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Invited review article

How much, how fast?: A science review and outlook for research on the instability of Antarctica's Thwaites Glacier in the 21st century

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ABSTRACT

Constraining how much and how fast the West Antarctic Ice Sheet (WAIS) will change in the coming decades has recently been identified as the highest priority in Antarctic research (National Academies, 2015). Here we review recent research on WAIS and outline further scientific objectives for the area now identified as the most likely to undergo near-term significant change: Thwaites Glacier and the adjacent Amundsen Sea. Multiple lines of evidence point to an ongoing rapid loss of ice in this region in response to changing atmospheric and oceanic conditions. Models of the ice sheet's dynamic behavior indicate a potential for greatly accelerated ice loss as ocean-driven melting at the Thwaites Glacier grounding zone and nearby areas leads to thinning, faster flow, and retreat. A complete retreat of the Thwaites Glacier basin would raise global sea level by more than three meters by entraining ice from adjacent catchments. This scenario could occur over the next few centuries, and faster ice loss could occur through processes omitted from most ice flow models such as hydrofracture and ice cliff failure, which have been observed in recent rapid ice retreats elsewhere. Increased basal melt at the grounding zone and increased potential for hydrofracture due to enhanced surface melt could initiate a more rapid collapse of Thwaites Glacier within the next few decades.

1. Introduction

Mass loss from the Greenland and West Antarctic Ice Sheets is increasing (Shepherd et al., 2012; Stocker, 2014; Velicogna et al., 2014, Harig and Simons, 2015). Recent studies have identified significant ongoing ice loss from West Antarctic Ice Sheet (WAIS) in response to recent climate and ocean changes (Jenkins et al., 2011; Pritchard et al., 2012; Rignot et al., 2014; Mouginot et al., 2014; Dutrieux et al., 2014; Paolo et al., 2015). These studies suggest that the contribution of Antarctica to global sea-level rise could soon outpace all other sources, and a much more dramatic increase in ice discharge is possible within the next few decades (Joughin et al., 2014; DeConto and Pollard, 2016). The resulting acceleration in sea-level rise would require a large increase in adaptation or infrastructure replacement in coastal areas worldwide. This issue is of particular concern for the coastal United States and other parts of the northern hemisphere, where the impact of increased sea level would be amplified by around 30% due to changes in the global gravitational field arising from the ice loss (Bamber et al., 2009; Bamber and Riva, 2010; Hay et al., 2014). This static component can be intensified by storm surges that can locally raise sea level by several meters during an event (Biasutti et al., 2012).

Current mass loss underway in WAIS could lead to its eventual collapse through marine ice sheet instability (Weertman, 1974; Mercer, 1978; Alley et al., 2015). Evidence from sea-level records, marine sediment cores, and ice cores suggests that WAIS has collapsed before, possibly as recently as 125,000 years ago during the last interglacial (Scherer et al., 1998; Dutton et al., 2015; Steig et al., 2015). More recently, during the Last Glacial Maximum, WAIS was larger than today and extended seaward to the edge of the continental shelf. Geological evidence of its subsequent fast-paced retreat (Fairbanks, 1989; Alley et al., 2005; Overpeck et al., 2006) makes it clear that rapid marine-based ice loss is possible (Klages et al., 2015). However, the physical mechanisms that drive rapid retreat are poorly quantified because of a lack of direct observations. Key data needed to evaluate processes and project likely rates of ice loss are at present spatially sparse and span only a couple of decades. Few observations exist in the critical places: underneath the ice, in the ocean offshore, and in sub-ice-shelf cavities. Atmospheric data in the region are sparse and temporally intermittent.

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These gaps will need to be addressed before robust projections of the timing and rate of ice sheet collapse can be made (Alley et al., 2015; Holland and Holland, 2015).

In this paper, we present a review of recent research on the continuing evolution of WAIS, and provide a set of objectives for future work – called "*How Much, How Fast?*" – designed to improve our understanding of ice-ocean interaction and its impact on the interior ice sheet dynamics within the framework of the continuing changes in Antarctic climate, oceanic circulation, and ongoing ice flow changes. Central to achieving this goal will be: long-term continuous observations of the ice, atmosphere, and ocean; high-resolution mapping of the Thwaites Glacier catchment and Amundsen Sea; dedicated studies of key processes to understand behaviors and improve models at all scales; and a next generation of coupled models that include better physical and dynamical representations of the ice, solid-earth, ocean, and atmosphere components.

This paper is an outcome of discussions in 2014–15 convened by the National Academies attended by several of the authors (see National Academies of Sciences, Engineering, and Medicine, 2015), and is a formalized and expanded version of a white paper submitted to the US National Science Foundation in May 2016 by almost the same author group. Further discussions at the West Antarctic Ice Sheet Workshops (www.waisworkshop.org) of 2015 and 2016 and a Royal Society meeting sponsored the United Kingdom's National Environmental Research Council (NERC) helped shape the ideas presented (www.istar.ac.uk/wp-content/uploads/sites/5/sites/5/2016/05/West-Antarctica-Royal-Society-Meeting-Report-final.pdf). The white paper was part of the motivation for a joint NSF-NERC program solicitation released in October 2016 (NSF-NERC, 2016).

1.1. Geographic focus

This *How Much, How Fast*? WAIS science review and objectives for new research focuses on the key geographic area of ongoing rapid change: Thwaites Glacier and the adjacent Amundsen Sea. The possibility of surges and runaway retreat of West Antarctic glacier grounding zones into the central WAIS has long been recognized (e.g., Hughes, 1972; Weertman, 1974; Mercer, 1978; Lingle and Clark, 1979; Thomas, 1979). The specific vulnerability of Pine Island and Thwaites Glaciers and the danger of rapid retreat into their inland basins and central WAIS was emphasized by Hughes (1981).

Observations show unequivocally that the Thwaites Glacier ice-ocean system is undergoing the largest changes of any ice-ocean system in Antarctica (Mouginot et al., 2014; Paolo et al., 2015; Fig. 1). Recent assessments indicate that Thwaites is contributing ~0.1 mm a^{-1} to sea-level rise, a rate double its mid-1990s value (Rignot et al., 2008; Medley et al., 2014). Ice flow speed of lower Thwaites Glacier has increased by 50 to 100 m a^{-1} since 2009, and ice flux across the grounding zone of the Thwaites-Haynes-Pope-Smith-Kohler glacier complex has increased by 10–15 Gt a^{-1} since 2009 (Mouginot et al., 2014; Martín-Español et al., 2016; Gardner et al., 2017 in review). Gravitationally-determined mass loss estimates for WAIS have increased significantly since 2009, centered on the lower Thwaites region (Harig and Simons, 2015) and between 2011 and 2014 its surface lowered by 1.5 to 2.0 m a^{-1} (Helm et al., 2014; McMillan et al., 2014). Combined, these observations show that Thwaites Glacier has experienced a more significant increase in mass loss in the past few years than Pine Island Glacier (PIG), Totten Glacier, or the Antarctic Peninsula.

Recent coupled-system and ice-sheet models indicate that Thwaites Glacier has the greatest potential for further near-term increases in ice flux and consequent rapid sea-level rise (e.g., Joughin et al., 2014; DeConto and Pollard, 2016). Analysis suggests that major ice losses could occur within just decades to a few centuries — timescales that could strain society's ability to adapt. Thwaites Glacier has a wide ice front (~120 km) that interacts with the ocean, is grounded below sea level, and thickens inland, making it a textbook case of a potentially unstable marine ice sheet (e.g., Weertman, 1974; Schoof, 2012). A significant retreat of the Thwaites Glacier system would likely trigger a wider collapse of much of WAIS.

Two decades of work on WAIS has revealed the importance of accurate bathymetry, ocean circulation, and subglacial topography in governing rates of change over the past few decades (Payne et al., 2004; Jacobs et al., 2012; Jenkins et al., 2011; Stanton et al., 2013; Dutrieux et al., 2014; Smith et al., 2017). Specifically, investigations on PIG, the catchment to the east of Thwaites Glacier, highlight the challenges of making relevant observations necessary for model projections, largely due to scale differences. Recent modeling studies have suggested that PIG is likely to evolve slowly and steadily over the next century or two (Joughin et al., 2010; Favier et al., 2014); observations indicate that the ongoing mass loss will be modulated but likely not reversed by variability in the adjacent ocean (Medley et al., 2014; Christianson et al., 2016). There is less certainty about the near-term future evolution of the Thwaites Glacier system, which has a more direct connection between the deep WAIS interior and the ocean than does PIG (Vaughan et al., 2006; Holt et al., 2006). Over the past decade, new observations of bed.

Topography in this area have improved our knowledge to the point where models can partially predict flow dynamics, clearly identifying the possibility for rapid ice loss (Joughin et al., 2014; Cornford et al., 2015). Because of this potential, the most important Antarctic climate science and societally-relevant scientific insight on sea level in the next decade will come from an improved understanding of the Thwaites Glacier system.

Although the proposed research objectives focuses on Thwaites Glacier and areas with similar characteristics for observations, we note that coupled-system modeling efforts will need to encompass a much larger area to capture the relevant climate, ice, and ocean regions. Studies of processes relevant to a Thwaites Glacier collapse in other similar regions such as Getz Ice Shelf, the Antarctic Peninsula, and Totten Glacier may provide useful insight as well. Although the science objectives presented here are directed at Antarctic research, research aimed at Greenland's outlet glaciers and fjord ice-ocean interactions can also contribute in important ways to understanding the relevant processes (e.g., ice-cliff stability, ice-front circulation).

1.2. Research foci

A meeting held in January 2016 in Boulder, Colorado produced an outline of the research plan presented here, drawing upon the National Academies of Sciences, Engineering, and Medicine report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* (National Academies of Sciences, Engineering, and Medicine, 2015). The National Academies' report was guided by extensive, wide-ranging outreach to the Antarctic glaciological, atmospheric, and oceanographic research communities, and the results were broadly circulated. Research on the Thwaites Glacier-Amundsen Sea climate-ice-ocean-earth-life biogeophysical system emerged as the research target with the greatest level of community support.

Four fundamental questions for future research emerged from the National Academies' report and the January 2016 Boulder meeting:

1. Drivers: *Why is the West Antarctic Ice Sheet changing now*?
2. Boundary Conditions: *What is the present state of the West Antarctic Ice Sheet*?
3. Processes: *What mechanisms are involved in marine ice sheet collapse*?
4. Models: *How can we improve our projections of sea-level rise from West Antarctica*?

This review describes the steps necessary to address the four questions listed above, and briefly outlines the instrumentation and logistical needs required to meet these research goals. If these objectives are reached, the outcome will be a decadal-scale community effort

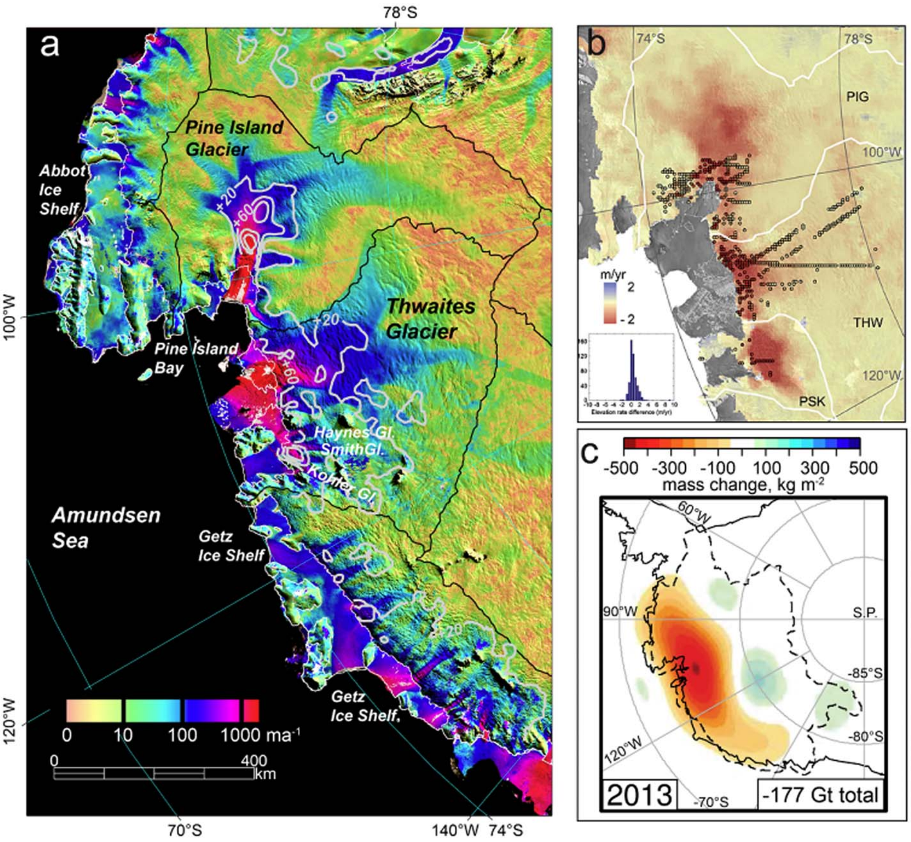

Fig. 1. Indications of recent significant increases in mass loss from Thwaites Glacier. a) Map of the central WAIS (Haran et al., 2014) overlaid with surface ice flow speed derived from Landsat 8 satellite image pairs acquired between October 2013 and March 2016. Basin outlines are shown as black lines (Zwally et al., 2012); speed change of grounded ice since 2008 in ma^{-1} is shown as thick white lines (Rignot et al., 2011b); ice edge and grounding zone are shown as thin white lines. b) Elevation change over the Pine Island, Thwaites, and adjacent glaciers derived from CryoSat-2 elevation mappings (adapted from fig. 3 of McMillan et al., 2014). c) Mass change inferred from satellite gravity measurements for calendar year 2013 (Harig and Simons, 2015); total mass loss within black dashed line is given in lower right of the inset.

that will advance our knowledge of how quickly WAIS will change and how much sea level will rise in response. The Thwaites Glacier system has been identified as a region of interest and is now the focus of an international collaborative effort. A joint US National Science Foundation (NSF) and UK Natural Environmental Research Council (NERC) program has been initiated for new research in the region. We review and update the research that led to this effort.

2. Research review of WAIS collapse: drivers, boundary conditions, processes, and model"

In the current scenario for a marine ice sheet collapse of Thwaites Glacier and then WAIS, the collapse is initiated by changes in atmosphere and ocean drivers that affect ocean circulation, surface accumulation, and summer surface-melt rates (e.g., Parizek et al., 2013; Joughin et al., 2014; Feldmann and Levermann, 2015; DeConto and Pollard, 2016). In particular, warm, dense mid-depth ocean water surrounding the Antarctic continental shelf is upwelled onto the continental shelf (Circumpolar Deep Water, CDW). This CDW moves toward the ice fronts and ice-shelf grounding zones along troughs in the bathymetry, causing increased melting and retreat at the ice-ocean interfaces. This process thins the ice shelves, reducing drag along their sides and at local pinning points on sea-floor highs, which in turn reduces the buttressing i.e., the resistive stress that the ice shelves exert on the grounded ice (Thomas, 1979; Paolo et al., 2015). Thinning ice shelves lead to faster grounded-ice flow (Pritchard et al., 2012). Faster flow of grounded ice leads to further thinning, causing previously grounded ice to float as the grounding zone retreats farther inland along a retrograde slope (i.e., the bed deepens inland), leading to more ice crossing the grounding zone and a smaller accumulation area (e.g., Weertman, 1974; Chugunov and Wilchinsky, 1996; Schoof, 2007, 2012; Durand et al., 2009). This positive feedback process is the marine ice sheet instability.

The retreat of a marine ice sheet could be exacerbated if surface-meltwater-driven hydrofracture or other processes lead to rapid calving of the ice shelf and ice front (e.g., Scambos et al., 2000, 2003, 2009; MacAyeal et al., 2003; Pollard et al., 2015; DeConto and Pollard, 2016). Following removal of the ice shelf, cliff failure could dramatically increase the rate of grounded marine-terminating glacier calving (Bassis and Walker, 2012; DeConto and Pollard, 2016). In combination, these processes could trigger a rapid deglaciation of the marine basins of WAIS, potentially in a few decades or centuries.

Changes in snow accumulation over the Thwaites Glacier catchment can affect the timing of collapse. Antarctic snow accumulation rates are expected to increase over the next century, resulting from an increase in the atmospheric moisture holding capacity due to warming (Krinner et al., 2007; Ligtenberg et al., 2013; Lenaerts et al., 2016). Under such a scenario, additional snow accumulation within the Thwaites Glacier catchment could delay the onset of collapse, mitigating a small portion of the sea-level contribution from WAIS (Joughin et al., 2014).

Each aspect of this marine ice sheet collapse scenario has a background of existing research results, as well as areas in need of further study. We review the existing level of understanding and projections in the framework of our four questions (drivers, boundary conditions, processes, and models).

2.1. Drivers: why is the West Antarctic Ice Sheet changing now?

While both the rate and extent of recent ice-sheet change are now well documented, there is an urgent need to better identify and measure

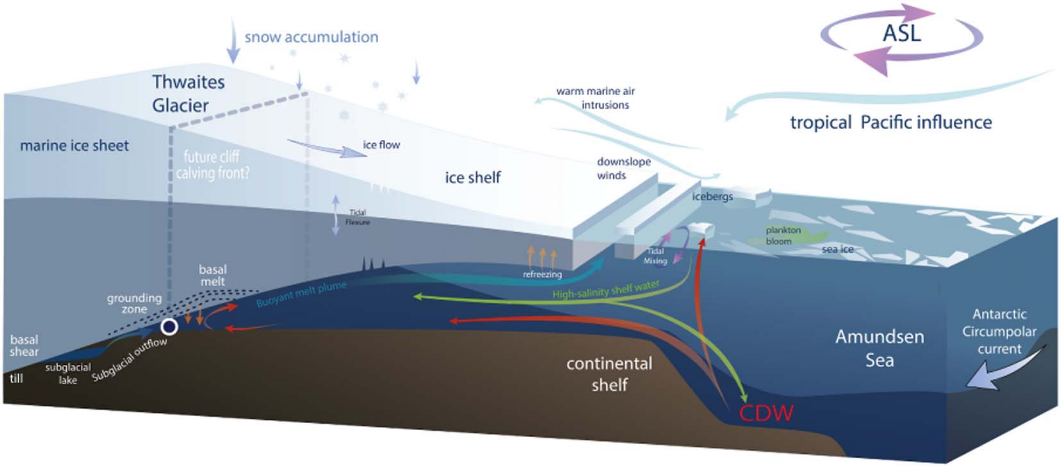

Fig. 2. Schematic of key drivers and some of their effects for the Thwaites Glacier – Amundsen Sea region.

the drivers of the observed change. The large-scale drivers of the system, such as changes in ocean or atmospheric circulation, or surface mass balance variability, arise from a complex group of changes linked to global processes. Advancing our knowledge of the processes governing these drivers will improve our ability to project future change.

2.1.1. *Present-day atmosphere and ocean*

Ice sheet mass balance change in the Thwaites region is driven by the influence of ongoing warming in the ocean and atmosphere and significant circulation changes in these two systems (Shepherd et al., 2004; Steig et al., 2009, 2012, 2013; Bromwich et al., 2013; Schmidtko et al., 2014; Li et al., 2014). Seasonally stronger westerly winds in the northern Amundsen Sea sector have driven a change in ocean circulation, favoring intrusions of warm salty deep water (CDW) across the continental shelf break in the Amundsen Sea Embayment toward the grounding zones of Thwaites Glacier and adjacent ice outlets (Thoma et al., 2008; Steig et al., 2012; Walker et al., 2012; Paolo et al., 2015; Turner et al., 2017).

The details of how wind forcing entrains CDW over the continental shelf break and through bathymetric troughs leading to the Thwaites Glacier ice front remain poorly known, making attribution challenging (e.g., Arneborg et al., 2012; Assmann et al., 2013; Kalén et al., 2016; Jenkins et al., 2016). Ekman transport, induced by along-slope currents over the continental slope and shelf break, can contribute to the cross-shelf transport (Wåhlin et al., 2012) and buoyancy forces can drive the bottom flow down the troughs toward the ice shelf (Wåhlin et al., 2013). Numerical models confirm the dominant role played by changing winds in key regions in shifting the transport of ocean heat from open ocean to the ice sheet (Dinniman et al., 2015), with a lesser role of changing atmospheric temperature.

The strengthening of the regional westerly winds that have forced warmer waters to the grounding zones can be attributed primarily to remote changes occurring in the tropics (Schneider and Steig, 2008; Ding et al., 2011; Bracegirdle, 2012; Steig et al., 2012, 2013; Dutrieux et al., 2014; Simpkins et al., 2014; Clem and Fogt, 2015; Clem and Renwick, 2015; Fogt and Wovrosh, 2015; Li et al., 2014, 2015a, 2015b). However, there is also likely a component of change resulting from larger-scale circulation changes (the Southern Annular Mode, or SAM) owing to stratospheric ozone depletion and increased greenhouse gases (e.g., Thompson et al., 2011; Arblaster et al., 2011). Although the anthropogenic origin of the ozone and greenhouse-gas forcing is unequivocal, it remains unclear whether the tropically-related circulation changes are distinguishable from natural, unforced climate variability (Steig et al., 2013). Furthermore, there is strong SAM modulation of the tropical teleconnection affecting West Antarctica, and vice versa (e.g., L'Heureux and Thompson, 2006; Ding et al., 2012; Fogt and Wovrosh, 2015; Wilson et al., 2016).

Understanding these changes and projecting their future course is further complicated by variability in the nearby Amundsen Sea Low (ASL), a persistent but fluctuating minimum in atmospheric pressure that has been called “the pole of variability” for the Antarctic atmosphere (Connolley, 1997; Turner et al., 2013; Hosking et al., 2013, 2016; Raphael et al., 2016). By imparting surface wind stress on the ocean, changes in the ASL drive changes in deep ocean circulation near the continental shelf edge. Changes in the mean intensity or location of this low-pressure area also influence the frequency and strength of warm marine air intrusion, with profound effects on the climate of West Antarctica on seasonal to multi-decadal time scales (e.g., Bromwich et al., 2004; Krinner et al., 2007; Nicolas and Bromwich, 2011).

The large, climatically driven spatial and temporal variability of snowfall in the Amundsen Sea embayment is not fully captured by available data due to sparse spatial coverage and short records. For instance, a recent study found no significant change in snow accumulation over much of the Thwaites catchment (Medley et al., 2013), but the observations cover only a 32-year interval (1980–2011), making it difficult to adequately distinguish long-term trends from natural variability.

Regional oceanic changes in the ocean of the ice sheets include a warming of the CDW layer (e.g., Gille, 2002) and a change in the mean flow of the Antarctic Circumpolar Current (Martinson and McKee, 2012). Downstream of the interface with ice in Pine Island Bay, CDW is observed to be gradually modified (cooler and fresher; Wåhlin et al., 2010, Wåhlin et al., 2013; Jacobs et al., 2012), leading to a slow freshening of the mid-level ocean water in the coastal seas downstream (Jacobs and Giulivi, 2010). Recent studies of ocean soundings along the continental shelf break seaward of Pine Island and Thwaites glaciers, and the adjacent Dotson and Getz continental shelf areas highlight this gradual freshening and deepening of CDW, and show the value of dense multi-year measurements (Fig. 3; Jacobs et al., 2011, 2012, 2013). An extended program of measurements with moorings would facilitate a better attribution of CDW transport across the continental shelf break, and the scaling of how coastal wind patterns help drive the water toward the ice interfaces.

2.1.2. *Century-scale atmospheric trends*

Records from shallow ice cores collected under US research efforts such as the International Trans-Antarctic Scientific Expedition (ITASE), as well as related British Antarctic Survey programs, have played an important role in complementing the short instrumental climate record, helping to understand the atmospheric and oceanic drivers of recent changes in WAIS and the Antarctic Peninsula (Schneider and Steig, 2008; Steig et al., 2013). Coastal ice core records from the base of the

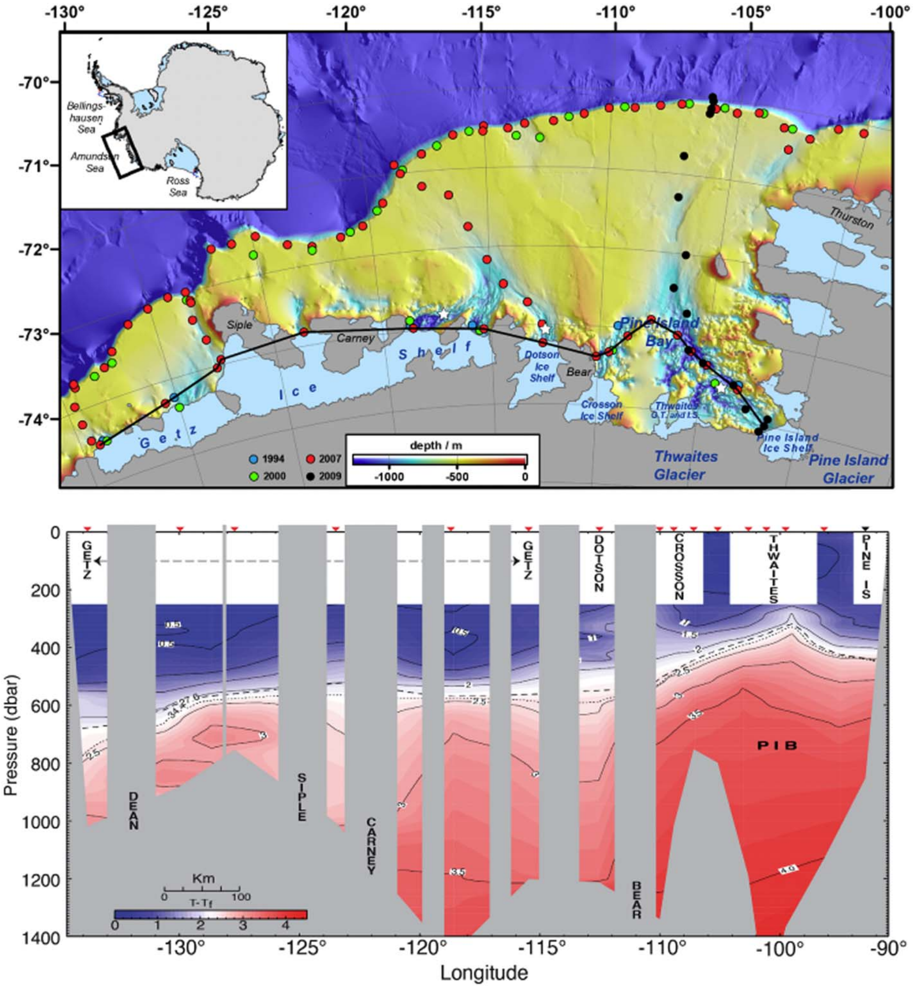

Fig. 3. Ocean bathymetry and thermal profile across the Amundsen Sea Embayment and Getz Ice shelf. Top, ocean bathymetry and conductivity-temperature-depth (CTD) measurements (filled circles, color-coded to year of collection) and mooring sites (white stars). Black line near the ice shelf fronts and down Pine Island Bay links the CTD casts used in the profile, at bottom.
(Adapted with permission from Jacobs et al., 2012, their figs. 1 and 2)

western Antarctic Peninsula have provided important information documenting a shift in the position of the ASL for the past few hundred years, providing a dynamical explanation for the large 20th century increase in snow accumulation in that area (e.g., Thomas et al., 2015). Coastal ice core records from James Ross Island near the northern Antarctic Peninsula, have similarly been invaluable in documenting the rapid 20th century warming and increased surface melt in that region to levels unprecedented in the past 1000 years (Abram et al., 2013). This record revealed that circulation-induced atmospheric warming led to a nonlinear increase in surface melting, a process that climate models indicate could expand greatly across Antarctic ice shelves in a warming future (Trusel et al., 2015).

Records from shallow ice cores situated along the Amundsen Coast, including on coastal ice domes adjacent to Pine Island Bay and on nearby ice shelves, could reveal even more information specific to the Thwaites Glacier and Amundsen Sea region, but are lacking across the study region. Two records from the US ITASE traverse lie at the edge of this region but are at much higher elevation and end in 2001 (Steig et al., 2013). This observational gap is particularly concerning as the high natural climate variability across West Antarctica means that the instrumental period may be insufficient to document the variability in many of the drivers responsible for large-scale ice sheet changes or the impact (e.g., Medley et al., 2013; Previdi and Polvani, 2014).

2.2. Boundary conditions: what is the present state of the West Antarctic Ice Sheet?

It is essential to map the current boundary conditions of the atmosphere-ice-ocean-earth in the Thwaites Glacier region. While much has been learned in the past two decades, mapping at improved resolution is needed to advance predictive models and understand processes in greater detail. The major boundary conditions of the Thwaites Glacier system include the following: the detailed shape of the surface of the ice sheet; ice sheet thickness; surface accumulation and near-surface density; temperature and fabric within the ice; the shape of the base of the ice sheet, its thermal state (frozen or thawed), and geothermal flux; the location of the grounding zone and its rate of change; the shape (detailed ice thickness) of the ice shelves and glacier fronts; and the bathymetry of the sub-ice shelf cavities and the adjacent Amundsen Sea out to the continental shelf break. Each boundary condition has a different influence on the mass balance and dynamics of Thwaites Glacier, and each respond differently to oceanic and atmospheric drivers. Next-generation ice sheet modeling will require higher resolution maps of these boundaries to best project changes on decadal to centennial time scales.

2.2.1. Ice sheet surface, flow, and thickness observations

The number and spatial resolution of mappings of ice-sheet surface elevation, ice velocity, and ice thickness have greatly increased in the last few decades. Landsat data have provided the means to map ice velocity and ice-front positions in parts of the Amundsen Sea Embayment since the 1970s (Joughin et al., 2003; MacGregor et al., 2012; Mouginot et al., 2014). Synthetic aperture radar data allowed the first comprehensive, high-spatial resolution mappings of ice velocity and grounding zone position in the early-to-mid 1990s (Rignot, 1998; Rignot, 2001; Rignot et al., 2002, 2008, Rignot et al., 2011a, 2011b, Rignot et al., 2014; Mouginot et al., 2014). These velocity data were supplemented by ice-sheet surface elevation mapping and change detection using radar altimetry (Bamber, 1994; Wingham et al., 1998) and, later, satellite laser altimetry in the early 2000s (Pritchard et al., 2009, 2012). Ice sheet surface elevation is today mapped several times per year via advanced satellite radar altimetry and key regions are mapped seasonally with airborne laser altimetry. Changes in ice sheet surface elevation and velocity identified the Thwaites Glacier basin as a region of rapid change (e.g., Rignot et al., 2002; Pritchard et al., 2009, 2012; Mouginot et al., 2014; Rignot et al., 2014; Paolo et al., 2015). The current satellite constellations (InSAR, optical, radar altimetry) and annual airborne campaigns (e.g., NASA's Operation IceBridge) support a detailed ongoing analysis of the Thwaites Glacier region (Mouginot et al., 2014; Rignot et al., 2014; Christianson et al., 2016; Joughin et al., 2016; Khazendar et al., 2016) that has provided the basis for the observational and modeling results leading to this initiative.

Ice thickness of the Thwaites basin was first comprehensively mapped on a 15-km grid in 2004–2005 by a collaborative UK/US airborne ice-penetrating radar campaign (Holt et al., 2006; Vaughan et al., 2006). Since that time, Operation IceBridge and the Center for Remote Sensing of Ice Sheets have continued to collect ice thickness data in some areas near the Thwaites grounding zone. These new data, combined with mass-conservation gridding techniques (Rignot et al., 2014) and new analytic techniques for extracting subglacial bedforms and hydrology from radar profiles (Schroeder et al., 2013, 2014) have greatly improved our knowledge of ice thickness and bed topography.

Model results, however, remain highly dependent on detailed bed topography at the limit of presently available resolution. Modeling that incorporates detailed ground-based bed mapping of PIG has shown that the resolution of the ice thickness grid strongly influences model results (Joughin et al., 2010; Favier et al., 2014; Seroussi et al., 2014; Nias et al., 2016) and is insufficient to allow high-resolution modeling in most locations (Parizek et al., 2013). Acquiring new knowledge of the bed topography and morphologic character of the Thwaites Glacier bed is a top priority for this initiative.

2.2.2. Internal and basal ice observations

The ice rheology, internal ice temperature, crystal fabric, distribution of crevasses, and past history of deformation all exert basic controls on current and future ice flow. These parameters have been inferred in the upper Thwaites Glacier and other locations from radar and seismic internal reflectivity, and by drilling and sampling (e.g., Horgan et al., 2011; Matsuoka et al., 2012). Some internal reflections indicate transitions in ice fabric, marking layers capable of greater deformation with respect to applied stresses (Peters et al., 2012; MacGregor et al., 2015a). The radar and seismic layer geometry and amplitude have been used as constraints in ice-sheet models to infer past ice flux, accumulation rate, and basal conditions (e.g., Neumann et al., 2008; Christianson et al., 2013; Koutnik et al., 2016; MacGregor et al., 2015b, 2016a, 2016b). These all point to useful observational data sets for forecasting the evolution of Thwaites Glacier.

Most of the base of Thwaites Glacier is thawed, but some critical ice flow transitions such as the eastern shear margin may reflect thawed-to-frozen bed transitions (MacGregor et al., 2012; Schroeder et al., 2015). Recent advances in analysis of phase-sensitive airborne radar data allow better mapping of the thermal state of the bed and the subglacial hydrologic system (Schroeder et al., 2013, 2014; Schroeder et al., 2015). Targeted high-resolution ground-based radar and seismic campaigns conducted over critical areas will strengthen the interpretation of existing basin-wide airborne data and provide ground-truth validation.

2.2.3. Subglacial geology

The geology beneath an ice sheet exerts a direct control on the flow of the overlying ice (Anandakrishnan et al., 1998; Bell et al., 1998). This subglacial geology is of particular concern for Thwaites Glacier, because this basin is part of a broader rift basin with several subglacial volcanoes and associated geothermal anomalies that influence the regional thinning pattern (Corr and Vaughan, 2008; Jordan et al., 2010; Bingham et al., 2012; Chaput et al., 2014; Schroeder et al., 2014). Further constraining the nature of the geology beneath Thwaites Glacier will help distinguish the subglacial contribution to ongoing regional changes from atmospheric and oceanic forcings.

Subglacial geology is best observed either in situ (through drilling) or using ground-based active-source seismic methods, which regularly image subglacial sediment and bedrock (e.g., Peters et al., 2006; Muto et al., 2016). The internal layers of the ice sheet may also deform in response to changes in friction at the ice-bed interface, resulting from spatial variation in subglacial hydrology, basal friction, and rate of basal melting where the geothermal flux is sufficiently high (Fahnestock et al., 2001; Catania et al., 2003; Christianson et al., 2013; MacGregor et al., 2016b). Hence, a comprehensive radiostratigraphy of the Thwaites Glacier system, comparable to earlier work for the Greenland Ice Sheet (MacGregor et al., 2015a), could clarify where subglacial geology has a significant influence upon ice flow.

Knowledge of conditions at the base of Thwaites Glacier is crucial for understanding both ongoing ice-flow and grounding-zone changes as well as for predicting where and when future rapid changes could occur. Many of the critical parameters describing bed conditions, including the distribution of thawed versus frozen bed regions, geologic structure, geothermal heat flow, erosion rates, presence of subglacial water, and locations of sediments, are not available at the necessary resolution in the Thwaites drainage to understand the interactions among them. Together, these properties influence the bed strength and the basal traction that resists flow and how the ice-bed interface responds over time. Marine surveys of the bed in front of Thwaites show both till and bedrock features (Nitsche et al., 2013). The distribution of these in the region just upstream of the grounding zone, and farther, will greatly influence how the ice sheet evolves.

2.2.4. Ocean bathymetry, grounding zone, ice shelf, and ocean cavity observations

Bathymetric mapping of the Amundsen Sea continental shelf has revealed the presence of deep channels, carved by extended glaciers from the Pine Island Bay area during past glacial epochs (Fig. 3a). These channels have been shown to be the primary pathways by which warmer ocean water is directed to the glacier fronts and sub-ice-shelf cavities (Jenkins et al., 2011; Dutrieux et al., 2014).

Within and near the grounding zones of Thwaites Glacier, three distinct types of ice-ocean interfaces are present: a relatively flat ice shelf, near-vertical ice cliffs, and tidewater areas having extensive crevassing (Parizek et al., 2013; Schroeder et al., 2015). Bed geometry, sediment wedges, and various dynamical feedbacks can stabilize the grounding zone for long periods, while other mechanisms and feedbacks can cause unstable retreat once triggered (e.g., Weertman, 1974; Alley et al., 2007; Schoof, 2007; Parizek et al., 2013). Repeat mapping of the grounding zone across the Amundsen Sea Embayment has demonstrated that it is retreating at rates up to hundreds of meters per year in the regions of faster flow (Rignot et al., 2011a; Rignot et al., 2014). Currently, interferometric synthetic aperture radar has mapped the grounding zones to a resolution of ~250 m on seasonal timescales (Joughin et al., 2016).

2.3. Processes: what mechanisms are involved in marine ice-sheet collapse?

Many of the key processes inherent to the dynamics of retreating marine ice sheets are not well understood, either from lack of basic knowledge, or more commonly, from lack of detailed site-specific data for model calibration and parameterization. These processes include: (1) grounding zone changes arising from ocean-driven melting, grounding zone sedimentation, tidal effects, and formation of new pinning points as grounded ice becomes ungrounded; (2) ice-ocean interface processes in other areas of contact, such as melt plume formation, feedbacks to ocean circulation from melt-induced buoyancy, generation of sub-ice-shelf channels, and tidal and seasonal changes that transport ocean water to and away from the interface; (3) ice-cliff processes, including ice cliff strength, fracture processes, the role of surface melt, and mélange processes that may slow the progress of cliff failure; (4) the effects of warm marine air intruding over the ice sheet and ice shelves or other drivers of surface melting, and of changes in snow accumulation and surface melting, and water storage in firn; (5) hydrofracture on the ice-shelf and glacier surface; (6) ice-sheet sliding and subglacial sediment deformation, and viscous and stick-slip processes; and (7) the role of subglacial water both beneath the fast flowing grounded ice and at the ice-ocean interface where it can trigger basal ice shelf melting and impact sub-ice-shelf ocean circulation and channel formation.

These processes and subsequent feedbacks require dedicated observational study with the aim of improving their representation in predictive models. Although these processes are best studied in the Thwaites Glacier and Amundsen Sea regions, studies of other similar Antarctic systems and also targeted work in Greenland and elsewhere can contribute to our understanding of Thwaites Glacier evolution.

2.3.1. Grounding zone processes

Grounding zone retreat may be accelerated by the effects of deep local basins and channels, but can be slowed by the effects of sedimentation wedges (e.g., Alley et al., 2007) and local high spots (pinning points) that remain in contact with the ice shelf after grounding zone migration upstream (e.g., Christianson et al., 2016). Basal and surface crevasses preferentially form at the grounding zone, driven in part by tidal flexure. These crevasses weaken ice shelves and likely contribute to complete break off beyond some threshold. Tidally-driven flexure can compact till sediments inland of the grounding zone, contributing to stability (e.g., Christianson et al., 2013), but can also pump ocean water well inland, favoring instability (e.g., Walker et al., 2013a, 2013b). Sedimentation near the grounding zone tends to stabilize it (Alley et al., 2007), as do isostatic crustal response and self-gravitational effects on local sea level.

Understanding the processes arising from the Thwaites-specific grounding zone interactions, and incorporating them to diagnostic and prognostic models, require high-resolution data from near the grounding zone and in the sub-ice-shelf cavity.

2.3.2. Ice-ocean interface processes

Ice-ocean interface processes related to ice-front, grounding line, and ice-shelf melting are central to understanding ice shelf weakening and grounding line retreat (Dinniman et al., 2016). Recent change has highlighted the important role that ice-ocean interaction plays in ice-sheet stability, which had sometimes been overlooked in the past (Joughin et al., 2012). The ocean's large heat capacity means that shifting currents or warming water can substantially alter the rate of melting at the ice-ocean interface(Rignot and Jacobs, 2002). This interaction is particularly important at Thwaites where little melting presently occurs at the ice-air interface, but considerable (tens of meters) melting occurs beneath the glacier's ice shelf (Jacobs et al., 1992; Khazendar et al., 2016). Furthermore, removing ice from the land-terminating margin requires that heat be supplied to melt or sublimate ice in situ, limiting the rate of loss. In contrast, ocean currents can rapidly carry away excess ice to melt elsewhere as it calves from an ice-ocean terminus in response to forcing at the boundary (e.g., oceanic or atmospheric heating), enabling rapid retreat. As mentioned earlier, the ice-sheet grounding line, where the grounded ice sheet transitions to a floating ice shelf, often lies at a point of tenuous stability such that small initial perturbations can trigger large-scale retreat (i.e., marine ice-sheet instability; Weertman, 1974).

2.3.3. Ice-cliff processes

Ice-cliff processes have recently been recognized as having the potential to cause rapid ice-front retreat, and would exacerbate the ongoing thinning and retreat observed at Thwaites Glacier (Bassis and Walker, 2012; Bassis and Jacobs, 2013; Pollard et al., 2015; DeConto and Pollard, 2016). The grounding line of Thwaites Glacier lies currently on the seafloor 600 m below sea level (Fretwell et al., 2013; Millan et al., 2017), too shallow to trigger ice-cliff failure. However, the seafloor is > 1000 m below sea level only 25 km inland, and therefore has the potential to form unstable ice cliffs > 100 m high. Beyond a (presently uncertain) threshold of increased rifting, surface melting or basal melting, ice shelves have been observed to break off entirely, leaving calving ice-front cliffs above a deeply grounded glacier front (Hanson and Hooke, 2003; Motyka et al., 2011; Joughin and Alley, 2011; Bassis and Walker, 2012; Alley et al., 2015). The rate of retreat is linked to the rate of cliff-failure-driven calving, which likely increases significantly with cliff height because higher cliffs are under higher stresses. Current data and theory suggest than an ice terminus height of significantly more than ~100 m above waterline will trigger repeated brittle failure of the ice front, leading to very rapid retreat. Studies of the Antarctic Peninsula and Greenland have shown that brief episodes of ice cliff instability led to significantly faster retreat (e.g., Scambos et al., 2004; Scambos et al., 2011; Joughin et al., 2008; Xie et al., 2016).

2.3.4. Ice-Earth coupling

Interactions between changing ice load and the underlying Earth are important in West Antarctica, where the West Antarctic Rift System is characterized by high heat flow, a low-viscosity mantle zone, and thin lithosphere (Gomez et al., 2015). Self-gravitational feedbacks between a retreating ice-sheet margin and the surrounding ocean can cause local relative sea-level to drop, which can stabilize grounding zones, i.e. a negative feedback effect (Gomez et al., 2013). Most current ice-sheet models use simplistic representations of the underlying Earth, such as Elastic Lithosphere Relaxing Asthenosphere (ELRA) models, that fail to capture the realistic viscous response of the Earth or the gravitational-sea level feedbacks that could be critically important for Thwaites Glacier.

2.3.5. Surface melting and hydrofracturing

Intrusions of warm marine air over WAIS and its peripheral ice shelves may become more frequent as global temperatures increase and as air circulation patterns shift. With strong and sustained advection of warm air from the north, coastal areas around Pine Island Bay could experience prolonged melt episodes, as occurred in January 2016 (Fig. 4a; Nicolas et al., 2017). The frequency of these events has been shown to be related to the position and strength of the ASL (Nicolas and Bromwich, 2011).

Accumulated surface meltwater is of concern because it can cause crevasses to propagate downward through the entire thickness of the grounded ice or ice shelf in a process known as hydrofracture. Meltwater ponding and resulting hydrofracturing has been an important contributing factor of past ice shelf collapses in the Antarctic Peninsula (Scambos et al., 2000, 2003). Although surface melting typically occurs every austral summer on the ice shelves along the Amundsen Sea coast (Fig. 4b; Trusel et al., 2013), the phenomenon remains generally short-lived and has not yet reached the intensities observed in the Antarctic Peninsula (Kuipers Munneke et al., 2014; Trusel et al., 2013, 2015). Nevertheless, the potential for hydrofracture

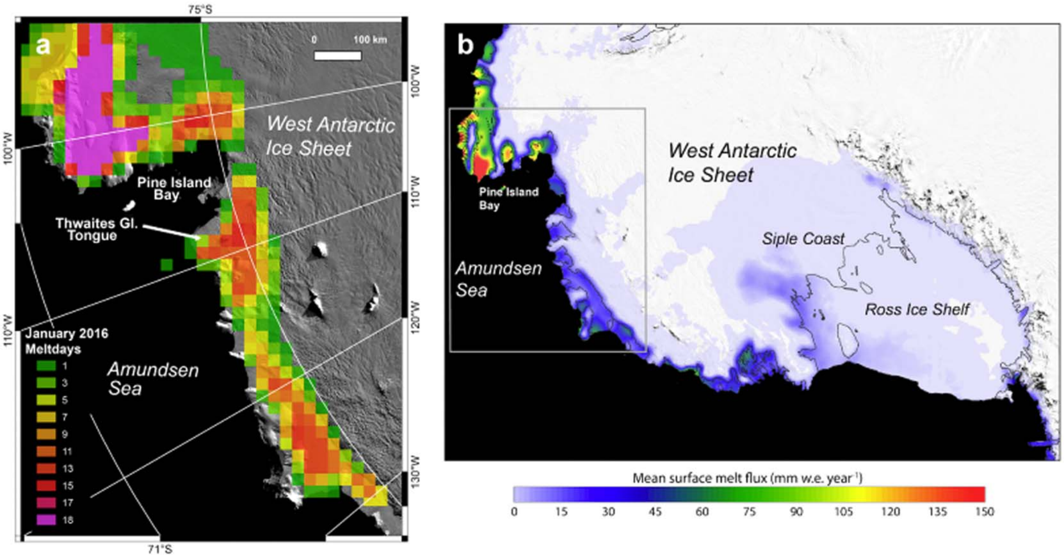

Fig. 4. January 2016 surface melt event in the Thwaites region (adapted from Nicolas et al., 2017), and 1999–2009 mean surface melt flux for the western WAIS (as discussed in Trusel et al., 2013). (a) Melt days in January 2016 arising from a warm marine air intrusion estimated from passive microwave satellite observations. (b) Average summer surface melt flux for 1999–2009 in millimeters of water showing the relatively common occurrence of melt across ice shelves and the result of an extensive, but relatively low intensity, melt event across WAIS in 2005.

underscores the importance of understanding factors governing the frequency and amount of surface melt and how these processes may evolve in the future.

Recent modeling experiments have shown that, under future high-emission scenarios, enhanced surface melting and subsequent hydrofracturing could potentially destabilize ice shelves outside of the Peninsula, particularly when they lead to ice-cliff failure (DeConto and Pollard, 2016). An important caveat to such projections is that current climate models continue to poorly simulate fundamental aspects of climate and climate variability in the Amundsen Sea region (e.g., Bracegirdle et al., 2013, 2014). Nonetheless, process studies of the drivers of surface melting and high-resolution regional climate modeling can help identify the likely onset of widespread melting depending on future emissions pathways and atmosphere circulation changes. Further process-based studies of Antarctic surface hydrology and the integration of climate projections with numerical ice-shelf models is an important component of addressing the problem and generating plausible sea-level projections.

2.3.6. Basal sliding and subglacial till deformation

Basal sliding and subglacial deformation are the primary processes by which Thwaites Glacier flows rapidly and ultimately discharges into the Amundsen Sea. Modeling studies have demonstrated that basal conditions are a large source of uncertainty once retreat initiates. Depending on how the bed is characterized in the rheological model, the response to driving stress can vary dramatically. For example, a more plastic rheological bed may resist retreat for longer than a linear-viscous bed, but once initiated, retreat is likely to proceed more quickly (Parizek et al., 2013).

Sliding can occur either on cavitated glacier beds (e.g., Lliboutry, 1983, Kamb, 1987; Schoof, 2005) or over subglacial tills (Alley et al., 1986; Iverson, 2012), where water pressure and availability determine the strength of the interface. Understanding the distribution of till and bedrock as well as the roughness of the bed is essential.

The interaction of initial bed conditions and the overlying ice determine the evolution of basal tractions that resist ice flow and influence rapid deglaciation (e.g., Tulaczyk et al., 2000; Leeman et al., 2016). Improved understanding and parameterization of basal sliding under different and evolving conditions is also needed, as are better inversions for initial basal conditions, which vary significantly between models and require additional observational validation (Joughin et al., 2014; Sergienko and Hindmarsh, 2013).

2.3.7. Subglacial hydrology

Subglacial hydrology has a strong influence on ice sheets, from controlling the onset of fast ice flow (e.g., Bell et al., 2007) and influencing the strength of subglacial materials (Kamb, 2001; Iverson, 2012), to potentially modulating large-scale ice velocity (e.g., Stearns et al., 2008; Siegfried et al., 2016) and basal melting at the grounding zone and beneath the ice shelves (e.g., Le Brocq et al., 2013; Alley et al., 2016; Marsh et al., 2016). Tracking the movement of water and mapping the subglacial drainage network are necessary to understand subglacial hydrology (Smith et al., 2009, 2017).

Subglacial water availability and rate of formation depend on the balance between geothermal flux, surface temperature and accumulation, ice thickness and basal shear stress, and the rate of basal water flow (e.g., Joughin et al., 2004). Subglacial water networks may gain or lose water by basal melt, refreezing, or exchange with subglacial storage, including aquifers (e.g., Christoffersen et al., 2014). Water can remain distributed across the bed, or become channelized, or be temporarily stored as lakes that experience cyclical filling and drainage (e.g., Carter et al., 2017), each with very different implications for lubrication of ice flow (e.g., Flowers, 2015). Channels can be opened from inland to the coast and can then remain open by tidal pumping and serve to extend the destabilizing influence of warming ocean water farther inland (e.g., Winberry et al., 2009; Walker et al., 2013a, 2013b; Horgan et al., 2013). Subglacial drainage may also nucleate channels in ice-shelf bases that can locally weaken the shelves (Alley et al., 2016). Additional sub-ice-shelf channelization and associated fracture may be triggered by processes downstream of the grounding zone (Vaughan et al., 2012). Finally, subglacial outflow across the grounding zone contains fine-grained sediments and nutrients that may act to fertilize the Southern Ocean (e.g., Wadham et al., 2013; Vick-Majors, 2016).

2.4. Models: improving our projections of future behavior

The threat of rapid mass loss of WAIS, and Thwaites Glacier in particular, is based on theoretical and numerical studies of marine ice sheet instability which involves strongly increasing ice flux across grounding zones as they retreat into basins with bedrock deepening upstream, after an initial loss of buttressing by floating ice shelves (Weertman, 1974; Schoof, 2007).

Drastic retreat of WAIS in this manner (sometimes termed 'collapse') was partly reproduced by ice sheet models in the 2000s, particularly during simulations emulating past warm interglacial periods of the Pleistocene (e.g., Ritz et al., 2001; Raynaud et al., 2003; Pollard and DeConto, 2009). However, these studies used coarse spatial resolution and simplified climate and ocean forcing, and in most cases induced retreat in all major embayments simultaneously (Ross, Weddell, Amundsen, Bellingshausen) without distinguishing the PIG/Thwaites sector.

Motivated by observed recent thinning and incipient retreat of PIG and Thwaites (e.g., Rignot et al., 2014), many recent modeling studies have focused on this region using higher spatial resolutions and/or more rigorous ice dynamics (Morlighem et al., 2010; Gladstone et al., 2012a; Parizek et al., 2013; Docquier et al., 2014; Dutrieux et al., 2014; Favier et al., 2014; Joughin et al., 2014). As a whole, these studies indicate that future rapid retreat of PIG and Thwaites Glacier grounding zones, forced by climate and ocean warming, will evolve on time scales of a century to one millennium. The timing of retreat of the outlet glaciers depends sensitively on small-scale topography of bedrock sills, small-scale troughs and rises upstream of the modern grounding zones, and dwindling buttressing by the remaining floating ice downstream (Durand et al., 2011; Favier et al., 2012; Parizek et al., 2013). However, Thwaites Glacier connects more directly to the deep central basins where retreat could become especially rapid, and a collapse of Thwaites is more likely to entrain adjacent basins into collapse.

Consistent with these studies, numerous large-scale modeling studies conducted in the last two years (spanning all of WAIS or Antarctica) have simulated future collapse of WAIS (Cornford et al., 2015; Feldmann and Levermann, 2015; Golledge et al., 2015; Ritz et al., 2015; Winkelmann et al., 2015) under various climate-warming scenarios. These studies find that future grounding-zone retreat into the central WAIS region is expected on time scales of a few centuries to a millennium, contributing several meters to global mean sea level rise, beginning with retreat of the Pine Island Bay glaciers.

Even faster and more drastic future retreat of WAIS was recently simulated by DeConto and Pollard (2016), who proposed additional physical mechanisms to explain geologic evidence of high sea-level stands ~10–20 m above present during the warm mid-Pliocene period ~3 Myr ago, and 6–9 m higher during the more recent Last Interglacial (~125 ka; Pollard et al., 2015; Dutton et al., 2015). In their model, assuming business-as-usual greenhouse gas emissions, the central WAIS can collapse on time scales as short as ~100–200 years, with initial retreat occurring in the PIG and Thwaites Glacier basins (Fig. 5). Moreover, their study specified a maximum retreat limit, and faster rates may be possible. The proposed mechanisms driving the accelerated retreat include the hydrofracturing of ice shelves by increased surface melt, and the structural failure of large ice cliffs at the grounding zone described above. The role of surface melt focuses attention on the timing of future atmospheric warming around Antarctica, in contrast to increasing sub-ice ocean melt which plays the central role in most recent modeling studies.

3. Research objectives for the coming decade

This *How Much*, *How Fast*? science outline, focused on Thwaites Glacier catchment and the adjacent Amundsen Sea, is aimed at improving our understanding of marine ice sheet collapse and increasing our skill at forecasting critical changes in the system and the resulting rates of sea-level rise.

A transformative advance in our understanding of the processes driving WAIS change will require a coordinated research effort with measurements taking place over an extended period. Short-term variability of the Thwaites geophysical system must be measured and parsed from longer-term variations driven by external forcings. How the drivers of this variability interact, and how they are modulated by local ocean and sea ice behavior, need to be better quantified. The *How Much*, *How Fast*? observational program aims to provide more-comprehensive atmospheric and ice-sheet data necessary to evaluate these large-scale processes for the Thwaites Glacier region. This in turn will support advanced models, ranging from global to local scales, to better constrain system response in the coming decades to centuries.

In the discussion below, we provide an approximate scale for future research in the *How Much*, *How Fast*? focus region (e.g., number of observation sites, resolution of measurements) as a reference for the scope of the effort needed to produce an adequate improvement in our understanding of the system. (See Table 1).

3.1. Atmosphere and climate

Installation and maintenance of an improved atmospheric observation network in WAIS will provide measurements to improve atmospheric model simulations and capture climate change and variability. A network of four stations installed over the PIG region in the last decade has pointed out biases in atmospheric reanalysis products (Jones and Lister, 2015). Part of the improved research infrastructure should include a suite of ~6 new automatic weather stations (AWS) along the two main flowlines of Thwaites Glacier and another 4 AWSs along the coast between the eastern Ross Ice Shelf and Thwaites Glacier (see nominal Thwaites-region AWS locations in Figs. 6 and 7). New AWSs should include basic meteorological measurements (temperature, pressure, winds, humidity) and, for those in the Thwaites region, instruments to measure surface and near surface processes including energy balance, snow accumulation, snowpack temperature, and firn compaction rates. The meteorological observations should be telemetered in near-real-time. The proposed Thwaites network of approximately 6 AWS with ~100 km spacing should be linked with accumulation radar surveys and shallow boreholes, especially along flow lines.

The installation of a fiducial atmospheric observation station (e.g., instrumented tower) at Byrd Station would continue the existing climate change record started there in 1957 (Bromwich et al., 2013). The goal is to provide continuous high-quality atmospheric measurements, similar to those currently collected at Summit, Greenland by NOAA (basic surface atmospheric variables, radiation fluxes, surface energy balance, firn temperature measurements, cloud sensors, and precipitation). This would provide a continuation of an observation series at Byrd Station that spanned several decades in the 1950s–1990s. While early data came from human-attended instrument observation, the proposed fiducial site can be automated with extensive redundancy and Iridium telemetry to operate unattended year-round.

A comprehensive shallow ice coring campaign is desirable to provide a high-resolution (seasonal to annual) reconstruction of past atmospheric and oceanic driver variability and trends (as described in Section 2.1.2 above), as well as to investigate the role of atmospheric and oceanic processes (e.g. ASL position, intensity, and potential links to the central Pacific variability) in Thwaites Glacier surface mass balance and surface melt variability over recent decades to centuries. This ice core record should complement continued remote sensing observations of melt and surface mass balance variability (e.g., Trusel et al., 2013; Medley et al., 2013), while providing direct measurements of annually-resolved accumulation rate and surface melt intensity.

Glaciochemical proxies (such as sea salts and methanesulfonic acid, or MSA) can be developed to provide additional information on past sea ice and polynya variability and their atmospheric drivers (e.g. Thomas and Abram, 2016; Criscitiello et al., 2013, 2014). Stable water isotope records and borehole thermometry can be used to reconstruct a longer-term temperature record from coastal West Antarctica and further document recent decadal-scale warming over WAIS (Orsi et al., 2012; Steig and Orsi, 2013; Steig et al., 2013). As accumulation rates are high along the coast, it would be possible to derive sub-annual information at many sites. There are multiple locations for shallow (10–100 m), small-diameter ice cores depending on the target variable of interest (e.g., surface melt, accumulation rate, or ice chemistry) including on

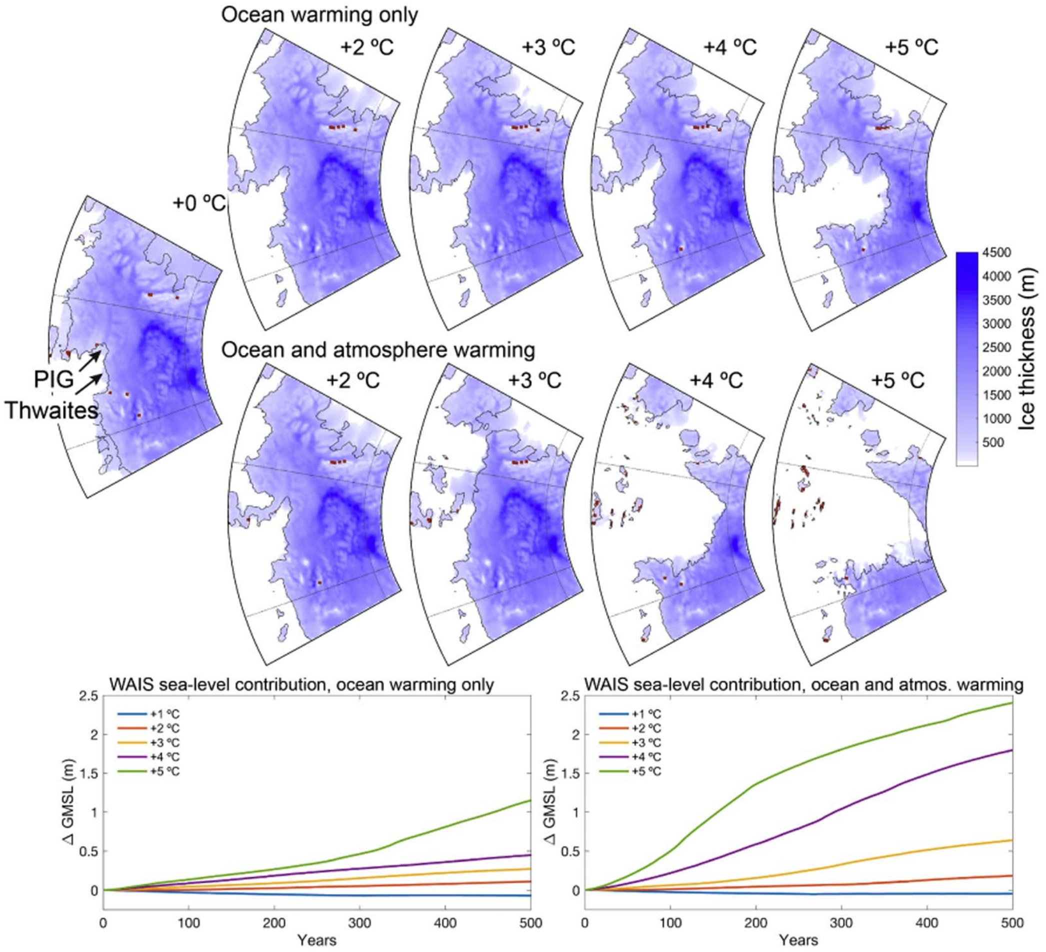

Fig. 5. WAIS model simulations run for 500 years, applying uniform ocean warming (top row) or uniform oceanic and atmospheric warming (middle row), to a baseline mid-20th century climatology used in previous simulations (DeConto and Pollard, 2016). These simple sensitivity tests demonstrate the rapid retreat of Thwaites Glacier once a climatic threshold is exceeded. The warming required to trigger retreat is reduced when the influence of processes driven by both sub-ice oceanic warming and the warming of atmospheric temperatures (leading to surface meltwater production) are considered. Contributions of WAIS to global mean sea-level for the simulations are shown at bottom.

the Thwaites Glacier itself (along flowlines or across the grounding zone) as well as on small ice domes, separated over a significant longitudinal range across WAIS-Amundsen Sea coastline (Fig. 6).

3.2. Ocean

Accurate ocean bathymetric data are necessary on the continental shelf to determine the steering of deep water from the continental shelf break to the ice front. For significant improvement, a 500-m grid of bathymetric measurements is needed, supplemented in key areas with high-resolution side-scanning sonar to identify finer details and provide clues to present-day interactions between the ice and the underlying bed. Local circulation patterns driven by the ocean bathymetric geometry, which can influence water mixing and mass transport, will require a ~ 250 m grid at key sites. Bathymetry should be acquired for the entire study area, specifically the continental shelf extending from Thurston Island westward across the full length of the Getz Ice Shelf, with emphasis on the Thwaites continental shelf.

Another critical need is an extended time series of ocean-water properties and circulation changes. Obtaining these data will require the development and deployment of instrumentation designed specifically for studying the interface between an ice sheet and the ocean, the grounding zone region, and the sub-ice-shelf cavity. We need to understand processes in this near-field region, close to the grounding zone, which could be achieved through data acquired by new ocean and on-ice instrumentation as well as airborne and ground surveys. A major goal in the near-field is to distinguish between the sources of freshwater input to the ocean (notably subglacial water flowing into the ocean from beneath the grounded ice or melting of the ice-shelf base), as each source will have a different impact on ice-ocean dynamics.

Ocean observations are best obtained through an integrated program of continental shelf and sub-ice shelf moorings, and open-ocean and sub-ice-shelf vehicles, such as gliders. Targeting processes near the grounding line would require installing and maintaining a minimum of several long-term ocean moorings near the Thwaites Glacier. Additional far-field moorings are needed in the major troughs near the continental shelf break (at least two moorings for each trough) to understand ocean variability in the Amundsen Sea. Airborne deployment of ocean sensors to measure temperature and salinity (e.g., Airborne Expendable Conductivity Temperature Depth Probe, or AXCTD, and mini-Argo floats) will expand the geographic coverage of observations during field campaigns. Boreholes through the Thwaites ice shelf will facilitate the installation of through-ice moorings with laser-stimulated fiber optic Distributed Temperature Sensors (DTS) and traditional mooring instruments, to enable the measurement of ice and water temperature profiles, as well as ocean salinity and flow at specific depths.

Additional information could be acquired by autonomous vehicle transects or casting profiles in the ocean linking the mooring sites from the grounding zone out to 200 km. Beneath the ice shelf regions, sub-ice-shelf vehicles could be used to assist in mapping bathymetry and studying the processes beneath the ice shelf. Repeated autonomous vehicle transects running from the grounding zone to the continental shelf edge will provide critical integrating data regarding water circulation and water modifications occurring in the sub-ice shelf

Table 1
Science infrastructure plan for *How Much, How Fast*?

Measurement system	Location	Units	Contribution
Ocean Moorings, distal zone (not shown in Fig. 2)	Bathymetric trough areas, Amundsen Sea continental shelf break.	~6	Drivers: fundamental measurements of ocean water types and circulation, diurnal to multi-year scales
Ocean Moorings, proximal to ice	Ice front and shelf regions	~5	Drivers: fundamental measurements of the link between large-scale ocean variability and near-ice delivery of warm water; Processes: ocean circulation and water mixing, identifying rates and sources of freshwater input.
Through-the-ice moorings	Ice shelf and multi-year fast ice areas	~4	Processes: ocean circulation and water mixing, rates and sources of freshwater input. Ice shelf thickness change, basal melting and mixing.
ApRES + GPS stations	Thwaites Gl. trunk, grounding line, ice shelf areas	~15	Processes: ice thickness changes, firn densification, vertical strain in the ice column, ice shelf basal melt rates, grounding line retreat, ice shelf tidal flexure; Boundary Conditions: till character, and grounding-zone processes.
Automated Weather Systems + GPS	Coastal areas near Thwaites Gl. and adjacent regions	~6	Drivers: atmospheric measurements to establish baseline conditions and variability in surface mass balance; establishing connections and teleconnections to broader climate patterns
Fiducial weather station, tower	Byrd Station or WAIS Divide site	1	Drivers: atmospheric measurements to establish baseline conditions and variability in surface mass balance; establishing connections and teleconnections to broader climate patterns
Shallow coastal ice cores	Ice domes, ice shelves and glacier margins adjacent to Amundsen Sea	~10	Drivers: near-term record (past 150 years) documenting decadal-scale variability of ASL position and intensity, ENSO impacts, regional accumulation rate, temperature and surface melt.
Traverse radar/gravity/shallow core	Upper Thwaites catchment	~400 km	Boundary Conditions: ice thickness, bed topography, till character and freeze-thaw state, accumulation and recent climate history, bedrock density
Combined seismic/radar/ gravity surveys	Lower Thwaites trunk, shear margins, grounding zone	~80 × 80 km variable grid density	Boundary Conditions: ice thickness, bed topography, till character and freeze-thaw state, ice thinning rate, subglacial hydrology, ice layering and fabric.
Automated Underwater Vehicle surveys	Grounding line, sub-ice shelf, near-coastal ocean	500 m–grid, 250 m in focus areas	Processes: ocean circulation and water mixing, identifying rates and sources of freshwater input, bathymetry.
Airborne geophysics surveys	Thwaites Gl., grounding zone, ice shelf areas	Variable flight-track density	Boundary conditions: ice thickness, bed topography, till character and freeze-thaw state, ice layering, ice fabric, subglacial hydrology, sub-ice geology
Air-deployed instruments	Thwaites Gl., proximal ice fronts	Several 10s	Processes: *ocean* circulation and water mixing, identifying rates and sources of freshwater input, bathymetry; *glacier* speed in dynamic crevassed areas, grounding zone.

cavity. Measuring salinity, chemistry, and circulation near the grounding zone with these vehicles, supplemented by the on-ice moorings, will lead to a better assessment of the role of subglacial hydrology in sub-ice-shelf ocean circulation.

Integration of sea-ice extent, concentration, and thickness data should continue. "Winter water" formation, forced by sea-ice formation, can cool the top several hundred meters of the water column, some of which enters the ice-shelf cavities under certain conditions. Such integration can be done at adequate resolution (~1 km) using existing or planned airborne and satellite missions, but should be augmented by data from moorings and casts.

3.3. Ice sheet and ice shelves

Surface elevation and surface ice velocity are two critical boundary conditions that require near-continuous monitoring because changes in surface slope and ice flow are continuous; measurement of both parameters should remain a high priority for NASA and other space agencies. Current and planned satellite altimeter missions (specifically, the ongoing CryoSat-2 mission, and the ICESat-2 satellite planned for

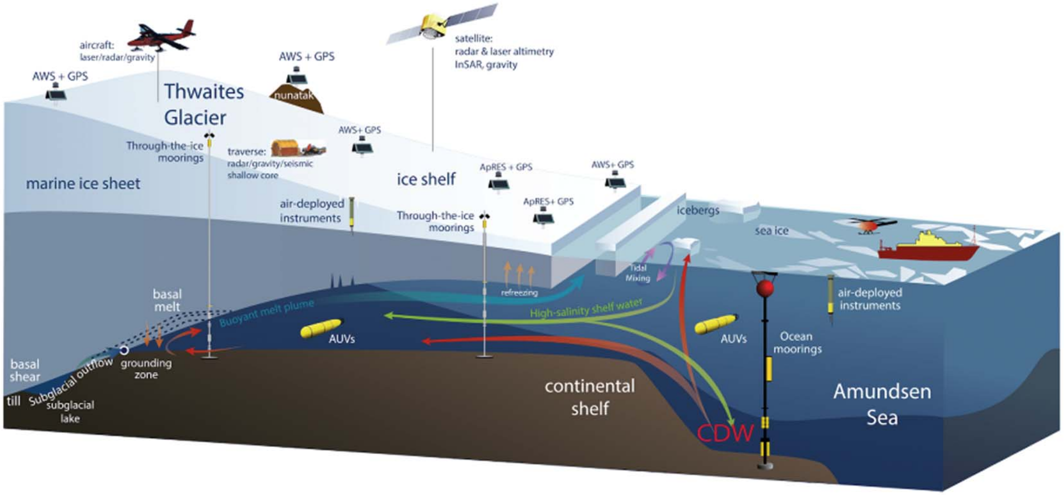

Fig. 6. Schematic of instruments and research activities for the How Much, How Fast? future research objectives.

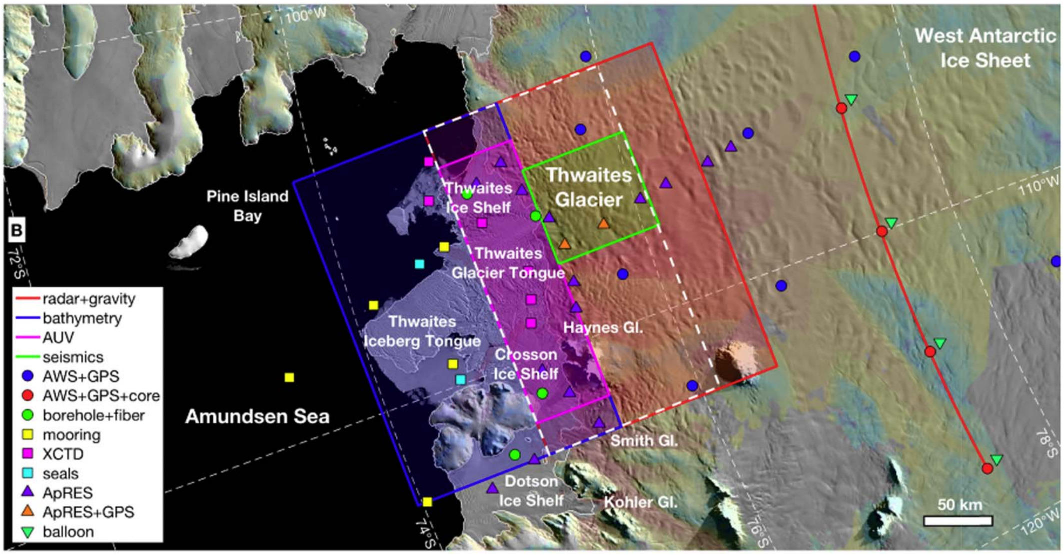

Fig. 7. Notional scope of field science activities in WAIS under How Much, How Fast?. Red box indicates Amundsen Sea Embayment (ASE) focus area. Base map shows the ASE region, with surface morphology from MOA (Haran et al., 2014) and surface ice-flow speed from a synthetic aperture radar compilation (Rignot et al., 2011b). Boxes and symbols show survey focus areas and potential instrument locations and traverse measurement sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

launch in 2018) will monitor surface elevation. Repeat ice velocity measurements at 250 m resolution should be produced annually on an ice-sheet-wide scale, and seasonally or shorter for the Thwaites Glacier front and adjacent ice shelf and grounding zone areas. Several existing and upcoming satellites are capable of supporting this program (e.g., TerraSAR-X; Sentinel-1 and -2; Landsat 8, meter-scale imagers, and NISAR).

Airborne missions such as to NASA's Operation IceBridge or NSF's IcePod can support once-annual mappings of ice surface elevation at decimeter resolution. Such mapping campaigns should acquire data at a spatial resolution at least 5 km. Sampling should be at higher resolution throughout the Thwaites Glacier basin in areas that are especially sensitive to change, e.g., ~250 m in the first 20 km inland of the current grounding lines and ~500 m in the next 50 km inland; this should be supplemented with 1-km grid surveys along the shear margins (Pritchard, 2014) and in transition zones from high to low basal shear stress in the main trunk. A continued airborne measurement strategy, similar to that of NASA's Operation IceBridge mission, which includes ice-penetrating radar, laser altimetry, and gravimetry, through the period of field activity for *How Much, How Fast?* would be greatly beneficial to its science goals.

Measurements of the detailed ice bed shape and the ice-bed interface properties are a key part of forecasting later evolution and pace of sea level rise. Airborne radar can contribute greatly to the bedrock shape and the thermal state of the interface, but till properties require seismic profiling. An extensive program (e.g., ~800 km) of ground-based radar surveys with seismic survey lines at key locations (total 100 km) to investigate the ice thickness and structure of Thwaites Glacier in the region 200 to 300 km upstream from the grounding line will provide essential information for models examining a critical ramp-up period in the evolution of Thwaites Glacier during collapse.

Mapping of ice shelf thinning rates across the entire floating portion of Thwaites Glacier and the adjacent Haynes, Smith, Kohler, and eastern Getz ice shelves should be conducted at 250-m scale on an annual basis using high-resolution optical stereo-imagery, and seasonally at coarser scale by integrating satellite radar and laser altimetry (CryoSat-2, and ICESat-2 which will launch in 2018). This will update and add detail to the time series of Pritchard et al. (2012) and Paolo et al. (2015). This effort should include validation of derived basal melt rates from a network of autonomous phase-sensitive radar (ApRES) installations to determine both the melt rate and the vertical strain at high-resolution.

Measurements of ice-shelf thickness and ocean water column thickness are needed at a resolution of ~250 m near the grounding zone to support process-related modeling of ice-shelf melt, including generation of sub-ice-shelf channels that may weaken shelves. Integrated mapping strategies for ice shelf thickness and sub-ice-shelf cavities should include airborne gravity, seismic bathymetry soundings, and radar profile soundings. Repeat mapping of grounding zones is needed across the Amundsen Sea Embayment, as they are retreating rapidly (Rignot et al., 2011a; Rignot et al., 2014; Christie et al., 2016). Currently, interferometric synthetic aperture radar has mapped the grounding zones to a resolution of ~250 m on seasonal timescales (Joughin et al., 2016).

Key details of the variations and feedbacks in the ice-ocean interface are possible only through in situ ocean observations at the ice base or in the sub-ice-shelf cavity. Technological improvements are necessary to achieve this, including the development of autonomous surface stations (through-the-ice moorings), and advanced underwater vehicles (AUVs). Surface stations should be deployed as multiple small arrays (e.g., two to three pairs of stations) to investigate the grounding zone environment at selected sites. Key data on the interaction between sub-ice-shelf oceanic plumes and eddies and the ice shelf ice are needed, requiring water flow rate measurements at several levels near the ice-ocean and ocean-bed interface. The design of these fixed stations must be sustainable with low logistical demand to allow collection of records across climatologically significant times (years to decades). Detailed (< 500 m grid profiles) measurements by AUVs in key areas of the sub-shelf cavity once or twice per field season would lead to rapid advances in understanding of multiple ice-ocean processes. AUVs should collect observations of (at least) water temperature, salinity, velocity, dissolved oxygen content, and suspended sediment content, to constrain models of sub-ice-shelf circulation.

Imagery, seismicity measurements, and in situ strain measurements (e.g., borehole tiltmeters and accelerometers) should be used to increase knowledge of ice fracture mechanics (location, frequency, mechanism) to inform models of ice cliff failure. Motion of icebergs and ice mélange, and measurements of ice mélange strength, should also be tracked using satellite data. In addition to buttressing the ice margin, mélange impedes atmosphere-ocean connectivity and transfer of wind stress to the ocean and thus has a significant effect on local ocean circulation, as well as potentially damping waves that would tend to stress the ice front (Joughin et al., 2008). Ice shelves may re-grow episodically during retreat, justifying additional study of calving from ice shelves. This work to understand the ice cliff failure and calving from adjacent ice shelves may be conducted at the Thwaites grounding zone and at other large ice cliffs (e.g., Crane Glacier in the Antarctic Peninsula; Scambos et al., 2004; Scambos et al., 2011), along thicker ice shelves such as Getz Ice Shelf, and in Greenland.

To validate and constrain hydrological process models, geophysical observations should be collected in targeted locations where large-scale transitions are observed (e.g., Schroeder et al., 2013) and non-steady-state behavior in the hydrological regime is possible (e.g., Smith et al., 2009, 2017). This effort should include repeat radar and seismic surveys, installation of autonomous GPS and phase-sensitive radar stations, and development of novel techniques for mapping subglacial conductivity structure (Mikucki et al., 2015, Foley et al., 2015, Key and Siegfried, 2017 in review).

All of the components of these systems are research targets for *How Much*, *How Fast*?. Selected other regions may also exhibit some of the key processes involved or contribute to an understanding of the history of the focus area. The interaction of Thwaites Glacier and the Amundsen Sea with the wider atmosphere and ocean are the basis for a broader study of global climate change, focused on these teleconnections, as part of *How Much*, *How Fast*?

3.4. *Solid earth*

The main goals of an observation program to understand the interplay of the underlying bed at Thwaites Glacier and vicinity should be a distributed program to gather geothermal heat flux measurements, data on the till strength and thickness in several areas of the glacier, and the rate of crustal uplift (and parsing that rate between its elastic and longer-term response rates).

As noted in Section 3.2, a traverse across the mid-to-lower glacier trunk aimed at detailed radar mapping of the bed should include gravity and seismic data. This will support inversions for bed characteristics and the underlying geology. Data on internal layer deformation from the radar profiles, combined with ice flow speed, can be used to diagnose basal friction (Christianson et al., 2014). Precise repetition of selected surveys in areas where erosion rates are likely to be high would allow quantification of subglacial sediment erosion and transport on decadal timescales (Smith et al., 2007), helping to characterize the till beneath the Thwaites Glacier trunk.

Observations of the bed conditions are needed over a significant part of the lower part of Thwaites Glacier, and especially near the current grounding zone (Horgan et al., 2013). Knowledge of the till rheology as well as the hardness of the bed in till-free regions is a key part of prognostic modeling. Detailed coincident measurements of tidally-modulated driving stress and flow speed, coupled with high-temporal resolution GPS measurements of ice flow near the grounding line, can yield estimates of basal shear stress and basal rheology. These values can then be used to inform large-scale models.

A GPS array of four to eight stable rock sites (nunataks in the vicinity of Thwaites) is needed to characterize the rate of uplift as mass changes occur in the region, and separate elastic response of the crust from longer-term mantle flow-driven rebound. This information will allow a refinement of modeling that examines the extent to which rebound (and sea level effects) could mitigate the pace of ice loss during a collapse of the ice sheet.

Satellite-derived velocity maps should be supplemented by high-temporal resolution flow-speed and surface slope observations from five or more continuous GPS stations on the lower portion of Thwaites Glacier and nearby areas to resolve high-frequency (seasonal to sub-daily) velocity fluctuations, which are diagnostic of ice dynamic response to variable basal rheology. While the most direct method of assessing the basal interface remains borehole sampling (e.g., Engelhardt et al., 1990), model-based inversions of time series of surface measurements can lead to a better assessment of the basal interface across the ice sheet.

3.5. *Life sciences*

The ocean's biological and solubility carbon pumps regulate deep-sea sequestration of carbon dioxide (CO_2) over geologic time scales, and their efficiency, especially at high latitudes, exerts control on atmospheric CO_2 levels over glacial-interglacial cycles (Sarmiento and Toggweiler, 1984; Sigman et al., 2010; Sigman and Hain, 2012). These pumps are also responsible for the ocean taking up about a third of the anthropogenic CO_2 supply (Le Quéré et al., 2015). Thus, large climate-driven changes to these pumps may trigger acceleration or deceleration of global forcing toward a warmer climate. Although regional biological impacts on the causation and progress of marine ice sheet collapse may be small, the effects of ice sheet melting and retreat on the ecosystem of the Amundsen Sea will be significant if a larger ice-front polynya with intensive algal bloom activity is formed. Since these processes are tightly coupled to ice-ocean interface processes, understanding how climate drivers of polynya formation and changing ice discharge impact ecological systems should be included as an ancillary, low-cost/high-impact component of the *How Much*, *How Fast*? science program.

Regional variation in the average productivity of coastal Antarctic polynyas can be explained by differences in nearby basal ice-shelf melt (Arrigo et al., 2015), with the Amundsen Sea Polynya (ASP) receiving the greatest melt from WAIS as well as having the greatest productivity. The high biological productivity and CO_2 uptake of the ASP (Mu et al., 2014) is attributed to increased availability of the limiting nutrient iron (Fe; Alderkamp et al., 2015), which has been linked to the melting WAIS (Yager et al., 2012, 2016). Modified Circumpolar Deep Water (mCDW) flowing from beneath the Dotson Ice Shelf transports high concentrations of dissolved and particulate Fe along with a high meltwater fraction (Sherrell et al., 2015; Randall-Goodwin et al., 2015). In the ASP, the extent and timing of sea ice cover, and therefore light availability (another major factor controlling biological productivity of the polynya), has also been linked to changes to the Thwaites Iceberg tongue (Stammerjohn et al., 2015).

Discharge from sub-ice-shelf channels contributes to formation of polynyas in some places (Mankoff et al., 2012; Alley et al., 2016), which influence sea-ice and water-mass formation. The polynyas along the Amundsen Sea coast are among the most biologically productive areas of the entire ocean, at least in part because of the melting ice sheet. Their presence is a result of oceanic processes but also of local and synoptic wind patterns, both of which are likely to change in the coming decades. In the near-term, this ecosystem's productivity may increase if micronutrient fluxes increase via glacial meltwater, but the mechanisms are poorly quantified and must be investigated before they can be incorporated into predictive models. Longer-term physical-biological coupling processes are even less clear, especially in a scenario of major ice-sheet retreat, but could be important at a global scale. By impacting the food web and increasing the uptake of atmospheric carbon dioxide, some offsetting carbon sequestration may occur. These ecosystem processes, once understood, may also serve as proxy measures of meltwater flux. The ASP also shows the greatest interannual variability in productivity, which may be useful for interpreting interannual variability of other WAIS records (Arrigo and van Dijken, 2003).

3.6. *Models*

WAIS is an active part of the globally-coupled atmosphere-ocean-sea ice-ice sheet system whose past, present and future behavior is usually simulated with global earth-system models. Representation of Antarctic and Southern Ocean physics in these models, and the input fields such as atmospheric re-analyses, need to be refined.

The body of ice-sheet modeling described above identifies the danger of large-scale retreat and collapse of WAIS, starting with grounding-zone retreat into the PIG and/or Thwaites basins within the coming century. To improve projections, particularly on decadal time scales, some clear needs have emerged: 1) conducting model intercomparisons to determine the rigor of ice model dynamics (full Stokes, higher order, or hybrid treatments; cf. Pattyn et al., 2013); 2) further sensitivity studies to determine the spatial resolution needed, both for ice dynamics and for bedrock topography (Durand et al., 2011; Gladstone et al., 2012b); and 3) better characterization and inclusion of basal properties and hydrology in the central WAIS basins (Parizek et al., 2013; Schroeder et al., 2013). Of particular importance is that most models lack physical representations of fracture processes involved in iceberg calving (Bassis and Walker, 2012), and also relevant to ice cliff failure that could control future ice-sheet evolution. Benchmarking or tuning to the recent instrumental record is important; however, because an ice-sheet collapse has not occurred during the observational record, a successful test does not demonstrate that the model will be successful in simulating anticipated ice sheet changes. The use of paleoclimate data from warmer periods in the past can partially solve this problem, although human forcing will likely exceed the rate of any past natural analogs.

Modeling efforts must advance ice, ocean, and atmosphere representations at all relevant spatial and temporal scales, and focus on the decadal-to-century evolution of the system (e.g., Alley et al., 2015; DeConto and Pollard, 2016). Currently, the full spectrum of teleconnection behavior in the atmosphere and ocean systems is not well-captured. Many key processes in the atmosphere, ocean, sea ice, and ice sheet occur at spatial scales too small to be resolved by global earth system models (grid cells of 20 km), e.g. oceanic eddies on the continental shelf that deliver heat to the grounding zone have a length scale of only a few kilometers (Thompson et al., 2014). The growing recognition that the ice sheet margins are responding to changes in the ocean and the atmosphere emphasizes the importance of simulating the evolution of regional atmospheric climate at spatial scales capable of resolving the complex intersection of ocean, sea-ice, ice shelves, and steep ice-sheet flanks that characterize the Amundsen Sea region and capture relevant processes such as iceberg calving, surface melting, hydrofracturing, etc. One approach is to use of adaptive grid models that place high spatial resolution where it is needed most (e.g., at the grounding zone). The Marine Ice Sheet Ocean Modeling Intercomparison Project (MISOMIP), an effort put forward by the World Climate Research Program, currently has such a focus on coupled, regional ice-ocean modeling of the Thwaites Glacier region and would greatly benefit from the observational data to be collect in this suggested research activity.

Process modeling efforts to address the *How Much*, *How Fast*? questions must build on both observational data from the new field-based studies proposed and information about past changes in the ice sheet. The focus on specific processes will directly support the effort to improve ice sheet models with the overarching goal of improving predictive capabilities. Each of the processes discussed above requires deeper understanding both in terms of the long-term nonlinear effects as well as the integration with other parts of the ice sheet-ocean-climate system.

A hierarchy of models spanning a range of complexity and capabilities will be required to address different components of WAIS system over a range of spatial and temporal scales. Understanding future ice loss will require models targeting specific processes and behaviors, models of coupled atmosphere-ocean-ice systems (described above), multicomponent models of intermediate complexity capable of running long simulations testable against geological records, and coordinated model intercomparison activities, examining simulations of Thwaites Glacier's response to specified forcings.

Lastly, “Modeling” and “observations” should not be viewed as separate entities, but rather as two aspects of an integrated whole. Modeling should guide design and implementation of observational campaigns, potentially with real-time adjustments in data collection as the results are interpreted, and coupled model improvements should result from comparisons between predictions and collected data. New and improved paleoclimatic data are not a focus of this paper, but their high value is recognized and endorsed here (see Section 4).

4. Summary – how much, how fast?

We have reviewed the state of current research and outlined several research objectives for the next decade of research in WAIS, focused on the Thwaites Glacier region and the adjacent Amundsen Sea, to address ideas presented in a 2015 National Academies' report, “A Strategic Vision for NSF Investment in Antarctic and Southern Ocean Research”. *How Much*, *How Fast*? is a direct response to address their identified key theme of constraining how much and how fast WAIS will change in the coming decades. *How Much*, *How Fast*? is based on four fundamental questions: (1) Drivers: Why is the West Antarctic Ice Sheet changing now?; (2) Boundary Conditions: What is the present state of the West Antarctic Ice Sheet?; (3) Processes: What mechanisms are involved in marine ice-sheet collapse?; and (4) Models: How can we improve our projections of sea-level rise from West Antarctica? The primary geographic focus of the *How Much*, *How Fast*? effort will be the Thwaites Glacier and the adjacent areas of the Amundsen Sea. This targeted effort will provide the template for studying the other portions of Antarctica that are likely to become increasingly vulnerable in the future, such as the Aurora and Wilkes basins in East Antarctica.

The initiative proposed here builds directly upon the recent history of US research investment in WAIS research. It also incorporates the international partnerships needed to undertake a large and coordinated study of global importance. The US, under both the NSF Antarctic Sciences field research programs and NASA via satellite and airborne missions, has made important contribution to understanding the central WAIS region. Indeed, the region was first mapped by US explorers and scientists such as Richard Byrd, Lincoln Ellsworth, and Charles Bentley.

More recently, several extensive international programs of oceanographic research, airborne reconnaissance, and ground-based geophysical surveys operating from WAIS Divide ice core site are largely responsible for the data currently available for model studies to identify the potential rapid evolution of Thwaites Glacier and the vicinity. WAIS Divide ice core itself, completed in 2012, provides the most precise record of climate and atmospheric conditions for the region for the past 68,000 years (WAIS Divide Project Members, 2013). Records from shallow ice cores under US and related UK programs have played an important role in complementing the very short instrumental climate record, helping to quantify the drivers of recent change in this region. Coastal records from ice cores could answer important remaining questions, but are lacking in most of the study region.

A further avenue for addressing the *How Much*, *How Fast*? plan, not discussed here, is the collection of new paleoclimate evidence from ice and sediment cores. The same National Academies' report that provided the basis for the *How Much*, *How Fast*? research plan acknowledged that a paleoclimate-based approach to understanding the potential of future rapid changes in sea level from WAIS collapse is also of high priority. The report noted that ice-core studies could provide decadal-scale records of change during past interglacial periods, when the central WAIS may have collapsed. The potential for a detailed record of climate for the Eemian (the most recent interglacial period prior to the present) from an ice core near the boundary of the West Antarctic and East Antarctic ice sheets (Hercules Dome) was underscored (Steig et al., 2015). Near-shore marine sediment records and cosmogenic isotope studies of bedrock obtained from shallow areas beneath the present-day ice sheet can provide important constraints on the timing and extent of WAIS retreat during this period as well. Such paleo-constraints on past ice sheet behavior are becoming increasingly important for model validation and the calibration of model physics used in simulations of future ice sheet evolution.

Answering the paired *How Much*, *How Fast*? question, and its component questions detailed here, is a major challenge. The Thwaites Glacier region is vast and difficult to access. Success will require a focused international community effort, major logistical support, and integrated international collaboration over the course of the next decade. The scientific discoveries and understandings will provide a tool for planning adaptation and risk management strategies for coastal communities, capital assets and natural environments around the world.

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