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Collaborative Research: Norwegian-United States IPY Scientific Traverse: Climate Variability and Glaciology in East Antarctica

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Final Report for Period: 02/2011 - 01/2012

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Principal Investigator: Hamilton, Gordon S.

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Organization: University of Maine

Submitted By:

Hamilton, Gordon - Principal Investigator

Title:

Collaborative Research: Norwegian-United States IPY Scientific Traverse: Climate Variability and Glaciology in East Antarctica

Project Participants

Senior Personnel

Name: Hamilton, Gordon

Worked for more than 160 Hours: Yes

Contribution to Project:

Dr Hamilton was the principal investigator for UMaine activities. He conducted data analysis, interacted with other US and Norwegian investigators in joint interpretation of results, and advised a graduate student working on the project.

Post-doc

Graduate Student

Name: Hall, Monica

Worked for more than 160 Hours: Yes

Contribution to Project:

Monica Hall was a graduate student in the Glaciology group at UMaine. She was awarded an MS in Earth Sciences for her work on accumulation rate variability across Antarctica derived from analysis of Ground Penetrating Radar (GPR) data collected during over-snow traverses (US ITASE and US-NO traverse). Dr Hamilton was her thesis advisor. Her principal activities were the development of a suite of software to automate the processing and calculation of accumulation rates from GPR, GPS and ice core data collected along traverses, subsequent analysis and interpretation of the results, and preparation of findings for peer-reviewed publication.

Name: Breton, Daniel

Worked for more than 160 Hours: No

Contribution to Project:

Dan Breton was a PhD student in the Glaciology group, advised by Dr Hamilton. His was mainly engaged in the analysis of firm properties along US ITASE routes, but he contributed to this project by writing software to automatically scan and geolocate stratigraphic horizons contained in GPR data.

Undergraduate Student

Name: Berry, James

Worked for more than 160 Hours: Yes

Contribution to Project:

James Berry recently graduated from UMaine with a BS in Earth Sciences. For the last two years of his degree studies, he worked in Dr Hamilton's laboratory, mostly on digitizing and processing GPR data. He used project data in one class project and his capstone thesis.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

US Army Corps of Engineers

We collaborated with Dr Steven Arcone of the Army's Cold Region Research and Engineering Laboratory (CRREL). Dr Arcone loaned the ground penetrating radar for field data collection, and co-advised Monica Hall (project graduate student) on data analysis techniques.

Other Collaborators or Contacts

We collaborating with other investigators from the US and Norway. Particularly strong collaborations were formed with Jon Ove Hagen (University of Oslo), Svein Erik Hamran (Norwegian Defense College), and Jack Kohler (Norwegian Polar Institute), and Tom Neumann (NASA) and Mary Albert (Dartmouth) for the purpose of designing radar and ice dynamics experiments for the field, and analyzing radar data.

Activities and Findings

Research and Education Activities:

Our principal activities were:

- (1) planning of oversnow traverses to map snow accumulation distribution in East Antarctica using ground-penetrating radar (GPR) methods;
- (2) development of a software package for extracting accumulation rates from oversnow GPR profiles;
- (2) analysis of data collected on traverses originating at South Pole;
- (3) training of a graduate research assistant in geophysical glaciology.

Findings: (See PDF version submitted by PI at the end of the report)

See attached.

Training and Development:

The project provided an opportunity for graduate student research in a multi-disciplinary and international setting. Monica Hall carried out studies of Antarctic accumulation process and patterns using radar data collected during the field traverses. It also increased our level of international collaboration.

Outreach Activities:

We contributed to IPY-related outreach activities developed as part of the US-Norway traverse. We also participated in several polar education workshops/visits at regional schools in Maine and incorporated traverse science into the the Climate Science education day at our institute in May 2010 and June 2011.

Journal Publications

Hall, M.L.; G.S. Hamilton; S.A. Arcone, "Accumulation Rate Variability along Norway-US Traverse Route, East Antarctica", Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract C31D-0460, p. 1, vol. 90(52), (2009). Published,

Palmer (Hall), M.L., G.S. Hamilton, S.A. Arcone, V.B. Spikes, D. Breton, "A computer method for deriving snow accumulation rates from ground-penetrating radar profiles over ice sheets", Computers and Geoscience, p. , vol. , (2012). Submitted,

Palmer (nee Hall), M.L., G.S. Hamilton, S.E. Campbell, S.A. Arcone, and J.L. Berry, "Accumulation Rate Variability along Norway-US Traverse Route, East Antarctica", Journal of Glaciology, p. , vol. , (2012). Submitted,

Bindschadler, R.A., H. Choi, A. Wichlacz, R. Bingham, J. Bohlander, K. Brunt, H. Corr, R. Drews, H. Fricker, M.L. Hall, R. Hindmarsh, J. Kohler, L. Padman, W. Rack, G. Rotschky, S. Urbini, P. Vornberger, and N. Young, "Getting around Antarctica: new high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic ice sheet created for the International Polar Year", The Cryosphere, p. 569, vol. 5, (2011). Published, doi:10.5194/tc-5-569-2011

Books or Other One-time Publications**Web/Internet Site****URL(s):**

http://gcmd.nasa.gov/getdif.htm?hamilton_0538422

Description:

Global Change Master Directory entry for project data.

Other Specific Products**Contributions****Contributions within Discipline:**

Our work further developed the procedures for radar mapping of ice-sheet accumulation rates, and the analysis of those data.

Contributions to Other Disciplines:

Maps of the spatial and temporal distribution of snow accumulation across swaths of East Antarctica are an invaluable contribution to wider global climate change science.

Contributions to Human Resource Development:

A graduate research assistant was engaged fulltime on this project. Monica Hall graduated with an MS degree in Earth Sciences. During her time as a student, she receiving advanced training in electromagnetic imaging methods, scientific computing, and quantitative data analysis.

Contributions to Resources for Research and Education:

We enhanced our capability to perform geophysical imaging of ice sheet shallow sub-surfaces. Data collected as part of this project was incorporated into the undergraduate and graduate-level courses taught by the PI at UMaine.

Contributions Beyond Science and Engineering:**Conference Proceedings****Categories for which nothing is reported:**

Any Book

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference

OPP-0538422 FINAL TECHNICAL REPORT

1. Introduction

The mass balance of an ice sheet is the difference between the input from snowfall and the loss due to ice flow. While significant improvements have been made on quantifying the mass loss component by remote sensing of ice flow, relatively little is known about the distribution and variability of snowfall. The size and remoteness of the ice sheets present logistical challenges to data collection. Also, it is well known that snow accumulation rates vary over small distances which complicates the extrapolation of point measurements, such as from ice cores, into regional averages. Instead, spatially extensive high-resolution measurements are necessary to constrain the mass input across the ice sheet. As part of this project, we have developed an efficient method for obtaining accumulation rates from high-resolution ground-penetrating radar (GPR) profiles.

Differences in density with firn depth create dielectric contrasts which reflect varying amounts of transmitted electromagnetic energy, yielding bright and dark layers (strata) in a depth profile. These strata persist for hundreds of kilometers and are known to be isochronal. Widespread horizontal continuity creates the opportunity to investigate spatial as well as temporal variations in accumulation rates using radar profiling.

We developed a new method for extracting high-resolution accumulation rates from ground-penetrating radar profiles. We define high resolution as sampling of horizons at a horizontal spacing of 10–20 m. Our method requires a combination of GPR, global-positioning system (GPS), and ice core data and is successful at capturing small-scale spatial variability as well as decadal-centennial variability in snowfall. A suite of software tools enables the calculation of annually averaged accumulation rates for different time spans. While the methods and software were developed for ground-based data collection in Antarctica, they applicable to similar data sets collected in Antarctica and Greenland by airborne surveys such as Operation Ice Bridge.

2. Methods

Our method combines geolocated GPR data with ice core data to yield horizontally continuous profiles of accumulation rate averaged over various time intervals. The key is that layers, manifested by GPR reflection horizons, are isochronal (i.e., of the same age) . Several sets of observations and processing steps are involved as discussed below.

2.1 GPR Data Preparation

The GPR data were collected with a commercial antenna unit (GSSI Model 5103) operating at 400 MHz controlled by a GSSI Sir10B (from Geophysical Survey Systems, Inc.). Our method applies to other radar instruments and frequencies. The antenna unit contains both transmit and receive antennas, and was mounted in a sled that was attached to a traverse vehicle. The relatively steady pace of the tow vehicle produces an evenly spaced series of traces that we geolocate with GPS data. In this case 1 trace was generated approximately every 10 m along track.

The radar signals were recorded to approximately 120 m depth. Standard methods are used for post-processing the radar profiles. The sampling rate during the traverse was 8192 samples per trace and 16 bits per sample. Traces were then stacked to remove noise and to improve layer resolution. Two vertical filters and a horizontal stack were applied to the radar profiles to reduce signal noise. A Hilbert magnitude transform was used to enhance visual quality.

2.1 Layer Tracing

After processing radar profiles for noise reduction and visual enhancement in proprietary software, we export them to a generic open-source format (e.g. flat binary, or SEG-Y), then read the images into standard digitizing software (e.g. Surfer, ENVI, etc.) to extract distance and depth data. Each radar profile is composed of hundreds of horizons which, coupled with the lack of a robust layer-tracking algorithm, poses a challenge to digitizing. Our approach is to digitize layers using a semi-automatic method applied pixel by pixel along the entire GPR profile for each chosen horizon. The first step is to manually trace chosen horizons, which can be done quickly. We choose to trace only a few high amplitude horizons spaced approximately evenly in time, which satisfies our science goals. In principal, our software tools also apply to profiles with many chosen horizons. Second, a simple pattern recognition script written in Python assigns pixel coordinates to the manual outline. The advantages of this method are that an operator is able to quickly, accurately and consistently follow each horizon, and the script quickly extracts the spatial information. This process yields a set of precise values of two-way travel time, t , for each digitized horizon at every GPR trace along the entire profile.

2.2 Density Correction

The propagation speed of the radar signal is a function of the density of the medium through which it travels. Thus, two-way travel times need to be converted to depths using depth-density profiles. These profiles come from ice cores obtained along the GPR tracks. We can calculate the two-way travel time of the radio wave from the surface to any depth in the firn using the well-documented relationship between firn density and the real part of the dielectric constant. Thus we can derive the depth and age of each digitized horizon by re-sampling the ice core ages by time (ns). Densities are also re-sampled by depth so the total mass above each horizon can be calculated.

2.3 Geolocation of Stratigraphy

Kinematic GPS data were collected by a dual-frequency receiver mounted on the traverse vehicle. The sampling rate was every 30 s, corresponding to an along track spacing of 42 m at usual traverse speeds (~5 km/hr). Data were post-processed using standard kinematic methods to yield three-dimensional coordinates for each sampling epoch (and hence each radar scan) along the traverse route.

We transformed the post-processed GPS data from geodetic coordinates (latitude, longitude, and elevation) to a polar stereographic projection (in meters). Polar stereographic coordinates allow us to use a simple distance formula to calculate the distance traveled between two measured positions along the traverse. In order to geolocate the GPR data, we re-sample the GPS coordinates to every radar trace along the traverse given the known rate of trace acquisition, in this case approximately 1 trace per 10 m.

2.4 Calculating Accumulation Rates

An ice-core's depth-density profile is a function of local conditions such as temperature and accumulation rate, so we expect it to vary between collection sites. GPR surveys are designed to intersect ice core collection sites at intervals of 100-300 km. We use a weighted average of the depth-density profiles from the bounding ice cores based on the distance from each core site. We

also use the distance-weighted average depth-density profile to convert the thickness above the horizon into a mass. Dividing the total mass above the horizon by its age at each trace yields the average annual accumulation rate at every trace along the traverse. We repeat this process for each digitized horizon and for each segment, resulting in average annual accumulation rates for a range of time periods along the traverse route. For a ~100 km segment, this can represent 8–10 thousand accumulation rate samples, which provides a robust data set for the investigation of spatial and temporal variability.

We wrote a suite of software to perform these calculations in Matlab (Figure 1). The software is designed such that users of any skill level can use it if the appropriate data files are available. We divided the graphical user interface (GUI) into four sections corresponding to the three preparatory steps described above and the final calculation of accumulation rates. Required user inputs consist of descriptions of data files (i.e. the number of rows in the data set or the number of years covered by the data), descriptions of the traverse or flight line being analyzed (i.e. length), and the assigned dates (i.e. 1982 AD) of the GPR horizons.

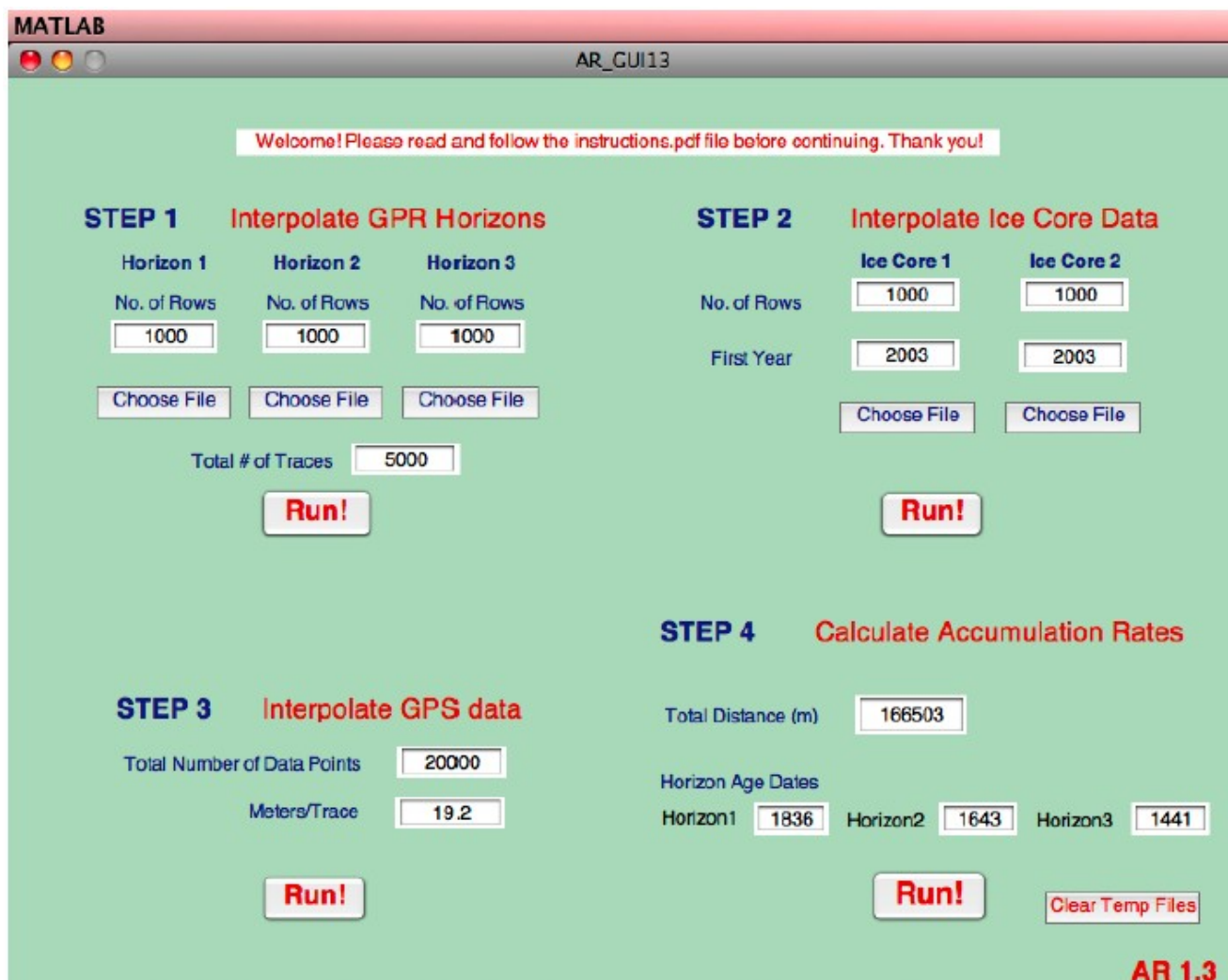


Figure 1. Screenshot of the GUI for the software used to compute accumulation rates from radar data.

3. Application

We use our software tools to extract accumulation rates along various traverse routes originating at South Pole station. Because our profiles are two-dimensional (distance and depth), we are able to examine both spatial and temporal variability in snowfall in interior East Antarctica.

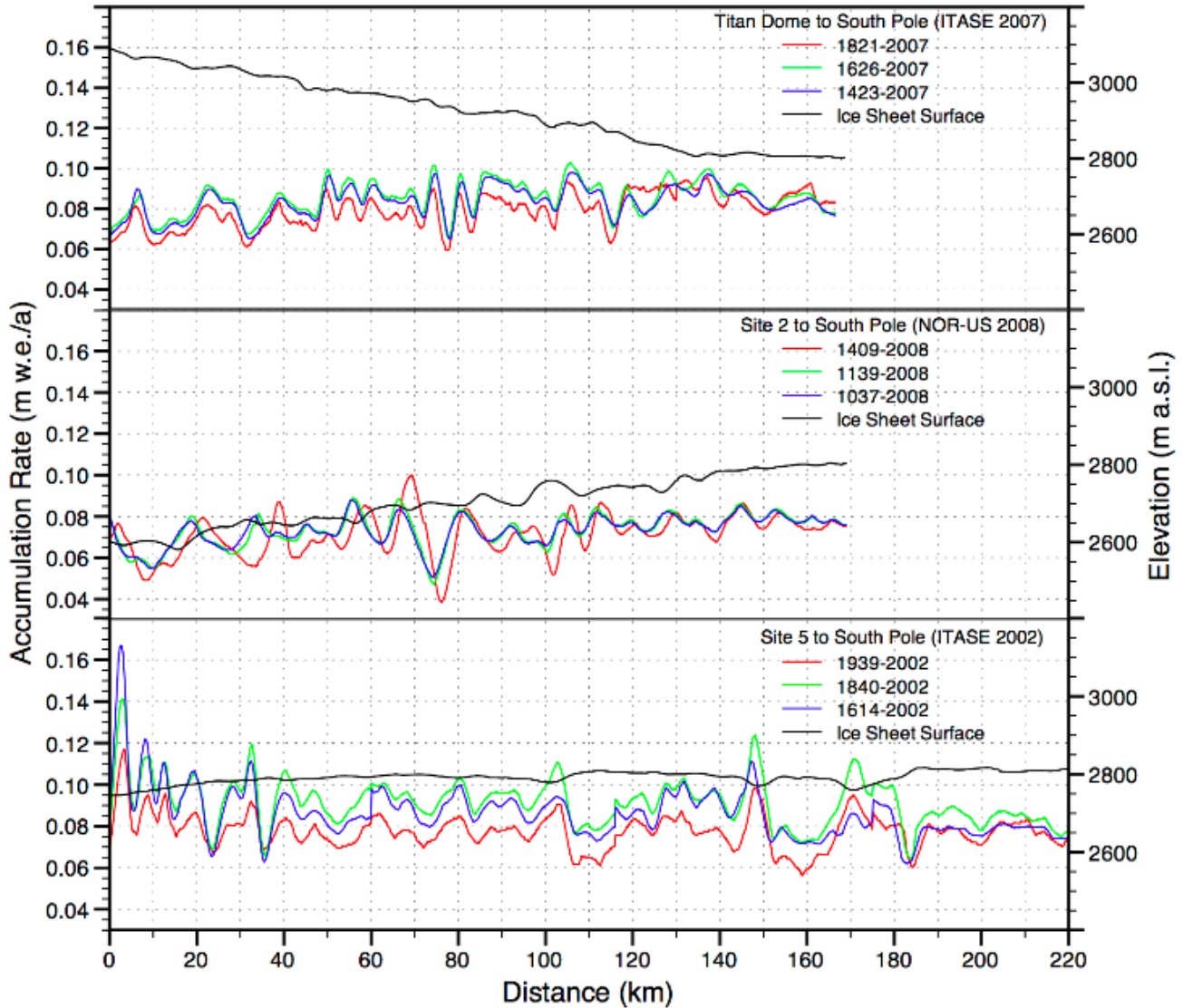


Figure 2. GPR-derived accumulation rates (color lines) and GPS-derived surface elevations (black line) plotted against distance for three traverse routes in East Antarctica. Note that each profile ends at South Pole.

The most striking observation in Figure 2 is the small-scale variability captured by our method that appears related to surface topography.

The Titan Dome to South Pole profile was collected in a portion of the EAIS within the Ross Sea drainage. Titan Dome is one of several high elevation summits of the EAIS. This part of the ice

sheet is at ~3100 m elevation and receives most of its precipitation from orographic lifting of air masses coming onshore from the Amundsen Sea and from clear sky precipitation. The overall trend for this profile is an increase in accumulation rates from Titan Dome to South Pole, which is consistent with the Amundsen Sea being the dominant precipitation source. From Titan Dome to South Pole (Figure 2, top), accumulation rates range from a maximum of 10.3 cm/yr to a minimum of 6.6 cm/yr (381 year average from 1626–2007) within a distance of only 5 km (between 75 and 80 km). The average accumulation rates for the entire profile are 7.9 ± 1.6 cm/yr from 1821–2007 (186 year average), 8.53 ± 1.6 cm/yr from 1626–2007 (381 year average), and 8.3 ± 1.4 cm/yr from 1423–2007 (584 year average). Average accumulation rates between horizons are 9.1 ± 2.0 cm/yr from 1821–1626 (195 year average), 8.5 ± 1.6 cm/yr from 1821–1423 (398 year average), and 8.0 ± 1.6 cm/yr from 1626–1423 (203 year average). (Note: All errors are 2σ , representing the 95th percentile).

The Site 2 to South Pole profile was collected in the Weddell Sea drainage of the EAIS. The elevation range for this traverse is ~2600 m at Site 2 to about 2800 m at South Pole. The dominant precipitation source in this region is from orographic lifting of air masses originating from the Amundsen and Weddell Seas. Accumulation rates follow an overall increasing trend between Site 2 and South Pole (Figure 2, center). The maximum accumulation rate of 10.0 cm/yr occurs within 10 km of the minimum of 3.8 cm/yr (599 year average from 1409–2008, between 90 and 100 km). Average accumulation rates along the entire profile are 7.1 ± 2.0 cm/yr from 1409–2008 (599 year average), 7.3 ± 1.6 cm/yr from 1139–2008 (869 year average), and 7.3 ± 1.4 cm/yr from 1037–2008 (971 year average). Average accumulation rates between horizons are Average accumulation rates are 7.8 ± 4.2 cm/yr from 1409–1139 (270 year average), 7.6 ± 3.2 cm/yr from 1409–1037 (372 year average), and $7.2 \pm$ cm/yr from 1139–1037 (102 year average).

The Site 5 to South Pole profile was collected in a region of Antarctica known as the ‘bottleneck’ where EAIS ice flows into West Antarctica. Precipitation comes largely from the Amundsen Sea, so it is somewhat similar to the Titan Dome to South Pole profile. Most of the precipitation is caused by orographic lifting, but we would also expect occasional storm penetration into this area based on its relative proximity to the coast. Between Site 5 and South Pole (Figure 2, bottom), accumulation rates follow a slightly decreasing trend with distance inland toward South Pole. Accumulation rates vary from just over 8 cm/yr to the maximum of over 16.5 cm/yr within a 10 km span from Site 5 (162 year average from 1840–2002, 0–10 km). Average accumulation rates along the entire profile are 7.7 ± 1.6 cm/yr from 1939–2002 (63 year average), 9.1 ± 2.2 cm/yr from 1840–2002 (162 year average), and 8.6 ± 2.4 cm/yr from 1614–2002 (388 year average). Average accumulation rates between horizons are 10.2 ± 2.8 cm/yr from 1939–1840 (99 year average), 8.8 ± 2.8 cm/yr from 1939–1614 (325 year average), and 8.3 ± 3.0 cm/yr from 1840–1614 (226 year average).

To investigate the relationship between accumulation rate and topography, we calculated the correlation coefficient, r , between accumulation rate and the gradient of the along-track surface elevation for each traverse segment. We note here that the traverses are not always oriented parallel to the steepest slope, or the dominant wind direction. The elevation data are smoothed using a 500 m moving average to facilitate this comparison, on the basis that winds are not driven by very small-scale topography (meters to tens of meters). The profiles of accumulation rate contain spatial trends (Figure 2) so we normalize the accumulation rate data with a linear fit and subtract the trend from each point. We use accumulation rates from only the youngest horizons for comparison because these are least affected by ice advection.

Our results are shown in Figure 3. Negative correlations indicate high accumulation rates are related to depressions and low accumulation rates with crests or flanks. However, our analysis yields the opposite case, as shown by positive values of r in Figure 3. There is no significant correlation between accumulation rate and surface slope for the profiles between Site 5 and South Pole and Titan Dome and South Pole. This might be due to the non-parallel orientation of the traverse routes to dominant slope and wind directions. We do obtain a significant positive correlation for the profile from Site 2 to South Pole, but this is contrary to the expected relationship. An explanation for this positive correlation is unclear, but might be because the traverse route is not oriented parallel to dominant slope or wind direction.

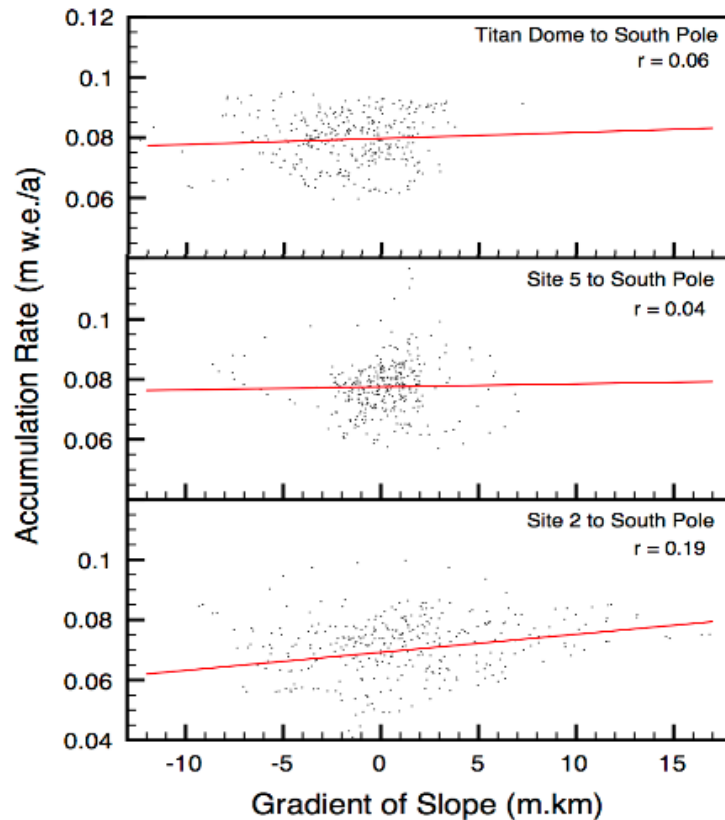


Figure 3. Correlation of accumulation (y-axis) and slope gradient (x-axis) for the three profiles shown in Figure 2.

Currently, it is unknown how climate warming is affecting the Antarctic ice sheet. Models predict an increase in accumulation rates over the continent, but the evidence for such a change is equivocal. Since our methods allow us to look at accumulation rates for many different time periods, we can investigate whether any observable temporal changes in accumulation rate have occurred in the areas and time periods covered by our data.

Direct comparison between data from the three traverses is difficult because they cover different time spans. This difference arises from different survey styles and different accumulation rates (i.e., lower accumulation rates lead to older horizon ages at a given depth).

The Norway-US data were recorded with a 200 MHz antenna while the ITASE data were recorded with a 400 MHz system. The 200 MHz antenna can image deeper into the firn layer than the 400 MHz antenna but has lower resolution near the surface so it is more difficult to digitize horizons from recent decades. Also, the Norway-US traverse traveled through a relatively low accumulation part of Antarctica (see Figure 3), so their horizons are much older than those from the ITASE traverses. This difference in temporal coverage between traverses affects the interpretation of spatial extent of temporal trends, but temporal changes in accumulation rate can still be determined within each dataset.

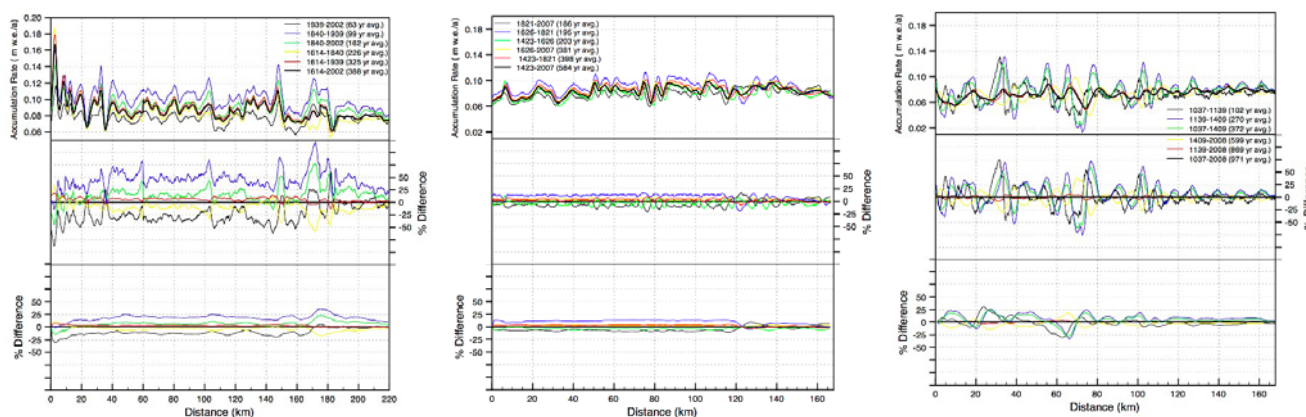


Figure 4. Comparison of accumulation rates over short time intervals to the long term average (thick black line) (top panel). Percent difference for these plots to the long term average (flat black line) (middle panel). Percent difference for 10 km smoothed data to the long term average (flat black line) (bottom panel). From left to right: Titan Dome to South Pole; ITASE Site 5 to South Pole; and US-NO Site 2 to South Pole.

we calculate the percent difference from the long-term average accumulation rate for each neighboring pair of dated horizons (Figures 3.4–3.6). The long-term average is 388 years (1614–2002) from Site 5 to South Pole, 584 years (1423–2007) from Titan Dome to South Pole, and 971 years (1037–2008) from Site 2 to South Pole. Because we are interested in climate driven changes over time, we calculate accumulation anomalies of the 10 km smoothed data from the long-term mean to determine any temporal changes in precipitation. This level of smoothing removes most influences of topography leaving residual trends most likely caused by climate variability.

From Site 5 to South Pole (Figure 3.4), the most recent, and shortest-term, accumulation rate data from 1939–2002 (63 year average) fall below the long-term average while the next longest averages (1840–1939, 99 year average, and 1840–2002, 162 year average) fall above the long-term average. Other longer-term averages closely follow the longest-term average for the entire length of the traverse. The accumulation anomalies show a change in pattern at 140 km, changing from being consistently above or below the long-term average to wavelength fluctuations in sign (Figure 3.4, bottom).

From Titan Dome to South Pole (Figure 3.5), the unsmoothed data vary far less than from Site 5 to South Pole with a range of less than 12–15% with the highest variability in the most recent time periods (1821–2007 and 1626–1821). For the first 125 km from Titan Dome, accumulation rates from the shortest-term and most recent period (1821–2007, 186 year

average) are consistently less than the long term average. Between 0 and 125 km from Titan Dome, the 10 km smoothed anomalies maintain a consistent sign and vary by ~10-20%. Between 125 km and South Pole, the 10 km smoothed data display a fluctuating pattern, although the percent differences are reduced to a range of ~5-7%.

From Site 2 to South Pole (Figure 3.6), the variability of the unsmoothed data from the long-term average is occasionally in excess of ~50% (for example, at 70 km and 75 km from Site 2). Between 115 km and South Pole, the anomalies are greatly reduced to ~25% and vary more regularly, remaining either positive or negative, not switching signs as frequently as before 115 km. Also, after 115 km, the shortest-term average (1037-1039, 102 year average) and the most recent horizon (1409-2008, 599 year average) fall below the long-term mean. The 10 km smoothed data show fluctuating patterns (~25-30%) until about 115 km from Site 2. At this point, the differences vary consistently from the long-term mean, maintaining one sign, and the range in variation is reduced to ~10-12%.

At some point along all three traverses, accumulation rates from the most recent time period fall below the long-term mean.

Deciphering patterns in the temporal variability of snowfall is problematic given the varying time spans represented by the data, the irregularity in cyclonic activity over short periods of time, and the effects of ice advection on the vertical comparison. Some profiles are suggestive of a recent decrease in accumulation rate, but it is difficult to say with any certainty if this is evidence for climate change in this region of the ice sheet. Accounting for ice movement is necessary to accurately analyze temporal variability in accumulation rates, especially when using horizons more than a few centuries old. Comparison with circulation models and weather station data could better elucidate the causes of any observed changes in the temporal trend of snow accumulation.

4. Summary

In this project, we:

- formalized a new method for deriving accumulation rates from a combination of ground-penetrating radar, ice core, and global-positioning system data and developed a suite of software tools to automate the processing chain.
- investigated the causes of the spatial variability in accumulation rates by analyzing the influence of topographic variations, climatic variations, and ice advection. We find that accumulation rates are affected by large-scale (katabatic winds) and small-scale topography (surface roughness) as well as the variability in cyclonic activity and storm penetration into the interior of the ice sheet. Ice advection complicates the analysis of temporal variability of accumulation rate, especially when old horizons (more than a few centuries) are used and ice speeds are fast enough to advect deeper layers through one or more surface undulations.
- compared our data set to accumulation estimates from three widely-used continental compilations to investigate the strengths and weaknesses of each. We find that, overall, the compilations capture large-scale spatial patterns (>100 km), although differences in resolution and methods cause systematic variations.
- investigated the necessity for high-resolution data versus low-resolution data by comparing the integrated total accumulation along each profile to corresponding values for each continental compilation. Results suggest that the ability of our methods to capture

small-scale spatial variations greatly improves the estimate for total snow accumulation and justifies the additional time and effort to acquire such high-resolution data.

- demonstrated the value of collecting similar high-resolution datasets to investigate spatial and temporal variability of accumulation rates.