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RECENT SURFACE MELTING IN WEST ANTARCTICA: COMPARISON OF REMOTE AND IN-SITU OBSERVATION

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ABSTRACT

A study of Ross Embayment melt-layers during the instrumental period shows that they can be detected reliably in cores as well as snow pits and that they form during warm summers. Focusing our study on four automatic weather station (AWS) sites on the Ross Ice Shelf and one AWS site on the West Antarctic Ice Sheet we find stratigraphic firn-core and snow-pit evidence for melt events during the austral summers 1982/83 and 1991/92. We develop a new passive microwave technique to identify melt, as well as a new calibration to improve the use of the previously published cross-polarized gradient ratio (XPGR) technique. Both these techniques are found to work well to identify Ross Embayment melt. Reliance on AWS air temperature records exceeding 0°C alone tends to overestimate melt occurrence. Melting occurred when a daily positive-degree-day threshold was exceeded in Automatic Weather Station data.

1. INTRODUCTION

Understanding how surface melting regimes in Antarctica respond to climate variability and change is important in order to better understand the climatic controls on the mass balance of the Antarctic ice sheet as a whole. Most of the Earth's fresh water is locked up as ice in the Antarctic ice sheet. If all of this ice were to melt, it could raise global sea level by more than 60 meters (IPCC, 2001). Currently most of the interior surface of the Antarctic ice sheet remains below freezing throughout the entire year (Zwally and Fiegles, 1994) and widespread melting is infrequent. Ice core records from the crest of Siple Dome in West Antarctica, for example, indicate melt occurring fewer than 5 times over the last 100 years (Das, 2003) where average summer temperatures remain well below 0°C (Das, et al, 2002; Das and Alley, in review.) These infrequent melting events do not contribute much to a change in mass-balance of the ice sheet. But small changes in air temperature could rapidly result in large areal changes in surface melt regimes across Antarctica due to the large size and low slope of much of the ice sheet. This could have widespread mass-balance and climatological implications. A small increase in the extent or duration of surface snow-melt would result in a lower albedo for the ice sheet. This would enhance the absorption of solar radiation as well as increase cloud formation, leading to an increase in absorbed net surface radiation (Bintania and van den Broeke, 1996), resulting in even more melting. If melting became more frequent or widespread, melt-water could begin to saturate the firn and leave the ice sheet as run-off, becoming a significant consideration in the mass balance of the ice sheet (IPCC, 2001). Meltwater is also an efficient mechanism of transporting heat down into the firn. The percolation and subsequent refreezing of meltwater at depth transports heat much more rapidly than either thermal conduction or diffusion (Paterson, 1994) so an increase in meltwater production at the surface would affect the thermal structure of the ice sheet as a whole, potentially increasing the possibility of rapid ice shelf disintegration and ice-sheet collapse, a present concern for West Antarctica (IPCC, 2001). Monitoring of melt extent over time may be quite useful in detecting climate change and learning whether such large polar amplification is or is not occurring.

There are a number of different methods available to glaciologists to observe surface melting or conditions conducive to melting. However different techniques view melt differently. These methods include: ground-based surface melting observations (as snow temperatures increase to 0°C and/or the liquid water content of the snow increases); records of air temperatures reaching or exceeding the melting point; determination of a positive energy balance; records of melt features preserved in surface snow, in firn or ice-cores; and remotely observed changes in snow surface or near-surface conditions through instruments sensitive to changes in snow liquid-water content or structure. The results (documenting the presence or absence of melting) from these fundamentally different methods have not been widely inter-compared. Especially for vast and remote regions such as the Antarctic ice sheet it is necessary to be able to use whatever technique is available, and it is rare to have more than one method of detecting or recording melt at any specific site or over any specific region. Yet we expect that these different methods used for observing or recording surface

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melting will return different results, as they are based on fundamentally different observing parameters.

Our aim in this study is to learn how these different measures of melting (through ground-based, weather-station and satellite observations) are related to each other. This will improve our ability to learn how melting and climate have changed and affected Antarctic processes in the past, and how they may change in the future. Our focus here is on the critical Ross Ice Shelf and Siple Dome regions of West Antarctica (figure 1). We are specifically investigating and comparing melting records at sites where we can combine these different techniques over the same extended periods of time, including during melting events. Our primary focus is on conditions at three AWS sites on the Ross Ice Shelf: Lettau, Gill, and Schwerdtfeger, which have overlapping stratigraphy, microwave and AWS records, although our results are applicable to much broader areas across polar regions which experience surface melt conditions.

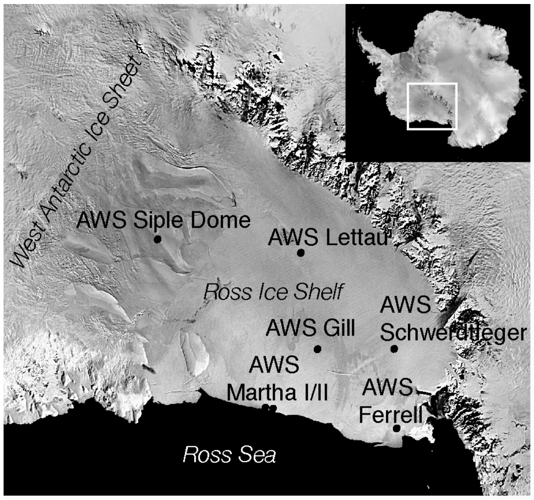

Figure 1. AVHRR image of Antarctica showing the location of the AWS sites in West Antarctica used in this study.

2. DATA AND METHODS

Surface melting is a rare and brief phenomenon in West Antarctica. Records of recent occurrence of surface melting include melt features preserved in firn and ice cores, as well as inferences from satellite data and weather station records. To understand melt processes in Antarctica, it is important to compare the occurrence and the physical characteristics of melt features found in the near-surface snow with corresponding records of recent climatic conditions. An ideal way to do this is to look at the snow stratigraphy at Antarctic Automatic Weather Station (AWS) sites, where at some sites meteorological information has been recorded for almost the past two decades. Additionally, if we hope to apply our results to larger areas of Antarctica where AWS locations are sparsely located, we need to relate our observations to remote-sensing techniques of observing and monitoring surface melting. Since melting is such an infrequent phenomenon over much of the interior of the Antarctic ice sheet, we limit this study to AWS sites on the Ross Ice Shelf (in addition to one site on Siple Dome) which experience relatively warmer summer temperatures, and are therefore more likely to have experienced melting during the instrumental period of the last couple of decades.

2.1 *AWS Records*

One way to try to “observe” melting conditions and events over West Antarctica is to look for intervals of time when air temperatures rise above 0°C and/or when the surface energy budget provides sufficient energy to raise snow temperatures to the melting point. In this study we are using data from the network of Automatic Weather Stations (AWS) available across West Antarctica operated by the Antarctic Meteorological Research Center (AMRC) at the University of Wisconsin. The AWS data are provided as quality-controlled 3-hourly measurements from the AMRC (ftp://ice.ssec.wisc.edu). Further detailed information about the AWS units can be found in Stearns and Weidner (1993). We refer to AWS-derived air temperature as T_A. Since none of the AWS data available for our region of interest include the necessary measurements to compute the net energy balance or include ongoing measurements of snow temperature, we use the available air temperature data to compute daily positive-degree-day factors for each site through each summer season where data are available. We calculate the positive-degree-day factor (PDD) as follows:

$$PDD\ (^\circ\mathrm{C}) = \Sigma\ [T\ (^\circ\mathrm{C} > 0) * t\ \ (\mathrm{hours})] / \ 24\ \mathrm{hours}. \quad (1)$$

Since we are using 3 hourly temperature data we estimate *t* by allowing each *T* measurement greater than 0°C to count for an entire 3 hour period. In addition to the decadal-length records from the AWS stations across the Ross Ice Shelf, we also include analyses of Siple Dome AWS data (1997-2000.) While this is a much shorter record than the other stations, we include this record as Siple Dome is the site of the WAIS deep ice core and currently the only location in West Antarctica with a Holocene length melt-layer record (Das, 2003) and is thus a region where we are interested in investigating melt processes and melt records.

2.2 *Snow and firn stratigraphy*

A second way to determine the occurrence of present and past melt events is through observations of the physical characteristics of the near-surface snow and the stratigraphy of deeper firn and ice layers. During visits to our study sites during the austral summer we did not experience any active melting conditions (not surprising, given the scarcity of such conditions.) This presents a challenge for how to observe the ongoing effects of surface melting on snow conditions and firn stratigraphy. We have used two approaches to alleviate the lack of in situ observations of active melting. First, at Siple Dome AWS we carried out a series of experiments designed to raise surface temperatures. This allowed us to create artificial surface melting conditions, and we were thus able to observe active melting and related changes in snow stratigraphy as well as the preservation of melt features. These results are presented in Das and Alley (in review). This study enabled us to better characterize melt features and to determine the effect of various lengths of melting intensity on the creation of near-surface melt features. Second, we investigate the melt features found in snow and firn stratigraphy at sites that have experienced melt in the recent past. We focus on results from this second method, measurements of regional snow stratigraphy, for this paper.

During the 1999-2000 austral summer field season one of us (SBD) visited four AWS sites (Siple Dome, Lettau, Gill and Schwerdtfeger.) We had also planned to visit Ferrell and Martha, but delays due to weather conditions and flight schedules did not allow us to reach these additional sites. Limited stratigraphic data are nonetheless available for Ferrell AWS from observations we made during an AWS maintenance visit in 1998-99. At each AWS study site we dug two-meter deep snow pits and drilled and collected five-meter deep firn cores (using the 4” PICO hand auger) to analyze the firn stratigraphy. For each site we measured density profiles and noted melt features as well as the presence of crusts, hoar layers and other stratigraphic features. In addition isotopic analyses were completed by the INSTAAR stable isotope lab at the University of Colorado following the method of White et al (1997). Finally, the cores and snow pit layers were dated using a combination of seasonal stratigraphy (from density and visual appearance, using the method of Alley et al, 1997) and stable isotope (δD and δ^{18}O) ratios. In this way we were able to date the occurrence of all melt features found.

2.3 Passive microwave satellite observations

Due to the harsh environment, remoteness and large surface area of Antarctica, satellite-based observations are an invaluable source of data about surface conditions. Microwave sensors respond to small changes in surface conditions over ice and snow and are a widely available source of ongoing information about surface melting in the polar regions. Here we are primarily using passive microwave imagery, which is well-suited for monitoring snow temperature, melt and surface conditions (e.g. Zwally and Fiegles, 1994; Abdalati and Steffen, 1995; 1997).

We are using DMSP special sensor microwave imager (SSM/I) data from 1987-2000 obtained from the National Snow and Ice Data Center (NSIDC) in Boulder, CO. They are arranged in 25x25 km grids and binned into daily averages. Passive microwave remote sensing measures the emitted thermal radiation from the ground. The passive microwave brightness temperature, T_B (K), measured by SSM/I sensors, is a product of the emissivity *e* and the mean temperature T of the snow layer,

$$T_B = eT. \tag{2}$$

Zwally (1977) has shown, using radiative transfer models, that the penetration depth (depth from which most of the escaping radiation is emitted) of passive microwave radiation for snow depends on the frequency, density, grain size, and the physical temperature of the snow. The onset of snow melting reduces the penetration depth due to the presence of liquid water in the snow. This results in an increase in the emissivity of the snow as surface scattering begins to dominate, resulting in an increase in T_B. SSM/I is a four-frequency, linearly polarized (horizontal and vertical) radiometric system with channels at 85.5, 37.0, 22.2 and 19.3 GHz. The increase in brightness temperature with the transition from dry to wet snow is dependent on frequency and polarization (Ulaby, 1986). As the snow melts, the water causes a greater increase in the horizontal T_B than the vertical at the same frequency; the lower frequencies are more responsive to melt onset (Steffen et al, 1993)

Previous studies have successfully used SSM/I data to derive spatial and temporal variations of summer melt on the Greenland Ice Sheet (e.g. Mote et al, 1993; Abdalati and Steffen, 1997; Joshi et al 2001) and Antarctica (Zwally and Fiegles, 1994). Different techniques have been developed for different areas, and it is a good idea to test or adjust the melt-derived parameters for different locations. For example, a thresholding technique that works well in determining which pixels are experiencing melt during the summer season in the wet snow zone of Greenland may not be appropriate for detecting the onset of brief melt events in the dry snow zone of Antarctica.

Here we evaluate a few different ways to potentially determine the onset and extent of melting at our study sites. The first method determines a threshold brightness temperature based solely on a single frequency and polarization. This threshold technique was used by Zwally and Fiegles (1994) in their study using 19 Ghz vertically polarized SMMR data to detect surface melting over Antarctica:

$$T_C = \langle T_B \rangle + 30\ \mathrm{K} \tag{3}$$

where T_C is the threshold value and $<T_B>$ is the mean annual brightness temperature. The threshold method was also used by Mote et al (1993) in Greenland:

$$T_{melt} = <T_{B\text{-}winter}> + 31K \qquad (4)$$

where T_{melt} is the threshold value and $< T_{B\text{-}winter} >$ is the mean winter value. We first evaluate melt using equation 3 above.

The second method we test utilizes multiple frequencies and polarizations (19H and 37V) to take advantage of their differing responses to melt. This cross-polarized ratio technique (XPRG) was developed by Abdalati and Steffen (1995; 1997) and is defined as:

$$XPGR=[T_B(19H)-T_B(37V)]/[T_B(19H)+T_B(37V)] \qquad (5)$$

They determined a melt threshold for SSM/I over the Greenland Ice Sheet (XPGR = -0.0158, where melt occurs when XPGR>threshold) by comparing XPGR values to ground data on surface wetness. This technique is based on the rationale that different frequencies and polarizations react differently to changes in surface conditions, notably the onset of liquid water, and can therefore yield a unique signature reflecting melting conditions (Abdalati and Steffen, 1997.)

We also present a new additional simple method to determine the onset of melt conditions, which utilizes a threshold technique based on calculating a step-change increase in T_B (dT_B) from one day (t) to the next (t+1) due to melt onset:

$$dT_B(K) = T_B(t+1)-T_B(t). \qquad (6)$$

Rapid changes in emissivity are typically restricted to the onset or termination of melt events. Since snow has a higher heat capacity than the surrounding air, we know the surface-snow temperature changes more slowly and less in magnitude than the air temperature. We can therefore determine a threshold by assuming the maximum air temperature difference ($dT_A max$) will always exceed the maximum snow-temperature difference. Using our analyses of the AWS records for these sites we can calculate what the maximum difference in air temperature between one day and the next has been over the past decade or so for a specific site.

$$dT_A max=T_A(t+1)-T_A(t). \qquad (7)$$

And can then define a melt threshold using $dT_A max$:

$$Tmelt = dT_A max(K). \qquad (8)$$

Furthermore, using this step change method we would also expect the end of the melt period (in this region the length of a melt period is not likely to be more than a few days) to be followed by a similarly sized downward step in T_B that we could calculate in the same way. We chose to use the 19Ghz, horizontally polarized channel here since its brightness temperature has the greatest sensitivity to melt onset.

This method could be made even more accurate if we knew what the relative emissivity (*e*) of the surface snow was for the wavelength and polarization being considered in equation (6) (in this case 19Ghz horizontally polarized). We could adapt this method for a better fit by adjusting T_{melt} by a factor of *e* as well as adjusting Tmelt for the increase in emissivity that occurs with the onset of liquid water in the surface snow (independent of any physical temperature change). We defer these techniques for possible use in later studies.

3. RESULTS

3.1 *AWS Records*

We analyzed the entire length of available T_A records from six AWS sites in West Antarctica (figure 2). These AWS have been in operation for varying lengths of time, from 3 to 18 years. The maximum recorded summer air temperature exceeded 0°C at some time at the five AWS sites on the Ross Ice Shelf. We also computed the daily positive-degree-day factors, following equation 1, for all the AWS stations. Although we have no field measurements or stratigraphic data from Martha AWS, we include this station in our analyses because it is the site that has experienced the highest summer temperatures of all of the WAIS Ice Shelf AWS sites, due to its low elevation, low latitude, and proximity to the ice shelf edge (therefore open water) during the austral summer season.

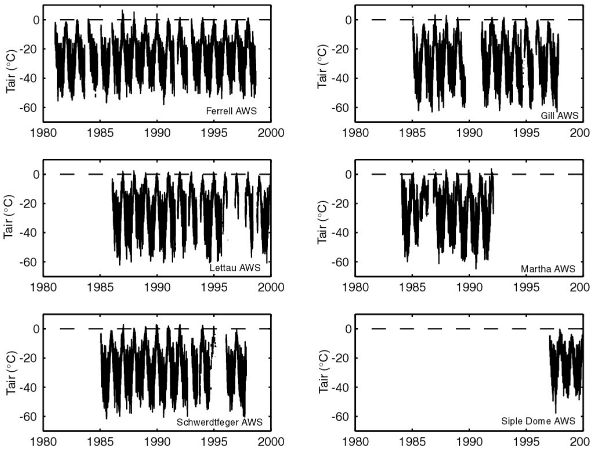

Figure 2. AWS T_A records and 0°C threshold (dashed line.)

The calculated daily positive-degree-day factors range from a minimum of 0.0125°C (observed at many stations) to a maximum of 1.465°C, which occurred at the Martha AWS on 11/25/1985. The percent of summers experiencing T_A>0°C ranges from 0% at Siple Dome to close to 90% at Martha (8/9 summers on record; results from stations Martha I & II are combined here.)

3.2 *Stratigraphy*

Stratigraphic results are from visual analyses of 2-meter snow pits and 5-meter firn cores collected at the AWS stations. Overall, we found zero to very few melt features at each of the AWS locations. We have identified melt-layers by their appearance: one- to few mm thick, laterally continuous, stratigraphically flat ice layers with few air bubbles. Aside from melt-layers we did not find any other melt features such as are described in warmer ice sheet locations (e.g. vertical ice pipes or non-continuous lenses) which experience significantly higher rates and frequencies of melt than in West Antarctica (e.g. Pfeffer and Humphrey, 1998.)

Melt-layers were found only at the Schwerdtfeger and Gill AWS sites. Schwerdtfeger had one melt-layer, dating from 1991-92. This feature was found at 2.85 m depth, and is 1 mm thick. Gill also has a melt-layer from 1991-1992 as well as another melt-layer from 1982-1983. The 1991-1992 melt-layer at Gill was at 2.17 m depth and is 1 mm thick. The 1982-1983 melt-layer at Gill was at 4.58 m depth and ranges in thickness from 2-3 mm.

3.3 *Passive Microwave Data*

The methods we applied to determine melt event occurrences using passive microwave data yielded slightly different results. Using the melt threshold technique similar to Zwally and Fiegles (1994) (equation 3) we find evidence for three melt events: two melt events at Gill AWS (Jan 7-13, 1992; Jan 26, 1999), one at Siple Dome AWS (Jan 6, 1992) and none at any of the other sites (figure 3.) The second method we used was the cross-polarized gradient ratio technique (XPGR) after Abdalati and Steffen (1997) (equation 5.) The results from this method indicate the occurrence of only a single melt period, which was found at Gill AWS (during Jan 8-13, 1992), with a six day period of XPGR values above the threshold value (figure 4). Finally, using the new threshold technique developed in this study (equation 6) our results show (figure 5) that melt conditions existed during two events at Gill AWS (Jan 7-8, 1992; and Jan 20, 1993) and during one event at Schwerdtfeger AWS (Jan 8, 1992.) All techniques applied show strong anomalies at Gill and Schwerdtfeger in January 1992, corresponding to melt-layers that were identified stratigraphically. And while SSM/I coverage does not extend back to the older 1982/83 melt-layer found at Gill, previous work by Zwally and Fiegles (1994) using SMMR data (the precursor to SSM/I sensors) found strong evidence for a melt event across the Ross Ice Shelf area in 1982-83.

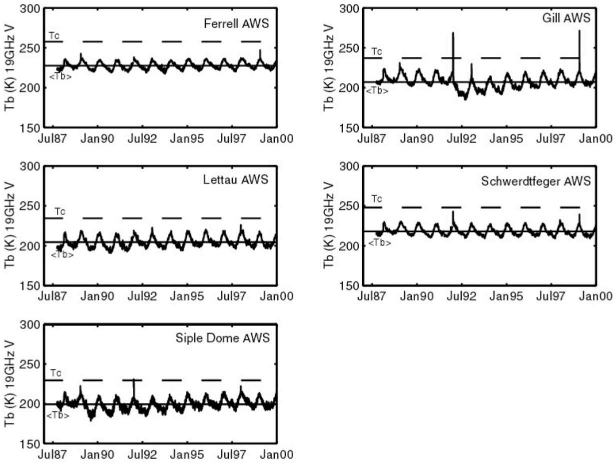

Figure 3. SSM/I T_B and mean annual T_B (<Tb>) and the corresponding melt threshold Tc (<Tb> + 30K.)

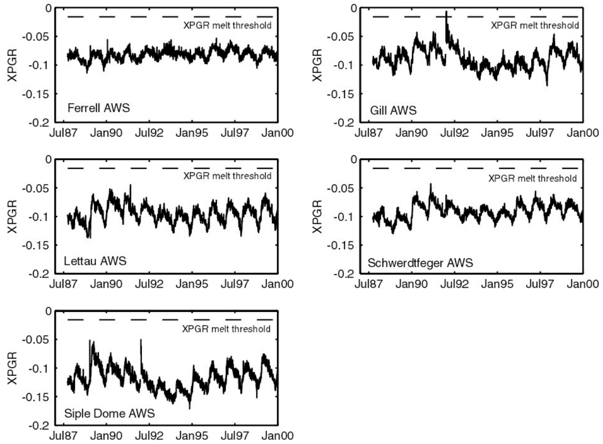

Figure 4. XPGR time series and XPGR melt threshold (as defined by Abdalati and Steffen (1997)).

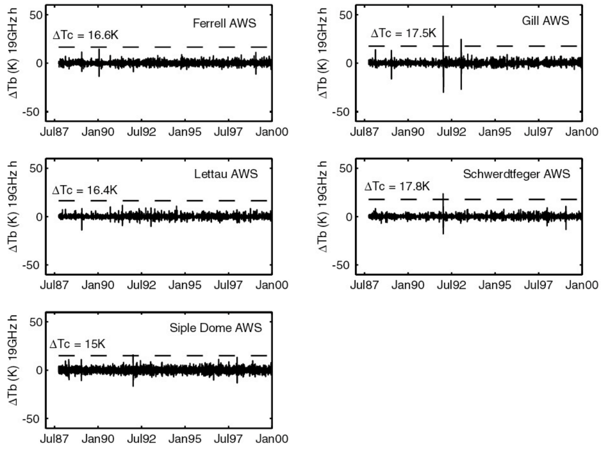

Figure 5. Daily difference T_B time series and melt threshold Tc.

4. DISCUSSION

4.1 *Interpretation of stratigraphic record and positive-degree-day factors*

Snow and firn investigations showing melt features in the stratigraphy present the most unambiguous evidence for past surface melting. When interpreting the stratigraphic melt record, though, we have to keep in mind there is also the possibility that a brief melting event generated liquid water in the pore spaces of the surface snow (which could have in turn affected the microwave brightness temperature) but did not disrupt the snow structure sufficiently to yield an observable melt feature in the firn core. In addition, there is the possibility that melt-water could be generated in sufficient quantities to migrate vertically downward and "contaminate" the previous year's firn layer with a melt feature. In this study, though, due to the scarcity of melt features as well as their small size, we believe none of the melt events seen were intense enough to generate sufficient amounts of melt water to affect any layers of firn deeper than the present years surface layer. Additional experimental work has placed some constraints on the amount of melting required to form a melt-layer in the stratigraphy, as well as what is required for a melt feature to migrate below the current summer's accumulation for this region (Das and Alley, in review). For comparison, we show these experimental positive-degree-day factor thresholds in combination with a histogram of all of the observed range of positive-degree-day factors from the full length of all the AWS sites from this study (figure 6). The 1991-92 melt-layers from Gill and Schwerdtfeger are also shown (*) above the positive-degree-day readings coincident with their formation.

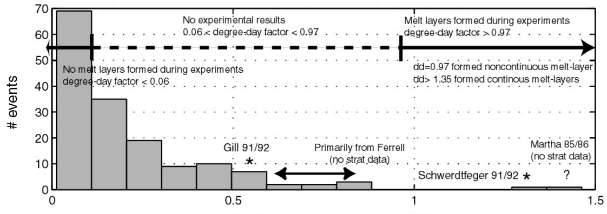

Figure 6. Histogram of PDD values for all summers and all AWS sites inthis study. The thresholds above are experimental values from Das and Alley (in review.)

We also found that these melt events occurred during the warmest summers on record at both Gill and Schwerdtfeger (figure 7; summer calculated as average air temperature from Dec 1 to Jan 31.)

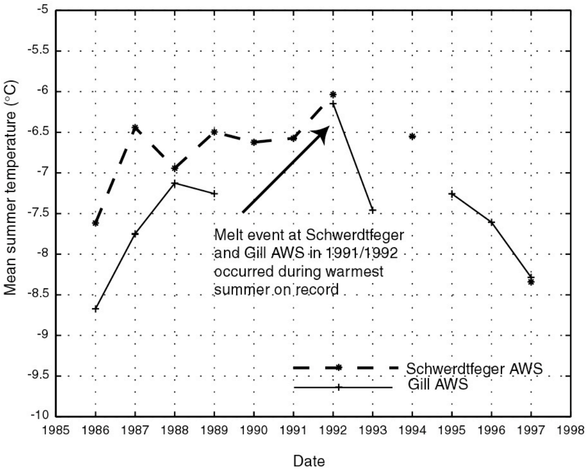

Figure 7. Mean summer T_A at Gill and Schwerdtfeger AWS

4.2 *Spatial and temporal coverage and sampling differences*

Clearly, the different techniques used to identify melting have different sampling. In time, stratigraphy integrates all processes that occurred, whereas AWS data are sampled at 3 hour intervals and SSM/I are daily averages. Spatially, stratigraphy samples a 1-meter wide pit or 0.1-m wide core, AWS samples locally while SSM/I has a 25x25 km resolution. In the AWS positive-degree-day "window" that produces discontinuous melt-layers, a core or pit may or may not detect an event, and the SSM/I anomaly may or may not rise high enough for long enough to be detected. However, our experience here and elsewhere indicates that moderately intense melt events are detectable stratigraphically and by SSM/I, provided the SSM/I is used in regions with relatively homogeneous pixels. (In mountainous regions, or even near steeper ice-sheet topography such as the Siple Dome ice divide, sub-pixel variations will affect SSM/I; in regions such as most of the Ross Ice Shelf, this is much less of a problem.)

4.3 A new passive microwave melt threshold

Satellite data, and passive microwave data in particular, clearly offer the best spatial coverage of the polar regions. Yet as seen in the results from this study, the use of three different SSM/I-derived techniques to determine surface melting in West Antarctica yielded three different results, which all differ from results using weather station temperature records or from snow and firn stratigraphy records. Strong anomalies in brightness temperatures and polarization ratios clearly accompany melting; however, techniques and thresholds must be chosen carefully to obtain a 1:1 correspondence between SSM/I and other data identifying melt events. Eventually, process studies and models of the controls of surface temperature and emissivity may allow more accurate quantification of degree of melt in smaller events. Until such results are available, though, regional calibrations such as ours can be used to identify more successful techniques and thresholds.

The best method we can propose from our results is to adjust the threshold XPGR value from that determined in situ by Abdalati and Steffen (1995;1997) in Greenland to a new threshold for West Antarctica. We can do this by determining a XPGR threshold that captures the melt events we know occurred from the stratigraphic data in 1991/92 (figure 4). When we do this, we define a new XPGR threshold for West Antarctica = -0.0427 (compared to the –0.0158 used by Abdalati and Steffen for Greenland) based on the melt events preserved in the stratigraphy at Schwerdtfeger AWS and Gill AWS.

5. CONCLUSIONS

To accurately monitor future melting, as well as to compare future trends in melt rates and melt event occurrences to the ice core record (our only record of events prior to the last couple of decades), we must understand how these different techniques of observing melt compare to each other. Most of what we learn about future melting trends over large areas of Antarctica will be based on interpretations of satellite data, while the only records we have of melt occurrence prior to the last few decades come from melt features preserved in the firn and ice and analyzed in snow-pits and from firn- and ice-cores. Our study shows that apparently disparate results from these different techniques provide a consistent picture if properly intercalibrated. We find stratigraphic firn-core and snow-pit evidence for melt events during the austral summers 1982/83 and 1991/92. The sites and times of melting had some of the largest AWS daily positive-degree-day factors and the largest SSM/I anomalies in our data sets, and occurred during the warmest summers on record. Finally, we use our results to propose a new, regionally calibrated XPGR threshold to use for West Antarctica.

6. FUTURE MONITORING OF MELTING

While our focus here is on a few AWS sites in the Ross Embayment region of West Antarctica, these results are more broadly applicable to polar regions in general, especially regions which experience little or infrequent surface melting. These areas are of critical concern to study and understand, as they are the potential transition zones between the dry, unmelted snow zone and more actively melting regions. Continued satellite monitoring of surface melting is necessary to understand the manifestation and effect of changing climate on these sensitive regions. Especially in light of recent studies linking changes in summer temperature and surface melting conditions to enhanced ice shelf melting and catastrophic ice shelf disintegration around the Antarctic Peninsula (e.g. Scambos et al, 2000; Fahnestock et al, 2002), special attention should be paid to monitoring future climate and melt conditions on the Ross and Filchner-Ronne ice shelves.

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