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Summer School in Glaciology, McCarthy, 2022

Exercises: Glacier meteorology / Energy balance

1.) ENERGY BALANCE – MELT CALCULATION

Assume a summer melt season and the glacier surface is at melting point (0°C), but the glacier is polythermal with a cold surface layer, i.e. below the surface there is a layer where the glacier's temperature is below freezing and therefore energy is consumed not only for melting but also to warm up that layer. The following variables (daily means) are measured at a weather station on the glacier. Heat fluxes providing energy to the surface are positive; heat fluxes away from the surface are negative (consuming energy). Energy sources are positive, energy sinks are negative.

Radiation:
Global (shortwave) radiation (**G**) = 200 Wm^{-2}
Albedo = 0.4
Longwave incoming radiation L_{in} = 280 W m^{-2}
Other heat fluxes:
Sensible heat flux (**Q_H**) = 30 Wm^{-2}
Latent heat flux (**Q_L**) = -20 Wm^{-2}
Warming of the cold surface layer consumes 5 Wm^{-2}.

Latent heat of fusion L_f = 334,000 J kg^{-1} (needed to compute **melt**)
Latent heat of vaporization L_{fv} = 2,883000 J kg^{-1} (needed to compute **sublimation**)

a) How much energy is available for melting Q_m?

$$Q_m = G - R + L_{in} - L_{out} + Q_H + Q_L + Q_{ice}$$

(R=reflected shortwave radiation)
Note that longwave outgoing radiation was not measured but it can be estimated from the radiation from the information given above. Note that the ice heat flux Q_{ice} is negative, if energy is consumed for warming the ice.

Net radiation (W m^{-2}) =

Energy available for melt (W m^{-2}) =

Answer:
Net radiation = 200 – (200x0.4) + 280 – 316 = 84 W/m2
Energy available for melt = 84 + 30 – 20 – 5 = **89 W/m2**

b) **How much melt occurs during that day in kg m^{-2} and in mm w.e. ?** (Note 1 W = 1 J s^{-1})

Answer:
Divide energy by latent heat of fusion: 89/344000 x 60x60x24 = 23 kg/m2 = **23 mm w.e.**
Divide kg/m2 value by density of water [kg/m3] to get m w.e. ==> (1 kg/m2 = 1 mm w.e.)

c) **How much ablation occurs during that day (in kg m^{-2} and in mm w.e.) ?**
Note that ablation includes all processes that remove mass from a glacier, i.e. also mass removed by sublimation (indicated by a negative latent heat flux).

Answer:
Because the latent heat flux is negative indicates sublimation, i.e. there is additional mass loss to the mass loss through melt.
Mass loss by sublimation = 20/2883000= 0.6 kg/m2 = 0.6 mm w.e. = 0.06 cm w.e..
Ablation = 2.3+0.6 = **23.6 mm w.e.**

Note sublimation requires a lot more energy than melt. If the latent heat flux was positive in this case an additional 20/344000 = 5.2 kg/m2=5.2 mm w.e. would melt,
i.e. total ablation would be **28.2 mm w.e.**

2.) TIME SERIES

Figure 1 shows hourly time series of meteorological observations and energy balance components at a weather station on a glacier.

a) **Label what is what on the figure**. Shown are

- air temperature (K), global radiation, latent heat flux,
- longwave incoming and outgoing radiation, net radiation,
- rain heat flux, sensible heat flux,
- relative humidity (%), and wind speed (m s^{-1}). All energy fluxes in W m^{-2}.

Answer: from top to bottom: Net, Sens, latent, precip, temp, hum, wind, Glob, Long in, Long out

b) **Identify a foggy and clear-sky day** (Name at least 2 indicators).

Answer: low global radiation, high long-wave radiation (high humidity is less good of an indicator)

c) **Identify a period of surface melting and a period with surface temperatures below freezing**

Answer: melting when longwave outgoing radiation is 316 W/m2, freezing: when it is less

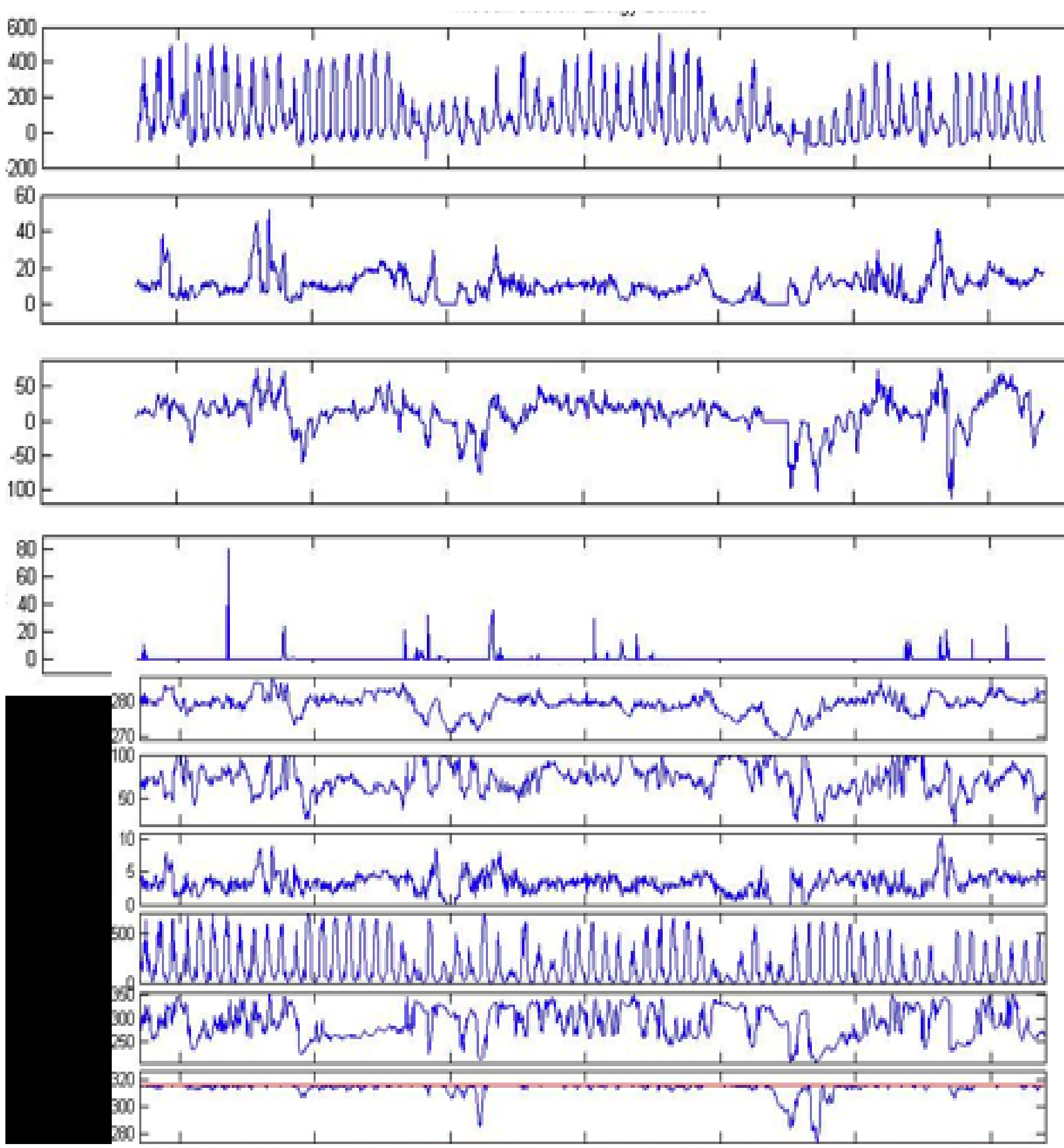

Figure 1. Meteorological observations and energy balance components on a glacier. Tics every 10 days.

3.) SPATIAL DISTRIBUTION OF ENERGY BALANCE COMPONENTS

Figure 3 shows the modeled spatial pattern of the energy fluxes on Storglaciären, Sweden, averaged over the period 7 June to 17 September 1993. The model is forced by weather station data from one station in the center of the glacier. Shown are (all energy fluxes in W m^{-2}):

• **sensible heat flux**	• **global radiation**	• **longwave incoming radiation**
• **latent heat flux**	• **diffuse radiation**	• **outgoing longwave radiation**
• **melt (in cm)** over the >3 months period.	• **net radiation**	• **direct radiation**

Air temperature (not shown) is extrapolated in the model assuming a linear decrease in temperature with elevation. Humidity and wind speed (not shown) measured at the weather station were assumed constant in space. The glacier surface was at the melting point during most of the period. Cloud cover was assumed uniform across the glacier.
Which component does each subplot show ? Note that the 3 smaller maps have a different scale (you can ignore them).

Answer: Per row from top to bottom: Direct, diffuse, global, long in, long out, net rad, sensible, latent, melt

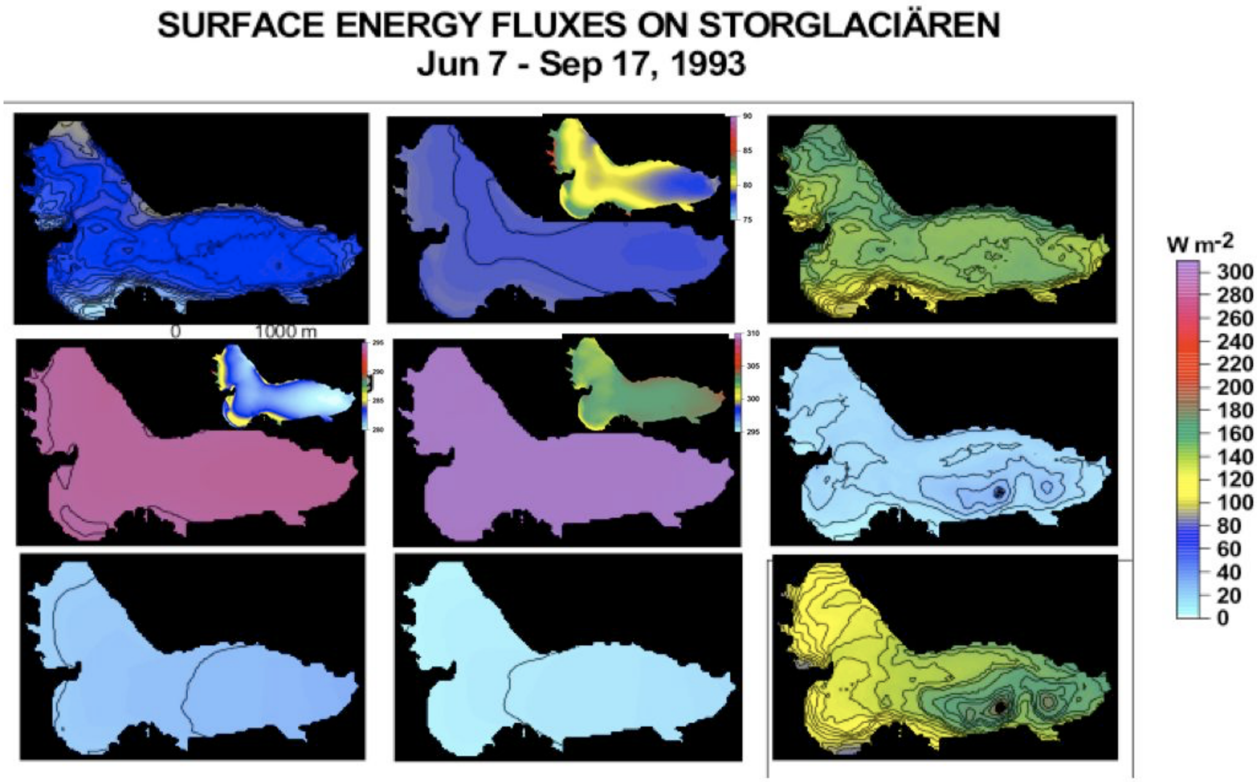

Figure 2. Calculated energy fluxes on Storglaciären, Sweden, averaged over the period 7 June to 17 September 1993. Note the smaller plots within some of the subplots show the same quantities with a different scale to better visualize any small spatial variations.

Additional exercises (optional) if time permits:

5.) EFFECT OF CLOUDS ON MELT

Assume a clear sunny day on a melting glacier in summer, suddenly thick low clouds start moving in: How will net radiation change? (Use numbers for illustration, for example assume G=600 Wm^{-2} (clear-sky), G=100 or 200 Wm^{-2} (cloudy);
Longwave incoming radiation L_{in} is typically around 250 W m^{-2} during a sunny summer day, while it is around 300 W m^{-2} during foggy conditions. Longwave outgoing radiation is fixed when the surface is melting.
(Clouds affect value of albedo but this should be neglected here in your considerations; assume that the albedo is constant).

Answer: Global radiation will go down, longwave radiation will go up.
The net effect on net radiation depends on the albedo, if albedo is very high, the change in net shortwave radiation does not change very much because almost all is reflected (>90%), so that the change in net longwave radiation may be bigger and the net effect that the radiation may turn positive in extreme cases.

6.) EFFECT OF RAIN ON MELT

Assume a rainy day with 10 mm d^{-1}. Daily mean near-surface air temperature is 10ºC. Calculate the rain heat flux and compare it to typical values of net radiation and the turbulent heat fluxes (see Figure 2 and 3).

$$Q_R = \rho_w c_w R(T_r - T_s)$$

ρ_w = density of water (1000 kg/m3)
c_w = specific heat of water, 4180 J kg^{-1} K^{-1}
R = rain intensity (e.g. mm/day)
T_r = rain temperature (K or Celcius)
T_s = glacier surface temperature (K or Celcius); assume melting surface

Answer:
1000 x 4180 x 0.015 m/d x 10 /(3600*24) = **4.8 W/m2**
(Division by 3600*23 to account for conversion of days to seconds (Rain heat flux is in W/m2, i.e. J/s/m2).

Note that even with this heavy and relative warm rainfall, the energy supplied by the sensible heat of rain is small compared to the other heat fluxes, and over longer periods (that include days without rain) usually negligible. However, rain can have indirect effects and thereby increase melt, e.g. decrease in albedo as snow becomes wet or mechanical removal of snow by water.