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An Overview of Interactions and Feedbacks Between Ice Sheets and the Earth System

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Key Points:
- Ice sheets are tightly coupled components of the Earth system
- Feedbacks arising from ice sheet/Earth system interactions impact ice sheet variability and change
- Observations and modeling of ice sheet/Earth system interactions will aid sea level rise projections

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Abstract Ice sheet response to forced changes—such as that from anthropogenic climate forcing—is closely regulated by two-way interactions with other components of the Earth system. These interactions encompass the ice sheet response to Earth system forcing, the Earth system response to ice sheet change, and feedbacks resulting from coupled ice sheet/Earth system evolution. Motivated by the impact of Antarctic and Greenland ice sheet change on future sea level rise, here we review the state of knowledge of ice sheet/Earth system interactions and feedbacks. We also describe emerging observation and model-based methods that can improve understanding of ice sheet/Earth system interactions and feedbacks. We particularly focus on the development of Earth system models that incorporate current understanding of Earth system processes, ice dynamics, and ice sheet/Earth system couplings. Such models will be critical tools for projecting future sea level rise from anthropogenically forced ice sheet mass loss.

Plain Language Summary Sea level rise from ice sheets depends closely on interactions between ice sheets and the surrounding Earth system. These interactions determine how forcings to the climate system (such as from anthropogenic climate influences) translate to ice sheet change, which in turn impact the surrounding environment. This set of two-way interactions between ice sheets and the Earth system forms the basis for important, yet poorly understood feedback loops. This review article describes the current state of knowledge of ice sheet/Earth system interactions and feedbacks and describes promising observational techniques for better understanding their behavior. It also highlights challenges and opportunities in modeling these interactions and feedbacks using coupled ice sheet/Earth system models, which will ultimately be used to predict future sea level rise caused by ice sheet loss.

1. Introduction

In the present Earth system, ∼58 m of sea level equivalent is sequestered in the Antarctic ice sheet (AIS) and ∼7 m is sequestered in the Greenland ice sheet (GrIS; Bamber et al., 2013; Fretwell et al., 2013, Figure 1). During the last ice age, additional ice sheets stored a further 130 m of sea level equivalent (Austermann et al., 2013; Clark et al., 2009). Loss of these paleo ice sheets reconfigured the land area available to humans via sea level rise (SLR) caused by the transfer of freshwater from ice sheets to the ocean. It is a distinct possibility that anthropogenically forced deglaciation of the GrIS and/or AIS could repeat this process—albeit in the presence of much increased coastal population density (Neumann et al., 2015). Consequently, robust projections of future potential ice sheet contributions to SLR are paramount for global climate adaptation and policy planning (Church et al., 2013).

Projections of ice sheet contributions to sea level change are numerous and based on a wide range of approaches that apply different methods for translating previous knowledge to projections of future conditions. At one end of the methodological spectrum are semi-empirical methods that apply past statistical relationships between climate and ice sheet conditions to extrapolate current trends into the future (Moore et al., 2013). Such models are likely the most accurate predictors of sea level change in the near-term (decadal timescales) and are thus highly valuable. However, they are likely to lose fidelity for longer-term (multidecadal and multicentury) projections of change, over which time the Earth system increasingly transits to unprecedented climate conditions that have not been experienced (i.e., directly observed or indirectly inferred),

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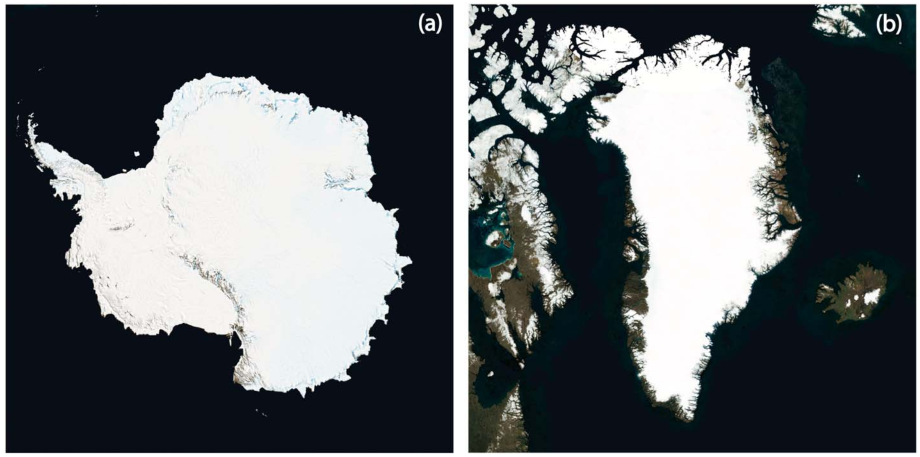

Figure 1. (a) Antarctic ice sheet (~58 m of sea level equivalent; Fretwell et al., 2013); (b) Greenland ice sheet (~7 m of sea level equivalent; Bamber et al., 2013). Cloud-free imagery courtesy of National Aeronautics and Space Administration Worldview (worldview.earthdata.nasa.gov).

and for which empirical relationships between climate change and ice sheet behavior lose robustness. On the other end of the spectrum are process-based models that attempt to project change using numerical models of various complexities simulating known physical processes and that can potentially be used to determine ice sheet evolution in Earth system states very different than the recent historical period. Improvement of these process-based projections through better understanding of ice sheet-Earth system interactions forms the primary objective for this review.

Ice sheets interact directly and indirectly with every other component of the Earth system (atmosphere, ocean, sea ice, land surface, lithosphere, and biology/biogeochemistry) through a diverse and interlinked set of processes and feedbacks. In turn, these Earth system components exert control on ice sheet evolution (taken to the logical extreme, these components determine at a fundamental level where ice sheets can or cannot exist; Cuffey & Paterson, 2010). This two-way interaction is the foundation of ice sheet/Earth system feedback loops that modify (in some cases, very strongly) ice sheet response to external climate forcings. The potential importance of two-way interaction between ice sheets and other components of the Earth system suggests that the former should be considered an intrinsically coupled component of the latter. It also indicates that process-based ice sheet model (ISM) projections of past and future change become unrealistic if this coupling is neglected.

Thus motivated, here we review current understanding of ice sheet/Earth system interactions and feedbacks. We also discuss current ice sheet/Earth system observational and modeling approaches and advances that hold promise for improving projections of future ice sheet contributions to sea level. Our goal is to provide a comprehensive overview on the subject of ice sheet/Earth system coupled behavior. Because the range of interactions with other Earth system components that ice sheets exhibit is so diverse, this review is broad in scope, draws from many disciplines, and therefore necessarily remains on a more general, conceptual level, sacrificing many interesting and important details. We encourage readers interested in specific topics of ice sheet/Earth system interactions to explore other reviews that are referenced in the main text and also highlighted in Appendix A. In general, we primarily highlight recent studies of ice sheet/Earth system dynamics, with the understanding that these advances are direct consequences of previous multidecadal research efforts.

We focus here on ice sheet/Earth system interactions as they manifest in the current and near-future (decades to millennia) Earth system, that is, associated with the present-day AIS and GrIS. However, where pertinent we also discuss continental-scale ice sheet changes in the past, where these changes provide relevant case studies. We point out that the fundamental ice sheet/Earth system interactions we describe here in the context of the AIS and GrIS played equally significant roles in climates of the recent and deeper geologic past, and also for present-day glaciers and ice caps, which are not discussed here.

This review is structured as follows. In section 2 we introduce and outline the primary mechanisms and pathways by which (a) the Earth system impacts both the GrIS and AIS and (b) the GrIS and AIS in return impact the Earth system. This provides the basis for section 3, in which we describe feedbacks that occur as a consequence of these two-way ice sheet/Earth system interactions. Finally, motivated in particular by the need for improved ice sheet and sea level projections that include ice sheet/Earth system interactions and feedbacks, in section 4 we discuss (a) future directions in observations of ice sheet/Earth system interactions and (b) potential approaches for the development of models that consistently and robustly represent ice sheet/Earth system interactions and feedbacks.

2. Ice Sheets as Components of the Coupled Earth System

Section Summary: In this section, we describe the two present-day ice sheets, the Antarctic and GrIS, and summarize how fundamental aspects of their behavior are controlled by ice sheet/Earth system interactions, and, in turn, how ice sheet changes exert a return influence on the Earth system.

Glaciers, ice caps, and ice sheets (collectively termed "land ice" to differentiate from sea ice, lake ice, and permafrost) on the Earth's surface appear due to the climate-regulated presence of snow packs that persist through summer months and, with continued snow accumulation over hundreds to thousands of years, compact into ice masses large enough to support gravity-driven flow. Ice sheets, the largest category of land ice, are continental-scale glaciers that have nearly entirely subsumed the underlying bare land topography in their expansion toward the coast from central, cooler and/or higher elevation regions. Today, two ice sheets exist on the planet: the AIS and the GrIS. The larger of the two, the AIS, originated from the Transantarctic, Dronning Maud, and Gamburtsev Mountains (Bo et al., 2009) approximately 33 to 34 million years ago during the global Eocene-Oligocene climate transition toward a cooler climate state (Katz et al., 2008; Stocchi et al., 2013). In contrast, a permanent GrIS appeared approximately 3 million years ago, likely originating as ice caps (small disjointed areas covered by ice) in the eastern and southern Greenland mountains coalesced (Lunt et al., 2008). It is likely that between first establishment and the present day, both the AIS and GrIS underwent significant fluctuations, from partially or even completely deglaciated on one hand (Naish et al., 2009; Schaefer et al., 2016), to extend to the continental shelf edge and — in the case of the GrIS — merge with other large glacial period ice masses. (Clark et al., 2009).

The present-day AIS and GrIS (Figure 2) are notably distinct in their configurations. Over 90% of the AIS coastline is characterized by marine margins, much of which consists of fast-flowing outlet glaciers or ice shelves (Bindschadler et al., 2011) — portions of the ice sheet that flow into surrounding oceans, respectively. Ice shelves account for ~12% of the total AIS area (Fretwell et al., 2013). The two largest ice shelves, the Filchner-Ronne and Ross, are situated in the marine-based West Antarctic ice sheet (WAIS) whose bedrock is situated below sea level and would remain below sea level even if the ice was removed and the underlying crust of the Earth was fully rebounded. Conversely, much of the larger East AIS resides on bedrock above sea level with the notable exception of several large basins such as the Lambert Glacier basin that feeds the Amery ice shelf, the third largest in Antarctica (Fretwell et al., 2013).

In contrast, the GrIS currently has few substantial ice shelves (>1% of total area), fewer marine-terminating glaciers, and overall resides on bedrock above sea level, with the primary exception of a few major outlet glaciers (e.g., Jakobshavn Isbræ, Helheim, and Petermann) whose beds lie below sea level and such glaciers tend to terminate in near vertical, partially submerged ice cliffs. For the broad interior of the GrIS, the bed has been depressed below sea level by the weight of overlying ice sheet but would mostly rebound above eustatic (global average) sea level if the overlying ice were removed. Thus, the GrIS is relatively more " terrestrial" than the AIS, both in its extension to the marine margins and its predominantly above-seaboard bed topography.

Below we explore the causes for this contrast, which leads to major differences in ice sheet/Earth system interactions (Figure 3 and Table 1) between these two contemporary ice sheets. Specifically, we first examine the interactions by which the Earth system controls ice sheet change. We then examine the interactions through which ice sheets exert a return influence on the Earth system. Finally, we consider feedbacks arising from the bidirectional nature of ice sheet/Earth system interactions.

2.1. Climate Controls on Ice Sheet Change

The difference between GrIS and AIS and configurations is both reflected in and caused by differences in Earth system processes controlling the mass balance of each ice sheet (Table 1). Ice mass balance refers to the state of the ice sheet at any point in time with respect to mass inputs and outputs. Ice sheet mass gain occurs via accumulation of snow [I_A, Figure 3], and mass loss occurs by surface meltwater runoff by surface melt, snow

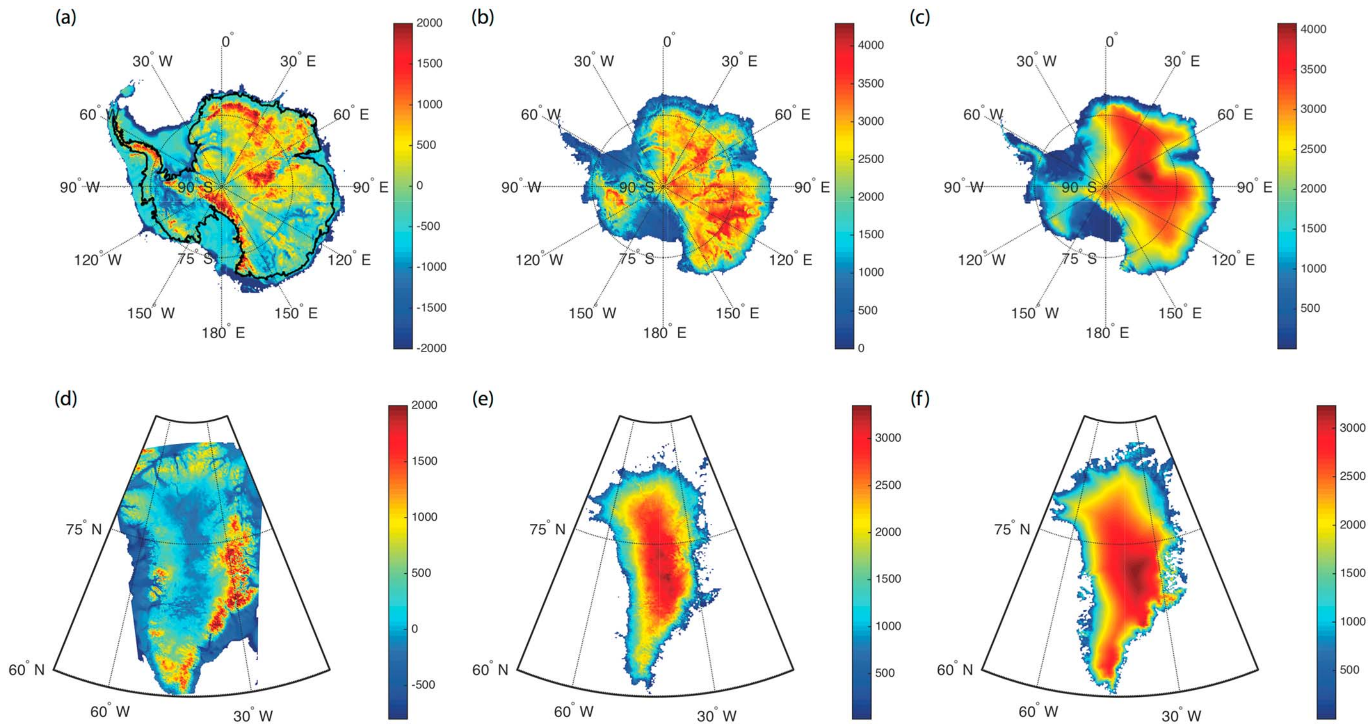

Figure 2. (a) Bed elevation (m), (b) ice thickness (m), and (c) surface elevation (m) of Antarctic ice sheet (Fretwell et al., 2013). Black line in Figure 2a denotes the grounding line. (d) Bed elevation (m), (e) ice thickness (m), and (f) surface elevation (m) of Greenland ice sheet (Bamber et al., 2013).

erosion, or sublimation of surface snow and blowing snow [I_a, Figure 3], ocean-regulated submarine melt, or ice-dynamics-regulated and ocean-moderated iceberg calving. [I_o, Figure 3]. In this section we contrast the interactions by which the Earth system impacts the GrIS and AIS.

2.1.1. Climate Influences on GrIS

Like all ice sheets, GrIS thickness and extent are regulated by prevailing climate conditions through mass gain from precipitation, surface mass loss from melting and sublimation, and ice loss to the oceans by iceberg calving or melting. The relative contributions of each term to net annual GrIS changes varying year by year.

Precipitation. GrIS precipitation is strongly influenced by cyclone activity in the North Atlantic (e.g., Chen et al., 1997; Ohmura & Reeh, 1991; Schuenemann et al., 2009; Schwierz & Davies, 2002). The majority of the synoptic systems (and hence, most of the Greenland precipitation) originate in the baroclinic zone off the North American East Coast (Pausata & Löfverström, 2015; Werner et al., 2001). However, their preferred trajectory varies with season, which is also reflected in the precipitation distribution over the ice sheet (Figure 4). In winter, during high North Atlantic storm activity, circulation systems typically follow a westerly trajectory (propagating with the westerly mean flow; Figure 5) across the North Atlantic and make landfall over the European continent. However, wintertime cyclones occasionally exit poleward of the main storm track to make landfall over the southern and southeastern parts of the GrIS. The moisture carried by these systems primarily falls as orographic precipitation on the steep ice sheet margins, with only a small fraction reaching the ice sheet interior (Figure 4a). Conversely, a combination of a generally weaker and more zonally symmetric westerly mean flow drives summer cyclones along a more southerly trajectory to more commonly impact the West Coast (Chen et al., 1997; Ohmura & Reeh, 1991; Schwierz & Davies, 2002). This change in preferred cyclone path generates strong seasonality in GrIS precipitation distribution (Figure 4), with summer precipitation dominating in the west and in the ice sheet interior, while winter precipitation dominating in the southeast coastal region (Steen-Larsen et al., 2011; Werner et al., 2000).

In addition, variability in total precipitation (snow plus rain) is regulated by regional patterns of naturally occurring internal variability, such as the phase of the Greenland Blocking Index (GBI; Hanna et al., 2016), the Atlantic Multidecadal Oscillation (Chylek et al., 2012; Lewis et al., 2017), as well as the North Atlantic Oscillation (NAO) (Hurrel, 1995), and episodic Rossby wave-breaking events on the flanks of the North Atlantic jet stream (Liu & Barnes, 2015). Greenland winter precipitation is moderately anticorrelated with the phase of

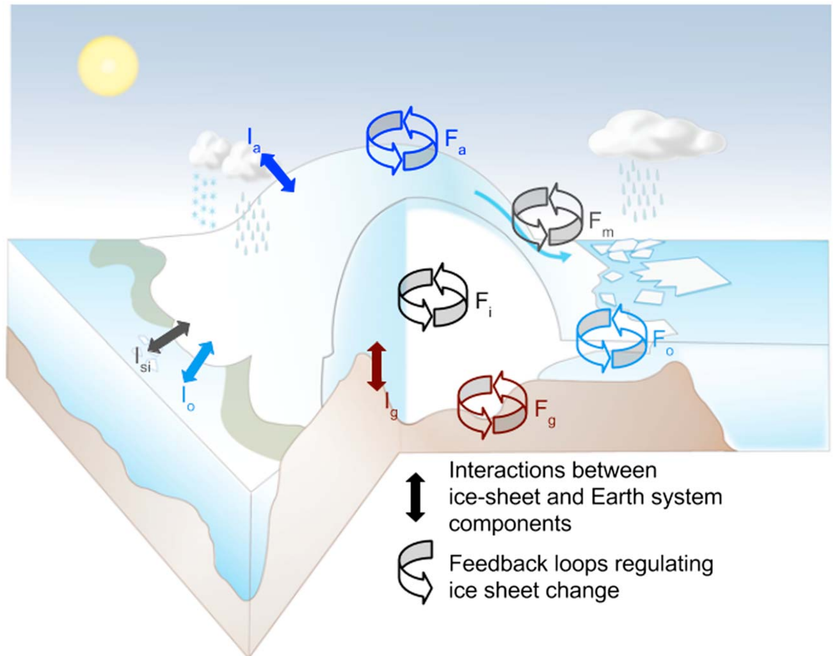

Figure 3. Summary of family of interactions (I) between ice sheets with other components of the Earth system: atmosphere (I_a), ocean (I_o), sea ice (I_{si}), and the solid Earth (I_g). These interactions, along with interactions between other Earth system components (*a*, *o*, *si*, and *g*), give rise to feedback loops (F). Feedback loops include those between the ice sheets and the atmosphere (F_a), ocean (F_o), and solid Earth (F_g). In addition, feedbacks likely exist that transit multiple Earth system components (F_m). Finally, internal (F_i) ice sheet feedbacks also exist.

the NAO (Bromwich et al., 1999; Hurrel, 1995; Hurrell & Van Loon, 1997). During positive NAO, a large pressure difference between the Icelandic Low and the Azores High promotes northerly flow across the Labrador Sea and western Greenland, and the North Atlantic jet stream is strong and has a well-defined southwest-northeast tilt in midlatitudes. This causes relatively reduced precipitation over Greenland. The opposite relationship is found for the negative phase of the NAO. Reasons for the anticorrelation is an active area of research, but the frequency of moisture intrusion events from the tropics—so called “atmospheric rivers,” which are tightly linked to Rossby wave-breaking events in midlatitudes (Payne & Magnusdottir, 2014)—has been shown to decrease in the western North Atlantic during positive NAO (Liu & Barnes, 2015). In addition, it is conceivable that the strong jet stream forms a more well-defined waveguide that makes the cyclones less likely to veer poleward toward the ice sheet.

In the recent historical climate, approximately 90% of the precipitation over the GrIS has fallen as snow, which directly contributes to the overall ice sheet mass *gain* (e.g., contributing to sea level *fall*; Ettema et al., 2009). The remaining 10% falls in liquid form (rainfall) on the low-altitude margins of the ice sheet in summer. As with all components of ice sheet mass balance, these relative fractions change significantly from year to year due to internal climate variability (Noël et al., 2015).

Surface melt/runoff. GrIS surface melting (Figure 6) arises from a net positive surface energy balance (SEB) over snow/ice at 0°C. SEB is the sum of the radiative, turbulent, and ground heat fluxes received by and emitted by the surface. Ice sheet SEB is negative throughout most of the year, when the surface loses energy to the atmosphere by longwave radiation emission. In the short summer season, incoming shortwave (solar) energy peaks, leading to a net positive SEB during daytime. Summer melt can be enhanced or constrained by the presence of clouds, depending on the time of day, cloud height, optical thickness, and microphysical properties (Bennartz et al., 2013; Hofer et al., 2017; Van Tricht et al., 2016).

A major control of summer surface melting is surface albedo, which determines the amount of incoming shortwave energy absorbed by the ice or snow. In the interior GrIS accumulation zone and over the entire ice sheet in winter, the surface is covered by highly reflective snow, with albedo exceeding 0.8 (Stroeve et al., 2013). In summer, the presence of aged and melting snow reduces snow albedo significantly (Flanner & Zender, 2006) and when the winter snowpack has been melted away completely, bare ice is exposed along

Table 1
Interaction Between Ice Sheets and Surrounding Earth System Components

Interface	Direction	Interaction
Ice sheet/atmosphere	to ice sheet	surface energy fluxes
		surface mass fluxes
	from ice sheet	surface topography
		ice sheet extent
		surface type
Ice sheet/lithosphere-mantle	to ice sheet	geothermal heat flux
		subglacial water pressure
		bed elevation
		bed type
	from ice sheet	ice base normal stress and mass loading
		ice basal velocity
Ice sheet/ocean	to ice sheet	sub-ice shelf energy fluxes
		sub-ice shelf mass fluxes
	from ice sheet	ice melt runoff
		iceberg calving
		gravitational sea level effects
		ice shelf geometry
Ice sheet/sea ice	to ice sheet	sea ice back stress
	from ice sheet	ice shelf displacement

the low-lying ice sheet coastal zones below the equilibrium line altitude. Ice has a much lower albedo than snow (< 0.6) and can be darkened further by the presence of biological activity (algae and cryoconite holes; Stibal et al., 2012; Stibal et al., 2017), deposition of atmospheric dust (Dumont et al., 2014) and/or black carbon (McConnell et al., 2007), or re-emergence of dust deposited in past drier and dustier climates such as the Last Glacial Maximum (Wientjes et al., 2012).

Once liquid water is produced at the surface (or delivered as rain), the surface and subsurface porosity, temperature, and density determine its subsequent fate. Ice is virtually impermeable, leading to the formation of supraglacial meltwater lakes (e.g., Sundal et al., 2009) or englacial firn aquifers (Forster et al., 2013) that store the water locally and supraglacial channels transporting the water primarily to moulins that route water to the ice sheet bed and, eventually, to ice margins (Chu, 2014). In the accumulation area, the perennial firn layer provides capacity to store and refreeze surface meltwater (Harper et al., 2012), although corresponding latent heat release warms up the firn and progressively reduces the meltwater buffering potential of the firn (Machguth et al., 2016; Noël et al., 2017; van Angelen, Lenaerts, et al., 2013). This highlights the importance of ice sheet firn characteristics in determining the runoff versus refreezing partitioning of GrIS surface meltwater.

Similar to summertime precipitation, variability in GrIS surface melt is regulated by large-scale summertime atmospheric anomalies, that is, a combination of summertime NAO, Atlantic Multidecadal Oscillation, and GBI indices (e.g., Fettweis et al., 2013; Hanna et al., 2012), upstream atmospheric conditions in North America, North Atlantic sea surface temperatures (SSTs), and Arctic Oscillation transitions (Solomon et al., 2017). Recent observations suggest an increasing dominance of surface melt-driven runoff as the primary factor in overall GrIS mass loss (Enderlin et al., 2014), although it is not clear to what extent this shift in the partitioning of GrIS mass loss terms is a signature of multidecadal internal climate variability versus secular, externally forced change—a problem common to ice sheet-focused change detection and attribution exercises (van den Broeke et al., 2017; Wouters et al., 2013).

Marine ice loss. Along the GrIS margins where outlet glaciers terminate in fjords, ice is lost via iceberg calving (Benn et al., 2017) and submarine melting (Straneo & Cenedese, 2015). The two processes are not entirely independent of each other (Benn et al., 2017) and are thus difficult to disaggregate. However, GrIS iceberg calving likely dominates over submarine melting at outlet glacier fronts due to the broad lack of extended GrIS ice shelves, which precludes the large surface area needed for melting to impact mass balance

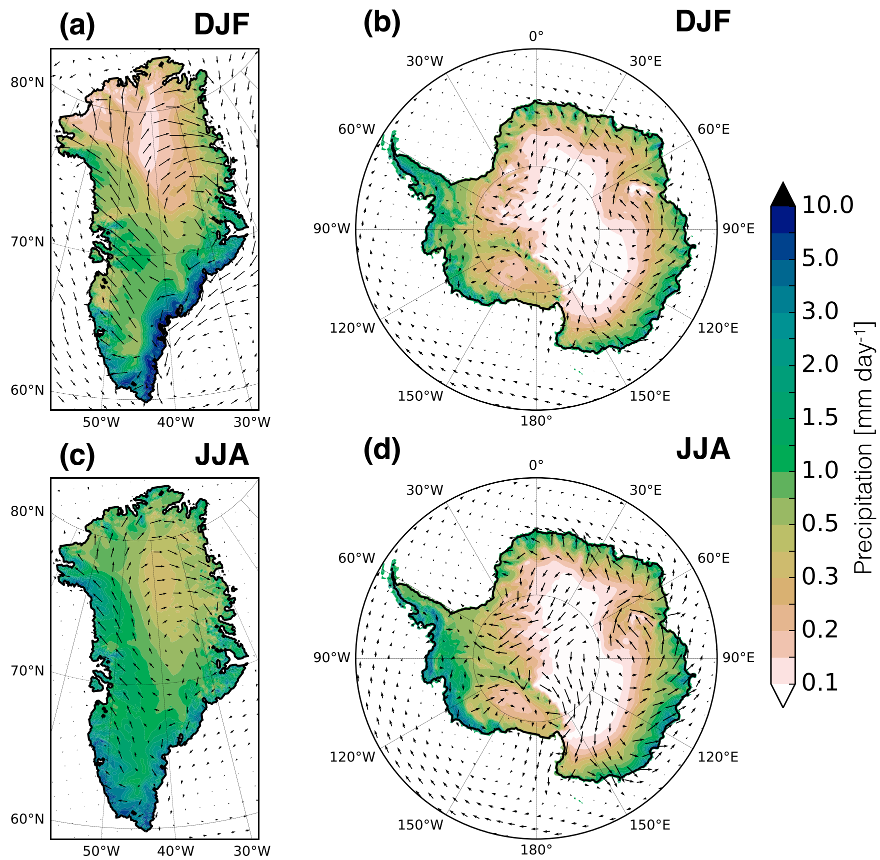

Figure 4. Daily average precipitation (mm/day) (shading) and 10 m wind (arrows) in (a, b) the December, January, and February (DJF) and (c, d) June, July, and August (JJA) seasons, separated between (a, c) Greenland and (b, d) Antarctica. The longest arrows correspond to approximately 10 m/s. Data are adopted from the Regional Atmospheric Climate Model version 2.3 (van den Broeke et al., 2017; van Wessem et al., 2018).

sufficiently before calving occurs (Truffer & Motyka, 2016). Calving in many GrIS outlet glaciers is to first order regulated by buoyancy-driven ice fracturing (Benn et al., 2017), which can result in dramatic break-up events as highly crevassed, fast-flowing outlet glaciers flow into deep water and calve. This process is primarily a function of ice velocities, the stress-and-strain history of ice arriving at the ice margin, and local ice dynamics at and near the calving front. However, local climate conditions play an additional role in controlling calving processes. For example, sea ice and mixed ice "melange" conditions appear to seasonally suppress calving events from outlet glaciers (Amundson et al., 2010). In addition, ocean-driven melting likely plays an indirect role, by accelerating the transition from grounded to floating ice across the grounding line or preconditioning iceberg calving by undercutting the floating face of marine outlet glaciers (Benn et al., 2017). This melting is tightly linked to a combination of advection of warm subsurface water masses into outlet glacier fjords (Carroll et al., 2016) and pluming of buoyant (summer) surface meltwater from subglacial discharge channels at outlet glacier calving fronts. The latter drives convective mixing of relatively warm ambient waters toward the vertical ice-ocean interface, greatly increasing melt rates there (Straneo & Cenedese, 2015) and thereby providing a link between summertime surface conditions and rates of marine ice loss (Truffer & Motyka, 2016).

GrIS marine ice loss displays a complex seasonal signature (Jackson et al., 2014), with variability regulated by a range of different factors, including the magnitude of surface melt exiting subglacial drainage systems, as well as regional ocean properties, winds, tides, and sea ice. Disaggregation and attribution of these individual impacts is hindered by sparse observations (particularly, during winter) and, in recent years, the cooccurrence of both intrusions of Atlantic waters and increased surface melting (Straneo & Cenedese, 2015). It is also currently difficult to separate the externally forced marine mass loss signal from that resulting from dynamical

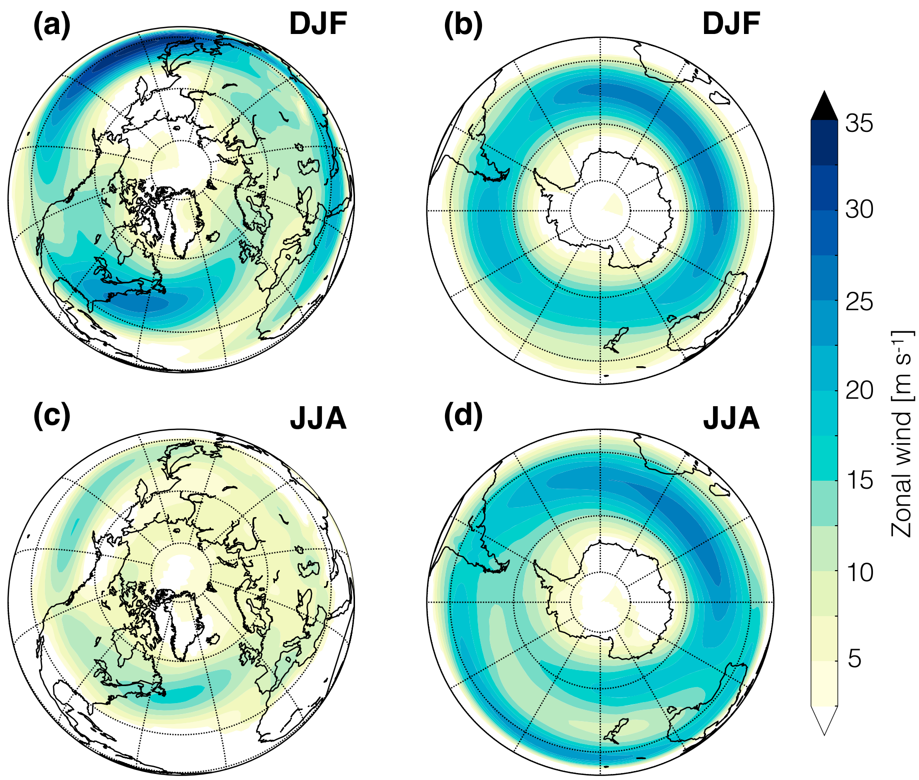

Figure 5. ERA-Interim (Dee et al., 2011) 500 hPa zonal wind in the (a, b) December, January, and February (DJF) and (c, d) June, July, and August (JJA) seasons, separated between (a, c) the northern and (b, d) the southern midlatitude and high-latitude regions.

ice sheet processes, the latter of which includes responses to past external forcing. Thus, the attribution of observed annually integrated changes in GrIS marine ice loss to specific climatic or ice-dynamical processes remains problematic.

2.1.2. Climate Influences on AIS

Like the GrIS, the AIS is regulated by the surrounding climate. However, significant differences arise due to higher ice sheet elevation, more zonally symmetric atmospheric circulation, and the thermal isolation due to the cold circumpolar Southern Ocean.

Precipitation. Present-day AIS mass gain via precipitation is almost totally dominated by snowfall (Van Wessem et al., 2014), in lieu of sufficiently warm atmospheric conditions for rainfall even in austral summer. The lack of continents and large-scale mountain ranges in the Southern Hemisphere midlatitudes drives a dominantly zonal atmospheric circulation (Figure 5). Although the Andes is comparable in height to the Cordilleran and Himalayan mountain ranges, their zonal width is considerably smaller than the deformation radius, thus they are largely unable to influence the atmospheric circulation on a scale that significantly impacts Antarctica. (The Rossby number associated with the flow-topography interaction is of order unity under typical midlatitude conditions; Ro = $\frac{u}{|f|\,L_x}$, where u {= 10 m/s} is the zonal L_x wind, $|f|$ ({= 10^{-4} s^{-1}} is the magnitude of the Coriolis parameter, and L_x {=10^5 m} is the zonal half-width of the mountain range. Assuming typical conditions at 45°S {values in parenthesis} yields Ro = 1, which indicates that rotation has less influence on the circulation, and the flow-topography interaction is primarily resulted in inertia gravity waves. Planetary waves with {Ro $\ll$ 1} are excited when the traverse of the westerly mean wind of a midlatitude mountain range has characteristic timescales much greater than Earth's rotation timescale.) However, waves induced by the Andes atmospheric flow-topography interaction are a source of cyclogenesis, making the midlatitude storm track in the Atlantic Ocean and Indian Ocean sectors the strongest and most pronounced in the Southern Hemisphere (Hoskins & Hodges, 2005). In addition, the Antarctic continent itself has a largely circular symmetry and is completely surrounded by ocean. Midlatitude circulation systems therefore typically propagate parallel to the ice sheet margin, and precipitation is dominated by coastal, orographically forced snowfall (Figures 4 and 5; Van Wessem et al., 2014). Precipitation on the high-elevation AIS interior—the

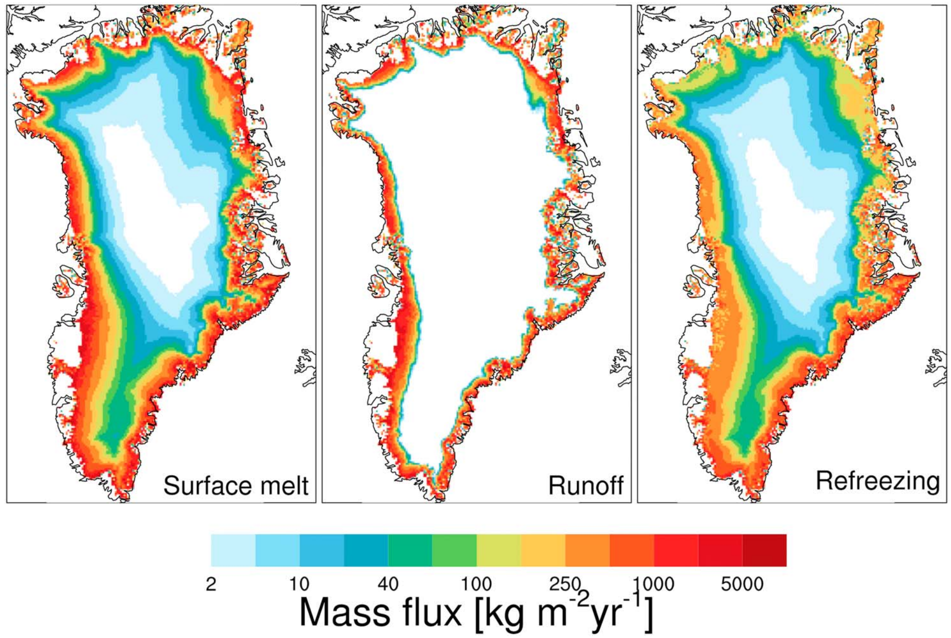

Figure 6. GrIS surface melt and resulting runoff versus refreezing as simulated by Regional Atmospheric Climate Model version 2 (Noël et al., 2017).

driest region on the planet—is dominated by diffuse "clear-sky" snowfall (diamond dust), with the remainder coming from synoptic systems that occasionally traverse the continent (Massom et al., 2004). Similar to Greenland, the coastal precipitation in Antarctica is greater in the winter season when the Southern Hemisphere storm track is most active (Figure 4).

Atmospheric rivers also play a role for AIS surface mass balance (Gorodetskaya et al., 2014). These high-accumulation events are associated with Rossby wave breaking on the flanks of the midlatitude jet stream (Payne & Magnusdottir, 2014) and are characterized by a narrow plume of moist tropical air extending into the continental interior. Although these events are relatively infrequent and typically only happen a few times per year, case studies suggest that they can account for as much as 80% of the annual precipitation in regions that are affected (Gorodetskaya et al., 2014).

Given the continental scale of the AIS, regulators of snowfall (both the mean state and variability) are best assessed regionally (Fyke et al., 2017), with patterns of variability including the Southern Annular Mode (SAM), El Niño–Southern Oscillation (ENSO), and nonannular components of the Southern Hemispheric circulation (Genthon & Cosme, 2003; Raphael, 2007; Marshall et al., 2017; Van Den Broeke & Van Lipzig, 2004). The SAM (or Antarctic Oscillation) is the principal mode of variability in the Southern Hemisphere extratropics on monthly and interannual timescales. It is generally believed to be driven by internal wave dynamics (Limpasuvan & Hartmann, 2000) and plays a major role for the AIS precipitation by influencing the latitudinal location of the jet stream and storm track. During the positive phase—characterized by an anomalously high pressure over Antarctica—the westerly wind field and storm track shift poleward. The SAM also helps modulate the strength and spatial location of quasi-stationary circulation systems, for example, the Amundsen-Bellingshausen Sea Low offshore of the WAIS, which blocks the flow and steers it toward/away from the continent. Reanalysis data suggest that SAM variability may result in regional annual precipitation variability of as much as 30% between positive and negative phases (Van Den Broeke & Van Lipzig, 2004).

Surface melt/runoff. Compared to the GrIS, Antarctic surface melt volumes are much smaller and limited to the flat, low-lying ice shelves in peak austral summer (December and January). Until recently, it was assumed that in the commonly cold Antarctic climate, all meltwater generated at the surface percolates and refreezes in the thick, cold firn. Although this is valid in many places, recent remote and in situ observations have highlighted the occurrence of liquid water storage and runoff from the AIS margins, often sourced close to ice shelf grounding lines, where local high atmospheric temperatures and low surface albedo are associated with vigorous atmospheric mixing and surface snow scouring (exposing low-albedo snow or ice) by katabatic winds, respectively (Bell et al., 2017; Kingslake et al., 2017; Lenaerts, Lhermitte, et al., 2017). On the Antarctic Peninsula, where surface melt rates are highest, the demise of Larsen A and B ice shelves in 1995 and 2002, respectively (e.g., Glasser & Scambos, 2008), has been related to the ponding of excessive meltwater on the ice shelf surface, generating surface-based downward propagating fractures in the ice, eventually leading to ice shelf instability (so-called hydrofracturing; Scambos et al., 2000). Here the downslope (foehn) winds generated by fierce, large-scale atmospheric westerlies interacting with the topography on the Antarctic Peninsula to episodically bring dry and warm air onto the ice shelves, leading to strong melt events (King et al., 2017), especially along the grounding line (Hubbard et al., 2016).

Sublimation. Snow and ice sublimation primarily occur in two conditions: (1) In summer, when solar radiation heats the snow and ice surface, the atmosphere is dry (i.e., relative humidity is low), but surface temperatures are below the freezing point ("surface sublimation") and; (2) driven by the high surface winds, both of katabatic and synoptic origin, snow particles are lifted from the surface and entrained in the atmospheric surface layer and/or boundary layer and exposed to the surrounding air ("drifting and/or blowing snow sublimation"). Surface sublimation peaks on East Antarctic ice shelves where summer temperatures rarely exceed the melting point, and over blue ice areas of interior Antarctica (Bintanja & Broeke, 1995). Blowing snow sublimation reaches highest values in the escarpment regions of the ice sheets, where surface slopes and associated katabatic winds are strongest. Blowing snow sublimation is the dominant surface mass loss term on the AIS, with an estimated (negative) contribution of around 10 to 20% (Lenaerts & van den Broeke, 2012; Palm et al., 2017) of total surface mass balance (SMB). In contrast to sublimation, evaporation (the phase change from surface meltwater to water vapor) is likely negligible since the vast majority of ice sheet meltwater either percolates into the snowpack or drains quickly into the subsurface.

Marine ice loss. With little surface runoff and relatively minor sublimation, AIS mass loss occurs predominantly by ice discharge into the surrounding ocean. Once across the grounding line, ice can flow over the ocean as part of ice shelves, where mass loss can occur by sub-ice shelf melting (~45% of total loss) and iceberg calving (~55% of total loss; Depoorter et al., 2013; Rignot et al., 2013). Antarctic sub-ice shelf melting is fundamentally controlled by the oceanic heat transported into sub-ice shelf cavities, which in turn is regulated by water mass transfer onto the Antarctic continental shelf. A complex chain of oceanographic processes links globally coupled Southern Ocean conditions (e.g., Santoso et al., 2006) to those at the ice/ocean interface and, in turn, melting (or freezing) at the ice shelf base. Subsequent coastal upwelling, sea ice formation, air-sea interaction, and internal ocean dynamics locally affect the amount of heat that can be delivered to the sub-ice shelf cavities.

Detailed and direct knowledge of ice shelf-wide melting/refreezing patterns is limited, presenting an obstacle for assessments of melting/freezing temporal variability and its attribution to ambient oceanic and atmospheric conditions. Satellite-based observations of basal melting/refreezing, ice shelf flow, and surface elevation change (Moholdt et al., 2014; Rignot et al., 2013) provide snapshots of ice shelf-base mass balance. However, as sub-ice shelf melting/refreezing is inferred from the divergence of ice shelf flow, it requires a number of assumptions (e.g., firn density, surface precipitation, ablation, etc.) that add analysis complexity. Aside from remotely sensed melt rates, indirect estimates of ice shelf-integrated net melting/refreezing can also be inferred from measurements of water mass properties and isotopic compositions collected at ice shelf fronts (Jacobs et al., 1970, 1996; Smethie & Jacobs, 2005). Multidecadal (although temporally sparse) observations suggest that the ocean circulation and stratification experience short- and long-term variability, which translates into variability of the heat flux into sub-ice shelf cavities (Jenkins et al., 2016; Turner et al., 2017) and associated sub-ice shelf melting/freezing (Paolo et al., 2015; Shepherd et al., 2004).

Figure 7 shows the mass balance (melting/refreezing) at the base of a range of Antarctic ice shelves. While in general ice shelves experience increased melting near the grounding line and at the calving front, a portion of the meltwater can potentially refreeze and thus become reincorporated into the greater ice (Wen et al., 2010). The spatial patterns of sub-ice shelf melting/refreezing on these large ice shelves is strongly modulated by the bathymetry of their sub-ice shelf cavities. Smaller ice shelves, especially those interacting with warmer ocean waters, predominantly experience sub-ice shelf melting and little refreezing (Figure 7), with spatial melt patterns reflecting strong two-way interactions between sub-ice shelf circulation and the shape of the ice shelf base.

AIS iceberg calving the other major marine-based term of the AIS mass loss budget, is dominated by the calving of large tabular icebergs (Figure 8) (Tournadre et al., 2016) and is largely regulated by

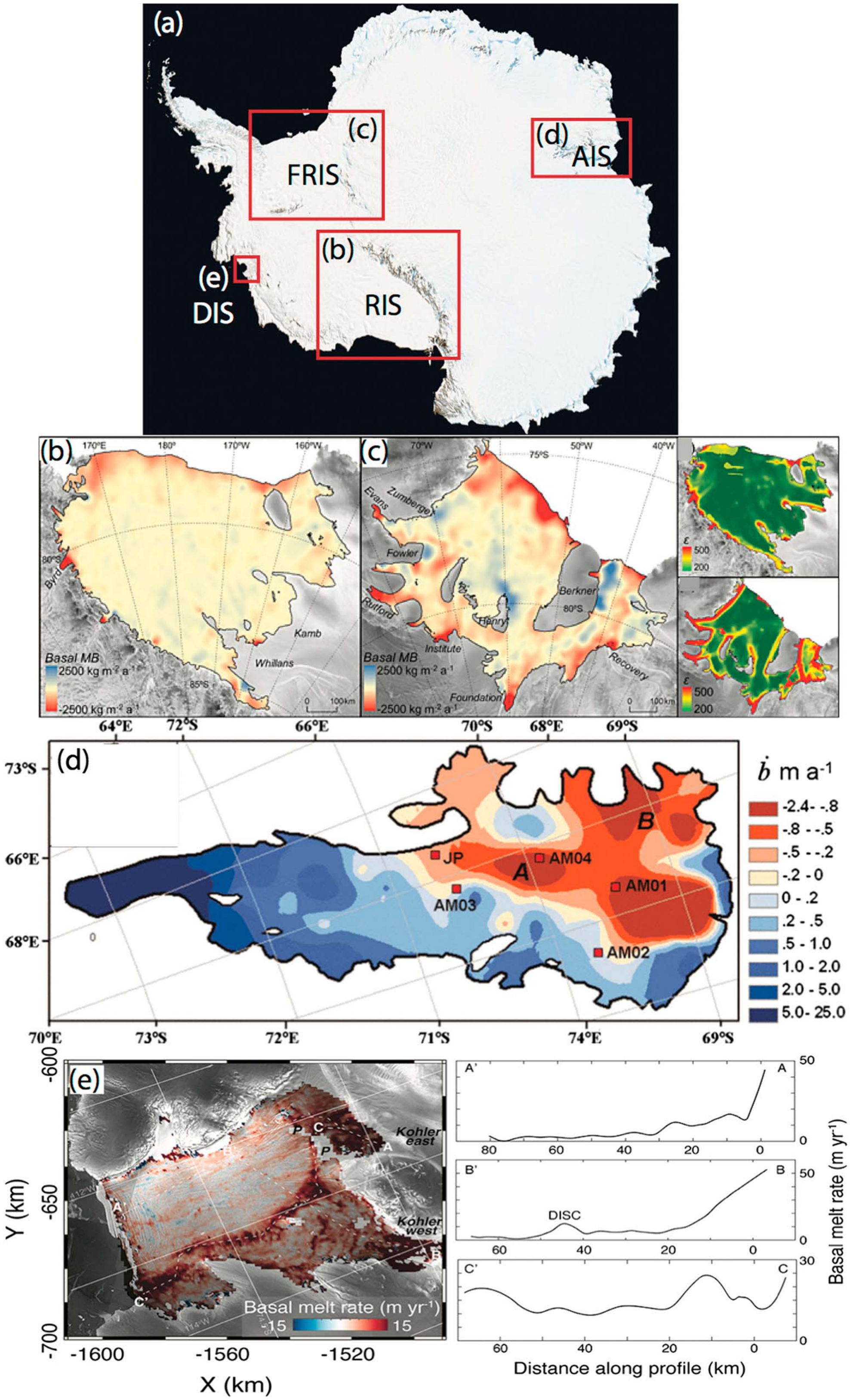

Figure 7. Examples of spatial melt rate estimates (m/yr) for Antarctic ice shelves. (a) Map of Antarctica, red rectangles outline areas shown in Figures 7b–7e; (b) melt rates of the Ross ice shelf (RIS; Moholdt et al., 2014); (c) melt rates of the Filchner-Ronne ice shelf (FRIS; Moholdt et al., 2014); melt rates of the Amery ice shelf (AIS; Wen et al., 2010, reprinted with permission from Cambridge University Press); (e) melt rates of the Dotson ice shelf (DIS; Gourmelen et al., 2017).

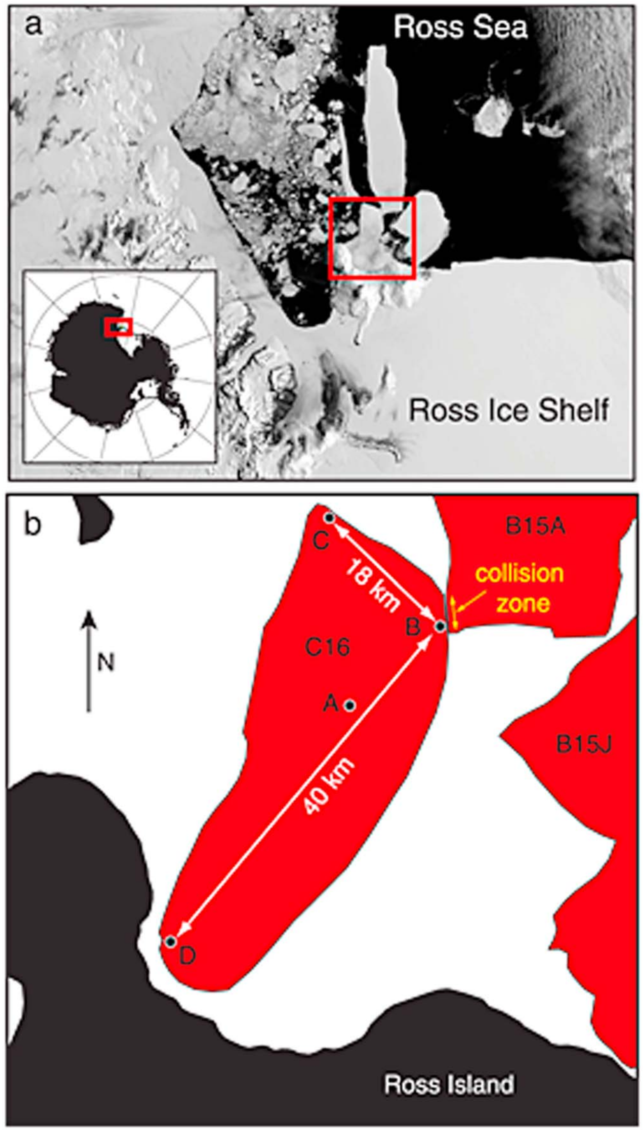

Figure 8. Icebergs in the Ross Sea, Antarctica. (a) Moderate Resolution Imaging Spectroradiometer satellite image of the Ross Island region of the Ross Sea, 2003. Inset shows location in Antarctica; red box shows zoomed sketch map of Figure 1b. (b) Iceberg C16. (MacAyeal et al., 2015).

ice dynamics. Large tabular icebergs are formed as a result of "rift" development—large, full thickness crevasses extending hundreds of kilometers—that usually originate at the same location due to interaction of ice shelf flow with geologic features (e.g., Roosevelt Island on the Ross ice shelf). The processes that control rift propagation are poorly understood (Bassis et al., 2005), and those that have been identified so include the presence of ice debris (Bassis et al., 2005), suture zones (McGrath et al., 2014) and marine ice (Jansen et al., 2015). With the low calving frequency of large tabular icebergs (roughly twice per century) and short observational record (from remote sensing or in situ) it is difficult to assess the effects of changing environmental conditions on calving. However, it is feasible that climate conditions (e.g., changes in storminess or in sub-ice shelf melting/refreezing patterns) may exert control on the frequency and size of calved icebergs (Bromirski et al., 2010; Kulessa et al., 2014; MacAyeal et al., 2006; Sergienko, 2017). At the other end of the calving spectrum, the so far rare disintegration of ice shelves could be viewed as an extreme case of calving, with the most likely triggering mechanism being hydrofracturing of previously weakened shelves (Domack et al., 2003). Observations of surface melt-driven hydrofracturing of Antarctic Peninsula shelves (Domack et al., 2003) and seasonal meltwater accumulation on other Antarctic ice shelves support an increasing role for climate in regulating calving, potentially in the

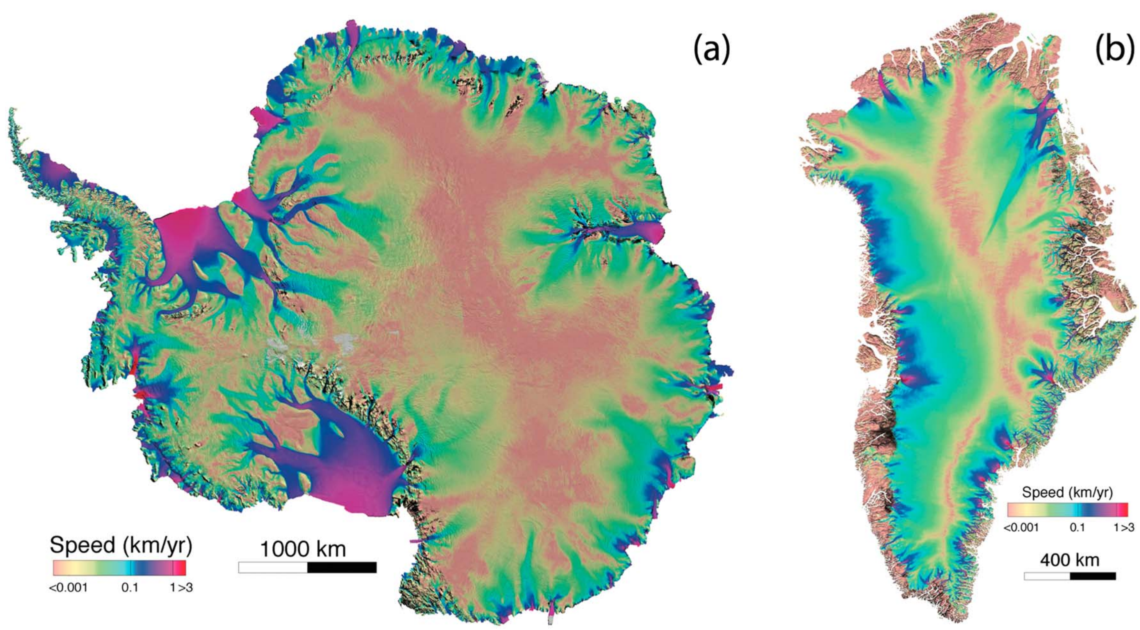

Figure 9. (a) Antarctic ice sheet surface velocity. (b) Greenland ice sheet surface velocity. Figures are reproduced with permission from Mouginot et al. (2017).

form of large-scale, surface melt-driven ice shelf disintegration events (Scambos et al., 2004). While this surface melt may have significant dynamical consequences over ice shelves, it does not presently significantly impact overall Antarctic mass trends through direct mass loss considerations.

2.2. Ice Dynamic Response to Climate Forcing

A basic nature of climate forcings (section 2.1) on established ice sheets is to predominantly add mass in the ice sheet interior via snowfall and predominantly remove ice mass on the edges by surface melting, ocean-driven subaquatic melting, and iceberg calving. The resulting spatial pattern of ice mass change contributes to interior thickening and coastal thinning, which is reflected in a positive surface gradient that trends from the ice sheet edge to the ice sheet interior. This promotes gravity-driven ice flow directed from the thicker interior of the ice sheet to its thinner margins (Figure 9). Ice sheet dynamics thus provides a fundamental control on ice sheet evolution and stability over long timescales (Cuffey & Paterson, 2010). On both long and short timescales, ice sheet dynamics determines the geometrical configuration of the ice sheet that in turn plays a dominant role in the impact of GrIS and AIS changes on the surrounding Earth system (section 2.3).

A number of comprehensive reviews focused on general ice sheet dynamics (e.g., Schoof & Hewitt, 2013) and dynamics specific to both the AIS and GrIS (e.g., Goelzer, Robinson, et al., 2017; Pattyn et al., 2017) already exist. These reviews detail the many intrinsic and often coupled processes that affect ice sheet flow that we very briefly summarize here. The pressure dependence of the ice melting point facilitates different ice flow regimes—one dominated by internal deformation (vertical shear) and another dominated by sliding at the ice/bedrock interface—and the switching from one to the other. The rate of ice deformation (or "creep") is a highly nonlinear function of temperature. Among other dynamic characteristics, this nonlinearity enables the following cyclic behavior, which is intrinsic to ice sheet flow: warm ice flows much faster than cold ice, leading to ice thinning, which leads to advective cooling that can ultimately freeze the ice to its bed. The reduced ice flow causes increase of ice thickness until the ice/bed interface reaches the melting point. This kind of "binge-purge" behavior was proposed by MacAyeal (1993) to explain long-term oscillatory behavior of ice sheets. The presence and movement of liquid water underneath ice sheets (see Flowers, 2015 for a detailed review or recent model developments and applications) enables a suite of feedbacks between subglacial hydrology and ice flow that operate on a number of different timescales (Marshall & Clark, 2002; Sergienko & Hindmarsh, 2013; Sergienko et al., 2007, 2014). Sliding of ice over the bed depends on the effective pressure—the difference between subglacial water pressure and ice overburden pressure—at the ice/bed interface. Thus, the subglacial hydrologic system is partly controlled by the pressure exerted by the overlying ice, leading to highly nonlinear and often counterintuitive behavior and feedbacks between ice sheet geometry/dynamics and subglacial water systems (Hiester et al., 2016; Hoffman & Price, 2014; Sergienko, 2013a).

2.3. Ice Sheet Regulation of the Earth System

As summarized in section 2.1, the Earth system plays a fundamental role in regulating both GrIS and AIS changes via direct influences from the atmosphere, ocean, sea ice, and solid Earth. In turn, due to their substantial topographic presence and both dynamic and thermodynamic responses to Earth system forcing (section 2.2), the ice sheets are able to exert a strong return influence on the Earth system (Table 1).

However, notable differences in the size and geographic location of the ice sheets result in major distinctions in this control: whereas Antarctica lies within the southernmost latitudes of the planet and is isolated by the circumpolar Southern Ocean, Greenland is surrounded by both ocean and nearby land at middle and high northern latitudes (~60°N–80°N). Combined with major differences in ice sheet characteristics, these very distinct geographic settings strongly influence the mechanisms by which the GrIS and AIS influence the surrounding climate. In the following section we examine the interactions that result in this difference.

2.3.1. Greenland Ice Sheet Influences on Climate

Atmospheric influences. Isolating Greenland's influence on atmospheric circulation is a challenging exercise, in part because of the complexity of the atmospheric and ocean dynamics in the North Atlantic, and also because most studies of GrIS deglaciation focus on warm climate states (high CO_2 and high insolation orbital configurations; e.g., Dolan et al., 2015; Otto-Bliesner et al., 2006; Ridley et al., 2005), which makes it hard to distinguish the climate impacts of deglaciation from those due to changes in other boundary conditions. Nevertheless, it is clear that the combination of an elevated surface and a high (surface) albedo dams cold air over the ice sheet interior. This gives rise to density-driven katabatic winds, which play a key role in the structure of the local atmospheric boundary layer and also influence cyclone development in the North Atlantic sector (Klein & Heinemann, 2002; Kristjánsson & McInnes, 1999).

Despite a substantial height and spatial extent, the GrIS exerts a fairly weak control on the planetary-scale atmospheric circulation, because it sits on the eastern edge of the lee wave downwind from the Cordilleran mountain range, a region where the low-level westerly mean flow is generally weak and largely parallel to the topography. This general flow pattern persists throughout the year but is particularly pronounced in winter when hemispheric-scale stationary waves help amplify the midlatitude flow (Figure 5). With the exception of occasional occurrence of a local wind phenomena known as the "Greenland tip jet"—localized jet stream emanating from the southern tip due to flow interaction with the ice sheet (Doyle & Shapiro, 1999)—the topographic Rossby wave forcing from the Greenland continent is limited as these types of waves are excited by sufficiently strong westerly mean flow normal to the topography (see Löfverström et al., 2014 and Löfverström & Lora, 2017 for a similar discussion on the limited atmospheric response to paleo ice sheets in northeastern North America). Topographic GrIS surface cooling, on the other hand, yields low-level subsidence, which promotes the formation of a quasi-permanent anticyclone over the ice sheet. However, due to the weak westerly mean flow, the diabatic wave response is largely confined to the GrIS region.

One method of characterizing the impact of ice sheet topography is to compare simulations with ice sheet topography present to parallel simulations with the same topography partly or fully removed. Modeling experiments with the GrIS removed show dramatic increases in the local surface temperature, both due to lower elevation and the replacement of ice and snow with lower-albedo bare land or vegetated surface (Hakuba et al., 2012; Otto-Bliesner et al., 2006; Ridley et al., 2005; Toniazzo et al., 2004). Surface warming is particularly strong in summer when the ground is heated by solar radiation (Ridley et al., 2005) and promotes the formation of a surface cyclone that effectively reverses low-level GrIS winds. In addition, the removal of steep ice margins yields a more even distribution of precipitation over the continent, with an increase in the interior and a decrease in coastal areas (e.g., Davini et al., 2015; Hakuba et al., 2012; Toniazzo et al., 2004). Sea breeze likely also emerge as important regulators of precipitation distribution over an ice-free Greenland continent in summer, whereas these are absent in the case of an existing ice sheet.

While the direct large-scale atmospheric impacts of GrIS topographic change appear limited, they can potentially have large indirect implications for the global climate due to their role in determining regional oceanic deep convection. For example, Davini et al. (2015) found that the reversal of the surface winds along Greenland's east coast when flattening the ice sheet weakens wind-driven ocean circulation in the Greenland-Iceland-Norwegian Seas, which in turn leads to a freshening of the northern North Atlantic and

Arctic Oceans. This results in a slowdown of North Atlantic Deep Water (NADW) formation and subsequent thermohaline overturning circulation, with potentially significant follow-on implications for global climate. Additionally, NADW formation is modulated by GrIS topography-controlled atmospheric jets (Pickart et al., 2003), which periodically drives intense mixing and cooling over the Irminger Sea — a mechanism that would be absent in a GrIS-free world with further dampening impacts on broader circulation strength. Such mechanisms clearly highlight the potential for GrIS topography to impact broader Earth system dynamics via atmospheric regulation of - in particular - regional ocean conditions.

Oceanic influences. The freshwater flux from GrIS to the surrounding oceans is composed of (1) surface runoff, (2) melting of open ocean icebergs, and (3) submarine melting of outlet glaciers and ice shelves.

Iceberg calving is regulated by ice flux across the grounding line and also changing position of ice sheet grounding lines (Benn et al., 2017): for example, increased calving could occur either from increased ice flux across a stationary grounding line or grounding line retreat in the presence of a constant ice flux. GrIS calving generally occurs within confined fjords that are often choked with ice melange (Amundson et al., 2010). This prevents icebergs from moving freely in response to ocean currents and wind stresses, and as a result, icebergs may spend several months pinned within fjords during which significant melting can occur (Enderlin et al., 2016; Moon et al., 2017), particularly, as deep iceberg keels are exposed to warm and rapidly circulating subsurface waters. As a result, the iceberg-sourced freshwater flux that reaches the open ocean is characterized by both solid (icebergs) and liquid (meltwater) components, where the latter is a combination of surface and iceberg melt in the summer and iceberg melt in the winter. GrIS-sourced icebergs distribute freshwater across a broad swath of the ocean as they decay and melt in response to increased temperatures and/or wave erosion (Bigg et al., 1997). GrIS calving rates and iceberg sizes exhibit notable seasonal variability, with the resulting open ocean freshwater flux at a maximum during Northern Hemisphere summer.

Greenland summer surface meltwater is predominantly routed to the ocean by moulins and the subglacial hydrological system (Greenwood et al., 2016; Smith et al., 2015) and, as a result, this water exits the ice sheet margin at the ice sheet bed. If the margin is land terminating (terrestrial), the meltwater ultimately enters the ocean at the surface via periglacial river networks. Once in the ocean, it remains as a concentrated near-surface lens due to its relatively low density. Conversely, if the margin is marine terminating, subglacial water discharge occurs at the depth of the grounding line that can be many hundreds of meters below sea level for large outlet glaciers (e.g., An et al., 2017). The input of buoyant meltwater at depth below near-vertical calving faces in confined fjords induces fundamentally different fjord circulation than surface-injected meltwater (Straneo & Cenedese, 2015). In the case of the latter, rapid ascent of buoyant plumes initiated by meltwater influx through typically highly stratified fjord waters provides a source of energy for turbulent mixing that acts to (1) provide heat to the ice/ocean interface and thus drive increased melting, (2) entrain warm and saline water upward, and (3) strongly dilute meltwater throughout the water column (Beaird et al., 2015). The net effect is that surface melt-induced runoff from Greenland's marine-terminating glaciers enters the open ocean as a vertically diffused signal (along with a similarly distributed iceberg signal), in sharp contrast to runoff from terrestrial margins. This distinction is largely neglected in extant climate models, yet it may have substantial impacts on projected behavior of the Atlantic meridional overturning circulation via NADW formation and its response to increased freshwater influx from the GrIS (e.g., Böning et al., 2016; Luo et al., 2016). As a result of this discrepancy between observed and modeled GrIS freshwater pathways, the oceanic impact of increasing GrIS freshwater fluxes in response to increasing surface melting and increasing calving and submarine melt remains unclear despite the large body of existing research on the topic.

2.3.2. Antarctic Ice Sheet Influences on Climate

Atmospheric influences. As with the GrIS, changes to AIS topography have an impact on atmospheric circulation. However, because of AIS size and geographic location, its influence on both local and global scales is different than the Northern Hemisphere counterpart.

Density-driven katabatic winds flowing from the AIS sheet interior (DeConto et al., 2007) are substantial atmospheric features that would be absent in lieu of AIS topography. Similar to Greenland, these winds control the structure of the atmospheric boundary layer and also help regulate the broad-scale austral winter sea ice extent. In addition, they are also important for global ocean circulation because, as they flow offshore (equatorward), they are steered westward via the Coriolis force (note that the Coriolis force acts orthogonal to the left of the motion in the Southern Hemisphere), promoting a strong oceanic coastal current and contributing to formation of the subsurface Antarctic Slope Front (Whitworth et al., 2013).

They also promote polynya formation and associated dense water formation on the lee side of stationary coastal features such as land-fast sea ice, ice shelves, and large tabular icebergs (Kusahara et al., 2011; Nihashi & Ohshima, 2015). Because this dense water is a component of Antarctic Bottom Water, AIS katabatic winds provide a direct link between AIS topographic steering of atmospheric circulation and global oceanography.

At a larger scale, extremely cold climate conditions over the Antarctic continent regulate the global-scale equator-to-pole temperature difference. Global modeling experiments with modern conditions but absent AIS topography show a dramatic influence on atmospheric circulation. Although the global mean temperature is found to be largely unchanged by the removal of the ice sheet due to cloud feedbacks and changes in global heat flux (Goldner et al., 2013; Singh et al., 2016), the temperature over the Antarctic continent itself is much higher due to changes in elevation and diabatic processes at the surface and in the free troposphere. This leads to enhanced top-of-atmosphere emitted longwave radiation, and in order to maintain the global temperature and energy balance, the rest of the globe compensates by cooling via adjustments of global meridional ocean and atmosphere heat transport budgets (Singh et al., 2016). Similar to many future projections under anthropogenic climate change (Shaw et al., 2016), the reduced equator-to-pole temperature gradient also yields a strengthening and a poleward shift of the midlatitude jet stream and storm track, resulting in more precipitation falling over the Antarctic continent. In the extreme case of a complete AIS deglaciation, the baroclinic zone (region where synoptic systems develop due to strong meridional and vertical sheer of temperature and wind) may shift from the Southern Ocean to the Antarctic continent (Singh et al., 2016). The same experiment suggests a weakening of the stratospheric polar vortex, which is an integral aspect of atmospheric chemistry and radiative transfer because it keeps trace gases (e.g., ozone) in the southern high latitudes throughout the austral winter.

Qualitatively similar model experiments exploring AIS inception using Oligocene (∼34–23 million years ago) continental topography, bathymetry, and elevated CO_2 concentration provide additional insight into AIS topography change impacts. Goldner et al. (2014) noted strong global impacts from AIS topography and albedo changes including significant atmosphere and sea ice–moderated deep ocean changes consistent with paleo-proxies after imposing a full Antarctic topography. Notable differences between the large-scale climate responses identified by Singh et al. (2016) and Goldner et al. (2014) highlight that different global responses to AIS topography imposition can occur from different models/resolutions, CO_2 concentrations, and continental geographies. This state and model dependence, often echoed across studies of ice sheet/climate interaction sensitivity, complicates state-independent identification of canonical relations describing AIS/Earth system interactions. Nonetheless, they consistently highlight the potential for significant climate impacts in response to large-scale AIS topographic change.

Oceanic influences. Iceberg fluxes and subshelf melting from AIS margins play a key role in the Southern Hemisphere and global hydrological cycle by returning water precipitated over the AIS to the ocean (albeit after a multithousand year delay due to sequestration as glacial ice). While the total fresh water flux from Antarctica into the ocean is minor relative to total Southern Ocean precipitation minus evaporation ($P - E$; Pauling et al., 2017), the specific locations of this freshwater injection lead to disproportionate oceanic impacts because these locations often coincide with critical locations for Southern Hemisphere bottom water formation.

AIS iceberg fluxes represent a spatially heterogenous three-dimensional freshwater source to the ocean, because large Antarctic iceberg drafts extend to several hundred meters and can thus melt at depth, far from their original calving locations. Locally, buoyant iceberg meltwater plumes act as additional sources of vertical mixing (Stephenson et al., 2011) and affect not only hydrography and sea ice production (Jenkins, 1999; Stern et al., 2016) but also primary productivity via export of glacially sourced dissolved iron to the otherwise iron-limited Southern Ocean mixed layer (Duprat et al., 2016). The location and thus climate impact of iceberg melting is largely dependent on iceberg size (Stern et al., 2016), because iceberg size determines the relative sensitivity to ocean/wind stress and sea surface tilt (Rackow et al., 2017). Smaller icebergs are more sensitive to the former and thus more quickly migrate northward to melt, while larger icebergs tend to migrate parallel to the Antarctic coast for longer periods in response to the combination of northward sea surface tilt and Coriolis force and greater sensitivity to depth-integrated Ekman layer velocities (Merino et al., 2016). The resulting hemispheric distribution of iceberg-sourced meltwater fluxes and associated net oceanic cooling is characterized by a near-Antarctic coastal maxima and three dominant branches associated with equatorward-trending arms of major Southern Ocean circulation gyres (Tournadre et al., 2016).

The impact of iceberg freshwater distribution on Southern Ocean oceanography and sea ice can be assessed from model sensitivity studies that systematically add or remove icebergs. For example, Merino et al. (2016) found a Southern Hemisphere sea ice volume increase of 10% in response to AIS iceberg presence. Imposition of iceberg melt also increased ocean stratification and associated mixed-layer depths. Using a dynamical-only model of the Southern Ocean sea ice/iceberg system, Hunke and Comeau (2011) identified an increase in sea ice production to the downwind side of icebergs, as they blocked previously formed sea ice on the upwind side and therefore generated local polynyas where new sea ice could form. By altering iceberg sizes, Stern et al. (2016) found that by redistributing the westward freshwater transport around the Southern Ocean, differing iceberg sizes were also capable of significantly altering regional sea ice concentrations. While large tabular icebergs provide the dominant fraction of freshwater delivered to the Southern Ocean (Tournadre et al., 2016), their low frequency of occurrence makes it difficult to create a reasonably continuous iceberg climatology for use in ocean and climate models. This is mitigated to some extent by the tendency of large icebergs to fracture into smaller icebergs relatively early in their life cycle (indeed, this appears to be the major mechanism for small iceberg creation; Tournadre et al., 2016). However, it still represents a problem similar to that of volcanic eruptions in that large iceberg calving events and volcanic eruptions both act as stochastic point-source forcings of the climate system that occur at discrete and currently hard-to-predict intervals, that challenge representation of their impacts in ocean and climate models (Rackow et al., 2017).

Unlike iceberg meltwater fluxes, ice shelf basal melting delivers a flux of freshwater to the open Southern Ocean along a line source close to the Antarctic coastline. This freshwater is initially generated at depth under ice shelves and is cooler and fresher than ambient ocean water masses due to pressure and salinity dependence of ice melting temperature. Subsequent buoyant shoaling of this water along the ice shelf base results in substantial ocean water mass modification, including supercooling and refreezing as frazil ice (Smedsrud & Jenkins, 2004). Sub-ice shelf meltwater exits cavities at the ice shelf calving front at depth, with subsequent small-scale processes and local recirculations of sub-ice shelf water masses resulting in complex hydrography in the vicinity of ice shelf fronts (e.g., Garabato et al., 2017a). As a result, a diluted ice shelf meltwater flux appears to often enter the open ocean as a buoyantly stable subsurface lenses (e.g., Loose & Jenkins, 2014).

Sub-ice shelf melting controls formation of ice shelf water — a mixture of fresh meteoric meltwater with high salinity shelf water formed during sea ice brine rejection — as well as other water masses that contribute to formation of Antarctic Bottom Water that fills much of the abyssal ocean (e.g., Nicholls et al., 2009). Through this mechanism, Antarctic subshelf melt fluxes play a large role in determining global thermohaline circulation characteristics, with implications for long-term climate evolution (e.g., Weaver et al., 2003). Despite its importance, many existing model sensitivity studies exploring impacts of Antarctic basal meltwater on broader oceanographic, sea ice and atmospheric conditions should be interpreted with caution because they often (but not always; e.g., Merino et al., 2016; Pauling et al., 2017) prescribe ice shelf melt water at the sea surface and often also overestimate meltwater fluxes. Notwithstanding this questionable application of ice shelf melt water, such studies have shown contradicting results (for example, the impact of subshelf melting on sea ice trends; Bintanja et al., 2013; Swart & Fyfe, 2013). Thus, robust isolation of ice shelf melt impacts on broader climate conditions remains an outstanding topic to study.

2.4. Solid Earth and Gravitational Influences

Ice sheet change impacts the solid Earth in a number of significant ways including isostatic interactions with the lithosphere and mantle, changes in Earth's gravitational field and rotational axis following mass redistribution, and physical and chemical interactions as a result of erosion and sedimentation processes.

Earth's lithosphere adjusts in response to the weight of an overlying ice sheet; as an ice sheet grows, the elevation of the lithosphere beneath decreases, and as an ice sheet shrinks, the elevation of the lithosphere beneath rises, according to the principles of isostacy (van der Veen, 2013). Adjustment of the lithosphere is also governed by the dynamics of a complex rheological material that can be approximated as viscoelastic; while there is an instantaneous adjustment due to the lithosphere elastic response, there is also a delayed adjustment due to the underlying viscous mantle that is regulated by the Maxwell timescale for a viscoelastic material (Turcote & Schubert, 2002). Significant complexities in understanding of the lithospheric response are due to the fact that rheological parameters of mantle and crust are strongly heterogeneous (Austermann et al., 2013).

Additionally, the transfer of mass between the ice sheets and oceans leads to perturbations in the orientation of Earth's rotation vector that further affect the spatial distribution of sea level, with maximum impacts at

45°N and 45° (see Figure 6 from Gomez, Mitrovica, Tamisiea, et al., 2010). As ice sheets grow (shrink) in size, they lead to positive (negative) regional gravity anomalies that cause sea levels proximal to ice sheets to rise (fall). This interaction, often referred to as ice sheet " self-gravitation," has long been recognized and was quantitatively explored in the context of modern-day ice sheet demise and SLR 40 years ago (Clark & Lingle, 1977). Nevertheless, its full impact on ice sheet-sourced SLR has only recently been fully appreciated by the wider community.

As ice sheets grow and advance they also erode their beds, thereby directly lowering the relative elevation of the bedrock beneath the ice sheet and delivering substantial sediment fluxes to their terrestrial and/or marine margins (Dalca et al., 2013; Rugenstein et al., 2014; Ohneiser et al., 2015; van der Wal & IJpelaar, 2017).

2.5. Section Recap

This section summarizes the processes by which the Earth system impacts ice sheet behavior and, conversely, the processes by which ice sheets exert a return control on the Earth system. Surveying these interactions reveals that they occur at both local and global scales and timescales ranging from minutes to millennia.

Contrasting Greenland and Antarctic Earth system interactions provides insights into the relative strengths of various interaction processes over each ice sheet. A summer net positive energy balance of sufficient magnitude to support robust GrIS ablation areas emerges as a crucial distinguisher between the two ice sheets. Substantial surface melt and runoff removes a large fraction of the GrIS ice mass before it can reach the ocean advected by ice flow, leading to a reduction in margin thickness, the presence of significant terrestrial GrIS margins, and the presence of substantial liquid runoff from GrIS subglacial hydrological drainage. It also results in major differences between GrIS and AIS ocean/ice interactions via the seasonal occurrence of strong subglacial flux-triggered submarine plumes and associated impacts at GrIS outlet glaciers. In combination, surface melt drives ice mass loss and — via summer subglacial melt water — plume-driven enhancement of marine ice melting, which may speculatively link surface melt to the lack of a substantial GrIS ice shelf presence. More fundamentally, surface melting may be a causal factor in the relative prevalence of GrIS fjord-constrained outlet glaciers relative to the AIS: modeling and sedimentological evidence indicates that with surface melting curtailed, the glacial GrIS subsumed many fjord systems within a broader Antarctic-style ice sheet complex extending in grounded form over much of the continental shelf.

AIS- and GrIS-specific impacts on the surrounding Earth system also exhibit differences related to their different geographic locations. For example, being isolated at the southern high-latitudes by a circumpolar ocean, the AIS impacts on atmospheric circulation are different from GrIS impacts. Ocean impacts are also very different, both by the varying fractions of near-coastal liquid freshwater input versus iceberg-supplied melt fluxes, and also by the relation of these fluxes to regional oceanic circulation patterns and sea ice production regions. In light of these differences, however, a distinct commonality that emerges between both ice sheets is their influence on the formation of global ocean water masses.

Contrasting AIS and GrIS interactions with the Earth System also illustrates major Earth system-forced ice sheet changes that may arise in a future warming world. For example, the 21st century trends from presently localized AIS surface melt (Kingslake et al., 2017; Lenaerts, Lhermitte, et al., 2017) toward more spatially pervasive low elevation atmospherically driven melt (Fyke et al., 2010; Trusel et al., 2015) could potentially enable GrIS-like behavior within the AIS. This would include establishment of robust AIS ablation zones and associated moulin complexes, over ice shelf hydrofracturing and grounding line-sourced austral summer under shelf meltwater plumes. In turn, projections of drastically increased GrIS ablation areas and associated summer runoff will — in addition to large-scale terrestrial ice loss, perhaps over the North Dome/South Dome ice saddle — inevitably drive major changes in marine margin melt regimes, with possible consequences for calving and ocean circulation. Independent of ice sheet freshwater flux impacts, oceanic forcing of both ice sheets (and vice versa) will likely change dramatically as well. However, these changes are at present very poorly understood in part because they will likely be dominated by complex oceanographic dynamical processes for which detailed investigations have only recently have been initiated using models of sufficient resolution (e.g., Garabato et al., 2017b; Hellmer et al., 2012; Lique et al., 2015; Spence et al., 2014, 2017). This gap in knowledge is particularly worrying, given that the ocean/ice sheet interactions will play a major role in modulating future ice sheet-sourced SLR.

3. Feedbacks Between Ice Sheets and the Earth System

Section summary. The goal of this section is to introduce a conceptual framework for analysis of ice sheet/Earth system feedbacks, catalog known ice sheet/Earth system feedbacks, and speculate about potential uncharacterized feedbacks.

Feedback analysis provides a " framework for the quantification of coupled interactions" that affect the evolution of complex dynamical systems (see Roe, 2009, and references therein). The Earth system is one such complex system, with distinct components exhibiting complex internal dynamics and interactions across a range of temporal and spatial scales. The concept that internal interactions between Earth system components can amplify or dampen the integrated system response to external forcing has been documented well over a century. Early hints of climate feedback analysis arise in seminal studies on ice age cycles (Croll, 1864) and the impact of greenhouse gases on global temperature (Arrhenius, 1896). More recently, studies of climate feedbacks have typically focused on the factors determining the response to radiative forcing (Hansen et al., 1984; Schlesinger & Mitchell, 1987). These studies usually use global average surface air temperature as a metric for evaluating the effects of such feedbacks (e.g., Flato et al., 2013). In addition to modifying the Earth system response to external forcing, feedbacks also enable internal (i.e., not caused by an external forcing) climate variability phenomena such as the ENSO (Bjerknes, 1966). As a result of Earth system feedbacks, the net impact of external climate forcings (e.g., orbital variations, meteor impacts, solar strength changes, tectonic configurations, volcanoes, anthropogenic radiative gas emissions, and anthropogenic land use changes) includes the direct response to forcing and also a signature of internal system dynamics (Figure 10). Feedbacks can be negative or positive. In the case of a negative feedback, sensitivity to a change in external forcing (in either forcing "direction") is dampened (reducing the effective strength of the original forcing), while a positive feedback amplifies the sensitivity to forcing (increasing the effective strength of the original forcing) (Roe, 2009). In both cases, while the instantaneous impact of feedbacks approaches zero for systems approaching a state of dynamic equilibrium (barring runaway positive feedbacks), feedbacks can nonetheless strongly influence the final state of equilibrium by determining the total change that the system experiences in response to forcing.

As we demonstrate in section 2, ice sheets exhibit direct interactions with every other major Earth system component. These two-way interactions take place over a wide range of spatial and temporal scales. The presence of extensive two-way interactions is the fundamental basis for feedbacks in the ice sheet/Earth system. These feedbacks are of critical concern, since they have the potential to significantly impact ice sheet evolution and the sea level response to external forcing. A conceptual framework consisting of (1) ice sheets and (2) "the rest of the Earth system" provides a convenient starting point for exploring ice sheet/Earth system feedbacks because it allows assessment of feedbacks explicitly in terms of their impact on ice sheet change (Figure 10). This definition as a starting point considers either (1) an initial externally imposed forcing applied to the Earth system or (2) a remotely generated but "ice sheet-independent" internal variability signal, either of which translates to an initial metric of ice sheet response. This ice sheet response then triggers additional mechanisms that induce Earth system changes, which in turn drive a net additional ice sheet modification that closes the feedback loop (Roe, 2009).

The choice of metric for ice sheet change depends on the specific question being asked. A metric of obvious practical relevance is that of ice sheet volume, which can be translated relatively easily to a measure of eustatic sea level change. Thus, we can specifically imagine a counterfactual world, in which a particular feedback (but no others) is absent as our "reference case," and assess the strength of the feedback by comparing the change in ice sheet volume in the reference case to the "realistic" case in which all feedbacks are operating for a similar external forcing (Figure 10). Models are essential for such feedback analyses because they allow for the construction of the counterfactual, feedback-disabled case. Conversely, feedback quantification using only direct observations of the natural system is difficult, since these observations already include the effect of all feedbacks. Developing model experiments in which parts of the coupled ice sheet/Earth system are disabled and comparing them to fully coupled counterparts may at first glance appear esoteric. However, it is worth noting that a large body of research examining ice sheet responses to climate change are in fact examining "counterfactual" worlds with feedbacks neglected (this neglect being most often a necessary simplification). Thus, measuring the difference between counterfactual and wholly representative models of ice sheet/Earth system interaction both quantifies the impact of feedbacks on the forced ice sheet response and also estimate the error associated with projections from studies that neglect feedbacks.

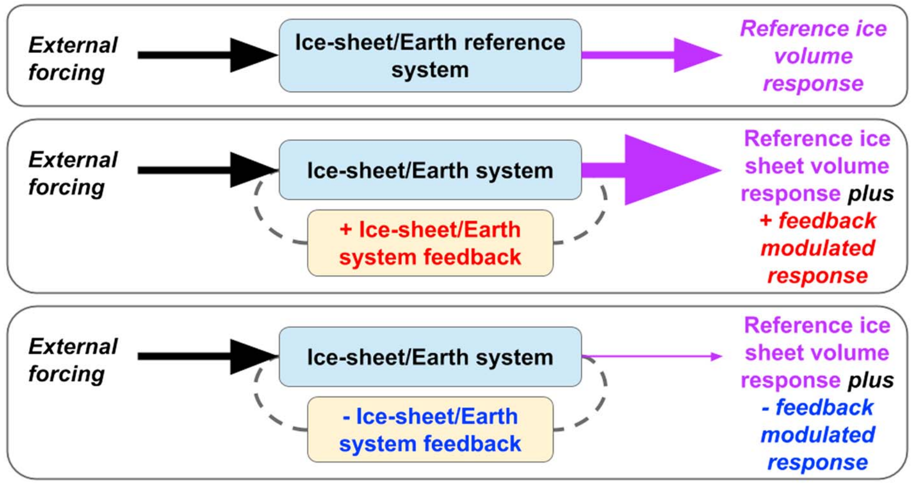

Figure 10. Schematic illustrating the operation of ice sheet/Earth system feedbacks. External forcings (forcings that are independent of ice sheet/Earth system interactions such as changes to Earth's orbit, anthropogenic carbon emissions, or low-latitude-sourced climate variability) are represented by black input arrows. The ice sheet/Earth reference system (top) denotes a hypothetical system in which a particular feedback loop of interest is absent. Additional positive/negative ice sheet/Earth system feedback loops are represented in red/blue, respectively (middle/bottom). Gray dashed lines represent the ice sheet/Earth system interactions that support feedback loops. Purple output arrows denote the ice sheet volume response to external forcing. A thicker/thinner purple arrow indicates higher/lower ice sheet volume response to the same external forcing—relative to the reference response—due to positive/negative feedback loops.

In the following sections, as we catalog ice sheet/Earth system feedbacks, we attempt to maintain the framework described above, in which feedbacks are described as reinforcing/dampening agents of ice sheet-integrated volume change in response to external forcing. This framework provides a perspective for relating feedbacks between ice sheets and other components of the Earth system to the interactions described in section 2. However, the interactions among feedback loops themselves (Roe, 2009) sometimes makes this task difficult due to nonlinear interactions and, in some cases, the impracticality of cleanly isolating one feedback from the rest of the climate system. We also note that in some cases we diverge from the "classical" definition of feedbacks that is premised on their ability to directly modify the effective strength of the original system input. In the ice sheet/Earth system setting, feedback loops may influence ice sheet volume not by altering the original mass change mechanism (for example, temperature-driven surface melting) but rather by altering a different forcing mechanism (say, iceberg calving). This broader definition simply reflects the diversity of ways that the Earth system and ice sheets interact.

3.0.1. Ice Sheet/Atmosphere Feedbacks

Geometry/SMB feedbacks. Feedbacks can arise between ice sheets and the atmosphere as a consequence of ice sheet geometry change. A fundamental negative feedback in glacial systems on sloped beds relates ice advance to ablation area size: if an external perturbation causes ice mass gain, the ice terminus will advance downslope, growing the ablation area. This growth will ultimately counter the original mass increase, bringing the ice sheet back into balance. In the case of a flat bed without a sufficiently large horizontal gradient in surface air temperatures to halt the ice advance through ablation, it is advance into warmer/drier climates, or advance to the coastline, that ultimately limits further ice mass growth (Oerlemans, 1981). These "stabilizing" negative feedbacks bear a practical similarity to the Planck radiative negative feedback that stabilizes idealized black bodies against runaway temperature change (Roe, 2009) (although unlike the Planck feedback, the stabilizing feedback relating ice size to ice change may have practical limits that if surpassed can lead to near-global "Snowball Earth" scenarios; Fairchild & Kennedy, 2007). Ice sheet size/change and Planck negative feedback mechanisms are also conceptually similar in that they are so fundamental to the operation of ice sheets/black bodies (respectively) that they are often implicitly assumed to be part of the reference system upon which additional feedbacks operate.

The next most well-characterized geometry/SMB positive feedback is the temperature-based elevation/SMB feedback (Oerlemans, 1981) that depends on the presence of ablation areas and atmospheric temperature change with elevation (i.e., lapse rates). As a result of these factors, an initial externally forced increase in ablation—for example, due to increased summer temperature—will lower ablation area elevation. This in turn causes additional melting as the ice surface experiences warmer low-elevation temperatures. The same mechanism also operates in reverse (as with all feedback processes). The impact of this feedback increases with greater levels of elevation change: using idealized ice loss geometries in an atmospheric model, Hakuba et al. (2012) estimated a $\sim$ 2°C increase in GrIS-averaged surface temperatures for each 25% GrIS volume loss increment, which is similar to earlier studies (e.g., Ridley et al., 2005), with the majority of this temperature increase arising from temperature lapse rate considerations. The importance of the temperature-based height/SMB feedback may have played a critical role in glacial climates characterized by ice sheets with large ablation zones, by triggering rapid deglaciation as thresholds in ice sheet geometry initiated the height/SMB feedback across a massive ice sheet area (Gregoire et al., 2016). The efficacy of the temperature-based elevation/SMB positive feedback also reflects a strong state dependence on the presence of summer melting conditions. As a result, in the present Earth system the GrIS has the immediate potential for temperature-based height/SMB feedback effects due to the presence of marginal ablation areas, while lack of ablation around the AIS margin suggests that this feedback would have little immediate effect (Oerlemans, 1981).

In addition to relatively straightforward temperature effects, changing ice sheet topography will drive regional feedbacks on ice mass balance and therefore volume, as large-scale topographic ice sheet changes (in the extreme case, equivalent to addition or removal of a large mountain range) impact local atmospheric dynamics, which in turn modifies circulation and associated ice sheet accumulation and melting patterns. Given the prevalence of orographic precipitation over the present-day margins of the GrIS and AIS, the first-order impact of surface lowering and retreat would be to decrease coastal precipitation, as the orographic precipitation tracks the retreating and shallowed ice margin slope. All else held constant, this would constitute a positive feedback on coastal ice mass balance due to decreased accumulation, but a negative (stabilizing) feedback landward as more moisture was able to advect and precipitate deeper into the interior. Hakuba et al. (2012) estimated a net negative feedback due to these effects as a result of increased snowfall, even in light of a reduced fraction of total precipitation falling as snow. Additionally, the subsequent increase in ice dynamic flow resulting from the steepened interior-to-margin surface gradient (Ridley et al., 2005) would compensate both local feedbacks after a time delay corresponding to the dynamics timescales. These effects likely had a large influence on North American ice sheet evolution during past glacial cycles (Löfverström et al., 2015; Löfverström & Liakka, 2016), highlighting their possibly influential role in future change in Greenland and Antarctica.

The integrated impact of height/mass balance feedbacks can be estimated in coupled ice sheet/Earth system models (ESMs) by letting SMB evolve but not updating the topography to reflect melt-forced elevation changes. Over a time period of one to three centuries it appears that the positive feedback associated with elevation loss dominates in these experiments. Using such an approach, Vizcaino et al. (2015) attributed an 8–11% additional GrIS mass loss by year 2100 and 24–31% by year 2300 to integrated height/SMB feedbacks, with the higher relative impacts occurring for the lower (e.g., RCP2.6) forcing scenarios (van Vuuren et al., 2011) and their post-2100 extensions. Other recent estimates of height/SMB feedback strength using coupled models (9% by 2150 under RCP8.5; Le clec'h et al., 2017) and model-guided parameterizations (4.3% by 2100 and 9.6% by 2200 under Special Report on Emissions Scenarios A1B; Edwards et al., 2014) confirm the general conclusion that the temperature impact of height/SMB relationships dominates over precipitation impacts, at least on century timescales.

Albedo/melt feedback. A notable atmospherically driven positive feedback is the albedo feedback, in which warmer snow (especially snow with significant liquid water content) exhibits a lower albedo that in turn promotes further warming and/or melting. Like the temperature-based positive height/SMB feedback, the albedo feedback is unambiguously positive and strongly skewed toward the summer season as it is related to downwelling solar radiation at the surface (Lunt et al., 2004). As a result, both the height/SMB and albedo feedbacks work in tight coordination over long time periods, with an initial decrease in ice elevation causing warming and increased melting that in turn decreases albedo, thereby accelerating subsequent melting.

Over the GrIS, the albedo-melt feedback is well characterized (Box et al., 2012) (Figure 11): as snow melts, it exposes underlying snow, firn, and bare glacier ice with lower albedos, leading to increased absorption of incident solar radiation and thus further melt. The feedback is locally enhanced by low-albedo supraglacial lake formation (Tedesco et al., 2012) and accelerated exposure of previously buried, low albedo englacial material

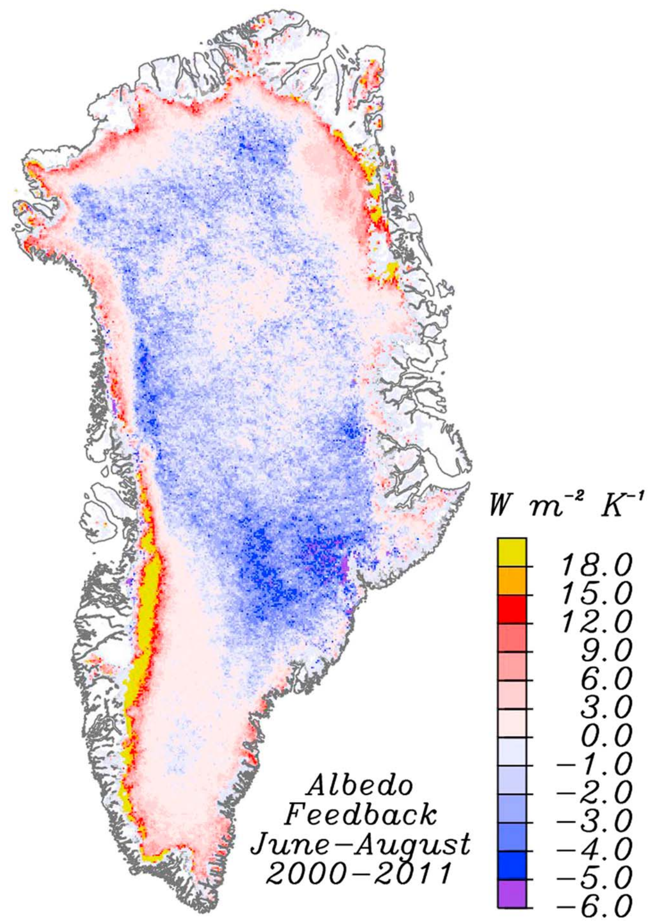

Figure 11. Estimated strength of the summer Greenland ice sheet albedo feedback, cast in terms of additional effective energy input to the surface energy budget. Reproduced with permission from Box et al. (2012).

in ablation areas (Tedesco et al., 2016; Wientjes & Oerlemans, 2010), both of which are directly related to initial melt perturbations and therefore internal aspects of the albedo/melt feedback loop. Beyond impacts of change from immediately local albedo effects, additional regional warming can also arise from the ice sheet retreat-driven replacement of relatively high albedo ice and snow with lower-albedo bare rocks and soil, or even lower-albedo vegetation. As demonstrated in coupled climate model simulations with and without a GrIS, this effect may even dominate over lapse-rate effects on near-surface temperature response during summer (Stone & Lunt, 2013), with significant implications for vegetation in inhibiting ice sheet regrowth after an initial loss.

Melt/discharge and accumulation/discharge feedbacks. A number of recent studies have pointed to the impact of increased atmospheric melt on GrIS ice discharge, through marginal ice thickness reductions and hence reductions in ice flux through outlet glaciers (flux being the product of velocity and ice thickness) (Fürst et al., 2015; Goelzer et al., 2013; Lipscomb et al., 2013; Vizcaino et al., 2015). This relationship can be interpreted as a negative feedback: an externally forced increase in melt draws down marginal ice thicknesses, reducing ice discharge across outlet glacier grounding lines, and thereby lessening the rate of overall ice sheet mass loss. Reduction in ice flux occur for three reasons. First, a reduction in discharge occurs from decreased ice thickness and associated gravitational driving stress at the grounding line, lessening the discharge flux for a given velocity. Second, longer-term reductions in the ratio of marine to terrestrial margins also cause a reduction in across-grounding line flux. In the extreme case where a margin transitions from marine to terrestrial (as in the recent evolution of Tasermiut Sermeq in southern Greenland, Figure 12) discharge across the grounding line reduces to zero, leaving surface melt as the only method for further ice loss. Third, superlinear

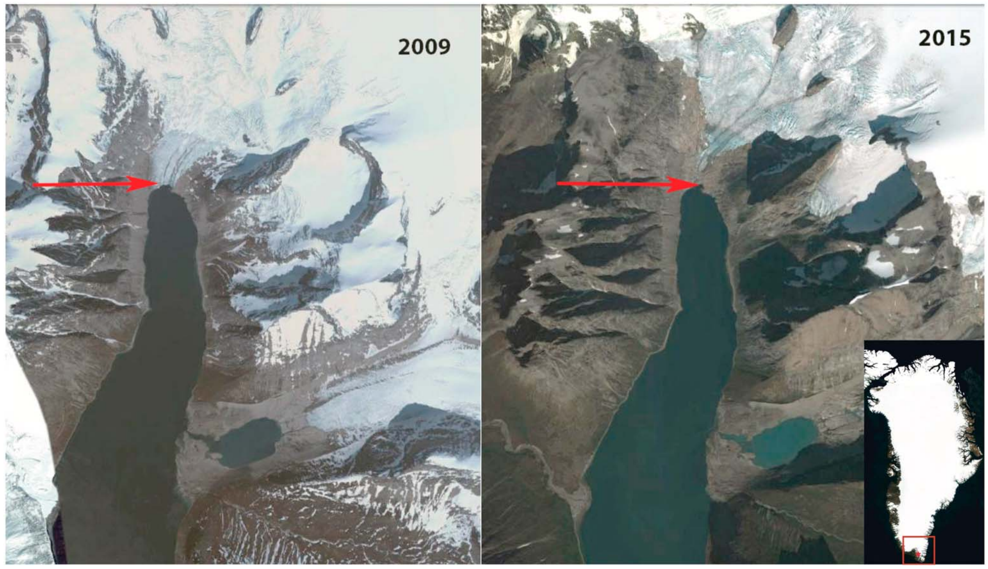

Figure 12. Ice evolution in Tasermiut Fjord, southern Greenland, between 2009 and 2015. Note that retreat of Tasermiut Sermeq (red arrow) from a marine to a terrestrial terminus. The red star in the red box on the inset map denotes the location of the fjord. Image courtesy of Mauri Pelto/American Geophysical Union.

inverse relationships between ice thickness and velocity for both internal deformation and basal sliding reduces the local ice velocity as a response to thinning ice. Thus, by itself, surface-driven melting causes ice slowdown — although the impact of this process relative to other melt-driven dynamical impacts such as basal hydrological controls (Hoffman et al., 2016) is unclear.

The surface melt-generated negative feedback also works in reverse (i.e., it dampens overall ice mass gain in response to decreased margin ablation). Additionally, a closely related mechanism operates in response to increased snowfall over AIS-like ice sheets with little or no margin ablation: as interior snowfall increases (as is expected in response to externally forced planetary warming as a consequence of the Clausius-Claperyon relationship; Frieler et al., 2015), the increased interior-to-coastal surface gradient steepens, driving increased coastal ice fluxes that mitigate a potentially large fraction of the initial snowfall increase (Winkelmann et al., 2012). Both the ablation and snowfall-modulated marine discharge feedbacks have been identified as major contributors to upcoming century-scale anthropogenically forced GrIS and AIS ice trends, reinforcing the need to calculate such interactions as part of SLR assessments.

Finally, an ongoing debate involves whether surface melt accelerates GrIS ice flow by pressurizing the basal hydrological system and reducing basal traction. This potential mechanism — which has been particularly studied over the GrIS given the presence of seasonal surface melt there — would represent a positive feedback on ice sheet mass loss because it superimposes initial mass loss from surface melt with an associated dynamic ice speedup. Initial suggestions that the gain associated with this positive feedback was substantial (Zwally et al., 2002) were based on summer-only observations and have since been tempered by recent theoretical (Schoof, 2010) and observational studies that identified subannual processes in GrIS subglacial hydrological evolution (e.g., Andrews et al., 2014) that may render the impact of summer speedup negligible on annual and interannual timescales (Shannon et al., 2013; Tedstone et al., 2013).

3.0.2. Ocean/Ice Sheet and Sea Ice/Ice Sheet Feedbacks

Ice sheet/ocean feedbacks (F_O, Figure 3) emerge as a consequence of ocean-forced ice sheet change. These feedbacks are much less well understood than ice sheet/atmosphere feedbacks. This is due partly to incomplete understanding (and incomplete models) of the underlying ocean/ice interactions under AIS ice shelves and against GrIS calving fronts. Nonetheless, recent efforts have applied current understanding to highlight several potentially substantial feedback mechanisms. Here we discuss ocean/ice sheet and sea ice/ice sheet feedbacks that rely on processes proximal to ice/ocean interaction regions, and feedbacks that rely on broader hemispheric-scale mechanisms.

Ice sheet/ocean feedbacks: A dynamic/thermodynamic ice/ocean mechanism that can be cast as a positive feedback arises from the relatively well-known "ice pump mechanism" (Lewis & Perkin, 1986), whereby the pressure and salinity dependence of the ice melting temperature causes preferential melting of deeper parts of ice shelf cavities. As the resulting buoyant turbulent plume rises it entrains warmer water from below, driving further melting that would not have occurred in stagnant waters. By this effect, an initial melt perturbation may be able to trigger a "heat engine" effect (Lewis & Perkin, 1986) that maintains self-sustained melting in a positive feedback that relies on ice melt thermodynamics coupled to plume buoyancy dynamics.

At the scale of individual ice shelf cavities, Arthern and Williams (2017) used a regional model of the Amundsen Sea sector of WAIS to identify a strong positive feedback associated with expansion of sub-ice shelf cavities due to initial sub-ice shelf melting increases. By driving exposure of previously grounded ice to warm ocean waters via dynamically regulated grounding line retreat, initial melting caused subsequent melting in a reinforcement of initial melt perturbation. The effect of this positive feedback was demonstrated by comparing simulations that accounted for melting of the newly exposed sub-ice shelf base to simulations where no melting occurred over such areas. At similar ice shelf scales, Sergienko et al. (2013) and Sergienko (2013b) identified another feedback between sub-ice shelf melting and geometry of the cavity and ocean circulation. Geometry changes as a result of ocean-driven melting caused changes in the sub-ice shelf circulation, which in turn determines the sub-ice shelf melting pattern that affects cavity geometry. An additional complexity of this finding was that not only the strength but also the *sign* of the feedback depended strongly on ambient ocean conditions as a result of the competing effects of ice shelf advection/deformation and sub-ice shelf melting. In circumstances where the sub-ice shelf cavity is filled with cold waters, melting is negligible compared to the ice advection and deformation and the shape of the sub-ice shelf cavity is primarily determined by ice shelf flow. Conversely, when the sub-ice shelf cavity is filled with warm waters, ice shelf deformation is negligible and the shape of the cavity is controlled by sub-ice shelf melting and advection of ice from upstream of the grounding line. Recent satellite-born observations of surface elevation changes of Dotson ice shelf (Antarctica) support the existence of this feedback mechanism (Gourmelen et al., 2017).

A potentially powerful feedback on long-term Antarctic mass change arises from the impact of meltwater on vertical mixing of heat in Antarctic coastal oceans (Fogwill et al., 2015; Menviel et al., 2010). Specifically, if AIS surface or basal melt were to increase, this would drive stratification of the water column, which would in turn reduce the vertical mixing of cold/warm polar waters downward/upward. This would in turn raise the temperature of middepth waters that are able to cross the continental shelf boundary and enter ice shelf cavities, increasing melt rates in a positive feedback loop. Evidence for co-occurrence of warmer middepth ocean waters and rapid marine ice sheet retreat during past Heinrich events (Marcott et al., 2011) lends strong observational support for this linkage, though, as with most observations, it is unable to disaggregate the direct- and feedback-derived signals.

Regional coupled system feedbacks: At larger spatial (regional and hemispheric) scales, ice sheet geometry changes likely trigger regional oceanic responses that in their turn feed back on ice sheet volume. Characterization of these feedback mechanisms is currently mostly speculative and typically also invokes atmosphere/ocean/sea ice interactions, making their representation in models dependent on an extensive chain of highly model dependent and interrelated processes. Nonetheless, modeling still provides valuable insight into the qualitative nature of these feedbacks. Goldner et al. (2013) noted that under background Eocene-Oligocene climate conditions, AIS inception triggered large-scale increases in Southern Hemisphere, southward integrated ocean heat fluxes, creating a potential negative feedback loop on Antarctic inception by slowing the cooling of intermediate-depth waters. Kennedy et al. (2015) provided further insight into the potential for locally enhanced impacts from ocean-mediated feedbacks, including large regional SST increases. Knorr and Lohmann (2014) quantified an additional change to over-ice SATs due to offshore ocean-ice feedback response to AIS growth as well as (perhaps most relevantly) large-scale patterns of subsurface ocean cooling around the Antarctic continent. However, because the latter three studies were limited to snapshot-style Atmosphere-Ocean Global Circulation Models simulations (i.e., excluding ice dynamical processes), they were unable to assess full ocean/ice feedback strengths. Furthermore, large discrepancies between studies related to the use of different models, paleo-geographies, and boundary conditions highlight lack of convergence in understanding with respect to the impact of ice sheet/ocean impacts (Kennedy et al., 2015). Nonetheless, a common indication of possible large-scale AIS ice sheet/ocean feedbacks emerges, pointing to the large potential for future discoveries in this field.

Ice sheet/ocean feedbacks influencing outlet glacier dynamics that dominate GrIS margins are much less well understood than even poorly characterized AIS ice sheet/ocean feedbacks. Most likely they are of a somewhat different character than Antarctic ice/ocean feedbacks given differences in ambient air and ocean conditions, fjord geometry and the presence of substantial subsurface injections of surface meltwater both at depth and at the surface. For example, buoyant plume effects are also present in GrIS fjords but differ in their interactions with ambient ocean circulation relative to AIS sub-ice shelf environments because they flow up more vertical calving faces and are confined to restricted fjord settings (Carroll et al., 2016). Thus, feedback mechanisms operating within AIS-proximal oceans are not likely to translate directly to GrIS environments, indicating the need and opportunity for dedicated GrIS ice sheet/Earth system feedback analyses.

3.0.3. Ice Sheet/Solid Earth Feedbacks

Ice sheet/solid earth interactions result in both positive and negative feedbacks. Here we discuss these in two broad categories: feedbacks with the solid Earth via isostasy and Earth's gravitational field, and feedbacks as a result of erosion and sedimentation processes.

Ice sheet/isostasy and ice sheet/gravity feedbacks. Feedbacks between ice sheets and the solid Earth arise from ice sheet-regulated changes in the shape and elevation of the ice-bedrock interface beneath ice sheets, sea surface height, and ice sheet self-gravity (de Boer et al., 2017; Gomez, Mitrovica, Tamisiea, et al., 2010). The primary feedback associated with viscoelastic relaxation and recovery of the lithosphere beneath a terrestrial ice sheet is generally understood to be negative; a growing ice sheet will depress the lithosphere beneath it, which lowers the overall ice sheet elevation and thereby decreases the net surface mass balance. These interactions have been incorporated in ISMs that also contain representations of solid Earth processes for several decades (Oerlemans, 1980). For marine-based ice sheets, the (instantaneous) elastic uplift that accompanies ice sheet loss and grounding line retreat acts as an additional negative feedback via regulation of the marine ice sheet instability (MISI) process (Schoof, 2007; Weertman, 1974). This occurs because isostacy partially replaces the submarine depression left by the departing ice sheet, reducing regional sea level. As sea level has a control on marine ice sheet grounding line position, reduced sea level effectively dampens a fraction of the initial external forcing driving ice sheet loss (Gomez, Mitrovica, Tamisiea, et al., 2010; Gomez, Mitrovica, Huybers, et al., 2010). Additionally, gravitationally induced changes to sea level following marine ice sheet decay and retreat lead to a regional drop in sea level, serving as a further negative feedback on additional ice sheet mass loss.

Interdependencies between these individual mechanisms mean that—particularly for marine ice sheets such as the AIS—feedbacks arising from interactions between isostacy, gravitation, and rotation are best described simultaneously (de Boer et al., 2017; Gomez, Mitrovica, Tamisiea, et al., 2010; Figure 13). To this end, work has arguably progressed farther in multifeedback analyses of ice sheet/solid Earth interactions than in any other domain of ice sheet/Earth system study. For example, following previous studies investigating the impacts of a fixed sea level on marine ice sheet dynamics, Gomez, Mitrovica, Huybers, et al. (2010) revisited ice sheet and solid Earth feedbacks by allowing sea level to adjust according to self-consistent, isostatic, and self-gravitational effects. They theoretically demonstrated that the net feedback effect of isostatic, self-gravitation, and sea level impacts associated with marine ice sheet mass change is negative, with damping of externally driven ice sheet change. Gomez et al. (2012) confirmed these theoretical results using an idealized ISM coupled to viscoelastic solid Earth and gravitationally self-consistent sea level models.

Conclusions drawn from these findings have led to subsequent development and application of more complex coupled ice sheet/solid Earth models to both paleo and future sea level simulations. For example, a simulation of AIS over the last 40 kyr suggests that ice sheet/Earth system feedbacks have effectively damped the sensitivity of ice sheet growth and decay to external forcing by ~2 m of eustatic sea level equivalent, by restricting the rates of both grounding line advance and retreat (Gomez et al., 2013). Other work investigating the role of time delays in the viscous mantle response to orbital insolation change highlights that this process is a strong determinant of related feedback strengths and depends closely on the timing of externally forced transient change. This has potentially large implications for setting glacial/interglacial cycle timing (Abe-Ouchi et al., 2013): by keeping the surface elevation low precisely when a low surface mass balance threshold is reached, delayed rebound hastens ice sheet retreat and ultimately leads to its collapse.

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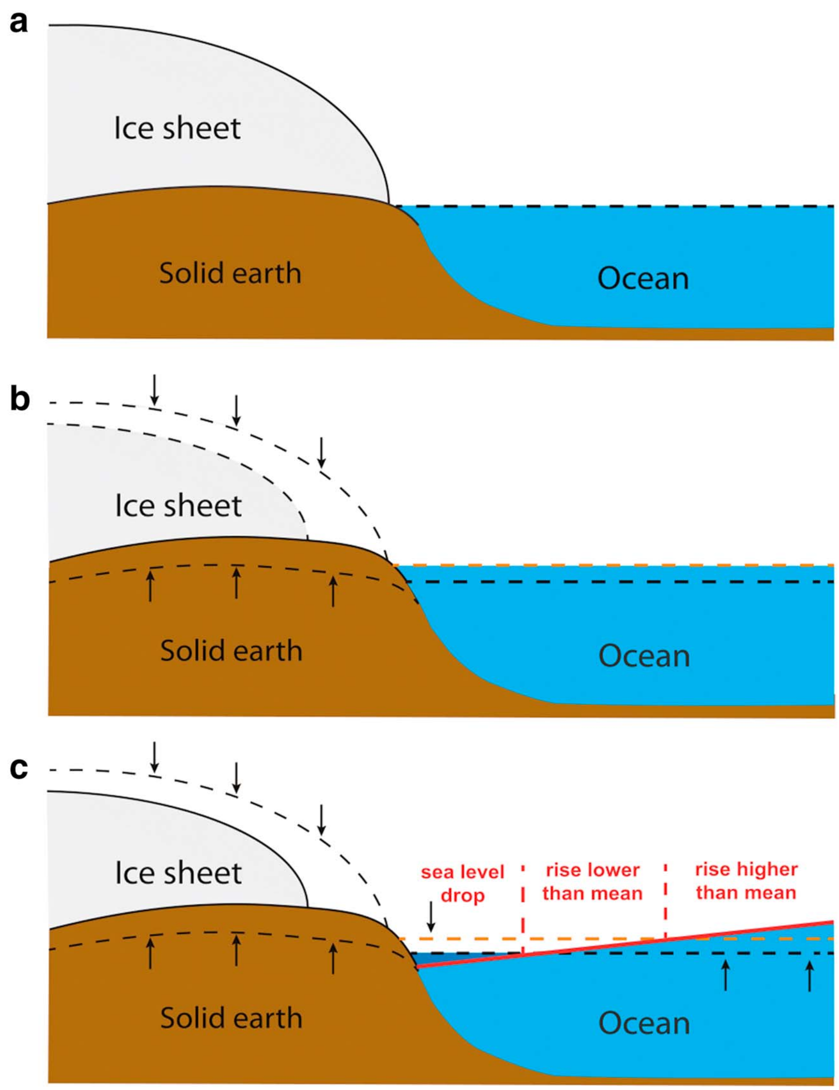

Figure 13. Schematic illustration showing the impacts of ice sheet, viscoelastic, and gravitational model coupling on simulated sea level change. (a) An initial, equilibrium ice sheet (gray), solid Earth (brown), and ocean (blue) configuration. (b) Only the ice sheet and viscoelastic Earth models are coupled, so that a reduction in ice thickness (e.g., via a mass balance perturbation) leads to uplift of the bedrock beneath the ice sheet and a uniform increase in sea level (dashed black lines indicate initial reference surfaces). (c) When a gravitation model is also coupled, simulated ice sheet mass loss also leads to a simulated sea level drop proximal to the ice sheet and SLR far from the ice sheet (solid red line), relative to the case with no gravitational coupling (dashed red line). The image has been reproduced with permission from de Boer et al. (2017).

Interactions between marine ice sheet dynamics and isostacy were also identified by Bassis et al. (2017) as a possible explanation for the puzzling timing of Heinrich events that record North American ice sheet collapses during the coldest glacial periods (Heinrich, 1988; Hemming, 2004). Using an idealized model framework, Bassis et al. (2017) suggested that maximum ice sheet advance during cold stages would depress Hudson Strait submarine sill depths, allowing warm intermediate-depth ocean waters access to ice sheet marine glacier termini, thereby triggering MISI and associated iceberg production with a periodicity that accurately reproduces that of observed Heinrich events.

These paleoclimate examples highlight feedback mechanisms that may regulate future collapse of GrIS and AIS marine sectors. For example, Gomez et al. (2015) performed multimillennial AIS simulations under forcings representative of elevated greenhouse conditions. They demonstrated a critical sea level sensitivity to mantle viscosity, with a stronger negative feedback on sea level change for low viscosities, which result in more rapid, localized bedrock uplift, regional sea level fall, and even ice sheet readvance. Depending on forcing

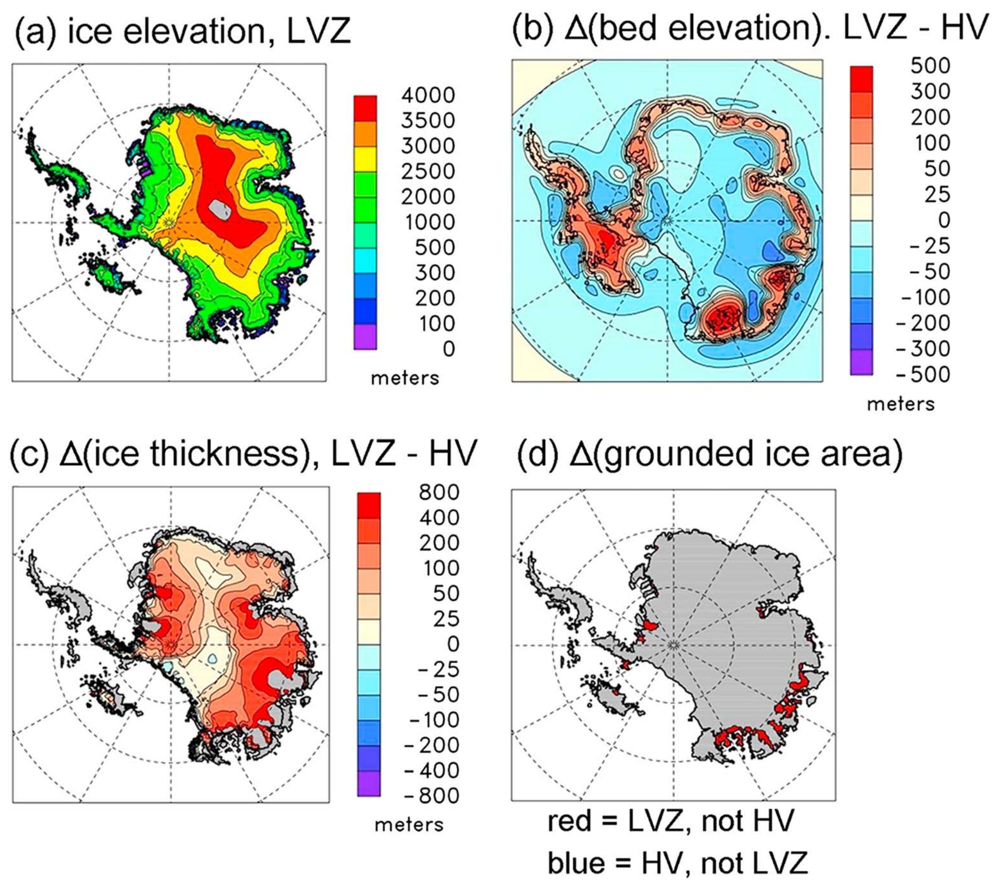

Figure 14. Impact of differing Earth viscoelastic properties on ice sheet retreat, as regulated by ice sheet/solid Earth interactions and feedbacks during AIS retreat in a warm-world simulation. Differences show the impact of a unanimously thin lithosphere and low viscosity mantle (LVZ) versus a standard solid Earth profile (HV). In particular, the LVZ profile results in less ice sheet mass loss (b–d) as a result of a stronger negative feedback between ice sheet mass and solid Earth changes (Pollard et al., 2017).

magnitude and simulation length, the cumulative sea level differences arising from sensitivity to mantle viscosity approaches ∼5 m of eustatic sea level equivalent (Figure 14; a finding qualitatively similar to Konrad et al., 2015). Thus, coupling between ISMs, gravity models, and solid Earth models with variable, nonlinear, viscoelastic rheologies is likely critical for accurate projections of AIS-derived sea level projections.

Ice sheet/erosional feedbacks. Ice sheets are strong erosive and physical weathering agents, particularly during phases of active ice sheet growth. Increases in erosion and physical weathering coincide with increases in chemical weathering, which would decrease atmospheric CO_2 levels, lead to cooling, and thus reinforce initial ice sheet growth in a positive feedback loop (Raymo & Ruddiman, 1992; Raymo et al., 1988). This process could be further accelerated through sea level lowering, which would expose more continental shelf material for erosion (Norton & Schlunegger, 2017). The potential thus exists for a combined positive feedback between ice sheet inception, erosion, weathering, and atmospheric conditions favorable to further ice sheet growth. However, this hypothesis has been contested based on arguments that global cooling was a cause for, rather than a result of, coincident increases in global erosion rates. Controversy on this topic continues, with arguments being presented in support of, for example, Herman et al. (2013) and Maher and Chamberlain (2014) and against, for example, Molnar, (2004) and Willenbring and von Blanckenburg (2010).

3.0.4. Undiscovered Ice Sheet/Earth System Feedbacks

The number of direct interactions between ice sheets and the surrounding Earth system documented in section 2 suggests the presence of substantial undiscovered ice sheet/Earth system feedbacks beyond those cataloged in sections 3.0.1–3.0.3. The potential presence of uncharacterized feedbacks increases combinatorially in light of potential feedback loops passing through multiple non–ice sheet-Earth system components (F_m, Figure 3). Active exploration and characterization of new feedback mechanisms is not an idle exercise:

broad inabilities to explain paleo-observations indicating high ice sheet sensitivity to Earth system changes (e.g., Levy et al., 2016; Schaefer et al., 2016) suggest that our present catalog of ice sheet/Earth system feedbacks is incomplete, which is concerning with respect to future SLR predictions. Here we leverage known Earth system interactions to speculate on several relatively unstudied GrIS and AIS feedback mechanisms that could be fruitful to explore. We emphasize that this list of speculative feedbacks is not exhaustive, nor do we claim to have sufficient evidence that they cause significant impacts. Rather, we illustrate them here primarily to demonstrate and motivate the process associated with identifying new ice sheet/Earth system feedbacks.

1. Stratification of near-ice sheet ocean surface waters from ice sheet melt would drive two effects: first, a decrease in large-scale overturning strength and poleward heat transport; and second, increased high albedo sea ice concentration (Vizcaíno et al., 2008). Both effects would drive atmospheric cooling, decreasing marginal ablation relative to the case where these interactions were not influential, closing a negative ice sheet/Earth system feedback loop.
2. Reduced evaporation from increased sea ice coverage and cooler SSTs would cause reduced over-ice moisture transport and near-coastal snowfall relative to the case with steady ocean circulation (Vizcaíno et al., 2008). This set of mechanisms would represent a positive feedback effect that could potentially counteract the temperature-based ocean circulation feedback.
3. Carbon cycle dynamics could be another ocean-related positive feedback loop: in addition to temperature and precipitation effects, circulation weakening would inhibit oceanic CO_2 drawdown in sites of deep convection (Sabine et al., 2004) and thus lead to a positive feedback of enhanced ice sheet melting.
4. Large-scale ice sheet topography loss significantly impacts regional atmospheric circulations. In the case of GrIS, this could shift Greenland tip jet location/strength (Doyle & Shapiro, 1999) with impacts on deep ocean convection in the Irminger Sea (Pickart et al., 2003) and subsequent feedbacks on GrIS snowfall and summer melt.
5. Meltwater-driven runoff fjord stratification could alter subglacial discharge plume dynamics, with impacts on ocean-driven calving front melting and also undercutting of calving front faces, with feedback implications for subsequent iceberg calving rates (Benn et al., 2017).
6. Increased meltwater transport to the ice sheet bed could provide a substantial heat source for basal ice (Colgan et al., 2015) if some meltwater is refrozen at depth. This would increase unfrozen bed area that is sensitive to increased hydrology-regulated sliding and increase ice deformation rates. Both effects would lead to increased ice velocities in a positive feedback, for example by lowering surface elevation and thereby increasing melt.
7. Emergence of new AIS melt regimes (Trusel et al., 2015) could potentially drive greater occurrences of hydrofracture-triggered ice shelf collapse (Scambos et al., 2004) in regions that currently exhibit stable ice sheet systems. This would complement initial surface melt-driven mass loss in a positive feedback.
8. Increased sedimentation from glacial erosion could impact ocean biogeochemistry in complex ways (for example, via Southern Ocean iron fertilization). This could in turn influence ice sheet conditions via biologically produced aerosol/cloud and global CO_2 radiative mechanisms.

3.1. Consequences of Ice Sheet/Earth System Feedbacks

3.1.1. Response to Forcing

Feedbacks regulating ice sheet change arise from ice sheet/Earth system interactions over the course of full coupled system response to an applied external forcing. Persistence of this forcing is a major factor in considering the magnitude of the feedback-modulated ice sheet response. For example, subtle changes of greenhouse gas concentrations and orbitally driven solar insolation over thousands of years appear capable of driving massive ice sheet changes enabled by atmospheric (Gregoire et al., 2016; Liakka et al., 2016; Löfverström & Lora, 2017; Löfverström et al., 2014, 2016), oceanic (Hu et al., 2010; Marcott et al., 2011), and solid Earth (Abe-Ouchi et al., 2013; Bassis et al., 2017) feedbacks. Similarly, recent projections of change in response to persistent (millennial-scale) anthropogenic forcing that include ice sheet/climate interactions point to the crucial importance of these feedbacks in accelerating the Anthropocene ice sheet/Earth system toward a deglaciated state that is fundamentally different from that of the last million years (Ganopolski et al., 2016; Robinson et al., 2012).

3.1.2. Response to Ice Sheet-"Independent" Internal Variability

Feedbacks also moderate the ice sheet response to variability signals that are internal to the Earth system but are nonetheless largely unaffected by ice sheet/Earth system interactions. Such ice sheet-independent Earth system variability can arise from internal climate variability that is generated far afield from ice sheets, such as climate oscillations like ENSO and the NAO that naturally occur at subseasonal to interdecadal timescales and are generated by lower-latitude processes that are largely free of ice sheet influence (Andresen et al., 2012; Dutrieux et al., 2014; Hanna et al., 2012). It can also arise at shorter timescales from, for example, diurnally controlled surface meltwater fluxes (Andrews et al., 2014) and even hourly scale tidal periodicities in surrounding seas (Gudmundsson, 2006). Notably, while these examples of remotely generated climate variability drives prominent ice sheet responses at local scales, it is unclear that they alone can promulgate large-scale, secular whole-ice sheet volume changes without also being accompanied by longer-term forced trends.

In addition to external forcing arriving from "remote" climate sources, it is increasingly recognized that ice sheets exhibit substantial internal variability in their own right that arises from internal dynamical nonlinear processes (Brinkerhoff & Johnson, 2015). For example, AIS subglacial lakes under fast-flowing ice streams tend to form and drain on multiyear (3–5 years) timescales (Fricker et al., 2007) that may modulate centennial-scale ice stream stagnation/activation (Bougamont et al., 2015; Rose, 1979) and ice discharge to the ocean. Similarly, iceberg calving displays temporal variability at a range of scales: the AIS calves both small ice bits (∼100 m^2) at hourly periodicity and large tabular icebergs (∼10–100 km^2) every 10–100 years. The case for GrIS internally generated ice sheet variability is less clear. However, individual observations of surging glaciers (Hill et al., 2017) suggest a role for tidewater glacier surge dynamics (Pfeffer, 2007), in which inland erosion and terminal sedimentation that are connected by subglacial meltwater transport pathways instigate internally generated cyclicity (e.g., Brinkerhoff et al., 2017).

To the extent that each of these above sources of stochastic ice sheet-independent internal Earth system variability (either arising from far-field Earth system or internal ice sheet processes) imparts an ice sheet change, they will also generate an additional superimposed feedback-generated response. To the extent that ice sheet-independent internal variability reflects a red noise forcing of regional-ice sheet/Earth systems, the presence of net positive ice sheet/Earth system feedback mechanisms likely promotes greater ice sheet volume variance, although this may be counteracted by the low-pass-filter nature of ice sheets due to their long response times relative to the frequency of variability (Roe, 2009). In general, it seems apparent that much work remains to characterize the potential role that ice sheet-independent internal variability plays in modulating feedback-modulated ice sheet response to longer-timescale external forcing signals.

3.1.3. Modulation of Ice Sheet Tipping Points

Besides cyclical internal variability, ice sheets also exhibit nonlinear and potentially irreversible behavior near unstable tipping points. This was epitomized by the (likely) climate-triggered 1995/2002 collapse of the Larsen A/B ice shelves—both present since at least the last glacial maximum (Domack et al., 2003)—which produced a dramatic speedup of upstream outlet glaciers (Scambos et al., 2004). The presence of extensive surface melt ponds during several summer seasons prior to irreversible disintegration suggests that collapse was caused by atmospheric warming over weakened shelves, leading to catastrophic hydrofracturing. Similarly, the MISI theory (Weertman, 1974) suggests that ice streams with grounding lines that migrate onto retrograded slopes can undergo irreversible retreat (Schoof, 2007; Weertman, 1974), leading to potentially rapid marine ice sheet collapse. Recent modeling of this behavior (Gudmundsson et al., 2012; Robel et al., 2016) has highlighted a sensitivity to a number of parameters (e.g., lateral confinement and basal conditions), thus suggesting the potential for a wide range of MISI-like threshold responses to grounding line migration that are highly dependent on local geometrical and ice dynamic conditions. Importantly, such behavior—which differs from stochastic internal variability—will be accompanied by an additional feedback-derived response. An example of this behavior is given by Arthern and Williams (2017), who described the role of submarine melt feedbacks in enhancing a previously triggered MISI retreat.

The combined impacts of (1) external climate forcing, (2) remote and ice sheet-generated internal variability, and (3) potentially highly nonlinear threshold ice sheet behavior make it very difficult to identify the triggering process and the chain of events leading to present-day observations of ice sheet change (e.g., increased GrIS discharge rates and migration of the WAIS grounding line). However, a common thread in the ice sheet response to all these drivers of ice sheet change is the mediating role of ice sheet/Earth system feedbacks. Thus, disaggregating the drivers of observed changes and constraining projections of future ice sheet change will increasingly rely on use of coupled ice sheet/ESMs that carefully consider the full set of external signals, internal variability and thresholds, and important ice sheet/Earth system interactions and feedbacks.

3.2. Section Recap

Emerging research suggests that feedback loops between ice sheets and the Earth system may play a pivotal role in regulating ice sheet response to external climate forcings and internal variability. However, quantitative characterization of the known set of ice sheet/Earth system feedbacks remains far from complete. Furthermore, additional ice sheet/Earth system feedback loops almost certainly remain undiscovered—particularly those that rely on dynamical changes of atmosphere, ocean and sea ice circulation, and feedback loops that transit more than one non–ice sheet-Earth system component.

Observations, while crucial in identifying the ice sheet/Earth system interactions that form the basis for understanding feedbacks, are not conclusive in their own right for quantifying feedback strengths, leading to a typically heavy reliance on modeling frameworks. However, model uncertainty and—more fundamentally—lack of sufficient model representation of ice sheet/Earth system interactions hinders robust feedback analyses. Thus, many available studies of ice sheet/Earth system feedbacks tend toward qualitative feedback behavior assessments, leading to a distinct lack of quantitative assessments of ice sheet/Earth system feedback factors and their state dependence and inter-dependence. Additional complication arises because even if feedbacks are resolved, estimation of feedback strengths depends on model structural and parametric uncertainties. This has large and concerning implications for accurate SLR projections, because if the coupled ice sheet/Earth system is characterized by net positive ice sheet/Earth feedbacks (as seems likely), uncertainty in net feedback strength amplifies uncertainty in the system response (e.g., ice sheet volume change) to a known forcing change (e.g., Roe & Baker, 2007).

Motivated by these research gaps and challenges, in the following section we turn to promising observational and modeling research directions that are most likely to improve our understanding of ice sheet/Earth system interactions and feedbacks.

4. Research Directions

Section summary. In this section, we describe major observational and modeling capability gaps. We also highlight new observational and modeling approaches that hold promise for improving understanding of ice sheet/Earth system interactions and feedbacks.

Accounting for coupled interactions between ice sheets and the broader Earth system across multiple temporal and spatial scales requires treatment of the former as integral and inseparable components of the latter. This treatment, crucial for improved projections of anthropogenically forced SLR, calls for explicit accounting of ice sheet/Earth-system interactions and feedbacks in determining coupled system evolution. Improving understanding of ice sheet/Earth system interactions and their regulation of future SLR requires tools and techniques that specifically examine coupled system behavior. In support of this goal, substantial opportunities exist for (1) improving observations of ice sheet/Earth system interactions and (2) implementing these interactions in models. As the feedbacks described in the previous section arise from interactions between ice sheets and at least one other component of the Earth system, their quantification involves simultaneous observations or modeling of at least two components of the Earth system. Such efforts will directly inform the role that these interactions and closely associated feedbacks play in the ice sheet response to imposed change from external climate drivers and also remotely generated climate and internal ice sheet variability.

4.1. Observational Directions

Traditionally, individual observational campaigns have been designed to investigate the behavior either of ice sheets or ice sheet-proximal Earth system components in relative isolation. This leads observational campaigns or modeling efforts that are focused on improving understanding of specific (sets of) physical processes, without deep consideration of interactions and feedbacks with other climate components. Subsequent linkages between these observations to elucidate ice sheet/Earth system interactions are then made post facto. In contrast, expansion of synchronized *multicomponent*, *spatiotemporally extensive* observations of ice sheet and Earth system change could greatly aid the disaggregation of causal factors driving GrIS and AIS change and the return impact of this change on local, regional, and global climate and the role of consequent feedbacks. Synchronized observations are important because they allow connections to be made between an initial Earth system change and a corresponding ice sheet response (or vice versa). In this way, interaction mechanisms can be explicitly elucidated.

Similarly, observations collected during campaigns primarily focused on past climate have became invaluable source of information used for understanding temporal aspects of the feedbacks described above and also tools to verify hypothesis of the long-term evolution of the Earth system. Thus, paleoclimate research programs (e.g., PALSEA and PAIS) and the deep ocean drilling projects (e.g., ANtarctic geological DRILLing and Integrated Ocean Drilling Program) focused on observational constraints of past sea level have yielded wealth of information about possible ranges of behavior of paleo ice sheets.

Recent advances in fundamental understandings of ice sheet/Earth-system interactions obtained by post facto linking of observations of both ice sheet and Earth system changes provide motivation for future work that more directly targets interaction behavior. For example, both sub-ice shelf cavity and nearby oceanographic observations (Jenkins et al., 2010) have augmented simultaneous ice sheet observations (Paolo et al., 2015) to greatly improve our understanding of oceanic controls on sub-ice shelf melting, iceberg calving, ice flow (Depoorter et al., 2013; Holland et al., 2008; Liu et al., 2015), and conversely, the impact of ice sheet changes on oceanographic conditions (Bartholomaus et al., 2016; Lacarra et al., 2014). Precipitation, accumulation, and snow-drift measurements (Monaghan et al., 2006; Palerme et al., 2014) allow for better disaggregation of continental-scale ice mass gains measured by satellite gravity-based measurements, while quantification of atmospheric and surface summer conditions (Bennartz et al., 2013; van de Wal et al., 2012) place simultaneous surface melt, ice flow variability, and ice shelf collapse observations (Andrews et al., 2014; Scambos et al., 2004; van Angelen, Broeke, et al., 2013) in the context of broader climate trends. Sea ice and iceberg observations are important for connecting sea ice and iceberg behavior to ice sheet dynamics and mass balance trends (Amundson et al., 2010; Day et al., 2013). The strength of these complementary observations in capturing interaction processes highlights the potential for directed multidisciplinary efforts to understand the drivers between ice sheet change. Recent projects that epitomize this multicomponent approach include the "How Much, How Fast" project to understand Thwaites glacier evolution (Scambos et al., 2017) and the "Oceans Melting Greenland" project (Fenty et al., 2016). A greater focus on large scale multidisciplinary projects of this sort holds great promise for better characterizing the ice sheet/Earth system interactions that will regulate future SLR.

Spatiotemporally extensive observations are important because they provide a broader picture of ice sheet or Earth system change that is often lost in the case of individual pointwise measurements, which hold the risk of significant "aliasing" (either in time or space), as locally or regionally confined variability that dominates large-scale forced signals (van der Veen & Bolzan, 1999; Frezzotti et al., 2005). For example, the National Aeronautics and Space Administration Gravity Recovery and Climate Experiment (GRACE) and IceSat and ESA CryoSat missions have provided a unique assessment of recent time-evolving ice sheet mass change (e.g., Forsberg et al., 2017) that has increasingly formed the benchmark for ice sheet and coupled ice sheet/Earth system validation activities (e.g., van den Broeke et al., 2016; Price et al., 2017). Successful National Aeronautics and Space Administration GRACE Follow-On (GRACE-FO) and IceSat-2 projects will ideally extend this data set of ice sheet mass variability and change, particularly in combination with the upcoming IceSat 2 campaign. However, such datasets have difficulty discriminating between various terms in the overall mass balance, making continued and enhanced in situ observations crucial. To the extent that many pointwise measurements of ice sheet and climate state are critical in building a broader picture of large-scale coherent variability and change, reconstructions that generate gridded climate fields derived directly from databases of ice, snow, and firn core records (Monaghan et al., 2006; Thomas et al., 2017) are important tools for recognizing large-scale forced trends. Continued efforts to extract snow, firn, and ice core records of past climate from previously unsampled locations are critical to improving such reconstructions and should be guided by outstanding spatial data gaps, such as in coastal and interior East Antarctica (Thomas et al., 2017). Assessments of accumulation across transects using emerging airborne snow penetrating radar and novel Global Positioning System techniques (e.g., Lewis et al., 2017; Siegfried et al., 2017) may extend upon more established ice core-based records. However, neither ice core nor radar-based data acquisition efforts can address measurements of surface ice loss, particularly in the GrIS ablation area, and a recent compendium of all available GrIS ablation measurement (Machguth et al., 2016) highlighted that such measurements remain extremely sparse in space and time (van den Broeke et al., 2017) due to the need to measure ablation rates using (laborious) point-based, in situ methods. Finally, one of the most critical ice sheet/Earth system interfaces—AIS subshelf cavities and GrIS ice shelf calving fronts—remains very poorly sampled in any spatiotemporally complete manner, with the exception of recent pioneering explorations using autonomous vehicles

(Jenkins et al., 2010; Stevens et al., 2016) and instrumentation of the ocean cavity via through-ice coring. The lack of direct observations of conditions under ice shelves contrasts starkly with the importance of sheet/ocean interactions in determining ice sheet contributions to SLR, highlighting an urgent need for further progress in this area.

4.2. Modeling Directions

Insights gained from available observations provide the basis for assessing current interactions between ice sheets and the broader Earth system. However, future climate projections—including estimates of ice sheet-sourced SLR—cannot be based on present-day observations alone: they require understanding gained from observations to be incorporated coupled ice sheet/ESMs, which can then be used for projections. With this motivation in mind, the climate modeling and glaciological communities are increasingly collaborating on construction of coupled models that represent—with varying levels of abstraction—ice sheet/Earth system interactions and feedbacks.

Modeling using observation-validated coupled ice sheet/ESM frameworks will be critical for detailing the feedback-regulated ice sheet and SLR response to climate forcings—particularly due to ongoing anthropogenic carbon emissions. We expect projections of ice sheet change from such models to be remarkably high profile, as they inform global climate adaptation policies related to SLR. However, the current state of modeling is challenged by incompletely represented polar climate and ice sheet dynamical processes, substantial technical and computational hurdles associated with development of coupled ice sheet/climate models, and the presence of poorly constrained polar climate and ISM bias and uncertainty (Vizcaino, 2014). Thus, extensive opportunities exist for model improvements that are underpinned by an urgent societal demand for better SLR projection capabilities. Here we summarize important directions for modeling advances in (1) ESMs, (2) ISMs, (3) ice sheet/Earth system coupling, and (4) model validation and uncertainty assessment.

4.2.1. Earth System Models

Ice sheet evolution depends on the mean state, variability, and the rate of change of the regional climate. Thus, polar processes in regional and global ESMs must be accurately represented if these tools are to be used for robust future projections of ice sheet change and SLR projections. The present state of these models highlights extensive opportunities for research and development toward improving their representation of ice sheet-relevant polar processes.

Atmosphere and snow/firn processes. Increased attention to atmospheric conditions determining surface accumulation and ablation has highlighted important areas for future improvement. Recent surveys of conditions above ice sheets in global climate models and reanalyses (e.g., Chen et al., 2011; Palerme et al., 2016, 2017; Yan et al., 2014) have identified important atmospheric biases that manifest particularly in global ESMs. Being constrained by available observations, reanalyses provide a much closer match to independent observational benchmarks, and regional climate models that use reanalyses as lateral boundary constraints are also closer to the observational benchmarks (e.g., Noël et al., 2015; Van Wessem et al., 2014). However, biases in global ESMs are of greater importance for future projections since output from these models is used to drive ISM experiments, either via direct use of model data, explicit two-way ice sheet/Earth system coupling (section 4.2.3), or dynamical/statistical downscaling. In all these cases, global model atmospheric biases translate into biases in both ice sheet accumulation and ablation, which can be substantial (e.g., Belleflamme et al., 2013; Lenaerts, Van Tricht, et al., 2017; Palerme et al., 2017) and difficult to attribute to causal factors given the tightly coupled nature of polar climate dynamics. For instance, ablation areas that play a critical role in the ice sheet response to climate change (e.g., the GrIS ablation area) are often completely unrepresented on relatively coarse global model grids, making direct use of outputs of global models as forcing for ice sheet projections unfeasible. Thus, substantial efforts are needed in both characterizing and improving representations of ice sheet-relevant atmospheric conditions and subsequent ice and snow responses.

An important area of potential atmospheric model improvement is reducing existing biases in the representation of liquid-bearing and mixed-phase clouds over ice sheets (Lenaerts, Lhermitte, et al., 2017; Van Tricht et al., 2016). These biases drive subsequent biases in the simulated surface energy balance and surface melt. An example of surface condition improvement through atmospheric model development is demonstrated in Figure 15, which shows that cloud liquid water path (the vertically integrated mass of cloud liquid water) in the Community Earth System Model is severely underestimated with respect to CloudSat-Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation remote sensing observations. In turn, this leads to large biases in downward longwave radiation at the surface. Including improved cloud microphysical parameterizations,

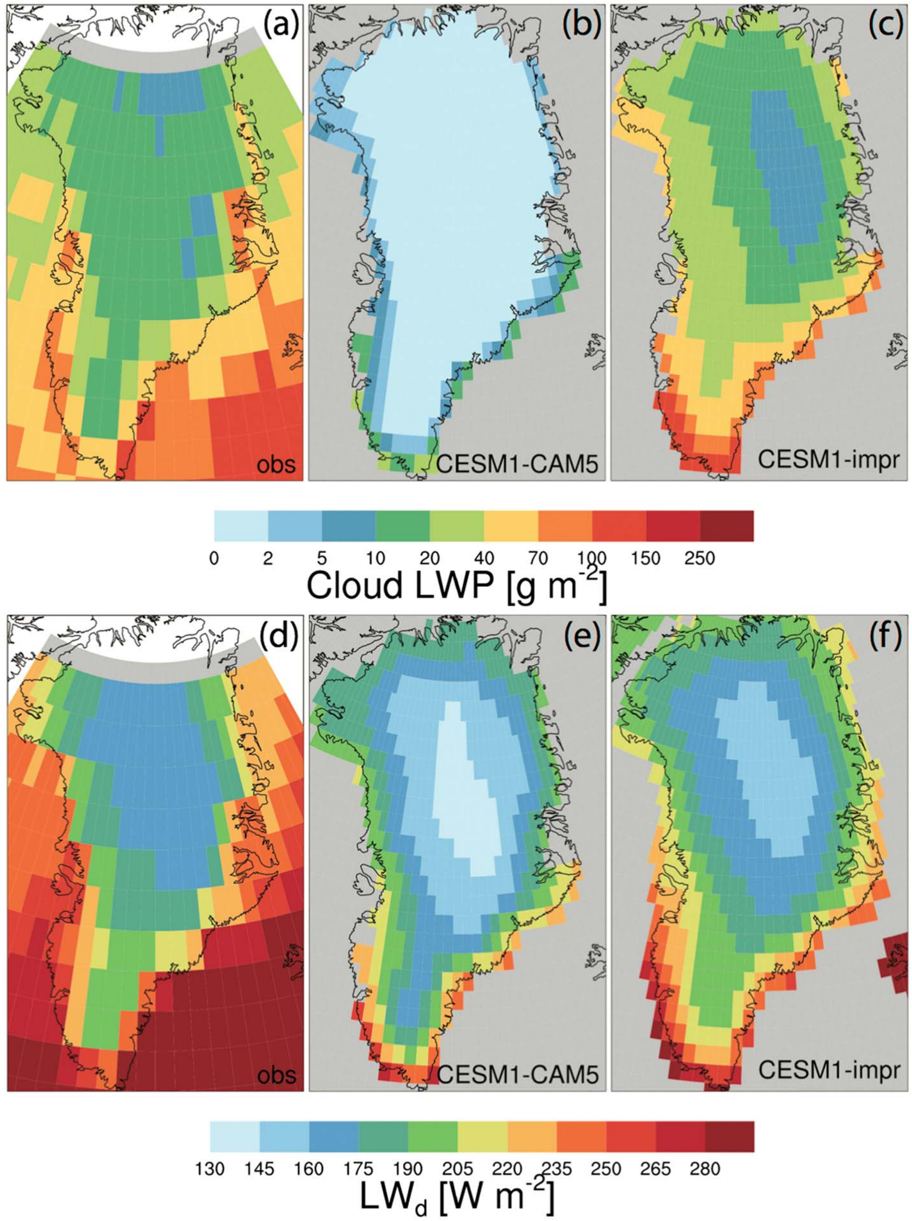

Figure 15. (a) Annual mean cloud liquid water path and (b) downward longwave radiation, (a and d) observed by CloudSat-CALIPSO (2008–2010; Van Tricht et al., 2016), (b and e) simulated by CESM1-CAM5 (1970–2000; Kay et al., 2015), and (c and f) simulated by a new version of CESM1 with improved cloud microphysics (1970–2000). CALIPSO = Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation; CESM = Community Earth System Model.

which allow for supersaturated liquid in low-level clouds, greatly improves the representation of cloud liquid water path over Greenland and reduces the associated downward longwave radiation bias. Such examples highlight the need for accurate cloud representation over ice sheets and their impact on the ice sheet surface energy balance and surface mass loss.

Simulating ice sheet mass balance also depends on accurate representation of snow and firn (the intermediate state between fresh snow and solid ice). Yet perennial snow and firn of the type that exists over ice sheets are typically poorly represented in global-scale models, which historically have been designed and calibrated with the primarily goal of reproducing seasonal snowpacks. Thus, an outstanding challenge in the context of improving SLR projections is to more faithfully represent perennial snow and firn processes over ice sheets in ESMs. Initial steps in this direction are ongoing (van Kampenhout et al., 2017) and have the potential to significantly influence 21st century ice sheet runoff projections by impacting the ability of simulated snow and firn columns to retain liquid water—an effect that has been demonstrated to be crucial in transient simulations using regional modeling studies (Munneke et al., 2014; Noël et al., 2017). A particular opportunity for improvement lies with the adoption of dedicated firn models (Steger et al., 2017) that better simulate snow densification, formation of refrozen ice lenses, and liquid water retention. These processes both directly impact observed ice sheet and ice shelf mass balance and indirectly control ice dynamical behavior such as ice shelf hydrofracturing.

Ocean processes A growing body of observations pointing to significant impacts of the ocean circulation and its changes on ice shelves and ice sheet margins (e.g., Alley et al., 2015; Joughin et al., 2012), lack of representation of such processes in global ESMs increasingly apparent. This deficiency partly arises because the horizontal resolution required to resolve mesoscale and submesoscale eddies responsible for heat transport to the continental shelves from the open ocean precludes global coverage for long simulations with present supercomputing resources. Similarly, lack of vertical resolution in global models leads to poor representation of small-scale, near-coastal, high-latitude oceanographic features such as eddies, coastal currents, and near-coastal oceanographic fronts (e.g., Böning et al., 2016; Lique et al., 2015; Spence et al., 2014), all of which are important for explicitly capturing ocean/ice sheet interactions and feedbacks. Continental shelf and fjord bathymetry also plays a critical role in the exchange of water masses between narrow fjords, marginal seas, continental shelves, and the deep ocean, making it a critical factor in the communication of open ocean properties with both Antarctic ice shelves and Greenland calving faces (e.g., Nitsche et al., 2017; Rignot et al., 2016). However, bathymetry is not only poorly resolved (or not resolved at all) in standard-resolution global models but also is often not even well characterized by bathymetric surveys in many coastal GrIS and AIS regions. A clear challenge for ice sheet-focussed ocean simulations thus emerges, to sufficiently increase vertical and horizontal ocean resolution around the AIS and GrIS while also retaining sufficient computational resources for ensembles of multidecade to multicentury simulations—a specific example of a pervasive compromise in Earth system modeling (Smith et al., 2014) that may be overcome by efficient variable-resolution ocean model meshes (e.g., Ringler et al., 2013) or physically consistent parameterizations for near-ice sheet oceanographic processes (e.g., Hallberg, 2013).

Beyond resolution, a typically absent ocean modeling capability that is necessary for capturing AIS/ocean interactions is the ability to accurately simulate sub-ice shelf cavity dynamics, including their changing geometries as a function of ice shelf melting and deformation and the grounding line migration. However, this capability requires significant development of internal ocean model physics and as yet is largely unavailable in both global and regional ocean models and ocean reanalyses (Dinniman et al., 2016). This capability will build from the successful implementation of static ice shelf cavities in a number of models (see review by Dinniman et al., 2016), which will likely see increasing (and important) near-term research activity.

Finally, existing multimodel analyses of global model subsurface ocean conditions around the ice sheets (Little & Urban, 2016; Yin et al., 2011) that build on broader analyses of simulated offshore subsurface ocean conditions (Heuzé, 2017; Sallée et al., 2013) illuminate important model and region-dependent biases that future studies focusing on ice sheet/ocean interactions will need to address. Because these water masses play an important role in determining the condition of near-coastal waters, biases in simulations of these water masses exert a strong role in determining sub-ice shelf melt rates. Improvement in large-scale ocean biases—especially in the Southern Ocean, North Atlantic, and Arctic Seas—will have a direct and large impact on simulations of AIS and GrIS response in coupled ice sheet/ESMs and therefore represent an important area for research targeting improved SLR projections.

4.2.2. Ice Sheet Models

While ISM development has experienced substantial progress in recent years, a number of outstanding challenges remain that have a direct bearing on projections of ice sheet change and SLR from coupled ice sheet/ESMs.

Ice sheet basal conditions determine whether gravity-driven ice flow is dominated by internal shear or basal sliding that takes place in the presence of subglacial water and thus has a strong influence on ice dynamics and consequently ice sheet geometry. However, the majority of ISMs being coupled to ESMs use simple basal sliding relationships that represent either viscously (MacAyeal, 1989) or plastically (Bueler & Brown, 2009) deforming substrata. In contrast, available observations suggest that *evolving* subglacial hydrology exhibits a critical control on basal sliding and thus must also be considered (Bougamont et al., 2015; Kyrke-Smith et al., 2015). Ultimately, poor understanding of basal processes (related to lack of observational constraints) represents a major impediment in realistic representation of ice sheet behavior, such as the dendritic organization of present-day ice streams (Ng, 2015). Recent advances in subglacial hydrology theory (e.g., Flowers, 2015) are leading to development of a new class of subglacial flow models (e.g., Werder et al., 2013) capable of simulating the evolution of both the distributed and channelized components of subglacial hydrological systems. Coupling such models to ice flow models within ESM frameworks will be an important aspect in improving the fidelity of coupled ice sheet/Earth system simulations (Bueler & van Pelt, 2015), especially as they are linked to simulated surface melt conditions.

Another outstanding challenge is the simulation of iceberg calving, which despite being a primary mode of ice sheet mass loss (Depoorter et al., 2013) and a strong regulator of grounded ice dynamics (Furst et al., 2016) remains poorly understood. A "calving law"—a comprehensive relationship between ice sheet/ice shelf conditions and calving processes that captures a wide range from hourly calving of small ice bits from outlet glaciers to roughly twice-century calving of large tabular icebergs from Antarctic ice shelves—remains elusive. Existing empirically constructed relationships often predict unstable ice front behavior (Hindmarsh, 2012), while physically based models tend to focus on isolated aspects of calving (Bassis & Ma, 2015). Poor comprehensive understanding of iceberg calving leads to insufficient and widely varying calving representations in ISMs. This in turn leads to overly simplified representations of the flux of glacial ice into oceans in coupled ice sheet/ESMs. Numerous advances go beyond traditionally used vertically integrated calving parameterizations (e.g., Nick et al., 2009) that simulate fracture and crevasse propagation through the ice column (e.g., Ma et al., 2017). Improving understanding of calving processes using a variety of approaches (observational, experimental, theoretical, modeling, etc.) and their efficient representation in ISMs remains a priority for ongoing and future research.

Perhaps most concerning with respect to future SLR contributions is a poor understanding of the mechanisms of abrupt ice sheet behavior, particularly ice shelf collapse and—perhaps most importantly—MISI, which precludes coupled SLR projections from accounting for the possibility of such events in a robust and consistent manner. In the case of MISI, poor mechanistic understanding is hindered both by the absence of direct observations near the grounding line and limitations of current MISI theories, which are limited to steady state configurations and thus are not directly suitable for treatments of transient grounding line migration. Improving understanding of such phenomena represents a critical research frontier with dramatic implications and opens a number of research directions and opportunities. These are currently being spearheaded by community efforts to characterize complex ice sheet behavior using idealized marine ice sheet/ocean model intercomparisons (e.g., Asay-Davis et al., 2016) and promise to enhance process level understanding of marine ice sheet behavior and ice sheet/ocean coupling that will directly inform the more realistic AIS and GrIS problems.

4.2.3. Ice Sheet/ESM Coupling

Given adequate representation of both Earth system and ice sheet physics and dynamics, the formidable task still remains of coupling ISMs into ESMs in order to resolve ice sheet/Earth system interactions and feedbacks. Historically, ice sheets were considered static components of the Earth system within ESMs, resulting in deeply engrained assumptions requiring extensive efforts to reconfigure and rectify. Atmospheric, ocean, and land model components in extant ESMs almost universally have fixed boundaries (i.e., that do not evolve over the course of simulations). This conflicts with the evolving vertical and horizontal extents of ice sheets that cover/uncover bare land or open ocean and displace sea ice or enable new areas for sea ice growth. Consequently, model infrastructure must be put in place to reflect ice sheet geometry changes in corresponding non-ice sheet component geometries. Work is increasingly active in major Earth system modeling centers to implement these fundamental changes. Similarly, amendments to boundary conditions in many regional ocean models have now been made to allow explicit simulation of ocean circulation in sub-ice shelf cavities with realistic Antarctic geometries (e.g., Dinniman et al., 2016; Kusahara & Hasumi, 2014; Schodlok et al., 2016). However, advances in the development of fully coupled ice shelf/ocean-circulation models that allow for dynamic changes of sub-ice shelf cavity geometries are as yet largely limited to specialized and/or idealized model frameworks (Asay-Davis et al., 2016; Gladish et al., 2012; Goldberg et al., 2012; Jordan et al., 2017; Sergienko, 2013b), with only a few emerging, regionally constrained exceptions (e.g., Seroussi et al., 2017).

In addition to the general problem of dynamic earth system component boundary consistency, implementation of ice sheet coupling introduces the need to communicate new and novel data fields between ice sheets and surrounding Earth system components to represent the interactions described in section 2. For atmospheric coupling these new fields include SMB, ice temperature, and (in return) ice sheet topography and areal extent. Ocean coupling requires new data fields such as ocean velocities, temperature and salinity, ice geometry, subshelf melt rates, and grounding line and calving front positions (Asay-Davis et al., 2017). As with ice shelf melt fluxes, implementation of icebergs additionally requires the ability to inject freshwater fluxes at depth, which extends the standard methodology of adding oceanic freshwater fluxes to the surface ocean layer. From a technical coupling perspective, choices must also be made on the frequency of coupling between ice sheets and the surrounding system, which reflect both the timescales of ice sheet and ocean/atmosphere dynamics and also the important timescales of ice sheet/Earth system interactions.

The difference between characteristic ISM spatial resolutions ($\sim$1 – 10 km) and ESM resolutions ($\sim$10 – 100 km) presents another challenge in ice sheet/ESM coupling. While existing coupling schemes are generally capable of horizontal interpolation between these scales, the need to also consider vertical subgrid-scale gradients in temperature, humidity, and radiation around ice sheet margins has led to new elevation-dependent subgrid schemes for specific use over ice sheets within ESMs (e.g., Fischer et al., 2014; Fyke et al., 2011; Lipscomb et al., 2013; Quiquet et al., 2017). These allow for the explicit simulation of GrIS ablation areas within coarse-grid ESM land model components, which are typically responsible for the simulation of snow and therefore are generally used to calculate SMB for ice sheet use. Such schemes are still immature, for example, no satisfactory method yet exists for a mass-conserving subgrid representation of precipitation that does not introduce spatial artifacts to the remapped higher-resolution field on the ice sheet grid. In addition, it may well be necessary to introduce similar schemes under ice shelves to accurately capture subshelf melt distributions at narrow but dynamically critical grounding lines. Improved model design in the area of conservative, inline remapping is thus critical and will be essential for accurate coupling of ice sheets to the atmosphere and ocean components of ESMs.

Another outstanding challenge in ice sheet/Earth system coupling relates to temporal scales: ice sheets display characteristic timescales that are up to an order of magnitude longer than other slow-responding Earth system components (e.g., the deep soil and deep ocean carbon reservoirs) and many orders of magnitude longer than the shortest-timescale component (the atmosphere). This disparity means that standard fully coupled "spin-up" simulations — in which the coupled system is typically integrated to equilibrium under constant preindustrial climate forcing — are computationally intensive or simply unfeasible. An additional nontrivial complication arises from the long thermal and dynamic memory of ice sheets, which leads to the need to consider transient last glacial maximum conditions as part of any procedure for generating a reasonable preindustrial coupled ice sheet/Earth system state. Various partly coupled equilibration and inversion-based initialized techniques have been constructed to circumvent this difficulty (e.g., Fyke, Sacks, et al., 2014; Perego et al., 2014; Vizcaino et al., 2015), but all have some potential of introducing artificial signals due to sacrifices in the name of computational expense. Recognizing this, community efforts are now beginning to formally address ISM initialization for SLR projections (Goelzer, Nowicki, et al., 2017). However, no clear "best" solution has yet emerged and much work still remains, particularly in adequately initializing ISMs within a fully coupled ESM framework.

4.2.4. Validation and Bias Reduction

Successful model validation is a prerequisite of future climate projections (Flato et al., 2013). Integration of ice sheet components into ESMs produces a new set of simulated fields and related model biases (i.e., associated with ice sheet volume, internal temperature structure, and iceberg flux) to analyze as part of the model validation process. Identification of such biases, which arise from ice sheet and non – ice sheet component deficiencies and poor representation of ice sheet/Earth system coupling, often relies on extremely limited ice sheet and polar observations. As ice sheets are increasingly included in simulations of the historical period (Eyring et al., 2016), novel methods for leveraging these sparse observations to assess and improve the performance of ice sheets within coupled ESMs will increasingly complement other more established ESM bias reduction efforts. An important question in the context of model validation is "what level of bias is acceptable?" This is an important question particularly in light of coupled ice sheet/Earth system simulations, which are constrained by boundary conditions far from ice sheets themselves. Such models operate according to best understandings of (sometimes incomplete) physical relationships applied to coarse numerical grids and thus are prone to model-observation bias throughout the Earth system (including, potentially, ice sheet bias; e.g., Löfverström & Liakka, 2018). The trade-off between bias and resolution of ice sheet/Earth system interactions and feedbacks will be a persistent topic requiring careful consideration when designing coupled ice sheet/Earth system simulations for the purpose of future SLR projections.

Uncertainty in SLR projections from ice sheet/ESMs arises from differences in component models (structural uncertainty), parametric uncertainty (Bindschadler et al., 2013; Smith et al., 2014; Palerme et al., 2016; Yan et al., 2014), uncertainty in future anthropogenic carbon emissions scenarios (Goelzer et al., 2012; Vizcaino et al., 2015), and the presence of underlying ice sheet/Earth system internal variability (Deser et al., 2012). Understanding and probabilistically quantifying these sources of uncertainty as part of SLR projections derived from ESMs will be critical for informing on-the-ground sea level risk assessment and adaption planning efforts. Yet while it is certain that introduction of new ice sheet components will increase the scope of existing ESM model uncertainty, only preliminary efforts have been made to try to isolate and quantify this effect on projections of SLR (Fyke, Eby, et al., 2014).

As the above discussion suggests, coupled ice sheet/ESMs are currently in their infancy and face a range of substantial technical and scientific challenges. Nonetheless, they hold great promise for providing consistent insight into fundamental models of ice sheet/Earth system variability and change and thus are important targets for major modeling centers.

5. Summary and Conclusions

A primary objective of this review is to survey interactions between present-day ice sheets and the broader Earth system, and feedbacks enabled by these interactions. The strength and balance of ice sheet/Earth system interactions (section 2) are markedly different for the two present-day ice sheets: ice sheet/atmosphere interactions are arguably dominant for GrIS, while ice sheet/ocean interactions play a more critical role in AIS change. Internal ice sheet dynamics play an important role in translating ice sheet/Earth system interactions into ice dynamic discharge, for both ice sheets. The dominance of specific ice sheet/Earth interactions and associated ice sheet responses is not time invariant—they changes in response to external climate forcings and internally driven Earth system variability.

Two-way interactions between ice sheets and other components of the Earth System enable feedback loops that can both amplify and dampen the integral response of the coupled ice sheet/Earth system. Major known feedbacks and their mechanisms are described in section 3. Although many of these feedbacks have been recognized for a long time (e.g., the albedo feedback) and their effects have been described qualitatively (i.e., identification as positive or negative feedbacks), in most cases their quantitative assessments do not yet exist. This is concerning, given past empirical and future model-based evidence that ice sheet/Earth system feedbacks play very important roles in modulating ice sheet changes. In order to facilitate these assessments, we encourage the use of formal feedback analysis approaches, which dominantly rely on models that can explicitly resolve ice sheet/Earth system couplings. Also important is clear identification of reference models, background climate states, and evaluation metrics for which feedback strengths are measured. By approaching the study of ice sheet/Earth system feedbacks in a consistent manner, intercomparisons between independent feedback analysis efforts will elucidate the (perhaps large) measure of model uncertainty inherent in ice sheet/Earth system feedback estimation.

As we demonstrate in section 3, the presence of multiple feedback loops between ice sheets and every other Earth system component, compounded with the presence of multicomponent feedback loops, makes ice sheet evolution to external climate forcings (such as anthropogenic carbon emissions) an extremely process-rich and complex dynamical process. We argue that the complexity that arises from ice sheet/Earth system feedbacks makes it impossible to fully understand ice sheet behavior—including robust projections of future sea level rise—if ice sheets are treated as isolated units that simply respond to external forcings. Instead, ice sheets must be considered as integral components of a tightly coupled Earth system. This requires approaches that explicitly target ice sheet/Earth system interactions in order to elucidate feedbacks and are open to the very real potential for as-yet-uncovered feedbacks that arise either from known and as-yet unknown interactions.

In section 4 we focus on the two fundamental approaches—observations and numerical modeling—that can improve understanding of ice sheet/Earth system interactions and feedbacks. Synchronized, spatiotemporally extensive observations across the ocean, atmosphere, and ice sheets will be critical to disaggregate causal factors in ice sheet change and the subsequent impact of this change on local, regional, and global climate. However, obtaining these observations will require sustained and sophisticated multicomponent data acquisition and analysis efforts. Modeling using observation-validated coupled ice sheet/climate model frameworks will be critical for detailing the feedback-regulated ice sheet response to climate in the presence of internal ice sheet/climate variability. However, modeling is complicated by technical and computational hurdles in developing coupled ice sheet/ESMs; the presence of poorly constrained model bias and uncertainty; and the compromise between computational resources, spatial and temporal resolution, resolved processes, and simulation ensemble size.

Careful observation and modeling-driven consideration of the coupled ice sheet/climate system will generate new hypotheses regarding ice sheet/climate interactions, which observations and modeling can subsequently test. This type of consideration requires simultaneously deep expertise in disparate aspects of the coupled Earth system, ranging from ocean eddies to polar cloud radiative properties to ice stream dynamics. It calls for a new generation of coupled ice sheet/climate researchers who can bridge disparate Earth science disciplines to uncover new links between the ice sheets and the broader Earth system. These scientists will increasingly be called upon to assess interactions within the coupled ice sheet/Earth system, as part of the larger, urgent, goal of projecting future SLR driven by anthropogenic forcing.

Appendix A: Specialized Reviews

Here we list a subset of reviews that have informed the present work and provide windows into subsets of the broader topic of ice sheet/Earth system interactions.

1. Moore et al. (2013): sea level rise prediction methods
2. Truffer and Motyka (2016): subaqueous melting
3. Straneo and Cenedese (2015): GrIS ocean/ice interactions
4. Greenwood et al. (2016): subglacial hydrology
5. Benn et al. (2017): iceberg calving
6. Chu (2014): GrIS hydrology
7. Roe (2009): feedbacks in the climate system
8. Schoof and Hewitt (2013): ice sheet dynamics
9. Flowers (2015): subglacial hydrology modeling
10. Pattyn et al. (2017): Antarctic ice sheet dynamics
11. Goelzer, Robinson, et al. (2017): Greenland ice sheet dynamics
12. Hanna et al. (2013): recent ice sheet mass changes
13. Vizcaino (2014): coupled ice sheet/climate modeling
14. Turner et al. (2017): Amundsen Sea coupled Earth system interactions
15. Joughin et al. (2012): ocean forcing of ice sheets
16. Alley et al. (2010): ocean forcing of West Antarctic ice sheets

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