Ice and Climate Project 2

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1 Introduction

With rising global mean surface temperatures due to greenhouse gas emissions, the ice sheets of Antartica and Greenland are expected to shrink. To improve melt projections for the scientific community and provide more robust data for sea level change models, we look at the Surface Energy Balance (SEB) over an ice sheet in west Greenland. Here, we want to investigate how the SEB, near surface climate and melt energy changes if the atmospheric temperature increases with 1 K. For that, we are using the data from a SEB model that is optimized to align its output with observations. In this project, we will answer the research question for one particular point of the ice sheet, located just above the ELA. This research question may look trivial initially, but when increasing the air temperature the energy fluxes and other parameters like the surface temperature are perturbed, too. Therefore, to answer this research question, we first will explain how the energy fluxes will change if we perturb the surface temperature.

2 Data and Methods

2.1 Data

The data that will be used in this project is made available from the Automated Weather Station (AWS) located in west Greenland. In particular, the AWS were positioned along a K-transect at four different locations: S5, S6, S9 and S10. In this project, the data from Station S10, an AWS at 1850 m above sea level in the lower accumulation area located just above the ELA, is used. The data is processed with a surface energy balance model to interpret and align the observations and rectify errors. The data contains hourly measurements for numerous variables, most notably short-wave, long-wave, sensible and latent heat, ground and melt heat fluxes as well as temperature, wind and humidity measurements. (Munneke et al., 2018)

The data is being used to answer our research question. Throughout the paper, data that comes directly from the SEB output is labeled with the subscript SEB. The available data spans the time period from beginning of 2009 until September 2019. There is, however, a discontinuity in the period of 27/10/2018-09/04/2019, where no data is available.

2.2 Surface Energy Balance

To assess changes in the near-surface climate we look at the surface from an energetics perspective. Adding all energy fluxes gives an idea of the net energy flux on the surface which is then used for melting

$$M_{\text{surf}} = SW_{\text{net}} + LW_{\text{down}} + LW_{\text{up}} + SHF + LHF + Gs. \tag{1}$$

Here, SW_{net} is the net short-wave flux, $LW_{\text{down}} + LW_{\text{up}}$ is the net long-wave radiation flux, SHF and LHF are the sensible and latent heat flux and Gs is the heat flux from the ground. Data for all of these fluxes is comprised in the output of the SEB model. When the atmospheric temperature changes, some of theses energy fluxes must be altered, too. These changes are discussed in the following subsection.

2.3 Energy Flux Adjustments

In this section all energy fluxes relative to the surface that are perturbed by the increased air temperature are reviewed. This includes the long-wave radiation, which can be divided into the long-wave down (LW_{down}) and long-wave up (LW_{up}), the sensible heat flux (SHF), the latent heat flux (LHF) and ultimately melt. Other fluxes including shortwave radiation (SW_{net}) and ground heat flux Gs are not assumed to change in first order approximation as the incoming radiation from the sun and the heat from the earth is independent of atmospheric temperature and the albedo is assumed to stay constant.

2.3.1 Downward Long-wave Radiation $\mathrm{LW_{down}}$

A black body, an object with perfect emissivity, emits long-wave radiation proportional to its cubed temperature T^4, following the Stefan-Boltzmann law

$$\mathrm{LW} = \sigma T^4, \tag{2}$$

with σ the Stefan-Boltzmann constant. The atmosphere, however, is not a perfect emitter and thus its long-wave radiation must be adjusted to

$$LW_{\mathrm{down}} = \epsilon \sigma T_{\mathrm{2m}}^4, \tag{3}$$

Here, T_{2m} is the air temperature at 2m heigh and we introduced the emissivity ϵ. It can be computed using the output of the SEB model at every time step according to

$$\epsilon = \frac{LW_{\mathrm{down}}^{SEB}}{\sigma (T_{\mathrm{2m}}^{SEB})^4}. \tag{4}$$

2.3.2 Upward Long-wave Radiation $\mathrm{LW_{up}}$

Similarly to $\mathrm{LW_{down}}$, $\mathrm{LW_{up}}$ is highly dependent on temperature. Here, however, as we are looking at the energy emission of the ground, it is the surface temperature T_{surf} that governs the energy flux and we assume perfect emissivity

$$\mathrm{LW_{up}} = -\sigma T_{\mathrm{surf}}. \tag{5}$$

While the increased air temperature certainly influences the surface temperature, it is unclear to what extend T_{surf} needs to be adjusted. Consequently, to understand this and other energy fluxes, it is crucial to find the adjusted surface temperature $T_{\mathrm{surf}}^{\mathrm{adj}}$. A good place to start is to estimate the surface temperature $T_{\mathrm{surf}}^{\mathrm{est}}$ with the surface temperature outpout from the SEB $T_{\mathrm{surf}}^{\mathrm{SEB}}$. This is reasonable as the perturbation is expected to be small, and consequently we can write the upward long-wave radiation as a first order Taylor expansion of Equation (5)

$$\mathrm{LW_{up}} = -\sigma (T_{\mathrm{surf}}^{\mathrm{est}})^4 - 4\sigma T_{\mathrm{surf}}^{\mathrm{est}} (T_{\mathrm{surf}}^{\mathrm{adj}} - T_{\mathrm{surf}}^{\mathrm{est}})^3. \tag{6}$$

The linear form of this equation with respect to $T_{\mathrm{surf}}^{\mathrm{adj}}$ will prove to be useful later.

2.3.3 Sensible Heat Flux (SHF)

The sensible heat flux is typically modelled as

$$\mathrm{SHF} = c_s U_{\mathrm{10m}} (T_{\mathrm{2m}} - T_{\mathrm{surf}}). \tag{7}$$

While U_{10m} can be taken directly from SEB output, c_s must be found individually for each time step. This is done by

$$c_s = \frac{SHF^{\mathrm{SEB}}}{U_{\mathrm{10m}} (T_{\mathrm{2m}}^{\mathrm{SEB}} - T_{\mathrm{surf}}^{\mathrm{SEB}})} \tag{8}$$

While the factors discussed above are assumed to stay constant when the atmospheric temperature is increased by $\Delta T = 1\,°\mathrm{C}$, both the air temperature at 2m height T_{2m} and the surface temperature T_{surf} are changing. The temperature at 2m height is assumed to change in concert with the atmosphere by ΔT. Consequently, in first order, the SHF changes linearly with this changing temperatures with

$$\mathrm{SHF} = \mathrm{SHF}^{\mathrm{SEB}} + c_s U_{\mathrm{10m}} (\Delta T - (T_{\mathrm{surf}}^{\mathrm{adj}} - T_{\mathrm{surf}}^{\mathrm{SEB}}), \tag{9}$$

which again is linear in $T_{\mathrm{surf}}^{\mathrm{adj}}$.

2.3.4 Latent Heat Flux (LHF)

The latent heat flux depends on the specific humidity difference between the ground and the atmosphere at 2 m. With the relative humidity being one on the surface and $RH_{2\,\mathrm{m}}$ at 2m, the latent heat flux becomes

$$LHF = c_l U_{10\,\mathrm{m}} \left(RH_{2\,\mathrm{m}} Q_{\mathrm{sat,2m}} - Q_{\mathrm{sat,surf}} \right). \tag{10}$$

The saturated specific humidity is strongly temperature dependent and is given by

$$Q_{\mathrm{sat}} = \frac{6.1121 \cdot m_v}{P \cdot m_{\mathrm{air}}} \exp\left[\frac{c_1 T}{T + c_2}\right] \text{ with } \begin{cases} T \leq 0: & c_1 = 22,587 \quad c_2 = 273.86\,^\circ\mathrm{C} \\ T \geq 0: & c_1 = 17,502 \quad c_2 = 240.97\,^\circ\mathrm{C}, \end{cases} \tag{11}$$

and the respective temperatures at 2m and on the surface can be plugged in.

Thus, the change of atmosphere temperature changes the saturated specific humidity and with that the LHF. The factor c_l is assumed to be proportional to c_s. To find the proportionality constant α, a linear function is fitted using `numpy.polyfit`.

2.4 Updating the Surface Energy Balance

After the different energy fluxes have been adjusted as a response to the increased atmospheric temperature, the updated SEB reads as follows

$$M_{\mathrm{surf}}^{\mathrm{adj}} = SW_{\mathrm{net}}^{\mathrm{SEB}} + LW_{\mathrm{down}}^{\mathrm{adj}}(T_{\mathrm{atm}}) - \sigma (T_{\mathrm{surf}}^{\mathrm{est}})^4 - 4\sigma (T_{\mathrm{surf}}^{\mathrm{est}})^3 (T_{\mathrm{surf}}^{\mathrm{adj}} - T_{\mathrm{surf}}^{\mathrm{est}}) + SHF^{\mathrm{SEB}} + c_s U_{10\mathrm{m}} (\Delta T - (T_{\mathrm{surf}}^{\mathrm{adj}} - T_{\mathrm{surf}}^{\mathrm{SEB}})) + LHF(T_{\mathrm{atm}}) + Gs^{\mathrm{SEB}}. \tag{12}$$

Here, some terms are dependent on the adjusted surface temperature which is not known. Therefore, we need to estimate how the surface temperature responds to the increased atmospheric temperature. This can be done by searching for a $T_{\mathrm{surf}}^{\mathrm{adj}}$ for which the SEB Eq. (12) is closed. As $T_{\mathrm{surf}}^{\mathrm{adj}}$ is linear in Eq. (12), the adjusted surface temperature can be found by

$$T_{\mathrm{surf}}^{\mathrm{adj}} = \frac{c^{\mathrm{fixed}}}{c^{\mathrm{adj}}}, \tag{13}$$

with

$$\begin{aligned} c^{\mathrm{fixed}} &= SW_{\mathrm{net}} + LW_{\mathrm{down}}^{\mathrm{adj}}(T_{\mathrm{atm}}) + 3\sigma (T_{\mathrm{surf}}^{\mathrm{est}})^4 + SHF^{\mathrm{SEB}} + c_s U_{10\mathrm{m}} (\Delta T + T_{\mathrm{surf}}^{\mathrm{SEB}}) + LHF(T_{\mathrm{atm}}) + Gs. \\ c^{\mathrm{adj}} &= 4\sigma (T_{\mathrm{surf}}^{\mathrm{est}})^3 + c_s U_{10\mathrm{m}}, \end{aligned}$$

assuming that the melt $M_{\mathrm{surf}}^{\mathrm{adj}}$ is zero initially. A good initial estimate for the surface temperature would be the observed temperature: $T_{\mathrm{surf}}^{\mathrm{est}} = T_{\mathrm{surf}}^{\mathrm{SEB}}$. The resulting $T_{\mathrm{surf}}^{\mathrm{adj}}$ induces melt if $T_{\mathrm{surf}}^{\mathrm{adj}} > 273.16\,\mathrm{K}$. The magnitude of the melt can then be found using Eq. (12) and setting $T_{\mathrm{surf}}^{\mathrm{adj}} = 273.16\,\mathrm{K}$. If $T_{\mathrm{surf}}^{\mathrm{adj}}$ stays below freezing, Eq. (13) can be solved again but this time setting the recently found adjusted surface temperature as $T_{\mathrm{surf}}^{\mathrm{est,\,new}} = T_{\mathrm{surf}}^{\mathrm{adj}}$. In our case, this process is repeated 10 times and on every instance it is checked whether melt occurs. If there is no melt after the last iteration, Eq. (12) is used a last time to get the melt. This time, however if $T_{\mathrm{surf}}^{\mathrm{adj}}$ is still below freezing, there will be a negative melt which represents the residual. If the residual is not zero, the SEB is not entirely closed. Ideally, the residual should be negligible compared to the other energy flux constituents. In the next section, the result from the adjusted model are presented.

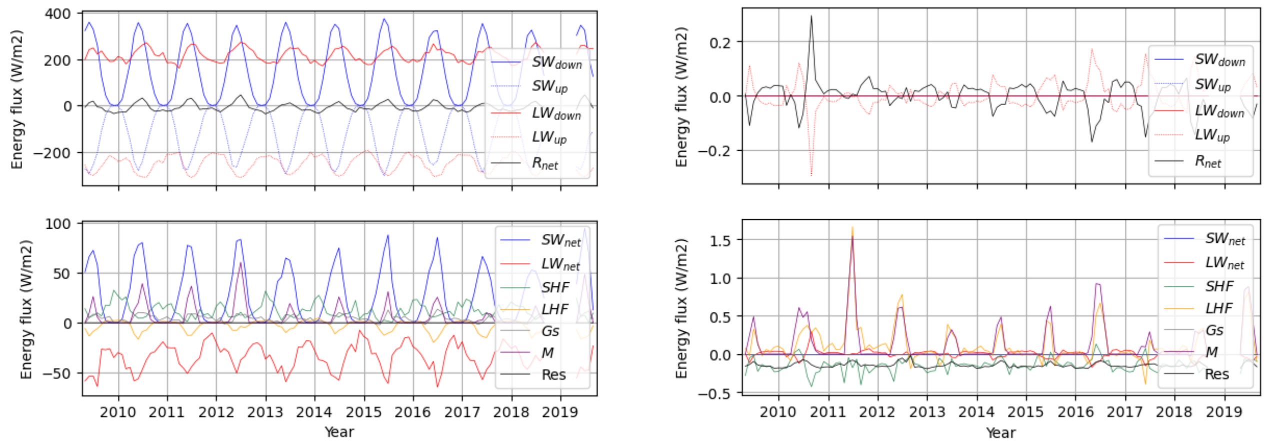
3 Results

To answer our research question, we modify the air temperatures to infer the adjusted energy fluxes with the methods described in the previous section. Before we use our model to find surface climate changes after an increased air temperature, we compare our model with the data from the SEB model output.

3.1 Justifying our model: The $dT = 0\,\mathrm{K}$ case

To evaluate the the validity of our computational model, we initially set $dT = 0\,\mathrm{K}$. This allows us to compare the flux values computed by our model with those derived from the original SEB output.

If our computational model follows the exact equations of the original model, we would expect no difference between the two runs. However, since the equations we use still rely on some approximations and the procedures explained below do not follow Munneke et al., 2018, we do expect to see some differences. In Figure 1(a), the monthly mean fluxes from our model are plotted.



(a) The monthly mean output fluxes from our computational model for $dT = 0K$.

(b) The computed fluxes from (a) subtracted from the fluxes as presented in the original data.

Figure 1: Monthly mean fluxes for $dT = 0K$ case. Note that $R_{\text{net}} = LW_{\text{net}} + SW_{\text{net}}$ and Res is the residue needed to close our SEB model.

From Figure 1(b) we can infer the differences between our model and the SEB data. It is evident that our model computes the different energy fluxes quite good with differences mostly far below $1\,\mathrm{W\,m^{-2}}$. Evidently, our model is good enough to reproduce the SEB output with a satisfying degree of accuracy. Now, we can use our model to simulate a sudden temperature increase in the atmosphere.

3.2 Increasing the surface temperature: $dT = 1$ K case

3.2.1 Energy Fluxes

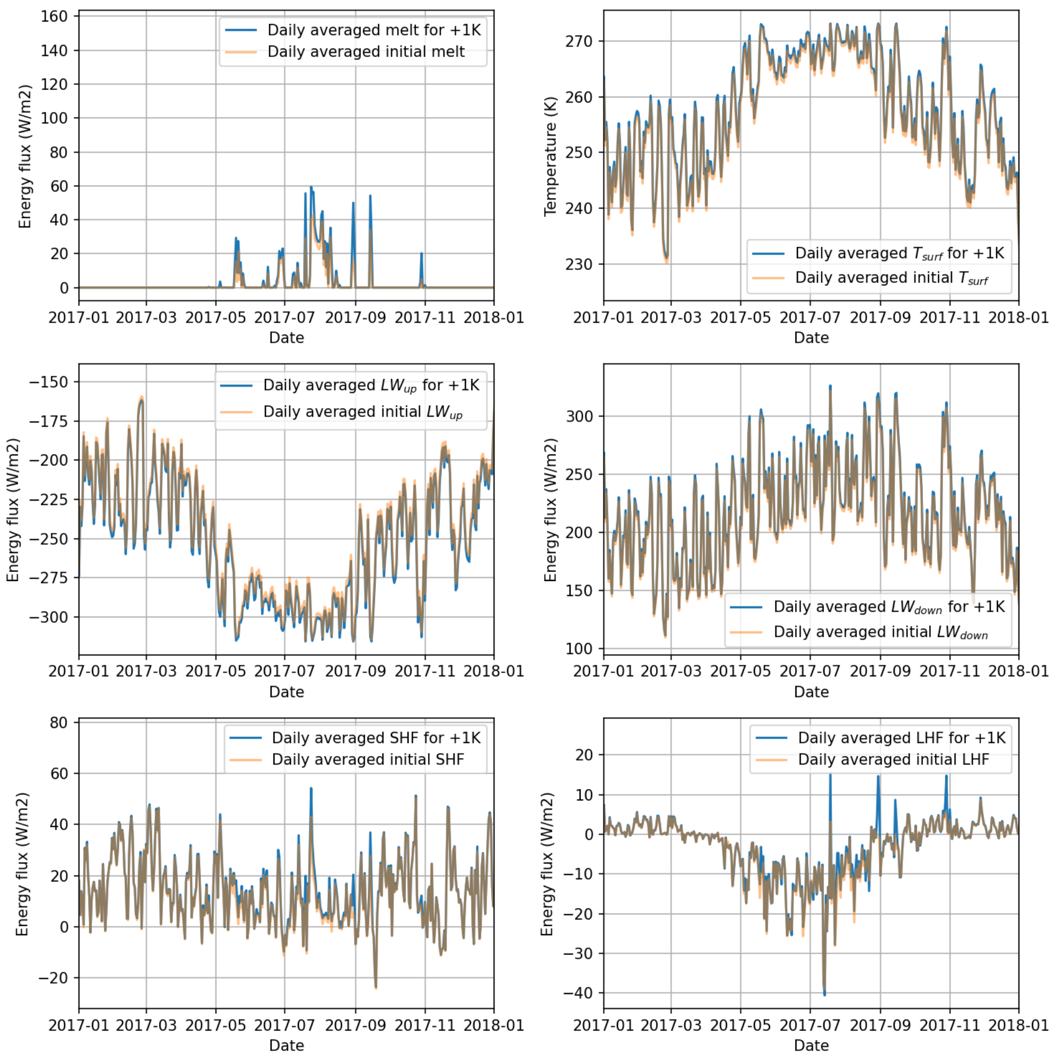


Figure 2: Daily averaged energy fluxes and surface temperature in 2017 for $dT = 1$ K and normal case. Note that the y-axis differ per plot.

Figure 2 shows the daily average energy fluxes and surface temperature for the original SEB model output (blue) and our model for increased atmospheric temperature (orange) for the year 2017 as an example of (sub)seasonal trends. While there is significant daily variability due to different weather conditions, it can be seen that if the atmospheric temperature increases, the melt increases, the Surface temperature increases, the LW_{up} decreases, LW_{down} increases, the SHF increases and the LHF also increases. All these effects are logical and expected to happen if the atmospheric temperature increases with 1 K. If the atmospheric temperature will increase by 1 K it comes as no surprise that the surface temperature will also increase. The relation between the two metrics might not be linear, but it is straightforward that the increasing of one results in an increase of the other one. Furthermore, this increased surface temperature logically also will increase the melt. A higher average surface temperature will result in a higher melt.

The observation of a more negative value for upward longwave radiation in the case of a +1 K temperature increase is consistent with our expectations. The increase in atmospheric temperature by +1 K implies an enhancement in the downward longwave radiation. An increase in LW_{down} would naturally lead to a greater surface temperature that then itself increases the upward long-wave flux. Consequently, this results in an amplified upward LW_{up}, which is manifested as a more negative value.

Like explained in the Methods, the LW_{down} is calculated with the atmospheric temperature. Therefore, if we increase the atmospheric temperature an increase in LW_{down} is the obvious effect. Therefore the increase in LW_{down} is the direct effect of increasing the atmospheric temperature.

Also, we can see in Figure 2 that both the SHF and the LHF increase with an increased surface temperature. With increased SHF, there is a greater energy flux from the atmosphere to the surface. This is also in line with Eq. (9), since the SHF changes linearly with dT and since the surface is warming somewhat less than the atmosphere, as will become clear later.

The LHF increases, but is overall still a net negative flux. The fact that the LHF increases, means that there is less energy being transferred from the surface to the atmosphere. Thus, there is less cooling of the surface due to latent heat in the 1 K case. This can be seen in Eq. (11), since the difference in saturated specific humidity between $Q_{\mathrm{sat,2m}}$ and $Q_{\mathrm{sat,surf}}$ increases when the atmosphere warms more than the surface. This increase in saturated specific humidity is most present during the summer months, when the temperatures are warmer. This increase in saturated specific humidity then directly translates to an increase in the LHF.

To closer study when the change in flux take place during the year, the daily averaged for the initial situation has been subtracted from the +1 K case, to see when these changes are most present. This can be found in Figure 3. The melt and surface temperature change will be discussed in the following section.

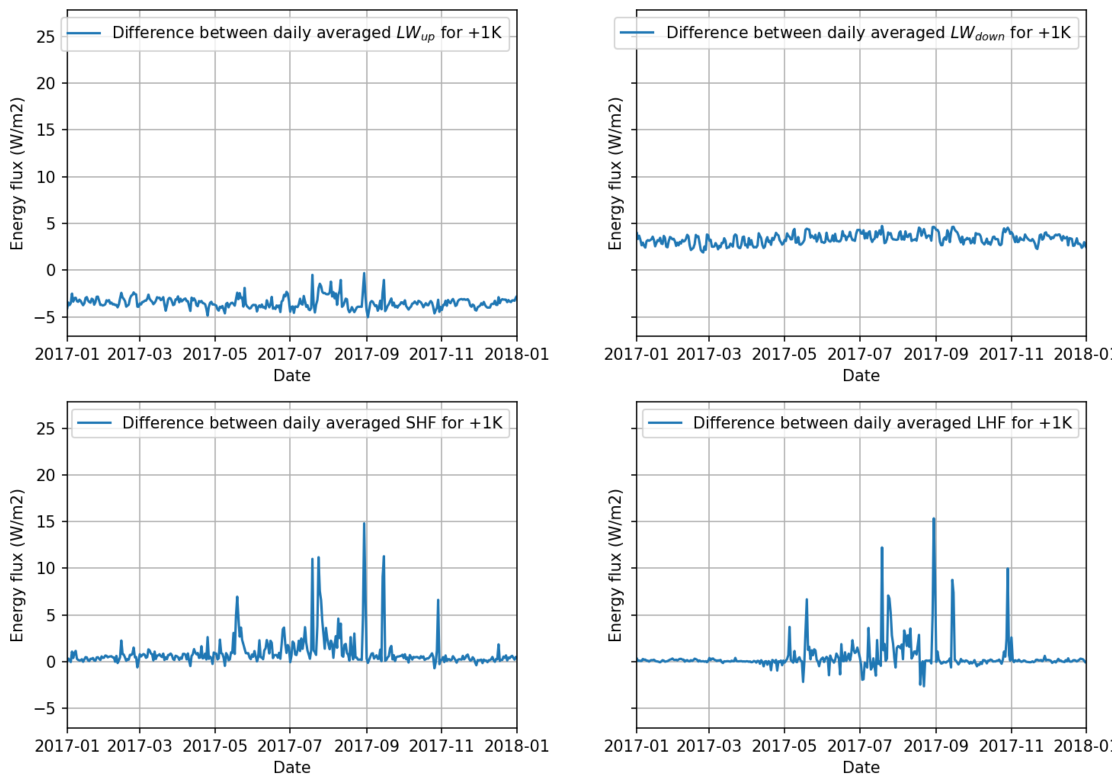


Figure 3: Daily averaged flux differences in 2017 between initial values and $dT = 1$ case for LW_{up}, LW_{down}, SHF and LHF. Note that the Y-axis is the same, thus effectively showing which flux is changing the most.

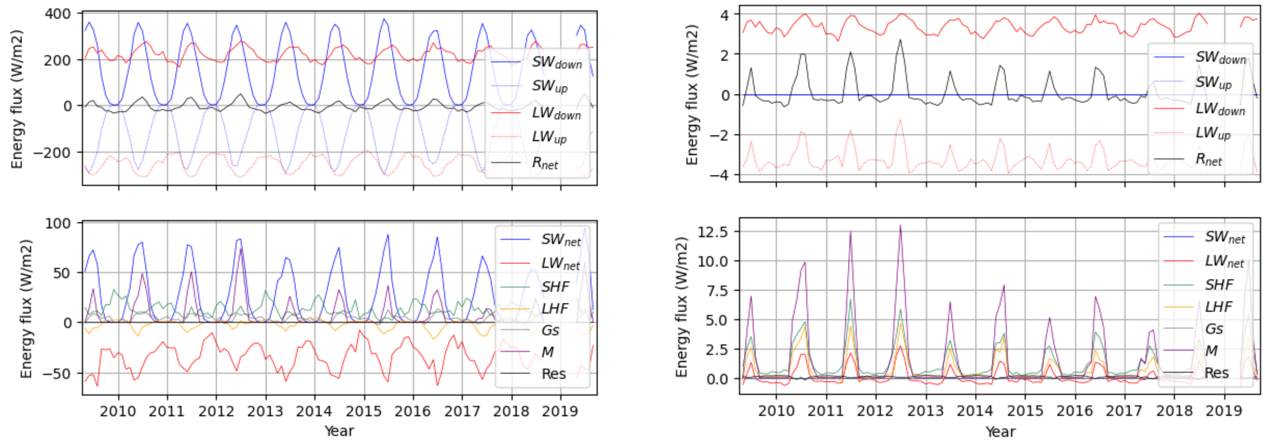
Both the LW_{up} as the LW_{down} stay relatively constant over the year. For the downward flux, this is because the atmosphere is always 1 K warmer than the initial phase. As this is a small perturbation, the response is almost linear even though the heat flux scales with temperature to the power of 4. For the upward flux, a larger variance is visible, especially during the summer months. Here, the surface temperature might be already at melting point during the day and can thus not increase further. As we are looking at daily averages, however, there is still an effect as surface temperatures typically drop below zero during the night and can therefore be influenced by the increased atmospheric temperature.

The SHF and the LHF change more during summer months.

For the SHF flux this is explained since the atmospheric temperature change is higher than the surface temperature change during summer. Like explained above and through Eq. (9), this difference is the main driver of the SHF.

The LHF gets more positive in summer since the same difference between the 2 meter saturated specific humidity and the surface saturated specific humidity is biggest during summer time, again as a result of the temperature effect discussed above. This difference then drives the increase of the LHF in accordance to Eq. (11).

If we combine the plots above, we can plot the entire SEB for the $dT = 1$ K case, but this time as monthly averages over the whole dataset.



(a) The monthly mean output fluxes from our computational model for $dT = 1$ K.

(b) The computed fluxes from (a) subtracted from the fluxes as presented in the original data.

Figure 4: Monthly mean fluxes for $dT = 1$ K case. Note that $R_{\mathrm{net}} = LW_{\mathrm{net}} + SW_{\mathrm{net}}$ and Res is the residue needed to close our SEB model.

The same trends as discussed above are visible here, but Figure 4(a) shows us that the SEB is closed as well for the $dT = 1$ K case as the Residue hovers close to zero. Figure 4(b) shows us in which years the 1 K atmospheric temperature increase would have resulted in the biggest change of fluxes. It becomes clear, that during the summer the biggest change is the melt, which exceeds 10 W m^{-2} in some years. Also important are the increased SHF, LHF and net LW that provide the energy required for melting.

3.2.2 Near-surface Climate

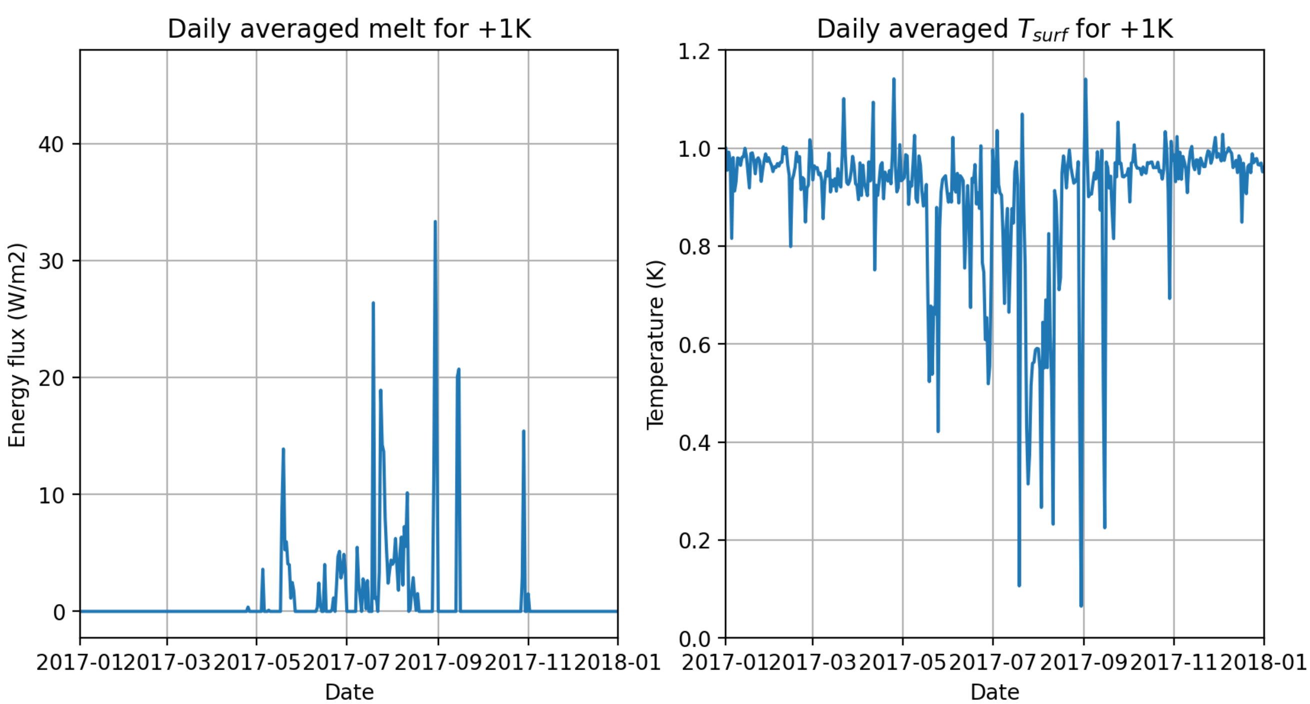


Figure 5: Daily averaged flux differences in 2017 between initial values and $dT = 1$ K case for melt and T_{surf}

As observed in Figure 5, there is a significant escalation in melt during the June-July-August(JJA) and September period. This is a predictable outcome given that our AWS is situated in Greenland, where these months correspond to the summer season. Additionally, it is noteworthy that our surface temperature change remains relatively stable at 1K. However, during the JJA and September period, which is characterized by melting events, there is a dip in the temperature increase. This can be explained because during melting events the surface temperature always will be at 273.16 K. Therefore, the relative temperature difference will be lower during melting events and additional energy can be directly converted to melt.

3.2.3 Melt

Lastly, we want to quantify the long-term effects of the temperature increase on the glacier. Therefore, we turn to Figure 6 which shows the cumulative melt over almost a decade from 2009-2019. Four different lines show the cumulative melt; the red one symbolizes the output of the original SEB model and the blue one for our model, both for an unchanged temperature.The fact that both lines move in concert with very little deviations once again underlines how close our model results are to the original SEB output. One key feature is that the cumulative melt only increases in the summer months, where the temperatures are high enough, and stagnates in the winter. The orange line shows the melt after an increase of the atmospheric temperature by 1 °C. Naturally, here, the accumulated melt is bigger and results in an additional melt of more than 1.5 mw e after the decade. If this melt is not compensated by additional accumulation, this will lead to a (faster) dying glacier and an elevated ELA. This could lead to the ELA move even higher than the height of the analyzed AWS. Note the unusually high melt in the summer of 2012, which would have been even more extreme with a higher atmospheric temperature.

With our model setup, we can also easily implement an atmospheric temperature decrease by 1 °C which is shown in the green line of Figure 6. Not surprisingly, here, the acumulated melt is lower than the reference by more than 1 mw e after a decade.

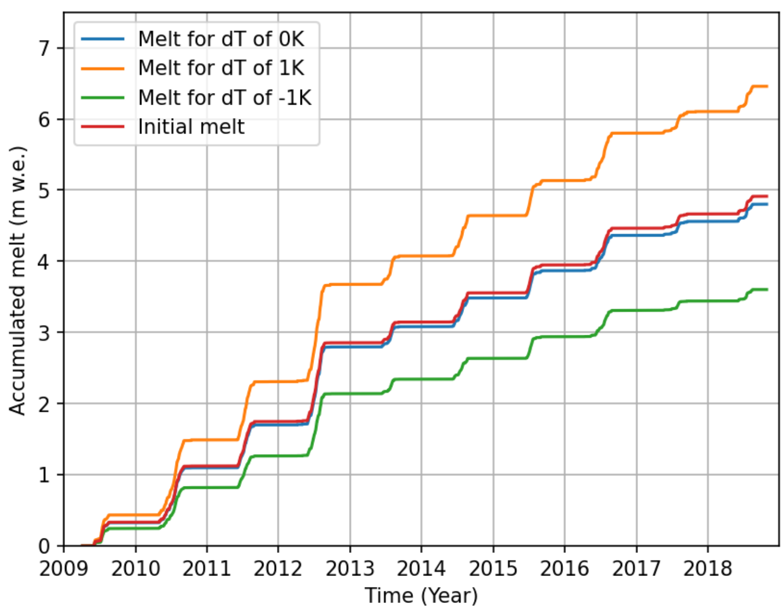


Figure 6: Accumulated melt between 2009 and 2010. 'Initial melt' is the melt that the given SEB model calculated. The difference between this melt and the $dT = 0K$ melt thus is the difference in models explained in the first section of this chapter. Due to the discontinuity of observations after 27/10/2018, the plot is capped off at this point.

4 Conclusion

In this project an existing SEB model outputting hourly climate and energy fluxes adjusted towards measurements of an AWS located on a glacier just above ELA in west Greenland is used. An increased atmospheric temperature leads to a perturbed LW down flux, increased the surface temperature which further influenced the LW up, SHF and LHF. In our model, the downwards LW flux increased due to the increased atmospheric temperature. The LW up flux decreased and got more negative due to the increased surface temperature. Similarly, the SHF increased and the LHF mostly increased, especially in the summer months. For the sensible heat flux, this is explainable looking at Eq. (9): as the atmospheric temperature difference is higher than the surface temperature difference in the summer, the SHF increases. With a similar argument, the Latent heat flux increases especially in the summer as then the specific humidity increases more in the atmosphere than at the surface.

This effects the near-surface climate, which changed, too: significantly more melt is observed during the summer months, while no melt changes are observed in the winter. This is reasonable as the winter temperatures are too low that slightly increased surface temperatures could induce melt. In the winter, the greater atmospheric temperature translated into an almost similarly high increase in surface temperature, presumably only limited by the emisivity of the atmosphere. In the summer, however, not all additional energy from the LW down flux is translated into increased surface temperature as it cannot rise above 0 °C. Consequently, especially melt increases and summer surface temperatures are less than 1 °C warmer. All of these changes lead to a greater accumulated melt more than 1.5 mw e higher than reference over a decade from 2009-2019. Similarly, the accumulated melt was less for an atmospheric temperature decrease by 1 °C.

While these results are straight-forward, one must acknowledge the limitations of our approach. The way the energy fluxes were adjusted assumed several unchanging parameters, such as the albedo, the 10m wind speed, the relative humdity, and c_s or c_l for the sensible and latent heat flux, respectively. Additionally, the assumption of a linear relationship between the two latter constants might be a very crude assumption. Consequently, the results as presented bear significant uncertainties that have not been quantified. Furthermore, it is important to note that even the data output of the original SEB does not necessarily represent the "truth" as some of the fluxes as the LHF and the SHF are not measured directly. It is also worth noting that this analysis may not be simply extended to higher temperature changes as might be required to research the impact of continuing climate change. This is because in a lot of the adjusted energy fluxes such as the LW up or the SHF, a linear reaction to the temperature change was assumed which is only reasonable for small perturbations. For higher changes, higher order terms should be taken into account. Nevertheless, this approach shows how observational data can be used to run experiments where climate parameters are changed. This could be used to run a more sophisticated climate change experiment where also other changing factors such as cloud cover, albedo and humidity could be taken into account.

References

Munneke, P. K., Smeets, C. J. P. P., Reijmer, C. H., Oerlemans, J., van de Wal, R. S. W., & van den Broeke, M. R. (2018). The k-transect on the western greenland ice sheet: Surface energy balance (2003–2016). *Arctic, Antarctic, and Alpine Research*, *50*(1). https://doi.org/10.1080/15230430.2017.1420952