The West Antarctic Ice Sheet Initiative

WAIS Science Plan Development, 2013-2016

The West Antarctic Ice Sheet (WAIS) is one of the most dynamic and intriguing regions on Earth. It is the last major marine ice sheet, with several of the largest and most variable outlet glaciers in the world. It has been the site of extensive research on glacier flow, ice stream shear zones, ice sheet hydrology, sub-glacial lakes, and ice shelf dynamics and history. **Studies of its climate, its oceanology, and its geology routinely reach the pages of the top peer-reviewed journals in science.** WAIS has been the site of two major recent ice cores, at Siple Dome and at the WAIS Divide and a third at Roosevelt Island. There are several extensive aerogeophysical mapping campaigns. It is a key study region for ice-ocean interaction, climate tele-connections, and polar climate change. Most importantly, it is one of the largest potential contributors to sea level rise in the coming centuries.

A dedicated meeting, emphasizing the broad range of connected research topics and integrated system science study is essential to maximizing the success of Antarctic glaciology research funding. No other meeting during the year (no AGU or EGU session, no symposium of IGS) combines the variety of climate, ice, geophysics, ocean, and paleoclimate study that the WAIS Workshop does. **The venue both maximizes the dissemination of results to the research community, and provides a venue that stimulates new ideas and collaborations.**

The WAIS Science Plan was first formulated in 1992, outlining research objectives and the current state of knowledge for glaciology and related earth system science disciplines for the region. It included annual workshops to review the science and refine the research path. Since then, **annual WAIS Workshop meetings have been held, beginning in 1993 with a goal of presenting science results and reviewing the science plan.** For most of this time, these were organized and led by Dr. Robert Bindschadler of NASA's Goddard Space Flight Center. At present, they are organized among a small group of hosts (S. Anandakrishnan, H. Fricker, T. Scambos, and E. Steig) at a series of venues. Support is coordinated by T. Scambos and NSIDC.

The continuing aim of the West Antarctic Ice Sheet Science plan, and the scientific motivation for an annual WAIS Workshop, is to understand the dynamics of marine ice sheets, ice shelves, and variable outlet glaciers, by identifying the key processes that govern them and their response to a changing climate and environment. The ultimate goal is to use this knowledge to improve projections of future sea level rise and the evolution of WAIS in the anthropogenic climate change era, and to describe how this ice sheet system interacts with the biosphere, ocean, and earth system. This requires an interdisciplinary approach including studies of various components of the earth system interacting with the West Antarctic Ice Sheet (e.g., Southern Ocean and atmosphere, underlying bedrock, and the physics of the ice itself), as well as present-day and paleoclimate studies and biosciences.

DRAFT of the WAIS INTEGRATED SCIENCE PLAN

The West Antarctic Ice Sheet (WAIS) is comprised of the major ice divides and outflowing glacier catchments lying on the Western Hemisphere side of the Transantarctic Mountain Range, and the majority of the two largest ice shelves in the world, the Ross and Ronne ice shelves. In our definition here, it includes the Antarctic Peninsula (AP) as well, although geographically this is often treated separately (Figure 1). We include the AP because many of the ice-ocean-climate processes governing the WAIS evolution are manifest in the AP, and because field and oceanographic research there is often seeking to characterize anticipated changes in the WAIS proper. Therefore, the WAIS includes both the rapidly evolving ice shelves and glaciers along the Amundsen and Bellingshausen Sea coasts (e.g., in Pine Island Bay, Rignot et al., 2002) and along the Antarctic Peninsula (Larsen, George VI, Abbot and Wilkins, Scambos et al., 2009; Berthier et al. 2012).

The WAIS has received a great deal of attention from researchers because much of it is grounded below sea level with a landward sloping bed (Lythe et al., 2001; Holt et al., 2006; Le Brocq et al., 2010; Vaughan et al., 2006) making it more susceptible to rapid collapse through grounding line retreat (Weertman, 1974; Schoof, 2007). WAIS has a current mass deficit of 132\pm26 Gt/yr which arises in large part from the loss of ice through the Amundsen Sea Sector (Chen et al., 2010; Zwally et al., 2005; Rignot et al., 2008), however some regions (notably the Siple Coast region) are experiencing growth (Joughin and Tulaczyk, 2002). Projected sea-level rise from the complete collapse of the WAIS is 3.3 m with regional variations in sea-level rise (Bamber et al., 2009). Marine seismic and bathymetric observations (Bart and Anderson; 2000) and sub-ice shelf sediment cores (Naish et al., 2009) indicate that the ice sheet has endured a dramatic history of expansion and collapse since it formed in the mid-Cenozoic, illustrating its sensitivity to changing climate.

The rapid collapse of the Larsen-B Ice Shelf in March 2002 (Scambos et al., 2003) provided an opportunity to document, via satellite observations, the rapid acceleration of ice streams and glaciers in response to the removal of the buttressing provided by the backpressure from the ice shelf; see, e.g., DeAngelis and Svarcka [2003], Rignot et al. [2004] and Scambos et al. [2004]. It is now clear that the grounded ice sheet is tightly coupled to the ice shelves, which exert strong control on ice sheet mass loss and thus influence global sea level.

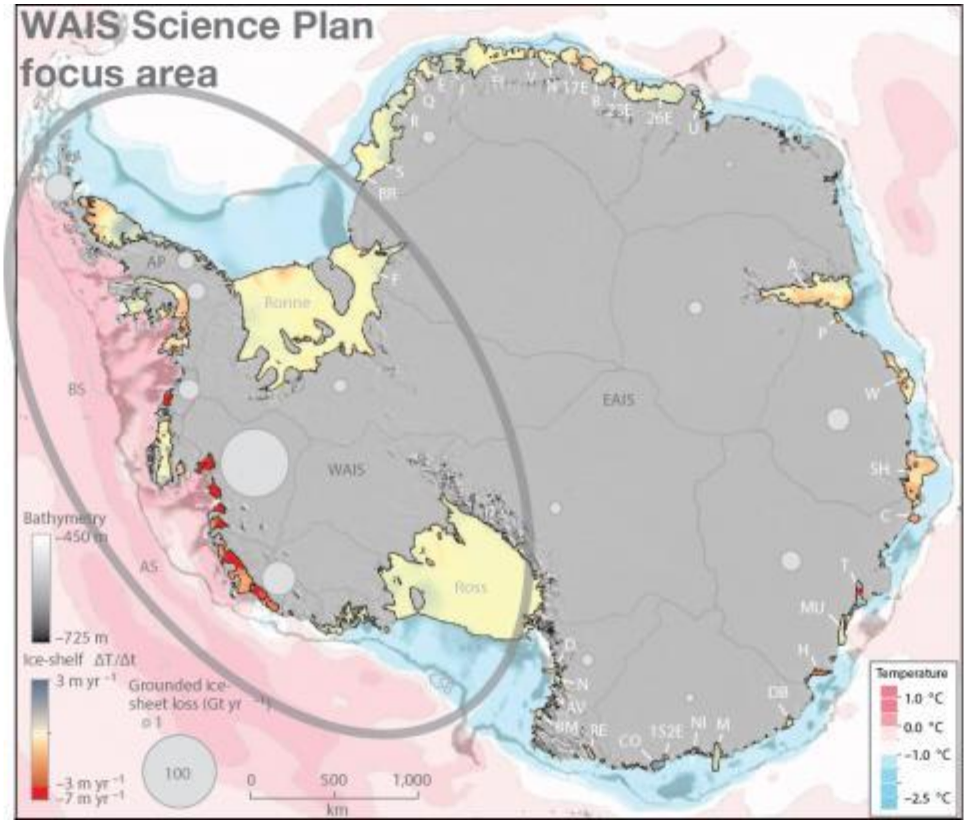

Figure 1. West Antarctic Ice Sheet Science Plan study area. Adapted from Pritchard et al., 2012.

Recent satellite studies (Pritchard et al., 2012, Bindschadler et al., 2011, Rignot et al., 2008) have shown that the mass balance of the WAIS and the circulation of the adjacent oceans are strongly coupled through physical processes which occur at the ice-ocean, ice-atmosphere, and ice-ocean-atmosphere interfaces at the fronts and bases of ice shelves and glacier tongues, and at the termini of tidewater glaciers. In particular, enhanced basal melting resulting from the intrusion of warmer CDW from the continental shelf under the ice shelves appears to be causing ice shelf thinning, and subsequently increased discharge of grounded ice (Pritchard et al., 2012); this is the primary driver of ice mass loss from WAIS. Improved understanding of these processes is essential so that they can be realistically represented in models of how ice sheets and glaciers would evolve in a changing climate, and to improve predictions of global ocean circulation and sea level change.

The West Antarctic Ice Sheet (WAIS) science plan was first formulated in 1992 and since then 19 WAIS meetings have been held annually since 1993. Over the nearly two decades of WAIS Workshop meetings, our understanding of the ice sheet has progressed, and it has become clear that further advances require an inherently interdisciplinary, integrated, and coordinated science focus. Several key processes have been identified which are driving changes on the ice sheet. While the WAIS meeting has always aimed to integrate research across scientific disciplines, a renewed focus on system-oriented research and interactions across major disciplinary boundaries is critical to understanding past, present, and future changes in this ice sheet.

Scientific Directions

The WAIS Workshop meetings provide an opportunity to define the course of future studies in West Antarctica in a setting where individual scientists can see the impact of their work in the context of the broader, multi-disciplinary community. To this end, we aim to identify some specific research goals here to shape the direction of funded research in West Antarctica, in conjunction with other groups (e.g. NRC, 2011). A recent NRC report Future Science Opportunities in Antarctica and the Southern Ocean has highlighted four research foci in Antarctica the coming decade. Three of these are relevant to the WAIS Science Implementation and we revise and expand upon them here.

We support the creation and funding of theoretical and modeling studies to quantify the WAIS contribution to sea level rise, and estimate the uncertainties on future projections of sea level rise arising from WAIS ice mass imbalance. This refers to surface mass balance, ice stream dynamics, and especially ice-climate and ice-ocean interactions. To what extent can we quantify the "noise" in the system, both in the ice sheet dynamic responses and in the forcings? Related to this is quantifying the variability in the forcing itself (e.g. what is the contribution of variations in atmospheric and ocean circulation to variations in, e.g., basal melting and ice shelf thickness or surface mass balance).

In general, the WAIS Workshop discussions will address questions regarding the interplay of the following components of the WAIS system:

External Forcings

- atmosphere (temperature, precipitation)
- atmospheric and climate dynamics (regional circulation, large-scale circulation patterns, climate change)
- ocean heat (circumpolar deep water)
- ocean circulation and change (wind stress, large-scale ocean circulation)
- geothermal fluxes

Response to external forcing

- ice dynamics, grounding line changes
- subglacial hydrology and basal freeze/thaw
- supraglacial hydrology on ice shelves vulnerable to collapse
- calving processes
- till generation and replenishment

Specific examples include:

1) How will the WAIS contribute to changes in global sea level?

a) theoretical studies of ice deformation and marine ice sheet – deep keel outlet glacier collapse (e.g. recent studies by C. Schoof, 2007; C. Schoof, 2012, Leverman et al., 2012);
b) high resolution ocean modeling work (e.g. recent studies by Thoma et al. 2008; Holland et al., 2010; Martinson, 2011).
c) coupled ice-atmosphere and ocean-ice-atmosphere models aimed at assessments of the century-scale responses of the WAIS as a whole and its component major catchments (e.g., the Pine Island embayment, Siple Coast, Antarctic Peninsula);
d) more focused and short-term analyses of glacier responses to change (I. Joughin analysis of Pine Island Glacier; Larsen Ice Shelf area ongoing and future responses, and integrated system science, LARISSA project);
e) improved instrumentation for data gathering in the sub-ice-shelf environment and the grounding line zone; improved radioglaciology for mapping ice layering, flow history, and grounding line dynamics (e.g., Scambos et al., 2013; Christianson et al., 2012).

2) What is the role of the WAIS and the Southern Ocean in the global climate system?

a) How will broad climate pattern changes (increasing SAM index, teleconnections from central Pacific warming) change ocean circulation and ocean interaction with the ice sheet boundaries? What roles will declining sea ice cover in the Amundsen / Bellingshausen Sea play in WAIS dynamics, and how will these conditions evolve in the future?
b) Southern Ocean / WAIS and AP continental shelf oceanography; analysis of newly available oceanographic data from research vessels and automated buoy stations (e.g. Jacobs et al., 2012);
c) Impact of surface melt on ice dynamics in the Peninsula and how will this change in the near future if surface melt increases? Model studies of lakes, fracturing, and lake formation-drainage stresses on the shelf;
d) d)Regional climate and ocean modeling (e.g. to address atmospheric forcing of ocean circulation relevant to ice shelf dynamics, and influences on surface melt and accumulation rates);
e) Provide constraints on variability to the modeling community -- model validation and design.

3) How has the geology of the WAIS region influenced its history, and its future evolution? How does the WAIS system interact with the polar biosphere?

a) geological structure of WAIS as a combination of tectonic processes, past glaciological erosion, and marine deposition;
b) formation of troughs on the Antarctic continental shelf and sedimentation processes during ice sheet growth and retreat;
c) sub-ice-sheet and sub-ice-shelf biosystems;
d) sea ice and the coastal zone biology; megafaunal interactions with the ice sheet, icebergs, and sea ice.

4) How has the WAIS responded to past climate changes? What role has the WAIS played in changing the planet in the past?

Insight into the future of the WAIS can come from studying its past. For example, the timing of ice recession in the Ross Sea following the last glacial maximum affords information about the mechanisms that control the position of the WAIS grounding line today. There is good evidence for past collapses of the WAIS (Scherer et al., 1998; Pollard and DeConto, 2009). Sediment analyses from properly sited marine sediment cores, multi-beam sonar, and marine seismic mapping provide a record of past extent of the ice, and the processes occurring during advance and retreat. The history of the WAIS also is important for reconstructing the overall Antarctic contribution to past sea-level changes, including meltwater pulses during deglaciation.

a) climate, chemistry, and accumulation records from ice cores;
b) cosmogenic nuclides in subglacial bedrock provides unequivocal evidence of ice-free conditions in the past. Short cores of bedrock at targeted locations would provide information about ice-sheet configurations during past interglacial climates, necessary for predicting the future.
c) more information from understudied areas akin to PIG-ASE area, e.g., Getz Ice Shelf; Ferrigno Ice Stream; Institute-Möller, Mertz, Totten, Jutulstraumen (mostly via remote sensing)
d) Identify and characterize regions of large dynamic change for focused and coordinated study, especially those which are interdisciplinary.
e) Small glaciers and ice caps surrounding Antarctica. These contain histories of past ice sheet thickness and extent and are also likely to contribute significantly to sea level rise over the next century.
f) Explore/drill to surviving Eemian ice (ice core community) and infer Eemian ice sheet volume and geographic distribution.

Technological Directions

Game-changing instrumentation is needed for further progress in WAIS field observation. This could include new antenna designs for radar sounding, new artificial seismic sources (such as those used in shallow lithospheric exploration by commercial concerns), new forms of shallow surface exploration (for snow studies), efficient drills, and new geochemical laboratory instrumentation.

Remote sensing improvements including integration of high-resolution, high-frequency imaging sensors, synthetic aperture radar data (ESA collaboration), high-resolution altimeters (IceBridge, ICESat-2 and Cryosat2), continuation of the MODIS, ASTER, SPOT, and Landsat programs for monitoring changes; and airborne radar data (IceBridge and CReSIS).

There have been other major advances in technology that have led to improvements in several areas including: the modeling of ice sheets in 3-D; increased spatial and temporal resolution of atmosphere, ocean, and coupled climate models; a wealth of new data from remote sensing (e.g.

airborne radar and high-resolution visible imagery); ice-penetrating radar advances, offshore multibeam bathymetry, and advances in observing the bed (enabled by new drilling and measurement technology). Furthermore, NASA, NSF-CDI and DOE are both funding advanced computing of ice sheets; this is also a focus at NCAR and other climate modeling centers internationally. A major focus for the WAIS science community for the next decade will be to take advantage of these advances observations and link them with the modeling advances.

Modeling: Model improvements (basin-scale, data-driven, predictive models and data assimilation) and continued creation of "process study" models that illuminate the processes and provide physical basis for parametrizations of these processes in large large-scale, climate system models.

Drilling Access: Current and future advances in drilling capabilities enabling access to ice shelf cavities, subglacial hydrology, subglacial sediments and rocks, deployment of englacial laboratories (relevant to questions of internal ice sheet dynamics, past ice sheet and climate history, ice shelves and their cavities, grounding line dynamics, subglacial lakes and water drainage pathways). New science goals and associated drilling technologies are being articulated by the Ice Drilling Program Office's "Long Range Science Plan" and the "Long Range Drilling Technology Plan". These documents are available at http://www.icedrill.org.

Planned drill developments include: Clean access drills (WISSARD, Frank Rack, developed for 2012/13 deployment); Rapid Access Drills; intermediate drills (versatile and capable of 1000-1500m - similar to the drill being used at Roosevelt Island by New Zealand).

Advanced In-situ automated systems (Sentinels, Autosub, AWS, Polenet, Seismic, Access drilling). Build on existing observation networks but extend them into areas of current interest to the WAIS community. Emphasis should be on both, extending temporal and spatial coverage of already proven sensors (GPS, seismic, AWS, etc.) but also migration of new technologies from other areas to Antarctica.

Seismology has contributed greatly to the exploration and further understanding of how Greenland's ice is changing. This new frontier in seismology is just starting to scratch the surface in the study of West Antarctic Ice Sheet processes. Recent studies, for example, shows the impact of ocean-wave environments on ice-shelf flexure (e.g., Peter Bromirski's work at SIO). [Also Bassis work at SIO and Winberry work on MacAyeal Ice Stream, detection of subglacial water flow]. Study of stick-slip motions of ice streams is also illuminated by the use of passive seismological array instrumentation. Over the next decade, the WAIS community should target several goals: 1. to detect both precursor and process-active cryoseism signals associated with ice-shelf collapse, 2. to further illuminate the role of ice-stream stick/slip behavior in controlling grounding line processes, 3. to additionally detect basal hydrological events, such as lake fill and drain episodes.

Computational advances that support large-scale models of systems over the long term. In addition, support for "process study" level model development to be undertaken in conjunction with the continued development of large-scale models.

Data: We plan to continue and expand the data repository efforts at NSIDC's AGDC and NSIDC's other data programs for WAIS-related data. The WAIS Workshop venue is a key part of this plan, facilitating more interaction between PIs and data management staff to discuss and manage data transfer, documentation, and metadata information submissions. Brokering of PI –managed data sets will be set up for appropriate cases. Data management is key to the advancement of the science(s) and to change detection in a complex evolving system.

Summary

The WAIS will continue to inform and educate the polar community on both the mechanisms of how the Earth surface systems interact and how this complex region will evolve in the anthropogenic era. We need an active research program, robust field access to all aspects of the ice and ocean in WAIS, and continued good funding to examine this key component of planet Earth.