SEB exercise, version 2.1

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The purpose of this exercise is to give you some feeling about how the near surface atmosphere and especially the surface energy balance (SEB) over an ice sheet looks like and how the different processes relate to each other and respond to changes.

The data provided are from weather stations part of the UU/IMAU weather station network, notably from four stations on the K-Transect, western Greenland, and four stations on the Larsen C ice shelf, Antarctic Peninsula. These stations measure temperature, relative humidity, wind speed, wind direction, and air pressure, the upward and downward radiative fluxes of short wave (SW) and long wave (LW), at about 2-4 m above the surface. Other measured parameters include the snow height and integrated ice melt. A list of all parameters in the data set is provided in the accompanying excel file.

As with all measurements, they might include errors, due to problems such as riming, lack of ventilation or heating, station tilt, sensor malfunctioning, transmission or storage issues etc. The measurements provided in the files are quality checked, calibration constants have been applied, and when possible / necessary, corrections ave been applied as well. These corrections include corrections for sensor tilt, heating of the unventilated sensors by solar radiation, rotation of the wind direction to relate to geographical north, and more. Although we have done our best to remove all errors / problems, there might still be some in the data set, so remember to remain critical.

The data also includes some output of a Surface Energy Balance (SEB) model. Where the SEB-model combines the weather station observations to calculate the terms in the surface energy balance that are not directly measured. In order to do so, the observations sometimes needed to be rectified, notably gap filled, due to measurements problems as described above.

Below in sections 1 and 2 folows a description of the SEB for snow and ice, how the different terms are calculated in an SEB model, and give suggestions on how you can adapt the provided data to investigate the impact of a change. In sections 3 and 4 the assignment itself is explained in a bit more detail.

1 The Surface Snergy Balance (SEB)

For a snow and ice surface we can write the SEB in the following way:

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

In this balance SW_{down} and SW_{up} are the short wave incoming and reflected radiation energy, LW_{down} and LW_{up} are the long wave incoming and outgoing radiation energy, SHF and LHF are the turbulent fluxes of sensible and latent heat, respectively, Gs is the ground heat flux, and in case there is a surplus of energy M_{surf} is the energy used to melt the surface. In some cases energy provided by rain is also added in this balance, but we assume this term to be negligible. Furthermore, the net radiative energy (R_{net}) is the sum of SW_{net} and LW_{net}, with $SW_{\text{net}} = SW_{\text{down}} + SW_{\text{up}}$, and $LW_{\text{net}} = LW_{\text{down}} + LW_{\text{up}}$. We use, unless stated otherwise, the convention that a positive flux value implies a flux towards the surface, and a negative value a flux away from the surface, this also holds for the ground heat flux. Note that in the provided weather station data all radiative terms are positive, which means that to conform to the sign convention the terms SW_{up} and LW_{up} should be multiplied with -1.

1.1 (Non-)closure of the SEB model (R)

Fundamental physics tells us that the sum of all the energy fluxes at the interface between the atmosphere and the subsurface must be equal to zero. However, when trying to measure all separate terms of the SEB, the SEB seldom really closes as a result of measurement uncertainties, and/or lack of process understanding. However, SEB models are generally based on assuming closure. This means that the sum of all terms on the right hand side of eq. (2) add up to 0 in case no melt occurs, and assuming all terms are known and included. In order to ensure closure the SEB model tries to find a surface temperature (T_{surf}) for which eq. (2) holds (r.h.s. = 0). In case this results in a $T_{\text{surf}} > 0°\text{C}$, T_{surf} is set to 0°C, all terms depending on T_{surf} are recalculated and the surplus of energy equals M_{surf}. This method is often called the Skin Layer formulation of the SEB. As a result, in the Skin Layer formulation, all terms which include T_{surf} (LW_{up}, SHF, LHF, and Gs), are based on the modelled T_{surf}, instead of an observed T_{surf} which can be calculated from observations of LW_{up}.

Note that in the provided data LW_{up}, SHF, LHF, and Gs are also available based on observed T_{surf}. When adding up all terms based on the observations of T_{surf} will not result in closure of the SEB. Equation (2) can in this case be rephrased as:

$$M_{\text{surf}} + R = SW_{\text{down}} + SW_{\text{up}} + LW_{\text{down}} + LW_{\text{up}} + SHF + LHF + Gs, \tag{2}$$

with R being a residual term representing the non-closure. In case of no-melt conditions, the size of R is evident, in case of melt it becomes challenging to distinguish between both. This can be done using observed surface height changes assuming a certain density of the subsurface.

In case closure is assumed, T_{surf} is determined using an iterative procedure. The r.h.s. of eq (2) can be written in terms of T_{surf} as the only unknown pararameter, but cannot be solved analytically. Below, in section 2 two methods to calculate T_{surf} are given.

In case of closure, the modelled T_{surf} can be evaluated against observations. Either by determining modelled LW_{up} from modelled T_{surf} and comparing it with measured LW_{up}. Or by determining the measured T_{surf} from measured LW_{up} and comparing it with modeled T_{surf}. In both cases the Stefan Boltzman relation is needed to convert temperature in energy, or viseversa ($LW_{\text{up}} = \varepsilon\sigma T_{\text{surf}}^4$). This evaluation only works in cases $T_{\text{surf}} < 0°\text{C}$. By tuning of unknown or less well known parameters in the SEB model (like surface roughness, initial snow density, and snow compaction rate) the differences between the modelled and measured LW_{up} or T_{surf} can be minimised.

The data files provide the fluxes both based on observed and modelled T_{surf}. In the latter case, the SEB is closed for a given atmospheric and (estimated) sub-surface state and $R = 0 W m^{-2}$. In this project, in order to assess the impact of changes, you need to use the energy fluxes based on modelled surface temperature. Then you can assess the impact of changes on all components of the SEB.

In some cases the SEB model cannot find a T_{surf} that satisfies all requirements, resulting in residual energy. This happens typically at the start of the data series when the initial snow pack of the model differs significantly from reality, or in case of sensor malfunctioning. The state of the snow pack is needed to calculate Gs.

Below follows a short description of each term of the SEB, providing you with some information on how to calculate them yourselves using the provided data.

1.2 Shortwave radiation → $SW_{\textbf{net}}$

The net short wave radiation (SW_{net}) is equal to

$$SW_{\text{net}} = SW_{\text{down}} + SW_{\text{up}} = (1 - \alpha) SW_{\text{down}}$$

with α the surface albedo, the fraction of radiation reflected by the surface. The incoming radiation SW_{down} depends on the solar zenith angle and cloudiness. The reflected radiation SW_{up} depends on surface characteristics such as snow vs ice, and dust / soot content.
SW_{down} and W_{up} are both provided in the data set.

The albedo can be calculated from the ratio between downwelling and upwelling radiation:

$$\alpha = SW_{\text{up}} / SW_{\text{down}}$$

However, radiation measurements are difficult for low solar angles (high zenith angles), therefore the albedo provided in the data files is based on daily totals of SW_{up} and SW_{down}.

Short wave radiation is able to penetrate the snow and ice surface. However, it is not trivial to implement the effect of radiation penetration in SEB calculations. If radiation penetration is taken into account, it is estimated that about half of SW_{net} is actually absorbed at the surface (SW_{surf}), and hence contribution to the SEB. The rest (SW_{int}) is absorbed mostly in the first few centimeters of the snow / ice layer, decreasing exponentially with depth. Radiation penetration is also very wavelength dependent, explaining for example the blueish color of light in crevasses. Note that no estimation of SW_{int} is provided in the dataset. In subsection 1.8 the possible implementation of radiation penetration is discussed in a bit more detail.

1.3 Longwave radiation → $LW_{\textbf{net}}$

Both the downwelling and upwelling longwave radiation are observed by the weather station. However, as explained above, in order to assess the impact of changes, you need to use the upwelling longwave radiation based on modelled surface temperature, for which the SEB is closed.

For this project, if you wish to investigate for example the effect of changes in atmospheric temperature, one of the terms that will be impacted is the longwave downwelling radiation. To assess the impact, you could approximate the apparent temperature of the free atmosphere (T_{Atm}) assuming unit emissivity, thus

$$LW_{\text{down}} = \sigma T_{\text{Atm}}^4 \qquad \rightarrow \qquad T_{\text{Atm}} = \sqrt[4]{\frac{LW_{\text{down}}}{\sigma}}.$$

Alternatively, you could define this atmospheric temperature as depending on the observed 2 m temperature, thus $F(T_{2\mathrm{m}})$, and estimate the emissivity of the atmosphere (ϵ):

$$LW_{\mathrm{down}} = \epsilon\sigma F(T_{2\mathrm{m}})^4 \qquad \rightarrow \qquad \epsilon = \frac{LW_{\mathrm{down}}}{\sigma F(T_{2\mathrm{m}})^4},$$

and finally using this emissivity to estimate a $T_{2\mathrm{m}}$ to vary.

The upwelling longwave emissivity depends on the surface temperature. The surface emissivity of snow and ice is estimated to be close to 1, therefore a surface emissivity of one can be (and is often) assumed. If you alter any of the fluxes, the surface temperature will alter as well, and hence the longwave emission. Thus:

$$LW_{\mathrm{up}} = -\sigma T_{\mathrm{surf}}^4,$$

including the correct sign convention.

Note that to solve the resulting system of the SEB for T_{surf}, it might be good to linearise LW_{up} as function of T_{surf} for the estimated solution $T_{\mathrm{surf}}^{\mathrm{est}}$:

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

In this equation, $T_{\mathrm{surf}}^{\mathrm{adj}}$ is T_{surf} after solving the SEB for $T_{\mathrm{surf}}^{\mathrm{adj}}$ providing an estimated T_{surf} of $T_{\mathrm{surf}}^{\mathrm{est}}$.

1.4 Sensible heat flux SHF

In an SEB model, the sensible heat flux is estimated using

$$SHF = c_s U_{10\mathrm{m}}(T_{2\mathrm{m}} - T_{\mathrm{surf}}). \tag{3}$$

Th parameter c_s is an exchange coefficient and depends on the surface roughness, but also on the atmospheric stability as turbulence is suppressed in a heavily stratified boundary layer. SHF (or)c_s) is usually, and also in our data set, calculated based on Monin Obukhov similarity theory and a bulk method. In our dataset SHF is provided for modelled and observed T_{surf}. More details on these methods and Boundary Layer processes and theories in general are presented in the course Boundary Layers (NS-MO414M).

If you update T_{surf} (or any other parameter in this relation), than you can choose to update SHF too. For example, you can take into account that $T_{2\mathrm{m}}$ is related to T_{surf} and to a temperature at some height in the boundary layer (T_{BL}). Note that T_{BL} is not the provided observed air temperature. You can approximate this T_{BL} with

$$T_{\mathrm{BL}} = T_{\mathrm{surf}} + \frac{T_{2\mathrm{m}} - T_{\mathrm{surf}}}{c_{\mathrm{BL}}},$$

with c_{BL} representing a fraction of the (potential) temperature difference between the boundary layer and the surface (thus $T_{\mathrm{BL}} - T_{\mathrm{surf}}$) is situated in the lowermost 2 meters of the atmosphere.

In case you assume T_{BL} to remain constant, and only T_{surf} affecting SHF, you end up with a linear relationship like

$$SHF(T_{\mathrm{surf}}^{\mathrm{adj}}) = SHF^{\mathrm{SEB}} + c_{\mathrm{TBD}} U_{10\mathrm{m}}(T_{\mathrm{surf}}^{\mathrm{SEB}} - T_{\mathrm{surf}}^{\mathrm{adj}}),$$

in which c_{TBD} is a constant that needs to be determined with the information given above, SHF^{SEB} is the SHF unaffected by T_{surf} changes, and $T_{\mathrm{surf}}^{\mathrm{SEB}}$ the unaffected T_{surf}. Note that when performing sensitivity experiments in which your change $U_{10\mathrm{m}}$ or $T_{2\mathrm{m}}$, SHF^{SEB} will change as well.

1.5 Latent heat flux LHF

Similar to SHF, the latent heat flux is estimated in an SEB model with

$$LHF = c_l U_{10\mathrm{m}}(Q_{2\mathrm{m}} - Q_{\mathrm{surf}}), \tag{4}$$

where the exchange coefficient c_l depends on the surface roughness and atmospheric stability (as was c_s). Also similar to SHF, LHF is usually calculated based on Monin Obukhov similarity theory and a bulk method. Note that for any given moment in time c_l and c_s are closely related (Eq. (3)).

Weather stations do generally not measure the specific humidity (Q, kg/kg) but measure the relative humidity (RH). RH is related to Q by $RH = Q/Q_{\mathrm{sat}}$ with Q_{sat} (kg/kg) the saturated specific humidity. Q_{sat} in turn is a function of temperature and pressure, and can be calculated using a relation based on the Clausius Clapeyron relation:

$$Q_{\mathrm{sat}}(T,P) = \frac{6.1121 * m_v}{P * m_{air}} \exp\left[\frac{c_1 T}{T + c_2}\right] \text{ with } \begin{cases} T \leq 0: & c_1 = 22,587 \quad c_2 = 273,86 \\ T \geq 0: & c_1 = 17,502 \quad c_2 = 240,97 \end{cases} \tag{5}$$

Here, m_v and m_{air} are the moleculair masses of water vapour (18.0153 g/mol) and air (28,9644 g/mol), respectively. The temperature T is in °C and P is the pressure in hPa.

Therefore, Eq. (4) can be rewritten to

$$LHF = c_l U_{10\mathrm{m}}(RH_{2\mathrm{m}} Q_{\mathrm{sat}}(T_{2\mathrm{m}}, P) - Q_{\mathrm{sat}}(T_{\mathrm{surf}}, P)), \tag{6}$$

in which $RH_{2\mathrm{m}}$ ranges from 0 to 1 and the surface relative humidity, due to the omnipresence of water, can be assumed to be 1.

Given that Q is measured only indirectly, adjusting the LHF, or rewriting this relation to solve for $T_{\mathrm{surf}}^{\mathrm{adj}}$ is a bit more cumbersome than most of the other terms in the SEB, while the impact on the SEB is generally smaller than the impact of SHF. Depending on the method of determining the T_{surf}, it is possible to take the impact of changes in T_{surf} on LHF into account.

1.6 Ground heat flux Gs

The ground heat flux is not measured by the weather stations, but modelled by the SEB model. The ground heat flux depends both on the evolution of the surface temperature as on the evolution of the near (< 5 cm) and deep ($5 - 50$ cm) snow and ice temperatures and densities. Without proper snow model, it is hard to re-evaluate Gs. Hence, it is advised to leave Gs as is, even though surface temperatures or melt amounts change in the requested sensitivity experiments. In a SEB model that includes a proper snow model Gs is estimated by:

$$Gs = k(T_{sn}, \rho)\frac{dT_{sn}}{dz},$$

where the effective conductivity k is a function of the snow/ice temperature T_{sn} and density ρ.

1.7 Melt M, or no melt

As long as the surface temperature is below 273.16 K, the SEB (Eq. (2)) closes with $M = 0$. This is because LW_{up} (being negative), SHF, LHF, G_s all decrease if T_{surf} increases. However, T_{surf} cannot rise above 273.16 K, hence if above melting point temperatures are required to close the SEB, the surface temperature is set to the melting point and the remaining energy is used to melt snow and ice.

1.8 Adjusting the SEB for radiation penetration

For none of the stations radiation penetration has been included in the calculations of the different SEB components. However, radiation penetration is an important process, especially over ice surfaces, with an estimated half of SW_{net} being absorbed below the surface. When including radiation penetration, the SEB will change, complicating the sensitivity analyses topic of this project. However, you could opt to include radiation penetration by including the energy fluxes of internal SW absorption (SW_{int}) and melt (M_{int}) and subsequently adjust Gs. In that case the SEB will chang to:

$$M_{\text{surf}} = SW_{\text{surf}} + LW_{\text{down}} + LW_{\text{up}} + SHF + LHF + Gs,$$

with M_{surf} now specifically the melt at the surface, and SW_{surf} is the short wave radiation absorbed at the surface, excluding the part that penetrates into deeper layers, thus $SW_{\text{surf}} = SW_{\text{down}} + SW_{\text{int}} + SW_{\text{up}}$, and $SW_{\text{net}} = SW_{\text{surf}} - SW_{\text{int}}$ (remember the sign convention). The internal energy balance is given by

$$M_{\text{int}} = SW_{\text{int}} + G_{\text{int}}.$$

With the available information in this project, the internal ground heat flux (G_{int}) cannot be estimated, as the layer over which radiation penetration or internal melt occurs, is not well defined nor known. So, with $M_{\text{tot}} = M_{\text{surf}} + M_{\text{int}}$, we define the modified SEB as:

$$M_{\text{tot}} = SW_{\text{surf}} + LW_{\text{down}} + LW_{\text{up}} + SHF + LHF + Gs^{\text{mod}},$$

in which

$$Gs^{\text{mod}} = Gs - SW_{\text{int}} + M_{\text{int}}.$$

In practice, taking radiation penetration into account, leads to a strong reduction of the ground heat flux for sunny non-melting conditions, where the absorbed radiation reduces the subsurface temperature gradients. In that case, the SEB as formulated here, will not change when including the term SW_{int}. For conditions with internal melting, $Gs^{\text{mod}} \sim Gs$ as the internally absorbed radiation provides this heat, thus $SW_{\text{int}} = M_{\text{int}}$, and the upper part of the snow/ice pack is isothermal.

2 Methods to find adjusted surface temperature.

In order to find the adjusted surface temperature $T_{\text{surf}}^{\text{adj}}$ for which the SEB closes again, you have to iteratively solve the following equation:

$$M_{\text{surf}}^{\text{adj}} = SW_{\text{down}}^{\text{adj}} + SW_{\text{up}}^{\text{adj}} + LW_{\text{down}}^{\text{adj}} + LW_{\text{up}}(T_{\text{surf}}^{\text{adj}}) + SHF(T_{\text{surf}}^{\text{adj}}) + LHF(T_{\text{surf}}^{\text{adj}}) + Gs. \quad (7)$$

Here, the superscript *adj* refers to any adjustments you might have made to the original term. There are different methods to solve this, differing in complexity and accurary.

The first presented here is by linearising the above equation as much as possible in terms of $T_{\text{surf}}^{\text{est}}$, and $T_{\text{surf}}^{\text{adj}}$, with $T_{\text{surf}}^{\text{est}}$ the first estimate of T_{surf} and $T_{\text{surf}}^{\text{adj}}$ the resulting adjusted temperature:

$$M_{\text{surf}}^{\text{adj}} = SW_{\text{net}}^{\text{adj}} + LW_{\text{down}}^{\text{adj}} - \sigma {T_{\text{surf}}^{\text{est}}}^4 - 4\sigma {T_{\text{surf}}^{\text{est}}}^3 (T_{\text{surf}}^{\text{adj}} - T_{\text{surf}}^{\text{est}}) + SHF^{\text{SEB}} + c_{\text{TBD}} U_{10\text{m}} (T_{\text{surf}}^{\text{SEB}} - T_{\text{surf}}^{\text{adj}}) + \ldots, \quad (8)$$

which is a linearly disturbed SEB version of Eq. (2). Note that the terms LHF and G_s are left out in Eq. (8) and following for brevity, but should not be forgotten!. To solve this, assume initially that $M_{\rm surf}^{\rm adj} = 0$, and rewrite this equation to:

$$c^{\rm adj} T_{\rm surf}^{\rm adj} = c^{\rm fixed} \qquad \rightarrow \qquad T_{\rm surf}^{\rm adj} = \frac{c^{\rm fixed}}{c^{\rm adj}}, \tag{9}$$

in which the left hand side of the left hand equation includes all terms with $T_{\rm surf}^{\rm adj}$, and the right hand side all terms that are adjusted and might have $T_{\rm surf}^{\rm est}$ in them:

$$\begin{aligned} c^{\rm adj} &= 4\sigma {T_{\rm surf}^{\rm est}}^3 + c_{\rm TBD} U_{\rm 10m} + \ldots \\ c^{\rm fixed} &= SW_{\rm net}^{\rm adj} + LW_{\rm down}^{\rm adj} + 3\sigma {T_{\rm surf}^{\rm est}}^4 + SHF^{\rm SEB} + c_{\rm TBD} U_{\rm 10m} T_{\rm surf} + \ldots . \end{aligned}$$

In case this leads to $T_{\rm surf}^{\rm adj} > 273.16$ K, there is melting. In that case, $M_{\rm surf}^{\rm adj}$ is derived with Equation (8) using that $T_{\rm surf}^{\rm adj} = 273.16$ K. Otherwise, it is wise to repeat (a couple times) solving Equation (8) while updating $T_{\rm surf}^{\rm est}$ with the latest estimated $T_{\rm surf}^{\rm adj}$ untill the difference between two consecutive iterations is sufficiently small. Please note that updating $T_{\rm surf}^{\rm est}$ leads to different $c^{\rm adj}$ and $c^{\rm fixed}$.

The second method, the bisection method, is a root finding algoritm, and is slightly different, but also involves an iterative procedure. This method will search for the $T_{\rm surf}^{\rm adj}$ for which $M_{\rm surf}^{\rm adj} = 0$ (Eq. 7). To do that you calculate the rhs of Eq. 7 for different (smartly) chosen values of $T_{\rm surf}^{\rm adj}$. Assume the rhs of Eq. 7 to be function f and the interval $[T_{a0}, T_{b0}]$ the chosen $T_{\rm surf}^{\rm adj}$ interval. Now choose $[T_{a0}, T_{b0}]$ such that $f(T_{a0})$ and $f(T_{b0})$ are of opposite signs ($f(T_{a0}) * f(T_{b0}) < 0$). Now compute the midpoint $f(T_{m0})$ with $T_{m0} = (T_{a0} - T_{b0})/2$. Now determine the next subinterval $[T_{a1}, T_{b1}]$. In case $f(T_{a0})$ and $f(T_{m0})$ are of opposite sign, $T_{a1} = T_{a0}$ and $T_{b1} = T_{m0}$. Otherwise, in case $f(T_{b0})$ and $f(T_{m0})$ are of opposite sign, $T_{a1} = T_{m0}$ and $T_{b1} = T_{b0}$. Repeat this procedure until the interval $[T_{an}, T_{bn}]$ reaches a preset minimum, for which function f, or the rhs of Eq. 7, approaches 0. Now return $T_{mn} = (T_{an} - T_{bn})/2$ as the final estimate of $T_{\rm surf}^{\rm adj}$.
As in the first method, in case this leads to $T_{\rm surf}^{\rm adj} > 273.16$ K, there is melting and $M_{\rm surf}^{\rm adj}$ is derived with Eq. 7 using $T_{\rm surf}^{\rm adj} = 273.16$ K.

3 Work plan

1. Load the data into python, using the python code provided.

   - The file 'AnalyseSEBdata.py' provides a routine to read the SEB data file, provides examples of how data can be extracted from the class provided in 'SEB_functions.py', and how figures can be made. Furthermore, it shows a very simple SEB adjustment example, namely getting adjusted surface temperatures and surface melt by increasing $LW_{\rm down}$ only.
   - The file 'SEB_functions.py' provides the modules and routines to load the SEB model data. Data is provided in one variable of a class defined in 'SEB_functions.py'. The class (and thus variable) includes functions to extract the relevant data out of the variable. Call 'help(<*variable name*>)' for more information, or look into the python code.
   - Please note that the date and time are registered using the datetime type.
     See https://docs.python.org/3/library/datetime.html#datetime.datetime for more info on this type.

2. (Re-)construct and plot the SEB as modelled by the SEB model and provided in the data. Hence, adjust the code in 'AnalyseSEBdata.py' to your liking.
3. In teams of 2, select a research question, listed below and a location (weather station) to study.
4. Adjust the SEB component according to the research question, and consider to adjust also other fluxes if you think these will be affected by your research question. Write code that "closes" the SEB again, thus a code that finds a surface temperature or melt energy for which $SEB = M$ holds.
5. Write a brief report on this project, containing
   - The research question, and how you implemented that in the code. Please also mention which AWS location has been chosen.
   - List which other fluxes have been adjusted and discuss the equations and rationales of these adjustments.
   - Show, the original and adjusted SEB (e.g. typical monthly cycle) and surface climate, and discuss what you have learned from these changes about the sensitivity of the surface climate and snow melt to 'your change'.

4 Research questions

How will the near surface climate, SEB and melt change if:

1. atmospheric temperature rises / falls with 1 K?
2. the wind speed would always be half / double the wind speed now observed?
3. the snow/ice albedo would always be 0.85 / 0.7 / 0.3?
4. it always would be cloudy at your chosen site?
5. there never would be clouds at your chosen site?
6. the air at 2 m height would always be completely dry ($RH = 0\%$) or saturated ($RH = 100\%$)?

5 Variable look-up table

The variable names in the data files are not always easy to interpret, and some variables are, with variations, multiple times available in the files. Therefore, please check Table 1 and the file 'AWS_variables.xlsx' to use the right data. Otherwise the SEB budget won't close (that nicely). Variable names in the ANT and GRL data sets have the same names, but not all variables are provided in all data sets.

Change log

1.2: Added the equation for Q_{sat} (Eq. (5))
1.3: Corrected an error in Equations (6) and (5) and added this change log.
2.1: updated / extended the text, adapted text for updated data sets, added bisection method for T_{surf} calculation.

Table 1: Non-complete look-up table of suitable variables.

Variable	name in file	sign (convention followed)	comment
SW_{down}	SWd	always positive (yes)	
SW_{up}	SWu	always positive (no)	
SW_{net}	-	-	Calculate yourself
SW_{int}	-	-	Not provided
SW_{surf}	-	-	Not provided
LW_{down}	LWd	always positive (yes)	
LW_{up}	LWu_mod	always positive (no)	Based on modelled T_{surf}
LW_{net}	-	-	Calculate yourself
R_{net}	-	-	Calculate yourself
SHF	SHF_mod	varies (yes)	Based on modelled T_{surf}
LHF	LHF_mod	varies (yes)	Based on modelled T_{surf}
Gs	GHFup_mod	varies (yes)	Based on modelled T_{surf}
Gs^{mod}	-	-	Not provided
M_{surf}	meltE	positive (no)	
M_{tot}	-	-	Not provided
M_{int}	-	-	Not provided
T_{surf}	Ts_mod		
T_{2m}	t2m		
Q_{2m}	q2m		
U_{10m}	ff10m		