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Analysis of the Temporal Variability of Positive Degree Day Factors

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Abstract

The surface mass balance determines the growth or decay of an ice sheet, by taking the difference between accumulation and ablation. In this thesis snow and ice ablation is related to 2m-temperature through the positive degree day method. The positive degree day method takes into account the ablation rate of snow and ice and the number of measurements with temperature above freezing level in order to compute the proportionality constant between the two. Positive degree day factors for snow and ice are computed using data obtained from EC-Earth model simulations. The factors are computed for the present day climate and the Eemian in order to exploit their variability. The results demonstrate positive degree day factors to be visibly variating with the climate.

Contents

List of Abbreviations

AIS	Antarctic Ice Sheet
CDO	Climate Data Operators
GIS	Greenland Ice Sheet
PDD	Positive Degree Days
pictrl	preindustrial control run
SEB	Surface Energy Balance
SMB	Surface Mass Balance
std	Standard deviation

1 Introduction

The mass loss on the Greenland Ice Sheet (GIS) is increasing. From 1979 to 2006 the melting increased by 30% in the summer period. A large number of studies also show that the Surface Mass Balance (SMB) of the GIS has negative values, meaning that it is losing mass, dating twenty years back [12, 27, 22]. This makes it essential for us to understand more about the melting of ice sheets and glaciers and what effects a long term increase in temperature would have on them.

Human activity is the primary cause to the increase of greenhouse gases. Burning of fossil fuels, deforestation, agriculture and rice cultivation are all sources for the increase of greenhouse gases. All of these additional emitted greenhouse gases contribute to more radiation hitting the Earth's surface and resulting in a negative SMB. The so called greenhouse effect is a fairly easy concept: Incoming shortwave solar radiation passes through the atmosphere and warms the Earth's surface, then the outgoing longwave radiation is reflected back into space. However, most of the outward going radiation is trapped by so called greenhouse gases. Greenhouse gases are selective absorbers, meaning they do not stop visible incoming radiation but they absorb the outward going infrared radiation and reemit it back down towards the surface resulting in reheating of the surface [2]. In the present work melting rate is related to an increase in the temperature two meates above the surface.

The GIS, which is the primary area of interest in my thesis, has an ice volume of $2.85x106km^3$, which if melted would result in a 7.2m sea level rise [3]. In order to determine the growth- or decay rate of an ice sheet and/or an ice cap one looks at the SMB, which is snow gain minus melting. Melting is difficult to measure since it is a complex process that predominately is controlled by incoming solar radiation and mediated by both the temporal evolution of the albedo and heat fluxes between the surface and the atmosphere. These parameters are not always available, therefore the temperature 2m above surface has been suggested as a replacement for computing the melting. It has been found that temperature and incoming radiation are highly correlated [16]. The surface melting is related to the 2m-temperature through positive degree day (PDD) thinking. PDD is the sum of the number of measurements with temperatures above 0°C, and the proportionality factors between the number of meltings and the actual melting rate are called PDD factor [5].

This thesis will use two parameters, 2m-temperature and melt rate, in an attempt to calculate the PDD factor for two time periods. In order to access the variability of PDD in a changing climate, this thesis will compute PDD factors for the GIS for two different time periods, the Eemian and a preindustrial control run (picrl). The pictrl represents the current climate before the industrial revolution. Since the Eemian is the second most resent interglacial period, and is also said to represent an even warmer climate than the present day, it can provide a resemblance to possible future warming. In the present work a Matlab code will be constructed in order to compute the PDD factors. It is expected to find that the PDD factor does vary with the changing climate conditions. This result would make the PDD method more complex than if it in fact would be a constant factor that could be utilized for all climate states.

2 Background

2.1 Ice Sheets

Ice sheets are required to cover an area of at least 50,000 square kilometers, whilst glaciers are irrespective of size [15]. Glaciers are also controlled by the topography, while ice sheets and ice caps overrun the topography. Ice sheets are in constant motion, due to gravity they are slowly flowing downhill under their own weight. At the coastline of an ice sheet, the movement is faster as the ice flows through outlets called ice streams and ice shelves. As long as an ice sheet is gaining the same mass, in snowfall, as it loses through melting and through calving it will remain in equilibrium [23].

Ablation refers to the process in which an ice sheet experiences mass loss, this occurs when snow and/or ice is melted, evaporated, sublimated or when ice is detached through calving [3]. Melting is the dominating process on the GIS and is therefore the primary factor looked upon in this thesis. When an ice sheet gains mass, generally through snowfall, it is referred to as accumulation.

An ice sheet can be divided in to a number of zones, Figure 1. The two main zones are the ablation and accumulation zone. In the ablation zone mass loss is the dominating factor, where as in the accumulation zone mass gain is dominating. Within the accumulation zone there are four more zones; the dry-snow zone where air temperatures always stay below freezing and no melting occurs, the percolation zone where there is partial surface melting although the meltwater percolates through the snow and refreezes horizontally, eventually the meltwater has penetrated the entire snowpack creating the wet-snow zone, and at the outline of the snowpack the fourth zone, the superimposed ice zone, is created as widespread refreezing occurs [3].

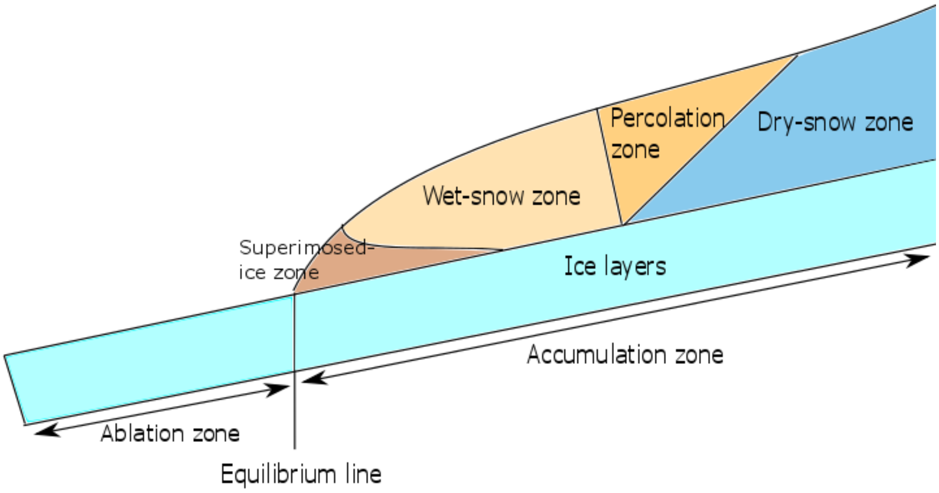

Figure 1: Sketch of an ice sheets different snow and ice phases.

2.1.1 The Greenland Ice Sheet

The Greenland ice sheet (GIS) is the largest mass of glacier ice in the northern hemisphere, and contains 10% of the Earth's fresh water reserve, although it is actually ten times smaller than the Antarctic ice sheet (AIS) [3]. Another big difference between the two ice sheets is the surface temperature, Greenland has a 10-15°C higher mean annual surface temperature [13]. During the summer half widespread melting is common on the GIS, but AIS hardly ever experiences any meltwater or runoff. This has an obvious explanation, the AIS is located directly at the South Pole whereas GIS is located at lower latitudes. There is also the fact that the AIS is secluded from the rest of the climate system, due to the Circumpolar Current as well as the position of the polar front, which generates clear and dry atmospheric conditions resulting in a heat sinking effect. Therefor it is highly unusual for temperatures to go above freezing-level [13].

The mean annual precipitation rate over Greenland varies vastly from north to south. In the north the rate does not go above 150mm/y, whereas in the most southern parts the rate can be as high as 2500mm/y. his large difference is mostly due to coastal effects and the Icelandic low, which is a semi-permanent low pressure system located between Iceland and southern Greenland [13].

2.2 Glacial-Interglacial Cycles

Glacial periods, also known as ice ages, refer to a time when ice sheets covered large parts of the northern hemisphere. Glacial periods are colder and drier than the interglacial periods. The most resent glacial period occurred 11500 years ago. Present day the Earth is in an interglacial period, the Holocene, and the only ice sheet in the northern hemisphere is the GIS [6].

The reason for these cycles is due to variations in the Earth's orbit, which generates changes in solar insolation. During interglacial periods the insolation in the northern hemisphere, and thereby the temperature, is above average values. However, interglacial periods do not occur at all events of peaks in insolation, this phenomenon is yet to be explained [6]. One interesting correlation is data showing insolation during July in the northern hemisphere [4], is in phase with temperature data taken from the Dome Fuji ice core in the AIS [14]. Thereby the insolation in the northern hemisphere influences the climate of the entire planet[6].

2.2.1 The Eemian

The Eemian took place 130 000-114 000 years ago, it is the second most recent interglacial period. During the Eemian temperatures were as high as 3-4K higher than present day [24], and the volume of the GIS was 30-60% smaller than today [18] [20], in addition to that the northern hemisphere insolation also was higher. The mass loss of the GIS in addition with glacial melting and partial melting in Antarctica resulted in sea levels being 5.5-9m higher than what we are experiencing today [8].

2.3 Surface Energy/Mass Balance

The surface melting of an ice sheet is foremost controlled by incoming solar radiation, but also by sensible and latent heat fluxes between the snow and the atmosphere, figure 2. Shortwave radiation, S_i is emitted from the sun and is absorbed or reflected by the ice, S_o. Longwave radiation is emitted from the ground, L_o, and the atmosphere, L_i. When water changes state, snow undergoing evaporation and sublimation, there is a release of latent heat Q_l. Sensible heat Q_s is the heat exchange between the ice sheet and the atmosphere. The Surface Energy Balance (SEB) is displayed in equation (1), which when negative results in snow and ice being melted, and when positive meltwater refreezes [3].

$$SEB = S_i - S_o + L_i - L_o + Q_s + Q_l \tag{1}$$

$$SMB = Accumulation - Ablation \tag{2}$$

SMB is the difference between accumulation and ablation, equation (2), snow gained minus snow lost. The SMB is measured in meaters. Accumulation refers to precipitation, condensation and refreezing and ablation refers to meltwater runoff, sublimation and evaporation. Accumulation usually occurs during 9 months of the year, whilst ablation only occurs during 3 months. This does not mean that there is only surface mass loss during the summer, sublimation and evaporation are dominating mass loss processes during the winter, due to dry conditions. Sublimation and evaporation is the transition of a substance from solid/liquid phase into gas phase respectively [15]

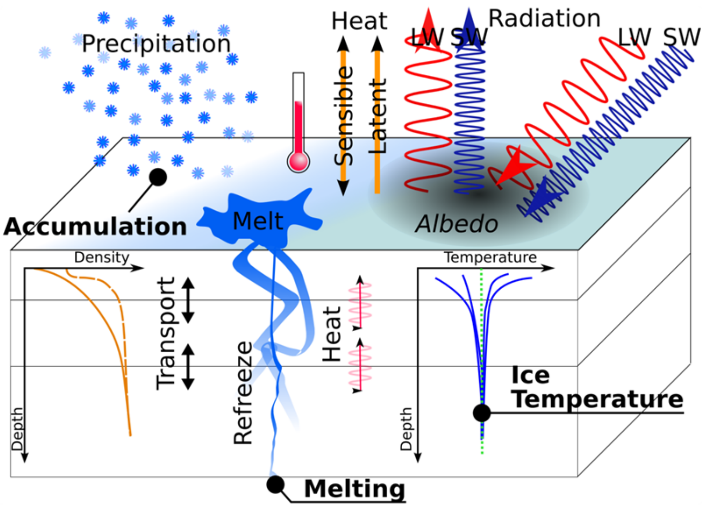

Figure 2: Sketch of processes controlling the surface mass and energy balance of an icy surface [21].

2.4 Positive Degree Day Method

PDD is the sum of the number of measurements with temperatures above 0°C, the proportionality factors between the number of occasions with melting A_s, A_i and the actual melting rate is the PDD factor k_i, k_s, (Equation 3 and 4) [5]. The PDD method was first tested in the Alps by Finsterwalder and Schunk in 1887, however, it was not tested under Greenland conditions until 1985, 1989 by Braithwaite and Oelsen. In 1991 it was modified by Reeh in order to calculate melting over the entire Greenland ice sheet [5].

The melt rate of snow/ice is determined by the SEB. The SEB includes several parameters, radiation, temperature, humidity, wind speed, surface roughness, snow and ice density and snow temperature, which are difficult to measure all year-round [26]. Therefore, it is not reasonable to make SEB computations for the surface of an entire ice sheet at all times [19]. The alternative method is temperature-index modeling, like the PDD method, it has been shown that temperature and melt has a strong correlation coefficient, 0.96, between ice melt and positive air temperature sums [5]. Studies have shown that longwave atmospheric radiation is the largest heat source for melt and that along with sensible heat fluxes it provides about 75% of the total energy source for melt [16]. These two heat fluxes are highly affected by temperature and thereby provide the main reason for the correlation between melt and air temperature.

The PDD method is not universal and the PDD factor should not be applied as a constant factor over the globe. Atmospheric structure, surface roughness and albedo vary vastly between locations. Therefore the PDD factor has to be determined experimentally. An additional problem with the PDD method is the time between temperature measurements. On days with temperature measurements below freezing the model generates zero melt, however, it is possible that the temperature exceeded the freezing level during the time between measurements [26].

Although the method is physically justified, it is questionable to use constant PDD factors under changing climate conditions. For instance, the Eemian, which was an interglacial period with similar temperatures as in northern Greenland for nowadays, indicates that constant PDD factors are not consistent with the simulated melting rates for these periods obtained from model simulations [25]. Therefore, it would be preferable to compute different PDD factors for different climate period. For instance, in a generally warmer climate, one can by reasoning understand that the surface snow probably contains more water causing a darker surface or uncover the subjacent ice which both decrease the albedo. This would increase the melt potential and would require higher PDD factors. Furthermore, an ice sheet like Greenland is a slow reacting climate component compared to other more rapidly changing components as the atmosphere and the ocean [17]. This makes it difficult to run an energy balance ice sheet model that covers the entire time scale of an ice sheet, which has a typical length of 12500 years.

3 Method

3.1 Surface Energy/Mass Balance Modeling

The already existing energy/mass balance model, EC-Earth, was used with help of supervisor Christian Rodehacke in order to obtain the ablation and accumulation rate. The model uses a large variety of factors as: temperature, insolation, thermal radiation, cloud cover, surface pressure, precipitation, wind and albedo, as input arguments while executing the calculations. The reason for the success of the EC-Earths model lies in the advance broadband albedo scheme. The model was run for the entire GIS during 50 years of the Eemian and picrl, recording data every 6th hour.

Figures presenting the total mean of the different climate conditions were produced using Climate Data Operators (CDO) and Matlab. "CDO is a collection of command line Operators to manipulate and analyse Climate and NWP model Data" [9]. Statistical time mean and monthly mean values were computed with CDO.

3.2 Positive Degree Day Modeling

During the first phase of the project the PDD factor was computed, this was done using Matlab. Temperature, accumulation and ablation data, with measurements every 6th hour, were used as input parameters. The temperature data was modified in order to require the PDD value. Data points that did not exceed 273.15K were excluded from the data set. Following, the modified temperature data points were multiplied with the time axis resulting in our PPD value.

$$A_s = k_s PDD_s \tag{3}$$

$$A_i = k_i PDD_i \tag{4}$$

$$PDD = PDD_s + PDD_i \tag{5}$$

After calculating PDD, the next focus was calculating the SMB, which as mentioned earlier is the difference between accumulation and ablation. In order to calculate the melting rate the data sets covering ablation and accumulation were used, snow melt was separated from ice melt, as they are to generate different PDD factors. This was performed through observing the excess of snow at the end of each day, along with the amount of accumulated snow. The excess from the day before was added into the SMB equation, however, day one of each year always stars with zero excess snow.

At the start of each year the excess is essentially accumulation minus ablation, every other measurement excess is accumulation minus ablation plus the excess from the previous measurement. At some point, all the snow has melted and ice will start to melt. This occurs when the excess snow is equal to zero, here the ice melt is simply the total melt minus snow melt.

If observing Figure 1, one can see the three different scenarios of melting on an ice sheet. On the surface of the dry-snow zone merely snow is melted, on the surface of the ice layer, within the ablation zone, only ice is melted, and between the equilibrium line and the dry zone both snow and ice melt will occur.

This provides all needed inputs to compute the PDD factors k_s and k_i in equation (3) and equation (4), since the total PDD is just the added amount of PDD for snow and ice, also when exclusively snow is melted $PDD = PDD_s$. k_s and k_i is computed in three steps, first step computes k_s exclusively, whilst the second step computes k_i, and the third case computes the combined scenario of both snow and ice melt. While computing k_i for the case were both snow and ice is melted, the k_s value from the previous time step is used, the melt rate is assumed to not change drastically between time steps. The standard deviation for k_s and k_i is also computed. All of these calculations were performed with the help of Matlab, for code see appendix.

In the present work problems with the models ability to process the ocean were discovered. In order to remove the data computed in the ocean a land/sea mask file was added to the code. This drastically changed the PDD factors for both climate states.

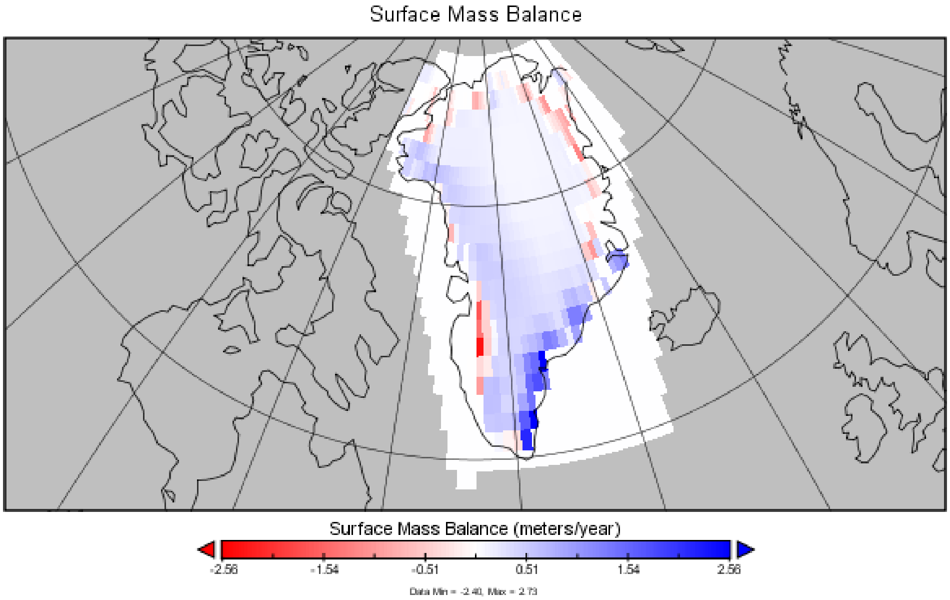

Figure 3: Surface Mass Balance for Greenland [1]

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Figure 3 is the SMB for present day Greenland and was used as reference while producing PDD factor plots for specific locations. Areas where the SMB is negative, marked red in the figure, are also areas where Greenland experiences the greatest amounts of melting. As one can see, the SMB is most negative in the southwest regions, which makes it a region of interest. The blue areas in the figure is where the SMB is positive and the ice sheet is gaining more mass than it loses.

4 Results and Discussion

4.1 Greenland Data

The figures in this section were produced in the present work, using Matlab, with data from the surface energy/mass balance modeling. The figures aim to state the different climate conditions during the Eemian and the pictrl. Figure 4 gives an overview of the grid used in the present work.

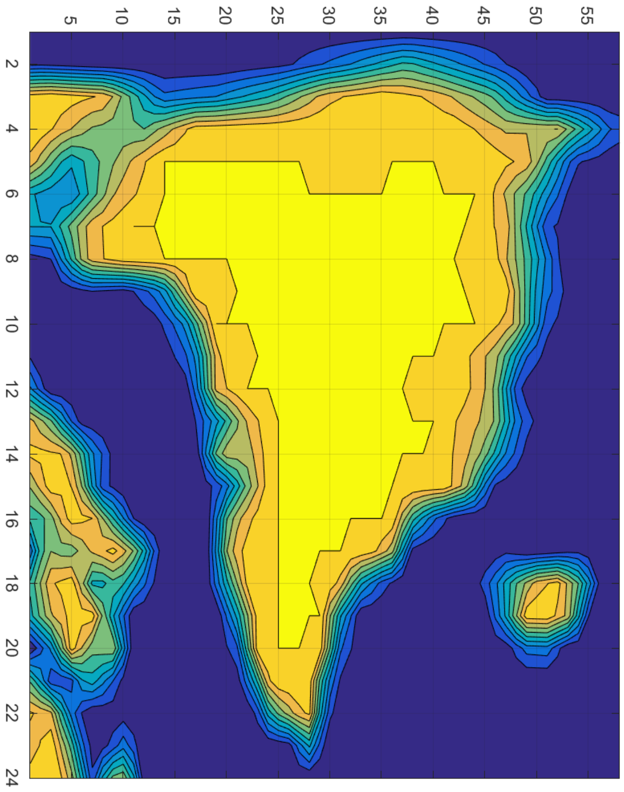
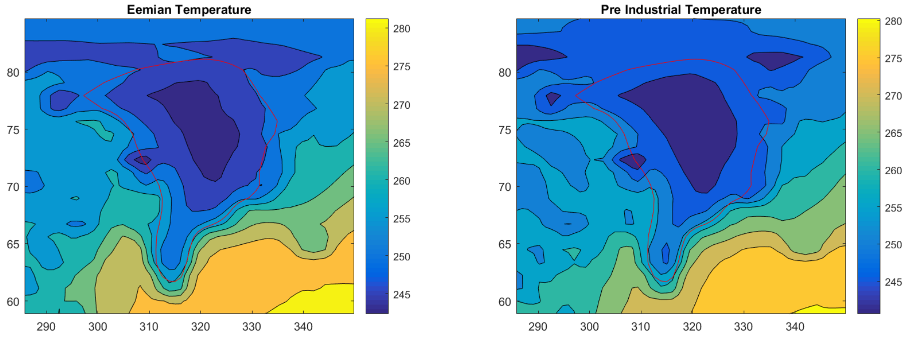


Figure 4: Grid used in model for the Greenland Ice Sheet



(a) Eemian (b) Pictrl

Figure 5: Mean temperature (K)

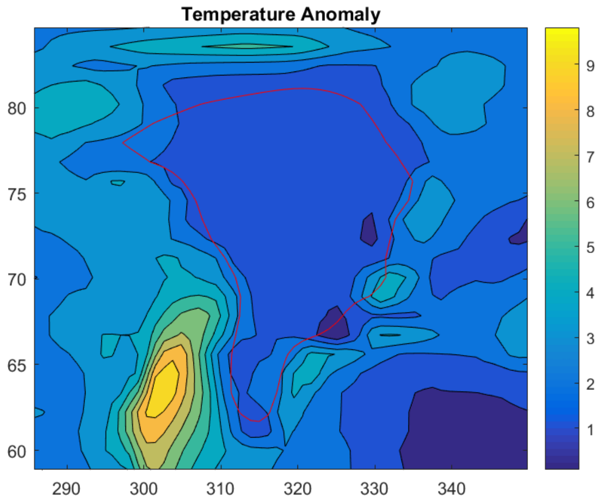
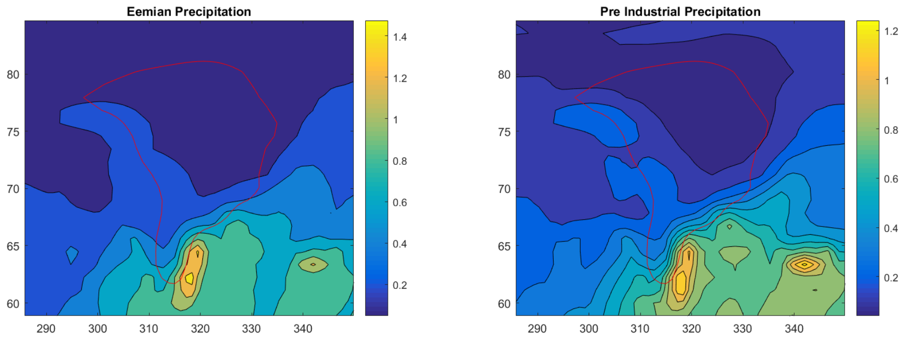


Figure 6: Temperature anomaly (K).

Observing the mean temperature for the Eemian in Figure 5a one can see that there is a warm sector located in the southeast over Iceland. This warm region is an effect of the Gulf Stream, which has a warming effect along the southern coast of Greenland. This effect is visible in the figure, as the mean temperature decreases further inland. These warmer regions along the coast are the locations where one can expect melting. In Figure 5b one can see that the cold inland area is even larger, furthermore the warm sector, from the Gulf Stream, does not stretch as far on the southwest side of Greenland.

Comparing the mean temperatures between the Eemian and pictrl, present day climate, Figure 6, the largest difference is in the ocean south west of Greenland. This area is called Labrador Sea. In the present day one can see the sea ice edge stretching near the warm spot during winter. In the Eemian simulation the winter sea ice edge is located further north. This allows more heat release from the ocean into the atmosphere. This effect drives the warming anomaly in the Labrador Sea and contributes to the overall lower air temperature in our present day climate.



(a) Eemian (b) Pictrl

Figure 7: Mean precipitation (m/y)

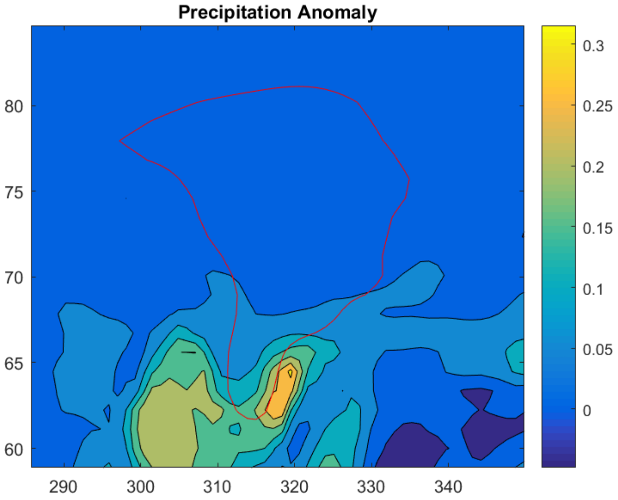
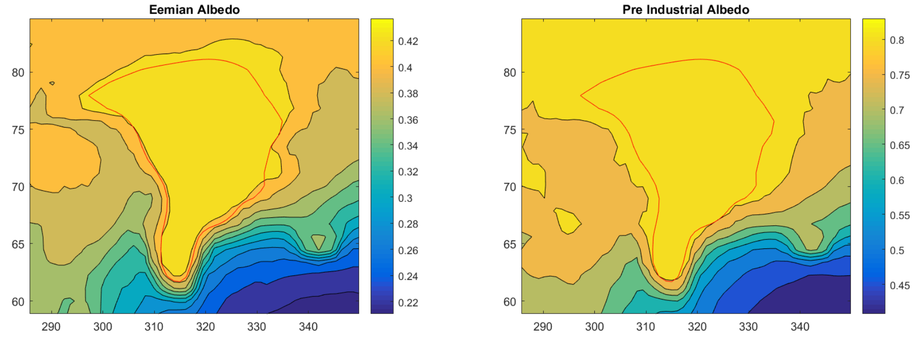


Figure 8: Precipitation anomaly (m/year) between Eemian and Pictrl.

Both the mean precipitation for the Eemian and pictrl, Figure 7a and 7b, have an area in the southeast where most of the precipitation is concentrated. This is an effect of the Icelandic low, which generates great amounts of precipitation. The anomaly between the two climate states, Figure 8, is largest in the southern parts around the Icelandic low. The northern parts are almost not affected by the changing climate, however, the warmer Eemian climate generates much more precipitation in the south.

Precipitation plays a huge role in the SMB being the only adding factor to the equation. The greater amounts of precipitation falling during the Eemian prohibits parts of the mass loss occurring due to melting. Moreover, snowfall affects the surface albedo. Snow is very bright and has a high albedo of 75-98%, with a common value of 85% [7]. However, the snow albedo decreases over time by snow processes [7].



(a) Eemian (b) Pictrl

Figure 9: Mean albedo

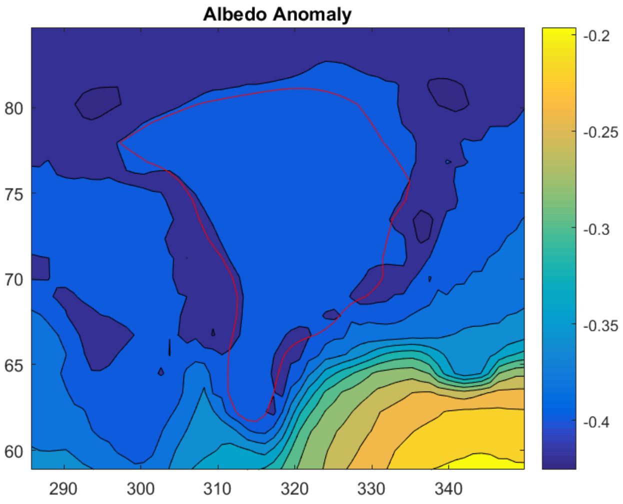


Figure 10: Difference in albedo between Eemian and Pictrl.

Another important factor for melting is the albedo. As mentioned earlier, the EC-Earth model uses the albedo for the snow and ice while computing the expected melting. A low albedo indicates a higher susceptibility to incoming radiation which would amplify the melting, whereas a high albedo would have the opposite effect.

In Figure 9a and 9b the albedo for the Eemian and pictrl is presented, and in Figure 10 one can see the difference between the two. The albedo for Greenland was much lower during the Eemian than in the present day climate. This result then indicates that less incoming radiation was reflected and therefore that the melting was amplified during the Eemian. The present day albedo is much higher, with an average value 0.8 aver Greenland, and contributes to sustaining the GIS.

4.2 PDD Factors

In Table 1 the mean PDD factors for Greenland during the Eemian and the pictrl is presented together with the mean temperature for these periods. The mean temperature of the Eemian is 2.5 degrees warmer than the pictrl which reflects the reality, and as one can see the PDD factors for both snow K_s and ice K_i generates a higher value during the Eemian. This indicates that the PDD factor, as expected, does change with the climate conditions. However, the K_i values are lower than expected whereas the K_s are a bit larger than expected. Previous studies has generated PDD values between 5-11 mm/day/K [11]. The low K_i values can be a result of the cold bias of the EC-Earth model. The bias generates too cold 2m-temperatures in the tropics and over land in the northern hemisphere during summer months [10].

Table 1: Mean temperature (K) and PDD factor for snow k_s and ice k_i (mm/day/K)

Climate state	Ki	Ks	Temperature
Eemian	0.7 ± 11.7	15.7 ± 1379.5	258.6
Pictrl	0.1 ± 1.2	14.5 ± 959.2	256.1

The low K_i mean result can be explained by observing Figure 11 and 13, where K_i, for the Eemian, is plotted against time in southwest respectively northwest Greenland. In both plots the PDD factors equal zero after approximately three years. This result is disturbing since it would indicate that the melting has stopped at this point. However, if plotting the ablation rate obtained from the EC-Earth model, at the exact same location, it gives indications for melting. The temperature for this location also generates temperatures above freezing which according to the PDD model would cause melting. Thereby, these two plots indicate that something is wrong, either with my Matlab code or with the input data constructed in EC-Earth. Regretfully there was not enough time to solve this problem.

Furthermore, this error results in a lower K_i mean, due to the large amount of K_i values that equal zero. Eliminating these values, by computing the mean and std just for the first three years, generates much more reasonable PDD factors 2.

Figure 12 and 14 only plots the first three years of the period. Here we can see melting at both locations and that the melting is only occurring during the summer months.

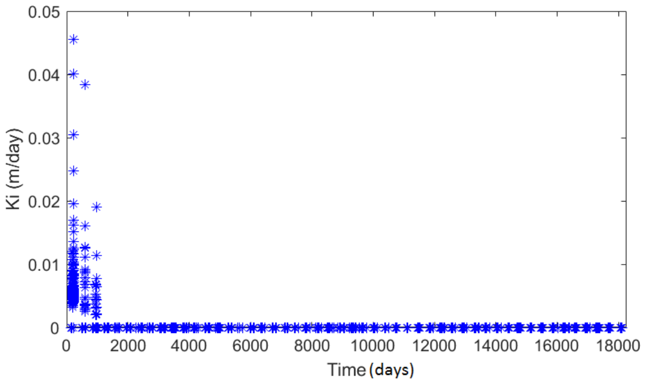


Figure 11: The PDD factor for ice K_i in southwest Greenland during the Eemian.

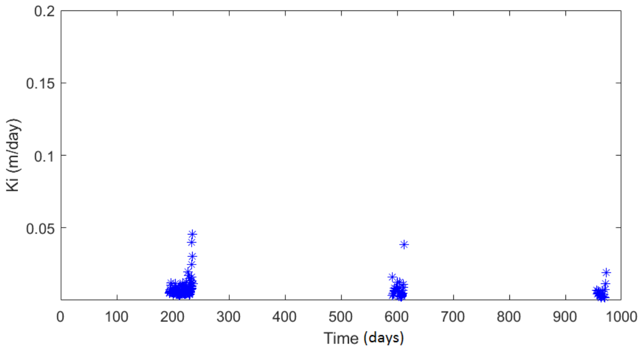


Figure 12: Detailed PDD factor plot for ice K_i in southwest Greenland during the Eemian.

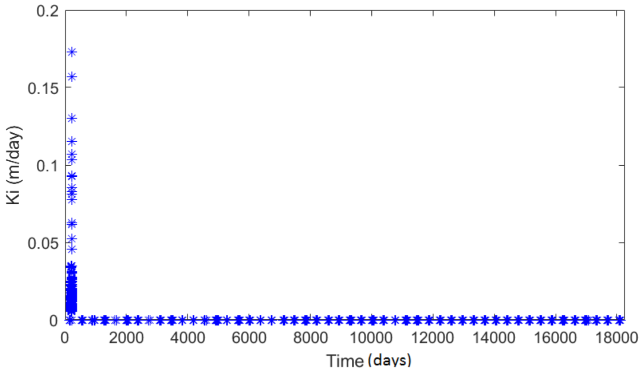


Figure 13: The PDD factor for ice K_i in northwest Greenland during the Eemian.

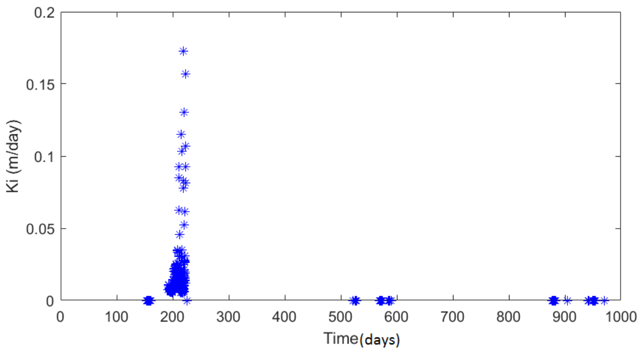


Figure 14: Detailed PDD factor plot PDD factor for ice K_i in northwest Greenland during the Eemian.

The standard deviation (std), which determines the variance of a data set, for K_i is within reason for both the Eemian and pictrl. The rather high std is an effect of the mixture of different regions with very variating climate conditions that generates a high variance. For example, regions in central Greenland never exceeds freezing level and therefore never experience any melting, while the capital in western Greenland, Nuuk, has a summer temperature of 22C. These two extremes generate PDD factors that differ vastly from the mean, leading to a large std. These effects can be observed in Figure 11 and 13, by noting the difference in the y-axis.

The std for the Eemian is fairly larger than the pictrl, but this was expected. A high std would indicate that there is more spreading within the data set. The Eemian experiences more melt in general than the pictrl, and should also have larger seasonal variations. During the summer months, June, July and August, Greenland experiences higher temperatures and more melting, and as winter approaches the melting rate decays. Therefore the Eemian has a higher variance which thereby leads to a higher std. Hence, it is indicated that one should perform a more regional PDD analyses.

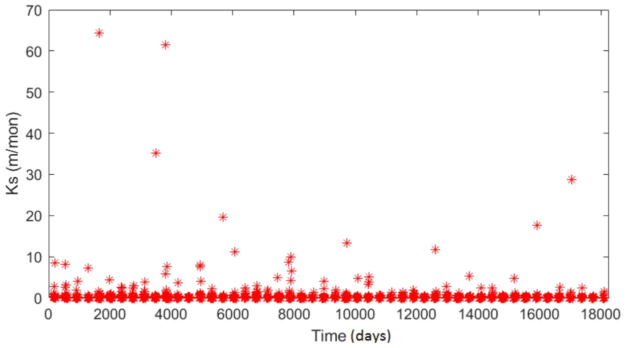


Figure 15: The PDD factor for snow K_s in southeast Greenland during the Eemian.

Furthermore, the std for K_s is gigantic and shocking at first approach. The same concept as for the std of K_i yields here as well. However, this result only enhances the argument for computing separate PDD factors for different climate conditions. In Figure 15 K_s is plotted for southeast Greenland. This figure demonstrates another reason for the large std, a few data points generate extreme PDD factors. The highest data point produces a value around 65 m/day/K. A PDD factor this large is of course an error value, in fact all the scattered values generates a PDD factor above 1 m/day/K and can therefore be seen as errors. All these deviations contribute to the std.

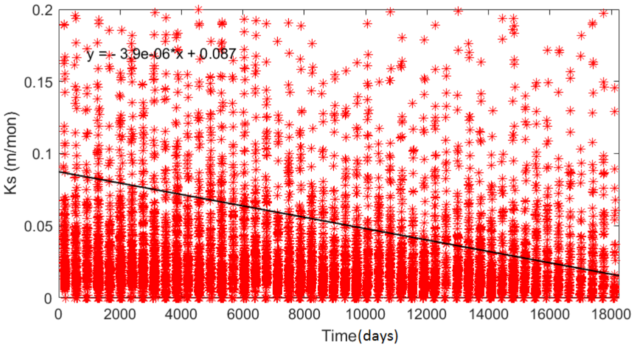


Figure 16: The PDD factor for snow K_s in southeast Greenland during the Eemian.

Table 2: Mean temperature (K) and PDD factor for snow k_s and ice k_i (mm/day/K) for the first three years of the data set.

Climate state	Ki	Ks	Temperature
Eemian	6.1 ± 26.6	24.2 ± 2059.0	258.9
Pictrl	1.8 ± 4.7	13.6 ± 545.7	255.3

Table 2 presents the mean PDD factors for the first three years of the data set. Now the means for ice are significantly higher and resemble results from previous studies. This result is much more desirable, nevertheless, three years is not enough time to base an analysis on, especially not when considering that an interglacial period extends over 15 000 years. K_s is somewhat higher, however, this is not unexpected since snowmelt was occurring during the entire data set. This can be observed in Figure 16, which once again is a plot from southeast Greenland during the Eemian. However, in this plot the data that exceeds 0.2 m/day/K is excluded from the plot. In this way we can observe the negative tilt of the linear regression, and perceive that the value of K_s is decreasing with time. This indicates that the PDD factor is a significantly varying factor and should not be used as a constant. Also, the trend seen in this plot argues that their is a problem with the input data or the forcing data. Moreover, the PDD factors for the Eemian are still higher than the ones for the pictrl, stating, yet again, that PDD factors are dependent on the climate conditions.

PDD factor plots where only produced for the Eemain, since almost no melting was experienced for the pictrl.

5 Conclusion and Outlook

In the present work of this thesis the temporal variability of PDD factors was analyzed in an attempt to improve the use of PDD factors. This was done by preforming SMB simulations and computing PDD factors for the Eemian and the present climate in Matlab.

K_i plots revealed that the code only produced melting for the three first years of fifty. Due to shortage of time and difficulty locating the source of this problem, the error was never corrected. Instead means where calculated for both the entire data sets and for the first three years only. However, this error did naturally compromise the results.

Nevertheless, both mean values state that the PDD factor is greater during the Eemian than the present day. The high generated PDD factor for the Eemian is an effect of the warmer climate, which then causes more melting. In both cases the PDD factor for snow is very much larger than the PDD factor for ice. This tells us that snow is easier to melt than ice.

The std can be perceived as large, this is most likely due to the large observation area. The large std for K_i can without hesitance be explained by both the variance of PDD factors between separate locations on Greenland and the uncertainty of using PDD factors as constants. However, the enormous std for K_s is most certainly due to the large error values generated in many points of the data set.

Based on the result one can conclude that there is a temporal variability of PDD factors because of different climate conditions. In future studies, it would be interesting to not only look at the temporal variability of PPD factors, but also more carefully analyze the regional variability.

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Appendix

```
clear all
close all

InputFile    = 'Output_SMB_2089_2139.pictrl.nc4';
ACC0         = ncread(InputFile,'acc'   ); % Accumulation rate m/s
ABL0         = ncread(InputFile,'amelt'); % Melting rate m/s
temp_org0    = ncread('ec31pictrl.GrIS_ATMOS_Month00.2089_2139.dm.nc4',
                      'Temp');
LSM = ncread('ECPI_VAR172_Landfrac_GrISbox.nc','LSM');

temp = temp_org0-273.15;
mask = (temp>=0);

nothing      = NaN;
length_ipos  = 58;
length_jpos  = 24;
time_length  = 18261;
time         = 1:time_length;


K_i_all = zeros(length_ipos,length_jpos,time_length);
K_s_all = zeros(length_ipos,length_jpos,time_length);

DeltaTime = 86400; % Time step between records in (sec) --- m/day
k_s_fallback = 0.005/(86400); % 8mm/day/K

for ipos=1:length_ipos
    disp(['IPOS=',int2str(ipos),' of ',int2str(length_ipos)])
    for jpos=1:length_jpos

        temp_pkt = squeeze(temp(ipos,jpos,:));
        mask_pkt = squeeze(mask(ipos,jpos,:));

        PDDpkt = mask_pkt.*temp_pkt;

        excess     = zeros([1, time_length]);
        snow_melt  = zeros([1, time_length]);
        ice_melt   = zeros([1, time_length]);
```

```
for i=1:time_length
    if(i==1)
        excess(i) = ACC0(ipos,jpos,i) - ABL0(ipos,jpos,i);
    else
        excess(i) = ACC0(ipos,jpos,i) - ABL0(ipos,jpos,i) + excess(i-1);
    end
    excess(i) = max(excess(i),0);

    if ( any(isinf(excess(i))) )
        keyboard
    end
    if (excess(i)<=0)
        % No snow => Only ice melting
        ice_melt(i) = ABL0(ipos,jpos,i);
    else
        snow_melt(i) = min(ABL0(ipos,jpos,i),excess(i));
        ice_melt (i) = max(ABL0(ipos,jpos,i)-excess(i) , 0);
    end

end
excess    = excess    .* DeltaTime;
snow_melt = snow_melt .* DeltaTime;
ice_melt  = ice_melt  .* DeltaTime;

k_s = repmat(nothing, [1, time_length]);
k_i = repmat(nothing, [1, time_length]);

excess_min = min(excess);
excess_max = max(excess);

for i=1:time_length
     if(excess_min>0)
          % Snow melt only
              if (PDDpkt(i) > eps)
                    k_s(i) = snow_melt(i)./PDDpkt(i);
              else
                    k_s(i) = nothing;
              end

     elseif(excess_max<=0)
          % Ice melt only
               if (PDDpkt(i) > eps)
                    k_i(i) = ice_melt(i)/PDDpkt(i);
```

```
                    else
                        k_i(i) = nothing;
                    end

                elseif(excess_max>00 && excess_min<=0)
                    %Snow and Ice melt
                    if (i==1)
                        k_s(i) = k_s_fallback;
                    else
                        k_s(i) = k_s(i-1);
                    end
                    divisor = ( PDDpkt(i)-(snow_melt(i)./k_s(i))  );
                    if (divisor > eps)
                        k_i(i) = ice_melt(i)./divisor;
                    else
                        k_i(i) = nothing;
                    end
                end
            end

            k_i(isinf(k_i)) = NaN;
            k_s(isinf(k_s)) = NaN;
            k_i_std         = std(k_i,'omitnan');
            k_s_std         = std(k_s,'omitnan');

        % PDDfactors for all points
            K_i_all(ipos,jpos,:) = k_i;
            K_s_all(ipos,jpos,:) = k_s;

            K_i_allstd(ipos,jpos) = k_i_std;
            K_s_allstd(ipos,jpos) = k_s_std;

        end
    end

K_i_all = cleanocean3d(K_i_all,LSM);
K_s_all = cleanocean3d(K_s_all,LSM);
```

References

[1] Present day greenland, 2011.

[2] CD Ahrens. *Meteorology Today: An Introduction to Weather and the Environment.* Belmont, USA, 2008.

[3] Douglas Benn and David J A Evans. *Glaciers and Glaciation.* Routledge, .., 2014.

[4] André Berger and Marie-France Loutre. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, 10(4):297–317, 1991.

[5] Roger J Braithwaite. Positive degree-day factors for ablation on the greenland ice sheet studied by energy-balance modelling. *Journal of Glaciology*, 41(137):153–160, 1995.

[6] National Climate Data Center. Glacial-interglacial cycles, 2008.

[7] K.M. Cuffey and W.S.B. Paterson. *The Physics of Glaciers.* Elsevier Inc., Oxford, UK, 4th editio edition, 2010.

[8] Andrea Dutton and Kurt Lambeck. Ice volume and sea level during the last interglacial. *Science*, 337(6091):216–219, 2012.

[9] Max Planck Institute for Meteorology. Climate data operators, 2016.

[10] W Hazeleger, X Wang, C Severijns, S Ştefănescu, R Bintanja, A Sterl, Klaus Wyser, T Semmler, S Yang, B Van den Hurk, et al. Ec-earth v2. 2: description and validation of a new seamless earth system prediction model. *Climate Dynamics*, 39(11):2611–2629, 2012.

[11] Regine Hock. Temperature index melt modelling in mountain areas. *Journal of Hydrology*, 282(1):104–115, 2003.

[12] RTWL Hurkmans, JL Bamber, CH Davis, IR Joughin, KS Khvorostovsky, BS Smith, and N Schoen. Time-evolving mass loss of the greenland ice sheet from satellite altimetry. *The Cryosphere*, 8(5):1725–1740, 2014.

[13] Philippe Huybrechts and Heinrich Miller. Flow and balance of the polar ice sheets. *in Hantel, M.(ed.): Observed global climate, Landolt-Börnstein New Series (Numerical data and functional relationships in Science and Technology), V/6, Springer Verlag (Berlin, etc.)*, 13:1–13, 2005.

[14] Kenji Kawamura, Frédéric Parrenin, Lorraine Lisiecki, Ryu Uemura, Françoise Vimeux, Jeffrey P Severinghaus, Manuel A Hutterli, Takakiyo Nakazawa, Shuji Aoki, Jean Jouzel, et al. Northern hemisphere forcing of climatic cycles in antarctica over the past 360,000 years. *Nature*, 448(7156):912–916, 2007.

[15] Ruth Mottram. Overflademassbalnce af gronlands inlandsis, 2014.

[16] Atsumu Ohmura. Physical basis for the temperature-based melt-index method. *Journal of Applied Meteorology*, 40(4):753–761, 2001.

[17] George Ohring. *Climate Change in North America*. Springer International Publishing Switzerland, London, 2014.

[18] Jonathan T Overpeck, Bette L Otto-Bliesner, Gifford H Miller, Daniel R Muhs, Richard B Alley, and Jeffrey T Kiehl. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science*, 311(5768):1747–1750, 2006.

[19] Niels Reeh. Parameterization of melt rate and surface temperature on the greenland ice sheet. *Polarforschung*, 59(3):113–128, 1989.

[20] A Robinson, R Calov, and A Ganopolski. Greenland ice sheet model parameters constrained using simulations of the eemian interglacial. *Climate of the Past*, 7(2):381–396, 2011.

[21] Christian Rodehacke. personal communication, 2016.

[22] Andrew Shepherd, Erik R Ivins, A Geruo, Valentina R Barletta, Mike J Bentley, Srinivas Bettadpur, Kate H Briggs, David H Bromwich, René Forsberg, Natalia Galin, et al. A reconciled estimate of ice-sheet mass balance. *Science*, 338(6111):1183–1189, 2012.

[23] National Snow and Ice Data Center. Quick facts on ice sheets, 2016.

[24] Susan Solomon. *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*, volume 4. Cambridge University Press, 2007.

[25] Willem Jan Van de Berg, Michiel van den Broeke, Janneke Ettema, Erik van Meijgaard, and Frank Kaspar. Significant contribution of insolation to eemian melting of the greenland ice sheet. *Nature Geoscience*, 4(10):679–683, 2011.

[26] Michiel van den Broeke, Carlijn Bus, Janneke Ettema, and Paul Smeets. Temperature thresholds for degree-day modelling of greenland ice sheet melt rates. *Geophysical Research Letters*, 37(18), 2010.

[27] H Jay Zwally, LI Jun, Anita C Brenner, Matthew Beckley, Helen G Cornejo, John DiMARZIO, Mario B Giovinetto, Thomas A Neumann, John Robbins, Jack L Saba, et al. Greenland ice sheet mass balance: distribution of increased mass loss with climate warming; 2003–07 versus 1992–2002. *Journal of Glaciology*, 57(201):88–102, 2011.