

Strawman Science Motivation for Coordinated Multidisciplinary Research in the Amundsen Sea Embayment, West Antarctica

Ad Hoc Pine Island Glacier/Thwaites Glacier Working Group
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Introduction

The West Antarctic Ice Sheet (WAIS) is the only remaining marine ice sheet from the last glacial period. The bed is primarily below sea level and slopes down from the coast to the interior. It has been hypothesized that the ice sheet may be susceptible to run-away grounding line retreat [Weertman, 1974] leading to rapid disintegration and sea level rise. Were the WAIS to completely melt, the water released is sufficient to raise global sea level by 5–6 meters. The likelihood of such a scenario, and the ice sheet’s sensitivity to climate forcing are topics of ongoing research. It is clear, however, that climate and ice dynamics interact in complex ways, with influence from the geologic boundary conditions and atmosphere and oceanic circulation patterns. The grounding line position and net balance are key parameters for observing ice sheet changes. Those data, when combined with accurate basal environment information, are critical for supporting model-driven hypothesis concerning the response of the WAIS to climate-change and sea-level change [Hughes, 1975; Mercer, 1978].

Ice discharges from the West Antarctic Ice Sheet to the sea largely by three major drainage systems: the ice streams of the Siple Coast (ice streams A-E) that flow into the Ross Ice Shelf, the ice streams that flow into the Filchner-Ronne Ice Shelf (Rutford Ice Stream, Carlson Ice Stream, Foundation Ice Stream), and the large ice streams that flow directly into the Amundsen Sea (Pine Island Glacier, Thwaites Glacier; Figure 1 is a Radarsat image of the region). The ice streams

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of the Siple coast and the Ross Ice Shelf have been studied by many investigators (mainly under the umbrella research initiatives such as RIGGS/RISP¹, SCP², and WAIS³) as have the ice streams flowing into the Filchner-Ronne Ice Shelf (under the umbrella initiative FRISP⁴). Due in part to logistical difficulties, there has been no coordinated effort thus far to understand the dynamics of ice flowing into the Amundsen Sea Embayment. We identify three overarching goals for coordinated, multidisciplinary research on the Pine Island/Thwaites drainage system of the Amundsen Sea Embayment of West Antarctica

1. Establish its mass balance and how it has changed through time and understand ice dynamics that may be unique to this system.
2. Quantify its boundary conditions in a fashion suitable for 3D ice sheet models and atmosphere/ocean/ice models.
3. Determine its sensitivity to oceanographic and meteorological forcing.

Overview

Much of the ice in the northernmost drainage basin of WAIS, the Amundsen Sea Embayment, flows through Pine Island Glacier (PIG) and Thwaites Glacier (TG). The flow mechanism for these glaciers is probably different than that of the Ross ice streams and the Filchner-Ronne ice streams. These two glaciers account for approximately 5% of the ice discharge of the entire Antarctic Ice Sheet [Vaughan and Bamber, 1998] and there is increasing evidence for rapid and recent changes in their flow behavior (Figure 2 shows the drainage basins for the glaciers of the region; from Vaughan *et al.* [in press]). The catchments of these glaciers are deep (approaching 2 km below sea level in the Byrd Basin) and they discharge to the sea in deep embayments of relatively warm water suggesting that they may be particularly sensitive to oceanic influences (Figures 3 and 4 show the surface and bed elevations, respectively). The accumulation rates are some of the highest in the continent (comparable to those of the Antarctic Peninsula) suggesting that the glaciers would be sensitive to changes in precipitation, storm tracks, and sea-ice cover. Sediment cores collected on the outer continental shelf show that grounded

¹Ross Ice Shelf Glaciological and Geophysical Survey; Ross Ice Shelf Project, Thomas *et al.* [1984]; Bentley [1984]

²Siple Coast Project, 1983–1994, see *Siple Coast Steering Committee* [1988]

³West Antarctic Ice Sheet Project, ongoing, see *WAIS Working Group* [1995]

⁴Filchner-Ronne Ice Shelf Program, ongoing, see *FRISP Report Series*

ice extended to the continental shelf break in the Amundsen Sea during the last glacial maximum. The last deglaciation was recent and rapid [*Kellogg and Kellogg, 1987*] since postglacial sediments on the outer shelf are much thinner in Pine Island Bay than on the outer shelf of the Ross Sea *Shipp et al.* [(submitted)]. If sedimentation rates of 10 cm/a are assumed the deglaciation could have occurred as recently as a few thousand years ago.

Mass Balance and Ice Dynamics

The PIG and TG catchments (together with the smaller, slow-moving “ridge PIT” between them) cover approximately 350,000 km² and extend 600 km in from the coast. Both PIG and TG are formed by a number of smaller tributaries that coalesce 70–100km from the coast into well-defined ice streams. The flow speed at the junction area is approximately 1 km/a rising to 2 km/a at the grounding line and rising still higher to 2.5 km/a [*Luchitta et al., 1995*] on the floating ice shelf. The driving stress in the tributaries is approximately 50 kPa, rising to >100 kPa near the grounding line [*Bentley, 1987*], leading *Vaughan et al.* [in press] to suggest that the tributaries are akin to ice streams and the main glacier akin to an East Antarctic outlet glacier.

The subglacial topography and character of the Amundsen Sea Embayment is poorly known. Traverse data and widely spaced radar sounding flight lines have delineated the broad outlines of the basins, highlands, and subglacial ridges of WAIS [*Drewry, 1983*]. A more-recent survey from Siple Station showed complex subglacial character (roughness, internal layering, and topography) along a line that crosses from inland ice onto a tributary and then onto the main part of PIG [*Vaughan et al., in press*]. The tributary appears to sit in a well-defined trough that extends down into the main trunk of PIG and has a substantially smoother bed than that of the inland ice. However, a large sill or shelf at the grounding line forces a large increase in driving stress as the glacier approaches the coast. Clearly the geology of this region plays an important role in the configuration of the PIG/TG trunks and tributaries.

The mass balance of the region is poorly known and the few measurements are at odds. The best estimate from comparisons of accumulation and discharge suggest the region is slightly out of balance (-2.4 ± 4 Gt/a or a surface elevation change of -1.5–3 cm/a) [see *Vaughan et al., in press*]. *Wingham et al.* [1998] measured the surface elevation directly from ERS-1 altimetry and suggests a surface lowering of -11 cm/a for the time period 1992–1996 for the TG basin. *Bentley and Giovinetto* [1991] calculated an overall positive mass balance for Antarctica

of 40–400 Gt/a, but assumed a positive budget of 50 Gt/a for the PIG basin. *Jenkins et al.* [1997] recalculated their overall mass balance assuming the PIG basin was in balance, and obtained a range of –10 to +230 Gt/a. If in fact the PIG basin has a large negative balance (as suggested by *Wingham et al.* [1998]), the overall budget for Antarctica would range further negative.

Ocean Interactions

Jenkins et al. [1997] describe oceanographic conditions for PIT and TG that are distinct from that of the Ross and the Filchner-Ronne Ice Shelves. PIG discharges into a 400–500 m deep bay with a 1 km deep trough carved into the seabed along its southern edge. The trough is filled with Circumpolar Deep Water (CDW) at depths greater than 800 m, but the shallower waters are influenced by glacial meltwater. The temperature along the ice front is above the freezing point suggesting that all the available heat has not been used for melting [*Jenkins et al.*, 1997]. The seabed beneath the ice shelf shoals by 200 m between the grounding line and the ice front [*Crabtree and Doake*, 1982] and the continental shelf to the north and west has rugged topography with many potential pinning points for a more extensive ice shelf or a more advanced grounding line. A decrease in CDW circulation in the PIG bay would dramatically increase the ice shelf thickness and lead it to quickly ground.

In the Ross and Weddell Seas, CDW is excluded from the continental shelf by cold, salty, dense water beneath the growing sea ice. The difference in the Amundsen Sea appears to be the low surface salinity due to high temperatures and high precipitation, low sea-ice removal, and (in a positive feedback) high basal melt rates of the ice shelves. *Jenkins et al.* [1997] speculate that the PIG ice shelf configuration would have been the norm during glacial periods because the fringing ice shelves of a much-expanded ice sheet would interact with warm CDW over a larger part of the ice sheet's perimeter. Thus the modern PIG and TG discharge fronts may be good analogs for typical ice front conditions during the glacial.

Climate Interactions

The South Pacific is a particularly important area for data collection, both for constraining and initiating any GCM intended to produce accurate results for West Antarctica. In addition, the high accumulation rates will produce high-resolution paleoclimate records that will address questions of anthropogenic change in cli-

mate. Most of the precipitation in West Antarctica crosses the coasts of the Bellingshausen and Amundsen Seas. A persistent low-pressure center off the coast in the southeast Pacific facilitates inland moisture transport and causes a peak in ice accumulation along the West Antarctic coast and at the interior divide [Bindschadler *et al.*, 1998]. There are currently no meteorological stations in the interior of the Amundsen Sea sector of the WAIS thus compilations of accumulation or temperature lack the level of detail needed for accurate modeling [Vaughan *et al.*, in press]. Results of fully coupled GCMs must be qualified by the current lack of data from much of the region.

Dynamic Behavior in a WAIS Context

The following observations have been made for the PIG/TG system.

- *Luchitta et al.* [1995] suggest that the floating portion of TG is speeding up (based on feature tracking in Landsat imagery and SAR images).
- *Rignot* [1998] has shown that the grounding zones of both of these glaciers has retreated. The grounding of PIG is complex but the simplest interpretation of the data is that the grounding zone has had episodic retreats in the period 1992–1996; the average retreat rate is $1.2 \pm 0.3 \text{ km} \cdot \text{a}^{-1}$.
- *Wingham et al.* [1998] used ERS radar altimetry to show that the lower 150 km of PIG is thinning at $11 \pm 1 \text{ cm/a}$. This thinning is most pronounced in the TG basin but extends across the whole region. The cause of this thinning is not clear.
- The PIG ice shelf has a large basal melt rate of 10–12 m/a [Jacobs *et al.*, 1996; Jenkins *et al.*, 1997], more than an order of magnitude larger than most Antarctic ice shelf basal melt rates.
- The ice front has retreated in the last 100 years at approximately 1 km/a [Kellogg and Kellogg, 1987], but is currently stable or readvancing [Jenkins *et al.*, 1997].

In summary, the PIG and TG are not in steady state. The magnitude (and even sign) of the change is poorly known, but the data suggest the ice streams are speeding up and their grounding zones are retreating. The PIG ice shelf is disintegrating rapidly and the TG ice shelf is gone. The catchments are probably strongly out of balance and thinning. We do not yet understand the implications of these observations for the WAIS.

Science Approach

WAIS/FRISP and previous large-scale umbrella research projects such as SCP, GSIRE, and RISP have shown the need for multidisciplinary research that includes meteorology, glaciology, geology, ice-coring, and oceanography. The logistical difficulties in studying the PIG/TG system favors an intelligently phased sequence that allows efficiently targeted work leading from satellite-based work to airborne-to ground-work to drilling and sampling (see WAIS Science Plan). Whether the field work will be performed from the a vessel in the Amundsen Sea or by LC-130 supported field camp on the ice sheet, or some combination of these two approaches, must be decided after the details of the science plan are better known.

The work can be divided by “platform” or by discipline, but must be justified in light of the overarching goals above. Here we list the work by platform in parallel with the existing WAIS Science Plan.

Satellite Satellite-based work has been the first priority for this region. Both catchments lie north of 79°S and are therefore fully-imaged. Existing satellite measurements have given high resolution measurements of elevation, surface reflectivity, surface velocity, visible and buried features, and brightness temperature among others. In the future, GRACE gravity and GLAS surface elevation observations will be available. These measurements are crucial for establishing the current state of the ice sheet, ice shelves, sea-ice, and the glaciers, with the key data being surface flow and elevation at <1 km grids. The primary advantages of the satellite work is that the data cover the whole area at high resolution (meters to km-scale) while requiring low field-logistics costs. All satellite measurements should continue for the lifetime of the project.

Meteorological Direct measurements of wind speed and direction, temperature, and accumulation rate are needed for establishing the current state of the system and for inputs to the modeling effort. In addition, weather data are needed for realistic logistics planning (cloudiness for flying conditions, etc.). Some of these data can be obtained by satellite imagery (AVHRR) but ground stations need to be established at key locations where more-detailed data are needed. These data are needed for the modeling effort. An AWS was successfully installed at the Amundsen/Ross flow divide during the 1999/2000 Antarctic field season in preparation for a future U.S. deep ice coring operation. Further AWS stations and shallow coring will occur

as part of the US/ITASE traverse from the Amundsen/Ross divide to Siple Station scheduled for 2001/2002.

Airborne The airborne geophysical measurements include surface and bed elevation, ice thickness, bed roughness, internal-layering, gravity anomalies, magnetic anomalies. These data are at high resolution along track and at medium resolution (km to 10s km) across track. Such measurements establish the current state of the ice sheet, and provide key bed character and elevation observations. Additionally, internal layer configuration observations will be critical for interpreting the dynamical history. Because of the high logistics cost of airborne data collection, the satellite data should be used to optimize placement and line-spacing of the grids.

Ground GPS measurements for registering the InSAR measurements are needed. In addition, targeted radar and seismic measurements are needed to determine bed character and internal layers and for subglacial and upper-crustal structure. The measurements speak to the current conditions and to determine the basal boundary condition for the modeling work. Short pulse radar work must be done for near-surface layering and accumulation rate variations. Finally, shallow coring for density, accumulation rate, and temperature; deeper drilling for temperature and sampling the bed needs to be done. These data (particularly temperature) are crucial for the 3D modeling.

Vessel The offshore measurements that are needed to establish the state of the Amundsen sea are the standard oceanographic (CTD), side-scan sonar for sea floor morphology, seismic for stratigraphy, and coring/drilling for paleoclimate data. All these data are for all three of the overarching goals of the project.

Table 1: Grid of platforms and measurements, and goals to be achieved (1=mass balance, 2=b.c. for GCMs, 3=flow sensitivity).

Platform	Key Measurement	Timing	Goals
Satellite	Elevation, Velocity, Grounding line	Early, Ongoing	1, 2
Meteorological	Accumulation, Weather	Early, Mid	1, 2
Airborne	Ice thickness, Internal layers, Bed character, Gravity, Magnetism	Mid	1, 2, 3
Ground	Detailed bed/sub-bed character, Snow density, Accumulation	Late	1, 2, 3
Vessel	Ocean state, Sea floor state	Mid, Ongoing	1, 2, 3

References

- Bentley, C. R., The Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS); introduction and summary of measurements performed., in *The Ross Ice Shelf; glaciology and geophysics*, edited by C. R. Bentley and D. E. Hayes, vol. 42 of *Antarctic Research Series*, pp. 1–20, American Geophysical Union, Washington DC, 1984.
- Bentley, C. R., Antarctic ice streams: a review, *J. Geophys. Res.*, 92, 8843–8858, 1987.
- Bentley, C. R., and M. B. Giovinetto, Mass balance of Antarctica and sea level change, in *International Conference on the Role of the Polar Regions in Global Change: proceedings of a conference held June 11–15, 1990 at the University of Alaska, Fairbanks.*, edited by G. Weller, C. L. Wilson, and B. A. B. Severin, vol. II, pp. 481–488, University of Alaska, Fairbanks, AK, 1991.
- Bindschadler, R. A., R. B. Alley, J. Anderson, S. Shipp, H. Borns, J. Fastook, S. Jacobs, C. F. Raymond, and C. A. Shuman, What is happening to the West Antarctic Ice Sheet?, *Eos, Trans. Am. Geophys. Un.*, 79, 264–265, 1998.
- Crabtree, R. D., and C. S. M. Doake, Pine Island Glacier and its drainage basin: results from radio echo sounding, *Ann. Glaciol.*, 3, 65–70, 1982.
- Drewry, D. J. (Ed.), *Antarctica: Glaciological and Geophysical Folio 2*, Scott Polar Research Institute, Cambridge, 1983.
- Filchner-Ronne, Filchner-Ronne Ice Shelf Programme (FRISP) Report Series, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, Serial.
- Hughes, T. J., The West Antarctic Ice Sheet: Instability, disintegration, and initiation of ice ages, *Rev. Geophys.*, 13, 502–526, 1975.
- Jacobs, S. S., H. H. Hellmer, and A. Jenkins, Antarctic ice sheet melting in the Southeast Pacific, *Geophys. Res. Lett.*, 23, 957–960, 1996.
- Jenkins, A., D. G. Vaughan, S. S. Jacobs, H. H. Hellmer, and J. R. Keys, Glaciological and oceanographic evidence of high melt rates beneath Pine Island Glacier, West Antarctica, *J. Glaciol.*, 43, 114–121, 1997.

- Kellogg, T. B., and D. E. Kellogg, Recent glacial history and rapid ice stream retreat in the Amundsen Sea, *J. Geophys. Res.*, 92, 8859–8864, 1987.
- Luchitta, B., C. Rosanovea, and K. Mullins, Velocities of Pine Island and Thwaites Glacier, West Antarctica, *Ann. Glaciol.*, 21, 277–283, 1995.
- Mercer, J. H., West Antarctic ice sheet and CO₂ greenhouse effect: A threat of disaster, *Nature*, 271, 321–325, 1978.
- Rignot, E. J., Fast recession of a West Antarctic glacier, *Science*, 281, 549–551, 1998.
- Shipp, S., J. B. Anderson, and E. W. Domak, High-resolution seismic signature of the late Pliocene fluctuation of the West Antarctic Ice Sheet system: A new perspective, Part 1, *GSA Bulletin*, (submitted).
- Siple Coast Steering Committee, Science Plan for the Siple Coast Project, Byrd Polar Research Center, The Ohio State University, Columbus, Ohio, 1988.
- Thomas, R. H., D. R. MacAyeal, D. H. Eilers, and D. R. Gaylord, Glaciological studies on the Ross Ice Shelf, Antarctica, 1973–1978., in *The Ross Ice Shelf; glaciology and geophysics*, edited by C. R. Bentley and D. E. Hayes, vol. 42 of *Antarctic Research Series*, pp. 21–53, American Geophysical Union, Washington DC, 1984.
- Vaughan, D., et al., A review of ice-sheet dynamics in the Pine Island Glacier basin, West Antarctica: hypotheses of instability vs. observations of change, Antarctic Research Series, AGU, in press.
- Vaughan, D. G., and J. L. Bamber, Presentation at WAIS Chapman Conf., 1998, orono, ME. Sept. 1998.
- WAIS Working Group, The West Antarctic Ice Sheet Initiative: Science and Implementation Plan, 1995, r. A. Bindschadler, Ed.
- Weertman, J., Stability at the junction of an ice sheet and an ice shelf, *J. Glaciol.*, 13, 3–11, 1974.
- Wingham, D. J., A. J. Ridout, R. Scharroo, R. J. Arthern, and C. K. Schum, Antarctic elevation change from 1992 to 1996, *Science*, 282, 456–458, 1998.