Project Description

NSFPLR-NERC: Thwaites-Amundsen Regional Survey and Network (**TARSAN**) Integrating Atmosphere-Ice-Ocean Processes affecting the Sub-Ice-Shelf Environment.

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Overview

Thwaites and neighboring glaciers in the Amundsen Sea Embayment (ASE) are rapidly losing mass in response to recent climate warming and related changes in ocean circulation (Scambos et al., in review). More dramatic mass loss may occur in the near future due to the marine ice sheet instability (Weertman 1974; Mercer 1978; Schoof 2007; Joughin et al., 2014), exacerbated by processes such as meltwater-driven hydrofracturing of ice shelves (e.g., MacAyeal et al., 2003; Scambos et al., 2009; Pollard et al., 2015) and ice-cliff failure (DeConto and Pollard 2016). Mass loss from the ASE could lead to the eventual collapse of the West Antarctic Ice Sheet (WAIS), which would raise the sea level by up to 2.5 meters in as short as 500 years (DeConto and Pollard 2016). **Such model predictions, however, are still lacking spatially and temporally detailed understanding of the dominant processes at and near grounding zones and the atmospheric and oceanic drivers of these processes.** *To fill this gap in understanding, we propose a network of atmospheric, ice, and ocean observations to more confidently understand the regional processes driving surface and basal ice melt and connect this ice melt with its impacts on ice-shelf stability and grounding line retreat.* Specifically, we will

- **Install Atmosphere-Ice-Ocean multi-sensor remote autonomous stations** (AMIGOS) on ice shelves for two years to provide sub-daily continuous observations of concurrent oceanic and atmospheric conditions;
- **Measure ocean properties** on the continental shelf adjacent to the ice-shelf fronts and into the sub-ice-shelf cavities to detail ocean transports and heat fluxes affecting the ice-shelf base; and
- **Constrain the current ice-shelf and cavity geometry, ice flow, and structure of the ice and firn** for two sites to better define the impact of ocean and atmosphere on the ice-sheet change.

We will use these observations to both answer specific research questions (detailed below) and to provide data and new ideas to support broader community efforts in ice-sheet modelling, climate modelling, and predictions for future mass loss.

The unique strength of TARSAN lies in interdisciplinary observations using robust, proven technology and complementary research-team expertise connecting the atmospheric processes directly to both ice and ocean properties and processes.

We propose to work on the eastern Thwaites Ice Shelf and compare it with the Dotson Ice Shelf (Figure 1). These two ice-shelf systems are connected through linked atmospheric drivers and upstream glacier dynamics, but influenced by different submarine troughs. This comparison allows us to separate the ocean from the atmosphere in their capacity as drivers of change.

Background and Motivation

External Drivers of Change

Increasing Antarctic ice-sheet mass loss (e.g., IPCC 2013; Velicogna et al., 2014; Harig and Simons, 2015; Paola et al. 2015) is fundamentally a result of global greenhouse-gas increases and Antarctic springtime ozone loss. These two shifts in the atmosphere's heat balance have led to changes in atmospheric-circulation patterns surrounding Antarctica (Thompson and Solomon, 2002; Arblaster and Meehl, 2006; Arblaster et al., 2011). In particular, these changes have strengthened westerly winds and intensified the Amundsen Sea Low (ASL, the climatological mean low-pressure system over the Amundsen Sea, e.g., Turner et al., 2012; Raphael et al., 2016). These altered wind patterns and the more intense ASL drive changes in ocean circulation (Figure 2) that are hypothesised to force a greater amount of relatively warm Circumpolar Deep Water (CDW) onto the continental shelf in the Amundsen Sea (Figure 3, Thoma et al., 2008; Steig et al., 2012; Jenkins et al., 2016) through deep, glacially-carved bathymetric troughs that extend beneath ice shelves to the grounding lines of the deepest, largest

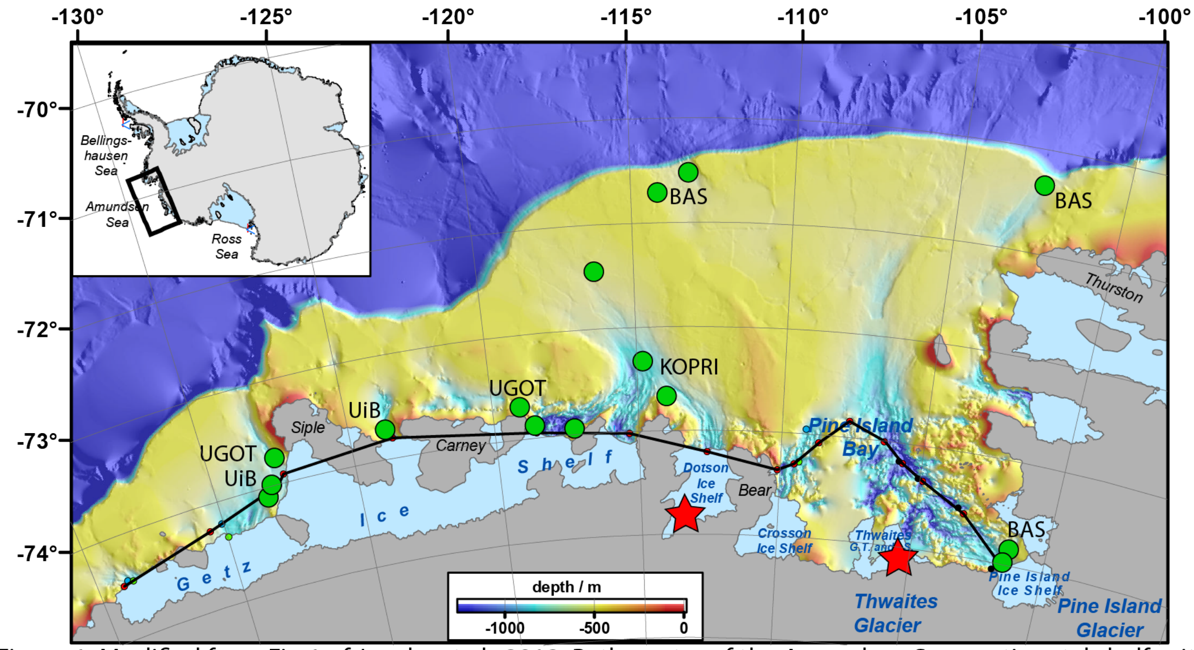


Figure 1: Modified from Fig 1 of Jacobs et al., 2012. Bathymetry of the Amundsen Sea continental shelf, with moorings (green dots) from BAS, KOPRI, and Universities of Gothenburg (UGOT) and Bergen (UiB). Red stars indicate the selected sites for AMIGOS-III (Fig 7). Black line is section shown in Figure 3.

glaciers in the region (Arneborg et al., 2012; Jacobs et al., 2012; Christianson et al., 2016). Increased sub-ice-shelf melting by increased heat flux associated with the CDW thins the ice and reduces ice-shelf buttressing, forcing grounded ice to accelerate. This acceleration increases the ice flux off the continent, leading to ice-mass loss from the ASE. *Neither the dynamic response of the ice shelf and grounding zone, nor the atmospheric and oceanic drivers, are sufficiently well understood yet to allow predictions for mass loss in the next century.* **Our proposed research will fill this gap in understanding by using concurrent atmospheric/ocean/ice observations to connect the drivers of change with ice dynamic response.**

A more intense ASL also invigorates atmospheric meridional moisture transport towards Thwaites/Dotson glacier basins, enhancing snowfall over the ice shelves. While this snowfall may mitigate ice-shelf mass loss controlled by basal melt, this same atmospheric flow pattern is associated with warm air advection that increases surface melting on the ice shelf (Nicolas and Bromwich 2011; Trusel et al., 2013; Lenaerts

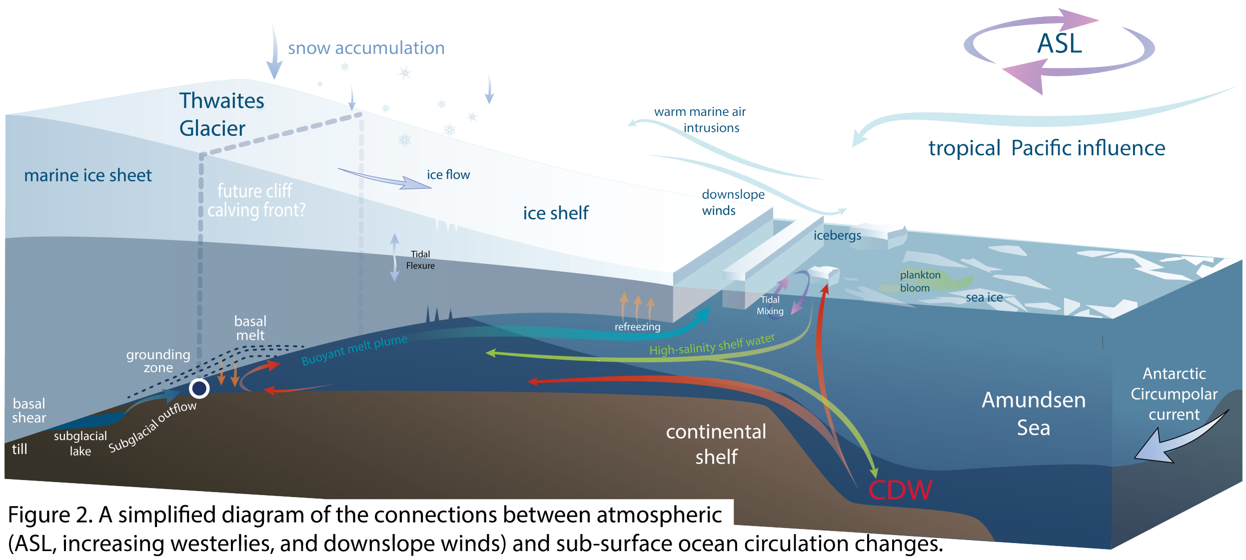


Figure 2. A simplified diagram of the connections between atmospheric (ASL, increasing westerlies, and downslope winds) and sub-surface ocean circulation changes.

et al., 2016; Nicolas et al., in review). *This complex balance between snowfall and surface melt determines ice shelf firn conditions that are indicative of the potential of ice-shelf instability through surface-induced hydrofracturing.* **TARSAN will assess the balance between these processes for the Thwaites ice-shelf firn over the last decades and consider the impacts of firn structure on future mass changes.**

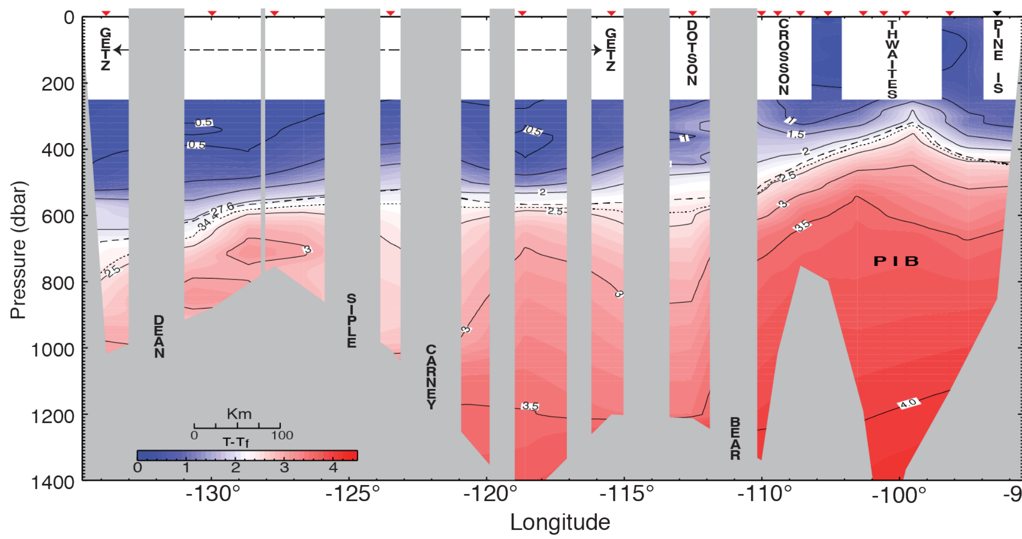


Figure 3: Fig 2 of Jacobs et al. 2012. Summary of temperature data (T above freezing point) for a series of 2007 and one 2009 CTD castings along the ice shelf edges (black line in Fig 1). Warmer ocean water with higher density marks the CDW layer in the region.

A host of recent studies highlight the importance of CDW-driven mass loss from the Antarctic Ice Sheet (e.g., Alley et al., 2016; Cook et al., 2016; Khazendar et al., 2016; Rintoul et al., 2016). Mass loss of WAIS is estimated at ~85 to 180 Gt a^{-1}, primarily via acceleration and thinning due to sub-ice-shelf melting of the large (20 to 50 km wide) Pine Island and Thwaites Glaciers (e.g., Rignot et al., 2011; McMillan et al., 2014; Harig and Simons 2015). *Pope, Smith and Kohler Glaciers, buttressed by Crosson and Dotson Ice Shelves, are relatively small but exhibit some of the fastest grounding-line retreat rates in the region* (McMillan et al., 2014; Mouginot et al., 2014; Paola et al., 2015; Khazendar et al., 2016; Scheuchl et al., 2016), with Smith Glacier retreating by up to 1.15 km/year between the mid 1990s and 2012 and losing the ice-surface elevation by up to 7 m/year between 2002 and 2010 (Khazendar et al., 2016).

Recent observation and modelling of the Pine Island Glacier system demonstrate that the flux of warm CDW into the sub-ice-shelf cavity modulates the rates of ice-shelf thinning and outflow of grounded ice at seasonal to interannual time scales (Dutrieux et al., 2014; Christianson et al., 2016). The continental shelf of the ASE is marked by two main deep troughs carved out during previous ice ages (Lowe and Anderson 2002; Graham et al., 2010). The eastern one, the Pine Island-Thwaites Trough (PITT; Figure 1), is a significant conduit of CDW reaching the sub-ice-shelf cavity of Pine Island Bay (Figure 3, Jacobs et al., 2012; Heywood et al., 2016; Jenkins et al., 2016). PITT branches off westwards in Pine Island Bay (Figure 1) and connects to sub-ice-shelf cavities of Thwaites and Crosson Ice Shelves (Millan et al., 2017). CDW-driven sub-ice-shelf melting (Jacobs et al., 1992; Jenkins et al., 2016) is presumably also causing the accelerating mass loss from Thwaites, Pope, Kohler and Smith Glaciers (Rignot et al., 2014; Khazendar et al., 2016). However, we currently lack oceanic observations beneath the ice shelves fed by these glaciers to confirm this. In addition, the similarly sized Dotson-Getz Trough (DGT, Figures 1 and 3) is relatively little studied (Ha et al., 2014; Miles et al., 2016) and current understanding of the ocean impact on the Dotson and Getz Ice Shelves and their feeder glaciers remains hypothetical. **By studying the intrusion of CDW and its interaction with ice at grounding lines and in sub-ice-shelf cavities for both of these trough systems, The TARSAN project will aim to distinguish local geometric effects from regional CDW circulation patterns that will be sustained through the changing geometry of a Thwaites retreat.** For example, basal channels, which are small-scale features that evolve through time (Alley et al., 2016) strongly impact sub-shelf circulation, turbulent mixing, and basal melt rates (Gladish et al., 2012; Millgate et al., 2012). The comparison of basal channels and other small-scale features in the contrasting environments of the Thwaites and Dotson Ice Shelves will illuminate the detailed mechanisms by which CDW interacts with ice shelves.

Ocean Processes on the Amundsen Sea Continental Shelf

CDW is the principal source of ocean heat in the ASE (Heywood et al., 2016; Jenkins et al., 2016). This water mass, circulating with the Antarctic Circumpolar Current, has core temperatures of approximately 2°C and is ubiquitous beneath the cold surface layer and broad thermocline that typically occupy the upper few hundred meters of the water column (Figure 3, Schmidtko et al., 2014). The main pycnocline separating CDW from surface waters typically deepens over the Antarctic continental slope to form the Antarctic Slope Front, which drives westward flow around Antarctica. The depth of the pycnocline is a key control on exchange across the shelf break and may be strongly dependent on the large-scale wind forcing (Walker et al., 2007; Thoma et al., 2008; Assmann et al., 2013; Walker et al., 2013; Spence et al., 2013; Jenkins et al., 2016). In the ASE, the pycnocline remains mostly above the level of the shelf break, especially where the shelf edge is cut by troughs (Jacobs et al., 2012), so CDW can easily reach the shelf (Jenkins et al., 2010). Shelf-break mixing processes cool the CDW by about 0.5°C (Jacobs et al., 2012), but otherwise leave it mostly unmodified. Once on the continental shelf, CDW is thought to follow the glacially-carved bathymetric troughs to the ice shelves (Thoma et al., 2008; Jacobs et al., 2011; Nakayama et al., 2013; Dutrieux et al., 2014). *The seasonality of the CDW properties on the continental shelf is still unknown, since almost all measurements are undertaken at the sea ice minimum in summer. And the relative importance of the different troughs leading to the most vulnerable ice shelves is still a topic of debate.* **TARSAN will directly fill this gap in observations and understanding by deploying sub-ice-shelf moorings and comparing the oceanographic properties and processes in the two trough systems.**

Both higher temperature (Jenkins et al., 2010; Stanton et al., 2013) and more intense circulation (Jacobs et al., 2012) can cause the high melting rates seen in the glaciers of Pine Island Bay in the late 2000s. Local air-sea interaction processes occurring in polynyas (St-Laurent et al., 2015) are argued to be crucial in setting the heat content of water entering the cavity. Recent studies, including a 5 year mooring record in Pine Island Bay, reveal a cold period during 2012, linked with a slowing of the rate of glacier acceleration (Christianson et al., 2016; Webber et al., 2017). The causes of this cold period are not definitively proven, but the importance of local atmospheric processes (St-Laurent et al., 2015; Webber et al., 2017) may dominate over the large-scale, non-local wind-driven effects at the shelf break some 400 km away. **TARSAN's coupled atmospheric-ice-ocean continuous observations will provide data to allow us to test hypotheses such as these.**

Ocean processes beneath, and close to, the ice shelves are particularly challenging to measure, and heat fluxes passing into most of the cavities of the ice shelves west of Pine Island Glacier remain unmeasured. Meltwater emanates as a buoyant plume and rises rapidly. Naveira Garabato et al. (2017) made the first measurements of turbulent mixing close to the front of Pine Island Glacier, which reveal instability processes that are thought to lead to mixing and determine the neutral buoyancy of the meltwater. **To capture these processes, TARSAN will take advantage of autonomous vehicles to survey the inflowing CDW, and the outflowing meltwater, close to the ice shelf front where it is too dangerous to venture with a ship, and into the cavity beneath the ice shelf.**

TARSAN: Integrated Atmosphere-Ice-Ocean Research Questions and Objectives

We aim to collect observations constraining the dominant processes affecting two critical systems: the Thwaites Ice Shelf and the Doston Ice Shelf. For each system, we will make observations near the ice-shelf front (using seal tagging, autonomous underwater vehicles, and gliders), on the ice-shelf surface and in the ocean cavity (using AUVs, seismics, radar, gravity and autonomous atmospheric-ice-ocean stations with borehole-deployed ocean instruments). We will integrate these observations with broader continental shelf observations (obtained through ship-based surveys and seal tagging), existing and concurrent moored time series, and the historical CTD database.

Specifically, **TARSAN will examine spatial and temporal linkages among atmosphere, ocean, and ice by collecting both long-term continuous observations at two sites coupled with targeted short-term regional observations. We will relate circulation**

beneath the ice shelves to the basal melting and glacier response to that circulation, including the effect of tides, seasons, and strong synoptic storms on the sub-shelf environment. TARSAN will allow us to assess the current CDW-driven change within the Thwaites Glacier system and to imply potential change for differing future geometries.

Our **specific research questions** are:

1. Ice-Dynamic Response: How are outlet glaciers and ice shelves in the Thwaites-Dotson system evolving at the present time? What are the impacts of the inferred high basal-melt rates on the ice shelves and at the grounding lines? How important to ice dynamics are local processes (such as basal channel evolution or presence of fast ice) and local geometry (such as pinning points) compared with larger-scale or spatially integrated processes (such as atmospheric forcing)?
2. Ocean Drivers and Sub-Ice-Shelf Circulation: What processes influence the exchange of heat and water masses (including CDW and melt water) between the Amundsen Sea continental shelf and the cavities beneath different ice shelves (emphasizing the ocean connections between the ice-shelf edge and grounding line)?
3. Atmospheric Drivers: Which atmospheric conditions determine the circulation into the cavity and incur greater basal melting? Which weather events promote large snowfall on the ice shelves, and which events induce surface melting? Do these atmospheric phenomena act uniformly across the region, or are there important spatial variations across the Thwaites-Dotson system? How are these locally measured patterns and processes linked to SAM, the position of the ASL, ENSO or other teleconnections?

TARSAN will answer these questions through Tasks 1-6, identified in the accompanying Project Management document, and cross-refer to delivery of these Tasks in the sections below. To deliver these Tasks,, we have a group of **research objectives**:

1. Collect the first co-temporal atmospheric, surface, englacial, and sub-ice-shelf ocean observations on Thwaites and Dotson Ice Shelves by installing automated multi-sensor stations with instrumentation on the surface, in the shelf ice, and in the ocean cavity (AMIGOS-IIIs: see later section). By connecting with undertaking AUV surveys of the cavities and firn core studies on the surface, we can evaluate the relationship between weather/climate forcing, ice surface and basal conditions, tidal forcing, and sub-ice-shelf oceanographic flow, and extract detailed sub-ice-shelf melting rates;
2. Measure repeatedly the flux of heat, freshwater and tracers (such as dissolved oxygen and noble gases) across ice-shelf fronts and assess the importance of turbulent mixing processes in altering the water mass properties entering and leaving the ice-shelf cavities; thus evaluate the dominant forcing mechanisms driving the variability in the heat flux entering the cavities;
3. Conduct the first ground-based geophysical surveys of the Eastern Thwaites and Dotson Ice Shelves, integrate with existing and new Thwaites surveys to define ice-shelf geometry, ice-shelf internal layering and basal structure (using ground-based radars); firn melt layer structure (using shallow cores and radar); sub-ice-shelf cavity geometry (using radar, active seismic profiles, and gravimetry); and determine ice flow constraints (GPS and remote sensing);
4. Provide the broader context of ice-shelf dynamics, atmospheric forcing, and ice and ocean properties (including the role of sea ice; Pettit et al., in prep) through monitoring and analysis of remote sensing data, available mooring data (Figure 1), ship-based multidisciplinary surveys and seal tagging throughout the five-year study; and
5. Integrate and share these new observations with other related field, remote sensing, and oceanographic data through the science coordination office and through our international collaborations.

TARSAN will address multiple target themes stated in the NSF-NERC call, to reduce the uncertainty of the WAIS contribution to global sea-level rise:

Boundary Conditions: We propose to further define the geometry of the ice-shelf cavities, measure ocean properties under the ice-shelf cavities, constrain dynamics of ice-sheet grounding line behavior, and detail the sub-daily connections between the atmosphere, ice, and ocean.

External Drivers of Change: Oceanographic measurements on the continental shelf coupled with AMIGOS-III will elucidate the link between atmospheric and oceanic drivers of change.

Processes Leading to Collapse: By studying behavior of two ice-shelf grounding line environments, affected by similar atmospheric conditions and upstream ice dynamics, but influenced by different submarine trough environments, we can better distinguish important processes and geometries. Our results will contribute to understanding current and future grounding-line dynamics as the Thwaites grounding-line geometry changes over the next several decades.

Forecasts for Future Change: Our observations and process studies will provide constraints for diagnostic and predictive modelling studies.

Table 1: **AMIGOS-III Proposed Design Components**

Structure, Power, and CPU
- •CPU: Student-designed single-board computer, ethernet, serial, and USB ports;
- •Iridium-NEXT modem and antenna;
- •10 cm tubular design, 2 m sections, total 6 m installed (1 m sub-surface, 5 m exposed);
- •Li batteries for winter; 4x100 amp-hr Pb gel-cells; 2 x 80 W solar panels.

Imaging: Surface /Sky condition
- •Camera system, station view mirror, flag line (not shown)

Weather / Climate
- •Vaisala WXT520 weather station, 2 m;
- •R. M. Young propeller wind-vector system at top of mast

Ice Motion and Strain Sensors
- •Dual-Frequency GPS – Topcon GRS-1 rcvr, PGA-1 ant.;

Snow-Firn Energy Balance Sensors
- •Albedometer (dual Apogee SP-212 all-sky lightmeters);
- • Campbell Scientific sonic snow-height sensor or similar
- •50-meter string, 8 PRT sensors.

Ice and Sub-Ice Ocean Sensors
- •DTS laser fiber optic cable thermal profiling system;
- •2 SeaBird MicroCAT SBE-37IMP CT sensors, 1 w/ press;
- •2 Nortek Aqua-Dopp Doppler current meters;

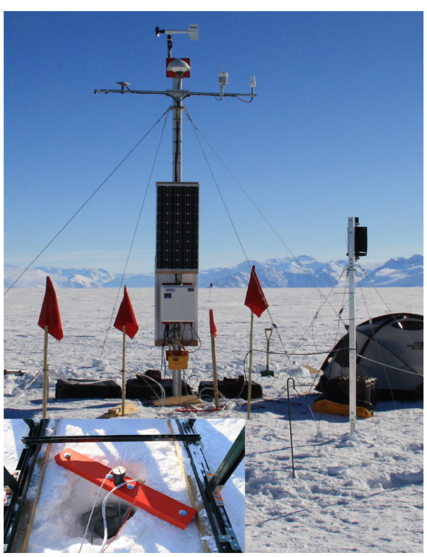
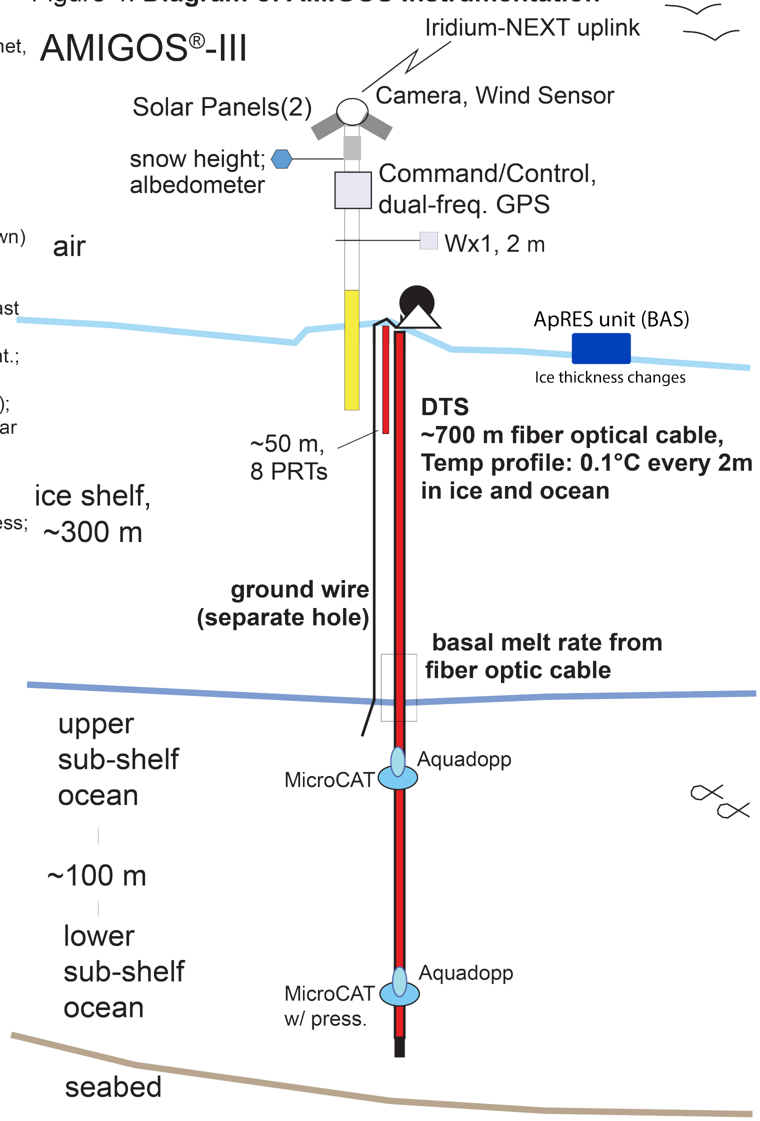


Figure 4: **Diagram of AMIGOS Instrumentation**



Research Components and Specific Plan

Atmosphere to Ocean Connection (Lead PIs: Scambos, Truffer; Tasks 1-3):

AMIGOS-III: Automated Meteorology, Ice, Geophysics, and Ocean Sensors are autonomous, Iridium-uplinked multi-sensor geophysics and weather measurement systems, similar in footprint and concept to an Automated Weather Station, but with a larger array of sensors for surface and near-surface glaciological investigation (Scambos et al., 2013). There are now 12 active AMIGOS stations installed in a wide variety of settings, from penguin colonies, to glaciers, to skiway sites in the Transantarctic Mountains. One key component of the stations are digital cameras capable of recording and transmitting surface changes and weather conditions.

Earlier AMIGOS were aimed at measuring surface and glaciological conditions, with limited subsurface temperature profile information. In February 2017, the first AMIGOS-II, designed to record ice and ocean conditions using both conventional ocean instrumentation and a thermal profile of the ice and ocean using a laser-stimulated fiber-optic Distributed Temperature System, was installed on the Nansen Ice Shelf near Terra Nova Bay. Access to the ocean cavity was provided by hot-water drilling conducted by UAF (Truffer), as is planned for this project. The AMIGOS-II was developed under an EAGER award from NSF, and installation was supported by the Korean Polar Research Institute (KOPRI). At the time ofs of this writing, all sensors including the DTS are working and transmitting data in near real time.

For this project, we will use **significantly augmented AMIGOS** (hereafter, AMIGOS-III; see Table 1 and Figure 4)**,** and we will **implement a new computer control system and code designed by a University of Colorado Engineering Department undergraduate team,** coordinated by co-PIs Sanders, Scambos, together with University of Nevada, Reno co-PI Tyler. This undergraduate group is part of the CU Space Grant program. Past Space Grant undergraduate teams have designed and built CubeSat satellites and other high-tech instrumentation successfully.

Several improvements will be aimed at increasing the overall robustness and redundancy, enhancing the power supply, and improving the near-surface science data collected. We will explore the possibility of increasing the data transmission volume using Iridium-NEXT components. We will upgrade the DTS system with a new, less power-consumptive instrument and with a fiber that can be switched to act as a distributed acoustic (seismic) sensor. Modifications to the overall station structural design will facilitate the recovery of key components of the systems at the end of the study. Table 1 shows the main AMIGOS-III components; Figure 4 provides an overview of the system layout. The new command, control, and communications design represents an excellent undergraduate experience in automated system design.

The Iridium connectivity of the AMIGOS-III is a key aspect of its reliability and energy efficiency. Iridium comms to date have allowed uploading of approximately 75 kbytes per day. We will aim to increase this to ~400 kbytes per day, to facilitate more detailed GPS and DTS data uplinks. Significant amounts data will be transmitted in single-burst mode allowing up to 1800 bytes per communication (potentially 20 kbytes per day). The Iridium systems also facilitate system re-configurations, e.g., for setting station and uplink demands to use lower power during winter, or for more intensive observations during periods of interest.

The AMIGOS-III ocean sensor string (Fig. 4) will consist of 2 Micro-CAT (conductivity and temperature) sensors (Seabird SBE-37-IMP), located at ~30 m below the ice base and ~30 m above the seabed. The sensors will include pressure measurement to determine the approximate drift of the string due to currents. Two current meters (Nortek Aquadopp IM-400) will be installed near the upper and lower Micro-CATs to record ocean current and direction. Overall, the system will document the ocean flow, water mass mixing, and the dynamic and thermodynamic variability of the sub-ice-shelf cavities. To further investigate basal melt rates and other properties (fracturing, basal shear at the grounding line; Pettit, 2012; Pettit et al., 2015), we will install a single hydrophone (HiTech HTI-92WB) on each ocean string. All CPU, peripheral systems, and surface sensors will be tested to -40°C separately and as assembled systems, as well as undergoing thorough operating tests prior to deployment at NSIDC and at CU's Engineering Department.

Finally, two Automated phase-sensitive Radio Echo Sounding (ApRES, Corr et al., 2002) systems designed by BAS, adapted for independent operation and overwinter data collection, will be left near two of the AMIGOS-III to provide two years of continuous ice thinning rate data at high (mm per day) precision. These units can be linked to the AMIGOS-III via an Ethernet cable and the data can thereby be uploaded in near-real-time.

Hot-water drilling system for access to the sub-ice-shelf cavity. The UAF hot-water drill will be used to access the ocean cavity. Each drill site will consist of two holes. A small diameter hole (13-15 cm) will be used to install a grounding wire for the inductive modem that will be used to relay oceanographic data to the surface installation of the AMIGOS-II. A larger diameter hole (20 cm) will be used to install the oceanographic instruments and an integrated DTS fiber-optic temperature profiler for the ice and ocean layers. This plan is very similar to what UAF successfully used in 2012/13 on Pine Island Glacier, with very similar observational goals (Stanton et al., 2013). We also just completed the installation of a AMIGOS-II through 400 m of ice at the Nansen Ice Shelf. The UAF hot-water-drilling system is modular, so it can be traversed by snow machine or airlifted by helicopter or Twin Otter aircraft.

Oceanography (Lead PIs: Heywood, Hall, Boehme; Task 2)

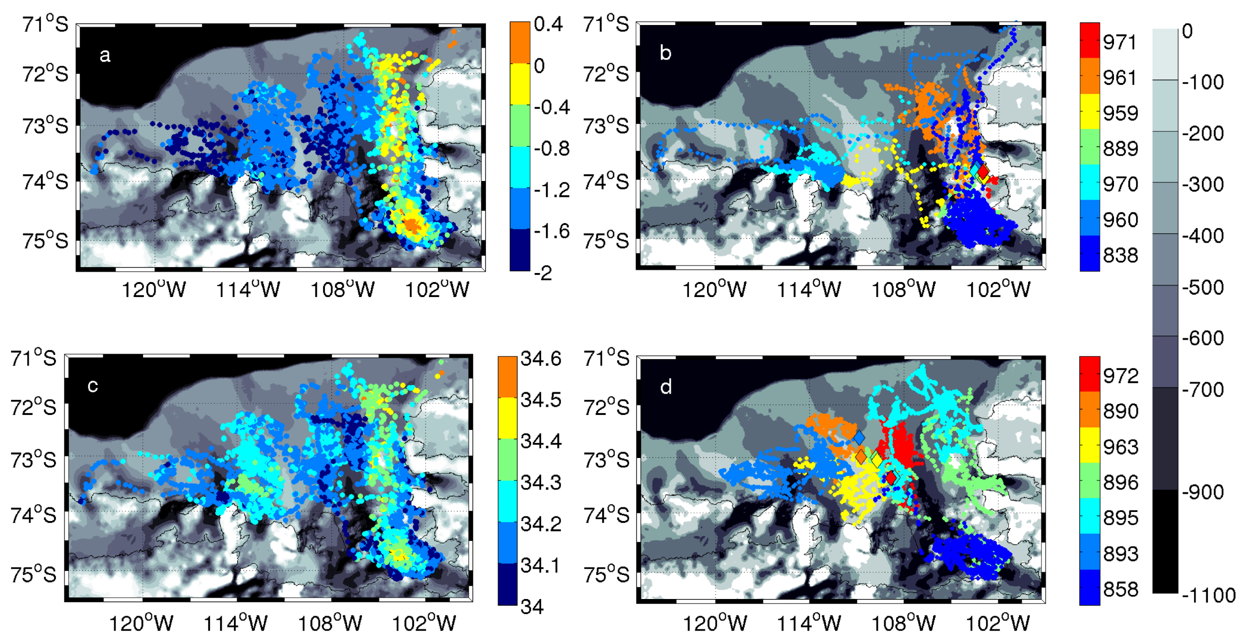
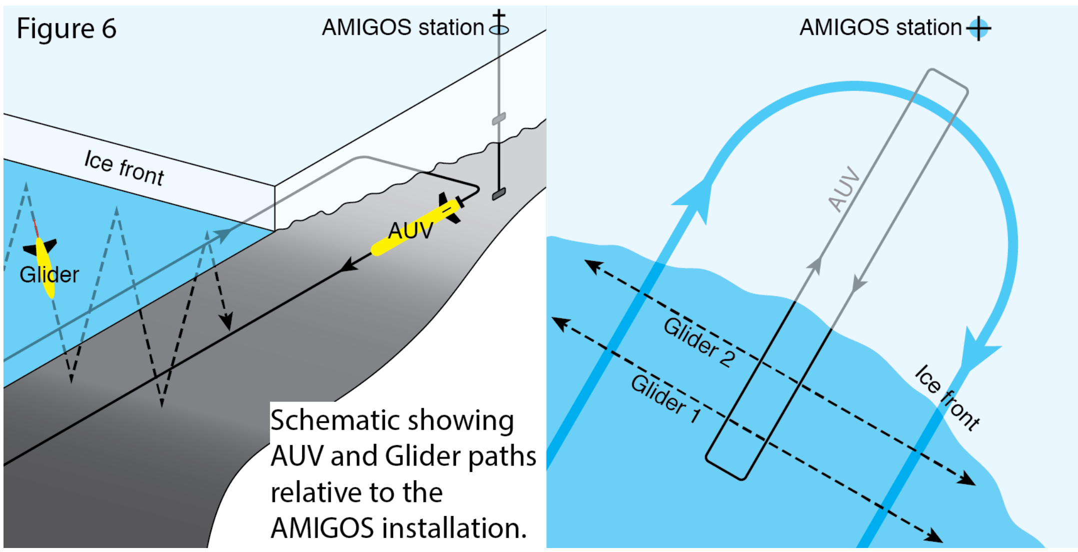


Figure 5. Seal tag data from 2014. (a) Potential temperature; (c) salinity at 300 m (Heywood et al., 2016); Tracks of (b) Elephant and (d) Weddell seals, diamonds are tagging location, colored dots are tag number.

TARSAN will document and study the circulation of water masses beneath the ice shelves and in their surroundings on the Amundsen Sea continental shelf. We will repeatedly measure the flux of heat, freshwater and tracers (such as dissolved oxygen and noble gases) across the two ice-shelf fronts, and assess the importance of turbulent mixing processes in altering the water mass properties entering and leaving the ice-shelf cavity. We will assess the variability of the water masses that influence the flow beneath the ice shelves by documenting properties throughout the year in several years. We aim to better understand the processes that bring the heat beneath the ice shelves, the variability of that heat flux, and seasonal/interannual variability in both inflows and outflows of meltwater. Studying two ice shelves will enable study of the role of bathymetry and turbulent mixing to ice flow and grounding line dynamical differences between the ice shelf systems. We will use a combination of techniques:

(i) *tagging seals with temperature and salinity sensors*. Sensors will be glued to the seals' heads each summer, and will transmit temperature and salinity profiles several times each day, until about October, thus providing full depth profiles throughout the winter each year (Boehme et al., 2009). From our experience in 2014 (Figure 5; Heywood et al., 2016), Elephant seals haul out on the Edwards Islands, and we would target these in the first instance. Weddell seals are found on sea ice floes, probably throughout the ASE continental shelf. These two species are chosen because they make relatively deep dives, usually to the sea bed, and remain in the region over winter. 38 tags will allow 12-15 tags in each field season (Figure 5 shows coverage with 14 tags yielding >10000 profiles). The spatial and temporal resolution of this dataset will enable us to investigate the different roles of surface atmospheric and ocean advective fluxes in modifying the waters on the continental shelf before entering the ice-shelf cavities.

(ii) *deploying the Gothenburg AUV* (available through Project Partner Anna Wåhlin, see letter of support) *and the UK's Autosub Long Range AUV*. These state-of-the-art autonomous vehicles will be able to navigate beneath the ice and measure temperature, salinity, current velocity, turbulence, dissolved oxygen and other variables (Dutrieux et al., 2014). They will make surveys, each of several days' duration, at fixed depths and at fixed distances from the ice shelf above them or from the sea bed, at speeds of ~1 m/s. They will bridge the data gap between the ice-front gliders and the through-ice AMIGOS, surveying long sections into the cavity (Figure 6), as was successfully undertaken during our 2014 campaign to PIG (Kimura et al., 2016). The resulting data will be used to evaluate water mass pathways, quantify turbulent mixing, identify forcing mechanisms and their variability.



(iii) *deploying ocean gliders*. These vehicles will make high resolution saw-tooth profiling surveys, with resulting profile spacing of order 1 km (necessary to resolve the small scale processes shown to be important, since the Rossby radius here is of order 1 km; Thompson et al., 2014). They typically travel at 10-20 cm/s vertically and 20-50 cm/s horizontally. They are ideally suited for repeated surveys along the ice shelf front (e.g. Miles et al., 2016), closer to the ice shelf than it would be safe to go with a ship, complementing simultaneous under-ice surveys with the AUVs. Two gliders will be deployed in front of each ice shelf, occupying parallel repeated along-shelf sections that, combined with the under-ice AUV data, will build up a 3-D, time-evolving picture of shelf-cavity exchange (Figure 6). All gliders will measure temperature, salinity, dive-average current velocity, and dissolved oxygen. Geostrophic shear will be referenced to the glider dive-average-current, suitably detided and smoothed, to provide a several-week time series of volume fluxes, heat fluxes and freshwater fluxes across the ice cavity entrance. At each ice shelf, one glider will additionally be equipped with a microstructure sensor system and one equipped with a passive acoustics hydrophone. The microstructure gliders will derive turbulent kinetic energy dissipation rate, diapycnal and isopycnal eddy diffusivity, and turbulent heat fluxes from (a) centimeter-scale velocity shear and (b) micro-temperature over an extended time period, impossible to achieve with a traditional tethered profiler. Passive acoustics will be trialled onboard the gliders as a means of monitoring ice shelf processes such as ice melt and fracturing (Pettit 2012; Pettit et al., 2015).

(iv) *collecting ship-based full-depth profiles of temperature, salinity, dissolved oxygen, noble gases and current velocity* using a CTD-rosette package, and turbulent mixing from a VMP-2000 tethered microstructure profiler. The latter will be used to validate data from the microstructure gliders, and to assess instability processes (Naveira Garabato et al., 2017). High-resolution (~5-10 km station spacing) sections will be occupied across the ice fronts at a safe distance, and along the troughs to the glaciers. Profiles will be used to calibrate sensors on gliders and AUVs. Components of vorticity will be derived and used to assess instability (Naveira Garabato et al., 2017). Noble gases will allow calculation of meltwater fluxes, when combined with geostrophic shear referenced to the Lowered ADCP on the CTD rosette.

(v) exploiting and analysing the array of moorings (providing time series of temperature, velocity and in some cases salinity, at a few depths in the CDW layer) being undertaken by BAS as a contribution to the Thwaites programme, enabling investigation into multi-annual variability of ice-shelf forcing. We will collaborate with KOPRI and Gothenburg to jointly analyse the mooring programmes that they lead in the region of Getz and the central trough.

We will use all the oceanography data sets to calculate the net heat flux entering each cavity. This will allow us to quantify the heat flux variability, and by integrating with the meteorological and glaciological forcing derived in TARSAN, the mechanisms driving that variability.

Ground-based Geophysics and Glaciology (Lead PIs: Pettit, Truffer, Muto; Task 3)

We will focus the ground-based ice surveys at two accessible locations: the eastern Thwaites ice shelf and the central Dotson grounding line because much of the Thwaites ice shelf is unsafe for ground-based surveys. The goal of the geophysics and glaciology data collection effort is to

(i) provide geometric constraints on the ice shelf, ocean bottom, and sub-ice-shelf cavity to provide additional detail to integrate with the BAS airborne survey and to extend coverage to the Dotson Ice Shelf, using *active-source seismics and gravity, as well as low frequency radio echo sounding profiles*;

(ii) capture the ice-shelf internal structure, ice-flow patterns, and changes in sub-ice-shelf geometry to study ice-shelf response to ocean heat transfer, *using high and low frequency radar, high-resolution seismic reflection profiling, phase-sensitive radar, Landsat-derived ice surface velocities supplemented by continuous dGPS and a local GPS strain network;* and

(iii) assess the firn properties across the survey site and their recent change through time to identify frequency and spatial extent of melt events in comparison to snowfall and accumulation patterns, using *shallow firn cores and high frequency radar, coupled with borehole temperature, time lapse imagery, meteorological data collected by AMIGOS.*

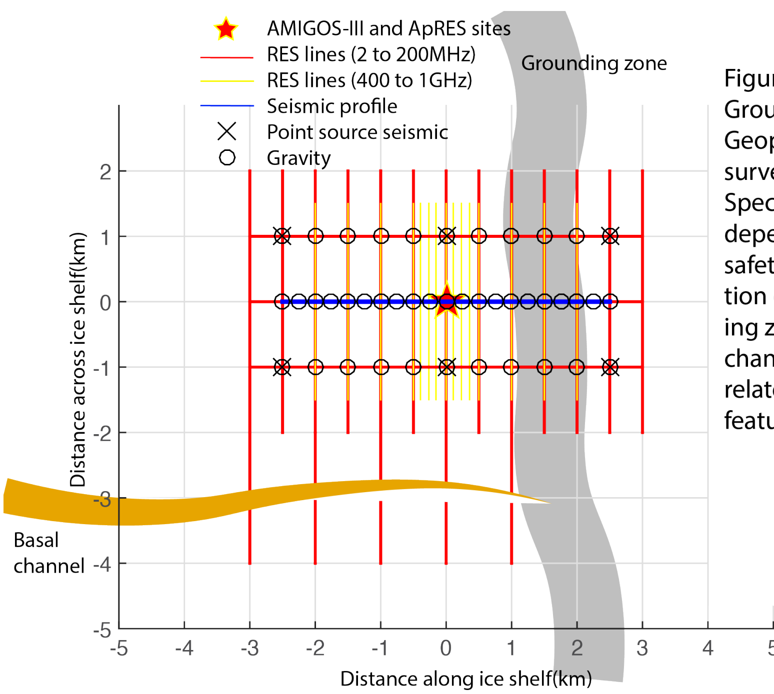


Figure 7 Ground- based Geophysical survey. Specific design depends on safety and location of grounding zone, basal channel, and related features.

Specifically these ground-based surveys (Figure 7) will include two types of active-source seismic surveys at each site: high-resolution reflection profiling survey, straddling the grounding line if possible and point-source soundings for the ocean and ice bottom. For the high-resolution profiling we will use an array of forty-eight 40 Hz single-channel geophones at 20-m spacing, with 0.5-kg explosive shots spaced at 240 m and 10 m deep. For the point-source sounding, we will use a short spread of 12 geophones spaced 1 m apart to record the reflection of a single shot from the ice and the ocean bottom. Each point-source shot will be 0.5-kg buried 5 m deep. The point-source sounding will be conducted at 6 locations (Figure 7). All Shot holes will be drilled with the UAF portable steam drill.We will make gravity measurements along the main seismic line and two additional lines 1 km to each side of the main seismic line, at 500-m spacing (Figure 7) using a Scintrex CG-5 Autograv gravimeter. The gravity survey will be conducted concurrently with the drilling of shot-holes for the seismic survey, such that all seismic and gravity work can be completed within 10 days at each site.

These data, in conjunction with AUV measurements of the ocean-bottom will provide much-desired in situ constraints to improve the Thwaites-Dotson sub-ice-shelf bathymetry as the currently available sub-ice-shelf bathymetry of Thwaites and Dotson Ice Shelves (Tinto and Bell, 2011; Millan et al., 2017) was modeled by inversion of airborne gravity data only. Without in situ ocean-bottom constraints and without accounting for the geologic heterogeneity, inversions can lead to incorrect ocean-bottom depths (Muto et al., 2013, 2016; Brisbourne et al., 2014).

We will use a suite of radio echo sounding (RES) systems from ~5MHz to 1000MHz to capture profiles at multiple spatial resolutions, both parallel and perpendicular to the ice flow direction. Figure 7 shows a nested grid of radar profiles around the AMIGOS site and across nearby basal channels. If possible with respect to safety, additional low frequency profiles will be collected up and downstream. We are collaborating with the British Antarctic Survey to supplement this with a newly designed helicopter-mountain low frequency radar (see letter of support).

Finally, the higher resolution RES (400-1000MHz) data collection will cover a smaller area near the AMIGOS and focus on on identifying melt layers within the firn column (Pettit et al., 2012; Pettit et al, in prep). To aid in interpretation of these radar, e will drill two firn cores 15-20m (depending on firn conditions) deep using a Kovacs ice corer. These will be photographed and measured in the field for density and melt layer thickness and frequency.

Remote Sensing (Lead PIs: Scambos, Lenaerts; Task 3)

NASA's Operation IceBridge, CryoSat-2, ICESat-2, and extensive sub-meter satellite stereo imagery provide new highly valuable information that will extend and provide a context for our ground-based surveys and in-situ instrumentation (as well as provide an assessment of safe areas for the field work). These data sets will be the basis for ongoing dH/dt estimates in the instrumented grounding zone areas of Thwaites and Dotson, integrating our observations and in particular looking for changes in dH/dt associated with persistent climate patterns. We will augment this largely altimetry-based approach for detecting ice mass changes with ice velocity mapping and morphological changes using the Landsat series satellite imagers (L1 to L8) to examine ice flow changes from the 1970s to ~2016 (e.g., Alley et al., 2016). We will also use the MODIS (Moderate-resolution Imaging Spectroradiometer) satellite image record at NSIDC to evaluate ongoing ice edge and structural changes on the ice shelf itself between 2001 and now (see nsidc.org/agdc).

Changes in grounded ice flux are likely being driven by intense sub-ice-shelf melting near the grounding line, which acts to steepen the surface slope near the grounding line and therefore increase the driving stress. As a first task for the proposed work, we will re-measure ice shelf and grounded-ice flow rates using Landsat 8 and meter-scale satellite data to constrain the exact changes in flow speed and strain occurring near the grounding line (Fahnestock et al., 2016; Hulbe et al., 2016).

The timing and distribution of sea-ice cover affects both atmospheric and oceanic processes as they interact with the ice shelf. Further, under certain conditions the presence of land-fast sea ice can contribute to modulating the ice shelf dynamics (Pettit et al., 2016; Pettit et al., in prep). Landsat and MODIS image series will allow us to evaluate the influence of sea ice on the dynamics of this ice-shelf system.

Finally, we will interpret remote sensing imagery (primarily radar backscatter (e.g. Trusel et al., 2013) and microwave brightness temperatures (e.g. Picard and Fily, 2007), partly available since 1979, to infer ice-shelf surface melt timing and spatial patterns, which we can then relate to regional and large-scale atmospheric processes in the atmospheric models, to further elucidate the role of surface conditions in the evolving stability of the Thwaites Glacier system in the future.

Atmospheric Reanalysis and Climate Models (Lead PI: Lenaerts; Task 1)

Atmospheric reanalysis (e.g. ECMWF ERA-Interim, shown to be one of the most reliable reanalysis data sets, Jones et al., 2016) will provide the climatic context for TARSAN. We will take the ERA-Interim reanalysis (Dee et al., 2011) and further downscale it to 5.5 km resolution by the Regional Atmospheric Climate MOdel for the broader Amundsen Sea Region and the period 1979 to present (RACMO2, Lenaerts et al., in prep.). This will allow us to link surface melt and snowfall events on the Thwaites Glacier system to atmospheric drivers. We will then assess the performance of the CMIP5/6 multi-model ensemble in simulating these drivers correctly in the present-day climate, allowing us to select best-performing models. Using these best models, we will analyze future changes of these atmospheric processes according to several global warming scenarios.

Summary of Data Collection and Field Efforts (together delivering Task 4)

	18/19 Season	19/20 Season	20/21 Season	21/22 Season
Ocean-Based Field Work	**James Clark Ross** seal tagging UGOT AUV testing CTDs	**Araon** ice front and subglacial cavity survey seal tagging UGOT AUV *National Geographic Photographer*	**Sir David Attenborough** continenal shelf, ice front, and subglacial cavity survey seal tagging AUVs and gliders CTDs	no ocean-based work
Ice-Based Field Work	Logistics only fuel cache	**Thwaites, Dotson Ice Shelves** AMIGOS-III installation ice-shelf survey radar surveys active seismic and gravity *Doug Fox Science Writer*	no ice-based work	AMIGOS-III recovery

Table 2: Field work plan showing interweaving of ocean and ice observa-tional efforts

The strength of TARSAN lies in the synthesis and interpretation of unique interdisciplinary observations of atmospheric, oceanic, and multi-level ice conditions spanning three years and four Antarctic field seasons (Figure 8) using robust, proven technology that will take advantage of our diverse research-team expertise connecting the atmospheric processes directly to both ice and ocean properties and processes. Oceanographic data collection will start in 2018/19 season with seal tagging, CTDs and Gothenburg AUV deployment utilizing the BAS logistics cruise to the northeastern Amundsen Sea on RSS James Clark Ross. These three TARSAN science tasks will be carried out by 6 people (2 for seal tagging, 3 for AUV deployment, 1 for CTDs and leading the science team), and is expected to take 18 days in total.

The installation of the AMIGOS-III units and geophysical work at two ice-shelf/grounding-line sites will occur in 2019/20 season, with 12 people deploying from the Araon via helicopter or via fixed wing. Over a 12-day period at each site, 4-person team will deploy the AMIGOS, while the radar and seismic/gravity team (3 people each) survey the surrounding area. A science writer will also deploy as part of the 12-person team. We request one camp manager from ASC (or other USAP contractor). The Araon cruise will host the seal tagging (2 people), Gothenburg AUV deployment (Wåhlin collaborator team), and a National Geographic Photographer who is working in partnership with the science writer.

An extensive TARSAN oceanographic science will be carried out in 2020/21 using RSS Sir David Attenborough, with 20 scientists including international partners from Gothenburg and KOPRI. The cruise will focus on deployment of gliders and AUVs, seal tagging, hydrographic surveys along the ice-shelf fronts with CTDs, tethered microstructure profiling, and water sampling for meltwater tracers. Total of 30 days of science close to the ice shelves is expected for this season with ~10 days of seal tagging, ~10 days of AUV deployments/recoveries, ~5 days glider deployments/recoveries and CTD surveys and tethered microstructure profiling occurring throughout the cruise.

AMIGOS-III and ApRES units will be retrieved in 2021/22 season with a team of two scientists and a mountaineer. AMIGOS and ApRES units will be valuable for other projects after the conclusion of TARSAN.

Remote sensing, climate models, and atmospheric reanalysis will be conducted in parallel with the field efforts. These data and analyses will provide initial information to select the safest and most scientifically useful field locations, to improve the field planning and experimental designs, and to provide contextual information for on-the-fly interpretation of field data.

TARSAN Project Synthesis: Deliverables for Climate and Future Sea Level (Tasks 4-6)

TARSAN will combine collected field data (AMIGOS and ocean surveys), atmospheric reanalyses, climate models, and remote sensing estimates of surface melt and sea ice concentration to assess the atmospheric conditions responsible for enhanced CDW intrusions under the ice shelf as well as changing ice-shelf-surface and firn conditions (Task 4). The simultaneous observations of ocean and atmospheric conditions performed by the AMIGOS-III, in combination with the firn cores and ground penetrating radar, will shed light on the local atmospheric phenomena (surface winds and temperatures) that drive changes in ocean conditions close to and under the ice shelves observed through the seal tagging, glider, and AUV campaigns (testing the hypotheses of St-Laurent et al., 2015), and changes to the ice shelf firn properties during snowfall and surface-melt episodes. Next, these local observations will be extrapolated in space and time using the downscaled ERA-Interim reanalysis using RACMO2. This will enable the upscaling of the local ice-shelf observations to regional atmospheric patterns, and link the latter to large-scale atmospheric circulations, in particular the location and strength of the ASL. On an even larger scale, we will relate ASL dynamics to climate oscillations acting on the Southern Hemisphere (El Nino Southern Oscillation, Southern Annular Mode). These results will allow us to link temporal and spatial variations in CDW under Thwaites/Dotson ice shelves to local and regional atmospheric circulations, and potentially global climate indicators.

The atmospheric and oceanic forcing of the system lead to surface melt and basal melt, respectively, which cause thinning of the ice shelf, release of bedrock pinning points, and grounding-line retreat and lead to instability in the glacier system. TARSAN will document the ice surface, basal, and flow changes in the two ice shelves over the period of the project using remote sensing and AMIGOS-III data sets. These documented changes provide the observations to allow TARSAN and other researchers to link ice to the atmospheric and oceanic drivers discussed above, and, ultimately, to provide the observations to constrain and calibrate ice-sheet models by other researchers.

High precision GPS from the AMIGOS-III, in the context of Landsat-derived velocities and high resolution imagery of surface features, will allow TARSAN researchers to use process modeling to improve our understanding of triggers and responses in the ice-shelf system. This understanding of the relation between triggers and responses within the ice-shelf system is a key reason for our choice to study two ice shelves, not just one. Ultimately, this will help improve parameterizations for processes within ice-sheet models.

Combining the downscaled atmospheric reanalysis with the longer history of Landsat and MODIS imagery and the firn cores and high frequency RES, we will assess the changing magnitude of surface melt over the last one to two decades and infer its impact on ice-shelf stability. Ultimately, this will provide key data for and improve our understanding of the role of surface melt as a surface boundary condition for ice-sheet modeling of the Thwaites Glacier.

Finally, we will assess the ability of CMIP5 and CMIP6 (available 2018-2019) climate models to simulate these linkages. The CMIP5 models currently represent ocean processes on the continental shelf poorly (Heuzé et al., 2013, 2015) but are now adding interactive ice shelves. TARSAN will provide a unique opportunity to confront these models with simultaneous multi-year data in ocean, ice and atmosphere. The best performing models will be selected to provide a perspective on the expected 21st century changes in atmospheric drivers of conditions above and beneath ice shelves; ultimately, improving projections of future sea level rise.

Broader Impacts and Educational Outreach

Impacts for Society: Coastal regions worldwide will be impacted by sea-level rise. In some regions around the coastal U.S., the sea-level rise resulting from the loss of the Amundsen Sea sector of the West

Antarctic Ice Sheet will be amplified by as much as 30% (Hay et al., 2014). Understanding the rate and timing of future collapse of the Thwaites basin and the Amundsen Sea sector is, therefore, critically important for local and national policymakers for mitigation and planning for coastal communities everywhere.

Impact for Science Community: The autonomous ice/ocean stations to be developed (AMIGOS-III) will be a major step forward in ice-ocean system monitoring, providing a wide array of data from a relatively inexpensive, intelligent, and easy-to-manage system. Further, the full TARSAN data set, including AMIGOS-III data set will be a rich source for future studies such as surface energy balance models, ocean mixing models, major weather patterns producing anomalous snow accumulation or surface surface. Glider profiles, specifically, will be transmitted in real time on the GTS and will be freely available to improve weather forecasts. The AMIGOS, seal tagging and autonomous vehicle campaigns will inform and optimise the design of cost-effective ocean monitoring networks such as the Southern Ocean Observing System (SOOS). This project also strengthens international collaborations with the inclusion of Korean and Swedish researchers in all aspects. While TARSAN does not address the issues of marine ecology, our data will be offered to seal biologists to study the importance of the physical environment on the animal's general well-being because little is known about how the temporal and spatial changes in the marine environment on the Antarctic shelf influence such top predators.

Broadening Participation: The lead PIs are both women, and the leadership team as a whole has a strong reputation for mentoring women in science from K-12 through graduate school. These efforts will continue specifically with Pettit continuing to oversee Inspiring Girls Expeditions (Girls on Ice, Carsten Conner et al., in review), which includes mentoring 10 to 15 early career scientists who are gaining leadership and teaching experience from this program.

Mentoring future Scientists and Engineers: The project supports multiple graduate students and post-doctoral researchers both in UK and US, and will provide a unique opportunity for an undergraduate engineering group at University of Colorado's Space Grant program. While the proposed research is expected to produce results of high scientific and societal importance with immediate impact, it is important to foster next-generation scientists and engineers who will identify and answer further scientific questions or meet the instrumentation challenges of tomorrow, and keep contributing to the society at large in the future. This project will provide a unique opportunity for graduate students and early-career scientists to experience first hand how to carry out field scientific research in Antarctica using cutting-edge technologies with established scientists in an international setting.

Public Engagement and Educational Outreach: Science writer Doug Fox (inc. National Geographic, Discover, and Scientific American) will be embedded with the field team and write a **series of articles highlighting the science and the societal impacts of this work**. Fox's focused, in-depth coverage of the research will be coupled with **a social media campaign**: "Live from the Ice". This social media campaign will include a weblog and Twitter feed that tells stories and announces intriguing observations in real time based on the measurements from the Iridium-uplinked AMIGOS-III data and tagged seals. The general model will follow the highly successful NSIDC Arctic Sea Ice News and Analysis website and the NASA Curiosity "Martian Diaries" , and @MarsCuriosity Twitter feed. The website will be hosted by NSIDC and include discussion of background concepts relating ice-shelf, ocean, and atmospheric processes. Monthly entries will include blogs, video blogs, or short educational videos, depending on the content and message, geared toward middle-school level science students and the science-interested public. The blog, Twitter feed, and other social media would be told from the perspective of sensor system at the edge of the ice, a tag on a seal, or the Autosub. The topics would range from the 'personal' – such as describing a storm or a cold weather event in the context of the Antarctic climate – to the expansive, such as discussing the Antarctic ice-sheet, climate change, and ocean conditions and events. One targeted audience for the blog is middle and high school students. Members of the public will be able to "adopt" a seal, and see the location of their seal on the website in real time, with the warmest and coldest water they encountered and the depth they dived to, superimposed on a sea ice image each day. We will publicize the social media feeds through the US National Science Teachers Association and UK Teacher-Scientist Network, and provide an alternative email listserv for teachers to follow all "Live from the Ice" stories. We will engage with the public early on in the project so that they can follow the project from start to finish. For selected stories, we will provide an annotated spreadsheet file with data, calculations, and plots for teachers to integrate into their teaching activities. AMIGOS-III and seal-tagging data including movement patterns of the seals will also be presented as interactive displays for schools and public science meetings incorporating live data feeds.The collaborative team members regularly participate in K-12 outreach efforts through local school presentations and field workshops, and would continue to conduct these during the proposed work.

Results from Prior Support

T. Scambos, E. Pettit, M. Truffer, E. Mosley-Thompson, and A. Gordon (B. Huber) *Collaborative Research in IPY: Abrupt Environmental Change in the Larsen Ice Shelf System, a Multidisciplinary Approach – Cryosphere and Oceans, 05/01/08-04/30/14, $2,550,000.* **(***Scambos, T., NSFPLR- 732921, CU $693787; Pettit, E., NSFPLR-855265, UAF, $228283; Truffer, M., NSFPLR-732602,UAF, $308367)*

Intellectual Merit: The LARISSA (Larsen Ice Shelf System, Antarctica) project studied sites of dramatic glaciological response to climate change in the northern Antarctic Peninsula. The primary goal was an improved, integrated understanding of ongoing and recent past changes in the ice, ocean, and biological systems. Despite challenging sea ice conditions significant glaciological data were collected, and oceanographic data collected from the Larsen A region and in the western fjords is contributing to an understanding of the relative importance of ocean versus atmospheric change in causing the collapse of the Larsen A and B ice shelves.

Broader Impacts: A major **article in *Scientific American*** was published in July 2012 discussing LARISSA and Antarctic climate change in the region. LARISSA contributed to undergraduate student experiences with Antarctic data and field work (Anika Petach, U.Colo.; Jason Theis, U.Alaska). LARISSA also supported a field workshop in glaciology for undergraduate students led by PI- Pettit.

Products: The CryO group acquired the LARISSA Site Beta ice core at the summit ridge above Leppard Glacier (447m to bedrock), began ice analysis, and completed a paleo-climate study based on borehole thermometry (Zagorodnov et al., 2012). Site selection work for the ice core (Pettit, Scambos) led to a 2-D ice flow model through the northern Antarctic Peninsula at ~66°S spanning the western and eastern Peninsula (Pettit et al., in prep.). The team also conducted a radar, GPS, and remote sensing survey of Röhss Gl. on James Ross Is. (Glasser et al., 2011). We installed 4 multi-sensor systems (Automated Met-Ice-Geophysics Systems, AMIGOS; see Scambos et al., 2013), 2 ice-site GPS stations, and 2 passive seismic stations at key sites, at the Site Beta ice core, Flask and Leppard Glaciers, Scar Inlet Ice Shelf, Foyn Point, and at Cape Disappointment overlooking the Scar Inlet Ice Shelf. AMIGOS have documented the Scar Inlet tidal range (max 3 m) and its increasing flow speed and modulation by fast ice (Pettit et al, in prep). Current Scar Inlet activity is still being tracked by AMIGOS and that föhn winds locally amplify regional warming (Scambos et al, 2012; Cape et al., 2015).

A. Muto, *Revealing Late Holocene Climate Variability in Antarctica from Borehole Paleothermometry, PLR- 1619793, $53,186, 10/20/15-06/30/17.*

Intellectual Merit: This project entails collection and analysis of data from automated firn thermal profiling units deployed in East Antarctica. The main goals are to further constrain the ~50-year surface temperature trends in the interior of Dronning Maud Land, and to compare them with satellite thermal infrared data. The project also involves preparing for possible temperature-logging in the existing deep boreholes at Dome Fuji in the near future. *Broader Impacts*: PI has made multiple visits to middle and high schools in Philadelphia and south-eastern PA to give presentations on polar research and climate change, and using research results in his teaching of undergraduate and graduate classes at Temple. *Products*: Firn-temperature data are being collected and part of the data has been submitted to NSIDC for public release.

J. Lenaerts, *No previous NSF support.*