How Much, How Fast?

A Decadal Science Plan
Quantifying the Rate of Change of the West Antarctic Ice Sheet Now and in the Future

Ted Scambos and Robin Bell

Richard Alley, Sridhar Anandakrishnan, David Bromwich, Kelly Brunt, Knut Christianson, Timothy Creyts, Sarah Das, Robert DeConto, Pierre Dutrieux, Helen Amanda Fricker, David Holland, Joseph MacGregor, Brooke Medley, David Pollard, Matthew Siegfried, Andrew Smith, Eric Steig, David Vaughan, Patricia Yaeger.

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EXECUTIVE SUMMARY

The West Antarctic Ice Sheet is changing. Multiple lines of evidence point to an ongoing, rapid loss of ice there in response to changing atmospheric and oceanic conditions. Models of its dynamic behavior indicate a potential for catastrophic, accelerated ice loss as climate change continues to push the system towards thinning, faster flow, and retreat. A complete collapse would raise global sea level by 3.3 meters (more than 10 feet) in the next few decades to centuries. A 2015 National Academies of Sciences, Engineering, and Medicine report, "A Strategic Vision for NSF Investment in Antarctic and Southern Ocean Research" states that constraining how much and how fast the West Antarctic Ice Sheet will change in the coming decades is the highest priority in Antarctic research.

This document builds on the framework developed in the National Academies report and presents a science plan designed to improve future projections of ice sheet evolution in the key area of current changes. A meeting in Boulder, Colorado in January 2016 was held to outline the plan, drawing on broad scientific community input. Four fundamental questions emerged from the National Academies report and the Boulder meeting:

(1) DRIVERS: Why is the West Antarctic Ice Sheet changing now?
While the rate and extent of the current ice-sheet changes are now well documented, there is an urgent need to better ***identify and measure the drivers of the observed change.*** The drivers of the system are complex, linked to global processes, and arise from both the atmosphere and the ocean. Advancing our knowledge of these drivers will improve our ability to project future change. Both observations and models show unequivocally that the Amundsen Sea is the region undergoing the largest changes, with Thwaites Glacier at the epicenter; therefore, we have identified this system as the crucial region to target for understanding the underlying drivers of the system.

(2) BOUNDARY CONDITIONS: What does the ice sheet look like?
Much our understanding of the current state of the Antarctic ice sheet is based on satellite observations. While these measurements have broad spatial coverage and provide compelling evidence of change, they lack critical details necessary to project future change. Direct observations on and near the ice surface, in the ocean, and at the ice-sheet margins can provide the necessary spatial and temporal detail of the current state of the ice sheet to support the development of accurate models of how it will change in the future. It is essential to ***map the boundary conditions*** of the ice sheet and its surroundings, beneath and within the surrounding ocean.

(3) PROCESSES: How do marine ice sheets collapse?
The West Antarctic Ice Sheet is a marine ice sheet with a base grounded below sea level. Marine ice sheets displace shallow seas and are critically sensitive to oceanic and atmospheric conditions with subtle changes in either leading to large changes in the ice sheet configuration. Many of the **key processes inherent in the dynamics of marine ice sheets** are not well understood. These processes and subsequent feedbacks require dedicated study so that they can be accurately represented in predictive models. Key components include: large scale behaviors; interactions between ice and ocean water; failure of ice cliffs; crevassing and calving; intrusion of warm marine air over the ice sheet; impact of enhanced surface melt; sub-glacial water transport and its impact on sliding at the ice sheet bed; the mechanics of grounding line retreat; and the potential impacts of a retreating ice sheet on the ocean and carbon cycle. Although these

processes are best studied in the Thwaites/Amundsen Sea region, studies of other similar Antarctic systems can be relevant as well.

(4) MODELS: What is our best projection of sea-level rise from Antarctica?
Models are fundamental to understanding observed changes and provide the only means to quantify the range of possible future scenarios. Modeling efforts must **advance ice, ocean, and atmosphere models at all spatial scales**, and focus on the decadal-to-century evolution of the system. Modeling efforts to address the *How Much, How Fast?* questions must build on both observational data from new field-based studies and information about past changes in the ice sheet. Models of the complete ice sheet should be validated against ice sheet changes in the ancient and recent past, optimized for the Antarctic environment, and include well-characterized processes that couple the atmosphere, ocean and ice-sheet systems, and are verified against observations.

Geographic Focus: The primary geographic focus of the *How Much, How Fast?* effort will be the **Thwaites Glacier and the adjacent areas of the Amundsen Sea**. The choice of the Thwaites system is due to the observation of current large changes underway there, the potential contribution to sea-level rise and the societally relevant timescale (decades to centuries) over which major changes are possible in this system. Thwaites Glacier has a wide ice front 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. A significant retreat of the Thwaites Glacier system would trigger a wider collapse of most of the West Antarctic Ice Sheet. Though we focus on Thwaites Glacier and closely related areas for observations, we note that modeling efforts will need to encompass a much larger area to capture the relevant climate processes.

Central to the success of this program will be: long-term continuous observations of the atmosphere and ocean; high-resolution mapping of the Thwaites Glacier catchment and Amundsen Sea; dedicated studies of key processes to improve models; and improved models with better coupling of the ice, ocean, and atmosphere systems. This document describes the steps necessary to address each of the four questions listed above. The instrumentation and logistical needs are briefly outlined. The outcome will be a decadal-scale community effort that will advance our knowledge of how quickly the West Antarctic Ice Sheet will change and how much sea level will rise in response.

The Thwaites Glacier region is vast and difficult to access. International collaboration will be essential to accomplishing the goals of *How Much, How Fast?*. The scientific community in the United Kingdom, led by the British Antarctic Survey, has also identified the Thwaites Glacier region as a focal point of their future work. A collaborative workshop held in the UK in March 2016 underscored keen mutual interest in the Thwaites/Amundsen Sea region and complementary research objectives. The U.S. and UK research communities are jointly pursuing support for increased research investment in the region with a view towards the wide-ranging benefits of a logistically and scientifically coordinated multinational study of the region.

INTRODUCTION

Mass loss from Greenland and Antarctica is accelerating and the contribution due to rapid ice loss from the West Antarctic Ice Sheet (WAIS) could soon outpace all other sources, which would strain our ability to adapt or replace infrastructure in coastal areas. This issue is of particular concern for the coastal U.S. where the impact of a surge in sea level stemming from rapid Antarctic ice loss would be amplified by 30% (due to changes in the global gravitational field arising from the ice loss). Several recent papers have identified major ongoing ice loss from WAIS in response to recent climate and ocean changes. These studies point to the potential for a further dramatic increase in ice discharge in the next few decades, leading to eventual collapse of the central WAIS through marine ice sheet instability.

Geological evidence based on sea-level records and marine sediment cores suggest that the West Antarctic Ice Sheet has collapsed before, possibly as recently as 125,000 years ago during the last interglacial. Whereas the ice sheet was greatly expanded and extended to the edge of the continental shelf just 20,000 years ago, collapse of a marine ice sheet has never been witnessed directly. Consequently, there are major gaps in our scientific understanding of marine ice sheet collapse. Key data needed to evaluate the processes and project likely rates of collapse are spatially sparse and span only short time periods. There are only a few observations from the coastal ocean offshore from the WAIS ice front and limited observations of basal properties beneath the central ice sheet. Therefore, our understanding of ice-ocean interaction and its impact on interior ice dynamics within the framework of continuing changes in Antarctic climate, ecosystems, and oceanic circulation is still evolving.

A transformative advance in our understanding of the processes driving West Antarctic ice-sheet change will require a coordinated research effort with measurements taking place over an extended period in selected, critical locations. Based on observations of ongoing changes and the most recent models, the area with the highest near-term potential for rapid, catastrophic ice retreat is the central West Antarctic — Thwaites Glacier in particular — driven in large part by changes in the adjacent Amundsen Sea. Events in the focus region have vividly demonstrated that a complex interaction is underway involving climate change, oceanographic circulation, and responses of the ice sheet, driving the system towards accelerated mass loss. In turn, the regional ecosystem and greenhouse gas exchanges are profoundly impacted. 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 past 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?.*

A further avenue for addressing the *How Much, How Fast?* mission 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. Near-shore marine sediment records and cosmogenic isotope studies of bedrock obtained from 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.

A decade of work on Pine Island Glacier, the next system to the east of Thwaites Glacier, has revealed the importance of bathymetry and subglacial topography in governing rates of change over the past few decades. The Pine Island Glacier effort highlighted the challenges of taking field observations and making those observations relevant to modeling efforts. Recent modeling studies have suggested that Pine Island Glacier is likely to evolve slowly and steadily over the next century or two. There is less certainty about the near-term future evolution of the Thwaites Glacier system, which provides a more direct connection between the deep West Antarctic interior and the ocean than Pine Island Glacier. 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 potential for rapid ice loss. In the next decade, the most important Antarctic climate science and societally relevant insight will come from an improved understanding of the boundary conditions and forcing mechanisms, coupled with details of ice front–ocean processes, and determination of the scale and timing of past ice sheet collapses.

The initiative proposed here builds directly upon the recent history of U.S. leadership and investment in West Antarctic research. It also incorporates the international partnerships needed to undertake a large and coordinated study of global importance. It addresses the top recommendation of the recent National Academies report “A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research” to invest in a better scientific understanding of this region. The United States, under both the NSF Antarctic Sciences field research programs and NASA via satellite and airborne missions, has been a global leader in understanding the central WAIS region. Indeed, the region was first mapped by U.S. explorers and scientists such as Richard Byrd, Lincoln Ellsworth, and Charles Bentley. More recently, several extensive programs of oceanographic research, airborne reconnaissance, and ground-based geophysical surveys operating from the 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. The 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. Records from shallow ice cores under U.S. research efforts, as well as related British Antarctic Survey programs, have played an important role in complementing the very short instrumental climate record, helping to understand the drivers of recent change in this region. Coastal records of from ice cores could reveal even more, but are lacking in most of the study region.

The National Academies report was guided by strong, 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 clearly emerged as the single target with the greatest level of community support. The identified research path and general location share wide international interest as well.

In this *How Much, How Fast?* science plan, we present a four-part strategy that systematically addresses why WAIS is changing, what the ice sheet looks like, the processes by which marine ice sheets collapse, and how WAIS might change in the near- and long-term future. The major activities will be to quantify the drivers of change, map the boundary conditions and physical state of the ice sheet, conduct key process studies that will help us understand the system, and improve our predictive models. **This plan outlines what we need to measure and the spatial scale of the needed measurements.**

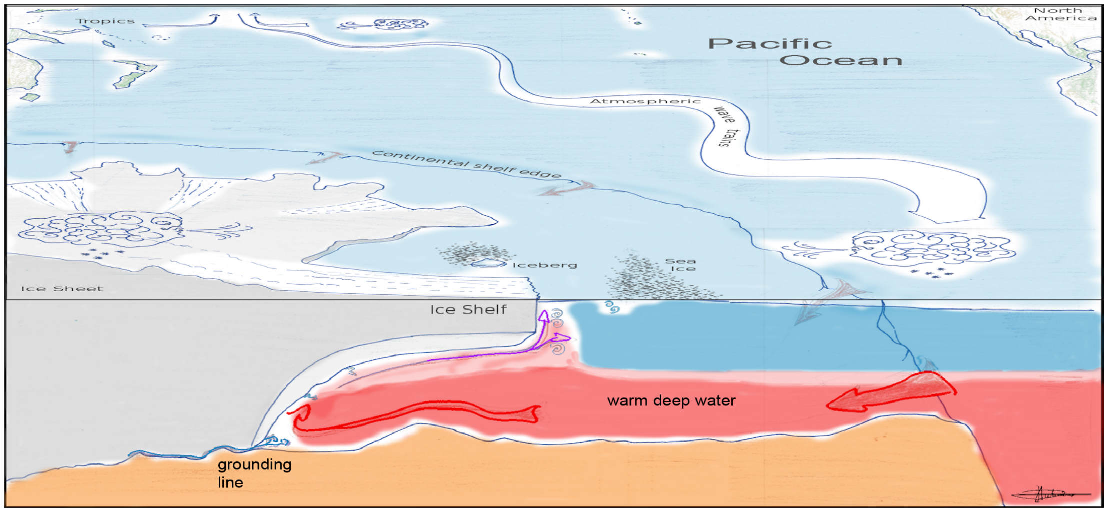

Figure 1. Cartoon of the Thwaites – Amundsen system and its large-scale teleconnections. *Artwork by P. Dutrieux and David Holland.*

THE FOUR PART STRATEGY –

Drivers, Boundary Conditions, Processes, and Models

The *How Much, How Fast?* science plan has the goal of 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. The plan has a specific geographic focus: Thwaites Glacier catchment and the adjacent Amundsen Sea.

(1) DRIVERS: Why is the West Antarctic Ice Sheet changing now?

Ice sheet changes in the focus area are driven by the influence of both a warming ocean and a warming atmosphere. Stronger westerly winds in the Amundsen Sea sector have driven a change in ocean circulation, resulting in the movement of warm, salty deep water across the continental shelf towards the grounding lines of large outlet glaciers such as Thwaites. This denser warm water moves toward the glacier fronts and ice-shelf grounding lines along troughs in the bathymetry, and causes greatly increased melting and retreat at the ice-ocean interfaces it encounters. This thins the ice shelves, reducing friction along their sides and with local pinning points on sea-floor highs, reducing the resistive stress that the ice shelves exert on the grounded ice. Thinner ice shelves lead to faster grounded ice flow. In turn, faster flow of grounded ice leads to thinning, causing previously grounded ice to float as the grounding line retreats farther inland along a retrograde slope (i.e., the ice thickens inland), and leading to more ice crossing the grounding line. This positive feedback process is the essence of the marine ice sheet instability. If, in addition, surface-meltwater-driven hydrofracture or other processes lead to rapid calving of the ice shelf and ice front, a 'cliff-failure' process can further exacerbate ice retreat. In combination, these processes may trigger a very rapid (decades to a few centuries) deglaciation of the marine basins of WAIS.

Past changes and the future trends of atmospheric and oceanic forcing are less clear. The stronger winds that have shifted warmer waters to the grounding lines have been driven by a combination of ozone hole effects on circulation in the austral spring and summer, decreased stratospheric temperatures due to increased greenhouse gases, and forcing from remote changes occurring in all the tropical oceans. These are at least partly caused by anthropogenic forcing. Tropical teleconnections are clearly impacting the West Antarctic atmosphere in the fall through spring, while stratospheric changes are important in the austral summer and fall. Understanding these changes and projecting their future course is further complicated by interactions with the nearby Amundsen Sea Low, a persistent but fluctuating minimum in atmospheric pressure that has been referred to as "the pole of variability" for the Antarctic atmosphere. Changes in the mean intensity or location of this low pressure area drive changes in deep ocean circulation near the continental shelf edge, and have dramatic effects on the surface mass balance of Thwaites Glacier on seasonal to multi-decadal timescales. How the drivers of this variability interact, and how they are modulated by ocean and sea ice behavior, nees to be better understood and 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.

Atmosphere observations: Critical to the goals of the *How Much, How Fast?* science plan is installation of an **improved atmospheric observation network** in WAIS, which will provide measurements to improve atmospheric model simulations as well as continue an established climate change record. Part of the improved research infrastructure should include a suite of (~6) new automatic weather stations (AWS) both along the coast and along the two main flowlines of Thwaites Glacier. These ~100-km-spaced weather stations should include basic meteorological measurements (temperature, pressure, winds, humidity), instruments to measure snow accumulation, snowpack temperature, and firn compaction rates. Ideally these data would be telemetered in near-real-time.

A fundamental requirement is a **fiducial atmospheric observation station** (60 m instrumented tower) at either Byrd Station or WAIS Divide to provide continuous high quality atmospheric measurements, similar to those currently observed at Summit, Greenland by NOAA (basic surface atmospheric variables, radiation fluxes, surface energy balance, firn temperature measurements, cloud sensors, precipitation, etc.). This can be fully automated with extensive redundancy and Iridium telemetry of data and station health to operate unattended year-round.

Ocean observations: 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 for the interface between an ice sheet and the ocean**. At the grounding line of Thwaites Glacier, distinct types of ice-ocean interfaces are present: a relatively flat ice shelf, near-vertical ice cliffs, and tidewater areas of large crevasses and channels. These varying configurations have distinct responses to changing ocean conditions. We need to understand processes in this near-field region, close to the grounding line, and this will 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 ocean moorings, sub-ice-shelf moorings, gliders, and open-ocean and sub-ice-shelf vehicles. Targeting processes near the grounding line will require installing and maintaining a minimum of five long-term ocean moorings along the coast from Pine Island Glacier to the Getz Ice Shelf. 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., 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.

Supplementary information could be acquired by autonomous vehicle transects or casting profiles in the ocean linking the mooring sites from the grounding line 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 line to the continental shelf edge will provide critical integrating data regarding water circulation and water modifications occurring in the sub-ice shelf cavity. Measuring salinity, chemistry, and circulation near the grounding line 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 during cruises.

Ice sheet observations: Coastal shallow ice cores from near the base of the Antarctic Peninsula have provided important information on the behavior of the Amundsen Sea Low for the past few hundred years as a context for the large 20th century increase in snow accumulation in that area. Stable water isotopes and chemistry provide additional information about temperature and sea ice behavior. A comprehensive ice coring campaign between the Ross Sea drainage and the Pine Island catchment would help provide a complete picture of the centennial Amundsen Sea Low behavior. It may be possible to derive sub-annual information at sites where annual snow accumulation is high. Borehole thermometry could be used to extend the long-term temperature record from coastal West Antarctica.

(2) **BOUNDARY CONDITIONS: What does the West Antarctic Ice Sheet look like?**

We consider the major physical boundary conditions of the Thwaites Glacier system to be: the physical properties of the surface of the ice sheet; the conditions within the ice such as temperature and fabric; the morphology of the base of the ice sheet, its physical state, and the nature of the underlying sediments and bedrock; the shape and the rate of change of the ice shelves or vertical glacier front; and the bathymetry of the Amundsen Sea and its sedimentary layering. Each has a different influence on Thwaites Glacier’s mass balance, and each responds differently to oceanic and atmospheric drivers.

Ice sheet surface and thickness observations: Surface elevation and surface ice velocity are two critical boundary conditions that require near-continuous monitoring because changes in ice flow and surface slope are continuous. Next-generation ice sheet modeling will require better resolution of these parameters, along with ice thickness, in order to map driving stresses, basal stresses, basal hydrologic conditions, and pinning points at the detail needed to project changes at the decade to century level. Changes in surface elevation and flow speed are also the primary signals of mass balance change. Current and planned satellite missions (specifically, ICESat-2) and aerogeophysical missions should support seasonal mappings of ice surface elevation and flow velocity at 250 m resolution on a basin-wide scale. Ice velocity is subject to forcing across numerous timescales, from hourly to millennial. Ice velocity measurements from satellite data (e.g., Landsat 8, meter-scale imagers, and NISAR) should remain a high priority for NASA and other space agencies.

Model runs incorporating detailed ground-based mapping in the Pine Island Glacier catchment have shown that the resolution of the ice thickness grid strongly influences model results. Improved ice thickness data throughout the Thwaites Glacier basin are essential for improving models of its future behavior. Specifically, the current 15 km grid must be improved to 5 km resolution or better. Even higher resolution data are needed in areas that are especially sensitive to change, e.g., near the current grounding line and at selected regions on the trunk and near the shear margins of the glacier. Airborne mapping campaigns will be most valuable if they prioritize a 5 km basin-wide grid, narrowing to ~250 m in the first 20 km inland of the current grounding lines, ~500 m in the next 50 km inland, supplemented with 1 km grid surveys along the shear margins.

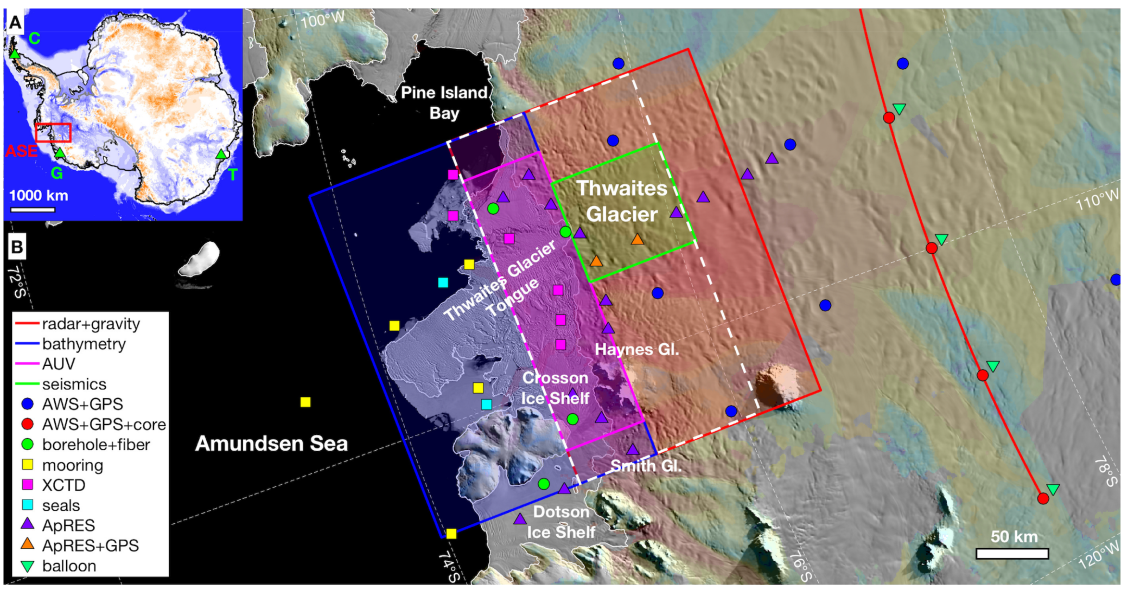

Figure 2. Scope of proposed fieldwork. A: *Map of Antarctic bed elevation (BedMap2; blue: bed below sea level; brown: above sea level). Coastline in black and grounding line in gray from MOA 2008-9. Red box indicates Amundsen Sea Embayment (ASE) focus area. Three other regions that will inform ASE process understanding are identified in green: Crane (C), Getz (G) and Totten (T).* ***B:*** *ASE region, with surface texture (grayscale, MOA 2008-9) and surface ice-flow speed (color, NASA MEaSUREs). Boxes and symbols show survey focus areas. White dashed box identifies main activity area, further described in Figure 3.*

Internal ice observations: The rheology of the ice itself, the internal ice temperature, the crystal fabric, and the past history of deformation all exert basic controls on current and future ice flow. These parameters can be inferred from radar and seismic internal reflectivity, and by drilling and sampling. Internal reflectors can indicate transitions in ice fabric, marking layers capable of greater deformation with respect to applied stresses. The radar and seismic layer geometry can be used as constraints in ice sheet models used to infer past ice flux, accumulation rate, and basal conditions. An extensive program (e.g., ~800 km) of radar surveys with seismic survey lines at key locations (total

100 km) to investigate the ice structure of Thwaites Glacier should be a part of the *How Much, How Fast?* research program.

Table 1: Primary Science Infrastructure Requirements for *How Much, How Fast?*

Measurement System	Location	Units	Contribution
Ocean Moorings, distal zone *(not shown in Figure 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, identifying rates and sources of freshwater input. Ice shelf thickness change, basal melting and mixing processes.
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 of 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
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 line	~80 x 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	500m-grid, 250m in focus areas	**Processes:** ocean circulation and water mixing, identifying rates and sources of freshwater input, bathymetry.
Airborne geophysics Surveys	Thwaites Gl., grounding line, 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

Sub-ice-sheet bed observations: The base of the glacier is perhaps the most critical boundary condition, as it is crucial for understanding both ongoing ice-flow and grounding-line changes as well as for projecting where and when future rapid changes may occur. Mapping the conditions at the bed should produce several high-priority datasets: the distribution of thawed versus frozen bed regions, geologic structure, geothermal heat flow, erosion rates, and presence of subglacial water, and locations of sediments. Few regions of the central WAIS have these datasets at the necessary resolution to understand the interaction among them.

Most of the base of Thwaites Glacier throughout the basin is thawed, but some critical ice flow transitions such as the eastern shear margin may reflect thawed/frozen bed transitions. Recent advances in analysis of phase-sensitive airborne radar data allow better mapping of the thermal state of the bed and the presence and distribution of basal water. Targeted high-resolution ground-based radar and seismic campaigns conducted over critical areas will strengthen the interpretation of basin-wide airborne data and provide ground truth validation.

The geology beneath an ice sheet often exerts a control on the flow of the overlying ice. Joint inversions of airborne gravity data with passive and active-source seismic data will enable mapping of sub-ice sedimentary basins, faults and tectonic features. Radar internal layers are primarily time-lines, and are deformed by flow over regions of varying topography or basal friction, and by basal melting. Thus, traditional gravity/seismic data inversions should also incorporate data on radar internal layer deformation, which when combined with modeled ice flow speed can be used to diagnose basal friction. Areas of high geothermal heat flow also deform the layers by melting ice beneath them, and can be identified with simple models. 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.

The interactions of basal sediments and water is critical to understanding ice discharge and behavior of the ice sheet. The rheology may vary from nearly linear to highly nonlinear. Linear rheology tends to localize response to perturbations, whereas nonlinear behavior limits local response while rapidly transmitting perturbations long distances, with important implications for stability or instability of grounding-zone locations. Knowledge of the linearity/nonlinearity as well as softness/hardness of the bed is essential for prognostic modeling. Detailed coincident measurements of tidally-modulated driving stress and flow speed, coupled with measurements of subglacial water can yield estimates of large scale basal shear stress and basal rheology. These values can then be used to inform large-scale models. 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.

Grounding line, ice shelf, and ocean cavity observations: The position of the grounding line, where grounded ice begins to float, is a critical input to ice sheet models. Bed geometry, sediment wedges, and various dynamical feedbacks can stabilize the grounding line for long periods, while other mechanisms and feedbacks can cause unstable retreat once triggered. Repeat mapping of grounding lines is needed across the Amundsen Sea Embayment. Currently, interferometric synthetic aperture radar can map grounding zones to a resolution of ~250 m on seasonal timescales. Ground-based data and airborne radar provide additional important information on grounding-line locations, character, and evolution.

The ocean-facing part of the Thwaites Glacier system includes an ice shelf, and this presents additional important boundaries. Ice-shelf cavity geometry has a strong control on ocean circulation and ice-shelf basal melt rate. Ice-shelf thickness and margin shear-strength are key components controlling grounded-ice buttressing and ice-sheet flux to the ocean. Measurements of ice-shelf thickness and water depth are needed at a resolution of ~250 m to support modeling of sub-ice-shelf oceanic plumes and eddies both of which play important roles in 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, radar sounding, and widely distributed phase-sensitive radar data for measuring thickness change.

Ocean bathymetry: Accurate ocean bathymetry is necessary to determine the steering of deep water from the continental shelf break to the ice front. For significant improvement, we will require a 500-m grid of measurements. Local circulation patterns influencing water mixing and mass transport at key sites will require a ~250 m grid. 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.

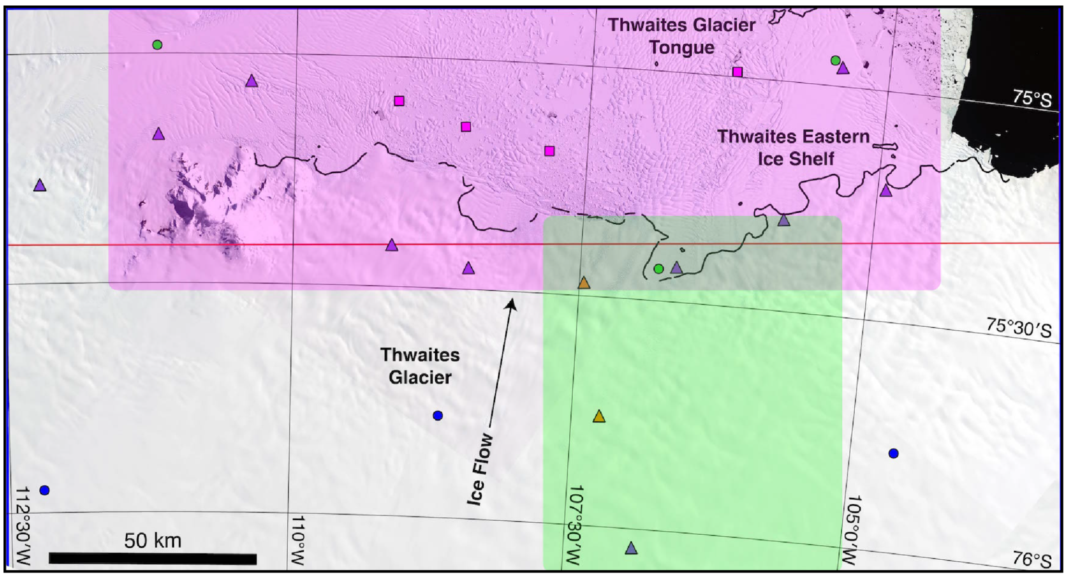

Figure 3. Proposed field activities near the Thwaites Glacier grounding zone *(white dashed box in Figure 2b). Boxes and symbols show survey focus areas as in Figure 2b. Purple box indicates sub-ice mapping region using moorings, radar, gravity, and seismic depth-sounding. Green box indicates area of dense radar-gravity-reflection/refraction seismic work from helicopter. Background imagery is a Landsat 8 natural color mosaic (Dec. 2015 - Jan. 2016). The grounding line (black) was mapped in 2011 from DInSAR data.*

(3) **PROCESSES: How do marine ice sheets collapse?**

Interactions among the glaciological, oceanographic, and atmospheric systems are the means by which the Thwaites Glacier and adjacent areas will evolve over the next century. Our understanding of ice sheet dynamics and the roles these processes can play has advanced tremendously based on the several decades of work on both the Siple Coast ice streams and Pine Island Glacier, but key processes that are inherent to marine ice sheet collapse remain poorly understood. These include: (i) grounding line processes such as tidal influences and flexure, inland penetration of ocean water, crevassing, sedimentation, and formation of pinning points during retreat; (ii) ice-ocean interface processes 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 of ocean water to and away from the interface; (iii) ice-cliff processes, including their strength, how rapidly they fracture and fail, and mélange processes that may slow the progress of cliff failure; (iv) the effects of warm marine air intruding over the ice sheet and ice shelves and of changes in snow accumulation and surface melting, and water storage in firn; (v) ice sheet sliding and subglacial sediment deformation, and viscous and stick-slip processes; (vi) the role of subglacial water both beneath the fast flowing ice and at the calving front where it can trigger basal melting and impact sub-ice-shelf ocean circulation and channel formation.

Each of these processes is critical to understanding how ice sheets collapse, but is poorly constrained. Some of these processes could be studied in part at sites other than Thwaites Glacier, where surface conditions or access may facilitate gathering a clearer or more detailed characterization, but measurements at Thwaites will be required because of site-specific aspects are important in future stability.

Grounding line processes are complex, and multiple forms of this ice-ocean interface occur in the Thwaites system. Retreating grounding lines may be accelerated by the effects of deep local basins and channels, but are restrained by the effects of local high spots that remain in contact with the ice shelf after the grounding line moves inland. Understanding the processes arising from this geophysical setting, and incorporating them to diagnostic and prognostic models, require high-resolution data from near the grounding line and in the sub-ice-shelf cavity. These will overlap in some regions with the data needed to characterize cliff failure. Basal and surface crevasses preferentially form at the grounding line, 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 inland of the grounding line, contributing to stability, but can also pump ocean water well inland, favoring instability. Sedimentation near the grounding line tends to stabilize it, as does isostatic crustal response and self-gravitational effects on local sea level.

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. Mapping of ice shelf thinning rates may be feasible at 250-m scale on an annual basis using high-resolution optical stereo-imagery, and seasonally at coarser scale by integrating satellite radar altimetry and contemporary satellite laser altimetry (ICESat-2 data are expected in 2018). These efforts should extend across the entire Thwaites Glacier front and adjacent high-melt rates on the Haynes, Smith, Kohler, and Getz ice shelves. This effort should also include calibration from a well-distributed network of autonomous phase-sensitive radar installations.

Key details of the variations and feedbacks in the ice-ocean interface are only available from 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 line environment at selected sites. 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 (at least) collect observations of water temperature, salinity, velocity, dissolved oxygen content, and suspended sediment content, to constrain models of sub-ice-shelf circulation.

Ice-cliff processes have possibly the greatest potential to cause rapid retreat. Beyond some as-yet-unclear thresholds of increased rifting or crevassing, surface melting or basal erosion by melting, ice shelves are observed to break off entirely, leaving calving ice cliffs above a deeply grounded ice front. The rate of retreat is linked to the rate of cliff-failure-driven calving, which likely increases significantly with cliff height because higher cliffs generate higher stresses. Current data and theory suggest than an ice terminus height of more than ~100 m above waterline will trigger repeated brittle failure of the ice front, leading to especially rapid retreat. The grounding line of Thwaites Glacier is currently positioned on seafloor 600 m below sea level, too shallow to trigger ice cliff failure. However, only 25 km inland the seafloor is greater than 1000 m below sea level, and therefore has the potential to form inherently unstable ~100 m ice-cliffs. 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) before onset of ice cliff failure can occur. Motion of icebergs and ice mélange should also be tracked using satellite data, because 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 stress the ice front. 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 line and at other large ice cliffs (e.g., Crane Glacier), and along ice shelves such as Getz.

Warm marine air intrusion over WAIS and adjacent ice shelves becomes more likely as global temperatures increase and perhaps as weather patterns shift. The Thwaites Glacier region can be subjected to intrusions of warm marine air, depending on the position and strength of the Amundsen Sea Low. Climatic shifts already underway influence the frequency and strength of these marine air intrusions, affecting snowfall and surface melting. The large, climatically driven spatial and temporal variability of snowfall in the Amundsen Sea embayment is not fully captured by available data, motivating our request for AWS stations and satellite and airborne mapping programs. The proposed Thwaites network of ~6 weather stations with ~100 km spacing should be linked with accumulation radar surveys and shallow boreholes, especially along flow lines. Future surface melting due to increased marine air intrusion could also destabilize remaining ice shelves and the grounded ice through hydrofracture. Process studies and high-resolution regional climate modeling can help identify the likely onset of widespread melting depending on future emissions pathways. Integrating melt projections with ice-shelf impacts of the melt is an important component of the problem.

Basal sliding and subglacial till deformation are the primary processes by which Thwaites Glacier flows rapidly and ultimately discharges into the Amundsen Sea. Understanding the subglacial rheology, lithology, and hydrology that control this flow, especially just upstream of the grounding zone, is essential to predicting its future flow patterns. Understanding the evolution of the base, particularly the distribution of water, till, and bedrock, is necessary for predicting change. The interactions of these in concert with the overlying ice determine the evolution of basal tractions that resist ice flow and rapid deglaciation. A suite of models informed by data is necessary to explore behaviors. Basal conditions are a large source of uncertainty once retreat is initiated. For example, a more-plastic bed may resist retreat for longer than a linear-viscous bed, but, once initiated, retreat is likely to proceed more quickly. Better parameterization of basal sliding under different (and evolving) conditions is also needed, as are better inversions for initial basal conditions, which often vary significantly between models and lack validation with observational data. Ideally, observations of these critical parameters are needed over a significant part of the lower part of Thwaites Glacier, and especially near the modern-day grounding line. Perhaps the best method to assess basal rheology is direct sampling of the bed. Drilling campaigns should be conducted in zones where the grounding line retreat may stabilize, especially where there are potential transitions in rheology. On a basin-wide scale, model-based inversions of time series of surface observables (GPS-derived ice velocity, near surface acceleration from tiltmeters and accelerometers, satellite mapping of ice velocity and thinning, focused on those places where rapid changes are occurring up to and including response to tides) will lead to determination and mapping of the effective till flow law beneath the entire glacier.

Subglacial hydrology has a strong influence on ice sheet processes, from controlling the onset of fast ice flow and influencing strength of subglacial materials, to modulating basal melting at the grounding line and beneath the ice shelves. Tracking the movement of water and mapping the sub-glacial drainage network are the keys to understanding subglacial hydrology dynamics. Sub-glacial water availability and rate of formation depends on geothermal heat distribution, ice thickness and basal shear stress. The resulting sub-glacial water networks may gain or lose water by basal melt, refreezing, or exchange with subglacial aquifers and groundwater systems. They may remain distributed, become channelized, or localize into lakes experiencing filling and then outburst flooding, each with very different implications for widespread lubrication of ice flow. Floods may open channels from inland to the coast, which are then kept open by tidal pumping and serve to extend the destabilizing influence of warming ocean water farther inland. Geophysical observations in targeted locations where models predict transitions and non-steady-state behavior in the hydrological regime should be collected in order to validate and constrain hydrological process models. 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.

Subglacial drainage may also nucleate channels in ice-shelf bases that can locally weaken the shelves. (Additional sub-ice-shelf channelization may be triggered by processes beyond the grounding line.) In turn, discharge from sub-ice-shelf channels contributes to formation of polynyas in some places, 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, productivity of this ecosystem may be enhanced 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. 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 might be included as an ancillary, low-cost/high-impact component of the *How Much, How Fast?* program.

(4) MODELS: improving our projections of future behavior

Models are fundamental to understanding the present state, the range of behaviors, and future scenarios of WAIS. 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 input fields such as atmospheric reanalyses, need to be refined. In addition, the full spectrum of teleconnection behavior is not captured. Many key processes in the atmosphere, ocean, sea ice, and ice sheet occur at spatial scales that are far smaller than can be resolved by global earth system models (e.g., oceanic eddies on the continental shelf that deliver heat to the grounding line have a length scale of a few kilometers) requiring the development of regional system models informed by process studies. These can then be nested within global Earth System models. A complementary approach is use of adaptive grid models that place high spatial resolution where it is needed most.

Development of multiple threads of models spanning a range of complexity and capabilities will be required to address different components of the system over a range of space and time 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, comparing simulations of Thwaites Glacier's response to specified forcings. Clearly, many modeling efforts addressing the coupled ocean-atmosphere system are ongoing, but targeted improvements needed to couple these to the Thwaites Glacier region will be needed.

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. Models must integrate paleoclimatic data to allow proper spin-up and to assess ice-sheet response to conditions that go beyond those observed during the instrumental period. Past ice sheets have experienced conditions as warm as those we may see in coming centuries, and the paleoclimatic histories of the ice-sheet responses to those conditions provide important constraints on future behavior that are not available from observations with modern measuring technologies. "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, 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.

<u>LOOKING FORWARD</u> – *How Much, How Fast?*

Addressing the question of *How Much, How Fast?* will require focused community effort, major logistical support and robust international collaboration over the course of the next decade. This targeted effort will provide the template for studying the other portions of Antarctica that are likely to become increasingly vulnerable in the future.

Implementing this decadal scale research plan will require a project office that will serve as a hub for planning coordination within the U.S., foster engagement of the broad scientific community, and coordinate mentoring of early career scientists. The coordination office will also work with the international science community to ensure effective targeting of the logistical resources. The coordination office will also bring together an interagency working group to aid in the effective use of resources with NSF as well as NASA, DOE and NOAA. A continuation of NASA's Operation IceBridge mission would be greatly beneficial for the *How Much, How Fast?* science goals. The data volumes from this project will be large, and the program office will foster open and transparent access to the rich new datasets acquired. The coordination office will also ensure the full integration the Thwaites-focused field work supporting the first two prongs of the program with the process-based and modeling-based studies. The office will also coordinate outreach and education activities, the development of web-based resources, and dissemination and sharing of data through existing infrastructure (e.g., NOAA, NSIDC). Only through full integration of these efforts will we make progress towards understanding how the system works and how it will change in the future.

To execute the *How Much, How Fast?* WAIS Science Plan, additional investments will be needed in supporting technologies and tools. The problem requires new in situ measurement instruments able to operate in key environments (sub-ice-shelf cavity, sea ice zone of the coastal ocean) and access to hard-to-reach boundaries (ice-bed interface). The ocean of the Amundsen Sea Embayment is not well instrumented and there are few coastal weather stations to support mesoscale climate analysis.

The timeline for the program should begin with the first field deployment in 2018-19 with the goal of early deployment of floats, stations, moorings and gliders to begin building the essential time series of data required. The logistical needs of this program necessitate innovative approaches and international partnerships. Coordinated surface, airborne and marine logistical support will be essential. A traverse capability will be needed for both science and transporting fuel, together with an airborne capability again both for science and transport, as well as regular research cruises with helicopter support to the region. Biennial 5-week cruises, including the international polar research fleet as well as U.S. assets, should target the most accessible period of mid-January to late-February.

SUMMARY – ***How Much, How Fast?***

We have described a plan for the next decade of research in WAIS, 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 the West Antarctic Ice Sheet will change in the coming decades. *How Much, How Fast?* is based around four fundamental questions: (1) Drivers: Why is the West Antarctic Ice Sheet changing now?; (2) Boundary Conditions: What does the ice sheet look like?; (3) Processes: How do marine ice sheets collapse?; (4) Models: What is our best projection of sea-level rise from 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.

Answering the paired *How Much, How Fast?* question is a major challenge. Success will require a focused community effort, major logistical support, and integrated international collaboration over the course of the next decade. The results will provide a tool for planning adaptation and risk management strategies for coastal communities, capital assets and natural environments around the world.