A Comparison of Passive Microwave Derive Melt Extent to Melt Intensity Estimated From Combined Optical and Thermal Satellite Signatures over the Greenland Ice Sheet For 2002

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ABSTRACT

Remote Sensing of surface melt extent and surface melt magnitude is important in studying ice sheet's mass balance and climatic changes in polar regions. Passive microwave Special Sensor Microwave/Imager data was used to monitor and study surface melt extent of the Greenland ice sheet. Optical and thermal satellite signatures, calibrated by melt water content derived from a physical snowmelt model was used to study the melt intensity (magnitude) of the Greenland ice sheet. By comparing passive microwave satellite data to optical-thermal satellite data, a comparison can established to determine if there is a correlation between surface melt extent and surface melt intensity (E-melt) across the Greenland ice sheet. Results were evaluated and showed a prominent correlation between surface melt extent and surface melt magnitude.

INTRODUCTION

Changes in global climate have implications for various components in the terrestrial system. Anthropogenic climate change is primarily a response to greenhouse gases emitted into the atmosphere. (J.T. Houghton et al., 1994) Increases in the amount of atmospheric greenhouses gases are correlated with increases in the earth's global average temperature. Assessment of the cryosphere's response to increase in global temperatures is important to understand and predict the long-term behavior of climate change.

Continental ice sheets such as Antarctica and Greenland are vulnerable to the effects of global warming and climate variability. The Greenland ice sheet is the second largest ice sheet in the world and has a surface extent of about 1.75 x 10^6 km^2 and an ice volume of 2.65 x 10^6 km^3 (C.J. Van der Veen 1991) . The Greenland ice sheet can be characterize by it different snow facies or zones, which are a result of climatic differences. (C.S. Benson 1962). These snow facies are categorized as either dry snow or wet snow zones.

The density of snow in these zones varies according to temperatures. The density of snow is very dependent upon the liquid water content in the snowpack. Wet snow occurs when surface temperatures are above the freezing point. Wet snow is partially melted and is therefore is denser than dry snow. Wet snow typically has a liquid water equivalence of 10:1 and for every ten inches of snowfall there is 1 inch of liquid precipitation that occurs. Dry snow occurs when surface temperatures are the below freezing point. Dry snow is less dense and can therefore accumulate to a higher depth than wet snow. Wet snow has a relatively low albedo (~0.65) for visible and near-infrared spectral bands which absorbs approximately 45% more incoming solar radiation than high albedo of dry snow (0.85) (Grenfell et al. 1994).

Dry-snow facies covers the high, central and northern regions of the ice sheet. Percolation zones are located in most of the southern regions and lower northern regions; wet-snow facies are only in the narrow marginal zone. A narrow marginal zone of the ice sheet can be subject to loss, by melting on land or by iceberg calving. (C.S. Benson 1962). Assuming an adiabatic lapse rate of 0.6°C/100 m (S. Orvig 1970), a slope above the equilibrium line of 0.4° (K. Steffen 1995), and a melt area perimeter of 3300 km, a 1°C temperature rise will increase the melt area by 79 000 km^2. Melt conditions of this extent cause a negative feedback in the earth's climate system and the global heat budget.

The Arctic in particular has exhibited a warming trend up almost twice as fast as the rest of the planet. [2] Warming Arctic temperatures contribute to a significant increase in the magnitude of melt extent on the surface of the Greenland ice sheet. Satellite data has shown an increasing trend in melt extent (the area of an ice sheet's surface experiencing an occurrence of melt (H.J. Zwally et al., 2002). Surface melt can accelerate the flow of outlet glaciers through crevasse deepening and results in the thinning of outlet glaciers

If the entire 2.85 million km^3 of ice on Greenland were to melt, global sea level would rise 7.2 m (approximately 23.6 ft.)(Warrick and Oerlemans, 1990). Sea level rise of this extent would be devastating to the world's costal population because of inundated wetlands, intensify costal retreat, and increase beach erosion. (N. Brooks et al., 2006)

Changes in the mass balance of continental ice sheets, such as Antarctica and Greenland, can be significant in a changing climate and can act as both a positive feedback if the mass balance is negative. Mass balance of an ice sheet is a measure of mass volume gain due to accumulation or mass volume loss due to melting and iceberg calving (Abdalati, W., and K. Steffen, 1997). Increases in the temperature of the ice sheet can result in enhanced surface melt on these large ice masses. Understanding the influence of surface melting on the mass balance of the Greenland ice sheet is important and an assessment of the melt dynamics through time is vital to monitoring periodical changes of the ice sheet. The surface melt of the ice sheet can be monitored using satellites that operate across a range of the electromagnetic spectrum. In particular, passive microwave systems have been used to track the spatio-temporal variability of melt extent (Mote et al., 1993). To understand the role of melt in climate change more information about the melt magnitude beyond just occurrence and extent is necessary. A new technique to map the melt magnitude, beyond the melt extent has been developed.

In this project there will be a comparison of Greenland's surface melt extent derived from passive microwave data to the magnitude of surface melt derived from optical/thermal data over a period of five years. This comparison will evaluate how significant measured changes in the extent or the occurrence of melt have been through determining the amount or intensity of melt over the same period.

II. BACKGROUND

Microwave brightness temperature measurements between 3 GHz and 90GHz have found sensitive to snow type and water equivalent. Microwave data has a high sensitivity to liquid water that is present in a snow pack (G. Maceloni et al., 2001). There is a distinct increase in upwelling microwave emission, which is noticeable when there is an increase in the water content in the firn.

In the past, various methods have been used to study melt signatures of the Greenland ice sheet using single channel or multi-channel satellite passive microwave signatures. Passive microwave data at frequencies near channel 19 and 37 GHz are well suited because solar illumination is not necessary and these channels are slightly weakened by cloud cover. For example, (Mote et al., 1993) used the 19GHz vertically polarized channel to calculate difference between daily brightness temperature (T_B) and winter mean brightness temperature:

$$(T_B - T_{winter}) \qquad [1]$$

When a pixel displays a brightness temperature on a particular day in excess of the winter mean plus the difference threshold, that day was classified as experiencing melt. Zwally and Fiegles (1994) used a similar technique that was applied to investigate snowmelt of the Antarctica Ice Sheet. In their study they calculated the difference between daily brightness temperature and mean annual brightness temperature:

$$(T_B - T_{annual}) \qquad [2]$$

using the 19 GHz polarized channel. A 30K melt threshold was chosen to identify melting.

Steffen et al. (1993) used the normalized gradient ratio (GR) derived from the 19 GHz and 37 GHz horizontally polarization channels as a surface melt index:

$$GR = (T_B{}^{19H} - T_B{}^{37H}) / T_B{}^{19H} + T_B{}^{37H}) \qquad [3]$$

A melt threshold was determined by comparing a time series of GR values with in situ air temperature data. Abdalati and Steffen (1995, 1997) replaced the 37 GHz horizontally polarized channel with the 37GHz vertically polarized channel in GR, and created the cross polarization gradient ratio (XPGR):

$$XPGR = (T_B^{19H} - T_B^{37V}) / (T_B^{19H} + T_B^{37V}). \qquad [4]$$

Abdalati and Steffen (2001), estimated the melt extent of the Greenland ice sheet from (1979-1999) using passive microwave data from Special Sensor Microwave Radiometer and Special Sensor Microwave /Imager. The analysis showed a positive trend of 1% of melt extent increase per year that occurred mostly in the western region of the ice sheet. Steffen (2004) conducted an updated analysis of the Greenland ice sheet from (1979-2002). This analysis showed a 16% increase in melt extent with an anomaly in melt extent during melt season of 2002.

Ashcraft and Long (2006) compare multi-sensor approaches to mapping melt extent and occurrence over GIS and indicate that passive microwave based approach may underestimate melt extent. In response, Wang et al (2007) used enhanced scatterometer data from QuikSCAT (QSCAT) to estimate melt extent at a higher spatial resolution (~ 5km2) than passive microwave approaches (25km^2) from 2000 through 2004. They determined that average melt duration for any given year ranged from 14.3-20.5 days with a range in proportion of area experiencing melt between 44.2 and 79.2%.

Ramage and Isacks (2002) introduced a new approach called the diurnal amplitude variation (DAV) for detecting snow melt in Alaska. Their analysis used the difference between brightness temperatures during ascending (late afternoon) and descending (early morning) passes:

$$DAV = T_B^{ascending} - T_B^{descending} \qquad [5]$$

This method combined DAV threshold of 10 K and the T_B threshold of 246K to account for melt and refreezing that might occur during the evening.

Tedesco (2007) applied DAV to monitor snowmelt over the Greenland ice sheet from measurements derived SSM/I using the 19 GHz horizontally polarized channel or the 37 GHz vertically polarized channel. In this study, we compare melt extent and duration derived from passive microwave approaches to melt magnitude which provided an estimate of surface liquid water fraction over Greenland by using coupled optical/thermal signatures calibrated by a modified version of the physical snowmelt model SNTHERM89.

III. METHODOLOGY

Passive microwave data has been used to study the areal extent and duration of snowmelt that occurs on the Greenland ice sheet. A new approach has been developed to retrieve melt magnitude (surface liquid water fraction by volume) from satellite data that collects in the optical and thermal parts of the electromagnetic spectrum. The data analyzed for this study covers the anomaly that occurred during the 2002 melt season. The effective analysis period is only for a segment of the ablation season, which ranges from (early) June through (early) July. A coastline mask was applied to the ice sheet to extract pixels that only lie on the ice sheet. This mask was generated from the digitization of the Quaternary Map of Greenland produced by the Geological Survey of Greenland. Pixels that contained a combination of ice and land were removed in order to eliminate land contamination that would produce incorrect results of surface melt.

Special Sensor Microwave/Imager (SSM\I) data was collected from the National Snow and Ice Data center (NSIDC) where they binned and gridded measured upwelling brightness temperatures into daily averages of 25km x 25km grid cells. The SSM/I data has several different channels which are: 22GHz (vertical polarization) and both vertical and horizontal polarizations for 19GHz, 37GHz, and 85GHz. The SSM/I data was dividing into two separate files for ascending and descending orbit observations. These observations were taken in the early morning around (about 1800 hours local time) and later afternoon around (about 0600 hours local time). The 19 GHz and 37 GHz frequencies were chosen because of there response to melt events. The 19 GHz frequency is more sensitive to melt that occurs in the firn, than the 37 GHz frequency which is due to the change in emission depth. (K. Steffen et al., 1993). The liquid water content in the snow pack causes an increase in the horizontal brightness temperatures than the vertical brightness temperatures for both frequencies. This is due to the dielectric properties of air-snow when snow is wet. The cross polarization gradient ratio technique and diurnal amplitude variation technique applied to the SSM/I data and was used to determine the melt extent and melt duration across Greenland.

Moderate Resolution Imaging Spectroradiometer (MODIS) optical-thermal 8-day composite 1km resolution products of Land Surface Temperature (LST) were selected also to be used in this study. In the passive microwave spectrum optical and thermal measurements increase spatial resolution but decrease spatial coverage due to clouds. Cloud coverage is one major limitation that causes a reduction in full daily acquisitions over Greenland (Klein and Stroeve, 2002). The MODIS 8-day composite had the least amount of cloud cover than other daily images which made it more efficient to use. There are a total of six 8-day composite scenes during this study, covering the period of May 25 to July 12, 2002. Estimation of surface melt intensity was achieved by using coupled optical/thermal signatures calibrated by a modified version of the physical snowmelt model SNTHERM89 augmented to simulated snow over glacier ice. This empirical retrieval has been designated as effective melt intensity (E-melt) primarily because it represents an integrated measure of liquid water fraction over an 8-day period at $1km^2$ within the upper 5cm of the glacial firn.

IV. RESULTS

For each ice pixel, the cross-polarized gradient ratio and diurnal amplitude variation was calculated according to Equation 2 & Equation 4. For each ice pixel, a melt intensity value was calculated using the SNTHERM89 snowmelt model. Graphs were produced to display the relationship between surface melt magnitude and daily surface melt extent/occurrence for each of the six 8-day composite periods ranging from Julian dates 153 to 193.

We found that there is a good correspondence between daily melt occurrence and melt magnitude. Figure 1 shows that various ice pixels experienced higher XPGR E-melt values when pixels experienced surface melt for a period of four and five days. XPGR highest E-melt values range from approximately 0.10 to approximately 0.12. In Figure 1, XPGR had no pixels that experienced eight continuous days of melt. However, DAV detected pixels that had experienced melt for eight continuous days and has no E-melt value greater than 0.07. XPGR method presented a negative correlation between melt extent/occurrence and melt magnitude. Figure 2, demonstrates a major increase in E-melt values for DAV and a decrease in XPGR E-melt values. Figure 2's pixels that experienced melt for a period of four to eight days had DAV E-melt values that lie between approximately 0.082 and approximately 0.095. DAV E-melt values decrease significantly from composite period 161 (Figure 2) to composite 169 (Figure 3). Figures 2, 3, 4, and 5 show pixels that experienced melt continuously for a period of two to five days showed no significant decrease or increase in XPGR melt intensity values. Figure 6, shows that pixels that had a melt experience for 7 days had the highest average melt. The lowest average E-melt value for composite period 193 for pixels that experienced melt for a period of two days.

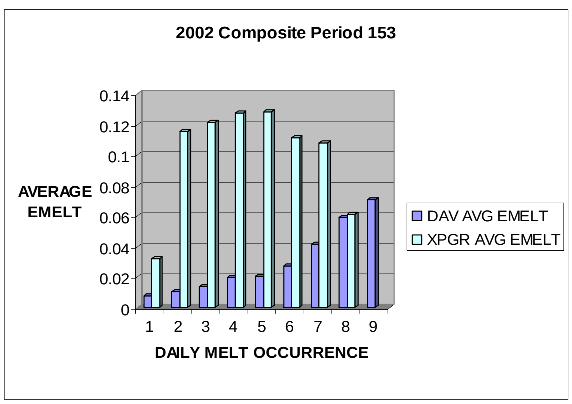

Figure 1. Bar graph of surface melt extent/occurrence derived from XPGR and DAV verses melt magnitude derived from MODIS for composite period 153. This composite period consists of Julian dates 153, 154, 155,156, 157,158, 159, and 160.

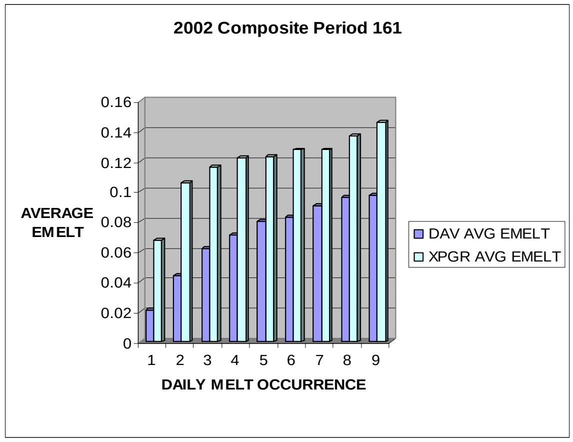

Figure 2. . Bar graph of surface melt extent/occurrence derived from XPGR and DAV verses melt magnitude derived from MODIS for composite period 161. This composite period consists of Julian dates 161,162,163,164,165,166,167, and 168.

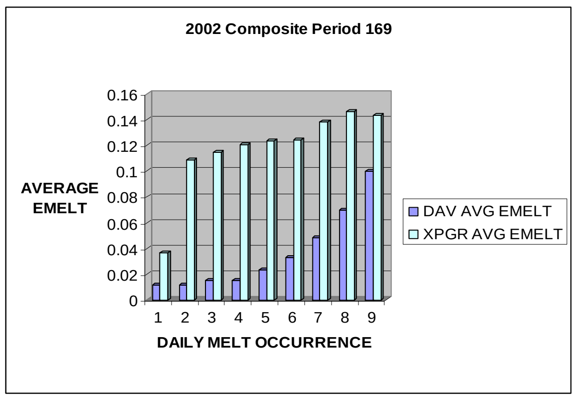

Figure 3. Bar graph of surface melt extent/occurrence derived from XPGR and DAV verses melt magnitude derived from MODIS for composite period 169. This composite period consists of Julian dates 161,162,163,164,165,166,167, and 168.

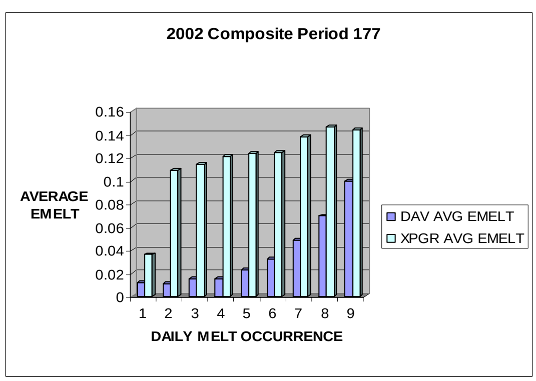

Figure 4. Bar graph of surface melt extent/occurrence derived from XPGR and DAV verses melt magnitude derived from MODIS for composite period 177. This composite period consists of Julian dates 169,170,171,172,173,174,175,176, and 177.

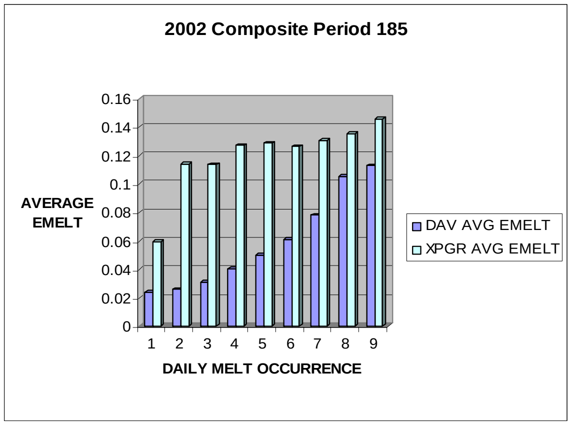

Figure 5. Bar graph of surface melt extent/occurrence derived from XPGR and DAV verses melt magnitude derived from MODIS for composite period 185. This composite period consists of Julian dates 178,179,180,181,182,183,184, and 185.

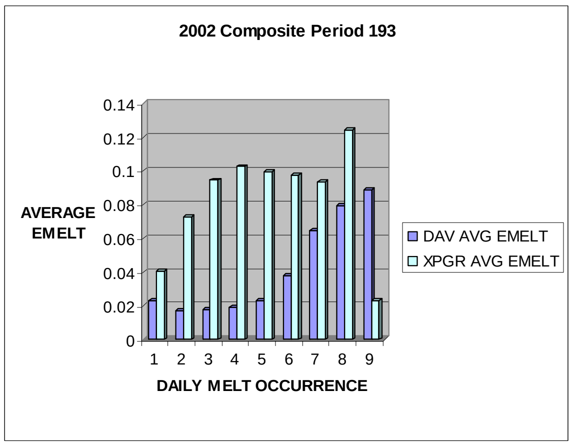

Figure 6. Bar graph of surface melt extent/occurrence derived from XPGR and DAV verses melt magnitude derived from MODIS for composite period 193. This composite period consists of Julian dates 186,187,188,189,190,191,192, and 193.

V. CONCLUSIONS

Results indicate that DAV shows a much more proportional relationship to melt magnitude than XPGR consistently during the analysis period. Both techniques show a scaled increase in melt occurrence with melt magnitude from the mid part of the melt season (Day 153- June 3) than later in the melt season (Day 193-July 12). Difference in the comparison of XPGR and DAV to E-melt may be due to the ability of DAV to track more night time persistent melt, producing higher occurrences of melt. E-melt values derived from surface reflectance and temperature may be sensitive the diurnal effects as well resulting in a stronger relationship to DAV than XPGR. Further work is necessary to explain these trends.

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