. Since then, initial focus has been on developing uncertainty constraints on SSL global mean (+/-65°N/S) – and developing an internal uncertainty budget that allows interrogation of and separation of the sources of the overall uncertainty. Major sources of uncertainty include

- the effect of filling of missing vertical levels in a profile (this is the so-called climatological uncertainty in this product),
- uncertainty associated with poor sampling within a 5 degree cell (relative to the scales of variability within the cell), and
- unsampled cells in a given month.

As mentioned in version 1.1 of D1.1, added value from SST observations have the potential to substantially reduce uncertainty in upper levels, and to provide improved information on the statistics of variability in the upper levels – to better constrain uncertainty estimates in these regions. Approaches adding SST to the SSL estimate, including the formal propagation of uncertainties will be explored to quantify impact of including SST and associated covariance information.

Propagation of uncertainty from grid to global and regional means: our approach allows propagation of uncertainty that takes account of local variability i.e. the production of basin scale SSL with formally estimated uncertainty is possible that accounts for some regions (e.g. North Atlantic) being more variable than others.

The approach also provides a base to extend backwards in time to less – well – sampled eras. Current method may require some modification in cases of very sparse sampling, but interrogation of how sparse sampling affects aspects of uncertainty budget will be an initial focus.

4.3 Ocean mass component

The GRACE mission has ended end of 2017. The GRACE-Follow-On mission is scheduled for launch at 19 May 2018.

The first assessment of present-day global mean sea level budget under the auspices of the WCRP involves a comprehensive review of OMC estimates from GRACE. The related discussion among authors of GRACE OMC estimates (not yet published) has consolidated the common experience and the current level of agreement of results. It has also pointed out methodological issues that authors disagree upon.

A study by Blazquez et al. (2018) explored the uncertainty of GRACE estimates of mass redistribution between ocean, ice sheets, glaciers and land water in an integrative study by creating a large ensemble of results from varying methodological parameters. They conclude that the uncertainty of GRACE-based ocean mass change is on the order of 0.5 mm/yr and that the uncertainty is dominated by uncertainties in geocenter motion and in GIA.

Scanlon et al. (2016) conducted assessment of GRACE mascon solutions for applications land water storage change which provide valuable background information for the interpretation of mascon solution results and their differences.

4.4 Glaciers contribution

Within the SLBC_cci project, the glacier WP focusses 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. Two new datasets (glacier inventories for Novaya Zemlya and Franz-Josef-Land) have been created since v1 of this document (Rastner et al., 2017, Schaub et al., 2018). Both are improved regarding the now available time stamp for each glacier and both are temporarily much more constrained. Whereas the former inventories for both regions have been compiled from various satellite images (Landsat, SPOT) acquired between 2000 and 2010 over a period of about 10 years (Moholdt et al., 2012), the new ones have mostly been derived from Landsat scenes acquired in 2013 and 2015 (one scene from 2016) for Novaya Zemlya and from a single Sentinel 2 scene acquired on 12.9.2016 (two tiles from July 2016), i.e. within a day rather than stretched over 10 years. Moreover, drainage divides have been improved and topographic information for each glacier was updated using the ArcticDEM that has a much better temporal match with the glacier outlines and a much higher quality than the datasets used before.

4.5 Ice sheets contribution

Antarctic Ice Sheet:

Since the IMBIE1 project ended, data from CryoSat-2 has become available. This has added an extra 7 years of information to the SEC time series. The processing system that produced the time series has been upgraded in several ways (Shepherd et al. 2019). New methods of estimating the SEC of the unobserved regions of the ice sheets have been developed, both between a satellite's ground tracks and beyond the latitude limits of the satellite's orbit. The between-track estimates are based on spatially-limited triangulation, followed by a velocity-guided interpolation (using BISICLES) on the ice sheet margins, i.e. within 100km of the coast, and mean estimates elsewhere. Beyond the orbit limits, SEC is estimated from an annular region, 80°S-81°S. Most drainage basins within that region are treated together but Zwally basin 18 is a special case: its snow area is treated separately, and its ice area, which includes the Kamb Ice Stream, is used to estimate all unobserved ice, since the unobserved ice area is continuous.

An improved, time-varying, ice and snow density mask has been developed for the Antarctic Ice Sheet. Cross-calibration between satellite missions has been extended to include CryoSat-2, and now uses a method that compares fitted linear-trending annual sine curves around the time series from the overlapping periods between each pair of satellites. Previously data was aggregated into epochs 30 days long, but to cope with noise issues the epochs have been extended to 140 days.

Greenland Ice Sheet:

A fundamental challenge we face – and that we have not solved yet – is the conversion between volume and mass changes for the radar altimetry-derived volume changes for the Greenland

Ice sheet. The problem is related to the changing penetration of the radar into the snow as a result of a changing climate.

As an attempt to understand and constrain this effect we have carried out an extensive analysis of the surface elevations from CryoSat-2 and Altika for the period where data is available from both. It is assumed that Altika maps a surface much closer to the physical surface than CryoSat-2 does.

Seal level fingerprint:

A thorough benchmarking exercise in the sea level fingerprint-community has been carried out. The benchmarking of the numerical implementation of the sea level equation has resulted in a paper submitted to Geophysical Journal International.

4.6 Land water contribution

The standard algorithm used to compute river flow velocity (assuming bankfull discharge conditions) will be replaced with a new improved algorithm, resulting in better model-based estimates of interannual and seasonal TWSA relative to GRACE-derived (usage of CSR mascon solution) estimates.

4.7 Arctic Ocean sea level budget components

The work builds on the following input data:

- Ocean mass variations in WP220 from TU Dresden.
- Sea level pressure from MOG2d; Hadley Center; Univ. Washington.
- Arctic Ocean in situ data (i.e. bottom pressure data, tide gauge data (PSMSL), hydrography from Ice Tethered Buoys, possible Year of Polar Prediction Campaign data).
- Fields from regional/global DTU (DTU15MSS, DTU15MDT, DTU10BAT) models. DTU Arctic Altimetric Sea Level Record was tailored, edited and processed according to Cheng et al. (2015), and are referenced to the DTU13 Mean Sea Surface (Andersen et al., 2015).
- Fields from the TOPAZ operational model with data assimilation. NERSC TOPAZ4 is a coupled ocean and sea ice data assimilation system for the North Atlantic and the Arctic Ocean that is based on the Hybrid Coordinate Ocean Model (HYCOM) and the Ensemble Kalman Filter data assimilation (Sakov et al., 2012; Xie et al., 2017).

Under the assumption that the geoid is time invariant the changes in the sea level will be balanced by a change in the MDT. As such, the mean sea level changes will also invoke changes in the large-scale ocean circulation and hence the heat and freshwater transports. The main contributing components and their uncertainties to the sea level variations in the Arctic Ocean arise from mass changes, changes in atmospheric pressure, changes in steric height and tides. In addition, uncertainties are also connected to the effect of polar gaps. These individual components and their uncertainties are further addressed below.

Mass changes: Area weighted integrated trends for the ocean mass changes are: CSR 1.5 mm/yr, ITSG -4.5 mm/yr, JPL 4.5 mm/yr, and GSFC 5.4 mm/yr. Blazquez et al. (2018) conclude that the uncertainty of GRACE-based ocean mass change is in the order of 0.5 mm/yr.

Atmospheric pressure: The time variable sea level pressure might contribute to sea level variations on decadal scales of up to 0.4 mm/year (i.e. Svendsen, 2015; Svendsen et al., 2016).

Steric height: The TOPAZ4 products include sea surface height (meters; relative to geoid), and steric height (meters). The TOPAZ4 covers the North Atlantic and entire Arctic Oceans bounded by 20°N-90°N and 180°W to 180°E with a spatial resolution of 0.125°. The temporal coverage is from 2003-2015 at a monthly resolution. The mean sea level trend is 3.0 mm/yr. In comparison the steric trend is 1.2 mm/yr. This yields a contribution from ocean mass redistribution of 1.8 mm/yr. As the in-situ hydrographic observations in the Arctic Ocean are sparse (e.g. EN4) the accuracy of the steric component is questionable.

Polar gaps: The annual and seasonal variation in sea ice coverage eventually bias availability of altimetric observations. The Sentinel-3 (A/B) satellites operate at an inclination of 98.65° leaving a Polar Gap of 27%. In comparison, the approved Surface Water Ocean Topography (SWOT) satellite will have an inclination of 78° leading to a polar gap of 35%. The data coverage clearly influence the estimation of sea level trend.

5 Preliminary thoughts on science roadmap

This section is intentionally brief because the development of a more elaborated roadmap is under way in parallel to preparing this document.

The science and societal requirements that motivate the roadmap, may include

- The need for sea level projections
- Requirements and activities by WCRP, CMUG, C3S
- Questions following from the present SLBC_cci: Requirements for further developments on the involved datasets; additional data needs; ESA possibilities to support those needs?
- Questions on sea level impact research: How can sea level research serve as input for coastal impact research?
- Need for closer cooperation with climate modeling community to support them with data for model validation/assimilation?

That said, the roadmap should build on the capacity developed by the SLBC_cci consortium. Its aim is to propose an extension of the work of SLBC_cci.

The work can be ordered by the following categories

a. Extension in time of the core SLB components and of the global SLB assessment
b. Methodological improvements for the existing budget components and their uncertainty characterisation
c. Methodological improvements and extension for the budget assessments
d. Regionalisation of components and of the budget assessments
e. Involvement of new ECVs to cover missing components or to support core components

a) Extension in time of the core SLB components and of the global SLB assessment

It will be mandatory to extend temporal coverage (going through 12/2015 for the current SLBC_cci) to the more recent time (e.g. through 12/2018 and beyond). This will facilitate the assessment of the continuing evolution of sea level and a better separation and interpretation of interannual and long-term changes. This will involve the use of new sensors, such as GRACE-FO, Sentinel-3a and b, Jason-3.

b) Methodological improvements for the existing budget components and their uncertainty characterization

Every budget component addressed by SLBC_cci has its challenging aspects, regions, or uncertainty components. The SLBC_cci budget assessments provide additional indications on necessary improvements. It is consequential to improve the individual component methodologies, by taking advantage of the common budget assessment framework.

Improvements and further developments include the following aspects. The list is not complete and does not imply any priorization yet.

- Advancement of methods to take advantage of having hydrology model, glacier model, and GRACE/GRACE-FO to estimate LWS and glacier mass change. Here, one motivation for including modeling is the improvement of projection capabilities.
- Consistent treatment of GIA and degree-1 over the different components (ocean altimetry, GRACE for ice sheets, GRACE for ocean mass, GRACE for land water) and the improvement of confidence in GIA corrections.
- Improvement and addition on the land ice contribution assessment is an important option. Options include:
    - Antarctic peripheral glaciers (currently neither covered by Glacier model nor by altimetry analysis, simple to cover by GRACE)
    - Glacier mass changes due to changing dynamics (not included in the atmospherically driven global glacier modeling)
    - ice shelf indirect sea level contribution (by freshening)

From a sensor perspective, the potential of new sensors (some of them applicable to multiple components of the sea level budget) needs to be explored. They include:

- GRACE-FO
- ICESat-2 laser altimeter mission (will aid at resolving radar penetration, even back into past)
- CryoSat-2 swath mode for glaciers and ice caps
- Sentinel-3 altimetry (e.g. feasibility study for Antarctica and Greenland)
- SWOT
- river discharge from EO data.

Finally, the considerations and recommendations on further developing the observing system may be made.

c) Methodological improvements and extension for the budget assessments

Based on the SLBC_cci achievements, a framework should be established for assessing our understanding of sea level change by budget considerations.

This requires to further develop the assessment methodology, including

- approaches of time series analysis
- more rigorous account for error correlations in time and error correlations between different datasets

In addition, the following extensions of the budget assessment approach may be considered:

- detection and separation of climate signals (e.g. also by including acceleration) and attribution
- additional indicators of global mass redistributions, such as the dynamic flattening term C20 (= -J2).

Considerations on the operationalization of sea level budget assessments need to be made.

d) Regionalisation of components and of the budget assessments

Regional budget assessments (in addition to the global mean budget) are an obvious need in view of impact, adaptation and mitigation studies but also in view of assessing the process understanding. There are different scales of "regional", down to coastal sea level. A possible approach would be to distinguish regions that behave very similar or very dissimilar to the global mean sea level.

e) Involvement of new ECVs to cover missing components or to support core components

The inclusion of, or linkage to other ECVs and new ECVs in the CCI program may be considered. This is certainly a trade-off with size and manageability of the project, time spans covered by new ECVs, their expected availability etc. Possible examples include

- Water vapor (No emphasis of water vapor within SLBC_cci. Reliability of reanalysis results is not clear.)
- Snow (Snow is part of Land Water in SLBC_cci. EO data product might support the assessment)
- Lakes (Lakes are part of Land Water in SLBC_cci. EO data products might support the assessment)
- Ocean salinity (EO data products might support the Steric component assessment).

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Appendix

This appendix contains additional discussion related to the approaches for long-term rates of change outlined in Section 3.1.2

Discussion of the physical meaning of LTR determined by either approach

The $LTR_{average}$ has a straight-forward interpretation as the mean rate of change between t_1 and t_2. It does not use assumptions on the temporal behaviour of *z(t)* and does not adopt concepts to distinguish "long-term" from "interannual". The "long-term" character just arises from the length of the interval [t_1, t_2]. The effect of nonlinear signal components is deliberately included. Hence, non-linear components do not induce uncertainty of $LTR_{average}$. Only the uncertainty of *z(t)* induces uncertainty on $LTR_{average}$.

For $LTR_{regression}$ we discuss two different interpretations. Notably they imply two different concepts of uncertainty.

Interpretation 1 for $LTR_{regression}$: By applying the functional model (4) we assume that *z(t)* contains a physically distinct process that is linear in time. We want to separate this linear process. Non-linear components of *z(t)* are considered noise even if they represent true variations. Consequently, uncertainties of $LTR_{regression}$ according to Interpretation 1 are not only induced by uncertainties of *z(t)* but also by the limited ability to separate the assumed linear signal from other physical signals which may "mask" the assumed linear signal. Specifically, realistic uncertainty assessments need to account for serial correlation of disturbing signals.

Comment: A geodetic example where the linearity assumption is justified is the plate tectonic motion of geodetic points. It is intrinsically linear on decadal scales but is overlaid by non-linear signals of different physical origin and by observation errors. A different example where the linearity assumption is justified arises in contexts where data noise and data scarcity simply do not allow to explore non-linear components.

Interpretation 1, by assuming a unique linear trend of the long-term, seems incompatible with a practice of applying the regression to (arbitrarily chosen) sub-intervals of the total observation interval and interpreting the time-dependence of the obtained trends. In addition, applying the regression for subsequent sub-intervals usually implies discontinuities between the different regression lines, which compromises, again, a physical interpretation of the regression results. Figure 2 (section 3.1.2, light blue lines) illustrates the case.

In summary, since sea level change and its contributions are not strictly linear in time, the assumption of an intrinsically linear, physically distinct "long-term component" would need further justification. Otherwise, the meaning of the $LTR_{regression}$ remains ambiguous, and so does any uncertainty assigned to it.

Comment: The regression model (4) may be generalized to include a quadratic term $(a_5/2)\ t^2$, that is, an acceleration or deceleration a_5 of the long-term trend (e.g. Nerem et al. 2018). This model expansion may alleviate the problem. It shifts the problem from assuming a constant rate to assuming a constant acceleration.

Interpretation 2 for $LTR_{regression}$: We do not assume linearity of any physical process contributing to $z(t)$. We just use the regression as a well-defined mathematical operation that extracts from $z(t)$ a single number $LTR_{regression}$. This is useful, for example, in the context of comparing different time series on the basis of a single parameter $LTR_{regression}$ related to its overall change over time. According to this interpretation, uncertainties of $LTR_{regression}$ are induced solely by uncertainties in $z(t)$ but not by true physical deviations of $z(t)$ from the functional model (4). That means that uncertainty assessments cannot build on the stochastics of the residuals ε(t) of the regression.

Interpretation 2 of the regression approach does not offer a physical sense of the "long-term trend" thus obtained. The results should be stated in a sense like this: "A regression line fitted to $z(t)$ over the interval $[t_1, t_2]$ has the slope $LTR_{regression}$. The uncertainty of this result due to errors in $z(t)$ is xxx."

Discussion on the propagation of errors of $z(t)$ into the LTR

Errors of $z(t)$ that behave linear in time (such as the GIA correction) propagate directly into the LTR of either approach ($LTR_{average}$ and $LTR_{regression}$ with its Interpretation 1 or Interpretation 2).

Let us next consider the simple case of errors of $z(t)$ that are uncorrelated in time with an identical probability distribution. This is an idealized description of the noise part in satellite altimetry time series and GRACE-based time series. $LTR_{regression}$ uses all values $z(t)$ within $[t_1, t_2]$. $LTR_{average}$ in contrast uses only $z(t_1)$ and $z(t_2)$ (or a few more values of $z(t)$ in their neighbourhood). Therefore, due to the effect of averaging, errors will propagate less into $LTR_{regression}$ than into $LTR_{average}$. This is a recognized advantage of the regression approach.

Let us alternatively consider the case where $z(t)$ is derived from a series $(\Delta z/\Delta t)(t)$ according to (3) and that the errors of $(\Delta z/\Delta t)(t)$ are uncorrelated and identically distributed. This implies serial correlation of the errors in $z(t)$. This is an idealized description of the situation of the modelled glacier contribution from WP230 and the LWS contribution from WP250. (Note, however that more recently there is a trend in the glacier community to infer long-term changes from regressions rather than mean rates of change, because the former is more robust with respect to data errors.) It follows from the discussion in conjunction with (7) and (8) that, in this case, $LTR_{average}$ implies a lower propagated uncertainty than $LTR_{regression}$.

Discussion on the impact of "disturbing" signal components on the *LTR*

As discussed above, nonlinear ("interannual") physical signals in $z(t)$ induce uncertainty for $LTR_{regression}$ according to its Interpretation 1. How well is the regression approach suited to dampen the effect of such disturbing signals? While this discussion needs to remain vague in lack of a clear characterisation of "interannual", here we start with a simple scenario. We assume an interannual signal $z^{ia}(t)$ that is a random walk process: $z^{ia}(t) = \sum_{\tau=t_0}^{t} \frac{\Delta z^{ia}}{\Delta t}(\tau)\,\Delta t$, where $(\Delta z^{ia}/\Delta t)(\tau)$ is a sequence of independent identically distributed random variables with expectation value zero. For example, changes of ice sheet mass due to surface mass balance fluctuations have been modelled in this way (Rémy and Parrenin 2004). How does this interannual signal "corrupt" the *LTR*? Owing to the simple construction of $z^{ia}(t)$ we may immediately refer to Eq. (7) and (8) and the discussion there. We conclude that the RMS effect of $z^{ia}(t)$ on the *LTR* is smaller for $LTR_{average}$ than for $LTR_{regression}$. Of course, assuming different stochastic behaviours of interannual signals may lead to different conclusions.

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