Retrieval of Surface Melt Magnitude over Ross Ice Shelf, Antarctica Using Coupled Optical and Thermal Satellite Measurements

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ABSTRACT

Recent studies have indicated that Antarctic snowmelt is increasing at a staggering rate, contributing to dramatic sea-level rise, upwards of 60m, if current trends continue indefinitely. Unfortunately, we are not able to quantify snowmelt accurately from ground-based methods because there is sparse coverage in automatic weather stations. Satellite based assessments of melt from passive microwave systems are limited in that they only provide an indication of melt occurrence. Though this is useful in tracking the duration of melt, melt amount of magnitude is still unknown. Coupled optical/thermal surface measurements from MODIS were calibrated by estimates of liquid water fraction (LWF) in the upper 3cm of the firn using a one-dimensional thermal snowmelt model (SNTHERM). SNTHERM was forced by hourly meteorological data from automatic weather station data at reference sites spanning a range of melt conditions across the Ross Ice Shelf. Melt intensities or LWF were derived for satellite composite periods covering the Antarctic summer months. This empirical retrieval model allows determination of melt magnitude over other Antarctic Ice Shelves, such as Larsen, where surface melt has been well documented in contributing to the disintegration of the ice shelf.

Keywords: Antarctica; ice shelves; remote sensing; snowmelt; climatology; cryosphere

INTRODUCTION

With the recent dramatic collapse of the Larsen B Ice Shelf in 2002 and the partial collapse of the Wilkins Ice Shelf in 2008, the need to understand ice shelf dynamics has become more urgent. The collapse of Larsen B is known to have accelerated the flow rate of surrounding feeder glaciers by as much as 600% (Scambos *et al.*, 2004) for a time following the incident. This acceleration increases the amount of ice flowing into the Southern Ocean, thereby directly contributing to sea-level rise. Surface melt on Larsen B has been shown to not only have been substantial during the 2001-2002 melt season (Sergienko and MacAyeal, 2005) but also one of the primary causes of its collapse (van den Broeke, 2005). Surface melt can pond, flow, and collect in the numerous crevasses on ice shelves, causing further fracturing when a crevasse is more than 90% inundated with melt-water (Scambos *et al.*, 2000). Zwally *et al.* (2002) showed that ice sheet acceleration in Greenland at rates of over 10 cm/day have been documented and are coincident with episodes of

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increased surface melting. Because surface melt has a significant impact on ice shelf and ice sheet stability, maps of surface melt fraction would be beneficial to understanding what areas are at particularly high risk and the relative levels of ice shelf instability that may be possible.

The association between atmospheric warming and ice surface melt has been long established. Doake and Vaughan (1991) used remotely-sensed imagery in the visible spectrum to detect retreat in the Wordie Ice Shelf on the Antarctic Peninsula. They found strong correlations with long-term increases in atmospheric temperature across the region. Changes in atmospheric circulation have been thought to be occurring that have important implications for temperature trends over the Antarctic Continent. A trend toward high-index values of the Southern Annular mode has indicated a stronger circumpolar vortex, leading to increased temperatures over the Antarctic Peninsula and cooler temperatures in the continent's interior (Thompson and Solomon, 2002).

Previous studies have focused on the use of passive and/or active microwave data to detect the presence of surface melt, especially over Greenland. Abdalati and Steffen (1995) discuss using the XPGR (Cross-Polarized Gradient Ratio) as a way to combine the benefits of the strong relationship between surface melt and a horizontally-polarized microwave signal with the vertically-polarized signal which is not dependant on the spatial variability of surface temperature. While the QuikSCAT satellite was developed to measure surface winds over the ocean at a daily, 25-km resolution, it has proved useful in detecting surface melt of ice sheets due to the high sensitivity to liquid water in the snowpack (Nghiem *et al.*, 2001). Increases in snow wetness result in the absorption of microwave radiation and consequently a decrease in backscatter of more than an order of magnitude. These results were verified using temperature and radiation measurements from GC-Net surface station data. Steffen *et al.* (2004) compared the XPGR methodology with QuikSCAT data, and found the active microwave QuikSCAT imagery detected surface melt earlier and over a wider area than the XPGR methodology and was therefore superior.

Whereas passive microwave imaging, microwave scatterometry, and visible imagery have shown to be useful in detecting surface melt presence, alone they cannot quantify melt fraction. Certain properties of melting snow create distinct signatures in reflectance in the shortwave infrared portion of the electromagnetic spectrum. The refractive properties of ice and water are known to be similar in the infrared spectrum (Irvine and Pollack, 1968), however reflectance of shortwave infrared radiation at wavelengths between 1.0-1.3 μm is highly dependent on snow grain size (Wiscombe and Warren, 1980). Grain size, in turn, is proportional to the amount of snowmelt that has occurred. As snow melts, the grain size of the remaining solid ice increases as smaller grains are entrained into larger grains and liquid water fills the interstitial pore space (Colbeck, 1982). Larger grains of ice have an increased absorbance due to a longer photon path length through the medium. Reflectance, therefore, decreases as melt fraction increases. While grain size has been shown to affect the radiative properties of snow and ice, grain shape is not thought to affect the large-scale scattering of microwave radiation (Foster *et al.*, 1999). Reflectance in the near-infrared, however, is not driven solely by grain size. Surface litter and volcanic ash can increase reflectance in the near infrared while decreasing reflectance in the visible portion of the spectrum (Warren, 1982). Because of the non-linear dependence of liquid water fraction on surface reflectance, it is necessary to consider another variable. Snow surface temperature serves this function as high melt fractions are also associated with higher surface temperatures.

DATA AND METHODOLOGY

We outline a new method for detecting and quantifying surface melt using a coupled optical and thermal signature from MODIS satellite data. This method will allow for the potential for 1-km resolution compared to the 25-km resolution of the QuikSCAT imagery. While the temporal resolution is lower (8-day) than QuikSCAT, our method will allow for the determination of melt water fraction in the firn whereas active and passive microwave methodologies only detect the existence of melt above some threshold (usually one or three percent).

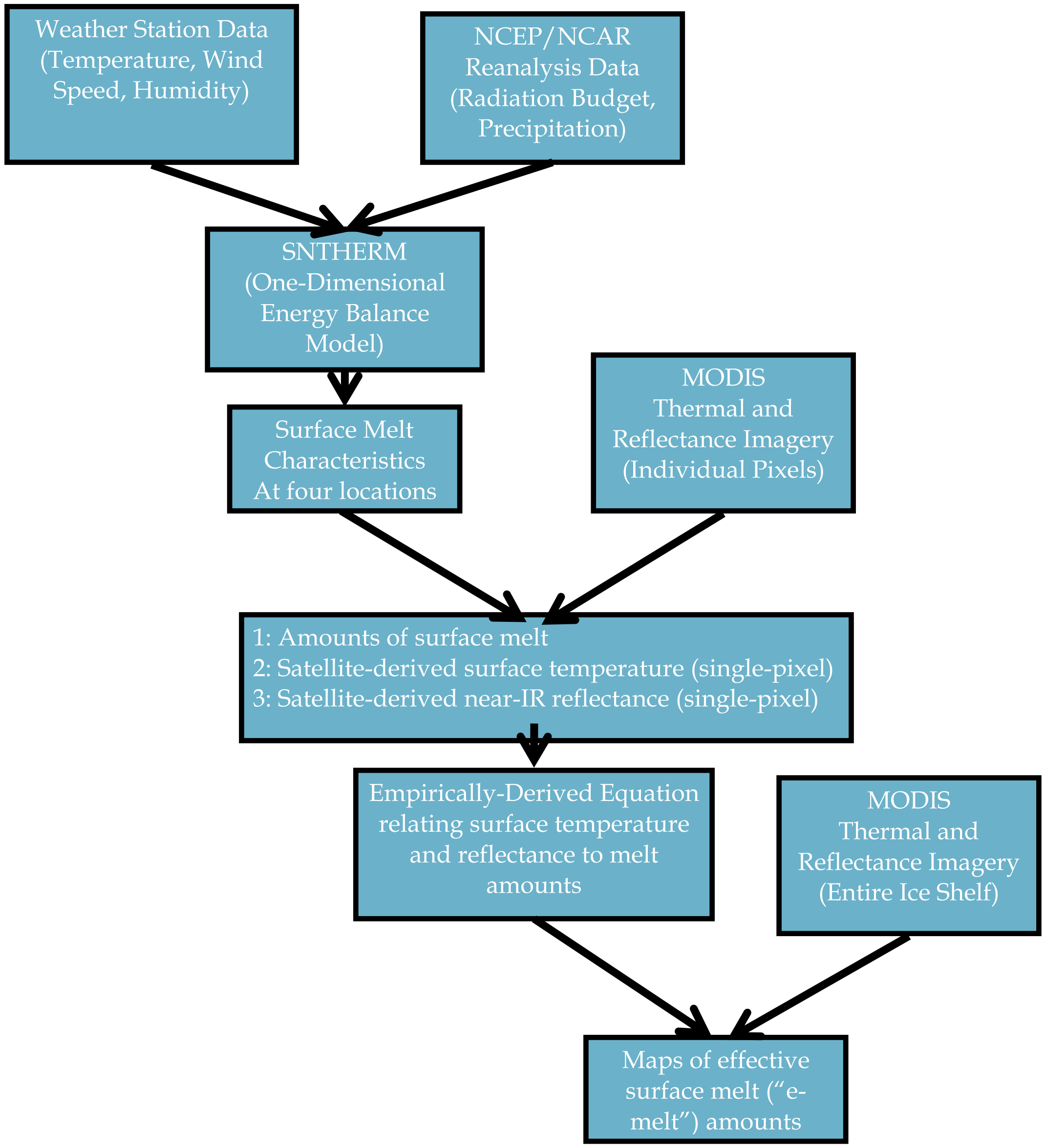

Figure 1. Surface melt mapping procedure.

A multi-step process is used to generate effective surface melt ("e-melt") maps for the Ross Ice Shelf (Figure 1). In order to calculate firn liquid water fraction, a one dimensional thermal snowmelt model (SNTHERM) is used (Jordan, 1991). Six-hourly weather station data from the University of Wisconsin Automatic Weather Station Project for three stations on the Ross Ice Shelf is used to drive the snowmelt model. These sites represent a diversity of melt climatologies to attempt to capture a wide range of melt values for the December 2002 to January 2003 time period. 2002-2003 was the year that Ross Ice Shelf experienced the largest melt extent and duration during the MODIS satellite record (Liu *et al.*, 2006). SNTHERM requires inputs of temperature, wind speed, relative humidity, precipitation, and radiation fluxes. The latter two variables, however, are not recorded by the AWS network. For these variables, it is necessary to use a reanalysis dataset. The NCEP/NCAR Reanalysis Project (Kalnay *et al.*, 1996) contains global precipitation and radiation flux data (among other variables) at a 2.5^{o} x 2.5^{o} resolution interpolated from satellite observations, weather station data, and forecast model output.

Reanalysis data for the high latitudes of the Southern Hemisphere is largely the result of model output. While there are several drawbacks to using the NCEP Reanalysis in the high latitudes of the Southern Hemisphere (Bromwich and Fogt, 2004), these are at their minimum during the summer melt season and in the latter part of the 1948-present data record.

The first two composite periods of each SNTHERM model run were discarded as model spin-up. Reflectance and Ice Surface Temperature was obtained from MODIS products available online at the NASA Earth Observing System Data Gateway. MODIS Aqua satellite band 5 (1.23-1.25 µm) 8-day composite data was used, available at 500m resolution (resampled to 1km). For ice surface temperature, the MODIS Aqua Sea Ice Extent and Ice Surface Temperature product with a 4km resolution was used. The SNTHERM-derived firn LWF along with MODIS temperature and reflectance data for the pixels corresponding to each of the reference sites were used to generate an empirically-derived equation of the form: LWF = f(IST, ρ), where IST represents ice surface temperature and ρ represents surface reflectance. This is done by assuming a planar (linear) correlation in three-dimensional space. Using this empirically-derived calibration equation, we then returned to the MODIS imagery to make maps of effective surface melt fraction (e-melt) for the entire Ross Ice Shelf

RESULTS AND DISCUSSION

Despite the small sample size, the model shows a statistically significant ($p=0.025$) relationship between LWF, Reflectance and IST of the form: **LWF = 0.007114 * (IST) - 0.293 * (ρ) – 1.704** (Figure 2). This equation is then used to calculate LWF in areas of the Ross Ice Shelf without AWS information.

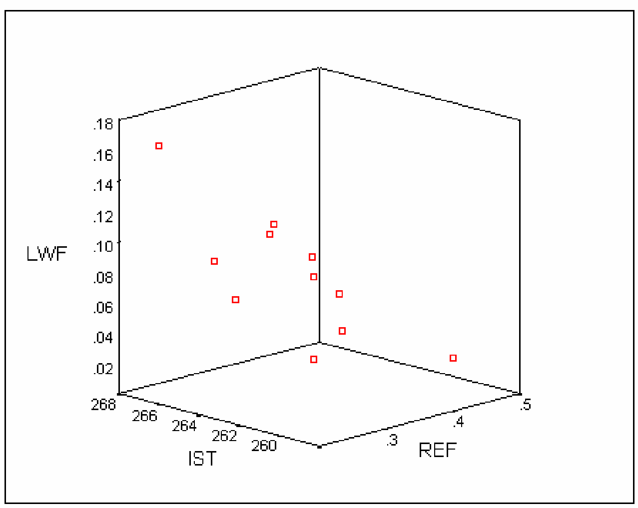

Figure 2. Near-IR Reflectance and Ice Surface Temperature vs. SNTHERM-derived Liquid Water Fraction.

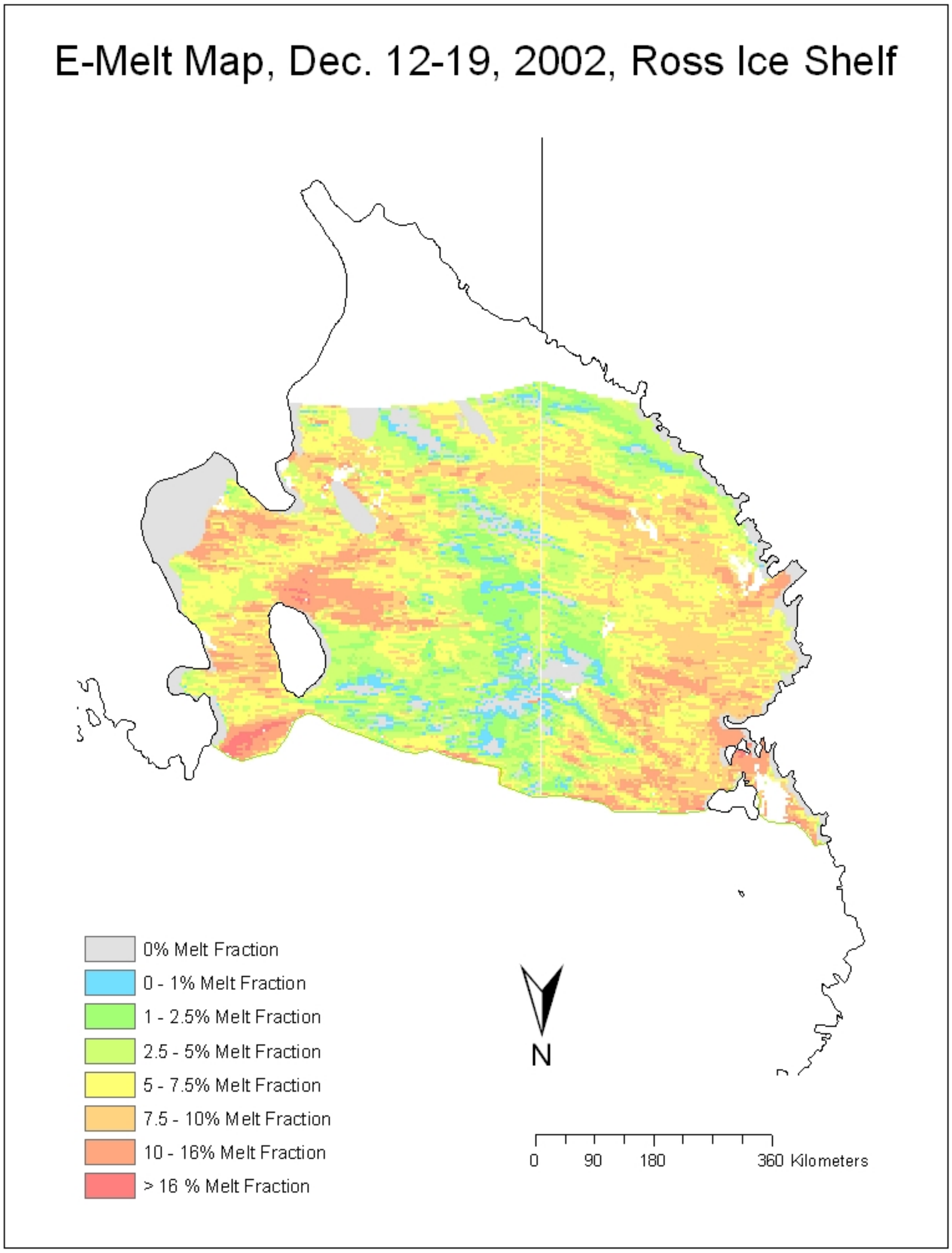

Figure 3. Ross Ice Shelf E-Melt Map, Dec 12-19, 2002.

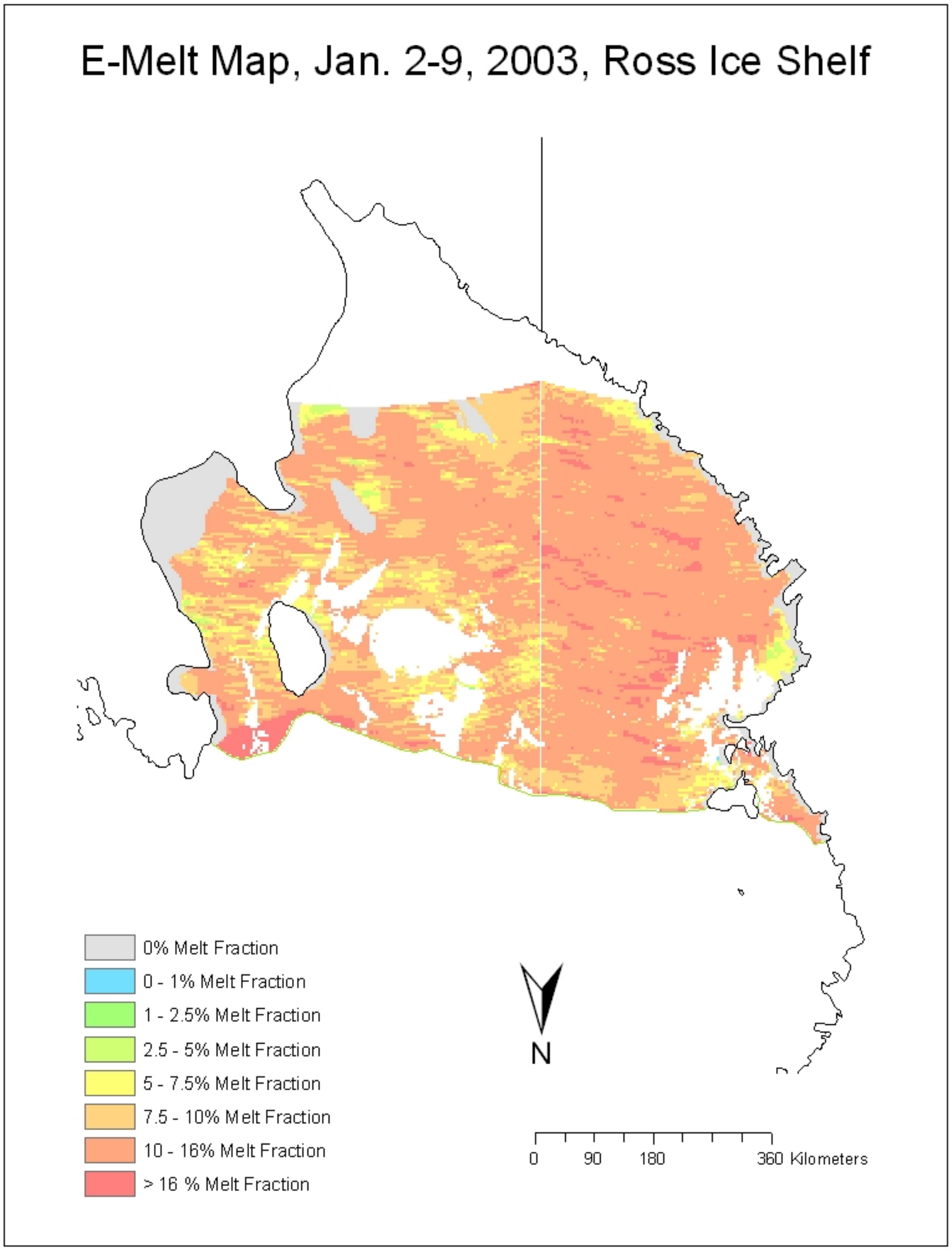

Figure 4. Ross Ice Shelf E-Melt Map, Jan 2-9, 2002.

Figures 3 and 4 are two e-melt maps for the Ross Ice Shelf region covering the 8-day composite periods beginning December 16, 2002 and on January 2, 2003. The January map represents a time of near peak melt on the Ross Ice Shelf for an anomalously warm melt season. The December map shows a period earlier in the season where temperatures are colder, and consequently liquid melt fractions are lower. The interior of the ice shelf remains cooler, especially in December, and there is less surface melt occurring here. It is interesting to note the high liquid melt fractions in the center of the ice sheet in January. These are associated with meridional wind anomalies of up to 4 m/s in the northerly direction averaged over the month, indicating that katabatic winds over the shelf were weaker than usual. Both maps show the effect of katabatic winds in the interior of the ice sheet which results in less surface melting in the center of the sheet than at the ice sheet margins.

Because this study is preliminary, the addition of more reference stations will naturally affect the calibration equation coefficients, and increase the range of surface melts over which this technique can be used to detect. Future research will expand this project to include all areas of the Antarctic Ice Sheet, with all available AWS sites. Ice surface temperature is available at 1km resolution from the National Snow and Ice Data Center, and future mapping will make use of this dataset. Eventually the surface mapping project will encompass over 30 weather stations and will result in a continental-scale map of surface melt fraction. The surface melt maps will serve as a resource for further examination of the changing climate in Antarctica, especially on volatile ice shelves. The extremely variable climate along the Antarctic Peninsula has shown a significant warming trend, which would correspond to larger amounts of surface melt on remaining glaciers, which could be detected by this method. This method could also be used to track amounts of surface melt over time, which if changing, would potentially be indicative of larger-scale climate shifts. Recent assessments of Antarctic climate change would be supplemented by the knowledge of where surface melt is occurring, and at what relative magnitude.

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