The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-16
Manuscript under review for journal The Cryosphere
Discussion started: 25 February 2019

The Cryosphere Discussions
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EGU

Estimate of Greenland and Antarctic ice-sheet total discharge from multiple GRACE solutions

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Abstract

In this work a method for the estimation of 2003-2010 monthly-mean total discharge from Greenland and Antarctica is presented. We show that measurements of time-variable gravity from GRACE when combined with estimates of precipitation and sublimation can realistically reconstruct the total discharge from the ice-sheets into the ocean. In particular, the total discharge has been calculated as a 8-member ensemble-mean obtained by combining multiple GRACE solutions with water fluxes from both an high resolution regional atmospheric climate model (RACMO2) and a global reanalysis (ERA-Interim). The gravimetric measurements of mass variations and the precipitation and sublimation atmospheric fields have been combined in the ice-sheets water mass balance equation, according to the main drainage basin systems. The use of the combined land-atmosphere water mass balance has also been tested, which however led to a large underestimation of total discharge. A comparison among the different GRACE solutions is also performed, highlighting similarities and differences and analyzing the possible causes. GRACE datasets show similar ice-sheet mass trends on Antarctica and over the majority of the Greenland basins, while significant differences (up to a factor of 1.9) have been found in mass-loss areas characterized by strongly negative water height trends. This is likely primarily caused by the

different pre-processing techniques applied to the raw gravimetric data.

1- Introduction.

Freshwater inputs to the ocean from land-ice and terrestrial water storage changes represent, along with the thermal expansion of sea waters, the major cause of global sea level change on short time-scales (IPCC AR5, 2014).

Antarctica and Greenland ice-sheets represent the vast majority of the Earth's ice. Satellite-based observations and SMB (surface mass balance) model simulations show a rapid acceleration of ice discharge from Greenland and Antarctica ice-sheets since 1992, by contributing of about 0.6 mm/yr to the rate of global sea level rise (Shepherd et al., 2012). The increasing ice mass loss from the polar ice-sheets is in particular due to an acceleration of flow speed of large West Antarctica outlet glaciers system (IMBIE team, 2018) and to an increase in runoff from the surface water melting in Greenland (Enderlin et al., 2014). Furthermore, recent observations suggest that ice dynamics may be a key factor in the response of coastal glaciers and ice-sheets melting especially in West Antarctica (Flament and Rémy, 2012). In Greenland, laser altimetric observations indicate a thickening of the high central ice-sheet during the 2003-2007 period, but also a significant increased loss from coastal outlet glaciers, due to surface melting and accelerated flow, has occurred (Zwally et al., 2011). Ice thickness surveys by NASA's Operation IceBridge suggest that, since 2009, surface mass balance rather than ice dynamics has dominated Greenland contribution to sea level rise (Enderlin et al., 2014). The Antarctic ice-sheet system is more complex, and presents large regional differences. Ice loss in West Antarctica is mostly due to the acceleration of outlet glaciers and, as a secondary effect, to enhanced melting caused by increasing temperature. In contrast, surface temperatures over most of East Antarctica are well below the freezing point and a small increase in air temperature cannot initiate melt (Stoddart et al., 2008). The cause of acceleration of other large outlet glaciers in West

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Antarctica is not fully understood, but may be related to sea-ice shelf instability (Holland et al., 2008; Mouginot et al., 2014). In terms of equivalent sea level rise, Greenland and Antarctica contributions have been estimated to be 0.17 mm/yr during the period 1992-2001 and 1.0 mm/yr during 2002-2011, which means that a six-fold increase in mass loss compared to 1992-2001 period occurred during the recent period (IPCC AR5, 2014). Furthermore, empirical methods based on the extrapolation of the ice-sheets induced sea level rise from Atmosphere Ocean General Circulation Models (AOGCMs) projections, suggest that such a contribution will be increasingly positive in the future (Gregory and Huybrechts, 2006).

Due to the increasing contribution of ice-sheets melting into the ocean and their important positive contribution to sea level variations, the availability of realistic estimates of ice-sheet total discharge is of major importance for the investigation and monitoring of sea level rise and to understand how the Earth system is responding to anthropogenic-induced global warming. If there exists no comprehensive global network for the monitoring of freshwater discharge into the world oceans (Alsdorf and Lettenmaier, 2003; Brakenridge et al., 2005), the situation is even worse for the Greenland and Antarctica ice sheets. Over land, river discharges are unevenly distributed, discontinuous over time, and have variable accuracies. To provide reliable estimates of river discharges, Fekete et al. (2000, 2002) followed a data-merging approach by using observed discharge data from the Global Runoff Data Center (GRDC; http://grdc.bafg.de) to constrain modeled estimates of runoff. Later, Dai and Trenberth (2002) improved the previous work by incorporating a river-routing scheme for the appropriate transport of the runoff into the ocean. Alternatively, terrestrial water storage (TWS) observations from GRACE satellite gravimetry mission combined with precipitation and evaporation data have been used to solve the water balance equation at basin-scale (or similarly estimating precipitation and evaporation using the atmospheric water balance equation) for the terrestrial freshwater discharge (Syed et al., 2007; Syed et al., 2009). In this study we present a new strategy for the calculation of an ensemble of monthly ice-sheet total discharge estimates, which, in the comparison with observations, has proved to be the best solution to reproduce realistic estimates of Greenland and Antarctica freshwater input into the ocean. According to the main drainage basin systems of the ice-sheet, we have constructed a 2003-2010 interannual dataset of total discharge from Greenland and Antarctica, calculated by combining GRACE gravimetry observations of ice-sheets mass loss and atmospheric model data of precipitation and sublimation. Differently from previous works, this is the first time that such a calculation is made over the ice-sheets regions, highlighting the innovation of the present study. Furthermore, multiple GRACE solutions and two different datasets of atmospheric model outputs have been applied in the calculation of the total discharge estimates. The importance of this study also resides in the potential application of such a dataset in the frame of ocean modelling. In fact, due to the lack of time-varying runoff measurements, land and ice runoff used in the current OGCMs simulations consist of climatological estimates that are assumed not to vary inter-annually; the increasing freshwater input from ice-sheets into the ocean is thus not considered in ocean simulations.

This study is structured as follows: we firstly introduce the methods (Section 2) and datasets used for the total discharge calculation (Section 3); in Section 4 we show the comparison among the different GRACE solutions; in Section 5 we present the results of the total discharge calculation and in Section 6 the use of different precipitation datasets to calculated the ice-sheet total discharge is performed and discussed; in Section 7 the main conclusions are summarized followed by a discussion.

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2- Approaches to compute total discharge from the ice-sheets.

Ice-sheet total discharge from Greenland and Antarctica were estimated by using two approaches, namely through the application of the land water mass balance equation (Syed et al., 2010) and the atmospheric water mass balance equation (Syed et al., 2009) over land (i.e., large river basins, drainage regions and continents). Here, we use a similar approach which is described in detail below.

2.1- Resolution of the surface mass balance.

In the first approach, the total discharge is calculated using the ice-sheets water mass balance equation:

$$\frac{\partial M}{\partial t} = SMB - D \quad (1)$$

where $\frac{\partial M}{\partial t}$ is the variation of mass in time over the ice-sheet; SMB = P – E - R is the surface mass balance, equal to the sum of solid and liquid precipitation (P), evaporation and sublimation (E) and meltwater runoff (R, note that this term is negligible in Antarctica where total discharge is almost totally due to ice flow; Van den Broeke et al., 2011); D is the ice discharge, i.e. the iceberg calving, that is the main process through which Antarctica ice-sheet is losing mass. The estimate of the total discharge (i.e. the sum of meltwater runoff R and solid ice discharge D) leaving the ice-sheet is therefore equal to:

$$R + D = P - E - \frac{\partial M}{\partial t} \quad (2)$$

The balance was applied to the whole of Greenland and Antarctica ice-sheets according to their main drainage basin systems, by computing the total volume of M, P and E within every *k* drainage basins (Eq. (3), (4) and (5)):

$$V_M^k(t) = \sum M(\lambda_{ij}, \theta_{ij}, t) * \cos\theta_{ij} * d\lambda_{ij} * d\theta_{ij} \qquad (3)$$

$$V_P^k(t) = \sum P(\lambda_{ij}, \theta_{ij}, t) * \cos\theta_{ij} * d\lambda_{ij} * d\theta_{ij} \qquad (4)$$

$$V_E^k(t) = \sum E(\lambda_{ij}, \theta_{ij}, t) * \cos\theta_{ij} * d\lambda_{ij} * d\theta_{ij} \qquad (5)$$

where θ and λ are latitude and longitude, respectively.

Geographical masks of the ice-sheets drainage system regions, based on surface slopes analyses, were derived from Luthcke et al. (2006) for Greenland and based on the sub-division of Rignot et al. (2008) for Antarctica. Greenland was thereby divided into 6 drainage basins (Figure 1) and Antarctica into 18.

Since GRACE data are given as monthly anomalies of mass, water storage changes are considered to have occurred between the mid-point (i.e. the 15th day) of two consecutive months. We have therefore computed compatible estimates of P and E by integrating daily averages between the 15th day of consecutive months as follows:

$$\int V_{R+D}^k dt = \int V_{P-E}^k dt - \left[\left(V_M^k\right)_{m+1} - \left(V_M^k\right)_m \right] \qquad (6)$$

where $\left(V_M^k\right)_m$ is the total volume of M over a certain drainage basin of Greenland/Antarctica expressed in equivalent water mass anomaly of the month *m*. This procedure was possible only for daily ERA-Interim data since RACMO data were available as monthly means only.

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2.2- The land-atmosphere mass balance.

In the second approach, the ice-sheet total discharge is computed by the use of the combined land-atmosphere water mass balance equation, obtained from Eq. (1) and the atmospheric moisture budget expressed as:

$$\frac{\partial W}{\partial t} = E - P - \nabla \vec{Q} \qquad (7)$$

where W is the total column water vapor and the last term on the right hand side is the horizontal divergence of the vertically integrated vapor flux.

By combining Eq. (1) and (7) we therefore obtain the total discharge (R+D) now expressed as:

$$R + D = -\frac{\partial M}{\partial t} - \frac{\partial W}{\partial t} - \nabla \vec{Q} \qquad (8)$$

On land, the method of Eq. (8) has been proved more accurate than Eq. (2) due to the large uncertainty in the atmospheric models evapotranspiration that is bypassed by the use of the combined land-atmosphere water mass balance equation (Syed et al. 2009). This is however questionable on land-ice, where the contribution of evaporation is negligible and large uncertainties on atmospheric moisture remain due to lack of a proper observational network.

Finally, the use of 8-member ensemble-mean total discharge has been tested. The ensemble-mean solution has been calculated by averaging the eight $R+D$ fields, obtained from Eq. (2), calculated by balancing, in turn, each of the four GRACE EWH dataset (JPL, CSR, GFZ and GRGS) once with RACMO2 regional model data and once with ERA-Interim atmospheric fields of precipitation and sublimation; these results will be discussed in detail in Section 5.

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3- Datasets.

3.1- GRACE solutions for water mass variations.

The GRACE space mission, sponsored by National Aeronautics and Space Administration (NASA) and Deutsches Zentrum fur Luft- und Raumfahrt (DLR), has been collecting gravity variations measurements since March 2002. It provides, at regular time intervals, monthly and 10-day global solutions of the Earth gravity field (e.g. Wahr et al., 1998; Tapley et al., 2004; Schmidt et al., 2006). These solutions are provided by different official centers as lists of Stokes coefficients (i.e., spherical harmonic coefficients of the geo-potential) up to degree 50-60, or equivalently at spatial resolution of 300-400 km. Changes in the gravity field are largely caused by the redistribution of water mass in the hydrological cycle (Wahr et al., 1998, 2004). GRACE measurements have enabled for the very first time to derive satellite-based global maps of terrestrial water storage variations. The Stokes coefficients are converted into surface mass density and expressed in units of mm of equivalent water height (Ramillien et al., 2006b). The solutions will be later called "equivalent water height differences" (EWH) since they are expressed as differences between the time-variable solution and a mean static gravity field.

In the present work we have tested the use of multiple GRACE solutions, released by different research groups: Deutsches Geo Forschungs Zentrum (GFZ - Potsdam, Germany), NASA Jet Propulsion Laboratory (JPL - US), Center for Space Research (CSR - US) and Groupe de Recherche de Géodésie Spatiale (GRGS) at the Center National d'Etudes Spatiales (CNES - Toulouse, France). These are monthly solutions at 330 km of spatial resolution (i.e. up to degree 60 of the spherical harmonics). Different pre-processing methods have been used

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to low-pass filter the high frequencies of the noise contained in the GRACE solutions. Moreover, applying an Independent Component Analysis (ICA) enabled us to separate water mass variations, which are meaningful geophysical signals, from the polluting noise, in particular the North-South striping. This post-processing technique was only applied to the CSR, GFZ and JPL data, which will be called "ICA-based" solutions in order to distinguish them from the GRGS data. In this paper, the more recent releases have been used for both the solutions: RL05 for ICA and RL03 for GRGS solution.

Once averaged over large geographical areas, the accuracy of the GRACE-estimated water mass change should not exceed 1.5 cm of equivalent-water height (Wahr et al., 2004; Ramillien et al, 2006a). Total errors in the Stokes coefficients are a combination of instrumental and processing uncertainties, effects of the truncation of the spherical harmonic spectrum (i.e., omission and leakage errors) and the lack of completeness of the dealiasing models used to remove the gravitational effects of varying atmospheric and oceanic masses (Velicogna and Wahr, 2013).

To have an idea of the mass variations of the two ice-sheets, we present the linear trends (over the period 2003-2012) of EWH for the CSR solution (Figure 2). We can observe a strong decrease of mass over West Antarctica (more than 10 cm/yr of equivalent water height) and a slight decreasing trend over the Antarctic Peninsula. East Antarctica shows neither loss nor accumulation of mass. Most of the Greenland ice-sheet is characterized by ice mass loss mostly concentrated in the south-eastern part but also on the northern-west edge of the ice-sheet, for the considered time frame.

As GRACE also detects multi-year deformation of the Earth surface such as the constant Post Glacial Rebound (PGR) re-adjustment of the last deglaciation, we have to remove this effect in our mass balance estimates. For this purpose, we used the global ICE-5G ice de-

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glaciation model (Peltier, 2004; Paulson et al., 2007) to estimate the PGR trends over Antarctica and Greenland. While the PGR effect is negligible for the Greenland ice-sheet, it is significant on Antarctica where the PGR rate can be of the same order of magnitude as the long-term ice mass change. Unfortunately, as PGR effects cannot be modelled accurately, uncertainties in our PGR-related trends, and consequently on our mass balance estimates, are suspected over Antarctica where the geological and long-term GPS observations that are used in the PGR simulation remain rare (Peltier, 2009).

3.2- Precipitation and evaporation data.

For precipitation and sublimation (terms P and E in Eq. (2)), we considered two different datasets: ERA-Interim atmospheric reanalyses and outputs from a regional atmospheric climate model. Furthermore, we have tested the use of other datasets of precipitation in the estimation of $R+D$ derived from ice-sheet water mass balance and thus compared the results; these additional precipitation datasets are: CMAP, GPCP and Sheffield data.

ERA-Interim is third generation global atmospheric reanalysis produced by the European Center for Medium-range Weather Forecasts (ECMWF). ERA-Interim covers the period from 1 January 1979 onwards, and continues to be extended forward in near-real time. Gridded data products include a large variety of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere. Vertical integrals of atmospheric fluxes and other derived fields have also been produced (Simmons et al., 2007; Dee et al., 2011). In our work we have used daily precipitation and sublimation fields at a horizontal resolution of 0.75°. Furthermore, we have applied a Gaussian filter with 400 km radius, in order to be consistent

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with the spatial resolution of GRACE data.

In this study we used the monthly outputs of 22-year simulations (1989-2010) performed with the Regional Atmospheric Climate Model (RACMO2) at high horizontal resolution of 11 km over Greenland and 55 km over Antarctica (van Meijgaard et al., 2008; Ettema et al., 2009). The model has been developed since 2005 at Koninklijk Nederlands Meteorologisch Instituut (KNMI) and is the second version of the regional climate model RACMO. This new version was built on the ECMWF physics package from cycle 23r4 embedded in the semi-Lagrangian (sL) dynamics kernel of the Numerical Weather Prediction (NWP) model HIRLAM5.0.6 (Undén et al., 2002). The model has been forced at the lateral boundaries and at the sea surface by ERA-Interim atmospheric fluxes from ECMWF operational analyses. The RACMO2 outputs consist of SMB, total precipitation and runoff fields. The sublimation fields have been deduced through the simple relation $SMB = P - E - R$. Nevertheless, the sublimation is not large and not very variable and the total precipitation and runoff determine most of the variability.

Regarding the total column water vapor and the horizontal divergence of the vertically integrated vapor flux, required for the coupled land–atmosphere water balance of equation (4) we used only ERA-Interim data product, as these parameters are not available from RACMO.

4- Comparison of GRACE solutions.

In Figure 3 the comparison between the time series of equivalent water height difference among all the GRACE solutions, over Greenland, East and West Antarctica, is shown. EWH time series of Figure 3 show that East Antarctica is experiencing an increasing of mass, with an acceleration since 2009. In contrast, West Antarctica and Greenland are losing mass since

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2003. The former shows a mass loss acceleration developing in August 2007, while the latter shows a pronounced negative trend through the whole time-span. The four GRACE datasets show similar ice-sheet mass trend on Antarctica and over the whole Greenland ice-sheet. To deepen our analysis, we have compared EWH time-series for the different Greenland drainage basins (Figure 4), evidencing the south-east Greenland coast (*basin 4*) as the area of highest mass loss of the ice-sheet, while the total discharge flux reaches its minimum values in correspondence of the north-eastern edge (*basin 2*). Even if in agreement in terms of maximum and minimum areas of mass change, the two groups of GRACE solutions, GRGS and ICA-based solutions, show significant differences in terms of trend magnitude. The major difference has been found at northern-west Greenland (*basin 1*, Figure 5 top panel), where the GRGS solution present a trend almost twice higher than the ICA one, which means a considerable impact in terms of equivalent sea level contribution from Greenland ice-sheet. Significant differences are also evident at the eastern coast, where the EWH trend of the two groups of solutions differ by a factor of 1.5 (*basin 3*) and 1.1 (*basin 2*). The difference is even more amplified in the southern-east part (*basin 4*), i.e. the area of highest ice mass loss. Over this particular drainage basin, the GRGS EWH time series exhibit an ice mass loss rates 1.6 times higher than JPL: -15.48 cm/yr with respect to -9.51 cm/yr (Figure 5, bottom panel).

Several causes can give rise to the marked differences in equivalent water height trends of the two groups of solutions. A considerable part is attributable to the different pre- and post-processing techniques applied to the two different GRACE datasets. In fact, distinct pre-processing methods have been used to filter out the high frequencies from the noisy GRACE solutions, in order to extract realistic hydrological signals on the continents. In particular, stabilization method have been applied to Level-1 of GRGS solutions and a Gaussian filter have been applied to Level-2 of CSR, GFZ, JPL solutions. The reader is referred to Wahr et

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al. (1998) for further details on GRACE data processing. A secondary effect of Gaussian filter method is to cut off the high frequencies from the EWH signal, which are then redistributed and spread over the surrounding areas. In fact, if the trend computation is not limited to the Greenland ice-sheet land but extended over a bigger area which also includes the surrounding ocean, few degrees off Greenland coasts, we can see a better match between GRGS and ICA datasets trend (Figure 6). In this case, in fact, the high frequencies, cut off by Gaussian filter method and redistributed in the surrounding areas, are now included in the ICA solutions trend, which now differ from GRGS by a factor of 1.4 and 1.2 for *basin 1* and *basin 4*, respectively. An additional effect that further influences *basin 1* is the positive EWH trend over Canada and the Canadian Arctic Archipelago, which is distinctively visible before the PGR correction (see Figure 2). This effect is probably spread over the close North-West Greenland with the consequence of further decreasing the negative ICA solution trend with respect to the GRGS one. Another possible source of difference is the application of the ICA method, employed to further filter the CSR, GFZ and JPL solutions, which has not been applied to the GRGS solution. In particular, this post-processing technique has been used with the aim to reduce the presence of north-south striping due to orbit resonance that limits the geophysical interpretation of the signal (Frappart et al., 2010, 2011). In order to test this hypothesis a comparison among EWH time-series before and after the application of the ICA method has been performed (not shown). Results suggest that the application of the ICA method is not responsible for the differences in EWH trends of the two groups, conversely after the application of this post-processing technique, EWH time-series of the ICA-based solution result to be closer to the GRGS solution tendency (not shown). Moreover, other possible causes can be attributed to differences in the static gravity field removed to the time-varying solution and to differences in the oceanic/atmospheric models used to dealias the

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GRACE solutions in order to remove the atmospheric pressure influence on satellite orbits and on the ocean state.

5- Total discharge results.

In order to validate the total discharge estimates from Greenland and Antarctica and hence to assess our method as a proper strategy for the realistic reconstruction of *R+D*, we have compared the results obtained from Eq. (2) and (8) with measurements of ice discharge, obtained by combining maps of surface velocities along ice-sheet coasts from InSAR data and ice thickness from Digital Elevation Model (DEM, Rignot et al., 2011). The comparison is made by subtracting the meltwater runoff (R) from the total discharge *R+D* in order to have consistent data with InSAR observations. Note that in the case of Antarctica a direct comparison is allowed, since runoff from the surface water melting is a negligible process at those latitudes and mass loss happens thus almost exclusively through solid ice discharge (Van den Broeke et al., 2011).

Results are displayed in Figure 7. Here we present the ice-discharge estimates obtained by using CSR GRACE data balanced once with RACMO (green line) and once with ERA-Interim (cyan line) precipitation and sublimation fields. Both estimates have been calculated by means of the ice-sheets water mass balance equation (2). In the comparison (Figure 7), we found that the use of precipitation and sublimation fields from RACMO regional model (green line) slightly overestimates observation values (magenta line) while the use of ERA-Interim (cyan line) slightly underestimates them. On the other hand, the ice discharge obtained by using the combined land-atmosphere water mass balance equation (8) (blue line) strongly underestimates InSAR data. In light of these results, we have decided to combine the two atmospheric datasets in an ensemble-mean, by also including all the GRACE solutions. The 8-member ensemble-mean solution (red line) turns out to be the curve that better fits with ice discharge observations; in fact, the ensemble-mean closely follows InSAR curve, except for some seasonal peaks not represented by observations. At this regard, we want to underline that InSAR data are available as yearly means only and this is also the reason why they cannot be used for *R*+*D* estimation.

As a further verification of the reliability of our method, in Figure 8 we have verified the correct representation of the climatological seasonal cycles of Greenland and Antarctica ensemble-mean total discharge. In Antarctica (bottom panel, red line) the total discharge shows two minimum in November and January, in accordance with the seasonal minimum of precipitation (see Figure 9 bottom panel). Precipitation over Antarctica is more abundant from March to October, which is particularly evident in the RACMO2 dataset (Figure 9 bottom panel, green line). In accordance, Antarctica *R*+*D* starts to increases in April reaching its maximum values in June after the precipitation peak. Our results are in accordance with the work of Ligtenberg et al. (2012) which using a combination of a firn densification model and a regional atmospheric climate model have shown that high temperatures and low accumulation cause Antarctica ice-sheet surface to low in austral summer, while in autumn, winter and spring the surface steadily rises, mainly due to higher accumulation rates. It is also in good accordance with seasonal change of Antarctica ice-sheet height derived from altimetry (Rémy et al., 2014).

Also over Greenland the seasonal cycle is correctly reproduced by the ensemble-mean total discharge (Figure 8 top panel, red line); the summer peak is in accordance with both realistic freshwater fluxes averaged over the 1991-2000 period (Marsh et al., 2010), even if shifted from June to July, and different SMB models inter-comparison (Vernon et al., 2013).

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With this further analysis we have demonstrated that our estimated *R+D* is representative of the interannual variability of the freshwater flux from land to ocean.

6- Total discharge derived from ice-sheets water mass balance with different precipitation datasets.

In this study we have chosen to perform the calculation of the ice-sheet total discharge by using two datasets of precipitation: ERA-Interim and RACMO2. This choice has been made in order to exploit the accurateness that a third generation reanalysis, as ERA-Interim, and that the high spatial resolution of a regional atmospheric model, as RACMO2, has in itself. Nevertheless, several accurate precipitation products are available. We have, hence, tested the use of other datasets of precipitation in the estimation of *R+D* derived from ice-sheet water mass balance and thus compared the results. In this way, we are able to assess the robustness of our method, once verified the similarity among all the resulting precipitation-derived total discharge.

The precipitation datasets involved in the comparison are CMAP, GPCP and Sheffield data. The CPC Merged Analysis of Precipitation (CMAP) is a technique which produces pentad and monthly analyses of global precipitation in which observations from rain gauges are merged with precipitation estimates from several satellite-based algorithms (infrared and microwave). The analyses are on a 2.5° x 2.5° degree latitude/longitude grid and extend back to 1979 (Xie and Arkin, 1997).

The Global Precipitation Climatology Project (GPCP) was established by the World Climate Research Program to quantify the distribution of precipitation around the globe over many years. The precipitation product is obtained by optimally merging estimates computed

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from microwave, infrared, and sounder data observed by the international constellation of precipitation-related satellites, and precipitation gauge analyses. The product is available since 1979 with horizontal resolution of 2.5° x 2.5° (Adler et al., 2003).

The Sheffield dataset of precipitation (Sheffield et al., 2006) is a global, 60-yr (1948-2008), 3-hourly, 1.0° dataset of land surface hydrology fields. The dataset is constructed by combining a suite of global observation-based datasets (GPCP, TRMM, GSWP-2) with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis.

In Figure 8, we compare mean seasonal ice-sheet total discharge derived with the mass balance equation (Eq. 2) by using different precipitation datasets: ERA-Interim (cyan line), RACMO (green line), CMAP (black line), GPCP (orange line) and Sheffield (magenta line). The comparison among the precipitation products is also shown (Figure 9). We can see that the various estimated $R+D$ are of the same order of magnitude on both Greenland (top) and Antarctica (bottom), with RACMO and Sheffield presenting the highest values of precipitation (Figure 9) and hence of total discharge values (Figure 8). Also in terms of seasonal cycle, all the precipitation-derived $R+D$ show a strongly similar interannual variability, presenting the same summer peaks of discharge in June and July. The similar behavior detected, confirms the robustness of our method and the reliability of the precipitation data, ERA-Interim and RACMO2, used in our study. It is however worthy to underline that caution has to be taken when precipitation reanalyses data are used for a study of Antarctica mass balance (Bromwich et al., 2011). In fact, data assimilation is still challenging in this region as reanalyses rely heavily upon a small number of ground-based and upper-air observations in Antarctica, especially in the interior of the ice-sheet. Moreover, the wind-blown snow (or wind-driven ablation), which, on short spatial scale, greatly affects the surface mass balance over Antarctica due to the presence of katabatic winds (Rémy and Frezzotti, 2006), is an important process that is not taken into account in ERA-Interim reanalysis.

7- Conclusions.

In this study, we have proposed a strategy useful for creating an ice-sheet total discharge dataset by combining multiple GRACE gravimetric data of ice mass variation on land-ice with atmospheric model data of precipitation and sublimation. For the atmospheric fields, we have tested the use of data from both an high resolution regional model, RACMO2, and ERA-Interim reanalysis. We have demonstrated the ability of our methodology to correctly reproduce realistic estimates of ice-sheet total discharge for the 2003-2010 period. In particular, in the comparison with InSAR satellite observations of ice discharge, it turned out that the best fit with observations is achieved with an ensemble-mean of multiple GRACE solutions (JPL, CSR, GFZ and GRGS data) in combination with the two atmospheric model datasets. Total discharge has been computed with the ice-sheets water mass balance equation, which was applied to the main drainage basins of Greenland and Antarctica, and this is the first time that such a balance is applied on land-ice. We have also tested the use of the combined land-atmosphere water mass balance equation, which, however, led to a large underestimation of the total discharge and has not been considered further.

The two groups of GRACE solutions (GRGS and ICA-based solutions) show important differences in the ice mass loss 2003-2012 estimates for the southeast Greenland coast and for the northwestern edge of the ice-sheet, both characterized by a strong negative signal of water height trend. Namely, the GRGS solutions exhibits a faster mass loss rate with respect to the

ICA-based, reaching a factor of 1.9 between the GRGS (-6.01 cm/yr) and the JPL (-3.22 cm/yr) solution over *basin 1*. The difference in the equivalent water height trends can be mainly attributed to differences in the pre- processing techniques applied to the GRACE solutions used to filter out the high frequencies from the noisy raw data.

The importance of this study also resides in the possible applications into which such an interannual ice-sheet total discharge dataset can be involved, as the exploitation in global, regional and coastal ocean modeling. It can be prescribed, in fact, as forcing input in ocean circulation models, in order to study the response of sea level, ocean mass properties and thermohaline circulation to a realistic freshwater coastal discharge. Ocean models, in fact, are a powerful tool for the study of sea level change and for the investigation of the impact that ice-sheet total discharge has, and could have in the future, on the ocean state and in particular on sea level rise. Nevertheless, most of the current OGCMs do not take into account this important source of freshwater input; in fact, due to the lack of time-varying freshwater flux measurements, land runoff and ice discharge used in the current OGCMs simulations only includes climatological estimates that are assumed not to vary inter-annually; therefore ocean simulations cannot take into account increasing ice-sheets contribution and its variability, ignoring, in this way, one of the main cause of global sea level rise.

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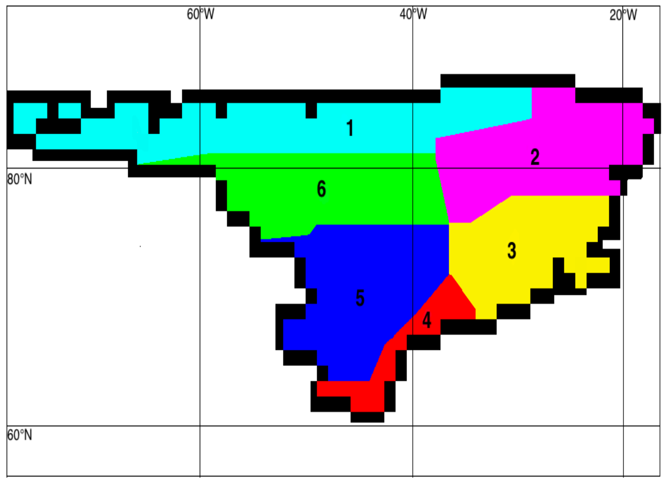

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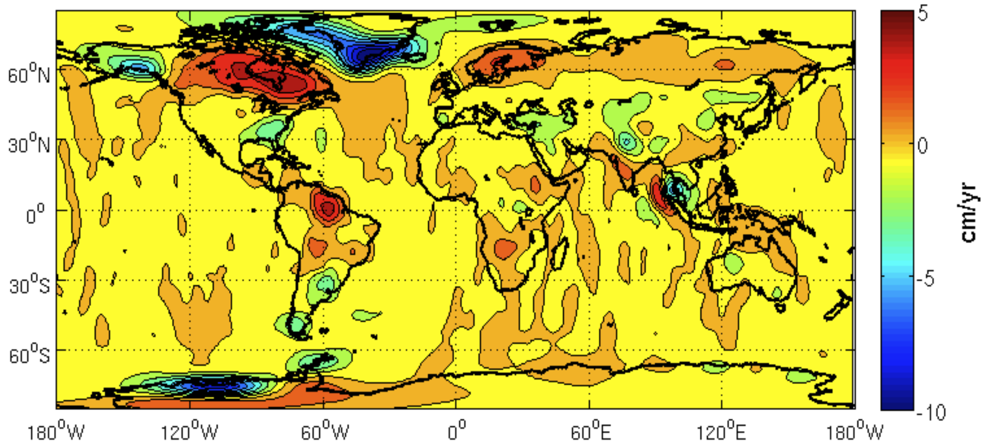

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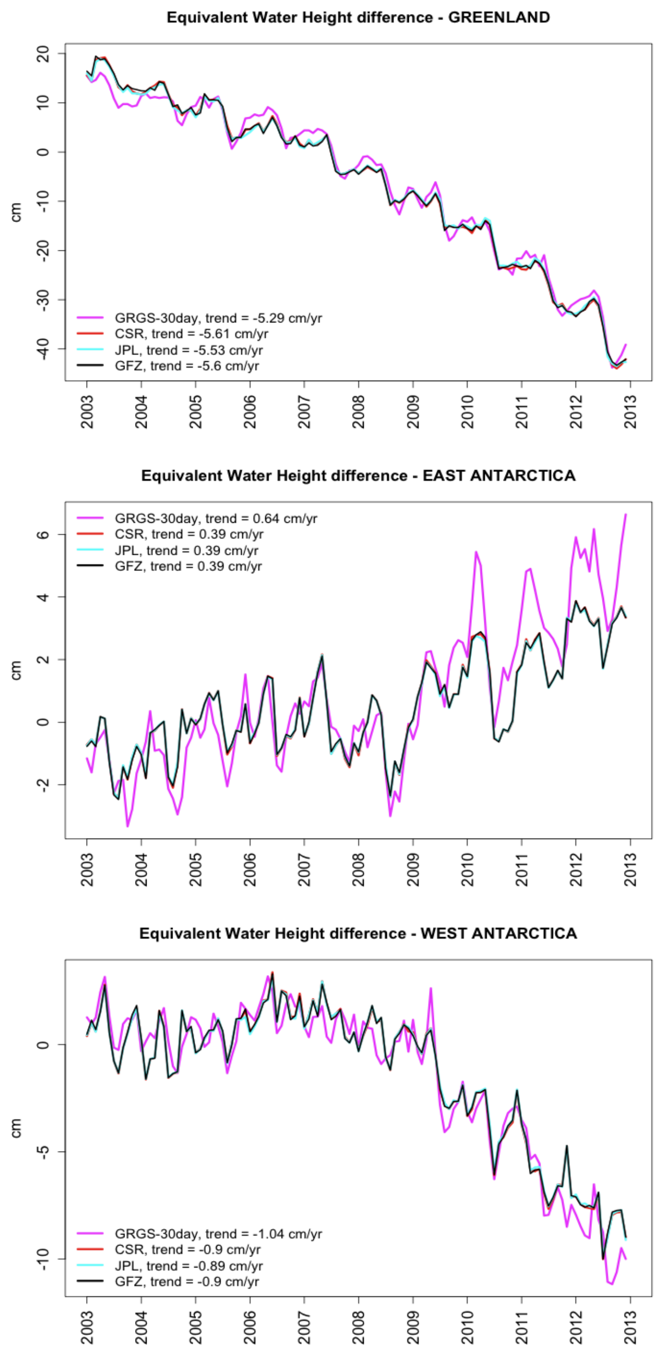

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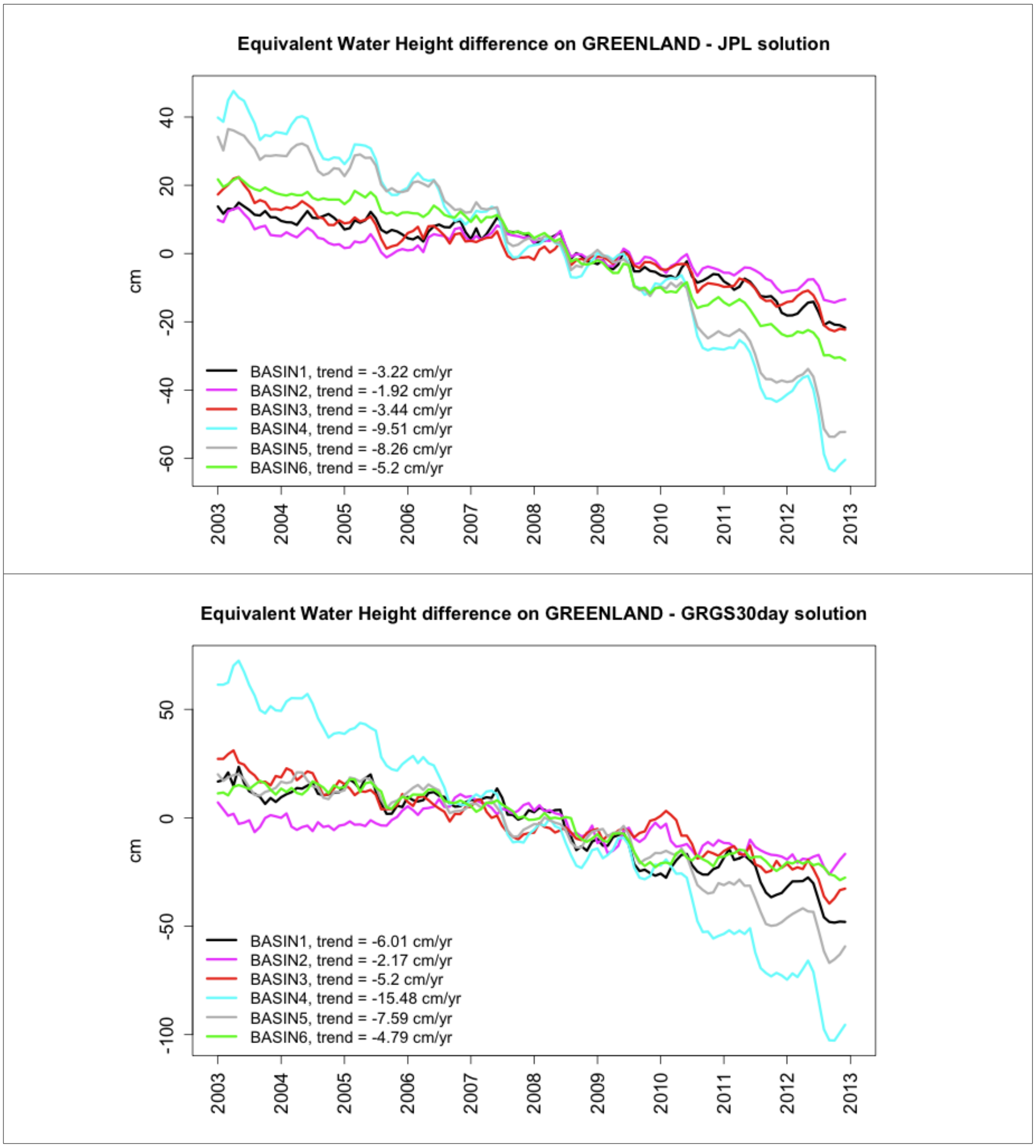

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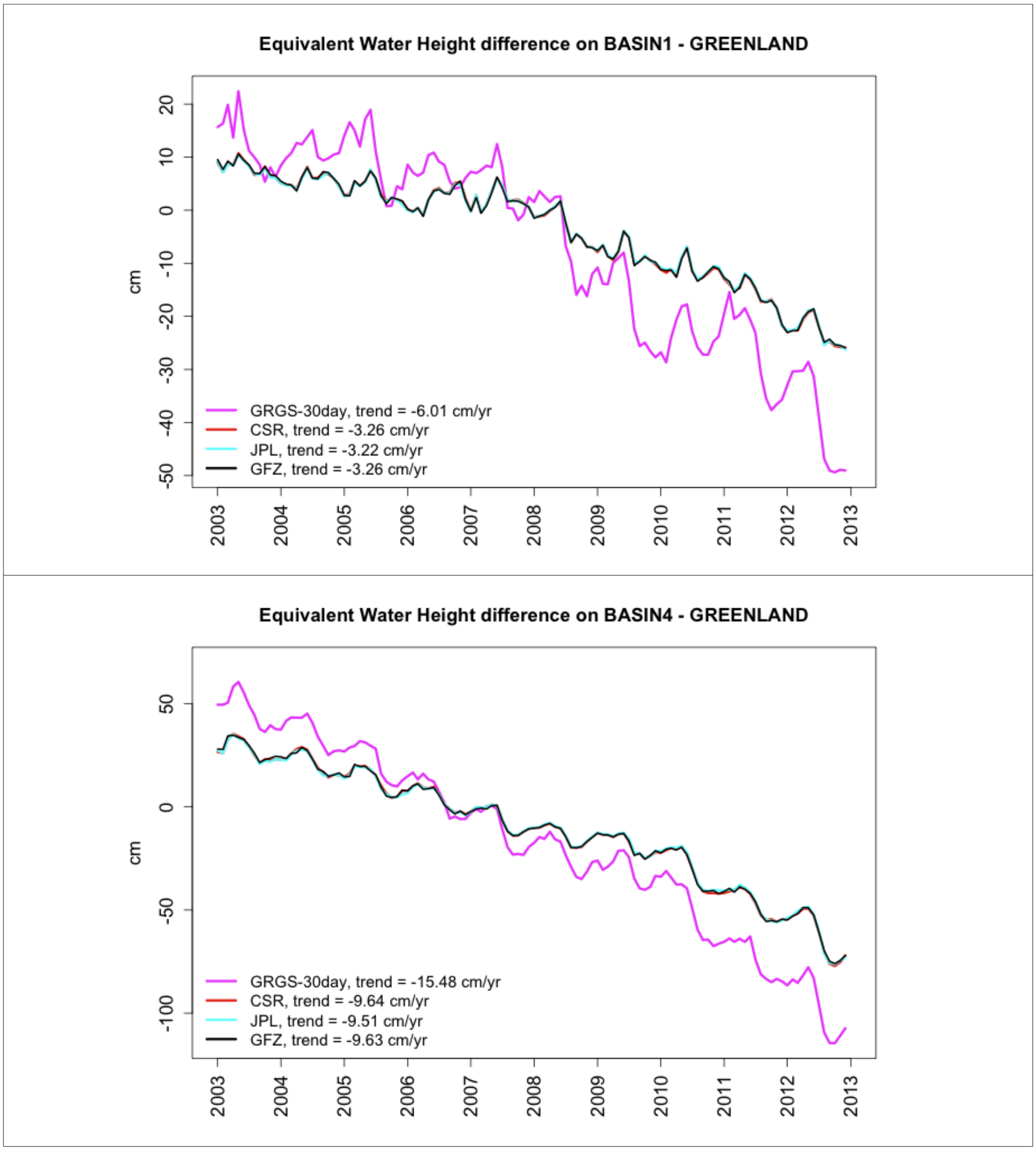

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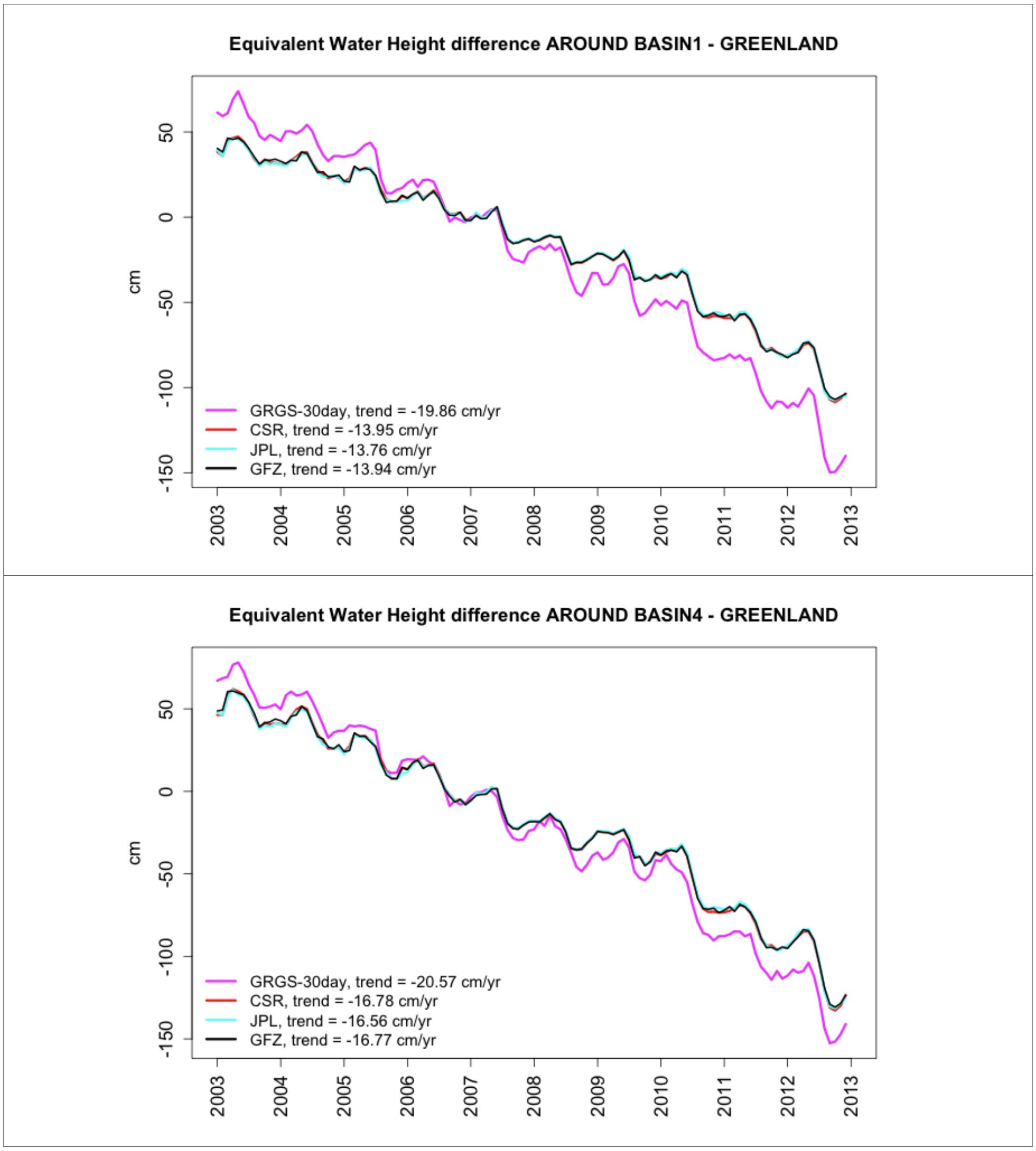

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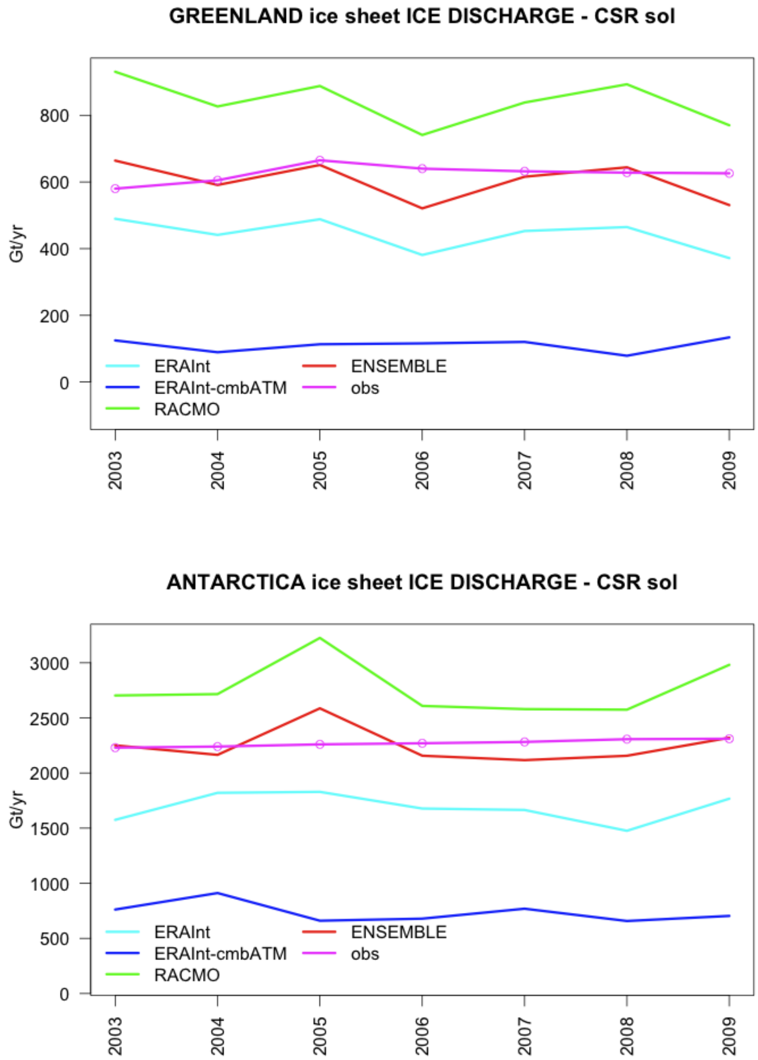

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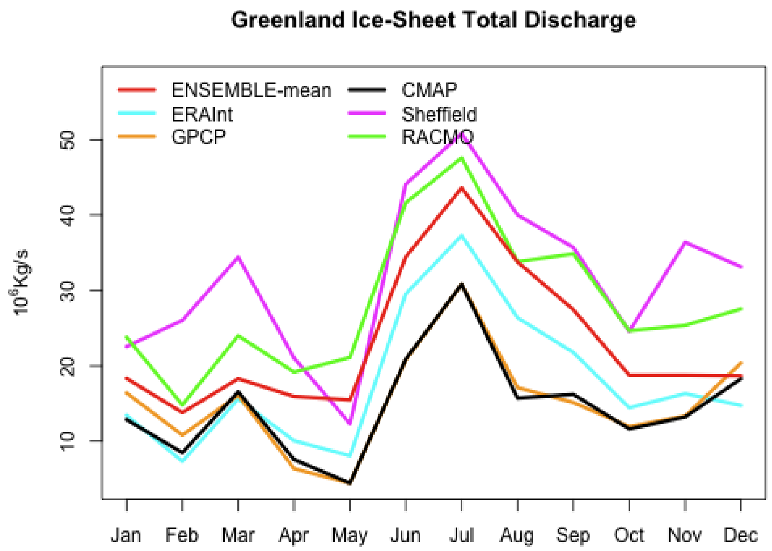

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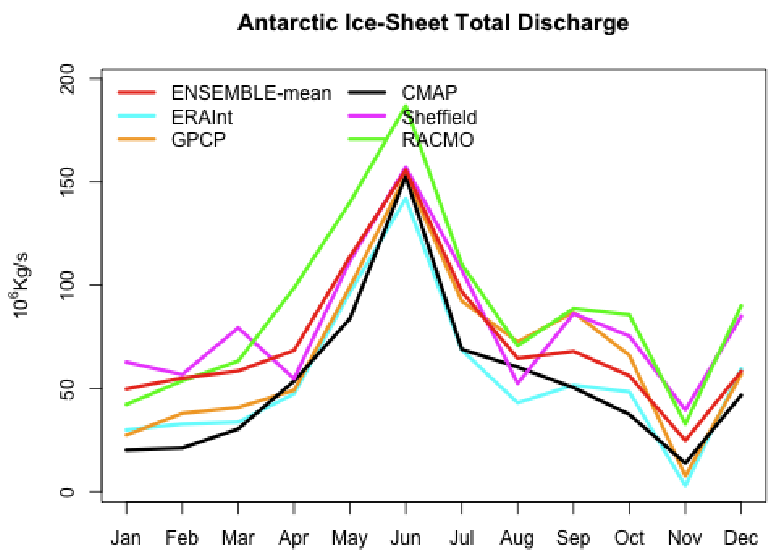

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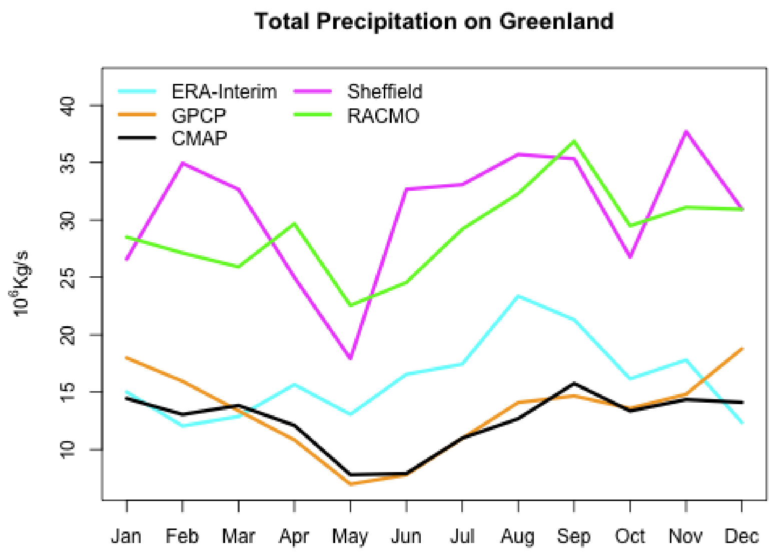

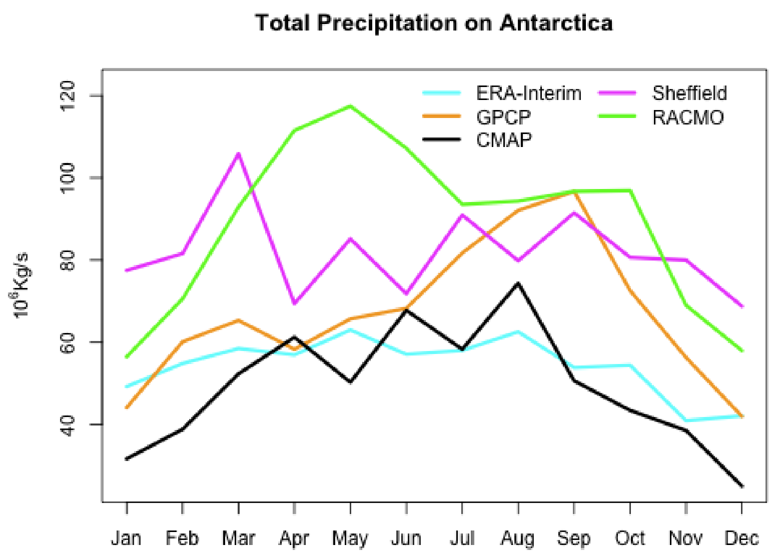

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