DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/57

PROMICE 2013

Report for the 2013 operational phase of the Programme for Monitoring of the Greenland Ice Sheet

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MINISTRY OF CLIMATE AND ENERGY

G E U S

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Contents

Summary

This report updates on Programme for monitoring the Greenland ice sheet (PROMICE) activities for the year 2013. It is not intended to give a complete overview of the program. More information about PROMICE may be found in 2007-2010 PROMICE report (Ahlstrøm et al. 2011) and in 2011-2012 PROMICE report (Andersen et al. 2013).

Unlike the previous 6 summers in a row with many melt records set, year 2013 was characterized by colder north air inflow along west Greenland. This lead to melt values from PROMICE automatic weather stations between -0.4 to 5.9 m, which is closer to average than previous record setting years. However, the results still imply a significant net mass loss from the Greenland ice sheet (further details in PROMICE newsletter 5, Appendix A).

Some main achievements for the year 2013 are:

- Successful monitoring by 22 Greenland ice sheet automatic weather stations.
- The first results of quantifying the melt from the entire Greenland ice sheet were achieved.
- The first results of quantifying the dynamic mass loss from the entire Greenland ice sheet were achieved.
- The PROMICE aerophotogrammetric map of all Greenland land ice was used to separate the mass loss due to the Greenland peripheral glaciers and ice caps from that of the ice sheet proper finding that 14% is due to peripheral glaciers and ice caps.
- PROMICE ground measurements lead to the adjustment of satellite measurements of melt extent from the US National Snow and Ice Data Center (NSIDC) in spring 2013 (further details in PROMICE newsletter 4, Appendix D).
- PROMICE provided a large part of the data presented on the Polar Portal a new website where Danish research institutions display the results of their monitoring of the Greenland ice sheet and the sea ice in the Arctic to the general public (polar-portal.org).
- The first meeting of the PROMICE advisory group was held (further details in minutes, Appendix C).
- A new combined PROMICE website and public database with PROMICE data was launched (promice.org).
- The PROMICE team contributed to 13 peer reviewed publications including one in Nature.
- Ten publications related to PROMICE were cited in the 2013 IPPC AR5 report.

Automatic weather stations

The network

The PROMICE station network currently includes eight Greenland ice sheet melt regions with a total of 22 automatic weather stations (AWSs) located on the ice sheet (Figure 1). In each region, one station is typically located in the lower ablation area close to the margin, and one in the upper ablation area. Exceptions are KAN_U and QAS_A, which are located in the lower part of the accumulation area, MIT – positioned on an independent glacier, and KAN_B – located on tundra, one km from the ice sheet. The AWSs measure the important meteorological variables: air temperature, pressure and humidity, wind speed, downward and upward solar (shortwave) and terrestrial (longwave) radiation. The AWSs also record temperature profiles in the upper 10 m of ice, GPS-derived location and diagnostic parameters such as station tilt angles. A pressure transducer and two sonic rangers measure snow and surface height change associated with ablation and accumulation. Most variables are sampled every ten minutes, with the data stored locally awaiting collection during maintenance visits. Hourly averages of the most transient variables are transmitted via satellite between days 100 and 300 of each year, while the remaining variables are transmitted each 6 h. Transmissions are made daily in the winter period. All data and metadata including sensor specifications are archived in the PROMICE database and made freely available for display and download at *www.promice.org*.

Figure 1. *Location and identification codes of PROMICE automatic weather stations. Dotted lines are elevation contours in m above sea level. Red dots represent PROMICE stations, blue dots others.*

Servicing the stations in the field

In 2013, we serviced PROMICE stations in five regions, Tasiilaq (TAS), Qassimiut (QAS), Nuuk (NUK), Kangerlussuaq (KAN) and Upernavik (UPE). Not visited in 2013 were the Kronprins Christian Land (KPC), Scoresbysund (SCO) and Thule (THU) stations.

In the visited regions, PROMICE activities and instrumentation are co-sponsored by other projects. PROMICE funding covers the maintenance of two AWSs per region (and none at KAN), but the programme receives data from three (QAS and NUK) or four (TAS and KAN) stations in some regions. For instance in the TAS region a new AWS was established close to the equilibrium line altitude to better capture the vertical gradients in meteorological quantities important for melt. This station is accompanied by a snow pack analyzer (SPA) that should provide important measurements during melt in spring. In the QAS region, an Extreme Ice Survey (EIS) camera was installed at the front of the large outlet glacier Qajutap, to accompany the GPS measurements performed on the glacier. An ablation stake transect with six locaitons was also installed to supplement the thress QAS automated ablation measurements. In the NUK region, the AWS work involved relocating NUK_U a few kilometers as a crevasse field was opening around the station. We also serviced NUK GPSs and an EIS camera. The KAN work was performed as part of a firn coring expedition, which involved camping on the ice sheet for three weeks. Finally, in the UPE region we replaced two GPS, and made maintenance visits to the two AWS and a camera already in place.

The most important success of the 2013 AWS maintenance was resolving data transmission problems. Various problems existed with the modems before the field season, not at the least that the manufacturer discontinued the production of the standard modem we use, requiring different wiring and logger programming. After the field season, all but one AWS (THU_L, which is not equipped with a modem yet) transmitted data.

Measurements

Figure 2 illustrates mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for all AWSs on the ice sheet. We briefly describe the measurements below.

Annual ablation totals in the southern part of Greenland typically amount to 3-9 m (at the lower TAS, QAS and NUK stations), while ablation totals at the more northerly SCO_L and UPE_L stations amount to 2-3 m at low altitudes (< 500 m a.s.l.). The ablation totals from the upper stations (>500 m.a.s.l.) amount typically to 0.0-3.0 m in the south (TAS, QAS, NUK, KAN) and 0.0-2.8 m in the North (KPC, SCO, UPE, THU). Year 2013 had for all regions less net ablation than the 2008-2012 average, ranging from 0.3 to 5.9 m at low altitudes. The same is valid for high elevation stations ranging from no net ablation to 2.2 m. Since the start of PROMICE, the AWS network recorded 84 annual ablation totals.

All PROMICE stations record a distinct annual cycle in air temperature. As is common in the Arctic climate, temporal variability is largest in winter due to a more vigorous atmospheric circulation. The amplitude in the annual air temperature cycle is largest for stations at the highest latitudes or highest elevations. This is because above-freezing temperatures that dampen variability are least common at these stations. The more northerly stations also have a larger annual temperature cycle due to the increasing contrast in the lengths of polar day and night with increasing latitude. The smallest amplitude in the annual temperature cycle is seen at QAS_L, the most southerly PROMICE site. The 2013 mean monthly temperatures were relatively high during winter and low during summer, contrasting with the record melt years of 2010 and 2012.

The wind regimes over the ice sheet are distinctly different between regions. Winds are stronger at the higher-positioned AWSs. The highest monthly mean wind speed values were recorded at KAN_M and KAN_U (1270 and 1840 m a.s.l.), and TAS_U and TAS_A

(570 and 900 m a.s.l.). The strongest mean wind occurs in winter, causing a more pronounced annual cycle. An exception is the THU region in northwest Greenland, which does not show a annual wind speed cycle. The THU AWSs are positioned on a protruding lobe of the ice sheet that does not sufficiently function as a barrier for mesoscale-scale weather systems, resulting in strong winds year-round. The AWS data indicate that storms are more common in the TAS region. Severe wind storm events are known as Piteraqs and build up momentum due to the alignment of katabatic and large-scale atmospheric circulation. These notorious storms have repeatedly caused severe damage to the town of Tasiilaq. The Piteraq on 27 April 2013 as measured at TAS_U was record setting in the PROMICE period, with winds exceeding 42 m/s (150 km/h) at about 3 m above the surface.

An important instrument on the PROMICE AWS is the radiometer, measuring the up- and downward radiative energy fluxes that govern the surface energy budget and thus melt of the ice sheet. Both the short- and longwave components show a large annual cycle, with distinct differences with latitude (see e.g. the length of the polar night from shortwave radiation). In regions with a more frequent cloud cover (e.g. TAS) the radiative fluxes show a larger inter-annual variability than in regions where clear skies prevail (e.g. KAN).

The surface albedo is generally high (>0.75) in the cold, snow-covered interior of the ice sheet, and lower along the ice sheet margin where melting occurs in summer. In wintertime, the ice sheet is fully snow covered except where wind erosion dominates. Depending on the location of each AWS in the ablation area, snow melt begins in April or May as seen from air temperatures and decreasing albedo. Thereafter, albedo drops throughout the melt season until snowfall occurs in autumn, producing a distinct annual cycle largest at the high-melt sites. Surface melt chiefly causes this annual darkening of the ice sheet surface as snow undergoes heat-driven metamorphosis, or completely melts to expose darker bare ice. The ice sheet surface may also darken as impurities collect on the ice surface or surface melt water filled features emerge. We find that surface albedo on average drops below fresh snow values as monthly-mean temperatures exceed –2°C due to an increase in surface melt. Although absorbed solar radiation is the primary source of melt energy, the melt-albedo feedback is initiated by the energy fluxes that respond to changes in temperature, such as downward longwave radiation and the turbulent heat fluxes. Since both atmospheric warming and ice sheet darkening increase surface melt intensity and melt area, the anticipated future warming will result in a self-reinforcing ice sheet mass loss contribution from the melt-albedo feedback. However, the 2013 albedo at many PROMICE stations was not lower than in previous years. At the PROMICE sites, where ice surfaces after the winter snow cover has melted, the length of the bare ice season is most important for annual ablation as the inter-annual variability in albedo minimum is small.

The bottom right plots in the AWS data figures illustrate GPS-derived elevation. All stations display a lowering over the years which is mostly due to the equipment being taken downslope with ice flow. The GPS data provide a remarkable amount of detail and information that is as yet unexplored. The small but distinct annual cycles in elevation suggest an intimate interplay between surface melt in summer and dynamic thickening in winter. Also, the lowering makes clear that once every few years the AWSs need to be relocated to their original position to safeguard that data series are from the same climate zone and consistent elevation.

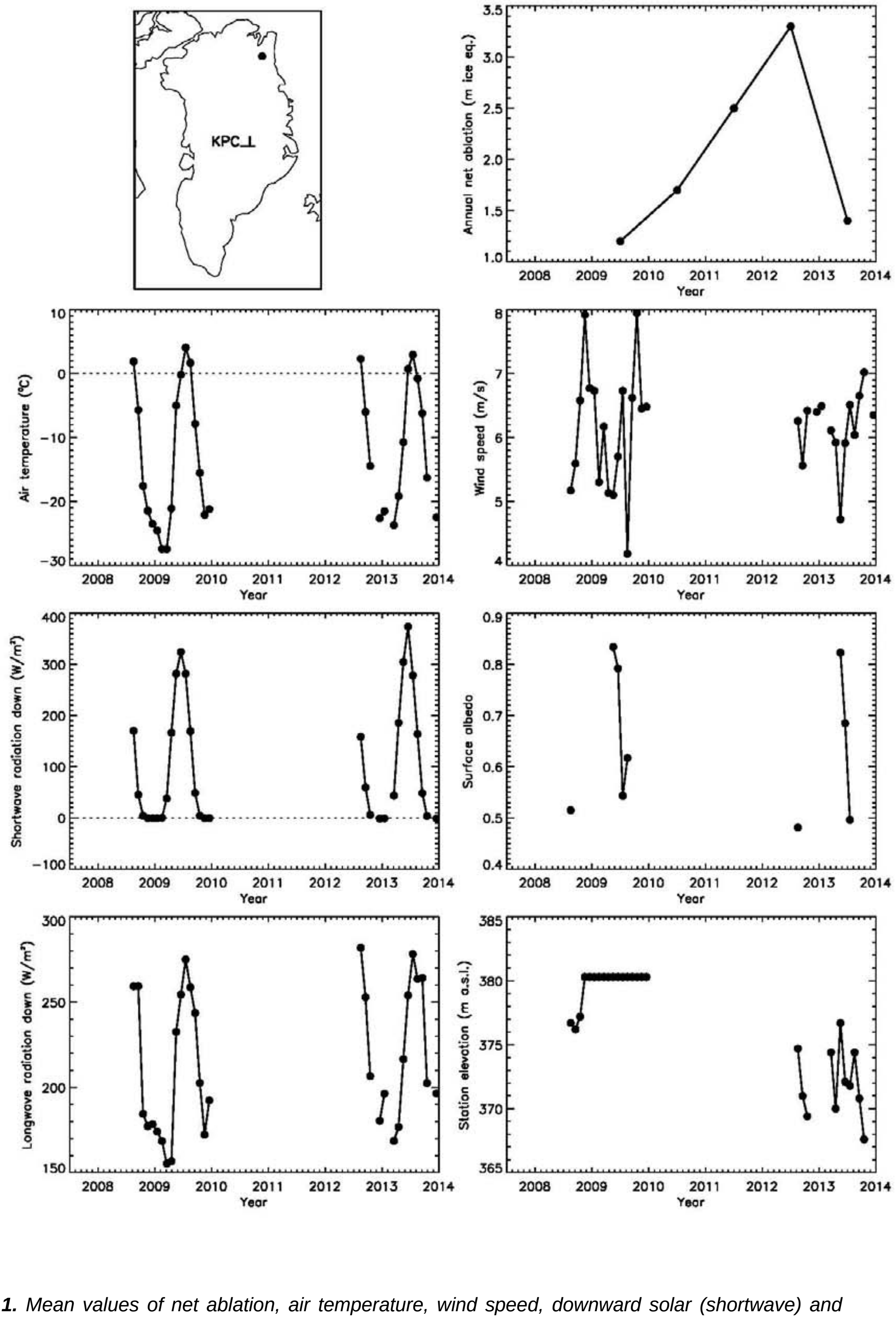


Figure 2.1. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for KPC_L AWS on the ice sheet.*

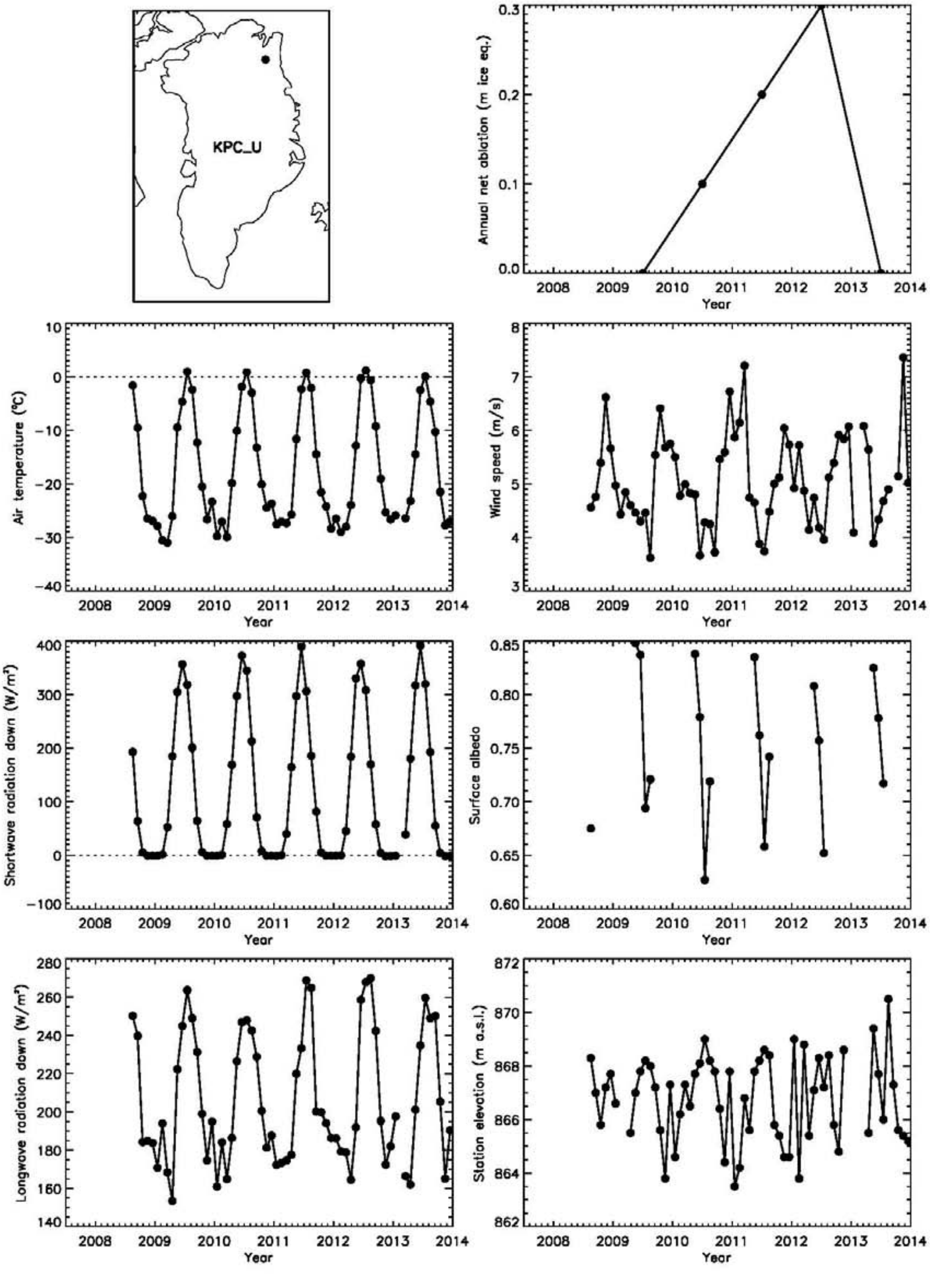


Figure 2.2. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for KPC_U AWS on the ice sheet.*

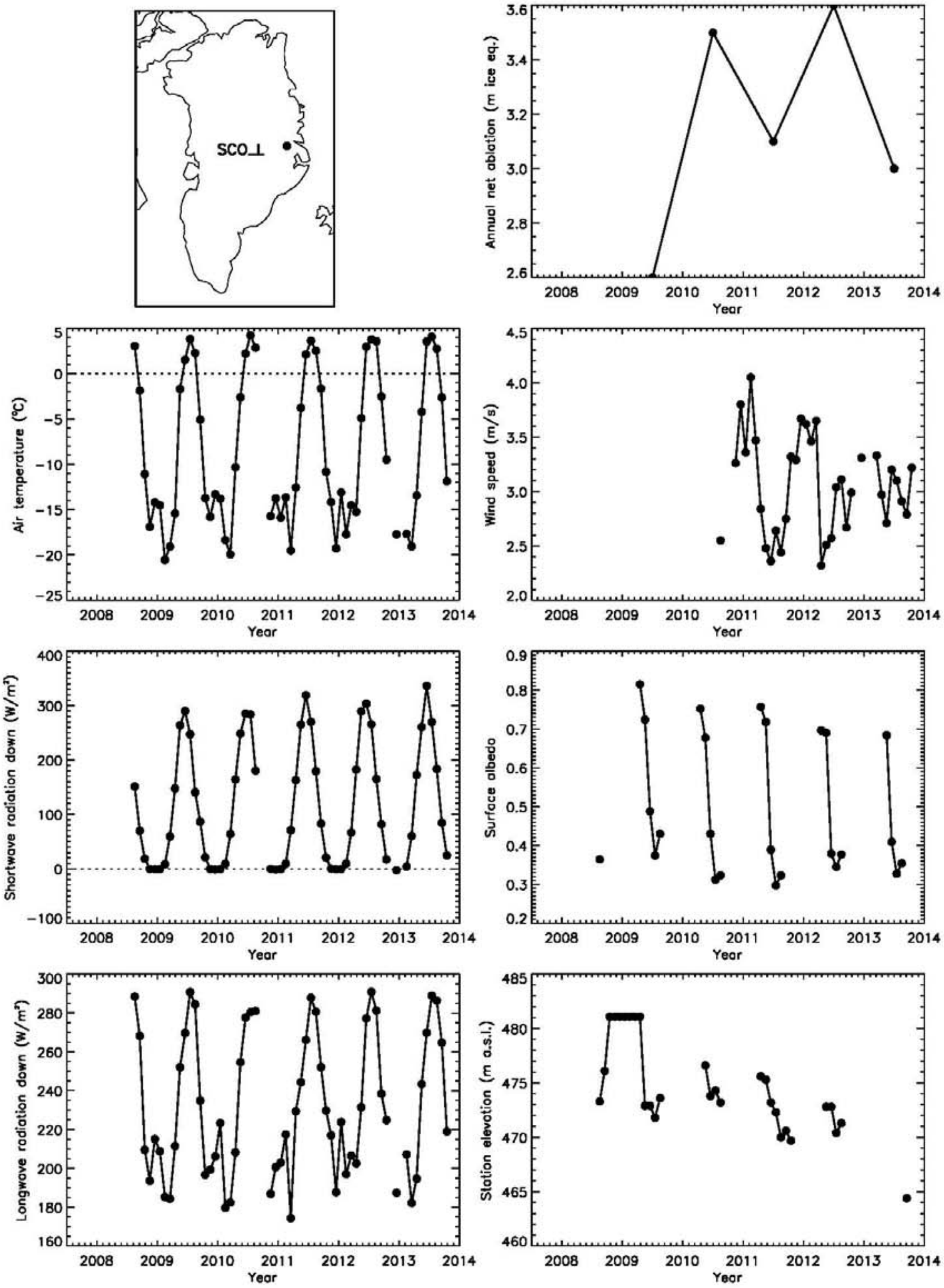


Figure 2.3. Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for SCO_L AWS on the ice sheet.

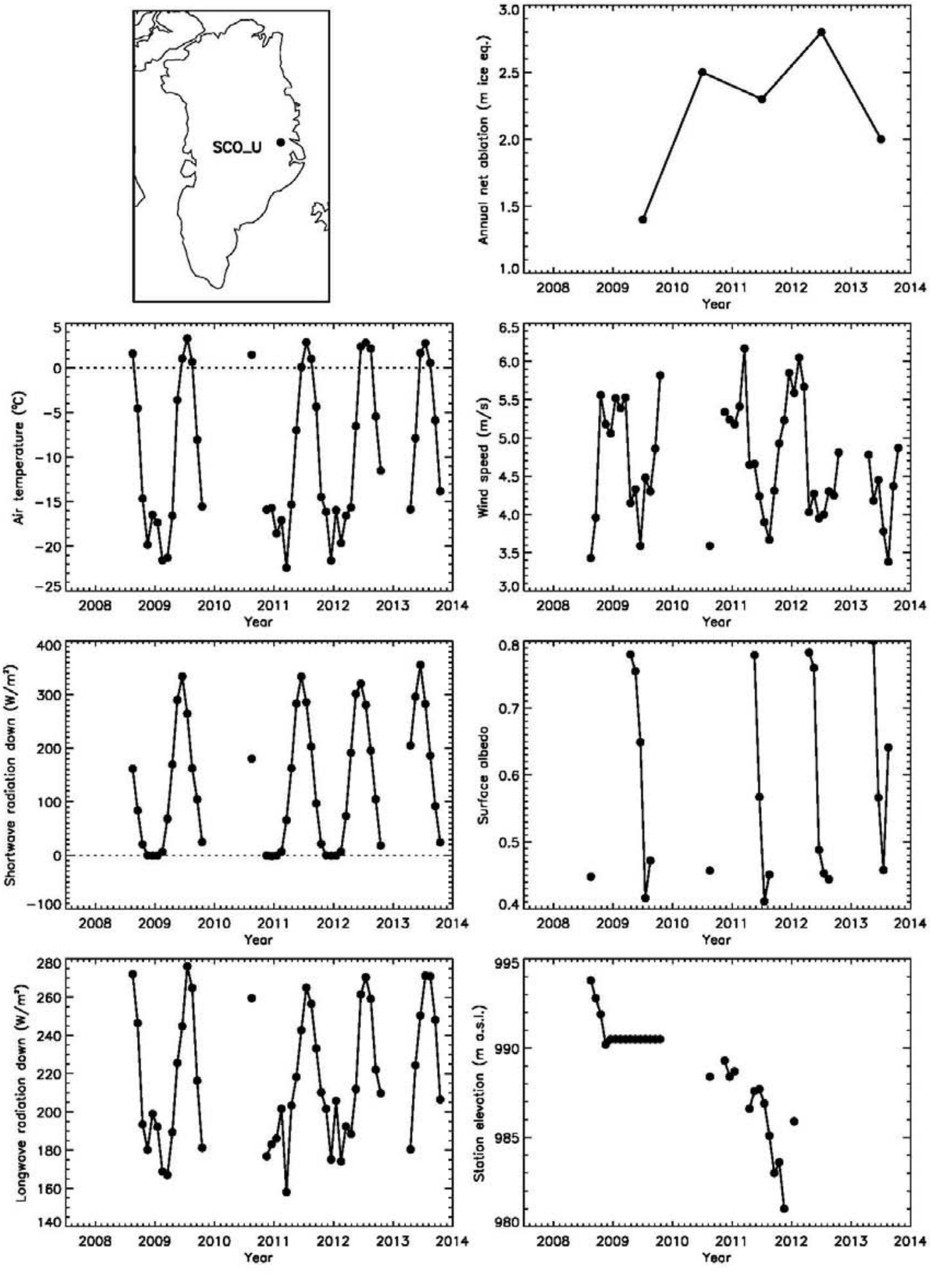


Figure 2.4. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for SCO_U AWS on the ice sheet.*

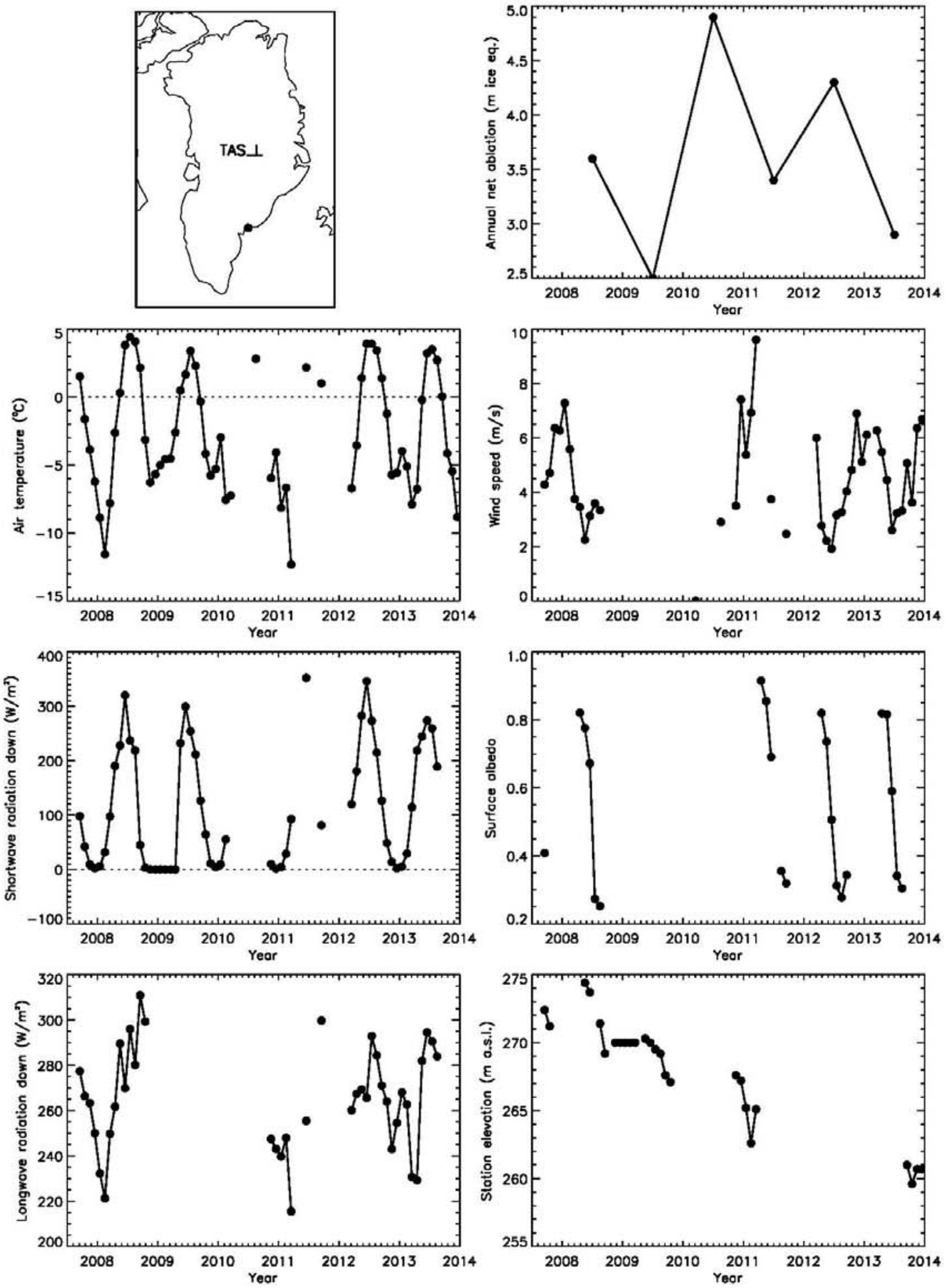


__Figure 2.5.__ Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for TAS_L AWS on the ice sheet.

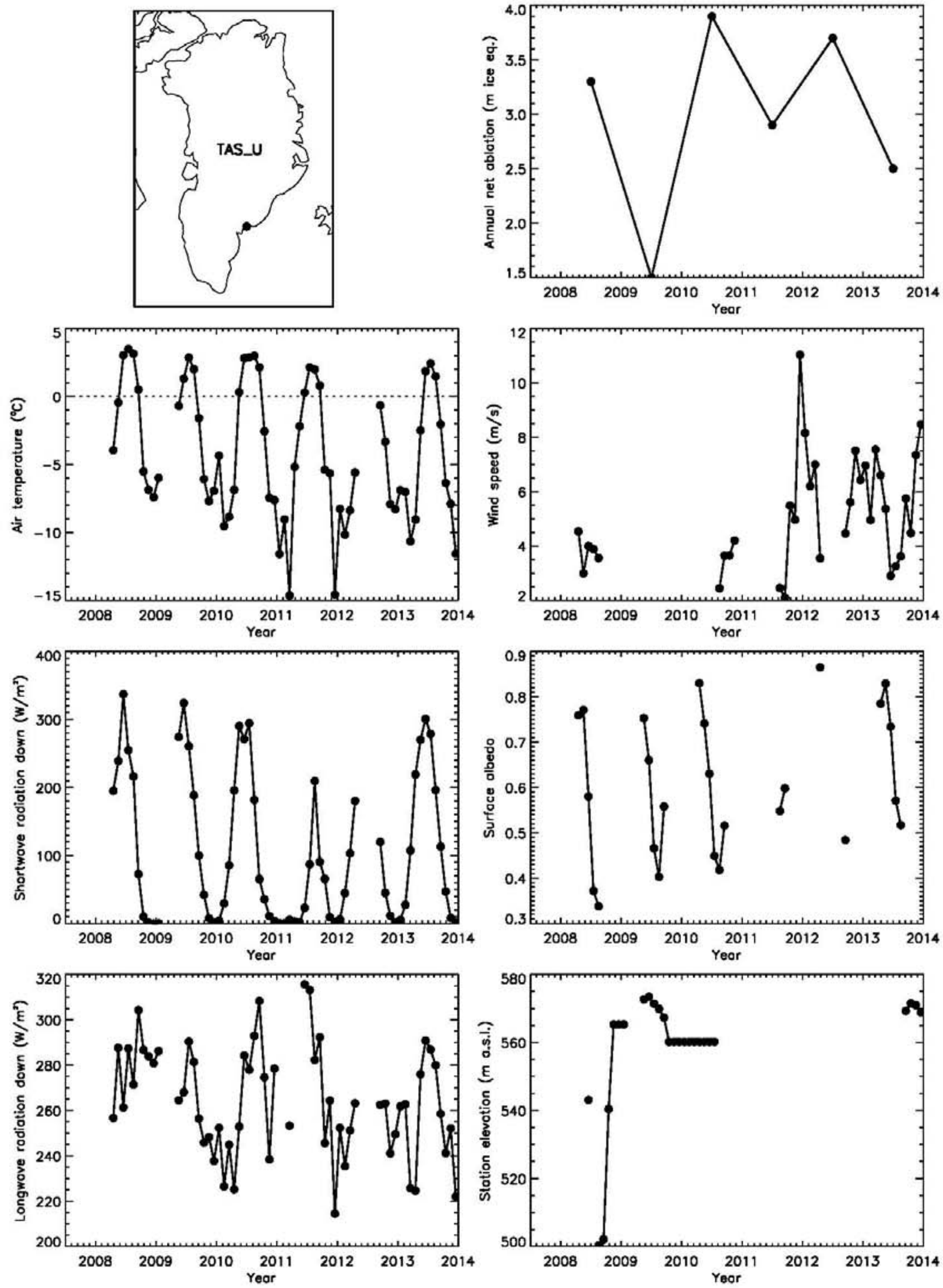


Figure 2.6. Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for TAS_U AWS on the ice sheet.

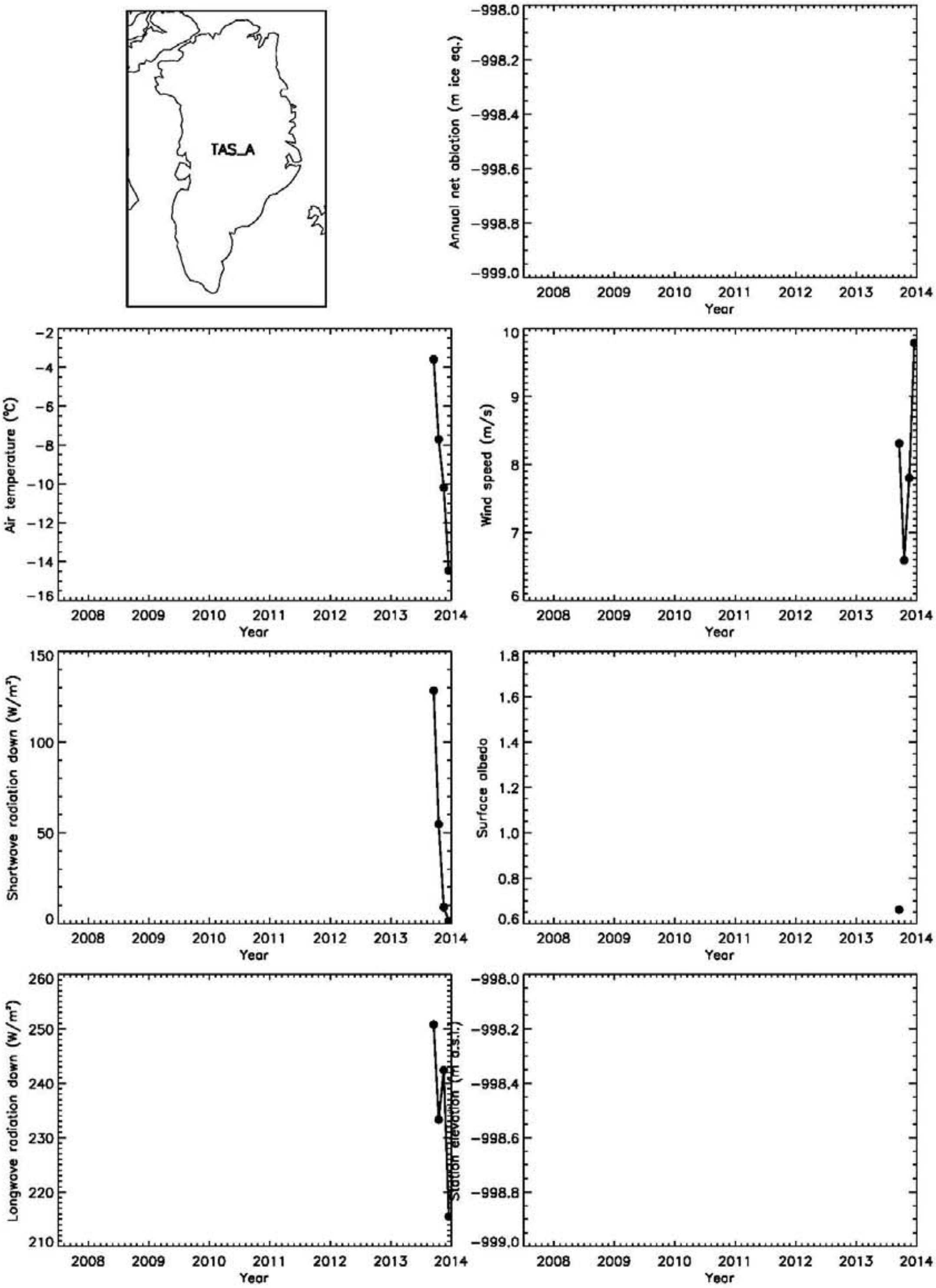


__Figure 2.7.__ Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for TAS_A AWS on the ice sheet.

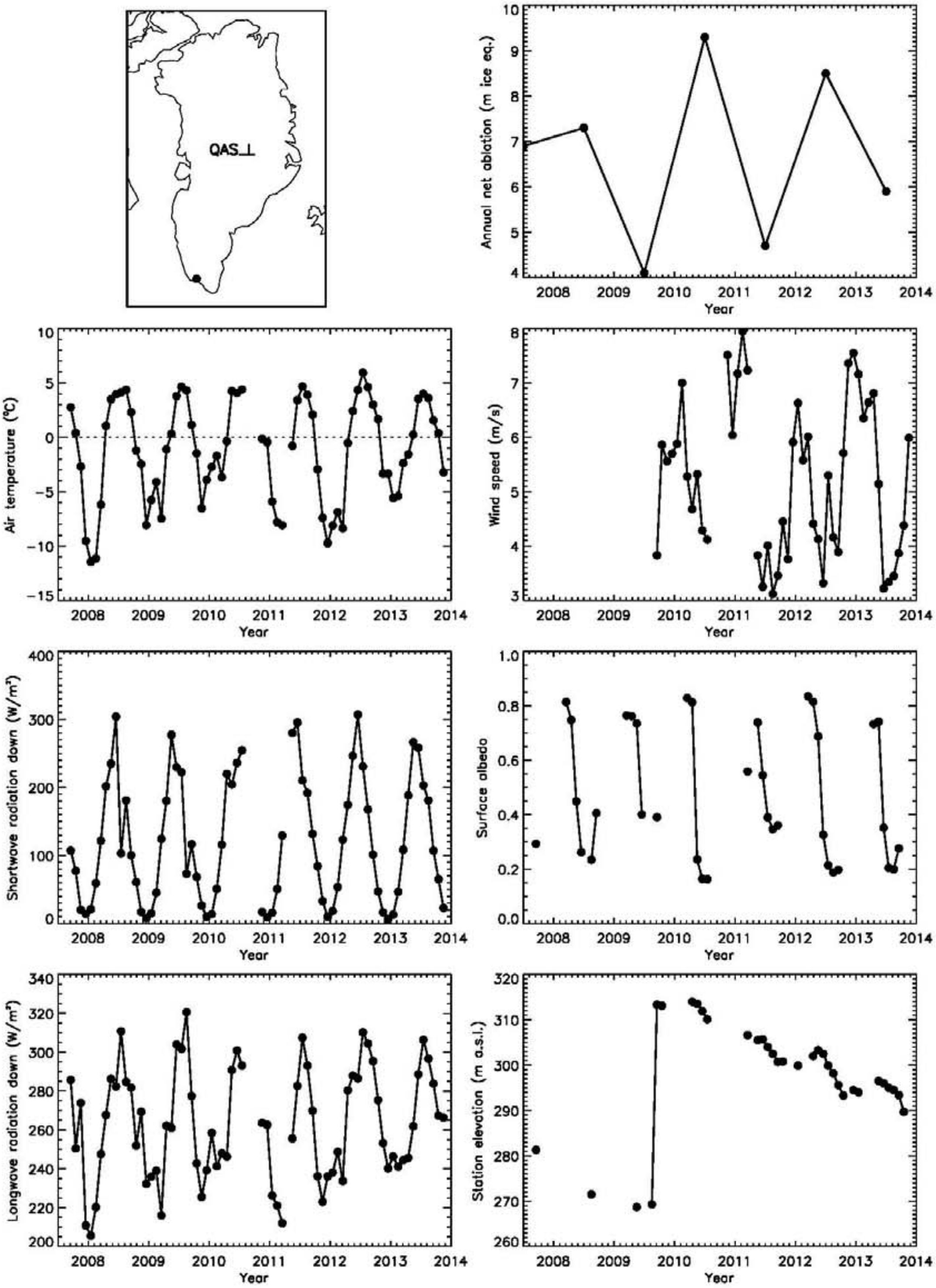


__Figure 2.8.__ Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for QAS_L AWS on the ice sheet.

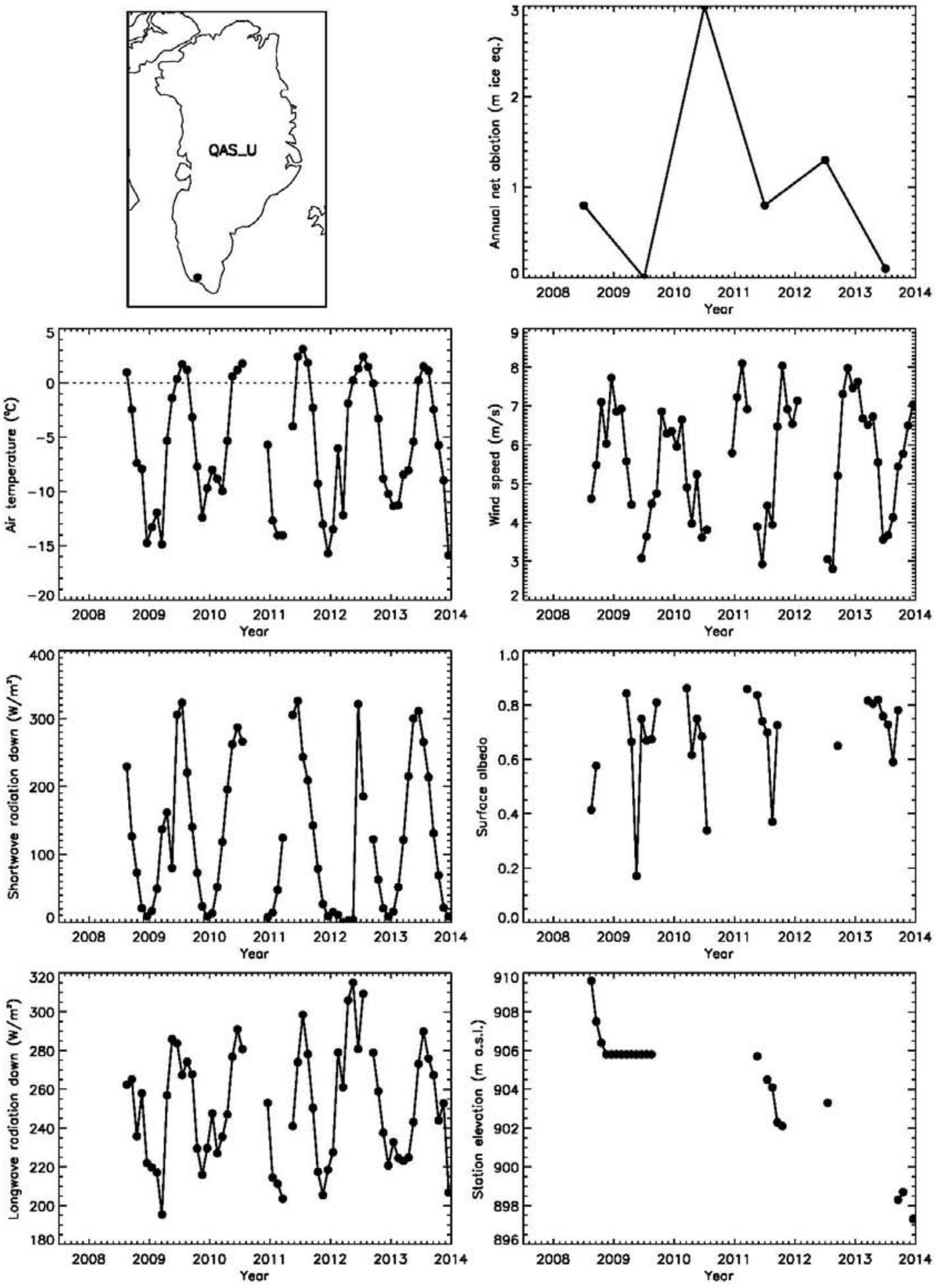


Figure 2.9. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for QAS_U AWS on the ice sheet.*

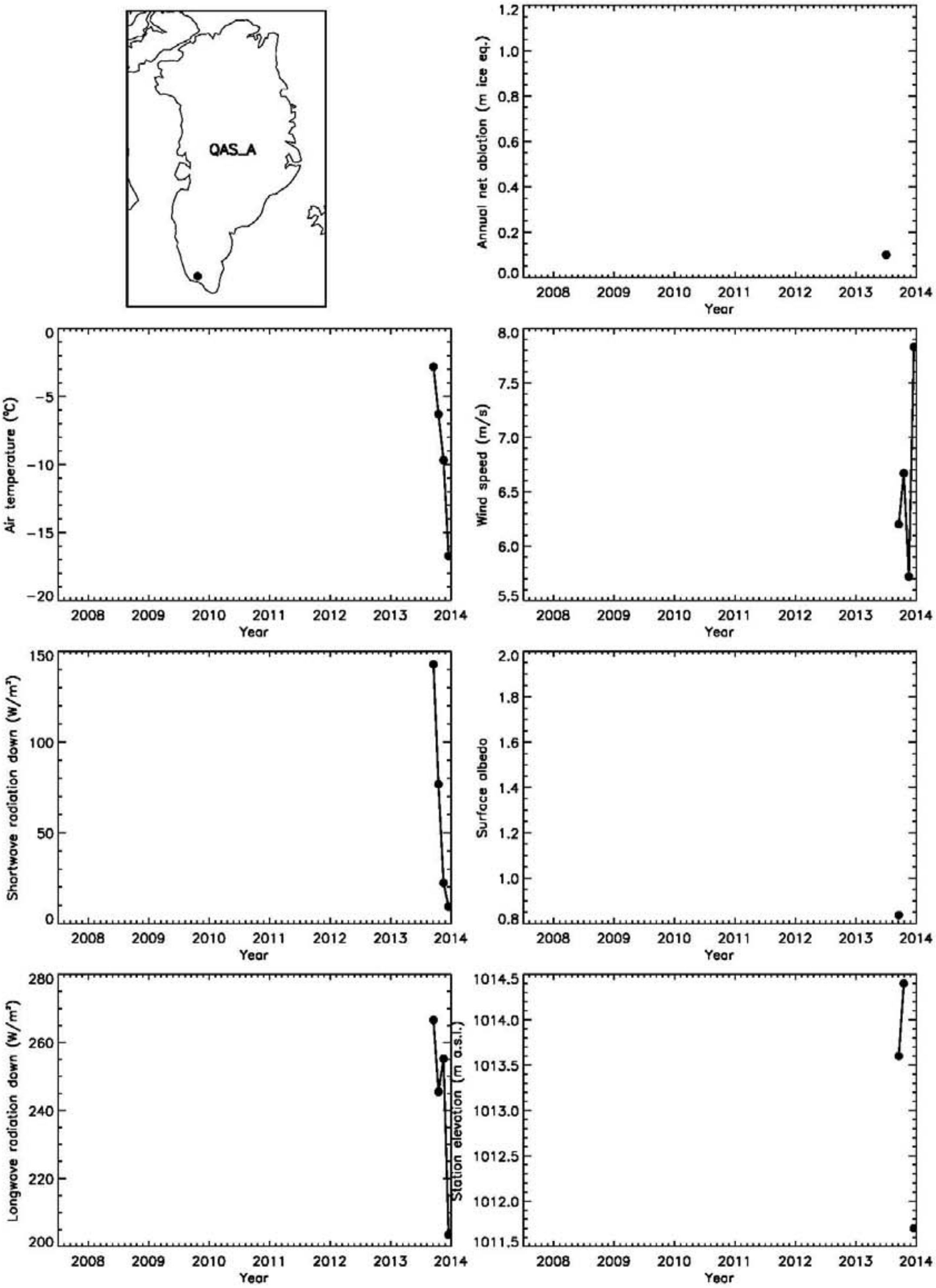


Figure 2.10. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for QAS_A AWS on the ice sheet.*

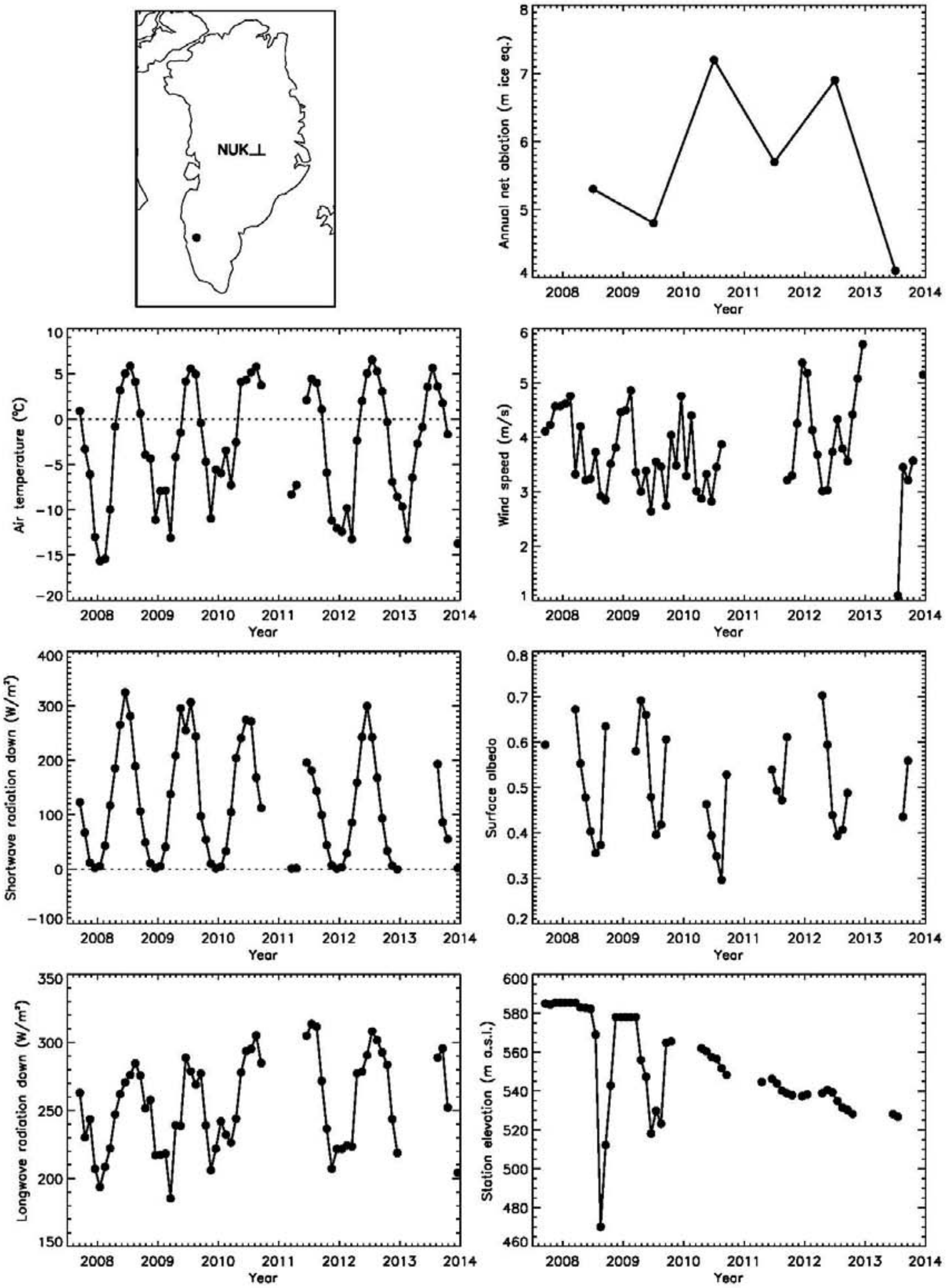
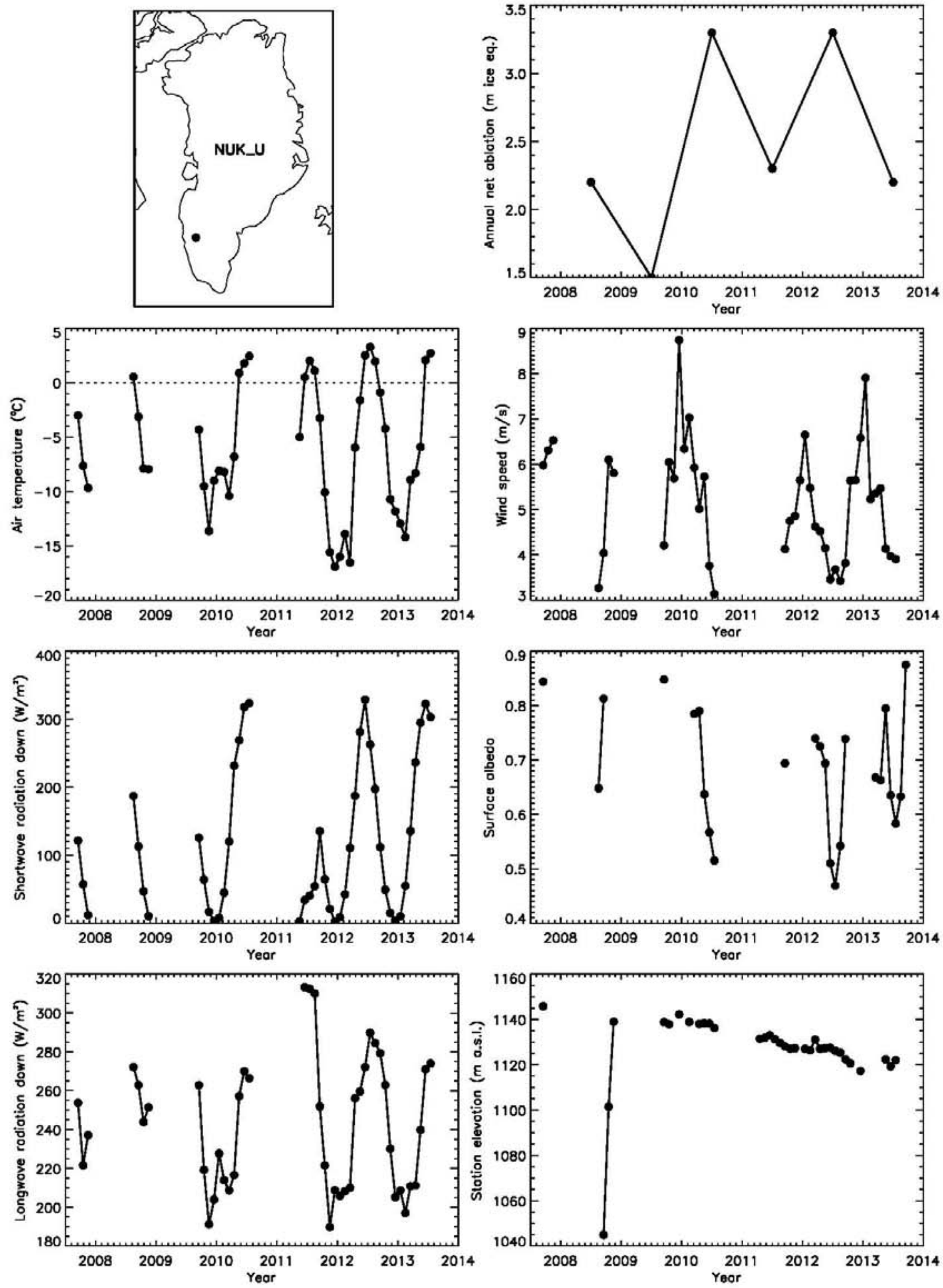


__Figure 2.11.__ Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for NUK_L AWS on the ice sheet.



Figur 2.12. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for NUK_U AWS on the ice sheet.*

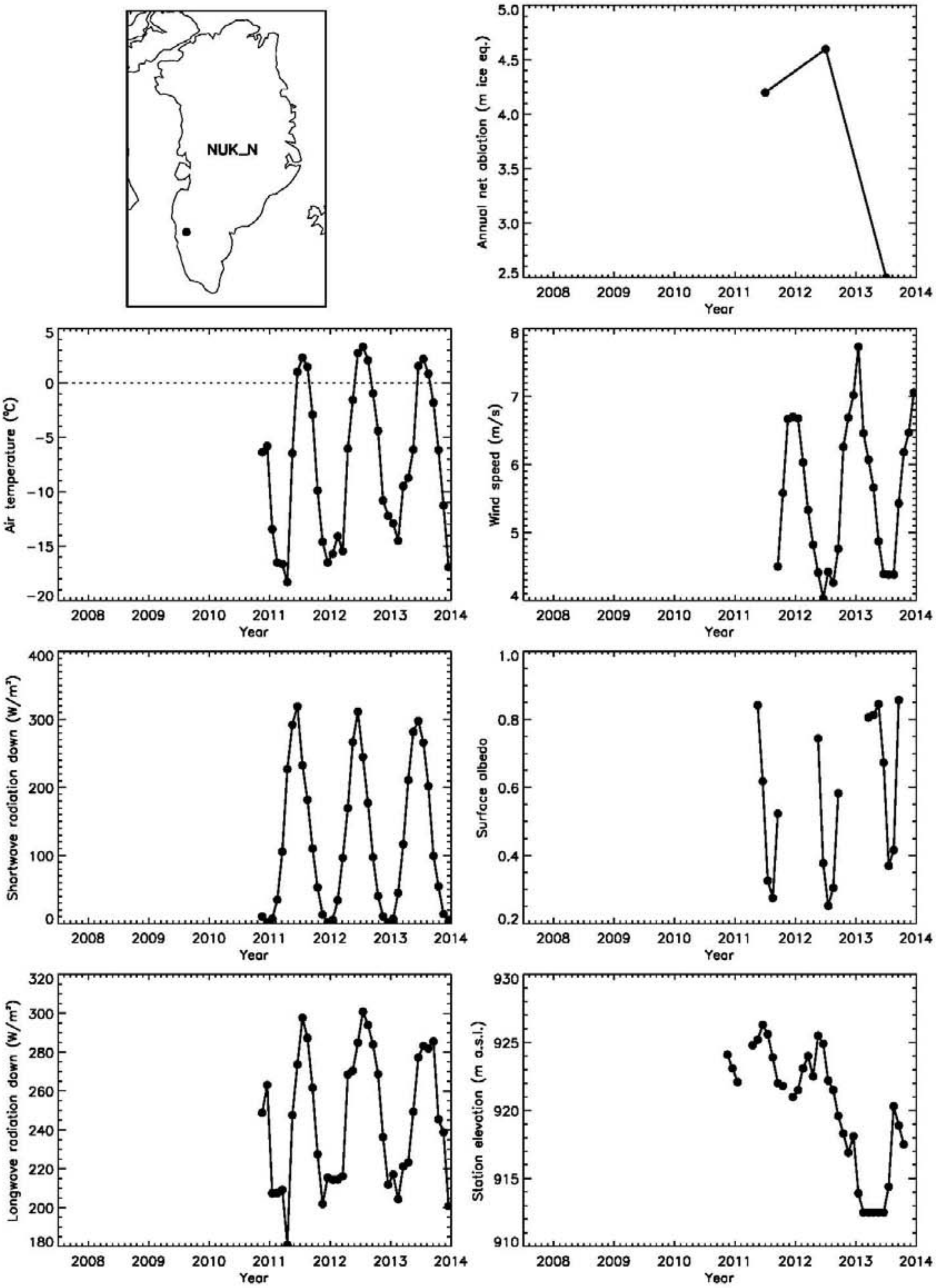


Figure 2.13. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for NUK_N AWS on the ice sheet.*

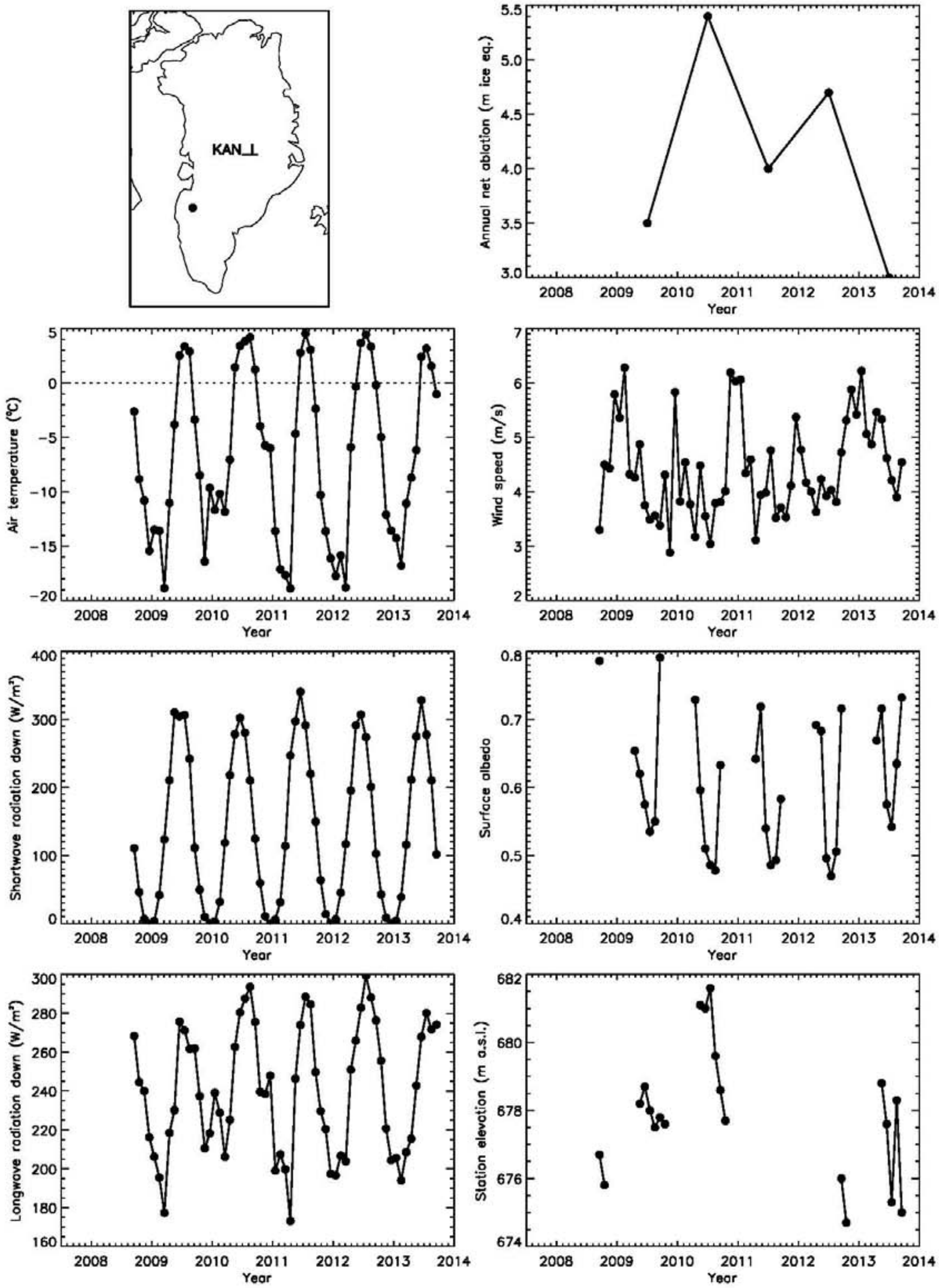


Figure 2.14. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for KAN_L AWS on the ice sheet.*

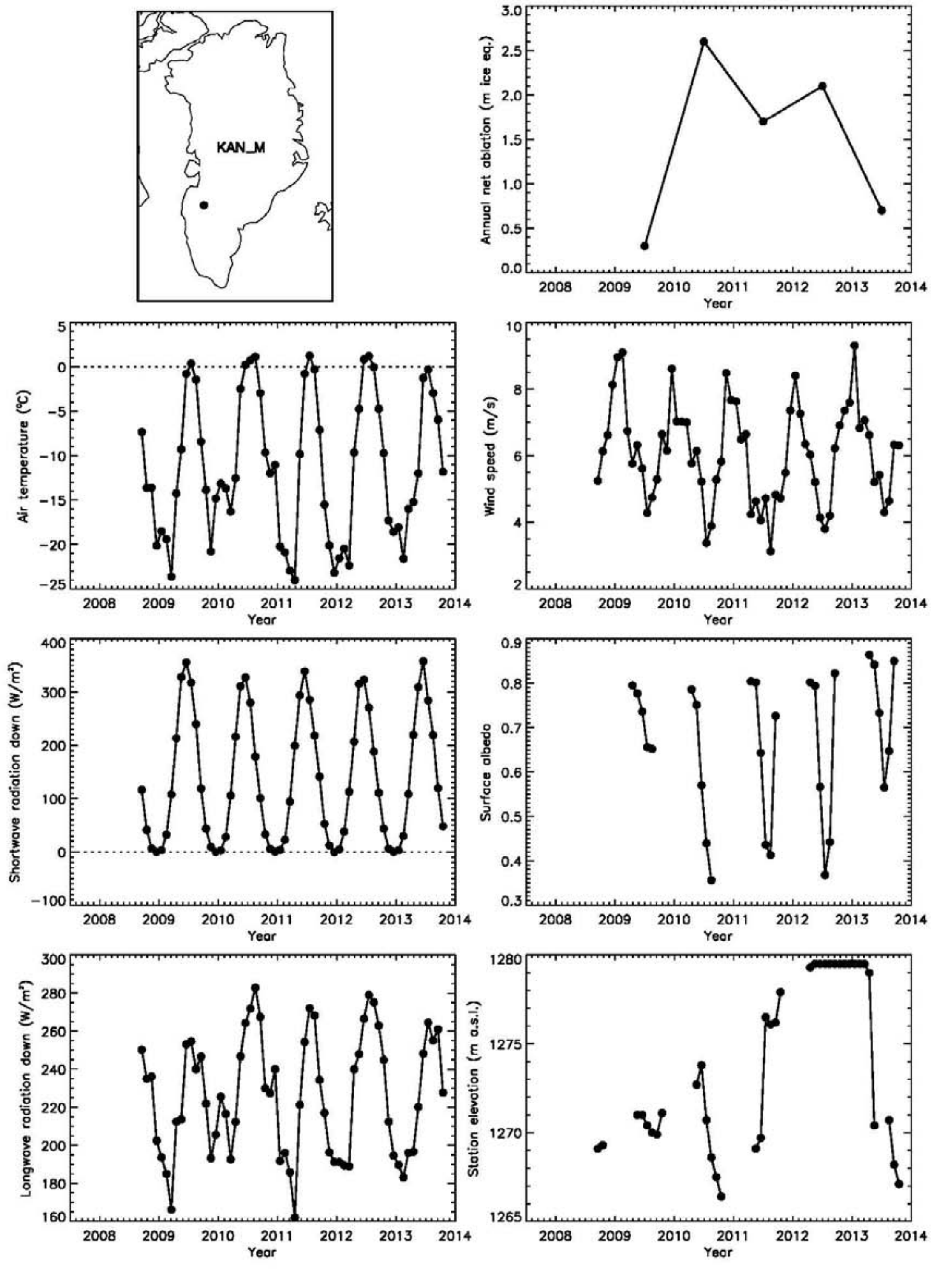


Figure 2.15. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for KAN_M AWS on the ice sheet.*

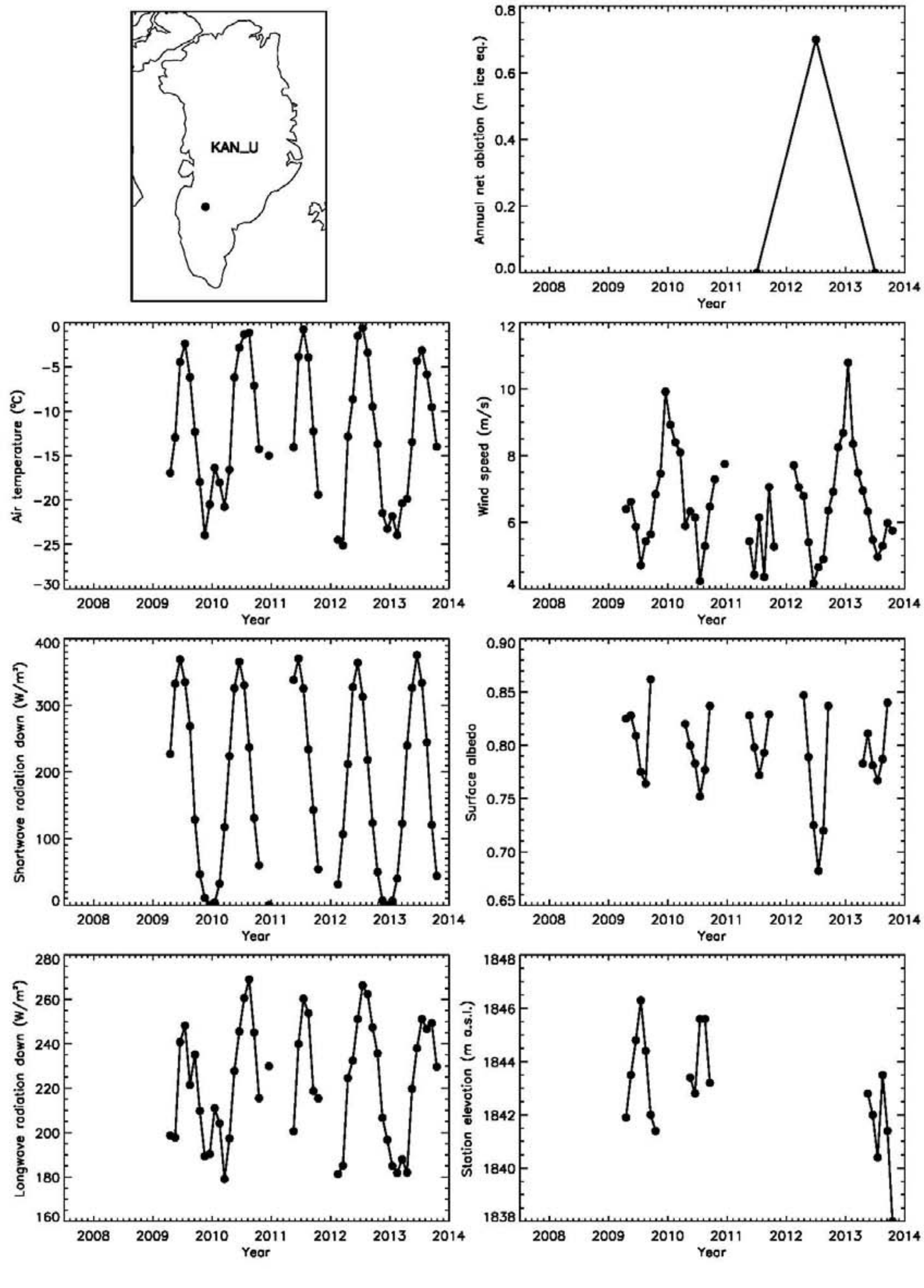


__Figure 2.16.__ Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for KAN_U AWS on the ice sheet.

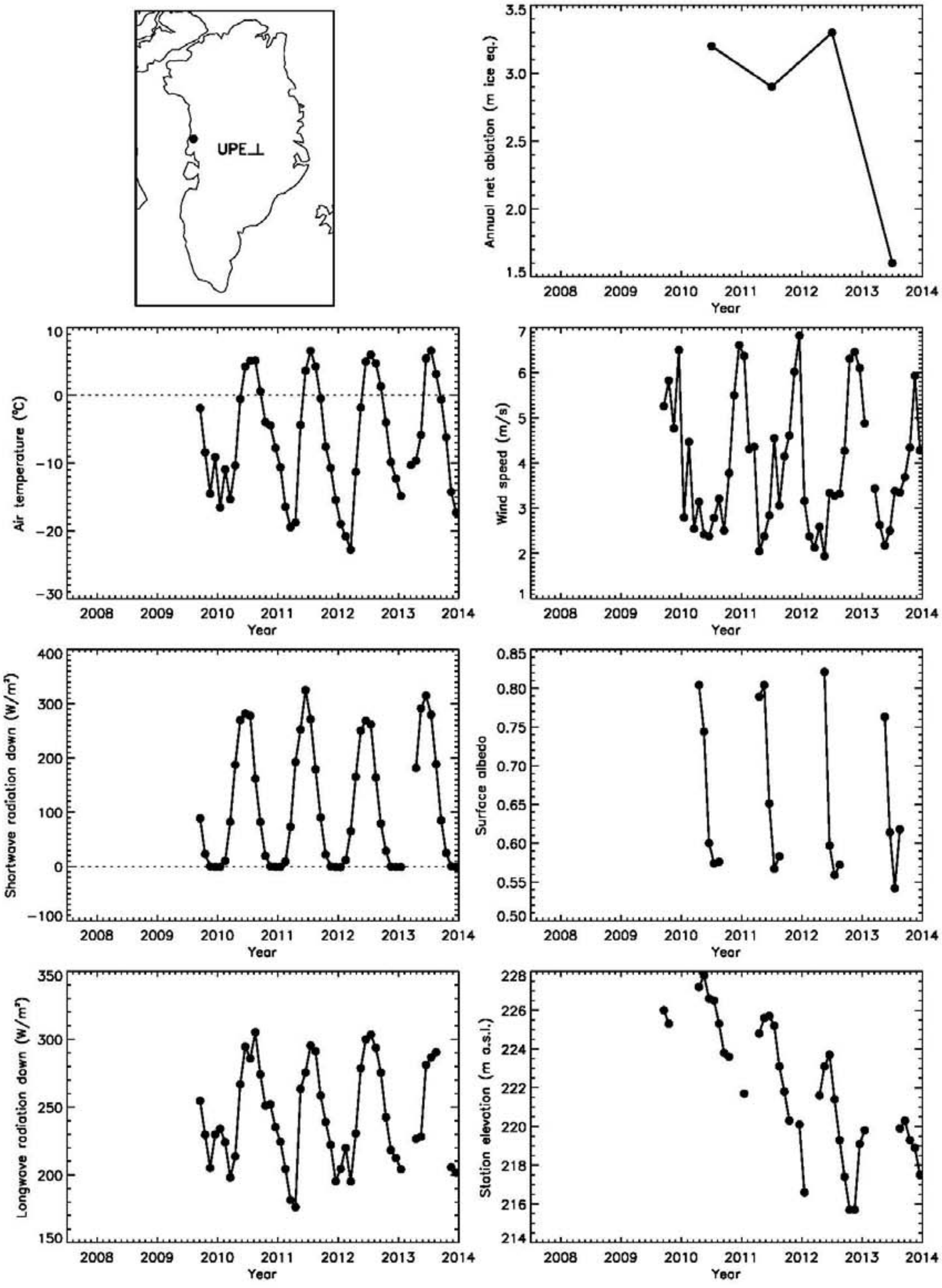


Figure 2.17. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for UPE_L AWS on the ice sheet.*

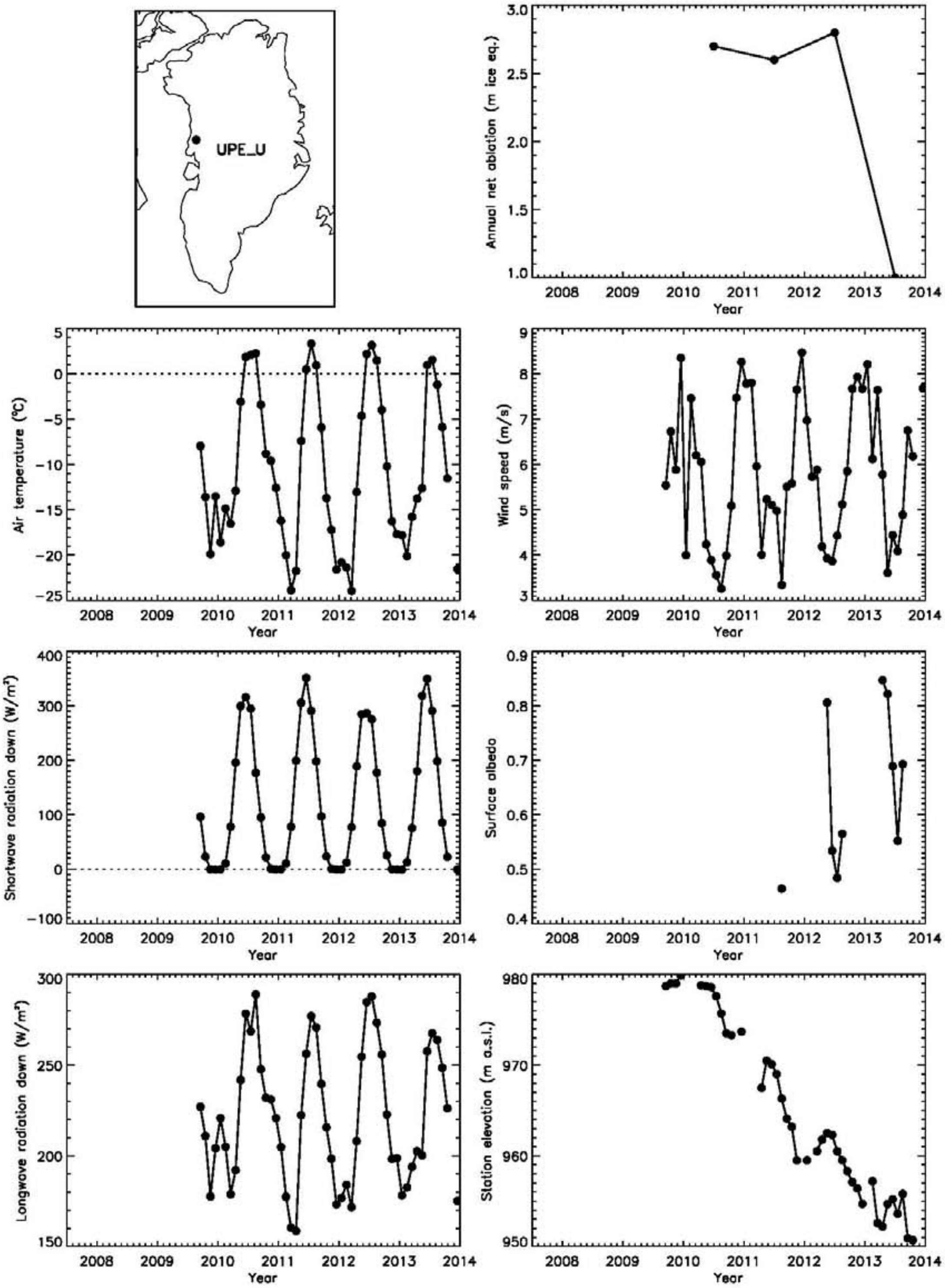


Figure 2.18. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for UPE_U AWS on the ice sheet.*

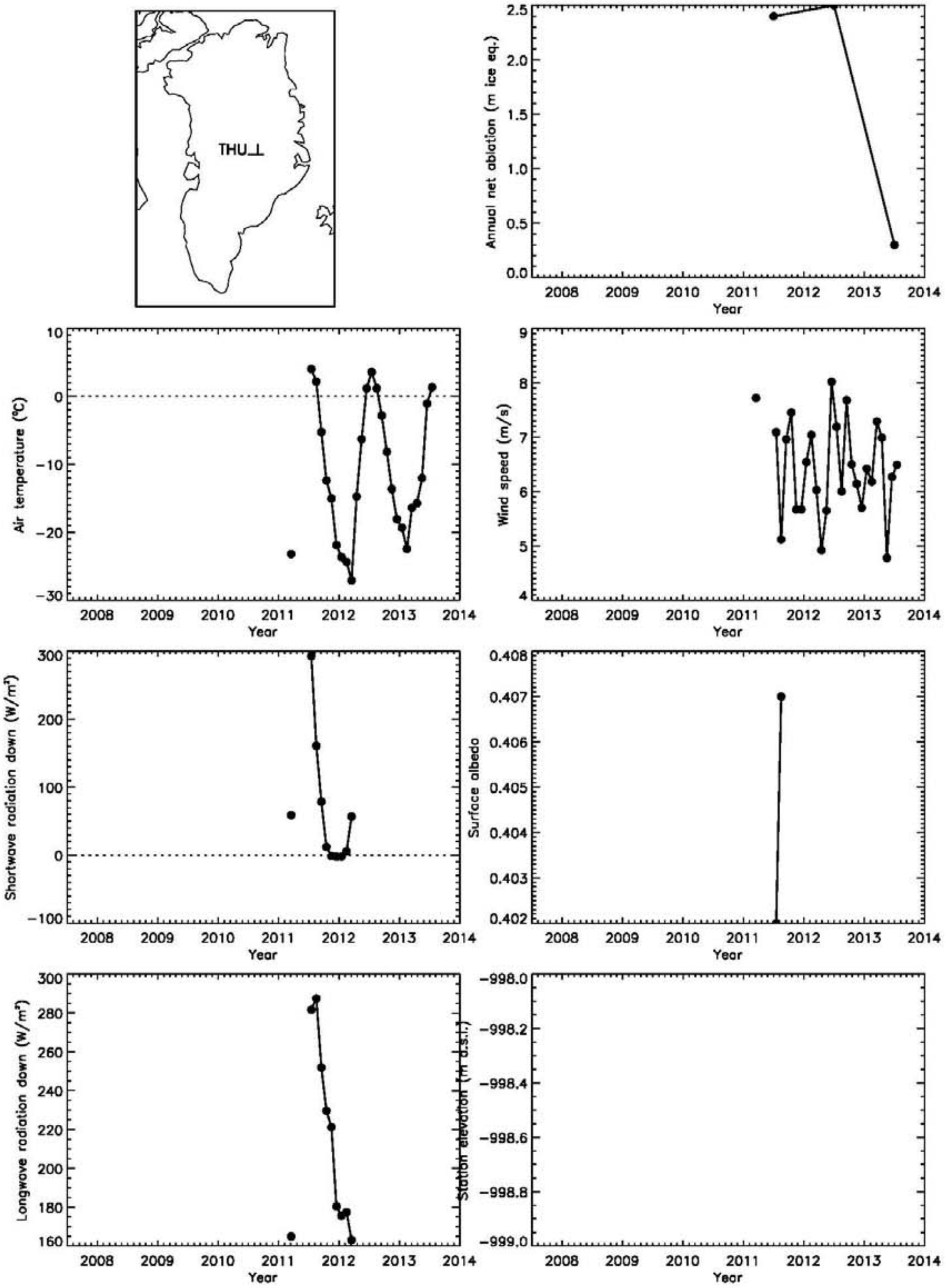


Figure 2.19. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for THU_L AWS on the ice sheet.*

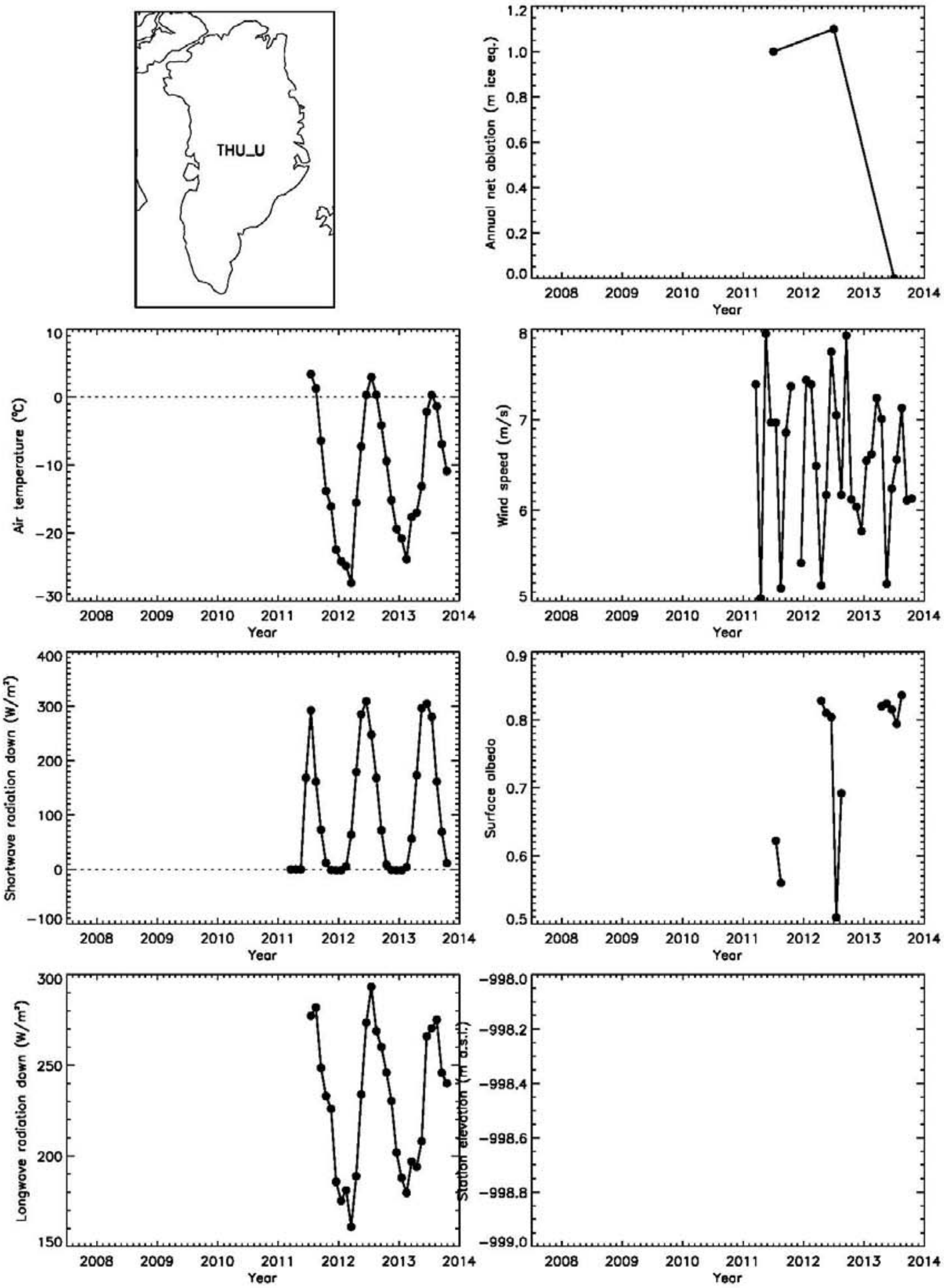


Figure 2.20. *Mean values of net ablation, air temperature, wind speed, downward solar (shortwave) and terrestrial (longwave) radiation, surface albedo and surface elevation for THU_U AWS on the ice sheet.*

Greenland melt

Motivation

Satellites such as the GRACE constellation provide a direct method for determining the mass loss of the Greenland ice sheet. This method, however, can only provide results on a regional scale and at limited temporal resolution, weeks at best. Importantly, the method does not distingusih between ice dynamic processes leading to changes in frontal ablation (mostly iceberg calving) and surface mass fluctuations by e.g. melt.

A popular approach to determining the ice sheet surface mass budget is using regional climate models, which calculate the energy and mass exchange at the surface of the ice sheet, and are forced at remote lateral boundaries by ECMWF reanalysis data. Such models provide useful estimates of the surface mass budget (Ettema et al., 2009; Fettweis et al., 2011) but can lack absolute accuracy. PROMICE stations provide the absolute accuracy and are being brought to bear in regional climate model development. That effort has recently focused on the Danish Meteorological Institute (DMI) HIRHAM model.

Yet, there are no purely observation-based estimates of the surface mass budget of the entire ice sheet. Remote sensing can be used to determine the surface melt area, but not melt volume. In-situ automatic weather station data provide relatively precise, but very local surface mass budget data. Combining observational datasets potentially allows melt quantification for the entire Greenland ice sheet. In 2013 PROMICE started exploring this possibility, yielding promising initial results.

Method

The PROMICE melt product is generated by calculations that rely on two observational datasets: near-surface air temperature and surface albedo, two prime drivers of surface melt. We calculate daily-average air temperature from PROMICE and GC-Net networks on the ice sheet. We calculate daily-average values from all available weather stations. We apply an automated quality check before inverse-distance interpolating the temperatures over the entire ice sheet surface, to obtaining the novel result of an in-situ temperature map. An example of this is shown in Figure 3 illustrating the elevation-dependent temperature over a five-day summer period in late June/early July in 2011. We chose this period for the example as it was one with few clouds, allowing a comparison with satellite-derived (MODIS) surface temperatures (Figure 4). Although the figures 3 and 4 do not illustrated exactly the same parameter (surface versus air temperature) and the MODIS temperature has a larger measurement uncertainty than that of the weather stations, the figures agree well and do not identify large errors with the air temperature interpolation. Problems with the interpolation would result in an increase of the difference between Figures 3 and 4 with distance from the weather stations.

The daily albedo used in our melt calculations is a destriped, regridded version of the MOD10A1 MODIS albedo product (Box et al., 2012). An example of this on a coarse 10x10 km grid is illustrated in Figure 5 for day 200 of 2013. This day exhibited a large cloud cover preventing remotely-sensed albedo observations. In our methodology, cloud gaps are filled by using the first available subsequent measurement, assuming small snow and ice metamorphoses on daily timescales (right panel of Figure 5).

Air temperature and albedo are both gridded onto a 1x1 km grid (Bamber et al., 2013). For every grid cell melt is estimated from air temperature and albedo, taking into account the latitudinal effect on the daily temperature cycle, and the top-of-the-atmosphere solar radiation that in part determines the net solar radiation absorbed at the ice sheet surface. This empirical relation is calibrated using the ablation measurements at the PROMICE weather stations.

The above method provides a daily observation-based estimate of surface melt volume for every location on the ice sheet. Finally, assuming that surface albedo is a first-order indicator of the firn’s available pore space and cold content, refreezing is parameterized as a function of it. This provides an estimate of surface meltwater runoff from the ice sheet, in addition to the amount of meltwater generated.

Validation

An important part of this study is the validation by means of discharge measurements. Several multi-year time series of meltwater discharge exist in Greenland, allowing a comparison between the PROMICE melt water runoff with an independent observation. An example of this is illustrated in Figure 6, in which discharge from the pro-glacial lake Tasersuaq in southwest Greenland is compared to our result, 15-day smoothed to (in basic form) account for delays in melt water routing through the glacial and lake systems. These results are encourating, as they illustrate that the calculations provide a correct order of magnitude for melt, and are capable of reproducing the temporal variability in discharge measurements. Do note that the refreezing, calculated as a simple function of albedo, was in part tuned for runoff to match the discharge measurements. After receiving more discharge time series from e.g. Asiaq (the Greenland Survey) we will be able to validate our results more thoroughly, and improve retention calculations further.

Preliminary results

This study provides us with several novel observation-based results, such as near-surface air temperature (and lapse rates therein), surface melt, meltwater retention and runoff at any location and date on the Greenland ice sheet. An example for surface melt is illustrated in Figure 7 for the same period shown in Figures 3 and 4. This map illustrates a familiar melt pattern, with higher melt in regions with lower albedo and/or higher temperatures. These results can be obtained for any day since the initiation of the PROMICE weather station network, with improved results for periods with a larger amount of measurements available (i.e. weather stations installed).

Required still, are: 1) an improved melt and retention calculation and 2) a detailed uncertainty analysis, which are planned for 2014. A first comparison with regional climate model results indicates that our calculations yield larger melt values at higher elevations, which will be investigated.

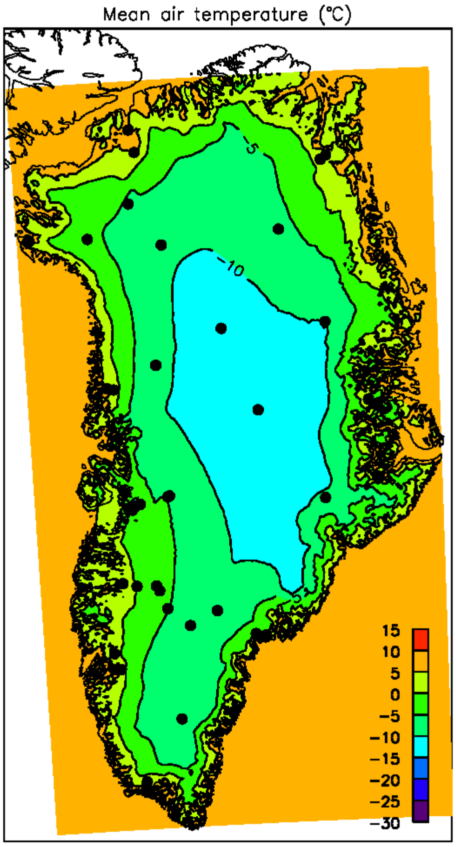


Figure 3. *Average near-surface air temperature for days 178-182 in 2011. The dots indicate the locations of the weather station used for the interpolation.*

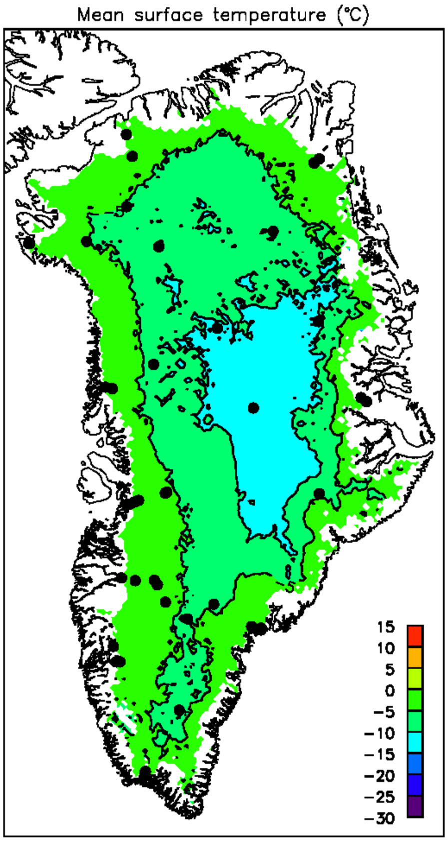


Figure 4. *Satellite-derived (MODIS) surface temperature for the same period as plotted in Figure 1.*

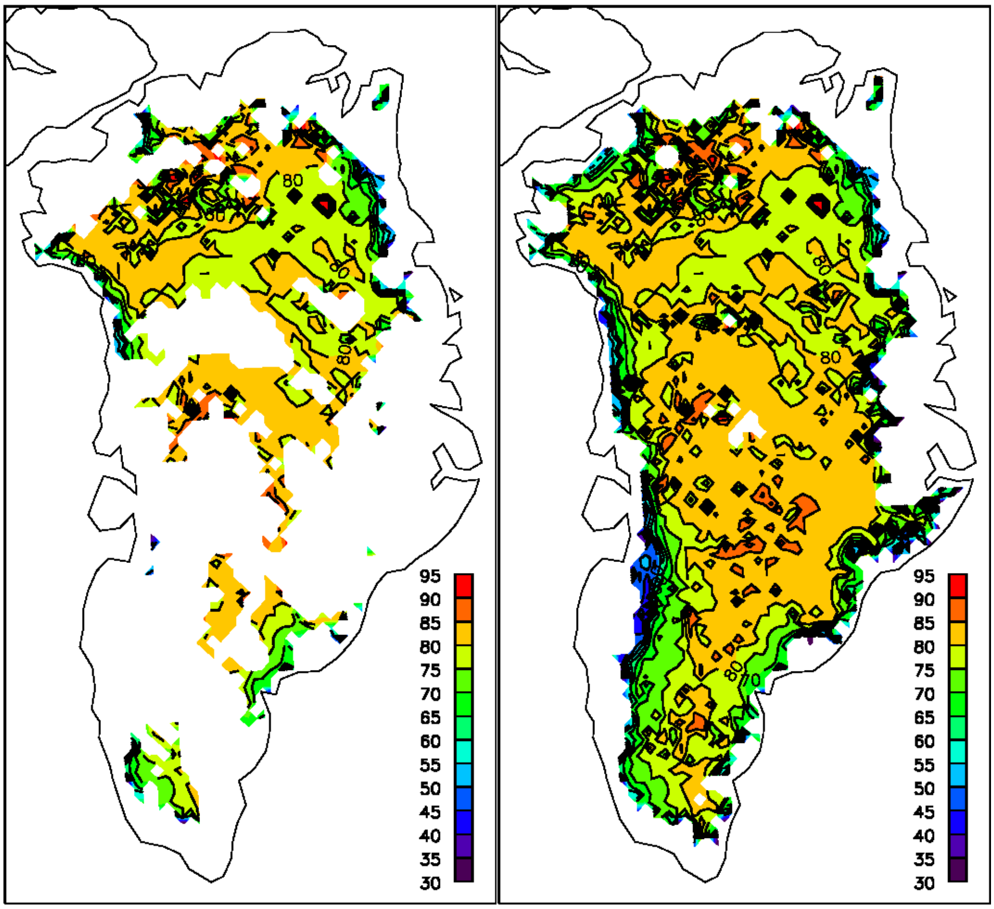


Figure 5. *MODIS albedo on day 200 of 2013 with cloud gaps (left) and with cloud gaps (largely) removed by using albedo from the three following days.*

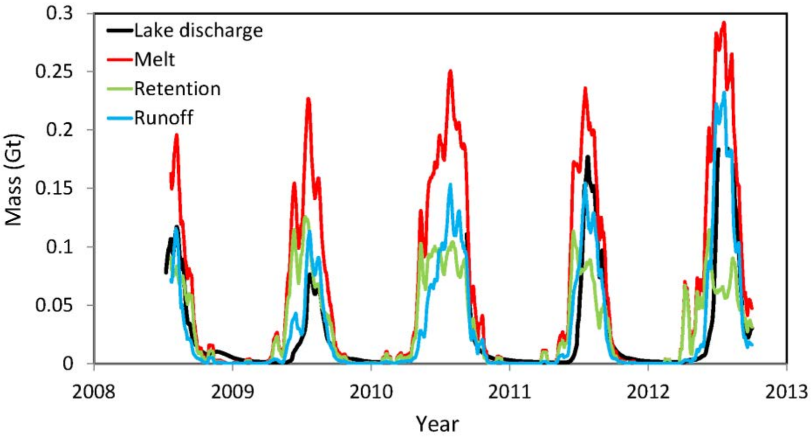


Figure 6. *Measured lake discharge (black) from the proglacial Tasersuaq lake compared to the surface melt water (red), retention (green) and runoff (blue) on the ice sheet within the hydrological catchment of the lake. The calculated quantities are 15-day smoothed to facilitate comparison with the lake discharge.*

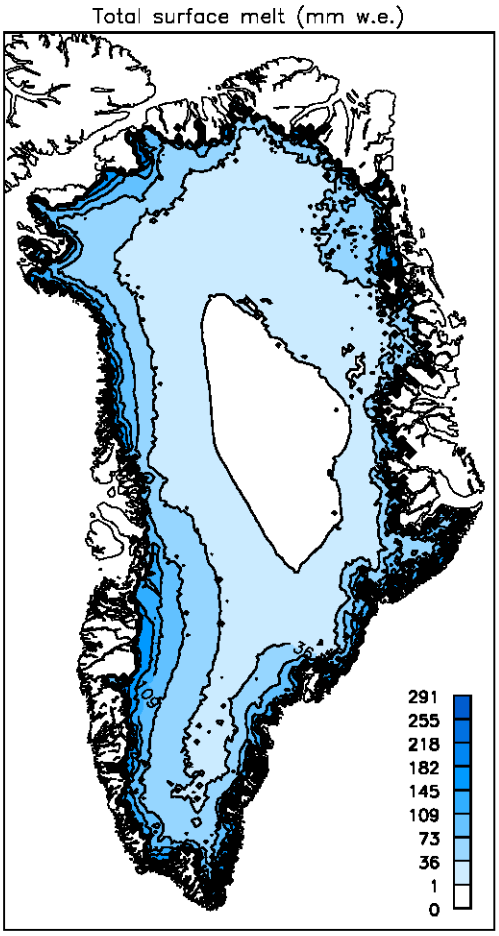


__Figure 7.__ Surface meltwater locally generated on the Greenland ice sheet for days 178-182 in 2011.

Dynamic mass loss

The ice sheet mass budget can be partitioned in two main components: surface mass balance (SMB) and iceberg discharge via glacier dynamics (D). Over the past decade, the surface mass balance proportion has accelerated relative to the D component, changing from 50% (van den Broeke et al., 2009) in the period 2000-2008 to more than two thirds (68%) 2009-2012 (Enderlin et al., 2014).

While climate models appear to capture the SMB response to climate change, the physical processes driving variability in glacier discharge are more complex. We have arrived at a stage where we can compute ice sheet flow discharge using PROMICE data. Here we present results from a 370 km wide West Greenland ice sheet catchment that includes the 6 km wide Jakobshavn Isbræ, and several other marine-terminating outlet glaciers, such as Store and Rink. We combine satellite-derived ice surface velocities, airborne ice thickness measurements, and modelled SMB to assess the dynamic discharge from Basin 7.

By quantifying the mass fluxes entering and leaving the ice sheet, we can calculate the amount of ice lost in the form of solid mass (icebergs, termed D) and then derive the total mass loss of the ice sheet. First we quantify the mass flux (F) discharging across a flux gate, upstream of the grounding line, defined by the path of PROMICE airborne ice thickness surveys conducted in the summers of 2007 and 2011 (Figure 8). With this flux known, D can be estimated by adding a correction for the surface melt (or gain), occurring downstream of the flight line. This component is here derived the from the regional climate model MAR v3.2. The PROMICE surface melt estimates described in the previous section may be used when more mature. Quantification of D then allows us to estimate the total mass balance (TMB) of the catchment. The TMB value is calculated as TMB=SMB – D , where SMB is the yearly SMB field for the entire basin.

Both the upstream flux (F) and downstream discharge (D) in Basin 7 are within uncertainty of their respective values in 2007 and 2011 (Table 1), i.e., no detectable change over the four years. We employ different airborne-derived ice geometry data in each year. The TMB, however, decreases by 6.2 Gt/yr. This suggests that despite the presence of several major tidewater outlet glaciers in Basin 7, the annual variability in mass balance of Basin 7 is primarily driven by fluctuations in SMB.

The 2007 TMB value (−31.5±8.6 Gt/yr) corresponds to a sea level rise contribution of ≈ 0.09 mm/yr and agrees within uncertainty with other studies of approximately the same area in similar time periods.

Year	F	D	TMB
2007	79.7 ± 6.1	70.6 ± 6.2	-31.5 ± 8.6
2011	77.7 ± 7.5	68.6 ± 7.6	-37.7 ± 8.9

***Table 1.** Mass fluxes in Gt/yr. Upstream fluxes (F), ice discharge (D), and total mass balance TMB (=SMB - D).*

In the PROMICE framework, this basin scale mass balance assessment is being extended to deliver basin scale mass balance and ice discharge estimates of the entire Greenland ice sheet over multiple observation years. This survey aims to improve partitioning of mass loss on basin scale, contributing to improved sea level rise projections for the Greenland ice sheet.

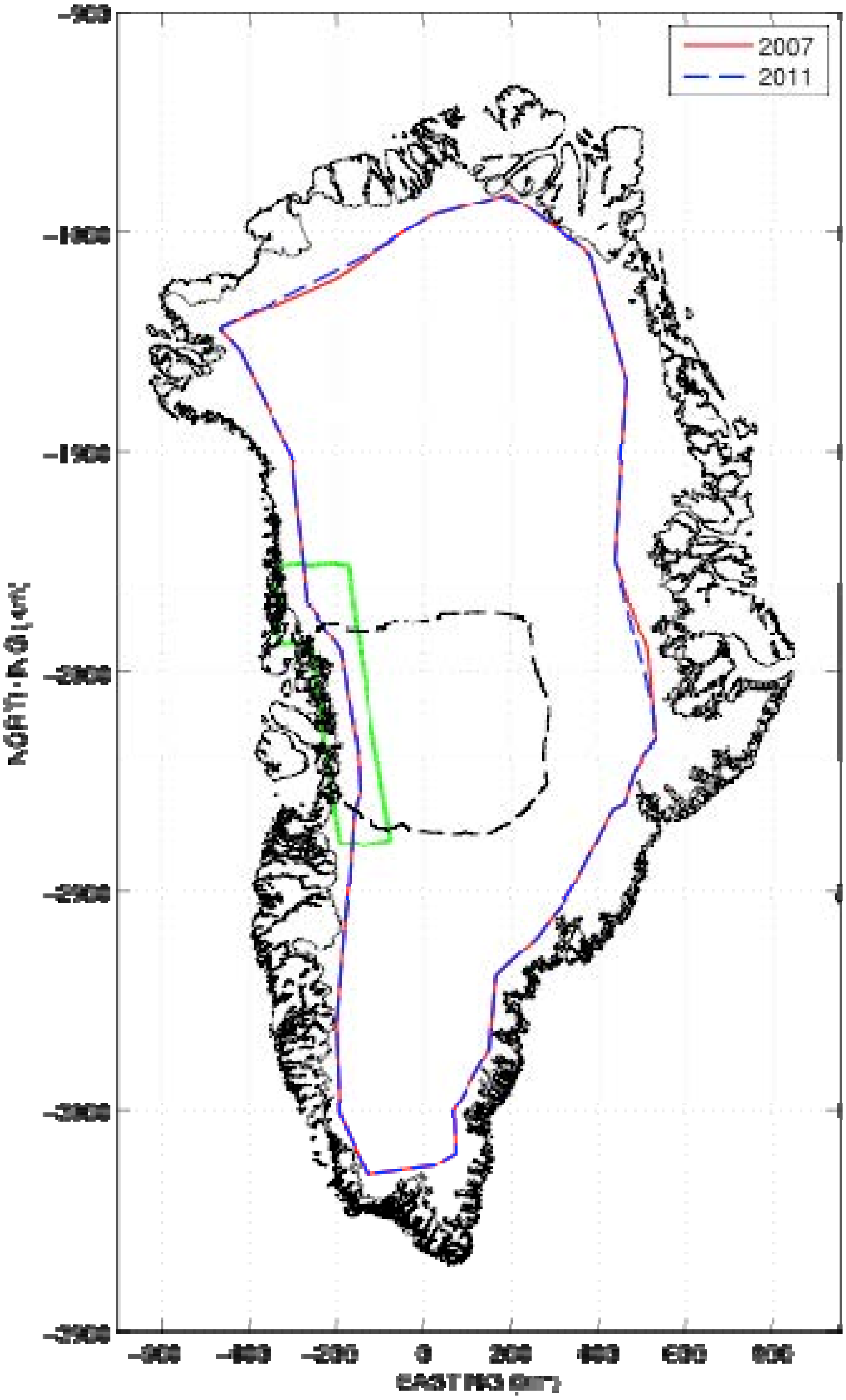


Figure 8. *2007 (red) and 2011 (blue, dashed) interpolated flight lines. Area of computed surface velocities for this study is outlined in green and the study catchment is shown in dashed black.*

Glacier mapping

During 2013 the glacier mapping work focused on the use and dissemination of the PROMICE aerophotogrammetric map of all Greenland land ice masses published in Citterio and Ahlstrøm (2013). The irregularly shaped ice-covered areas derived from the PROMICE glaciers map allowed constraining GRACE-the cryosphere-attributed signal (Fig. 9, Colgan et al., 2013). We found a mass loss of 218 ± 20 Gt a^{-1} due to the ice sheet proper, and 34 ± 5 Gt a^{-1} (or ~14%) due to Greenland peripheral glaciers and ice caps from December 2003 to December 2010. This mass loss from Greenland peripheral glaciers and ice caps exceeds that inferred from all ice masses on both Ellesmere and Devon islands combined. This partition therefore highlights that GRACE-derived "Greenland" mass loss cannot be taken as synonymous with "Greenland ice sheet" mass loss when making comparisons with estimates of ice sheet mass balance derived from techniques that sample only the ice sheet proper (Colgan et al., 2013).

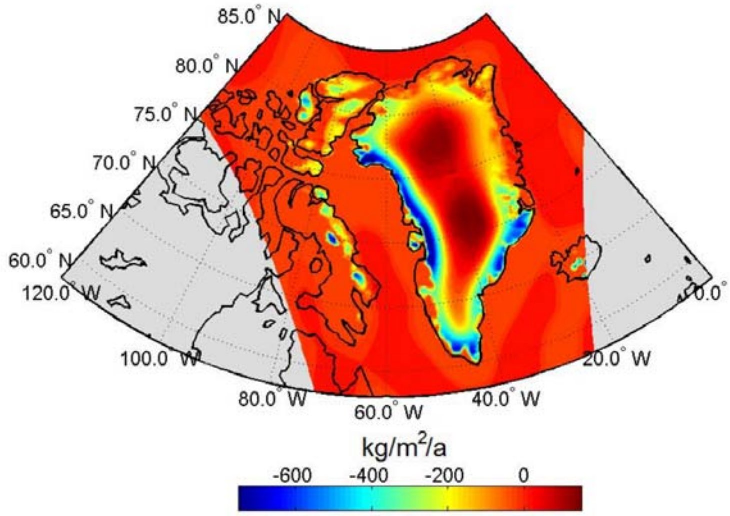


Figure 9. *Inverted rate of mass change constrained to the irregularly shaped ice-covered areas in Greenland (from the PROMICE glaciers map) and the Canadian High Arctic (from the Randolph Glacier Inventory). Color scale saturates at −750 and +150 kg m−2 a−1. Grey shading denotes areas beyond the inversion domain.*

The PROMICE glaciers map data, either as vectors or as derived gridded products (Fig. 10), have been delivered upon request (Sarah Aciego, University of Michigan, USA; Rene Forsberg, DTU-Space; Harper Collins Publishers, Scotland; Jacob Yde, Sogn og Fjordane University College, Norway). The vectors have also been improved on an ongoing basis when local artifacts have been found – these have all been minor local corrections with no significant effect on the Greenland totals in Citterio and Ahlstrøm (2013). Further and easier dissemination of the current revision of the PROMICE map through the internet is planned for 2014. As a convenience for users and to achieve a wider dissemination, a derived raster dataset of fractional ice cover matching the Greenland-wide grids of Bamber et al. (2013) will also be provided. This was not completed during 2013 due to time constraints and will be finalized in 2014.

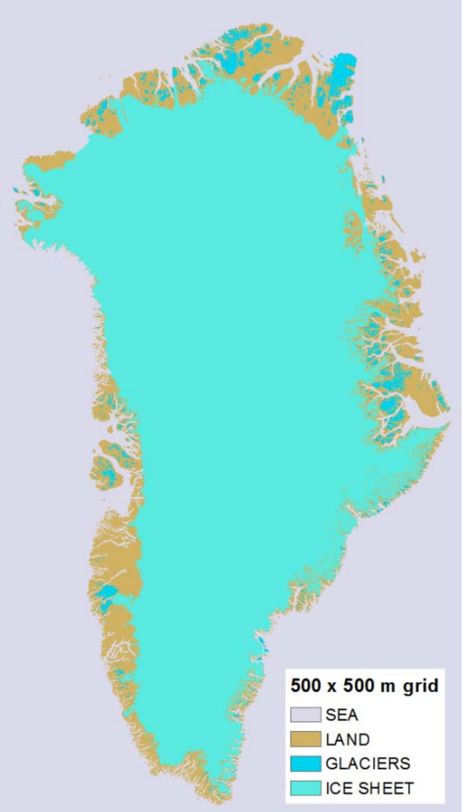


Figure 10. *The 500m cell size gridded dataset produced for DTU-Space from the Citterio and Ahlstrøm (2013) map.*

Work has been started toward using the Citterio and Ahlstrøm (2013) dataset for quantifying glacier extent change over time. The initial aim was to produce a glacier area change assessment between the mid-1980's (the PROMICE dataset) and approximately year 2000 (the inventory by Rastner et al., 2012). Due to the extensive work required to account for the different approaches adopted by the two datasets in splitting ice masses into individual flow units, and in considerations of the higher scientific impact, the work has been reprioritized to focus on the comparison of 1980's against current (year 2013) glacier extent, also taking advantage of the newly launched Landsat 8 satellite. A land classification algorithm is being developed that is based on spectral band ratios and incorporates a priori information on approximate glacier margin positions based on the existing glacier maps. Preliminary tests on a sample region show promising results (Fig. 11), with significantly higher accuracy then the classical thresholded band ratio methods used in past works (e.g. Citterio et al., 2009) and this work will continue in 2014.

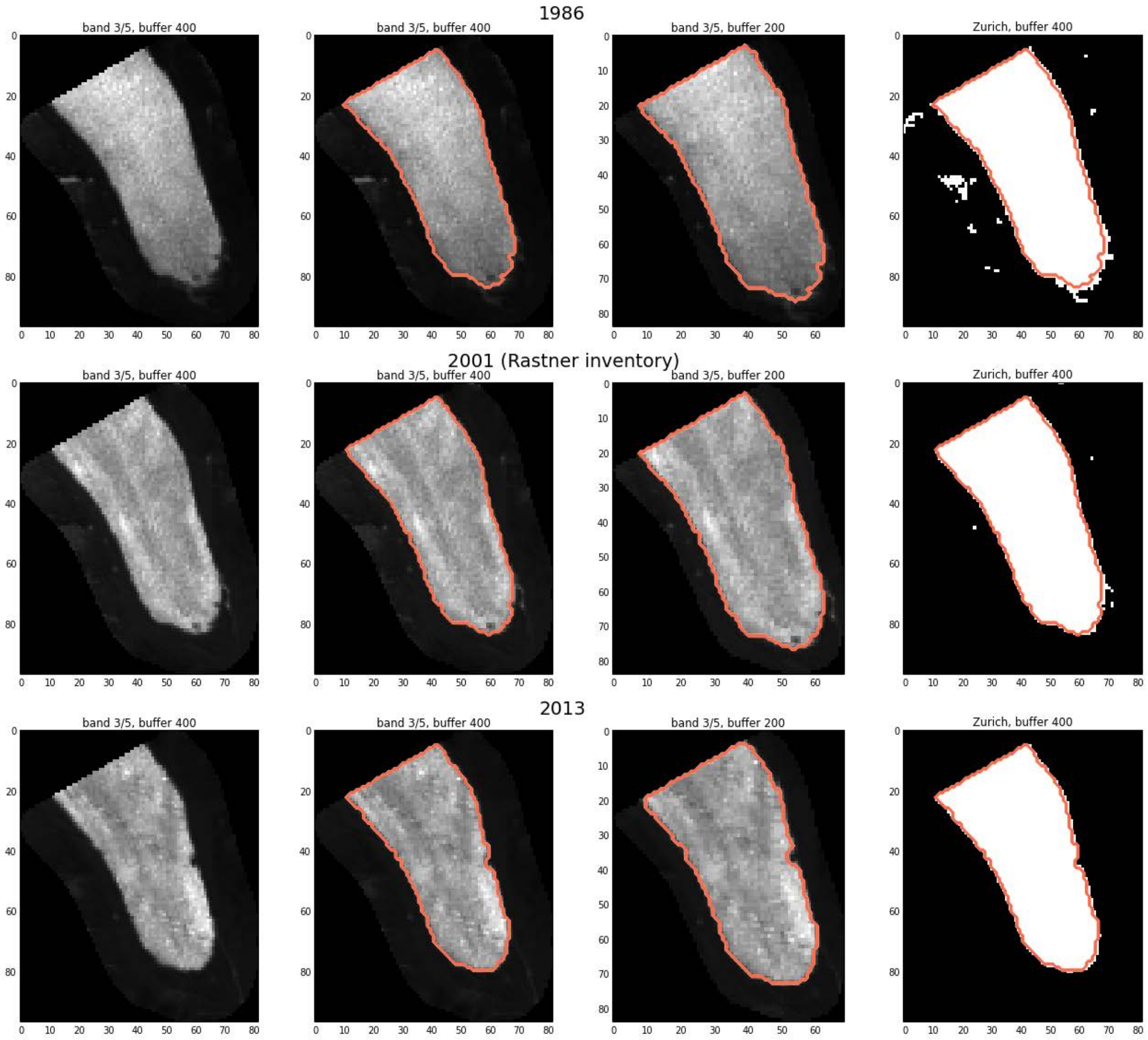


Figure 11. *Detail of the terminus and lower tongue of a test glacier (first column) showing the performance the glacier mapping algorithm being developed (red line, second and third columns) compared with the classical thresholded band ratio method (white: ice, black: land, fourth column).*

GPS & time lapse photography

On-site GPS instruments are utilized in PROMICE on two different platforms: on the automatic weather stations (AWS) and as separate trackers deployed directly on fast-flowing outlet glaciers. The first are useful for study of the interaction between surface meltwater and ice sheet movement and to trace the AWS movement in-between visits. The second are designed to evaluate the viability of ice-dynamic mass loss calculations in PROMICE as they record both the seasonal and inter-annual change in glacier velocity right where the ice is lost to the ocean as either icebergs or melt at the ice-ocean interface. The GPS tracker instruments and the data analysis methods were thoroughly discussed in Ahlstrøm and Box (2013) and only a concise status of 2013 activities is given here.

A major development has been the initiation of a PhD project entitled 'Modelling the Upernavik Glacier Complex' funded internally by GEUS with additional support from University of Copenhagen. This project is focused on utilizing the GPS tracker data in conjunction to velocity fields derived from satellite data as forcing to the Ice Sheet System Model (ISSM) which is a higher-order ice-dynamics model developed at the Jet Propulsion Laboratory of the California Institute of Technology (http://issm.jpl.nasa.gov/). Apart from looking into specific basic research questions on the nature of outlet glacier response to climate change, the project will also deliver the methodological development to quantify seasonal variability in ice-dynamic mass loss which is the primary concern for PROMICE (Andersen, M.L. et al, *in press*).

A further development has been an improved, more user-friendly website for accessing the near real-time GPS tracker information (http://geus.motionterra.com) with an easy-to-use Google Earth interface. In this way, access to tracker data is immediately available online by simple download or browser viewing, including on-screen GPS track-plotting and the most recent data and tracker statistics displayed by mouse-click.

GPS tracker data have been specifically showcased in Ahlstrøm et al. (2013) and as a presentation at the US CLIVAR International Workshop 'Understanding the Response of Greenland's Marine Terminating Glaciers to Oceanic and Atmospheric Forcing – Challenges to improving observations, process understanding and modeling', June 4-7, 2013 (http://www.usclivar.org/meetings/griso-workshop).

Tangible results from 2013 include:

- The first comprehensive *in situ* validation of satellite-derived velocity fields published as Ahlstrøm et al. (2013).
- Direct observational proof of Greenland-wide rapid accelerations and decelerations of fast-flowing ice-sheet outlet glaciers
- Onset of early-season glacier acceleration comes successively later in the year for northern glaciers
- Each individual glacier tends to annually reproduce its own pattern of seasonal velocity variation

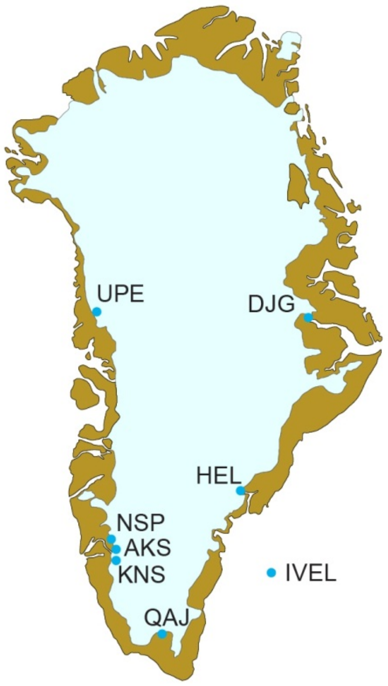


Figure 12. *Map showing glaciers with GPS trackers funded directly by PROMICE/IVEL.*

As of March 2014, PROMICE has 8 GPS trackers currently active and transmitting, while 3 GPS trackers have ceased transmitting, but may come back online. An attempt to get the three 'missing' trackers back online is underway by remotely re-programming them to extend the time they remain on to lock to GPS satellites. Active transmissions cover the following sites (see Fig. 12): Daugaard-Jensen Glacier (DJG), two Upernavik Glaciers (UPE), Kangiata Nunata Sermia (KNS), Akullersuup Sermia (AKS). Transmissions have ceased from a third Upernavik Glacier outlet, from Qajuutap Sermia (QAJ) and Helheim Glacier (HEL). The latter will most likely not be maintained due to cost considerations.

Time lapse cameras are currently in operation at an Upernavik Glacier, at Daugaard-Jensen Glacier, Kangiata Nunata Sermia and Helheim Glacier. Although the latter will most likely be terminated to reduce field costs, the others are producing high-resolution records of glacier movement that can be processed to yield field-of-view velocity fields at very high temporal (hourly) and spatial resolution (image-pixel scale). Apart from the velocity fields, the imagery also offers compelling outreach material as movies of ice-dynamic mass loss. Processing of these image archives to yield velocity fields are pending the involvement of students or a successful research proposal, but the potential outcome and the current outreach use justifies continued operation within PROMICE. The legacy monitoring dataset acquired increases in value every year, resembling ultra-high resolution satellite imagery acquired hourly.

Outreach

The PROMICE website (www.promice.org) has been restructured to include the PROMICE data base which was previously a separate site. The new improved website provides information on the project as well as the possibility to browse and download data. Due to the restructuring of the website we unfortunately have no total number of visitors for 2013. However, a general increase is observed with a current number of visitors per day of about 50 (April 2014).

The AWS data is a vital ingredient in determining surface melt of the Greenland ice sheet, and are crucial to many other surface mass balance studies that GEUS employees are involved in. But importantly, the data are becoming increasingly interesting to external people as well. As of December 2013, 84 different data users registered on the PROMICE website. Most users are from the US, and five are from Denmark, not counting GEUS personnel. As the data records grow in length and more people are aware of the PROMICE data products, the PROMICE website is visited more frequently and data downloads occur more often. The purpose of data download as stated by the users differs highly, ranging from scientific to educational and private. Here follow a few selected user-written purposes of download:

- Look into if there are correlations with oceanographic data, Tasiilaq meteo records and the Helheim calving front movement.
- For use in course work for module The Frozen Planet.
- Evaluate model surface parameterization for Greenland Ice Sheet.
- Educational purposes. It is intended that one (or more) MSc students work with these data as part of their research projects. Specifically, students are likely to address temporal variability of air temperature at different elevations on the ice sheet.
- We are analyzing upper ocean data from Kangersuneq fjord and are looking for weather data to see if they are correlated with mixing events measured by surface salinity drifters. This is a project funded through the Greenland Climate Research Center.
- I have a class on ice sheets and glaciers--we need to determine number of melt-days at a particular location, and I'm hoping the data from Promice will help me do it. Your positive degree days make more sense than a lot of the information I've been finding online. Thanks!
- Tracking weather is a long time hobby.

A number of products related to PROMICE are displayed on the Polar Portal a new website where Danish research institutions display the results of their monitoring of the Greenland ice sheet and Arctic sea ice to the general public. The PROMICE products presented are the AWS near real time measurements, calving front positions and an albedo based near real time estimate of total mass change of the Greenland ice sheet.

Two PROMICE newsletters were published (Appendix D).

Related projects

PROMICE demonstrates the Danish responsibility to monitor the Greenland ice sheet. The PROMICE AWS network presently includes 22 stations on the ice sheet. Only 14 of these are funded by PROMICE. The rest have been funded by other projects including Greenland Analogue Project (GAP), Linking sediments with ice-sheet response and glacier retreat in Greenland (SEDIMICE), Quantification of melt water refreezing on the Greenland ice sheet (REFREEZE), Greenland Climate Center project Impact of Glaciers near the Coast (Imglaco) and several more. In addition GEUS also maintains three stations on the A. P. Olsen ice cap in the GlacioBaisis project within the Greenland Ecosystem Monitoring framework.

In this way the monitoring effort is enhanced and PROMICE is provided with additional field instrumentation, logistics sharing and instrument knowhow, making it more cost effective. Also the field work of the smaller research project benefit strongly from PROMICE and would in many cases not have been feasible without the PROMICE platform to build upon.

PROMICE team members were in 2013 involved in a number of international research projects including the EU-funded Ice2sea, the European Space Agency (ESA) funded Climate Change Initiative Ice Sheets (CCI_Ice Sheets) and CryoClim and the Nordic Top Research Initiative Center of Excellence ‘Stability and Variations of Arctic Land Ice’ (SVALI) . These provided PROMICE with additional scientific insights and data.

Of high importance is the long term consistent knowledge and data which PROMICE can provide to the projects and which makes the PROMICE project team members attractive as project partners. E.g. Danish institutions have a strong involvement in the ESA CCI_Ice_sheets project and is lead by DTU-space. A large component of the project is concerned with ice velocity mapping. This is partly based on the ice velocity mapping knowhow maintained in Denmark due to the ice velocity mapping tools developed within PROMICE. Also data from PROMICE are valuable for validation of the satellite derived products in the ESA CCI_Ice_sheets project .

PROMICE team members in 2013 also performed a commercial evaluation of future hydropower potential of the Qorlortorsuaq Area, South Greenland. The work included installation of PROMICE type AWS’es and relied on modeling techniques developed within PROMICE.

In this respect, PROMICE provides knowledge and data of use directly for society and also for international projects enhancing the possibility of Danish involvement. At the same time PROMICE serves as a way to utilize and sustain the scientific insights, instruments and data obtained in the related research projects, adding value to PROMICE, the related research projects and the Danish realm.

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Appendix A – Science from the PROMICE team

This appendix details the scientific results produced by PROMICE team members with relation to their activities in PROMICE. This means that commercial activities apart from that dealing with the climate change-hydropower relationship have not been listed. The appendix is divided in three, showing 60 peer-reviewed scientific publications, 111 scientific conference contributions and 18 reports. Publication marked with * have been cited in the 2014 IPCC AR5 report.

Peer reviewed scientific publications

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2013

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Appendix B – PROMICE in the public arena

The list below features a list of individual non-scientific public appearances by PROMICE team members in the public arena. The entries describe widely different efforts, ranging from extensive popular papers to brief interviews on the phone, from appearing in BBC World News HARDtalk program to an interview by 7th grade pupils for their school assignment. The list specifically excludes presentations at scientific conferences and scientific publications which are listed elsewhere. The list is intended to document and testify the gravity of the outreach effort in PROMICE.

2007

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7. Ahlstrøm, A.P. (Interview-person) 2007: Glacier retreat in Greenland - new islands appear. Latham, H. (Journalist) BBC World Service Newshour.
8. Ahlstrøm, A.P. (Interview-person) 2007: Globale klimaforandringer og Indlandsisen [Filmet interview - Skoleprojekt]. 14 marts, 2007.
9. Ahlstrøm, A.P. (Interview-person) 2007: Grønland smelter - Danmark drukner. 17 april, 2007. Rasmussen, R. (Journalist) DR1 TV-Avisen.
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12. Ahlstrøm, A.P. (Interview-person) 2007: Indlandsisens bidrag til det globale havniveau [Telefoninterview - Skoleprojekt]. 14 marts, 2007.
13. Ahlstrøm, A.P. (Interview-person) 2007: Interview om Jakobshavn Gletscher og PROMICE overvågningen af indlandsisen. 26. juni, 2007. TV2 News.
14. Ahlstrøm, A.P. (Interview-person) 2007: Isbjergfabrikken går amok. 3. februar, 2007. Pedersen, M. (Journalist) Ekstrabladet.
15. Ahlstrøm, A.P. (Interview-person) 2007: Løft til Polarforskningen. 18. januar, 2007. Høxbroe, A. (Journalist) DR Radioavisen.
16. Ahlstrøm, A.P. (Interview-person) 2007: Ny ø i Østgrønland. Strøm, J. (Journalist) KNR Grønlands Radio.

17. Ahlstrøm, A.P. (Interview-person) 2007: Polarforskning. 18. januar, 2007. Bo, A. (Journalist) TV2 Nyhederne.
18. Ahlstrøm, A.P.(Interview-person) 2007: Gennembrud af isdæmmet sø ved Søndre Strømfjord. 6 september, 2007. Rosing, K. (Journalist) DR Radioavisen.
19. Ahlstrøm, A.P., T.B. Larsen and S.A. Khan (Interview-personer) 2007: Viden Om - Klimaets Kanariefugl [Deltager i programmet]. Marker, A. & Bendtsen, J. (Journalister) DR2 Viden Om.
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24. Ahlstrøm, A.P. and J.C. Yde (Interview-personer) 2007: Indlandsisen forsvinder. 6 marts, 2007. Steen, M. (Journalist) MetroXpress, 30-31.
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3. Ahlstrøm, A.P. (Interview-person) 2008: Den levende indlandsis. Møller, L.F. (Journalist) DR- P1 Natursyn.
4. Ahlstrøm, A.P. (Interview-person) 2008: Grønland smelter - en grøn ø i fremtiden. Lykke, K. (Journalist) Kanal København.
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6. Andersen, S.B. 2008: Hvorfor er gletschere blå? Ingeniøren, "Spørg Scientariatet", 2. februar, 2008.
7. Andersen, S.B. 2008: Hvorfor stiger verdenshavene, når isen smelter? Ingeniøren, "Spørg scientariet" - webside, 4. december, 2008.
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[http://www.dr.dk/Undervisning/verdensarv/dk_verdensarv/20090827163444.htm?play=%2FForms%2FPublished%2FPlaylistGen.aspx%3Fqid%3D1120057].

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11. Siewertsen, B., L.T. Pedersen, G. Adalgeirsdottir, K.K. Andersen and A.P. Ahlstrøm. 2010: Orientering om knækket istunge fra Petermann gletsjeren i Nordvestgrønland-RØD. 13/08-2010. Cover - til Klima og Energiminister Lykke Friis.

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3. Ahlstrøm, A.P. (Interview-person) 2011: Indlandsisen skrumper med rekordfart. 8 April, 2011. Ritzaus Bureau.
4. Ahlstrøm, A.P. (Interview-person) 2011: Deadline 22:30 Indlandsisen skrumper med rekordfart. 9 April, 2011. Martin Breum (Journalist) Danmarks Radio DR2, 5:40 minutter.
5. Ahlstrøm, A.P. (Interview-person) 2011: Indlandsisen skrumper med rekordfart. 9 April, 2011. Ritzau.
6. Andersen, S.B. 2011: Vokser isen på Antarktis? Ingeniøren, 8 oktober, 2011. Ingeniøren, Spørg Scientariet.
7. Andersen, S.B. 2011: Afbræk af Pine Island Glacier, Antarktis. DR-radioavisen, 4. November.
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6. Andersen, S.B. 2012: Ingen grund til panik over varm indlands is. Videnskab.dk 30. juli 2012.
7. Fausto, R.S. 2012: Radio24syv. http://arkiv.radio24syv.dk/video/6997330/3-planet-fra-solen-uge-36-2012.
8. Citterio, M. 2012: DR1 TV Avisen: video interview on the July event of surface melt conditions covering most of the Greenland ice sheet.
9. Citterio, M. 2012: July 21, 2012 - På sporet af den tabte is. PROMICE newsletter no. 2.
10. Citterio, M. 2012: June 6-7, 2012 - Joined experts discussion during the workshop on the future glacier monitoring network of Chilean glaciers and presented “Red glaciometeorólogica en Groenlandia: The PROMICE Network of Weather Stations in Greenland”.
11. Citterio, M. 2012: Lecture on ‘Remote sensing of Glaciers of ice and rocks on Disko Island’, Dept. of Geography and Geology, University of Copenhagen.
12. Van As, D 2012: Interviewed on climate tipping points by documentary makers for The Weather Channel and many more channels. Potentially 200 million viewers.

13. Van As, D. 2012: Interviewed on Greenland climate research by VPRO Dutch television.
14. Van As, D. 2012: Interviewed about the high melt and destroyed bridge in Kangerlussuaq, Sermitsiaq.

2013

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10. Fausto, R. S. (Interview person) 2013: Extreems in climate [Hong Kong TV]. August 2013.

Appendix C – Minutes from PPROMICE følgegruppemøde

23. April 2013 at GEUS

Participants**:** Dorthe Pedersen (DP) ASIAQ, Ruth Mottram (RUM) DMI, Peter Scmidt Mikkelsen (PSM) GCRC, Henriette Skorup (HSK)DTU-Space, Karen Edelvang (KE), Jason Box (JEB), Andreas Ahlstrøm(APA), Signe Bech Andersen (SIBA) GEUS

Not present: Aslak Grindsted, Dorthe Dahl Jensen, Rene Forsberg, Louise Sandberg Sørensen, Søren Rysgård, Peter Langen, Jens Hesselbjerg Christensen

Agenda

1. Presentations by SIBA and JEB
2. Discussion including the following questions
    - Points where we could improve?
    - How can we make the most of the data?
    - How to get the data distributed as widely as possible?
    - Possibilities for enhanced collaboration?

Minutes

1. Presentations by SIBA and JEB
2. Discussion

Points where we could improve?

RUM mentioned that the modelers require more data from North and Northeast Greenland to validate models. It would be interesting to have melt and runoff at 79 fjord

RUM enquired if accumulation measurements made by the automatic weather stations (AWS) which they are. Also Snowpack analyzers (SPA) have been set up at three sites in Greenland within the REFREEZE project.
APA asked if it is of interest to include SPA instruments in the PROMICE network assuming they turn out to work on the ice sheet?
RUM: Yes, they might even be used for operational correction of model estimates of refreezing.
HSK: SPA data could also be useful for converting altimeter data into mass change (volume -> mass conversion) where models are now used without supporting observations.

DOP: It would be interesting to have AWS sites in catchments where ASIAQ measures the discharge to facilitate closer comparison.
SIBA: This should be considered if moving or setting up new stations.

JEB: Should PROMICE work with velocity mapping at all considering that other research groups in the US do that already? Why not just receive the velocity maps from them and use that product?
APA/SIBA: As a monitoring programme we cannot rely solely on foreign research project results. The velocity mapping software and capabilities witch have been developed through the PROMICE project has also been leverage for the Danish involvement in the current ESA_CCI project where the velocity mapping work is currently partly funded from.

APA: Should resources be allocated more permanently to monitoring the velocity of outlet glaciers as has been done in a pilot study with current limited support within PROMICE?
RUM: GPS measurements very useful and fascinating. Could be interesting as a teaching tool.
SIBA: Also useful for satellite validation in the ESA-CCI project.

How can we make the most of the data?
RUM: DMI has used both PROMICE and GC-net data and the PROMICE product is excellent quality and is easy to use while GC-net is quite poor. Could you maybe improve the quality of the GC-net data? Different groups get different results when using GC-net data because there is no uniform treatment and quality assurance.

HSK: Airborne PROMICE datasets from 2007 and 2011 have proven very useful for satellite data validation.

HSK: Information on melt useful for work on Radar penetration.

How to get the data distributed as widely as possible?
RUM: Good idea to promote PROMICE datasets at the GCRC meeting in Nuuk in November.

RUM: A good idea could be to analyze the list of users of PROMICE data and target the possible audience more directly.

RUM: Also an idea to present the data at the IGS British Branch meeting which is fairly big.

RUM: Regular announcements on CryoList would be useful for distributing the data more widely in the scientific community.

Possibilities for enhanced collaboration?
RUM: Could request a closer collaboration between DMI and GEUS/PROMICE in terms of mutual use of observations and model results.

JB and RUM agreed to make comparison between Hirlam model data and PROMICE observations in the near future.

PSM: Collaboration with GCRC highly relevant when logistical opportunities arise. GCRC will have focus on North east Greenland in coming years. Zakenberg 2014, Station Nord 2015.

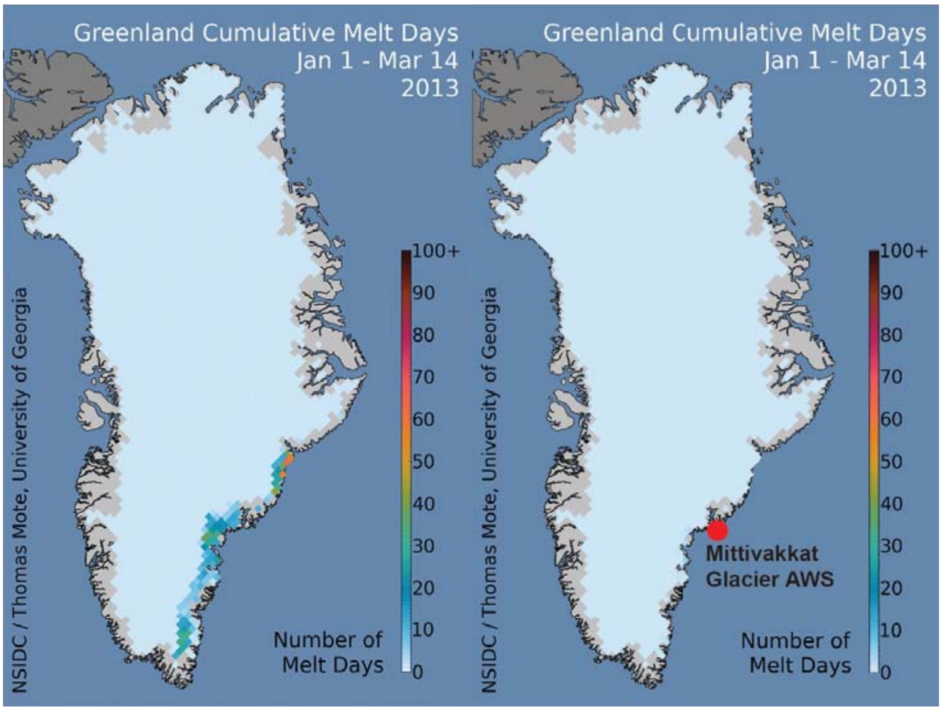
Appendix D – PROMICE newsletters

Programme for Monitoring of the Greenland Ice Sheet
No 4 • 2013

WARM SUMMER INFLUENCES MEASURING DATA FROM SATELLITE THE WINTER AFTER

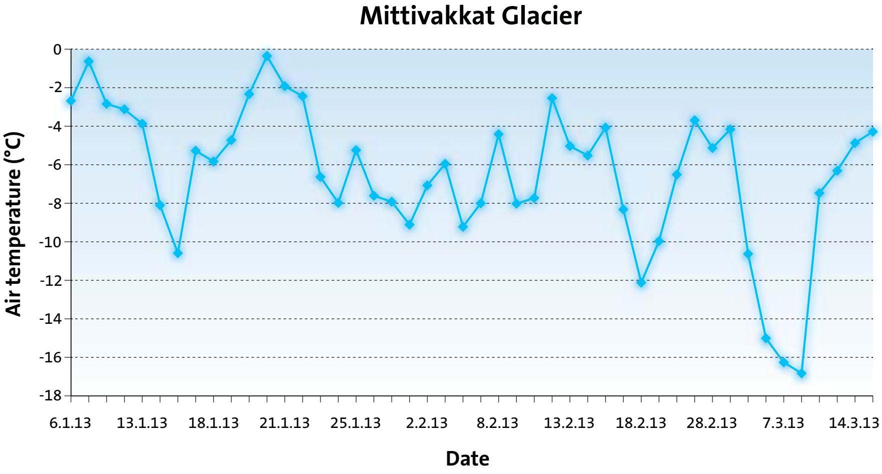
– PROMICE HELPS WITH THE ADJUSTMENT

Measurements from PROMICE's automated weather stations (AWS) on the surface of the Greenland ice sheet helps adjust satellite measurements of melt extent from the American National Snow and Ice Data Center (NSIDC). The adjusted data can be seen on their 'Greenland Ice Sheet Today' blog: http://nsidc.org/greenland-today/



The cumulative melt extent from NSIDC before the algorithm correction (left) and after the correction (right). The red dot shows the location of the PROMICE station at Mittivakkat.

The 'Greenland Ice Sheet Today' publishes daily measurements of melt based on passive microwave emissions measured from satellite. In February and early March, the melt maps posted indicated extensive coastal melt in south-east Greenland. This caught the attention of GEUS Professor Jason Box, as the melt did not agree with ground-based measurements from the PROMICE AWS. The local AWS data from the Mittivakat glacier along the south-eastern coast (see the graph) indicated that the air temperature did not rise to the melting point in February or early March.



The surface air temperature measured by the PROMICE station at Mittivakkat near the south-eastern Greenland ice sheet edge for early 2013. Temperatures did not exceed freezing at the site.

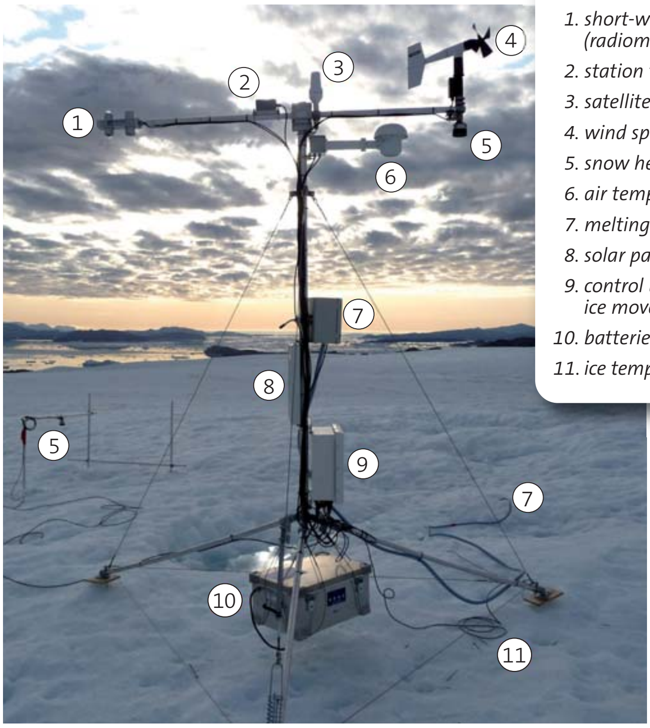
The extensive ice melting in 2012 influences the measurements in 2013

The melt extent algorithm used by 'Greenland Ice Sheet Today' was overestimating the melt extent as a result of unusually warm snow at depth following the intense melting that occurred last summer. The melt detection method, based on passive microwave emissions, is primarily sensitive to near-surface conditions, but it also gets some of its input from the snowpack several metres down. Heavy snow fell during the relatively warm winter insulating deeper snow. This contributed to anomalously high temperatures for the uppermost layers of snow this winter. The algorithm for deriving the satellite-based melt detection was adjusted for better agreement with the ground-based observations.

24 weather stations all the way round the Greenland ice sheet

Currently, GEUS operates 24 automatic weather stations in the region of the Greenland ice sheet margin mainly within the PROMICE network. The stations measure air temperature, relative humidity, wind speed and direction, atmospheric pressure, incoming and outgoing short- and longwave radiation, ice temperature, surface velocity, snow depth and ice ablation. The stations measure every 10 minutes. Hourly-average values are transmitted in summer (day of year 100–300) and daily averages during winter.

Data transmitted by the PROMICE weather stations are freely available for viewing in near real time and downloading at the PROMICE web site.



An automatic weather station on the ice near Upernavik. The instruments measure and include:

1. *short-wave and long-wave radiation (radiometer)*
2. *station tilt (inclinometer)*
3. *satellite communication*
4. *wind speed and direction (anemometer)*
5. *snow height (sonic height rangers)*
6. *air temperature and relative humidity*
7. *melting pressure sensor (ablation)*
8. *solar panel*
9. *control unit (incl. air pressure and ice movement)*
10. *batteries*
11. *ice temperature in the upper layers*

LINKS

http://www.promice.dk
http://nsidc.org/greenland-today/

PROMICE

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- The purpose of PROMICE is to monitor the mass loss of the Greenland ice sheet, both the melting on the surface and the volume of icebergs calved.
- PROMICE is headed by GEUS in cooperation with DTU Space and Asiaq. Furthermore the programme collaborates with the Danish Meteorological Institute and foreign universities and authorities.
- Read more about PROMICE on *www.promice.dk*, where you can find photos and videos, get direct access to measuring data from the ice sheet and the PROMICE outreach material. On the website you can also subscribe to our newsletter.

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PROMICE NEWSLETTER

Programme for Monitoring of the Greenland Ice Sheet

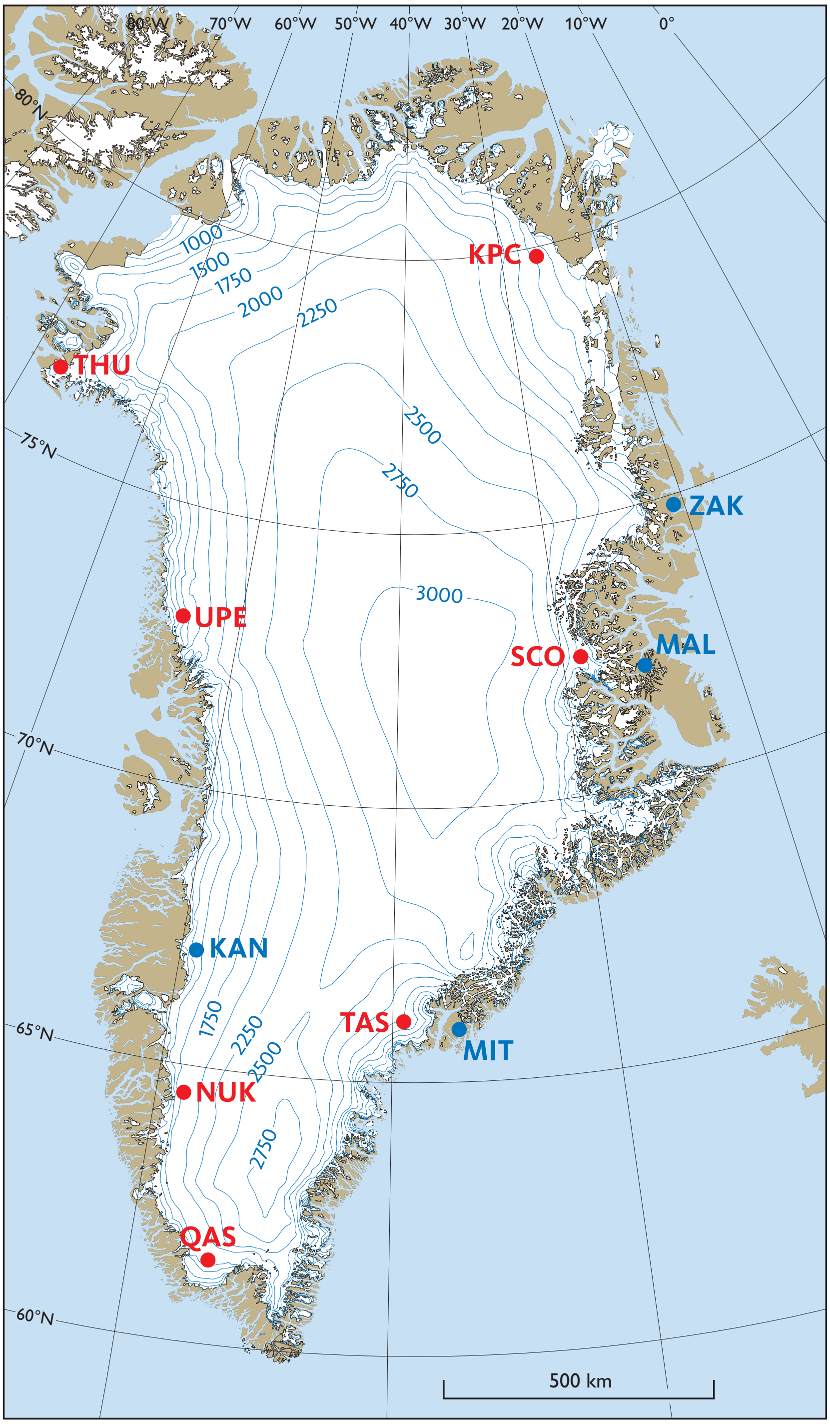
No 5 • 2013

ICE MELT CLOSER TO NORMAL

2013 ice melt recorded by PROMICE network of automatic weather stations was below the record year 2010 and 2012 values.

The PROMICE network covers the margin of the Greenland ice sheet which spans 2100 km north-south, and goes as much as 700 km below the Arctic circle where more than 9.3 m of surface ice melt has been observed in a single year (2010). Year 2013 ice melt for South and South-west Greenland ranged from 2.9 to 5.9 m (at TAS_L, QAS_L, NUK_L and KAN_L stations), while ice melt values at the more northerly KPC_L, SCO_L, UPE_L and THU_L stations range between 0.3 and 3 m at the lowest elevations (below 500 m above sea level). The melt values from higher elevation stations (above 500 m) range from 0.0 to 2.5 m in the south and from −0.4 to 2 m in the north.

Quassimiut lower station (QAS_L) is the lowest and southern most station where most melt has been observed. QAS_L is also special given that the melt data from this site extend 7 years earlier than at any other PROMICE site, back to year 2001. The average annual ice loss in the 13 years since 2001 is 6.5 m. This longer record teaches us a lesson. At all PROMICE sites in the shorter measurement interval since 2007, the 2013 melt anomaly seemed large, melt was 96% below average. Yet, considering the lengthier QAS_L record, the year 2013 ice melt was just 9% below the 13 year (2001-2013) average. Year 2013, while seeming 'cold' in recent memory was closer to 'normal' for this century.



The eight areas on the Greenland ice sheet where the PROMICE-operated weather stations are located. Two or three stations are placed in each area at different levels above the sea. In QAS in South Greenland there are three stations. The QAS_L station, mentioned in the text, is placed on the ice at a height of 310 m.

Unlike the previous 6 summers in a row that were characterized by many melt records set, year 2013 was characterized by colder north air inflow along west Greenland. Summer 2013 displayed overall lower atmospheric pressure, more clouds and more highly reflective snow cover despite some intense melt episodes in early June and late July. While melt onset in 2013 began early as in the record melt year 2012, the melt never got much momentum, being retarded by cooler air than of the recent years. 2013 melt was punctuated by snowfall a month earlier than in 2012 on 17 August. The big surprise for 2013, ironically, has been that it was closer to 'normal'.

More perspective comes considering that in this more normal year, still more ice is exiting Greenland than accumulating. The ice sheet is still contributing over 1 mm to global sea level rise. This result is according to our new surface albedo-based total mass balance estimate (see http://polarportal.org/en/greenland-ice-shelf/nbsp/total-mass-change/). So, what is 'normal' is still important for sea level.*dk*.

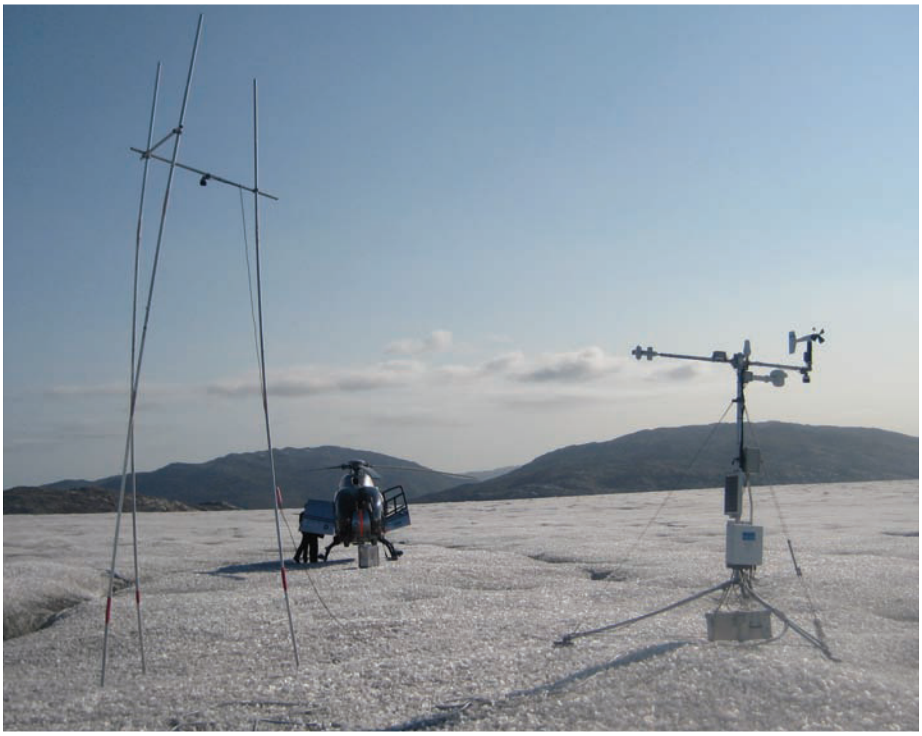


Figure 2. South Greenland PROMICE automatic weather station at the end of the 2013 melt season. From the stakes to the left of the weather station, the amount of melt (approximately 4 m) is directly visible. The melt is also measured with a pressure transducer system drilled into the ice.

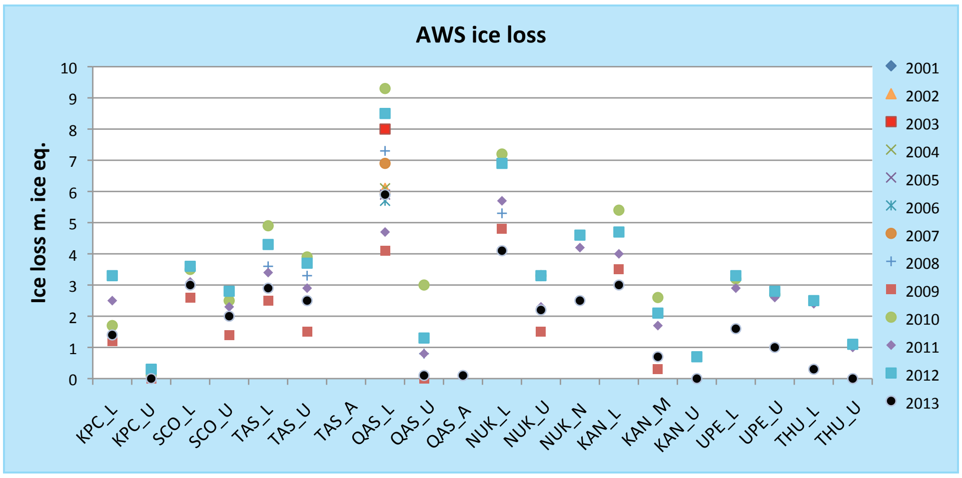


Figure 3. Yearly net ice loss in meters for the PROMICE AWS stations. The symbols indicate the distinct melt years. The ice loss is measured by a pressure transducer system drilled into the ice.

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- Information can also be found on **polarportal.org** a new website where Danish research institutions display the results of their monitoring of the Greenland ice sheet and the sea ice in the Arctic.

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