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Mass Balance and Accumulation Rate Along US ITASE Routes

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Final Report for Period: 09/2000 - 09/2005

Submitted on: 04/01/2006

Principal Investigator: Hamilton, Gordon S.

Award ID: 0196441

Organization: University of Maine

Title:

Mass Balance and Accumulation Rate Along US ITASE Routes

Project Participants

Senior Personnel

Name: Hamilton, Gordon

Worked for more than 160 Hours: Yes

Contribution to Project:

Dr Hamilton was responsible for overall project coordination. He designed the experimental strategies, conducted fieldwork during all four seasons of US ITASE, processed data, analyzed results, and prepared the results and interpretations for publication in peer-reviewed journals and at scientific meetings.

Post-doc

Graduate Student

Name: Spikes, Vandy

Worked for more than 160 Hours: Yes

Contribution to Project:

Blue Spikes completed his requirements for a PhD degree in Earth Sciences at the University of Maine. His thesis research was based solely on data collected by this project. He participated in three US ITASE field seasons, processed and analyzed field data, developed software routines for data analysis and visualization, and prepared manuscripts for publication.

His involvement in this project was supported (stipend and tuition) by a NASA Earth Systems Science Graduate Fellowship.

Name: Stearns, Leigh

Worked for more than 160 Hours: Yes

Contribution to Project:

Leigh Stearns is a PhD candidate in Earth Sciences at the University of Maine. A component of her thesis research involves field data collected during this project. In particular, she has been investigating the causes of backscatter variations in satellite radar imagery in terms of surface accumulation rates and topography. In the course of this project, she conducted fieldwork during three of the resurvey field seasons. She has also processed and analyzed data and is continuing to interpret the results.

Her contribution to this project was supported by funds from this award.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

U.S. Army Cold Regions Research and Engineering Laboratory

We collaborated closely with Dr S. Arcone at CRREL on snow accumulation variability across West Antarctica using combined GPS and GPR data. The collaboration includes sharing of data, frequent meetings to discuss processing strategies and collaboration on the interpretation of results. Jointly we advised a PhD candidate (Blue Spikes). Several joint publications resulted from this collaboration.

Saint Olaf College

We worked with Dr R. Jacobel and Dr B. Welch at St Olaf College by providing geodetic corrections for their deep ice sounding radar and on the ice dynamic interpretation of the results.

National Aeronautics & Space Admin Goddard Space Flight Center

We worked with Dr J. Zwally and Dr Li Jun of the ICESat project office on collaborative research into the causes of short-period fluctuations in ice sheet surface elevations, and by using field data as calibration and validation for ICESat laser ranging of the ice sheet surface.

NASA also supported Blue Spikes's involvement in this project by way of an Earth System Science Graduate Fellowship.

Other Collaborators or Contacts

We conducted informal discussions on the problem of interpreting GPR internal layering with Dr J. Kohler at the Norwegian Polar Institute and Dr Olaf Eisen at Alfred Wegener Institute.

We also interacted frequently with other US ITASE principal investigators, including data sharing and interpretation of results. In the latter part of the project, we enhanced our collaborations with international ITASE colleagues in Italy, France and the UK, and are involved in joint interpretations of common data sets.

Activities and Findings

Research and Education Activities:

The primary research activities in this project involved our participation in the four US ITASE field seasons (1999-2003). As part of the field program we collected ~5,500 km of continuous, precise GPS data along the traverse route. These geodetic data are used by ourselves and several other US ITASE investigators. We also installed 15 new mass balance (coffee can) stations in rarely visited regions of West and East Antarctica. Several shallow firn cores were collected to study local variability in snow accumulation around deeper 200-year ice core sites. As part of our collaboration with NASA, we performed detailed 3-dimensional mapping of surface topography and shallow stratigraphy to validate and better interpret results from the ICESat mission. Mass balance marker sites installed during earlier field seasons were visited and resurveyed. Three automatic weather stations close to the proposed Inland WAIS deep drilling site and operated for two years before being removed. The project supported the thesis work of one PhD student. Results were presented at several national and international meetings (WAIS, SCAR/ITASE, MGM, IGS, AGU) and published in peer-reviewed scientific journals.

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

Training and Development:

All those involved in the project developed their skills at planning and conducting field experiments. Specific skills included developing new software processing strategies for GPS data and for handling very large geophysical data files. Dr Hamilton has gained experience in being a primary advisor for a PhD candidate. Blue Spikes learned new skills in the design of scientific experiments and data processing. Leigh Stearns developed the responsibility to carry out fieldwork unsupervised.

Outreach Activities:

Participation in US ITASE outreach activities coordinated by the Boston Museum of Science (including providing educational content for the US ITASE web site).

Regular visits to local school groups (grades 2, 3, 5 and 8) to describe research activities in Antarctica.

Collaborative work with a middle school science teacher to develop and implement a polar science outreach program in Iowa and Kansas schools.

Invited participant at Maine Science Museum 'polar science weekend', presenting slide shows on ITASE research and providing hands-on experiments demonstrating glaciology and climate studies.

Teaching short courses on mapping and climate studies for high school science teachers.

Television and newspaper interviews on ITASE research.

Leigh Stearns (graduate student participant) was an NSF K-12 Graduate Fellow during the 2004-2005 academic year. During that time, she partnered with two local middle/high schools to develop and teach lesson plans (2 days per week for the school year) based on US ITASE research.

Journal Publications

Hamilton, G.S. and Spikes, V.B., "Assessing the performance of satellite altimeter derived digital elevation models of Antarctica using precision kinematic GPS profiling.", *Global and Planetary Change*, p. 17, vol. 42(1-4), (2004). Published

Spikes, V.B., Arcone, S.A., G.S. Hamilton, S. Kaspari and P.A. Mayewski, "Variability in accumulation rates from GPR profiling on the West Antarctic plateau", *Annals of Glaciology*, p. 238, vol. 39, (2004). Published

Hamilton, G.S., "Topographic forcing of local accumulation rate variability at South Pole", *Annals of Glaciology*, p. 214, vol. 39, (2004). Published

Spikes, V.B., G.S. Hamilton, B. Csatho and I.M. Whillans, "Thickness changes on Whillans Ice Stream and Ice Stream C, West Antarctica, derived from airborne laser altimeter measurements.", *Journal of Glaciology*, p. 223, vol. 49, (2003). Published

Kaspari, S.D., P.A. Mayewski, D.A. Dixon, V.B. Spikes, S.B. Sneed, M.J. Handley & G.S. Hamilton, "Climatic variability in West Antarctica derived from annual accumulation rate records from ITASE firn/ice cores", *Annals of Glaciology*, p. 585, vol. 39, (2004). Published

Jacka, T.H., G.S. Hamilton & 8 others, "A strategy for the collection and synthesis of Antarctic Ice Sheet mass balance data", *Global and Planetary Change*, p. 1, vol. 42(1-4), (2004). Published

Arcone, S.A., V.B. Spikes & G.S. Hamilton, "Stratigraphic continuity in 400-MHz radar profiles in West Antarctica.", *Annals of Glaciology*, p. 195, vol. 39, (2004). Published

Arcone, S.A., V.B. Spikes & G.S. Hamilton, "Deformation of polar firn by differential accumulation and ice flow: interpretation of a 400-MHz short-pulse radar profile from West Antarctica", *Journal of Glaciology*, p. 407, vol. 51, (2005). Published

Hamilton, G.S., V.B. Spikes & L.A. Stearns, "Spatial patterns in mass balance of the Amundsen Sea and Siple Coast sectors of West Antarctica", *Annals of Glaciology*, p. , vol. 41, (2006). Accepted

Arcone, S.A., V.B. Spikes & G.S. Hamilton, "Phase structure of radar stratigraphic horizons within Antarctic firn", *Annals of Glaciology*, p. , vol. 41, (2006). Accepted

Books or Other One-time Publications

Spikes, V.B., "A mass balance study of the West Antarctic Ice Sheet.", (2003). Thesis, Published
Bibliography: PhD Dissertation, University of Maine, Orono, Maine, 98pp.

Web/Internet Site

URL(s):

- (1) <http://www.secretsoftheice.org/>
- (2) http://www.earthscienceagency.com/products/absolute_earth/antarctic_snow_accumulation/
- (3) http://gcmd.nasa.gov/getdif.htm?Hamilton_0196441

Description:

- (1) Outreach site co-developed with the Museum of Science in Boston. Provides project background, as well as daily diaries from the field.
- (2) An interactive site displaying a selection of our data.
- (3) Metadata entry for project data.

Other Specific Products

Contributions

Contributions within Discipline:

Our enhance the understanding of spatial variability of snow accumulation in West Antarctica by providing quantitative estimates of variability and contributing to understanding the causes of the observed patterns. We also have contributed early field results on the glaciological environment near the proposed deep ice core in West Antarctica. Our kinematic GPS profiling of topography is providing a quantitative assessment of the performance of a new satellite-altimeter derived Digital Elevation Model (DEM) of Antarctica that is being widely used in the glaciological community. We have also contributed to the understanding of West Antarctic ice sheet mass balance, by conducting precise ground based measurements that are valuable in their own right and useful for validation of satellite remote sensing measurements.

Contributions to Other Disciplines:

We have contributed to improved analyses and prediction of satellite orbits over polar regions by making our GPS data available orbit analysis centers.

Contributions to Human Resource Development:

This project involves the training of one PhD student and provides classroom material for graduate (Remote Sensing of Snow and Ice; Ice and Climate Seminar; Climate and the Quaternary) and undergraduate courses (Earth Systems Science) in Earth Science taught by the Principal Investigator.

Contributions to Resources for Research and Education:

This project created an opportunity for Blue Spikes to conduct PhD thesis research on Antarctic glaciology. Results from this project will also be incorporated into a PhD dissertation being prepared by Leigh Stearns.

Project participants made regular visits to local elementary and middle school classrooms, and to local science museums, to describe Antarctic research and conduct hands-on science activities. Leigh Stearns formalized this activity through her award of an NSF K-12 Graduate Fellowship during the 2004-05 school year, when she taught middle and high school science classes using research material generated by this award.

We hosted a Teacher Experiencing Antarctica (Jan French) and followed up by providing feedback on classroom projects and providing field data for her students to use. In addition, one of us (Blue Spikes) has worked closely with Peggy Lewis, a middle school science teacher, to develop an outreach program in Iowa and Kansas. Blue visited several schools in these states earlier this year, engaging students in classroom experiments and presenting slide shows on our field research program. These visits received substantial local media coverage.

Contributions Beyond Science and Engineering:

http://www.earthscienceagency.com/products/absolute_earth/antarctic_snow_accumulation/

This website was developed by Blue Spikes, now graduated and running his pwn company, to demonstrate the capabilities of a 'virtual globe' browser developed, in part, by Spikes.

Categories for which nothing is reported:

Any Product

Major Findings – OPP0196441

Point estimates of mass balance (dH/dt) Local rates of change in ice sheet thickness were calculated at fifteen sites in West Antarctica (Figure 1) using the submergence velocity technique. This method entails a comparison of the vertical velocity of the ice sheet, measured using repeat global positioning system (GPS) surveys of markers, and local long-term rates of snow accumulation obtained using firn core stratigraphy. Any significant difference between these two quantities represents a thickness change with time. Measurements were conducted at sites located ~100-200 km apart along US ITASE traverse routes, and at several isolated locations (Table 1). All but one of the sites are distributed in the Siple Coast and the Amundsen Sea basin along contours of constant elevation, along flow lines, across ice divides, and close to regions of enhanced flow. Calculated rates of thickness change are different from site to site (Table 2). Most of the large rates of change in ice thickness (~10 cm/yr or larger) are observed in or close to regions of rapid flow, and are probably related to ice dynamics effects. Near-steady-state conditions are calculated mostly at sites in the slow moving ice sheet interior and near the main West Antarctic ice divide. These results are consistent with regional estimates of ice sheet change derived from remote sensing measurements at similar locations in West Antarctica.

Antarctic surface topography (GPS profiling) The Radarsat Antarctic Mapping Project Digital Elevation Model (RAMP DEM) represents the best currently available compilation of Antarctic surface topography. Satellite altimeter data provide the foundation

for most of the DEM, augmented where available with other mapping and survey information. We use precision global positioning system (GPS) data collected continuously along several profiles 150-320 km long in West and East Antarctica to independently assess the performance of the DEM in capturing the shape of the ice sheet surface. Overall, the DEM performs well at representing the gross morphology of the ice sheet north of 81.4°S. South of this latitude, where the DEM is unconstrained by high-resolution altimeter data, the DEM is less capable of capturing surface topographic detail, and elevation accuracy degrades. The comparison with GPS data indicates that the horizontal resolution of the DEM over well-constrained inland portions of the ice sheet is approximately 8 km. This resolution is larger than initial estimates, meaning that many of the important topographic details of the ice sheet surface are omitted. This omission has implications for applications using the DEM to understand patterns of local accumulation rate variability or for mapping ice flow features. There also appear to be some errors in the absolute elevations, especially in regions of relatively rugged inland topography where GPS elevations differ by up to 50 m from DEM elevations.

Spatial and temporal variability in accumulation rates (radar profiling) Firn stratigraphy detected with ground penetrating radar (GPR) is continuous over very long distances in Antarctica. We used annually-resolved ice cores to demonstrate that the stratigraphy is isochronal (Figure 2). Once this characteristic was established, we used the GPR data to produce estimates of accumulation rate along several 100 km-long profiles in West Antarctica (Figure 3). Accumulation rates are shown to be highly variable over short distances. Elevation measurements from GPS surveys show that accumulation rates

derived from shallow horizons correlate well with surface undulations, which implies that wind redistribution of snow is the leading cause of this variability. Temporal changes in accumulation rate over 25-185 year intervals are smoothed to the along-track length scales comparable to surface undulations in order to identify trends in accumulation rate that are likely related to changes in climate. Results show that accumulation rates along a 100 km-long profile in central West Antarctica have decreased in recent decades, which is consistent with ice core derived time series of annual accumulation rates measured at the two ends of the profile. These results suggest that temporal variability observed in accumulation rate records from ice cores and GPR profiles can be obscured by spatial influences, although it is possible to resolve temporal signals if the effects of local topography and ice flow are quantified and removed.

Local variability in accumulation rates (ice dynamics effects) Local variability in accumulation rates due to ice dynamics effects Snow accumulation rates are known to be sensitive to local changes in ice sheet surface slope because of the effect of katabatic winds. These topographic effects can be preserved in ice cores that are collected at non-ice divide locations. The trajectory of an ice core site at South Pole is reconstructed using measurements of ice sheet motion to show that snow was probably deposited at places of different surface slope during the past thousand years. Recent accumulation rates, derived from shallow firn cores, vary along this trajectory according to surface topography, so that on a relatively steep flank mean annual accumulation is ~18% smaller than on a nearby topographic depression. These modern accumulation rates are used to reinterpret the cause of accumulation rate variability with time in the long ice core record, which suggests that

ice dynamics and not climate change is responsible. The results highlight the importance of conducting ancillary ice dynamics measurements as part of ice coring programs so that topographic effects can be deconvolved from potential climate signals.

Spatial variability in accumulation rates (ice cores) Thirteen annually-resolved accumulation rate records covering the last ~200 years from the Amundsen Sea and Ross Sea drainage systems and South Pole are used to examine climate variability over West Antarctica. Accumulation is controlled spatially by the topography of the ice sheet, and temporally by changes in moisture transport and cyclonic activity. A comparison of mean accumulation since 1970 at each site to the longterm mean indicates an increase in accumulation for sites located in the western sector of the Pine Island–Thwaites drainage system. An analysis of local forcing of accumulation rate variability due to surface topography and ice flow reveals minimal influence, suggesting the increases are real climate events. This observation is consistent with an increase in cyclonic activity in this part of Antarctica.

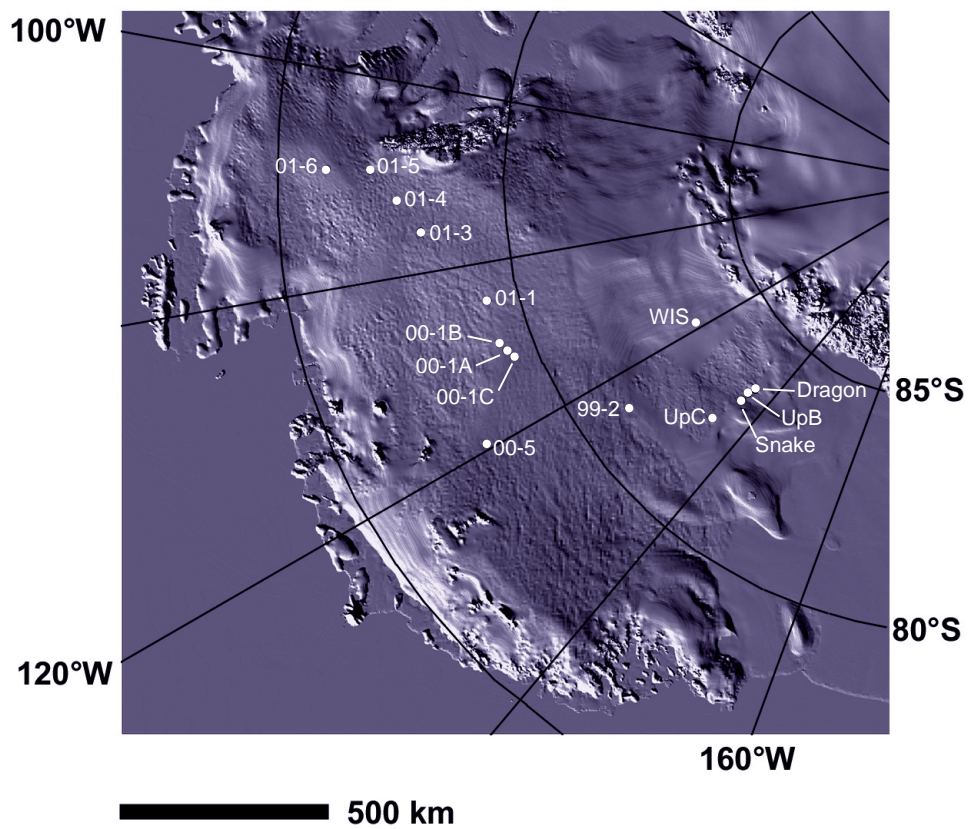


Figure 1. Shaded relief image of the OSU DEM showing the location of submergence velocity stations in West Antarctica. Illumination is from 90°W.

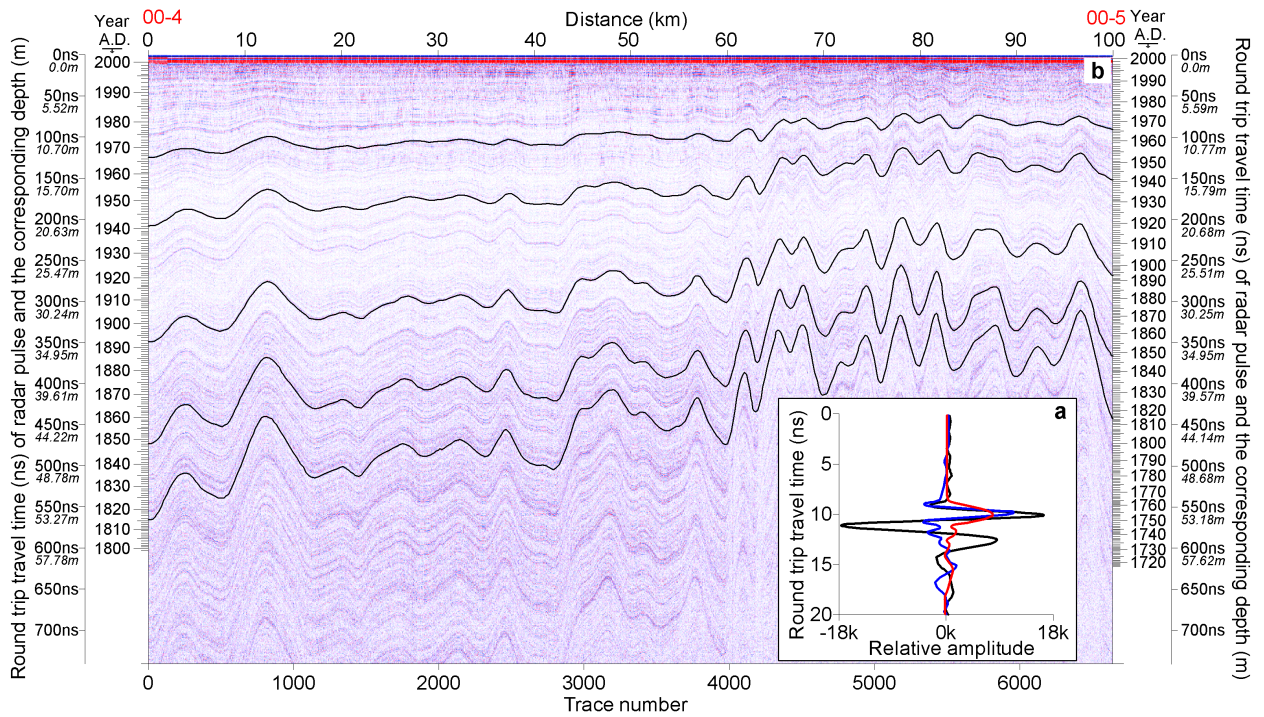


Figure 3. Radar data collected between US ITASE sites 00-4 and 00-5. (a) 400-MHz pulse shape as reflected by a high-density layer in firn (black line). The pulse has been deconvolved with a spiking routine (blue line) before performing the Hilbert magnitude transform (red line). (b) Radar profile after deconvolution and Hilbert transformation. The darkened horizons are tracked (black lines) to illustrate isochronal continuity between core sites. The deepest visible horizon at Site 4 has been tracked the entire distance (~550 km along-track) to Byrd Station. Signal fading related to surface undulations is apparent beyond 60 km.

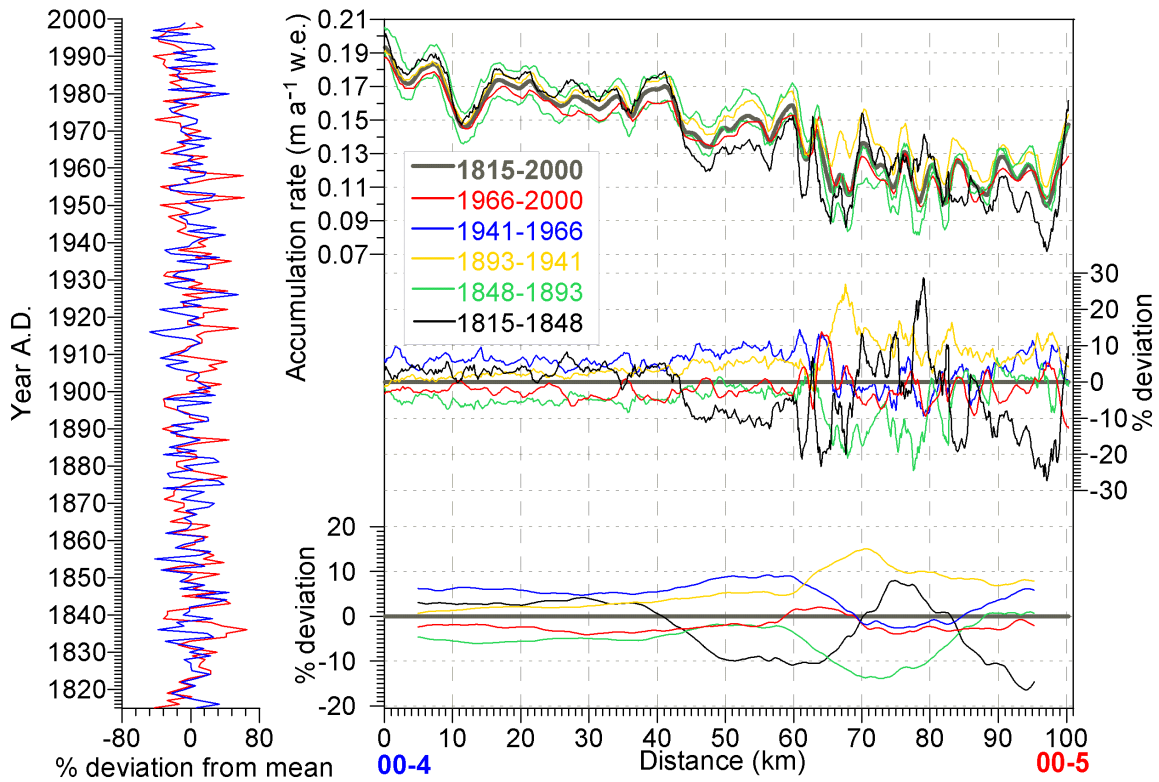


Figure 4. Changes in snow accumulation rate through time. *Left:* Variability of the annual accumulation rates derived from ice cores 00-4 (blue) and 00-5 (red). The variability is expressed as the percent deviation from each core-derived mean. *Top:* Calculated accumulation rates for time intervals defined by the horizons in Figure 3.17b (see legend). *Middle:* The deviation of each of the profiles in the top graph from a reference interval, which in this case is the interval from 1815-2000 A.D. *Bottom:* Profiles from the middle graph after being smoothed. The 10-km smoothing clips the ends from each profile.

<i>Site</i>	<i>Observation Dates</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Elevation</i>
Dragon	1992-Dec-02 1993-Nov-27 1996-Dec-03 1997-Nov-17	-83.57889°	-138.09750°	349 m
UpB	1995-Dec-09 1996-Dec-02 1997-Nov-17	-83.45583°	-137.81833°	338 m
Snake	1996-Dec-03 1997-Nov-16 2000-Jan-14	-83.26556°	-137.61889°	354 m
Inland-WIS	1996-Dec-02 1997-Nov-18	-83.50083°	-119.97333°	1069 m
UpC	1996-Dec-04 1997-Nov-16	-82.43917°	-135.97111°	526 m
99-2	1999-Dec-12 2001-Dec-22	-81.18833°	-125.90667°	963 m
00-1A	2000-Dec-01 2001-Dec-21 2002-Dec-18	-79.38375°	-111.23982°	1792 m
00-1B	2000-Dec-04 2000-Dec-21 2002-Dec-18	-79.29864°	-110.23722°	1804 m
00-1C	2000-Dec-02 2001-Dec-21 2002-Dec-18	-79.48622°	-112.35302°	1758 m
00-5	2000-Dec-16 2001-Dec-22	-78.08335°	-120.08042°	1701 m
01-1	2001-Nov-24 2002-Dec-19	-79.33028°	-104.89611°	1854 m
01-3	2001-Dec-05 2002-Dec-19	-78.12389°	-95.60972°	1618 m
01-4	2001-Dec-10 2002-Dec-20	-77.62250°	-92.26194°	1494 m
01-5	2001-Dec-14 2002-Dec-21	-77.06167°	-89.17278°	1259 m
01-6	2001-Dec-24 2002-Dec-22	-76.09667°	-89.01806°	1229 m

Table 1. Location of measurement sites and dates of survey occupation. Elevations are meters above the WGS84 ellipsoid.

Site	\vec{u} m a ⁻¹	\dot{b} m a ⁻¹	\dot{H} m a ⁻¹	Comparison \dot{H} m a ⁻¹
Dragon	1.98 at 296°	0.061 ± 0.021*	-0.098 ± 0.021	
Snake	12.7 at 221°	0.079 ± 0.02*	-0.189 ± 0.019	
UpB	416.1 at 242°	0.088 ± 0.018*	-1.316 ± 0.085	+0.032 ± 0.02 ^a -0.57 ± 0.08 ^b
Inland-WIS	11.32 at 261°	0.165 ± 0.018*	-0.019 ± 0.021	-0.64 ± 0.08 ^b
UpC	13.54 at 241°	0.095 ± 0.019*	+0.559 ± 0.019	+0.145 ± 0.022 ^a +0.35 ± 0.07 ^b
99-2	22.4 at 204°	0.120 ± 0.021	-0.167 ± 0.015	
00-1A	0.98 at 243°	0.223 ± 0.02	+0.014 ± 0.015	
00-1B	0.97 at 185°	0.240 ± 0.019*	+0.017 ± 0.018	
00-1C	5.71 at 254°	0.210 ± 0.022*	+0.016 ± 0.018	
00-5	0.93 at 045°	0.146 ± 0.021	-0.038 ± 0.020	} -0.09 ± 0.03 ^c
01-1	10.93 at 325°	0.300 ± 0.028	-0.220 ± 0.016	
01-3	34.21 at 016°	0.327 ± 0.027	-0.156 ± 0.018	} -0.21 ± 0.03 ^c
01-4	43.64 at 009°	0.350 ± 0.022	-0.249 ± 0.020	
01-5	32.31 at 050°	0.365 ± 0.028	-0.147 ± 0.028	
01-6	2.65 at 269°	0.397 ± 0.03*	+0.031 ± 0.027	

Table 2. Measured and derived quantities at each of the sites discussed in the text ($1-\sigma$ uncertainties are in parentheses). Horizontal velocities \vec{u} were derived from repeat GPS surveys. Accumulation rates \dot{b} were derived from ice core stratigraphy (Kaspari and others, 2004) and represent long-term averages (100-400 years). Asterisks denote ~40-year average accumulation rates derived from detection of bomb horizons. Rates of thickness change \dot{H} were obtained by solving eq. (1). Our results are compared, where possible, with other mass balance estimates: *a* represents spatial averages over 143,000 km² (for the UpC comparison) and 153,400 km² (for the UpB comparison) from Joughin and Tulaczyk (2002); *b* is from Spikes and others (2003) and represents a 5,000 km² spatial average over the closest region to UpB and a cross-over measurement at UpC; and, *c* represents spatial averages for slow-moving ice (<20 m a⁻¹) (~200,000 km²) and intermediate ice (~50-200 m a⁻¹) (50,000 km²) in the Amundsen Sea basin from Shepherd and others (2001).