Debris Thermal Modelling manual

Contents

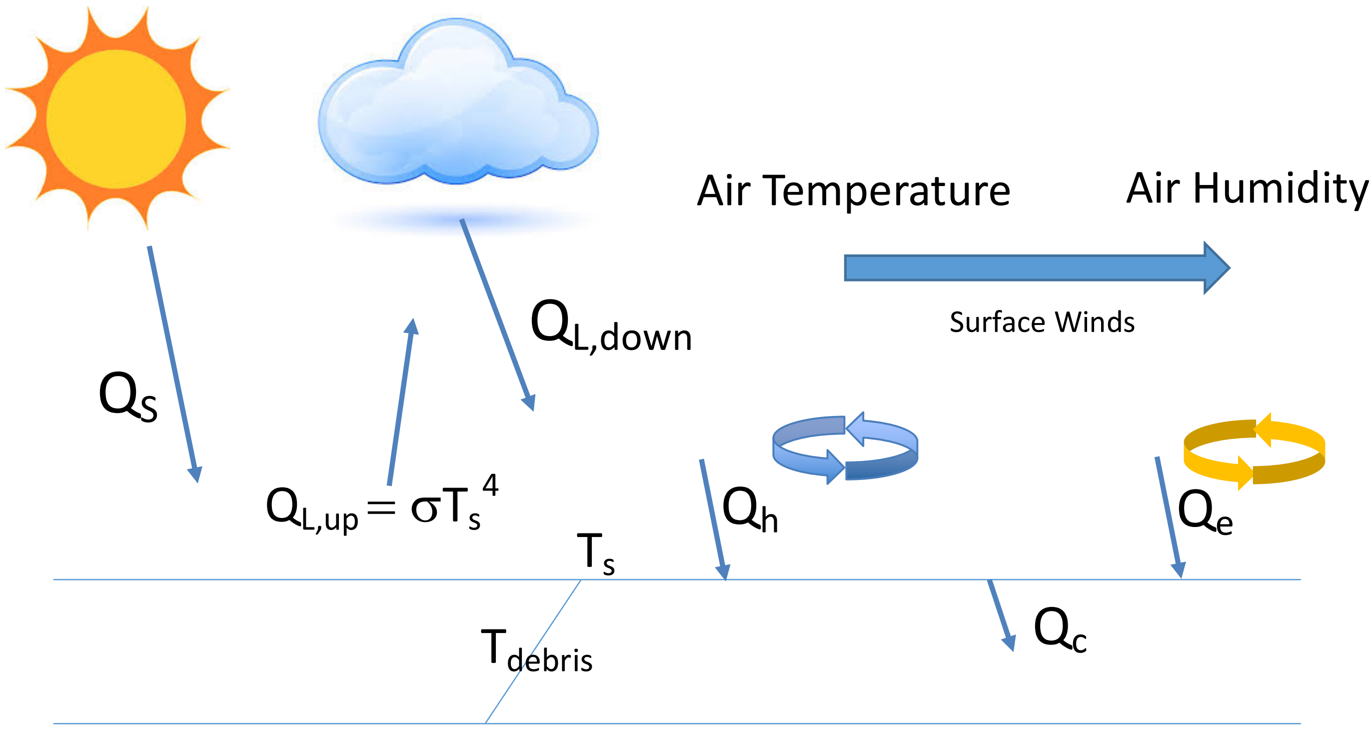
1. Learning Outcomes

- Understand the role of numerical models in studying physical processes; interpret model output and understand model limitations
- Understand the effect debris cover has on glacier ablation and the impact on glacier dynamics and shape
- Analyse heat transfer processes in a geoscientific setting (in this case, the surface and interior of a glacier debris layer)
- Gain skills producing figures used to make scientific arguments

2. Background

The amount of melt that takes place on the surface of a glacier has a strong influence on the size of the glacier, not to mention fluctuations in supraglacial, proglacial, and subglacial water supply. In steep mountainous regions there is often considerable debris fall on the surface of glaciers; and in volcanic regions there may be thick layers of tephra covering the glacier. This debris alters the surface albedo, often increasing the amount of shortwave radiation absorbed. However, this is not the only effect of the debris, as it is thought to lower melt rates considerably in some places. As a result, glacier snouts can in some cases extend well past the limiting point of "clean" ice, altering the size of the glacier, its dynamics, and sources of glacial melt streams.

We can think of the debris layer as a thermally conducting layer which interacts at its top surface with the atmosphere and delivers heat to (or removes heat from) the glacier at its bottom surface.

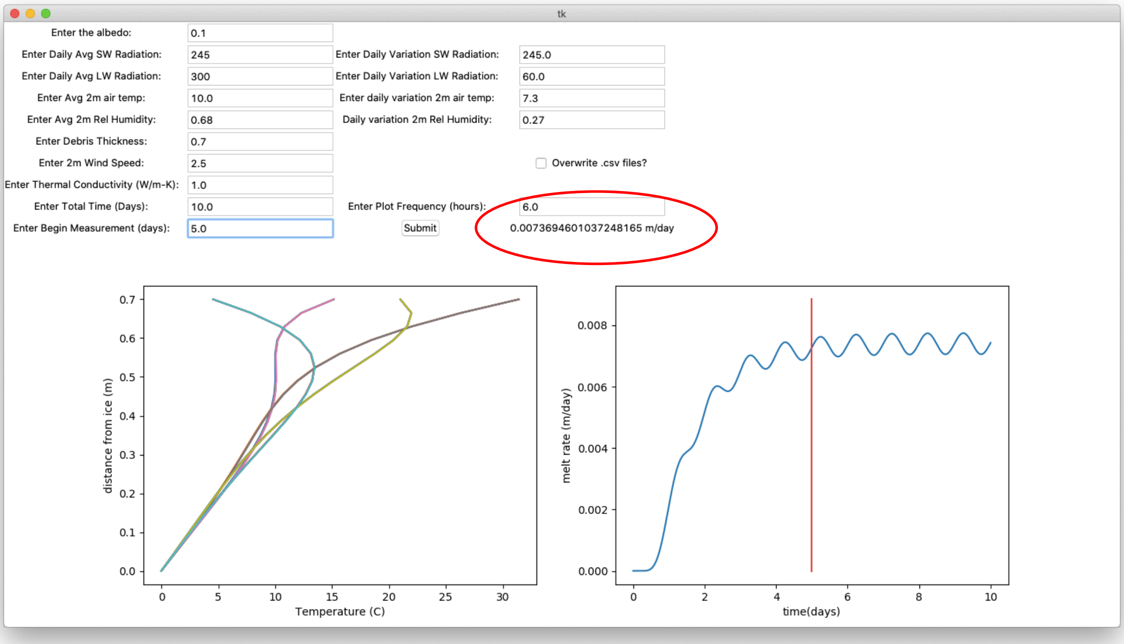


Energy enters and exits the debris surface in a number of ways: Shortwave Radiation (Qs), i.e. solar radiation; and Longwave Radiation (Q_L), i.e. infrared radiation. All matter emits longwave radiation dependent on its temperature. It we know the debris surface temperature (T_S), we know how much heat is radiated out ($Q_{L,up}$); however, longwave radiation from air and clouds ($Q_{L,down}$) depends on atmospheric conditions and must be measured. Surface winds cause heat to be transferred from the atmosphere into the glacier by turbulent mixing (Q_h); and, if the air above the glacier contains sufficient moisture, condensation takes place, releasing more heat (Q_e). Finally, heat is conducted into the debris, potentially to the debris-glacier interface (Q_c). These flux terms (aside from Qc) are described in Eqs. 5-9 of Nicholson and Benn (2006). Note that in that work, longwave radiation is defined as the difference between downwelling ($Q_{L,down}$) and upwelling ($Q_{L,up}$) as defined here.

3. Debris Temperature Model

Note: this section makes reference of *Nicholson and Benn [2006], "Calculating ice melt beneath a debris layer using meteorological data," J of Glaciology, 52(178)*. The .pdf is made available on Learn. (The first author is a graduate of the BSc Geography program at UoE.)

The console above is the interface for the temperature/melt model you will use. (this is from a mac – it will look slightly different on a PC.) There are a number of input boxes, and a "submit" button. For run instructions, see below.



Running the model.

The model (developed by D Goldberg) is a python program. First, download the file ThermApp.py from Learn and save it in a location/folder you will remember **– excel files you need to complete the assessment will be saved in this directory.** (**you may have to right-click the link and "save link as"**). When you view the file in a folder it should have a (🐍) icon. If not, there is a faulty python installation; let the lecturer or demonstrator know.

Double-click the file. 2 windows will open; the first is a Windows terminal (all black with only text). Do NOT close the windows terminal until you are done with the program.

The program window shown above will open next. There are a number of input boxes, explained under "**model inputs**". They will be filled in by default, but error checking is not great, so be careful to enter numbers only. Upon clicking "Submit", the windows console will begin listing numbers -- these are counts of the number of seconds elapsed in the model, once daily, so you can track progress.

When it is done, a text box (see red circle in the program display above) will display the *average melt rate over a specified period*, and the left-hand figure will plot *temperature profiles at specified time intervals*. Which profile corresponds to midday, when temperature is highest? The right hand figure will show the melt rate evolution over the model run.

You can open multiple instances of the program at once – but if you do this, I suggest you save a copy of ThermApp.py to a different folder before opening a new program window.

Workings of model
At the surface of the debris, all energy fluxes balance exactly. In terms of the diagram on page 1 this means that

$$Q_s + Q_{L,down} + Q_h + Q_e = Q_c + Q_{L,up}$$

exactly.

The model solves the *heat equation*: heat diffuses vertically down the temperature gradient (i.e. it diffuses from warmer to colder layers). The base (ice/debris interface) is assumed to always be at the freezing temperature (which may be inaccurate for very thin debris layers and cold surface conditions). Mathematically this is expressed by

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial T^2}$$

where k is thermal conductivity, c_p is specific heat and ρ is density. Solving this equation is beyond the scope of most undergraduate courses, but this is ok because you have been given a program which does it for you. What you *do* need to understand that is when temperature is increasing upward, heat flows downward, warming ice below and cooling ice above (heat flows *down gradient*). The **conductive heat flux into the base of the debris layer** determines the melt rate (eqs 1 and 2 of Nicholson and Benn).

In *thermal steady state* (as assumed by Nicholson and Benn), the conductive heat flux into the base is equal to Q_c (why?). But the model you will used does NOT make this assumption. Nicholson and Benn assumed a linear temperature profile which is steady in time – meaning conductive heat flux at the surface (Qc) and base are equal. **This is appropriate if meteorological forcing does not vary in time**. However in reality it does vary diurnally -- and as you will see, this means the temperature profile is not necessarily linear. The model you use evolves temperature profiles in time so you can evaluate the effect of diurnal variability. The different-colored profiles in the left-hand figure shown above are temperature profiles at different times of the day. *No legend is given and it may be difficult to tell from the figure which profile corresponds to which time. However, the excel files that are saved contain this information. The figure is just provided to give you an idea of the output.*

4. "Spinup Time"

The model will not give representative values of melt right away, because the debris internal temperature must adapt to the atmospheric forcing. (In all model runs, debris temperature is 0^{o}C initially.) The thicker the layer, the longer this will take. This can be likened to the "spinup" of a refrigerator – once turned on, it eventually reaches a steady cycle, but it is not cooled right away. This means that the period over which melt rate is averaged should not begin immediately.

There is a way for you to specify a time at which to begin measurement (see "Model Inputs": "Begin Measurement"). In the screenshot above, melt rate is averaged only between day 4 and day 5 – measurement begins at day 4, and the model runs for 5 days. Try to duplicate the result; then change the "Begin Measurement" time to 0 days. What changes? How does average melt rate change? Does it become larger or smaller?

Melt rate will eventually become constant (with constant forcing) or approach a steady cycle, such that the daily average is constant. When you are asked on the assessment for daily-average melt rate, this is the value you must give. If your estimate encompasses the spinup/warming stage of the model, your values will be incorrect. *Note: if your model has no daily variation, you can look at the last row of the* melthistory###.csv *file – provided the melt rate has become steady!*

You will need to determine how long you must run the model via trial and error. (in this demonstration, there is still an inter-daily trend in melt rate, and the model needs to be run longer.)

Finally, the model will take longer to run with thin debris layers and diurnal forcing.

5. Data Files:

The temperature profiles are saved to the file `TemperatureProfilesNNN.csv` in the same folder as ThermApp.py, where NNN is a number that the program updates each time (see **Overwrite files** at the end of section 6). The file, which can be opened in Excel, contains a table of rows which indicate temperature within the debris, spaced evenly from surface to base (with depths given). Each row corresponds to a separate time, with the logging times specified by **Plot Frequency**. At the top of the file are your parameter choices for this run of the model.

The time series of melt rate, as well as the relevant fluxes mentioned above, are also saved, in `MeltHistoryNNN.csv`. The series saved are, in order:

Time (at 5 min intervals, but given in seconds from midnight on the first day)
Melt rate
Q_s (shortwave radiation flux – positive when energy is directed downward)
$Q_{l,down}$ (longwave radiation from atmosphere – positive when energy is directed downward)
$Q_{l,up}$ (longwave radiation from debris surface – positive when energy is directed upward)
Q_h (sensible heat flux – positive when energy is directed downward)
Q_e (latent/evaporative heat flux – positive when energy is directed downward)
Q_c (conductive heat flux at the debris surface – positive when energy is directed downward)

Finally, the figures shown in the program will be saved in .png format.

As mentioned above, new files will be created for each run. **Please make sure that your directory does not become overrun with output files and unmanageable.**

6. Model Inputs

Physical parameters

Albedo: The percentage of incoming shortwave radiation that is absorbed. This is α in Eq 5 of Nicholson and Benn.

Daily Avg SW Radiation: The total incoming shortwave radiation, averaged over a daily cycle. This is Q' in Eq 5 of Nicholson and Benn. Units: W/m^2

Daily Avg LW Radiation: Downwelling longwave radiation ($Q_{L,down}$), averaged over a daily cycle. This is εl^* in Eq 6 of Nicholson and Benn. Units: W/m^2

Avg 2m Air Temp: The average daily air temperature in the atmosphere boundary layer (assumed to be measured at 2m above the surface, a conventional height). T_z in Eq 7. Units: degrees celsius

Avg 2m Relative Humidity: The average daily relative humidity in the atmosphere boundary layer. Relative humidity is the vapour pressure e_z divided by the saturation vapour pressure. T_z in Eq 7. Unitless

Daily Variation SW Radiation: $\Delta Q'$, the daily variation of Q'. At midday, SW radiation is ($Q'_{avg} + \Delta Q'$), and at midnight is ($Q'_{avg} - \Delta Q'$). If this box is zero, SW Radiation is constant.

Daily Variation LW Radiation: $\Delta\varepsilon l^*$, the daily variation of εl^*. At midday, LW radiation is ($\varepsilon l^*_{avg} + \Delta\varepsilon l^*$), and at midnight is ($\varepsilon l^*_{avg} - \Delta\varepsilon l^*$). If this box is zero, LW Radiation is constant.

Daily Variation 2m Air Temp: ΔT_z, the daily variation of T_z. At midday, 2m temp is ($T_{z,avg} + \Delta T_z$), and at midnight is ($T_{z,avg} - \Delta T_z$). If this box is zero, temp. is constant.

Daily Variation 2m Relative Humidity: ΔRH, the daily variation of relative humidity. At midday, 2m RH is ($RH_{avg} + \Delta RH$), and at midnight is ($RH_{avg} - \Delta RH$). If this box is zero, RH is constant.

NOTE: the model run always begins at midnight.

2m Wind Speed: The speed, in meters per second, of the wind in the atmospheric boundary layer which drives turbulent mixing of temperature and water vapor between the air and the debris surface. It is constant through the day.

Debris Thickness: thickness of debris layer in meters.

Thermal Conductivity: The parameter k from the heat equation, and eq 2 of Nicholson and Benn. Units W/m-K (or W/m-°C)

Model parameters

Total Time: Total model running time in days. Time steps (freq on which model variables are updated, NOT on which they are displayed) are once per hour (unless you can hack the code to change this..)

Plot Frequency: Profiles of temperature are saved and plotted (and written to file) at these intervals, given in hours.

Begin Measurement: After this time (in days), temperature profiles will be plotted (and saved to file) and melt rates will be averaged to give the average melt rate displayed on the console. The time will be indicated by a vertical red line in the right-hand figure.

Overwrite .csv files?: If this box is not ticked, the code will look for the most *recent* .csv files in the current directory, and increment the number in the file names before writing new files. If this box is ticked, then the output files will have an index of zero, i.e. TemperatureProfiles0.csv and MeltHistory0.csv will be written – even if these files exist (which could cause trouble if they are already open).

7. References:

Benn, D., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L., Quincey, D., Thompson, S., Toumi, R., and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth-Sci. Rev., 114, 156–174, doi:10.1016/j.earscirev.2012.03.008, 2012.

Hewitt, K., 2005: The Karakoram anomaly? Glacier expansion and the "elevation effect", Karakoram Himalaya. Mountain Research and Development, 25(4), 332–340.

Nicholson and Benn, 2006. Calculating ice melt beneath a debris layer using meteorological data. Journal of Glaciology, 52 (178) (2006), pp. 463–470