**Mass balance of the Greenland and Antarctic ice sheets and of the world’s glaciers – update since AR5 and what we need to know to make better projections**

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**Abstract.** Recent research shows increasing ice mass losses from the Greenland and Antarctic Ice Sheets and more generally from glaciers worldwide in the light of continued global warming. Here in an update of our previous ISMASS paper (Hanna et al. 2013) we review recent observational estimates of ice sheet and glacier mass balance, and their related uncertainties, first briefly considering relevant monitoring methods. Focusing on the response to climate change during 1992-2018, and especially the post-IPCC AR5 period, we discuss recent changes in the relative contributions of ice sheets and glaciers to sea-level change. We assess recent advances in understanding of the relative importance of surface mass balance and ice dynamics in overall ice-sheet mass change. We also consider recent improvements in ice-sheet modelling, highlighting data-model linkages and the use of updated observational datasets in ice-sheet models. Finally, by identifying key deficiencies in the observations and models that hamper current understanding and limit reliability of future ice-sheet projections, we make recommendations to the research community for reducing these knowledge gaps. Our synthesis provides a critical and timely review of the current state of the science in advance of the next Intergovernmental Panel on Climate Change Assessment Report that is due in 2021.

**1.0 Introduction**

Major uncertainties in predicting and projecting future sea level rise are due to the contribution of the two major ice sheets on Earth, Greenland and Antarctica (Pattyn et al., 2018). These uncertainties essentially stem from the fact that both ice sheets may reach a tipping point with a warming climate and that the timing of the onset of such a tipping point is difficult to assess. This is particularly true for the Antarctic ice sheet, where two instability mechanisms potentially operate, leading to a large divergence in timing of onset and mass loss, while the Greenland Ice Sheet is also particularly susceptible to increased mass loss from surface melting and associated feedbacks under anthropogenic warming.

The Expert Group on Ice Sheet Mass Balance and Sea Level (ISMASS; <http://www.climate-cryosphere.org/activities/groups/ismass>) convened a one-day workshop as part of POLAR2018 in Davos, Switzerland, on 15 June 2018, to discuss advances in ice-sheet observations and modelling since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). The talks and discussions are summarised here in an update of our previous review (Hanna et al. 2013) where we synthesised material from a similar workshop held in Portland, Oregon, USA, in July 2012. Here we focus, in the light of advances in the last six years, on what we need to know in order to make improved model projections of ice-sheet change. Apart from providing an update of recent observational estimates of ice-sheet mass changes, we also set this in a wider context of global glacier change. The paper is arranged as follows. In section (2) we discuss recent advances in ice-sheet observations; section (3) focuses on advances in modelling; and section (4) discusses recent and projected mass-balance rates for glaciers and ice caps, comparing these with recent ice-sheet changes, setting the latter in a broader perspective of global glacier change. Finally, in section (5) we summarise our findings and make key recommendations for stimulating further research.

**2.0 Observational estimates of ice-sheet total and surface mass balance**

In this section we summarise recent observation-based estimates of the total mass balance (TMB) of the Antarctic and Greenland ice sheets, also considering changes in surface mass balance (SMB; snow accumulation minus surface meltwater runoff) and – for marine-terminating glaciers - ice dynamics (solid ice dynamical discharge across the grounding line - the contact point of an ice sheet with the ocean where the ice mass becomes buoyant and floats - and subsequent calving of icebergs) where appropriate. Satellite and airborne observational techniques and modelling studies have provided a detailed representation of recent ice sheet mass loss and increase in ice discharge [Moon et al., 2012, Enderlin et al., 2014, Bigg et al. 2014, Shepherd et al., 2012, Shepherd et al. 2018, Rignot et al. 2019, Mouginot et al., 2019].

The main methods of estimating ice-sheet mass changes are: (1) satellite radar and laser altimetry, which measures changes in height of the surface over repeat surveys and by extrapolating over the surface area of interest estimates a volume change which, using knowledge or assumptions of near-surface density, is converted into a mass change; (2) satellite gravimetry, which effectively weighs the ice sheets through their gravitational pull on a pair of orbiting satellites called GRACE (or, since May 2018, the subsequent GRACE Follow On mission); and (3) the mass budget or component method, which compares SMB model output with satellite radar observations of ice velocity across a position on or close to the grounding line, from which ice discharge can be inferred if the thickness of ice at that point is also known.

All three methods have their strengths and weaknesses (e.g. Hanna et al. 2013, Bamber et al. 2018). Altimetry and, especially, gravimetry, require accurate quantification of Glacial Isostatic Adjustment (GIA; Section 2.3) which contaminates their signals. Gravimetry is limited by a relatively short time series (since 2002) and low spatial resolution (>100 km) compared with the other methods but is the only method directly providing mass change. Altimetry surveys provide elevation changes that need to be converted into volume and then mass changes, requiring knowledge of near-surface density which is often highly variable and uncertain for ice sheets. In addition, radar altimeter surveys do not adequately sample relatively steeper-sloping ice-sheet margins. However, ice-sheet altimetry surveys date back to the early 1990s. The mass-budget method involves subtracting two large quantities (SMB and discharge) and needs detailed and complete regional information on these components, which is recently available from satellite radar data for discharge while SMB cannot be directly measured at the ice-sheet scale but is instead estimated using regional climate and glaciology models. These have significant uncertainties in modelled accumulation and runoff (e.g. Fettweis 2018). However this is the only method that directly provides information about the physical processes causing mass change.

A major international research programme called ice sheet mass balance inter-comparison exercise (IMBIE; <http://imbie.org/> ) has attempted to reconcile differences between these various methods, and its second phase IMBIE2 has recently reported an updated set of reconciled TMB estimates for Antarctica (Shepherd et al. 2018) and is shortly expected to update previous results for Greenland. However, despite recent improvements in coverage and accuracy, modern satellite-based records are too short for attribution studies aiming to separate the contributions from anthropogenic greenhouse gas warming signal versus background climate variability to the contemporary mass loss [*Wouters et al.*, 2013], and proxy data such as ice cores are therefore used to overcome this limitation.

*2.1 Antarctic ice sheets*

Recent work agrees on significant and steadily growing mass losses from the West Antarctic Ice Sheet (WAIS) and the Antarctic Peninsula but highlights considerable residual uncertainty regarding the recent contribution of the East Antarctic Ice Sheet (EAIS) to global sea-level rise (SLR) (Shepherd et al. 2018, Rignot et al. (2019). For Antarctica there is relatively little surface melt but ice-shelf basal melt is much more significant (Rignot et al. 2013); the main mass losses are through dynamics, especially the stability of marine terminating glaciers which are susceptible to ocean warming, although SMB variations dominate interannual-decadal variability (Rignot et al. 2019). As a key output of the IMBIE2 project, Shepherd et al. (2018) built on Shepherd et al. (2012) by significantly extending the study period and reconciling the results of 24 independent estimates of Antarctic mass balance using satellite altimetry, gravimetry and the mass budget methods encompassing thirteen satellite missions and approximately double the number of studies previously considered. They found that the Antarctic ice sheets lost 2725±1400 Gt of ice, therefore contributing 7.6±3.9 mm to SLR, from 1992-2017, principally due to increased mass loss from the WAIS and Peninsula. However, they also found that EAIS was close to balance, i.e. 5±46 Gt yr-1 averaged over the 25 years, although this was the least certain region, attributed to its enormous area and relatively poorly constrained GIA (Section 2.3) compared with other regions. Shepherd et al. (2018) found that WAIS mass loss steadily increased from 53±29 Gt yr-1 for 1992-1996 to 159±26 Gt yr-1 during 2013-2017, and Peninsula losses increased by 15 Gt yr-1 since 2000, while the EAIS had little overall trend in mass balance during the period of study. The overall reconciled sea-level contribution from Antarctica rose correspondingly from 0.2 to 0.6 mm yr-1. These authors also reported no systematic Antarctic SMB trend, and they therefore attributed WAIS mass loss to increased ice discharge. Of particular concern is the case of ongoing grounding line retreat in the Amundsen Sea in West Antarctica, as well as basal melt of ice shelves through polynya-related feedbacks, e.g. in the Ross Sea (Stewart et al. 2019).

Rignot et al. (2019) used the mass budget method to compare Antarctic snow accumulation with ice discharge for 1979-2007, using improved, high-resolution datasets of ice-sheet velocity and thickness, topography and drainage basins and modelled SMB. Within uncertainties their TMB estimates for WAIS and the Antarctic Peninsula agreed with those of Shepherd et al. (2018) but they derived a -57±2 Gt yr-1 mass change (loss) for East Antarctica for 1992-2017, compared with the +5±46 Gt yr-1 mass for the same period derived in IMBIE2. Rignot et al. (2019) describe their uncertainties in ice thickness and SMB as “low” while highlighting large uncertainties in the IMBIE-2 EAIS mass estimates arising from volume to mass conversions with the altimetry data processing and significantly uncertain GIA corrections when processing GRACE data. Their results for East Antarctica are in stark contrast with Zwally et al. (2015) who, based on satellite laser altimetry, found EAIS mass gains of 136±28 Gt yr-1 for 2003-2008, attributing these to a residual dynamic thickening arising from an increase in snow accumulation during the Holocene rather than recently increased accumulation. However, the results of Zwally et al. (2015) have been questioned and have not been able to be reproduced by other workers (Scambos and Shuman 2016, Martín-Español et al. 2017). Bamber et al. (2018) describe “reasonable consistency between [EAIS mass balance] estimates” if they discount the outlier of Zwally et al. (2015). Notwithstanding, as highlighted by Hanna et al. (2013) and Shepherd et al. (2018), disparate estimates of the mass balance of East Antarctica, which vary by ~100 Gt yr-1, have not yet been properly resolved.

*2.2 Greenland Ice Sheet*

According to several recent estimates, the Greenland Ice Sheet lost 257±15 Gt yr-1 of mass during 2003-2015 (Box et al. 2018), 262±21 Gt yr-1 during 2007-2011 (Andersen et al. 2015), 269±51 Gt yr-1 during 2011-2014 (McMillan et al. 2016), 247 Gt yr-1 of mass - representing 37% of the overall land ice contribution to global sea-level rise - during 2012-2016 (Bamber et al. 2018), and 286±20 Gt yr-1 during 2010-2018 (Mouginot et al. 2019). A slightly greater mass loss of 308±12 Gt yr-1 based on GRACE gravimetric satellite data for 2007-2016 was given by Zhang et al. (2019). GrIS mass loss approximately quadrupled during 2002/3 to 2012/13 (Bevis et al. 2018). This increased wastage can be referenced to comparatively stable mean GrIS mass losses of 75±29 Gt yr-1 for 1900-1983 and 74±40 Gt yr-1 for 1983-2003 based on analysis of historic aerial imagery (Kjeldsen et al. 2015). The Greenland sea-level contribution over 1992-2017 was approximately one and a half times the sea-level contribution of Antarctica (Box et al. 2018). However this kind of average value masks very significant interannual variability of ±228 Gt yr-1, and even 5-year mean values can vary by ±102 Gt yr-1, based on 2003-2016 data; for example recent annual mass losses ranged from >400 in 2012 (a record melt year caused by jet-stream changes, e.g. Hanna et al. 2014) to <100 Gt just one year later (Bamber et al. 2018).

McMillan et al. (2016) found that high short-term mass balance variability was mainly due to year-to-year changes in runoff of 102 Gt yr-1 (~28% of the mean annual runoff value) with lesser contributions from annual snowfall variations of ~61 Gt yr-1 (~9% of the mean snowfall value) and solid ice discharge of ~20 Gt yr-1 (~5% of the mean annual discharge). Their interpretation of transient mass changes was supported by Zhang et al. (2019) who attributed big short-term (~3-year) fluctuations in surface mass balance to changes in atmospheric circulation, specifically the Greenland Blocking Index (GBI; Hanna et al. 2016), with opposite GBI phases in 2010-2012 (highly positive GBI) and 2013-2015 (less blocked Greenland). Also in the MODIS satellite record since the year 2000, Greenland albedo was relatively high from 2013-2018 after reaching a record low in 2012 (Tedesco et al. 2018). The relatively low GrIS mass loss in 2013-14 was termed the “pause” (Bevis et al. 2019). However, Zhang et al. (2019) inferred an acceleration of 18±9 Gt yr-1 in GrIS mass loss over the 2007-2016. Of course, given recent short-term variability, for example the recent slowdown of rapid mass loss increases in the 2000s and very early 2010s, such trends should only be extrapolated forward with great caution.

Greenland mass loss is mainly driven by atmospheric warming, and – based on ice-core-derived melt information and regional model simulations - surface meltwater runoff increased by ~50% since the 1990s, becoming significantly higher than pre-industrial levels and being unprecedented in the last 7000 years (Trusel et al. 2018). Enderlin et al. (2014) found an increasingly important role of runoff on TMB annual losses during their 2000-2012 study period, and concluded that SMB changes were the main driver of long-term (decadal or longer) mass loss.

However, just five marginal glaciers covering <1% of the GrIS by area were responsible for 12% of the net ice loss (McMillan et al. 2016), highlighting the potentially important role and sensitivity of ice dynamics; these authors alongside Tedesco et al. (2016) also found an atmospheric warming signal on mass balance in the northernmost reaches of the ice sheet. Taking a longer perspective from 1972-2018, using extended datasets of outlet glacier velocity and ice thickness, improved bathymetric and gravity surveys and newly-available high resolution SMB model output, Mouginot et al. (2019) reported that dynamical losses from the GrIS have continuously increased since 1972, dominating mass changes except for the last 20 years, estimating that 66±8% of the overall mass losses were from dynamics and 34±8% fromSMB. They concluded that dynamics are likely to continue to be important in future decades, apart from in the southwest where runoff/SMB changes predominate, and that the northern parts of GrIS – where outlet glaciers could lose their buttressing ice shelves - are likely to be especially sensitive to future climate warming.

*2.3 Glacial Isostatic Adjustment*

Processes associated with GIA must be accounted for when quantifying contemporary ice sheet change (Shepherd et al., 2018) and also when predicting the dynamics of future change (Gomez et al., 2015; Konrad et al., 2015). Specifically, ongoing changes to the height of the land surface and the shape of Earth’s gravitational field, in response to past ice-mass change, will bias gravimetry- and altimeter-based measurements of contemporary ice mass balance and alter the boundary conditions for ice sheet dynamics.

Numerical models can be used to estimate the geodetic signal associated with GIA (Whitehouse et al., 2012; Ivins et al., 2013; Argus et al., 2014) or it can be inferred via data inversion (Gunter et al., 2014; Martin-Espanol et al., 2016; Sasgen et al., 2017). Both approaches typically rely on the assumption that mantle viscosity beneath the major ice sheets is spatially uniform and high enough that the signal due to past ice-mass change is constant in time. However, recent work has revealed regions in both Greenland and Antarctica where mantle viscosity is much lower than the global average (e.g. Nield et al., 2014; Khan et al., 2016; Barletta et al., 2018; Mordret, 2018). This has two important implications. First, in regions where upper mantle viscosity is less than ~1019 Pa s the response to recent (decadal to centennial) ice-mass change will dominate the GIA signal, and may not be steady in time. In such regions a time-varying GIA correction, which accounts for both the viscous and elastic response to contemporary ice-mass change, should be applied to gravimetry, altimetry and other geodetic observations. Secondly, since GIA acts to reduce the water depth adjacent to a shrinking marine-based ice sheet, this can act to slow (Gomez et al., 2010) or reverse (Kingslake et al., 2018) the rate of ice loss, with the stabilizing effect being stronger in regions with low upper mantle viscosity (Gomez et al., 2015; Konrad et al., 2015). To better understand the behaviour and likely future of marine-based ice masses it will be necessary to quantify the spatially-varying strength of this stabilizing effect and account for feedbacks between GIA and ice dynamics within a coupled modelling framework (e.g. Pollard et al., 2017; Gomez et al., 2018).

**3.0 Recent advances in ice-sheet modelling**

*3.1 Modelling ice-sheet instabilities*

The marine ice sheet instability (MISI) hypothesises a possible collapse of West Antarctica as a consequence of global warming. This process, first proposed in the 1970s (Weertman, 1974; Thomas and Bentley, 1978), was recently theoretically confirmed and demonstrated in numerical models (Schoof, 2007; Pattyn et al., 2012). It arises from thinning and eventually flotation of the ice near the grounding line, which moves the latter into deeper water where the ice is thicker. Thicker ice results in increased ice flux, which further thins (and eventually floats) the ice, resulting in further retreat into deeper water (and thicker ice) and so on. This is especially true when the bedrock deepens toward the interior of the ice sheet, i.e., a retrograde bed slope, as is the case for the West Antarctic ice sheet. The possibility that some glaciers, such as Pine Island Glacier and Thwaites Glacier, are already undergoing MISI has been suggested (Rignot et al., 2014; Christianson et al., 2016). Thwaites Glacier is currently in a less-buttressed state, and several simulations using state-of-the-art ice sheet models indicate continued mass loss and possibly MISI or MISI-like behaviour even under present climatic conditions (Joughin et al., 2014; Nias et al., 2016; Seroussi et al., 2017). However, rapid grounding line retreat due to MISI or MISI-like behaviour remains highly dependent on the subtleties of subglacial topography (Waibel et al., 2018), limiting the predictive behaviour of the onset of MISI. In other words, geography matters.

The marine ice cliff instability (MICI) hypothesises collapse of ice cliffs that become unstable and fall down if higher than ∼90 m above sea level, leading to major the collapse of ice sheets during past warms periods [Pollard et al., 2015; DeConto and Pollard, 2016]. MICI is a process that facilitates and enhances Marine Ice Sheet Instability through a decrease in ice-shelf buttressing. MICI relies on the assumption of perfect plastic rheology to represent failure. Cliff instability requires an a priori collapse of ice shelves and is favoured by hydro-fracturing through the increase of water pressure in surface crevasses, which increases the opening term (Bassis and Walker, 2012; Nick et al., 2013; Pollard et al., 2015). Whether MICI is necessary to explain Pliocene high sea level stands has been questioned recently (Edwards et al., 2019).

International model intercomparisons on marine ice sheet models (MISMIP; MISMIP3d) greatly improved those models in terms of representing grounding-line migration numerically by conforming them to known analytical solutions (Pattyn et al. 2012; 2013). These numerical experiments demonstrated that in order to resolve grounding-line migration in marine ice-sheet models, a sufficient high spatial resolution needs to be applied, since membrane stresses need to be resolved across the grounding line to guarantee mechanical coupling. The inherent change in basal friction occurring across the grounding line – zero friction below the ice shelf – requires high spatial resolution (e.g., <1 km for Pine Island Glacier; Gladstone et al., 2012) for an accurate representation of grounding-line migration. Therefore, a series of ice-sheet models have implemented a spatial grid refinement, mainly for the purpose of accurate data assimilation (Cornford et al., 2015; Gillet-Chaulet et al., 2012, Morlighem et al., 2010), but also for further transient simulations where the adaptive mesh approach enables the finest grid to follow the grounding-line migration (Cornford et al, 2013; 2016). These higher spatial resolutions of the order of hundreds of meters in the vicinity of grounding lines also poses new challenges on data management for modelling purposes (Durand et al., 2011).

*3.2 Model initialisation, uncertainty and inter-comparison*

Despite major improvements in model sophistication, major uncertainties still remain pertaining to model initialisation as well as the representation of critical processes such as basal sliding and friction, ice rheology, ice damage (such as calving) and sub-shelf melting. New developments in data assimilation methods led to improved initialisations in which the initial ice-sheet geometry and velocity field are kept as close as possible to observations by optimising other unknown fields, such as basal friction coefficient and ice stiffness (accounting for crevasse weakening and ice anisotropy; Arthern et al., 2006; 2010, Cornford et al., 2015; MacAyeal, 1992; Morlighem et al., 2010, 2013). Motivated by the increasing ice-sheet imbalance of the Amundsen Sea Embayment glaciers over the last 20 years (Shepherd et al., 2018), and supported by the recent boom in satellite data availability, data-assimilation methods are progressively used to evaluate unknown fields using time-evolving states accounting for the transient nature of observations and the model dynamics (Gillet-Chaulet et al., 2016, Goldberg et al., 2013; 2015, 2016).

Ensemble model runs equally improve the predictive power of models by translating uncertainty in a probabilistic framework. The use of statistical emulators thereby increases the confidence in sampling parameter space (Bulthuis et al., 2019) and improving uncertainties in ice dynamical contributions to future sea-level rise (Edwards et al., 2019).

An important step forward since the Fifth Assessment Report of the IPCC (IPCC, 2013) is that process-based projections of sea-level contributions from both ice sheets are now organised under the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) and form an integral part of the CMIP process (Eyring et al., 2016; Nowicki et al. 2016; Goelzer et al., 2018a; Seroussi et al., 2018). ISMIP6 is working towards providing projections of future ice sheet mass changes for the next Assessment Report of the IPCC (AR6). It has recently finished its first set of experiments focussing on the initial state of the ice sheets as starting point for future projections (Goelzer et al., 2018a; Seroussi et al., 2018), which has seen an unprecedented return from ice sheet modelling groups globally. With ISMIP6, the ice sheet modelling community has engaged to evolve to new standards in availability, accessibility and transparency of ice sheet model output data (e.g. Goelzer et al., 2018b), facilitating model-model and data-model comparison and analysis.

ISMIP6 has strengthened the links between the ice sheet modelling community and the global and regional climate modelling communities, the ocean modelling community and the communities of remote sensing and observations of ice, ocean and atmosphere.

*3.3 Ice sheet model-climate model coupling*

Fully coupled AOGCM-ISM simulations with state of the art AOGCMs and ISMs are an emerging field of active research (e.g. Fyke et al., 2014; Fischer et al., 2014; Vizcaino et al., 2015; Reerink et al., 2016; Fyke et al., 2018) that ISMIP6 is also leading and supporting (Nowicki et al. 2016). This development will help to improve our understanding of processes and feedbacks due to climate-ice sheet coupling in consistent modelling frameworks.  
 Coupling approaches between atmosphere/ice/ocean/sea ice have been considerably developed since the AR5 (Asay-Davis et al. 2017; Pattyn et al. 2017; Favier et al. 2017; Donat‐Magnin et al. 2017) but there is still an important need to document the processes occurring at the interface between water and ice. Observation are currently developed to study the ocean characteristics below the ice-shelves using AUV/ROV (Jenkins et al. 2010; Kimura et al. 2016; Nicholls et al. 2006) and should offer critical information for modellers.

Regardless of ice sheets being an interactive component of the climate system, and the need to model on-going connections of global climate change with the mass budget of ice sheets, the coupling of ice sheet and climate models is only starting [*Nowicki et al.*, 2016; *M Vizcaino*, 2014]. Coupled models have been applied to investigate several outstanding questions regarding ice-climate interaction, particularly on multi-century and multi-millennia time scales, like impacts of meltwater on ocean circulation [*Mikolajewicz et al.*, 2007; *Ridley et al.*, 2005], regional impact of ice sheet area change [*Ridley et al.*, 2005; *Vizcaino et al.*, 2010; *Vizcaino et al.*, 2008], the role of albedo change on future ice sheet surface energy budget [*Vizcaino et al.*, 2014], elevation-SMB feedback [*Vizcaino et al.*, 2015], etc. On-going work on model development aims to include more interaction processes, such as the effects of ocean warming on ice sheet stability [*Straneo et al.*, 2013].

Due to their high computational cost, simulations ensembles (for ice sheet parameters as well as climate forcing) are rare in coupled ice-sheet and climate modelling, however necessary. These ensembles are essential tools to constrain uncertainty in century projections as well as to complement observations for the attribution of on-going mass loss. The first published ensemble accounting for internal climate variability in coupled Atmosphere-Ocean General Circulation and Ice Sheet modelling is in *Vizcaino et al.* [2015], which is also currently the only coupled study with results for Representative Concentration Pathways, in this case RCP3.0, RCP4.5 and RCP8.5. By comparing Greenland ice sheet mass balance evolution through years 1850 to 2300 from the three individual simulations of an ensemble under identical historical and (extended) RCP8.5 scenarios, the study shows a relatively high uncertainty from climate variability in the simulation of contemporary mass loss. However, and consistently with results for global climate projections from the last IPCC report, the dominant uncertainty for century and multi-century projections comes from scenario choice.

*3.4 Regional climate modelling and surface mass balance modelling: advances and challenges*

3.4.1 General

Recent efforts to collect, synthesise and quality-control in-situ observations SMB over the AIS and GrIS have greatly improved our confidence in these measurements (Favier et al. 2013, Machguth et al. 2016), yet the observational density remains too low to estimate ice sheet wide SMB based on interpolation of these data alone. Uncertainties remain especially large along the ice sheet margins, where SMB gradients are steepest and data density lowest because of adverse climate conditions (Arthern et al. 2006, Bales et al. 2009). Moreover, most in-situ observations constitute an integrated measurement, providing little insight in SMB component partitioning and seasonal evolution. Suitable co-located meteorological observations enable time-dependent estimates of SMB and surface energy balance components such as snow accumulation, sublimation and melt (van den Broeke et al. 2004 & 2011), but especially on the AIS surprisingly few (automatic) weather stations collect sufficient data to do so. In the GrIS ablation zone, the PROMICE automatic weather station (AWS) network has recently resolved this problem (Citterio et al. 2015).

Although their performance in simulating ice sheet SMB continually improve (Lenaerts et al. 2016, van Kampenhout et al. 2017), Earth System Models (ESMs) currently have insufficient (50-100 km) horizontal resolution in the atmosphere to properly resolve marginal SMB gradients, although upcoming variable-resolution ESMs may alleviate this. Moreover, as they do not assimilate observations, ESMs do not simulate realistic weather. Atmospheric reanalyses have similar low resolution but do assimilate meteorological observations, and hence can be used to force regional climate models (RCMs) at their boundaries. As a result, RCMs provide reasonably realistic ice sheet weather at acceptable resolutions: typically 25 km for the full AIS (van Wessem et al. 2018) and 5 km for AIS sub-regions (van Wessem et al. 2015, Lenaerts et al. 2012, Lenaerts et al. in review) and the GrIS (Lucas-Picher et al. 2012, Fettweis et al. 2017, van den Broeke et al. 2016). Further statistical downscaling to 1 km resolution is required to resolve SMB over narrow GrIS outlet glaciers (Noël et al. 2018). The resulting gridded SMB products cover multiple decades (1979/1958-present for AIS/GrIS, respectively) at (sub-)daily timescales, allowing synoptic case studies at the SMB component level but also multidecadal trend analysis. RCM products also helped to extend ice sheet SMB time series further back in time by guiding the interpolation between firn cores (Thomas et al. 2017, Box 2013).

Further improvements are needed: RCMs struggle to realistically simulate (mixed-phase) clouds (van Tricht et al. 2016) and (sub-) surface processes, such as drifting snow (Lenaerts et al. 2017), bio-albedo (Stibal et al. 2017) and heterogeneous meltwater percolation (Steger et al. 2017). A powerful emerging observational technique for dry snow zones is airborne accumulation radar (Koenig et al. 2016, Lewis et al. 2017), which together with improved re-analyses products such as MERRA (Cullather et al. 2016) will further improve our knowledge of contemporary ice sheet SMB.

Recently, there has been outstanding progress in closing the gap between global and regional climate models regarding the surface mass balance calculation, e.g., through downscaling with the elevation classes method [*Lipscomb et al.*, 2013; *Vizcaino et al.*, 2013]; and improvement of snow and ice physics representation for glaciated surfaces within the global climate models [*Cullather et al.*, 2014; *Lipscomb et al.*, 2013; *van Kampenhout et al.*, 2017]

3.4.2 Greenland

The elevation classes downscaling method has been applied in a number of studies on the Greenland ice sheet with the Community Earth System Model (CESM), such as regional climate and SMB projections [*Vizcaino et al.*, 2014] relationship between SMB variability and future climate change [*Fyke et al.*, 2014] or emergence of an anthropogenic signal in the SMB [*Fyke et al.*, 2014]. For the latter, the authors used a historical-RCP8.5 simulation (1850-2100) with coupled SMB and climate and fixed ice sheet topography. They identified a bimodal emergence pattern, with upward emergence in the interior due to increased accumulation, downward emergence in the margins due to increased ablation, and an intermediate area of no emergence due to compensating elevated ablation and accumulation. This study points to Greenland interior as an interesting area to monitor emergence, due to early emergence in connection with low SMB variability in connection with the dry and cold conditions relative to the ice sheet margins. As a follow-up to this study, the timings of emergence given in this study for a single model simulation should be revised with additional simulations, e.g., from an ensemble, as well as multi-scenario and inter-model comparisons. In addition, these results should be confronted with current observations of current SMB decline to identify whether the processes causing this decline are represented in the models [*Hanna et al.*, 2018].

3.4.3 Antarctica

Comparison of recent SMB with MB values from (IMBIE team 2018) reveals that present precipitation and SMB variations significantly control EAIS MB (Gardner et al. 2018) justifying that further SMB modelling improvements, validations, and inter-comparisons are still needed (Agosta et al. 2018; Favier et al. 2017). Thanks to observations, the inclusion of several key processes have been improved in models since the AR5, and more accurate parameterisations are now available like the ability to assess the role in the SMB of the stable atmospheric boundary layers on the continent (Vignon et al. 2017), the wind drifting snow, (Amory et al. 2017; van Wessem et al. 2018) or the glacial hydrology (Kingslake et al. 2017; Hubbard et al. 2016).

However, climate reanalyses used to force regional circulation models still present biases (Bromwich et al. 2011) most noticeably in moisture transport (Dufour et al. 2018). Constraining atmospheric moisture and cloud microphysics with ground-based techniques available in Antarctica (ceilometer, infrared pyrometer, vertically profiling precipitation radar (Gorodetskaya et al. 2015), polarimetric weather radar, micro rain radar, weighing gauges, multi-angle snowflake cameras (Grazioli et al. 2017a), etc.) is necessary to accurately model cloud evolution and precipitation. Data are only punctual justifying the use of distributed remote sensing techniques to characterize the Antarctic precipitation statistics and rates (e.g., Cloudsat products (Palerme et al. 2014)). However, processes occurring within 1 km above the surface are unreached by satellite sensors. This is a critical layer for SMB estimates as it is where sublimation impacts precipitating snowflakes (Grazioli et al. 2017b) and the drifting snow particles (Amory et al. 2017; van Wessem et al. 2018) leading to potential feedbacks on atmospheric moisture (Barral et al. 2014). Thus continental scale sublimation may be underestimated, suggesting MB and SMB agreement likely relies on large error compensations in models (Agosta et al. 2018) .

A better description of the atmospheric structure at regional and synoptic scales is needed during precipitation events, and particularly during events controlling the temporal and spatial SMB variability. Several studies present site specific results on precipitation origins (precipitation from synoptic scale systems, hoar frost, diamond dust (Dittmann et al. 2016; Stenni et al. 2016; Schlosser et al. 2016)) and on their impact on the local SMB. Synoptic-scale precipitation is known to control the inter-annual variability of accumulation in Dronning Maud land (Gorodetskaya et al. 2014), Dome C, and Dome F (Schlosser et al. 2016) through high intensity precipitation occurrences, but continental-scale studies for Antarctica are missing. High precipitation events are related to warm and moist air mass intrusions linked to mid-tropospheric planetary waves (Turner et al. 2016) leading to inland advection of moisture and are often connected with the main modes of atmospheric circulation variability at southern high-latitudes (Thompson et al. 2011; Turner et al. 2016; Nicolas et al. 2017; Bromwich et al. 2012). Moisture intrusions are also related to low-elevation surface melt via positive temperature anomalies as observed at WAIS (Nicolas et al. 2017) or on the Larsen ice shelves (Kuipers Munneke et al. 2018; Bozkurt et al. 2018). However, the synoptic causes of these events are still poorly known. Moreover, the feedbacks between melting and albedo, which may be critical for processes prior to ice shelf collapses (Kingslake et al. 2017), are poorly observed in the field. Currently, there is a large gap between the large scale on which remotely sensed information is currently obtained (Lenaerts et al. 2016; Kuipers Munneke et al. 2018) and the local scale on which the physical laws may be applied. This scaling problem is also particularly strong for processes involving erosion and the redistribution of snow (Amory et al. 2017), which occur at a decametre scale (Libois et al. 2014; Souverijns et al. 2018), whereas those observed using space- and airborne microwave radar (e.g., between 4 and 6 GHz) or ground penetrating radars (GPR) (Fujita et al. 2011; Verfaillie et al. 2012; Medley et al. 2013, 2015; Frezzotti et al. 2007) are relevant at the kilometre scale, the latter being more accurately the one controlling the SMB average modelled by regional circulation models (Agosta et al. 2018; van Wessem et al. 2018).

Despite improvements in regional-scale models, assessing the future SMB of Antarctica will rely on our capability to produce accurate future projections of the moisture fluxes towards Antarctica. These changes will be linked to changes in the sea-ice characteristics (Bracegirdle et al. 2017; Krinner et al. 2014; Palerme et al. 2017) and in the westerly circulation and the atmospheric blocking patterns around Antarctica (Massom et al. 2004), which are known to present biases in the CMIP5 simulations (Bracegirdle et al. 2017; Favier et al. 2016). For this reason, bias corrections based on nudging approaches or data assimilation schemes (Beaumet et al. 2017; Krinner et al. 2014) have been proposed to offer additional information to ensemble approaches. Nevertheless, utilizing paleo-climate information on the westerlies (Saunders et al. 2018), sea ice characteristics (Campagne et al. 2015), temperature (Jones et al. 2016), and SMB (Thomas et al. 2017) may be useful in constraining the modelled future climate variability and impacts in the southern hemisphere (Jones et al. 2016; Abram et al. 2014). This information will help to define when the SMB increase caused by the anthropogenic warming will emerge from the natural climate variability of Antarctica. This is currently expected to occur after 2020-2050 (Previdi and Polvani 2016).

**4.0. Recent and projected mass-balance rates for glaciers and ice caps**

We here review the advances, since the IPCC AR5, in the estimate of the contribution to SLR of wastage from glaciers and ice caps (henceforth, glaciers), as well as its projections to the end of the 21st century. At the time of AR5, the first consensus estimate of this contribution had just been published (Gardner et al., 2013), of 259±28 Gt yr−1 (0.94 ± 0.08 mm yr−1 SLE) for 2003–2009, including the contribution from the glaciers in the periphery of Greenland and Antarctica (henceforth, peripheral glaciers). For the longer period 1993–2010, AR5 attributed 27% of the SLR to wastage from glaciers (Church et al., 2013), above the combined contribution of the ice sheets of Antarctica and Greenland, of 21%, despite the global glacier volume is only ~0.6% of the combined volume of both ice sheets (Vaughan et al., 2013). Since then, the contribution to SLR from the ice sheets has grown at an accelerated rate, as discussed in earlier sections, which has resulted in a current dominance of the ice-sheet contribution despite the contribution from glaciers has also increased in absolute terms, as will be discussed in this section.

*4.1 Methods used to estimate the global glacier mass balance*

For estimating the global mass balance of glaciers, in addition to techniques already discussed for ice sheets, such as repeated altimetry or gravity observations, or the input-output method, other methods are commonly used. The purely observation-basedtechniques include the extrapolation of both in-situ direct observations by the glaciological method and geodetic mass balance estimates (Cogley, 2009), and the reconstructions based on glacier length changes (Leclercq et al., 2011, 2012, 2014). The *glaciological method* relies on point measurements of climatic mass balance (surface accumulation minus ablation) which are then integrated to the entire glacier surface (Cogley et al., 2011). Such measurements are available for a reduced sample of <300 glaciers (Zemp et al., 2015) of more than 200,000 glaciers inventoried worldwide (Pfeffer et al., 2014), which introduces a bias when extrapolating to the whole glacierized area of undersampled regions (Gardner et al, 2013). The *geodetic mass balance*, in turn, is determined using volume changes from DEM differencing and then converting to mass changes using an appropriate assumption for the density (Huss, 2013). The reconstructions based on observed glacier length changes convert these, upon normalization and averaging to a global mean, to normalized global volume change. The latter is converted into global glacier mass change using a calibration against the global glacier mass change over a certain period (Leclercq et al., 2011).

Finally, the modelling-based approaches for estimating past or current changes are mostly based on the use of climatic mass balance models forced by either climate observations or climate model output, calibrated and validated using surface mass-balance observations. As these techniques are based on a statistical scaling relationship, they are commonly referred to as *statistical modelling*, to distinguish them from the use of a *regional climate model* (RCM) to estimate, directly, the surface mass balance of an ice mass. The latter works well for ice caps, but not for glaciers, due to their complex topography and corresponding micro-climatological effects (Bamber et al., 2018). Based on statistical modelling, an analysis of the processes and feedbacks affecting the global sensitivity of glaciers to climate change can be found in Marzeion et al. (2014a), while the attribution of the observed mass changes to anthropogenic and natural causes has been addressed by Marzeion et al. (2014b).

*4.2 20th century and current estimates*

Much of the work done since AR5 has focused on improving the estimates for the reference period 2003-2009 (or some earlier periods), and on producing new estimates for more recent (or extended) periods. Both the reanalyses and the new estimates have been based on improvements in the number of mass balance or glacier length changes observations, and on the use of an increased set of gridded climate observations, and of more complete and accurate global glacier inventories and global DEMs. These improvements allowed Marzeion et al. (2015) to achieve the agreement, within error bounds, of the global reconstructions of the mass losses from glacier wastage for the periods 1961-2005, 1902-2005 and 2003-2009 produced using the various methods available. In spite of the agreement at the global level, strong disagreements persisted for particular regions such as Svalbard and the Canadian Arctic, likely because of the omission of calving in the statistical models. Marzeion et al. (2017), using a yet more extended set of glaciological and geodetic measurements (Zemp et al., 2015), gave a global glacier mass-change rate estimate of −0.61 ± 0.07 mm SLE yr−1 for 2003-2009 (including Greenland peripheral glaciers, but not those of the Antarctic periphery), obtained by averaging various recent GRACE-based studies (Jacob et al., 2012; Chen et al., 2013; Yi et al., 2015; Schrama et al., 2014) and several studies combining GRACE with other datasets (Gardner et al., 2013, and an update of it; Dieng et al., 2015; Reager et al., 2016; Rietbroek et al., 2016). The studies based on GRACE data consistently give less negative glacier mass balances than those obtained using other methods. Uncertainties in the GRACE-derived estimates remain important especially due to the small size of glaciers compared with GRACE footprint of ~300 km. Associated problems include the leakage of the gravity signal into the oceans, or the difficulty of distinguishing between mass changes due to glacier mass changes or to land water storage changes. Uncertainties in the GIA correction also remain, and the effects of rebound from the Little Ice Age (LIA) deglaciation have to be accounted for.

Parkes and Marzeion (2018) have analysed the contribution to SLR from uncharted glaciers (glaciers melted away and small glaciers not inventoried) during the 21st century. Although they will play a minimal role in SLR in the future, the important finding is that their contribution is sufficient to close the historical sea-level budget, so undiscovered physical processes are no longer required.

The most recent study to highlight is that of Bamber et al. (2018), who have updated the glacier mass-change rates presented in Marzeion et al. (2017) by adding new estimates of mass trends for the Arctic glaciers and ice caps and the glaciers of High-Mountain Asia and Patagonia, which together contribute to 84% of the SLR from glacier wastage. They combine the most recent observations (including CryoSat2 radar altimetry) and the latest results from statistical modelling, as well as regional climate modelling for the Arctic ice caps (Noël et al., 2018) and stereo photogrammetry for High Mountain Asia (Brun et al., 2017). They find poor agreement between the estimates based on statistical modelling and all other methods (altimetry/gravimetry/RCM) for Arctic Canada, Svalbard, peripheral Greenland, the Russian Arctic and the Andes, which are all regions with significant marine- or lake-terminating glaciers, where statistical modelling, which does not account for frontal ablation, is expected to perform worse than the observational-based approaches. Bamber et al. (2018) also present pentadal mass balance rates for the period 1992-2016, which are shown in Table Y and clearly illustrate the increase in global glacier mass losses. If we add to the mass budget for the last pentad (2012-2016) in Table Y the mass budget of −33 Gt yr−1 for the Greenland peripheral glaciers estimated by averaging the CryoSat and RCM values for 2010-2014 given in Bamber et al. (2018, Table 1), and the mass budget of −6 Gt yr−1 for the Antarctic peripheral glaciers over 2003-2009 estimated by Gardner et al. (2013), we get an estimate of the current global glacier mass budget of −266 ± 33 Gt yr−1 (0.73 ± 0.09 mm SLE yr−1).

**Table Y**. Pentad mass balance rates for all glaciers and ice caps, excluding the peripheral glaciers of Greenland and Antarctica. Modified from Bamber et al. (2018). The contributions from the peripheral glaciers are here excluded because in Bamber et al. (2018) the peripheral glacier contributions are included in those of the corresponding ice sheet because most data sources (many of them from GRACE) do not separate the peripheral glacier contributions. For reference, the mass-change rates during 2003-2009, according to Gardner et al. (2013), were of −38 ± 7 Gt yr−1 (0.10 ± 0.02 mm SLE yr−1) for the Greenland peripheral glaciers, and of −6 ± 10 Gt yr−1 (0.02 ± 0.03 mm SLE yr−1) for the Antarctic peripheral glaciers.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Pentad | 1992-1996 | 1997-2001 | 2002-2006 | 2007-2011 | 2012-2016 |
| Gt yr−1 | −117 ± 44 | −149 ± 44 | −173 ± 33 | −197 ± 30 | −227 ± 31 |
| mm SLE yr−1 | 0.32 ± 0.12 | 0.42 ± 0.12 | 0.48 ± 0.09 | 0.55 ± 0.08 | 0.63 ± 0.08 |

*4.3 Projected estimates to the end of the 21st century*

Among the post-AR5 studies on projected estimates of mass losses by glaciers to the end of the 21st century, we highlight those of Radić et al. (2014) and Huss and Hock (2015). While both approaches share many common features (glacier inventory, global climate models and emission scenarios, a temperature-index mass balance model, similar climate forcing for the calibration period and similar global DEMs), they have two remarkable differences. First, Radić et al. (2014) relies on volume-area scaling for initial volume estimate and to account for the dynamic response to modelled mass change, while Huss and Hock’s (2015) derive the initial ice-thickness distribution using the inverse method by Huss and Farinotti (2012), and the modelled glacier dynamic response to mass changes is based on an empirical relation between thickness change and normalized elevation range (Huss et al., 2010). Second, Huss and Hock (2015) model accounts for frontal ablation of marine-terminating glaciers, dominated by calving losses and submarine melt. While the results by Radić et al. (2014) suggest SLR contributions similar to the projections of Marzeion et al. (2012), the more updated and complete model by Huss and Hock (2015) predicts lower losses of 79 ± 24 mm (RCP2.6), 108 ± 28 mm (RCP4.5), and 157 ± 31mm (RCP8.5) SLE. Of these losses, ~10% correspond to frontal ablation globally, and up to ~30% regionally. In both models, the most important contributors to SLR are the Canadian Arctic, Alaska, the Russian Arctic, Svalbard, and the periphery of Greenland and Antarctica. Both models are highly sensitive to the initial ice volume.

The contribution from glaciers to SLR is expected to continue increasing during most of the 21st century. Note that the projections by Huss and Hock (2015) give average rates, over their 90-yr modelled period, between 0.88 ± 0.27 and 1.74 ± 0.34 mm SLE yr−1, depending on the emission scenario. However, this contribution is expected to decay as the total ice volume stored in glaciers becomes smaller as the low-latitude and low-altitude glaciers disappear and those remaining become confined to the higher latitudes and altitudes. The projections by Huss and Hock (2015) yield a global glacier volume loss of 25–48% between 2010 and 2100, depending on the scenario. In parallel, the contribution from the ice sheets is increasing at an accelerated path (e.g. Shepherd et al., 2013, 2018; this paper), and thus the sea-level rise caused by mass losses from the landed ice masses will more and more be dominated by the losses from the ice sheets (Table Z).

**Table Z**. Estimated contributions to sea-level rise by glaciers and by ice sheets over different recent periods. The data sources are indicated. The percentages indicate the relative contributions of the glaciers and of the ice sheets with respect to the total contribution from the landed ice masses.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 1993-2010  Church et al. (2013)  (IPCC AR5) | | 2003/05-2009/10  Gardner et al. (2013)  Shepherd et al. (2013) | | 2012-2016  modified from  Bamber et al. (2018) | |
| mm SLE yr−1 | % | mm SLE yr−1 | % | mm SLE yr−1 | % |
| Glaciers | 0.86 | 59 | 0.72 | 43 | 0.73 a | 40 a,b |
| Ice sheets | 0.60 | 41 | 0.95 | 57 | 1.10 a,b | 60 a,b |

a Including the contributions from the peripheral glaciers of Greenland and Antarctica.

b If the more recent estimate for the Antarctic Ice Sheet by Shepherd et al. (2018) for 2012-2017 were taken instead of that by Bamber et al. (2018) for 2012-2016, the contribution from the ice sheets would increase to 1.29 mm SLE yr−1 and the relative contributions would be of 36% for glaciers and 64% for ice sheets.

**5.0 Summary**

To (1) synthesize the above and (2) discuss future directions in combining ice-sheet observations with models in order to fill key knowledge gaps for making better projections

(section to be led by Edward Hanna and Frank Pattyn and Cat Ritz? but ALL contributing) – ~500-750 words?

Never before has there been so much new observational, especially satellite, data for assessing the state of mass balance of ice sheets and glaciers and their sensitivity to ongoing climate change. However, the usable satellite record is still relatively short in climate terms. One of the main remaining challenges is that satellite observations date back only 2-3 decades, which is a very short period for reference and evaluation of century-scale projections. Therefore, further extension of the ice-sheet satellite record into the past, for example through revised processing of earlier albeit lower quality observations following the method of Trusel et al. 2018, would greatly inform modellers. Also in the same line and for the sake of ice sheet mass and regional climate change detection and attribution, model evaluation and improved projections, the maintenance and extension of current automatic weather stations (e.g., Hermann et al. [2018]; van de Wal et al. [2012]) in the ice sheets is of key interest.

Our review highlights that, despite recent efforts, significant discrepancies remain with respect to absolute mass balance values for the EAIS, and so further studies are recommended to finally resolve this matter. In the case of the GrIS, there is a much higher (than Antarctica) level of agreement on a highly negative mass balance but absolute values vary by ~100-300 Gt yr-1 between recent years. These very significant fluctuations are mainly due to SMB changes that are in turn linked to fluctuations in atmospheric circulation and regional climate but ice dynamics may also have an important role to play in future changes, especially in regions away from the southwest, and the relative contributions of SMB and dynamics to future mass change remains unclear.

Continued monitoring is vital to resolve these open questions. Apart from ensuring the continuity of key satellite data provided by missions including GRACE Follow On (gravimetry) and ICESat2 (altimetry), and carrying out more frequent (annual) comprehensive inter-comparison assessments of ice-sheet mass balance, the cryospheric and climate science communities need to enhance existing collaborations on improving regional climate model and SMB simulations of Antarctica and Greenland (SMB\_MIP <http://climato.be/cms/index.php?climato=smbmip> is a key example), and also make further significant improvements to GIA models, as these are some of the key sources of residual uncertainty underlying current ice-sheet mass balance estimates.

Recent advances in ice-sheet models show major improvements in terms of understanding of physics and rheology and model initialization, especially thanks to the wealth of satellite data that has recently became available. However, recent model intercomparisons (Goelzer et al., 2018; Seroussi et al., 2019) still point to large structural and parameter uncertainties. Nevertheless, new techniques need to be further explored to improve initialization methods using both surface elevation and ice velocity changes, allowing for improved understanding of underlying friction laws and rheological conditions of marine-terminating glaciers (e.g., Gillet-Chaulet et al., 2018). Given that marine outlet glaciers are specifically sensitive to small-change topographic variations, multi-parameter ensemble modelling and the use of novel emulation methods to evaluate uncertainty will become an essential tool in ice sheet modelling.

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