The ice sheet surface energy balance

motivated by considering future ice sheet change

nature climate change

REVIEW ARTICLE

https://doi.org/10.1038/s41558-018-0305-8

The Greenland and Antarctic ice sheets under 1.5 °C global warming

Frank Pattyn[1*], Catherine Ritz[2], Edward Hanna[3], Xylar Asay-Davis[4,5], Rob DeConto[6], Gaël Durand[2], Lionel Favier[1,2], Xavier Fettweis[7], Heiko Goelzer[1,8], Nicholas R. Golledge[9,10], Peter Kuipers Munneke[8], Jan T. M. Lenaerts[11], Sophie Nowicki[12], Antony J. Payne[13], Alexander Robinson[14], Hélène Seroussi[15], Luke D. Trusel[16] and Michiel van den Broeke[8]

Even if anthropogenic warming were constrained to less than 2 °C above pre-industrial, the Greenland and Antarctic ice sheets will continue to lose mass this century, with rates similar to those observed over the past decade. However, nonlinear responses cannot be excluded, which may lead to larger rates of mass loss. Furthermore, large uncertainties in future projections still remain, pertaining to knowledge gaps in atmospheric (Greenland) and oceanic (Antarctica) forcing. On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.

Antarctica

- Long term mass balance increase due to warmer air causing more snowfall
- Potential loss of buttressing support from ice shelves
- Grounding line retreat and the marine ice sheet instability
- Open question: how does global warming relate to ocean dynamics that melt ice shelves?
- Open question: will Antarctic soon experience enough surface melt to have significant runoff?
- **The "standard thinking" about Antarctica is that change will originate from interactions with the *oceans*.**

Greenland

- Greenland has warmed by ~ 5 °C in winter and ~ 2 °C in summer since the mid-1990, which is more than double the global mean warming rate in that period.
- 70% of mass loss (2000-12) was due to melt and subsequent runoff.
- Open research project: What is the temperature-SMB relationship? Challenging because of: jet structure, cloud formation, …
- Melt-albedo feedback. Melting -> lower albedo -> more melting
- SMB-elevation feedback: melting -> lower elevation -> lapse rate -> more melting. Contributes 11% of change under a low-emissions scenario.
- **The "standard thinking" about Greenland is that change will originate from interactions with the *atmosphere*.**

Glacier meteorology and the surface energy balance

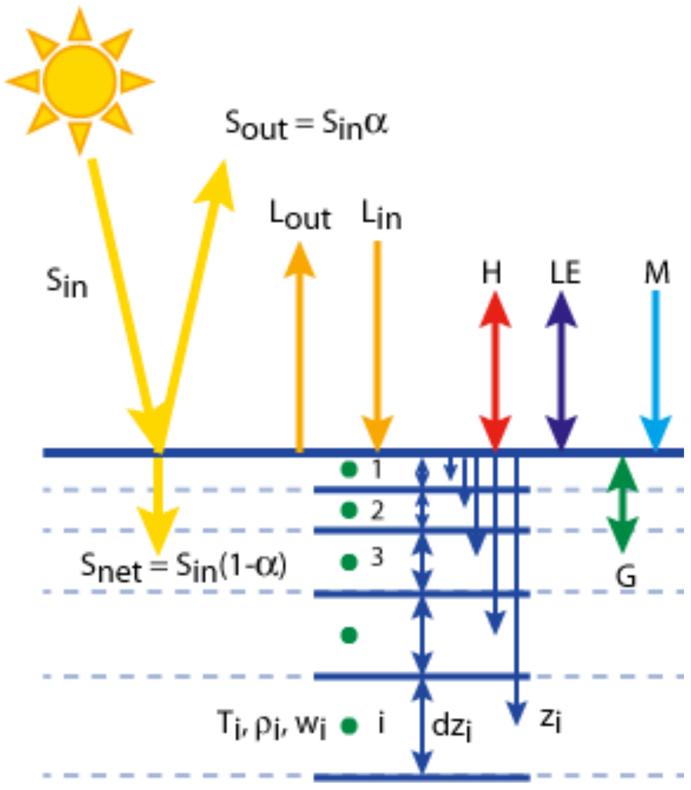
material heavily borrowed from the McCarthy Glaciology Summer School run by UAF as well as Cuffey and Paterson

The Energy Balance

- Ice melts at 0 C, but not necessarily when the air temperature is 0 C.
- Whether or not melting occurs depends on the energy balance:

1. Net short wavelength radiation
2. Net long wavelength radiation
3. Sensible heat flux
4. Latent heat flux
5. Ground heat flux
6. Precipitation heat flux

$$E = E_s + E_L + E_g + E_h + E_e + E_p$$



racmo

Outgoing longwave radiation, Stefan-Boltzmann law

- All matter radiates electromagnetic energy to its surroundings.
- A material that emits the maximum possible amount of radiation at a given temperature is called a *perfect radiator*, or a *black body*.
- Black body radiation follows the Stefan-Boltzmann Law,

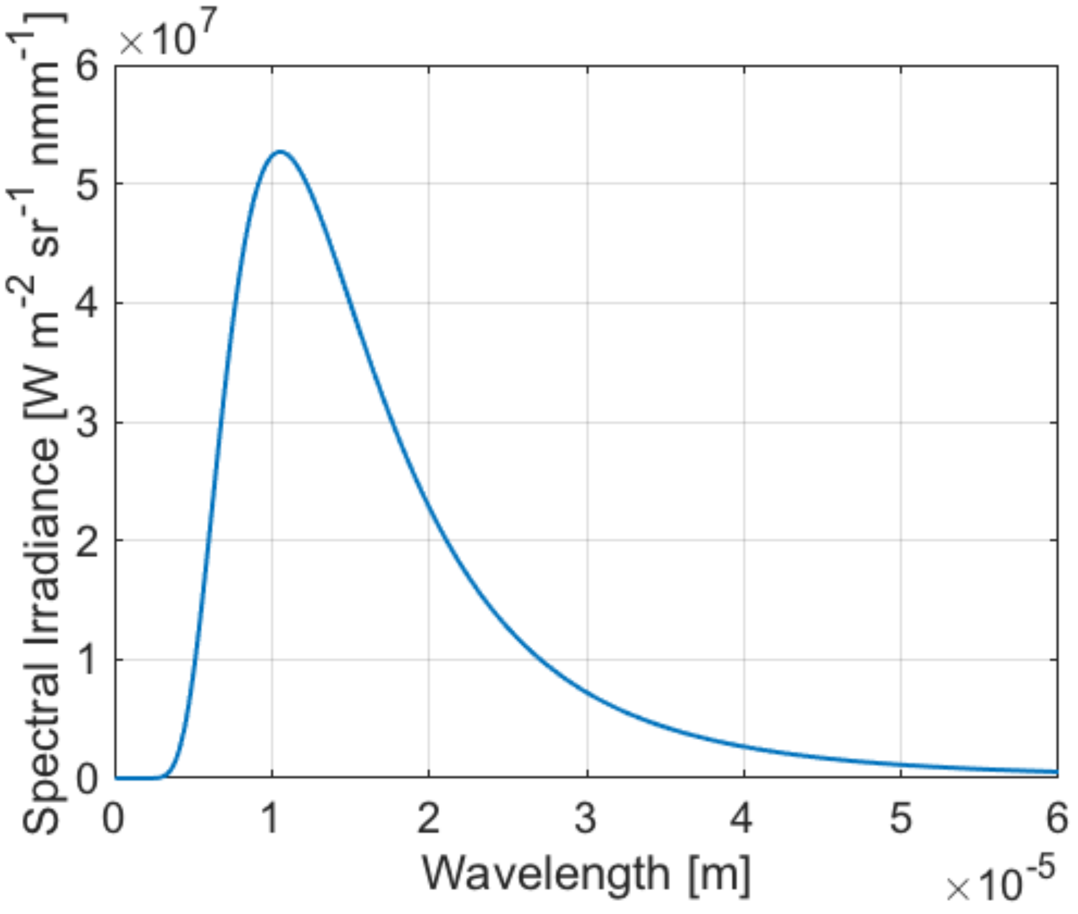
$$E_L^{out} = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2\ ^\circ K^4)}$$

- An icy surface at 0 C = 273.15 K therefore has an outgoing energy flux of **316 W/m^2** . Note that this amount is fixed as long as the surface is at the melting point. At the start of the melt season outgoing longwave might be less if the ice hasn't thawed to 0.

Radiation, Planck’s law

- Stefan-Boltzmann describes radiation over the entire spectrum.
- Planck’s law describes the distribution of this radiation over the spectrum.
- Objects at 273.15 K radiate in the infrared band.



If snow is a nearly perfect black body, why is it so reflective?

Incoming longwave radiation

- Incoming longwave radiation from the atmosphere also follows the Stefan-Boltzmann relation

$$E_L^{in} = \epsilon\sigma T_{atm}^4$$

- Unlike snow, the atmosphere is a less than perfect radiator and so the emissivity epsilon must be considered. For cloudy skies, epsilon~0.95 but for clear skies epsilon~0.5.

Radiation, shortwave and longwave

- The sun is about 6000 K and the Earth is about 300 K. The resulting radiation spectra have very little overlap.
- For this reason it makes sense to divide the spectra into two groups:
  - Longwave (5 to 50 um)
  - Shortwave (0.3 to 2.8 um)
- *If snow is a nearly perfect black body, why is it so reflective?*
  - Snow mostly emits radiation in the longwave band, and so its high emissivity is unrelated to its high albedo.

Radiation and albedo

Each radiation term (longwave and shortwave) has an incoming and outgoing component. The total radiation is then

$$\begin{aligned} E_r &= E_L + E_S \\ &= E_L^{in} - E_L^{out} + E_s^{in} - E_s^{out} \\ &= E_L^{in} - E_L^{out} + E_s^{in}(1-\alpha) \end{aligned}$$

The ratio between outgoing and incoming shortwave radiation is the **albedo,** α.

Radiation and albedo

The ratio between outgoing and incoming shortwave radiation is the **albedo, α**

 Cuffey and Paterson

Table 5.2: Characteristic values for snow and ice albedo, from a literature review by S.J. Marshall.

Surface type	Recommended	Minimum	Maximum
Fresh dry snow	0.85	0.75	0.98
Old clean dry snow	0.80	0.70	0.85
Old clean wet snow	0.60	0.46	0.70
Old debris-rich dry snow	0.50	0.30	0.60
Old debris-rich wet snow	0.40	0.30	0.50
Clean firn	0.55	0.50	0.65
Debris-rich firn	0.30	0.15	0.40
Superimposed ice	0.65	0.63	0.66
Blue ice	0.64	0.60	0.65
Clean ice	0.35	0.30	0.46
Debris-rich ice	0.20	0.06	0.30

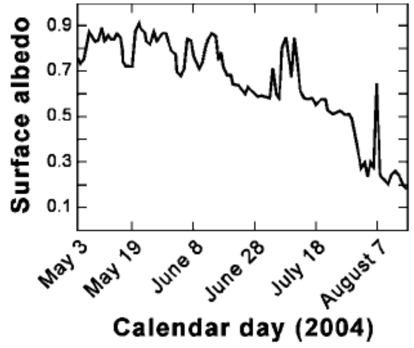
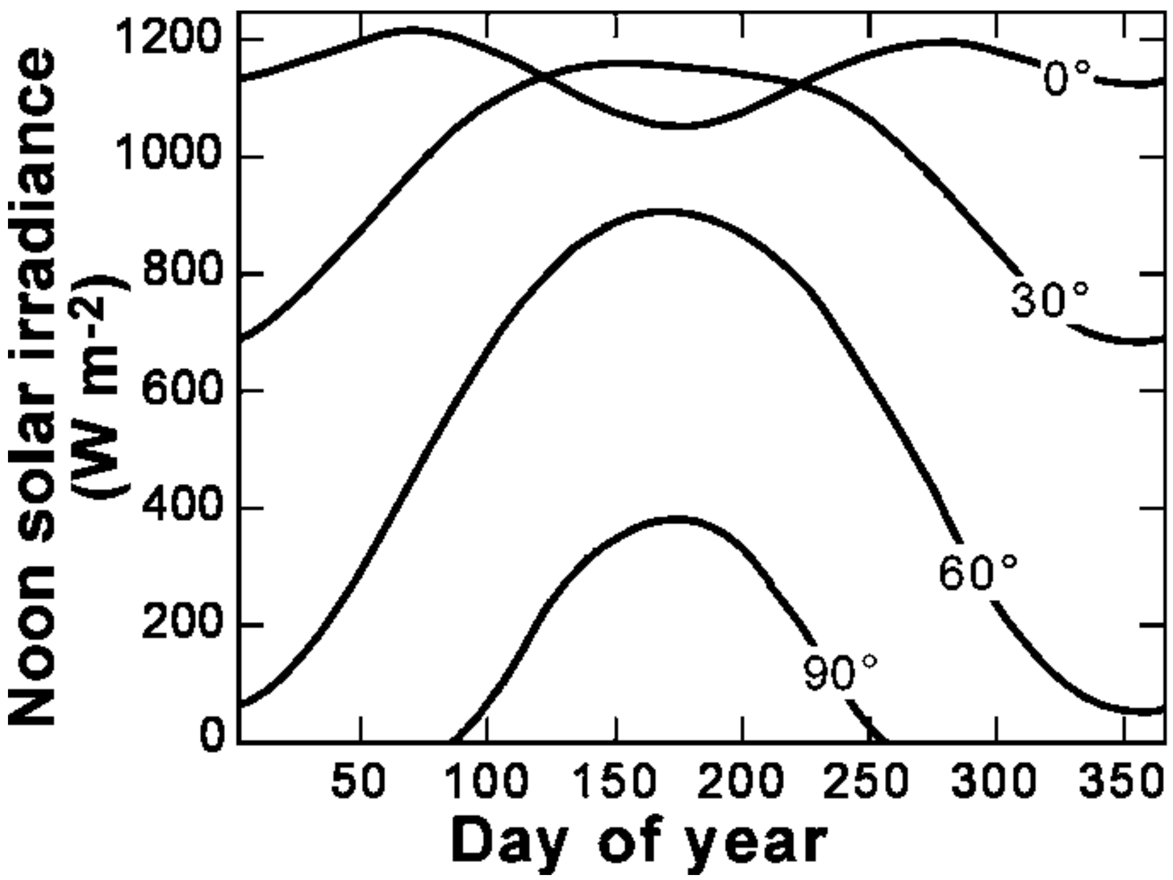


Figure 5.3: Variation of surface albedo in summer of 2004 at one location on Haig Glacier (data from Shea et al. 2005, courtesy of S.J. Marshall). Shown is the average mid-day (10:00–15:00) albedo, based on one-minute measurements by upward- and downward-looking radiometers. Rapid surface brightening (for example, on Aug. 6) occurs when new snow covers the surface. The transition from snow cover to bare glacier ice occurred July 28–30.

Incoming shortwave

- The top-of-atmosphere solar flux is E0 ~ 1367 W/m^2.
- **Direct** solar radiation is $\Psi E_0 \cos Z$
  - Z is the zenith angle (angle from vertical)
  - The transmissivity Psi(P,Z) between 0 and 1 and is 0.84 for clear sky
- **Diffuse** light may often also contribute, which can be modelled with an effective transmissivity, $\Psi_* E_0 \cos Z$
- A typical, seasonally-averaged Psi-star value for GrIS is 0.7, for a mountain glacier 0.5.



Turbulent sensible and latent heat fluxes

- Warm air flowing over ice adds sensible heat to the surface.
- Dry air flowing over ice removes moisture and therefore latent heat.
- Both of these processes occur through mixing in a *turbulent boundary layer.*

$$E_H = \rho_a c_a C_{\mathrm{H}}\, u\,[T_a - T_s]$$

$$E_E = \rho_a L_{v/s} C_{\mathrm{E}}\, u\,[q_a - q_s]$$

- C_E and C_H are *bulk exchange parameters*, u is the velocity, q is the moisture content, T is temperature, rho is density, c is the specific heat, and L is the latent heat.

Servicing the G3 AWS on the Amery Ice Shelf. (Photo: D. Colborne)

Ground heat flux

- Energy is required to heat up the ice "ground" surface

$$Q_g = \int_0^z \rho c_p \frac{\partial T}{\partial t} dz$$

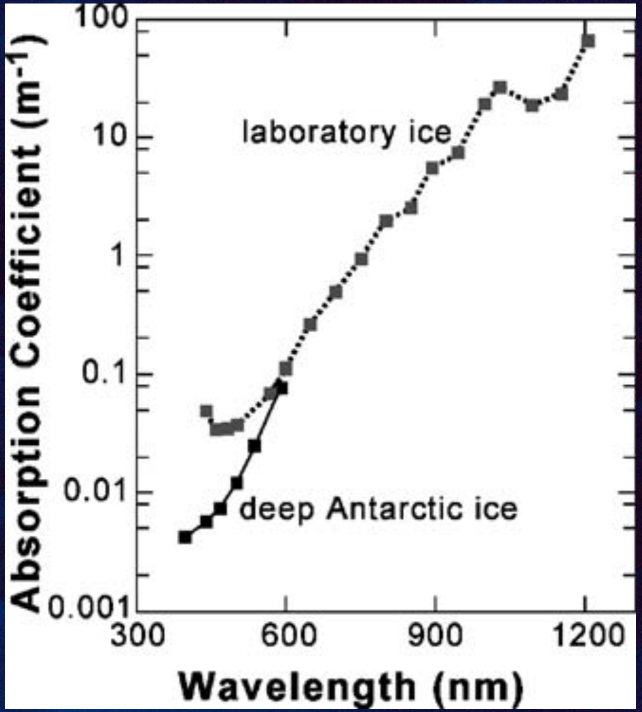
For temperature T, density rho, and specific heat capacity cp

Why does glacier ice look blue or white?

The shortwave radiative flux decreases at depth according to

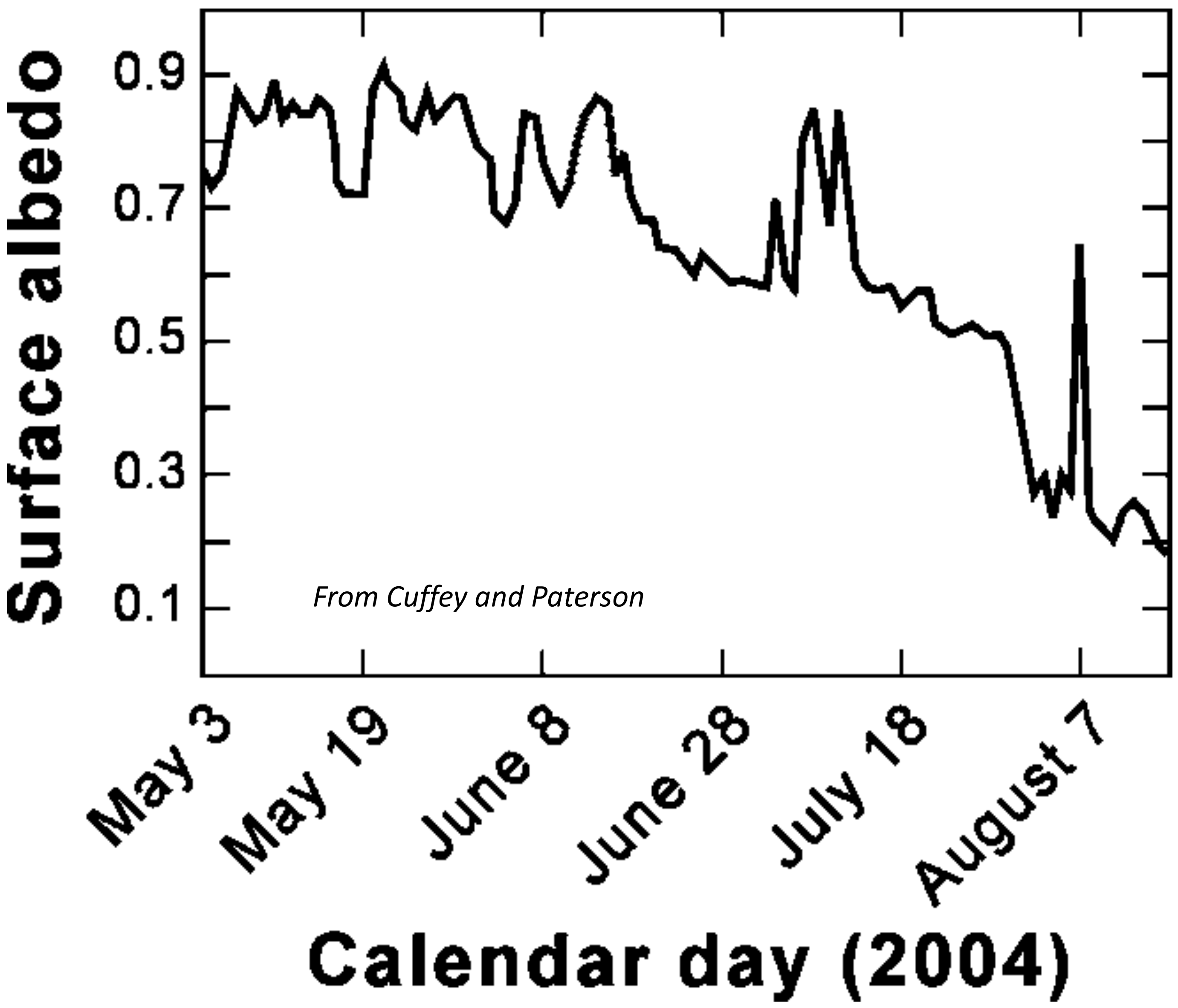
$$E_S^{in} \exp[-\chi \ell(z)]$$

where chi is the absorption coefficient.



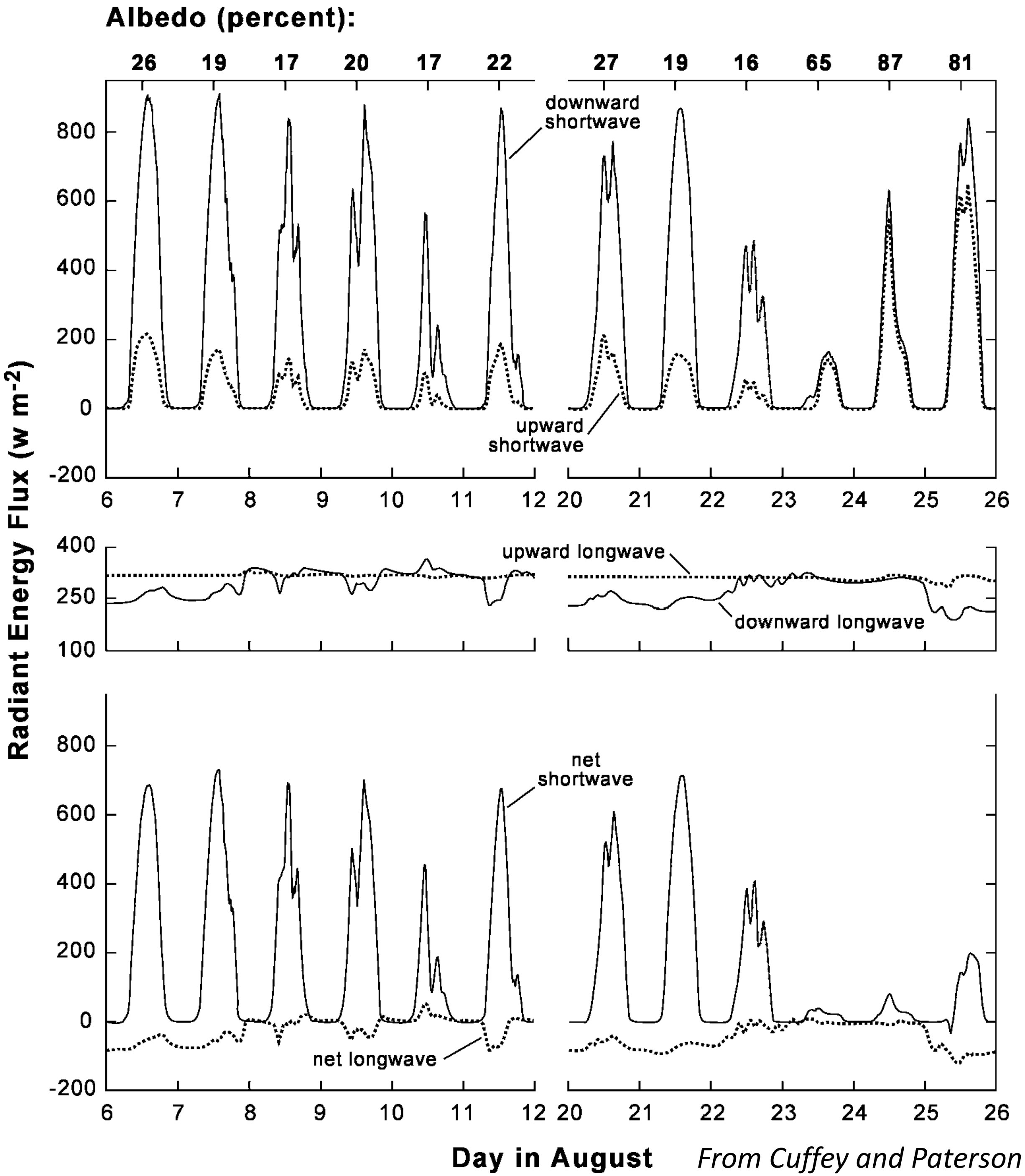
Case study
Haig Glacier, Alberta, Canada, 50.7 N

https://backcountryskiingcanada.com/


Surface albedo
0.9
0.7
0.5
0.3
0.1
From Cuffey and Paterson
May 3
May 19
June 8
June 28
July 18
August 7
Calendar day (2004)

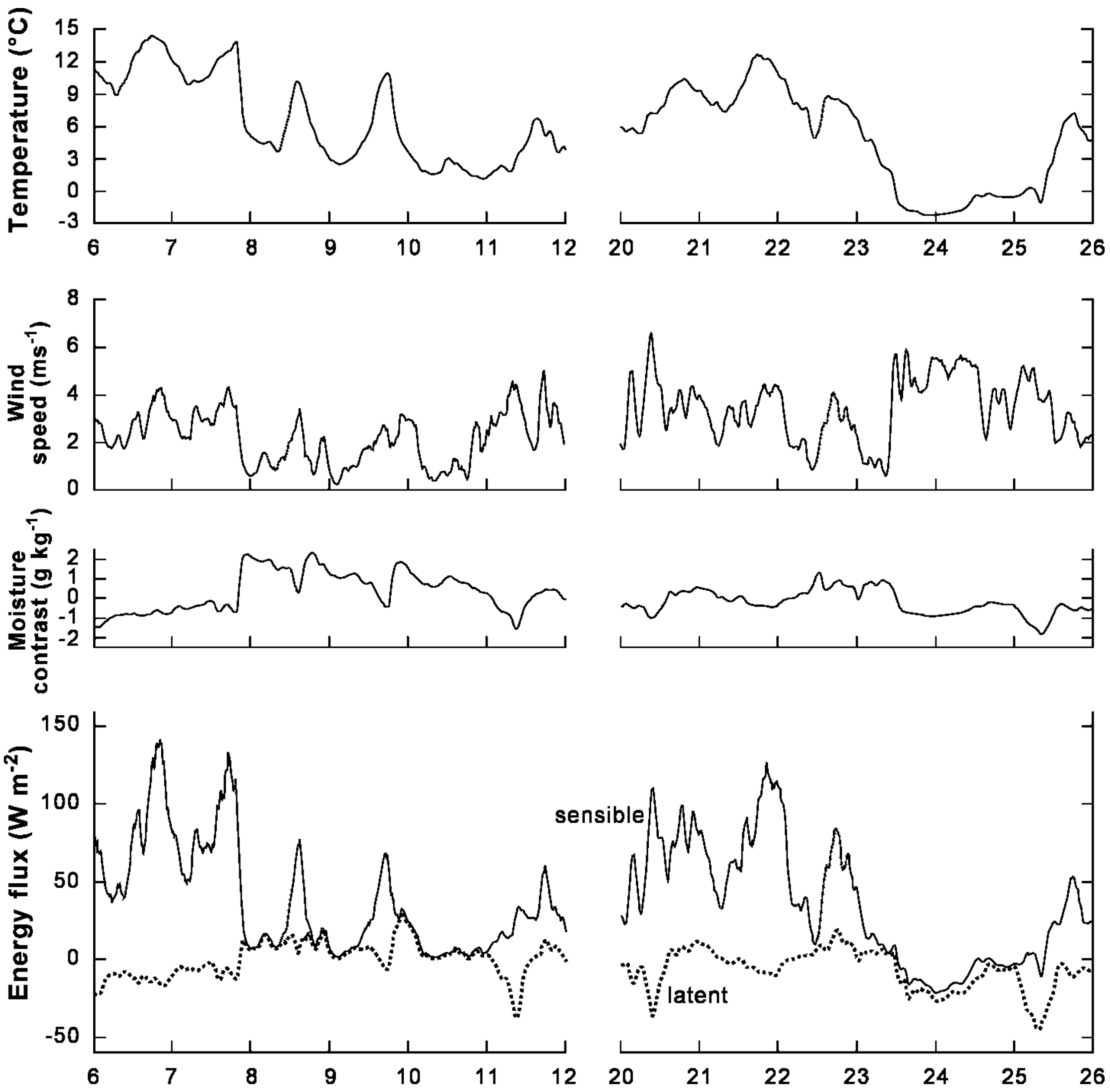
Field example: Radiant Fluxes

1. *Where is the biggest snowfall event? How can you tell? What is the total effect on the energy budget?*
2. *Why is there anticorrelation between net shortwave and net longwave?*
3. Where on the glacier was this site located?
4. *Why do both records start during sunny periods?*



From Cuffey and Paterson

Field Example: Turbulent Fluxes



From Cuffey and Paterson

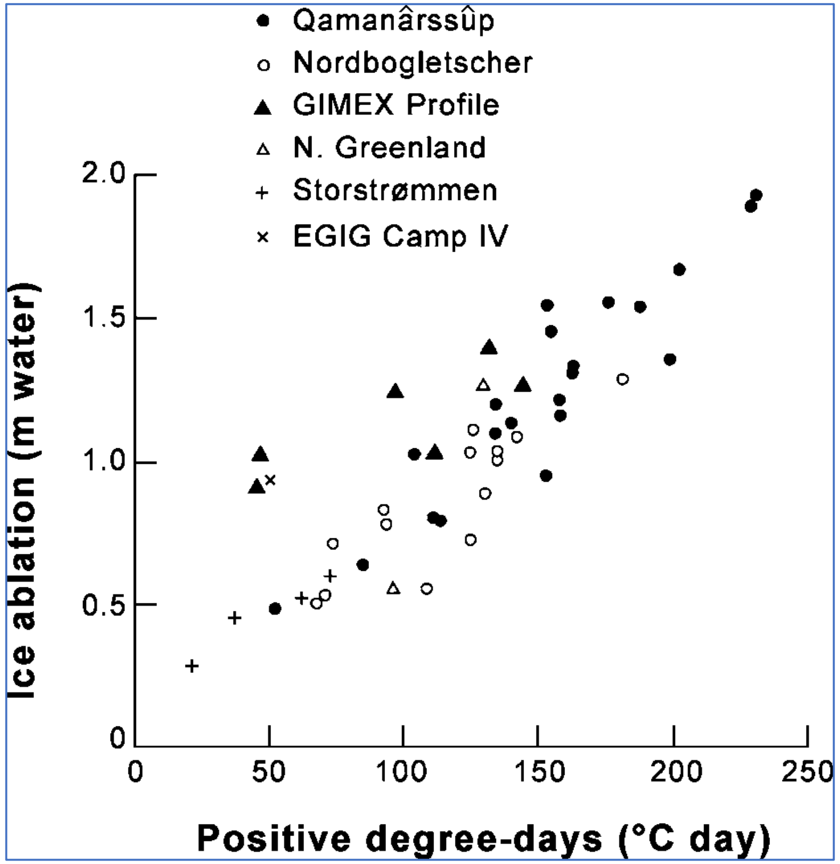
Modeling melting

Melting occurs when the glacier surface is

1. At the melting point, and
2. Has a positive net energy budget, $E > 0$

The resulting melt rate is, $\dot{m} = \dfrac{E}{\rho L_f}$

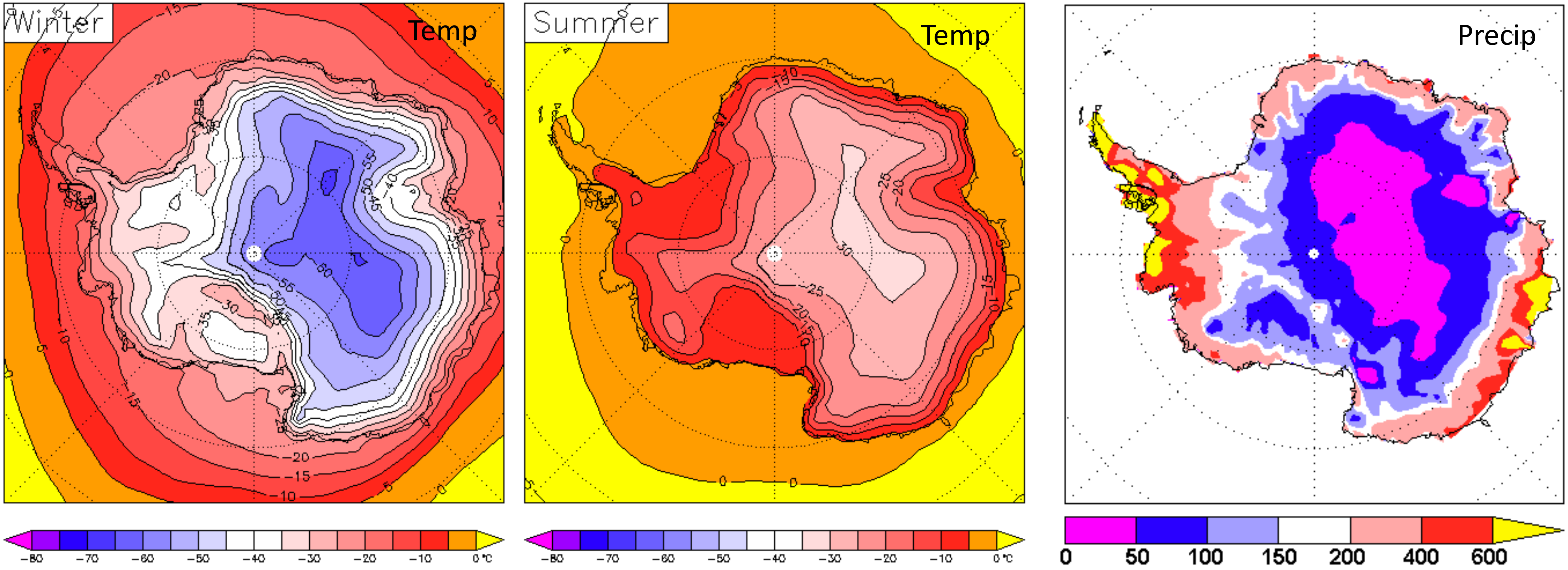
In practice, a "positive degree day" model is most commonly used.



From Cuffey and Paterson

Energy Balance Regimes

Energy Regimes: The coldest climates



Energy Regimes: The coldest climates

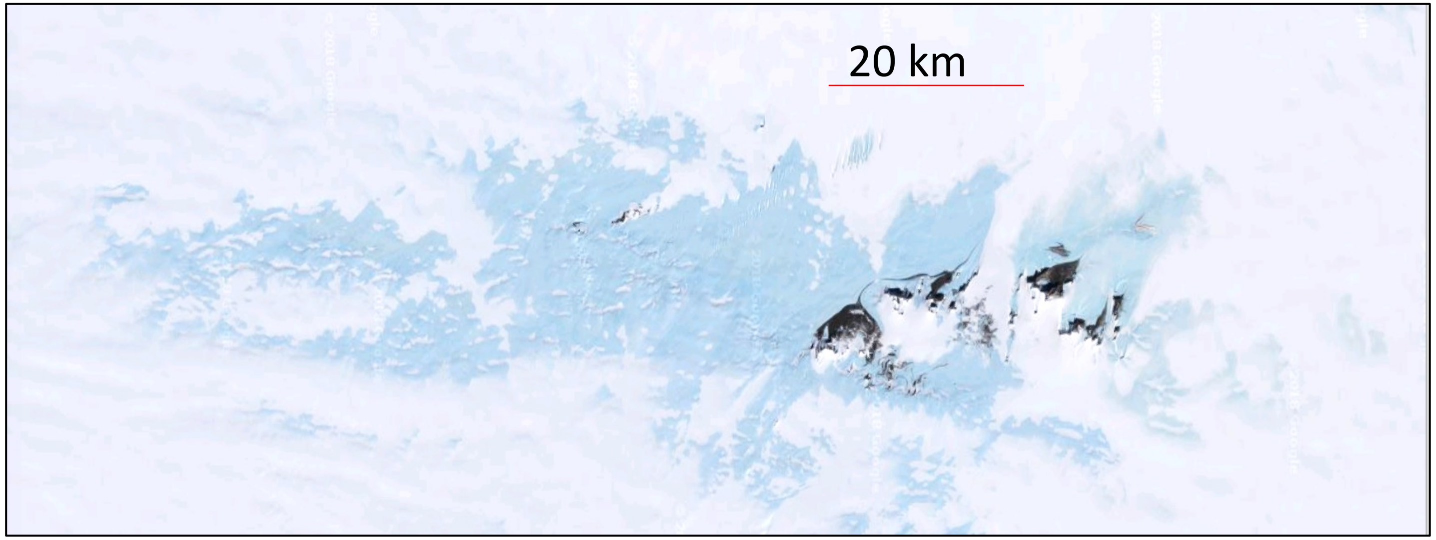
- Surface temperatures are well below freezing -> A positive energy balance results in *heating* rather than *melting.*

1. *Why does the sensible heat flux change sign seasonally?*
2. *What contributes to the radiative energy in the different seasons?*
3. *Why does the latent heat flux increase in the winter?*

Site	Elevation	Season	E_R	E_H	E_E
Vostok	3400 m	Summer	32	−25	−2
		Winter	−17	15	0
Mizuho	2230 m	Summer	20	−7	−8
		Winter	−38	37	0
Maudheim	37 m	Summer	9	6	†
		Winter	−22	13	†

† Not measured. *From Cuffey and Paterson*

Energy Regimes: Blue Ice Zones



1. How does the incident shortwave compare to the Canadian glacier example?

2. Why does the blue ice zone exist?

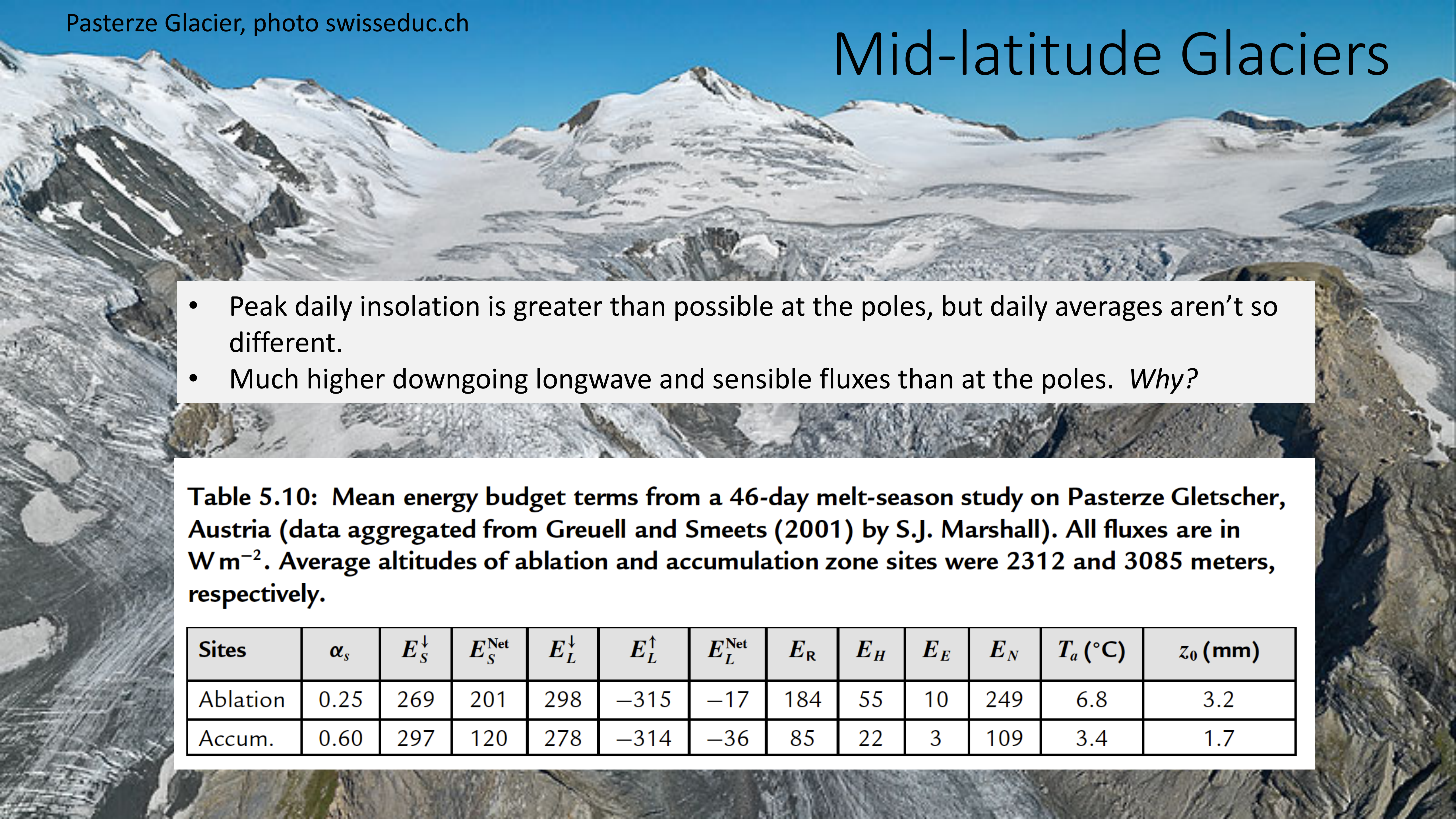
Table 5.9: Summer energy budget (W m^{-2}) for snow and blue ice areas in Dronning Maud Land, Antarctica (Bintanja 2000). Values are averages for N sites in each row.

Sites	α_s	$E_S^{\downarrow}$	E_S^{Net}	$E_L^{\downarrow}$	$E_L^{\uparrow}$	E_L^{Net}	E_{R}	E_H	E_E	E_G	N
Snow	0.82	334	63	185	−254	−69	−6	16	−9	−1	4
Blue ice	0.64	356	121	192	−279	−87	34	2	−26	−11	3

From Cuffey and Paterson

Mid-latitude Glaciers

Pasterze Glacier, photo swisseduc.ch



Pasterze Glacier, photo swisseduc.ch

Mid-latitude Glaciers

- Peak daily insolation is greater than possible at the poles, but daily averages aren't so different.
- Much higher downgoing longwave and sensible fluxes than at the poles. *Why?*

Table 5.10: Mean energy budget terms from a 46-day melt-season study on Pasterze Gletscher, Austria (data aggregated from Greuell and Smeets (2001) by S.J. Marshall). All fluxes are in $\mathrm{W\,m^{-2}}$. Average altitudes of ablation and accumulation zone sites were 2312 and 3085 meters, respectively.

Sites	α_s	$E_S^{\downarrow}$	E_S^{Net}	$E_L^{\downarrow}$	$E_L^{\uparrow}$	E_L^{Net}	E_R	E_H	E_E	E_N	T_a (°C)	z_0 (mm)
Ablation	0.25	269	201	298	−315	−17	184	55	10	249	6.8	3.2
Accum.	0.60	297	120	278	−314	−36	85	22	3	109	3.4	1.7


Low-latitude
Glaciers

Low-latitude Glaciers

- Low-latitude glaciers occur at high altitudes.
- At high altitude, low temperatures and dry air are common.
- The tropics have dry versus wet seasons due to seasonal migration of the ITCZ. Two wet seasons occur nearer the equator, in the “inner” tropics.

Zongo Glacier, Cordillera Real, Bolivia

- Which season is the primary ablation season? What drives ablation?
- Why is it important that the latent heat of sublimation is 8.5 times greater than the latent heat of melting?

Table 5.11: Energy balance and meteorological data from Zongo Glacier, Bolivia (Wagnon et al. 1999a). Data are for the hydrological year September 1996 to August 1997. Wet and dry seasons are November–February and May–August, respectively. All fluxes are in W m^{-2}.

Period	α_s^1	$E_S^{\downarrow}$	E_S^{Net}	E_L^{Net}	E_R	E_H	E_E	T_a (°C)	q (g/kg)	m_s (mm)	Subl. (mm)	f_E
Wet season	0.66	196	67	−54	13	4	−7	−0.3	5.8	327	27	0.41
Dry season	0.52	220	106	−95	11	9	−31	−3.8	4.4	107	117	0.90

[1] Based on the mean measured daily minimum albedo.

Thank you!