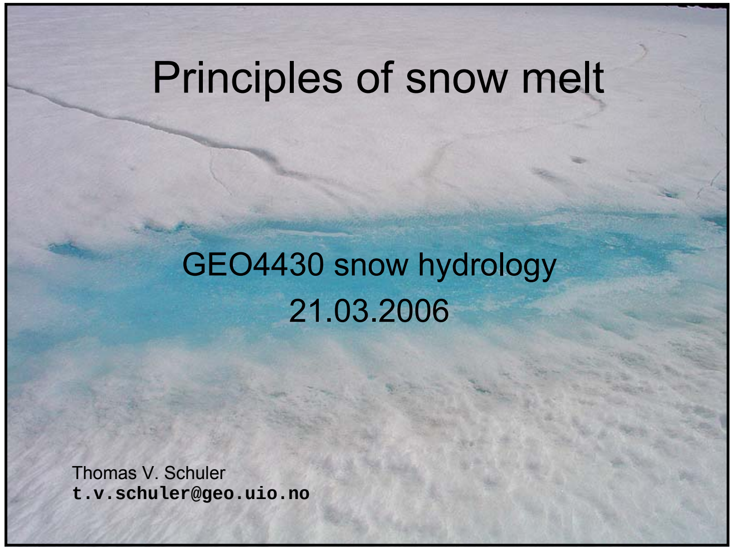


Principles of snow melt

GEO4430 snow hydrology

21.03.2006

Thomas V. Schuler
t.v.schuler@geo.uio.no

How does snow melt?

- We need energy to melt snow/ ice.

$$E = m_s \cdot L_f$$

$$\ldots = \rho_w h_{we} \cdot L_f$$

$$h_{we} = \frac{E}{\rho_w L_f}$$

E – energy (J)
m_s – mass (kg) of snow
L_f – latent heat of fusion = 333400 J kg^{-1}
ρ_w – density (kg m-3) of water
h_{we} – height of snow (m w.e.)

- Energy flux onto a unit surface:

Q (Wm^{-2}) = E (J) / t (s)

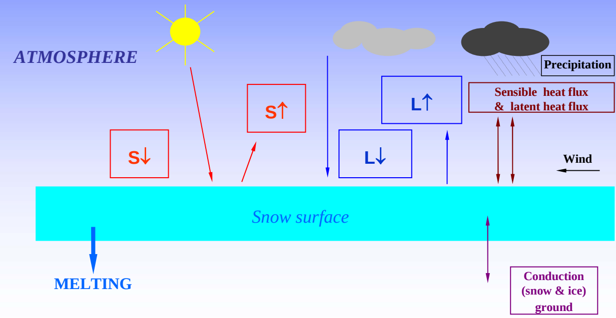
Amount of energy per unit time

Where does the energy come from?

Energy balance

$$0 = Q_R + Q_H + Q_L + Q_G + Q_P + Q_M$$

$$Q_R = S\downarrow - S\uparrow + L\downarrow - L\uparrow$$



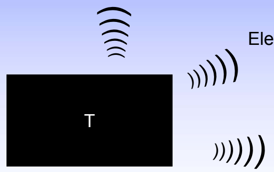
Radiation

- Black body radiation (Stefan-Boltzmann law)

  $Q = \sigma T^4$

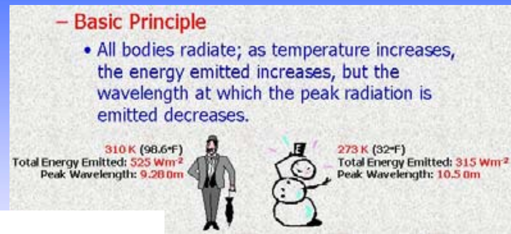
  $\sigma = 5.6703 \cdot 10^{-8}\ W\ m^{-2}\ K^{-1}$

Electromagnetic radiation



Real world:
Gray body radiation
$Q = \varepsilon \sigma T4$
ε – emissivity [0,1]

Radiation

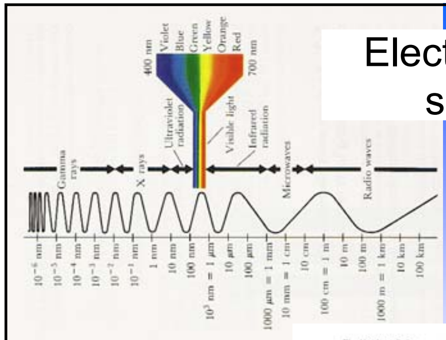


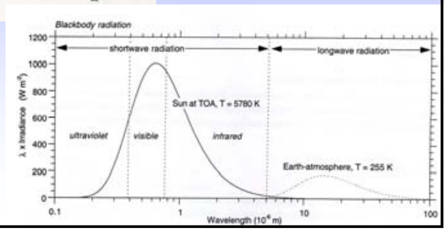
Wien's law:

$\lambda_{max} = 2.88 \cdot 10^{-3}\ T^{-1}$

[m] [m K] [K]

Electromagnetic spectrum





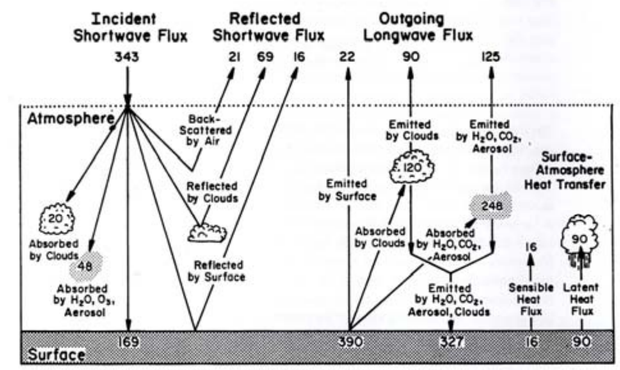


Figure 1.6 Estimated average energy budget of the Earth-atmosphere system (from Liou, 1980).

Radiation

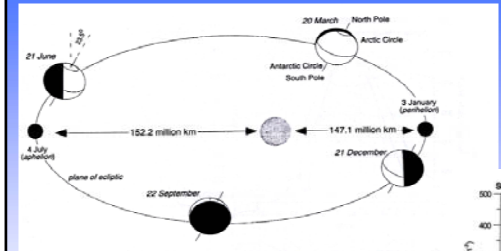


Figure 1.2 Present-day shape of the Earth's orbit around the Sun and its relationship to solstices and equinoxes.

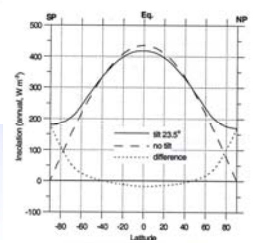


Figure 1.3 Annual mean insolation at the top of the atmosphere with/without tilt of the Earth's axis.

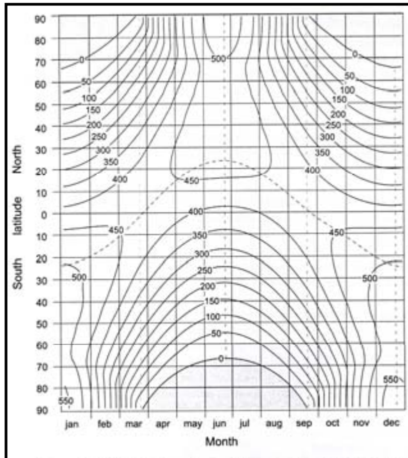


Figure 1.5 Daily insolation at the top of the atmosphere (W m⁻²). Vertical dashed lines indicate the equinoxes and solstices, curved dashed line the inclination of the Sun.

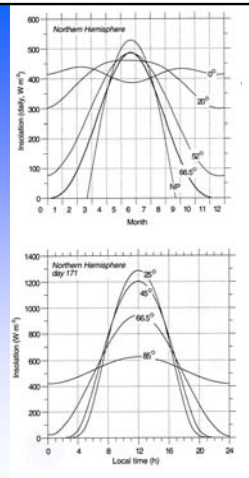
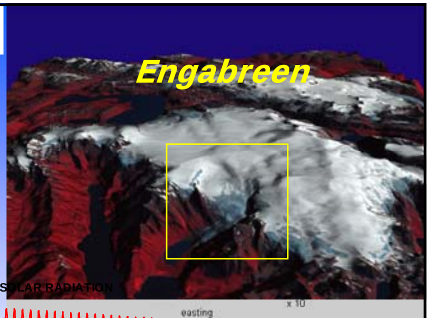


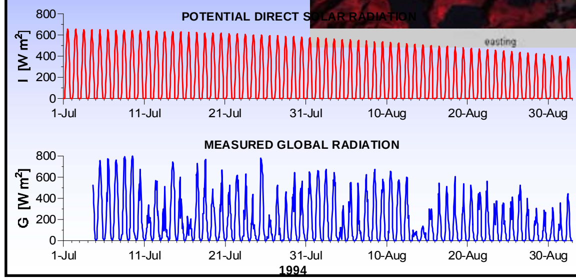
Figure 1.4 Daily mean insolation at the top of the atmosphere for 5 Northern Hemisphere latitudes (a, left) and daily cycle for day 171 (June 21)(b, right).

DEM of 25m resolution

GLOBAL RADIATION

- **S: 0.15-5 μm**
- **Direct / diffuse component**



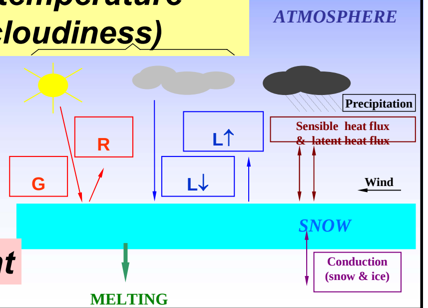


Longwave radiation

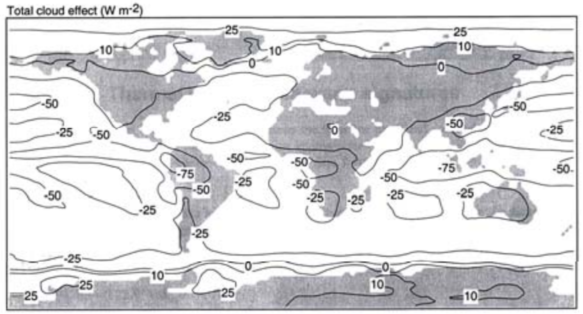
- ***4-120μm***
- ***Emitted by atmosphere (water vapour, CO_2, ozone)***
- ***Function of air temperature and humidity (cloudiness)***

$L\uparrow = \varepsilon \sigma T^4$
Max = 316 Wm^2

L acts day & night



Cloud effect:



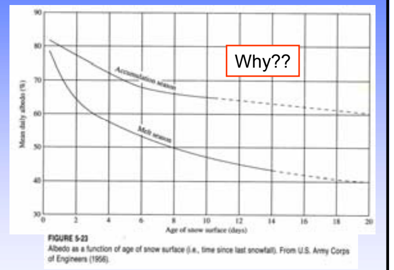
Effect of clouds on the annual mean net radiation at the surface. The total cloud effect is obtained by comparing the net radiation for clear-sky conditions with those for average conditions, i.e. with clouds.

Why are values positive in polar regions???

reflexion

shortwave reflectance = albedo

new snow	0.75 – 0.95
old snow	0.4 – 0.7
glacier ice	0.3 – 0.45
soil, dark	0.1
grass	0.2
rain forest	0.15



Longwave reflectance of snow: < 0.1

reflectance = 1 - emissivity

snow is dark on IR image!

snow emits a lot L↑

Turbulent heat fluxes

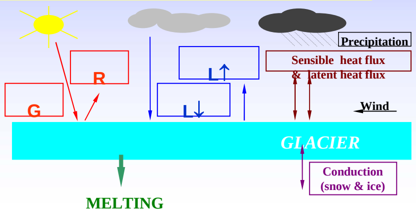
Sensible heat flux

- **Function of temperature gradient**
- **Function of wind speed**

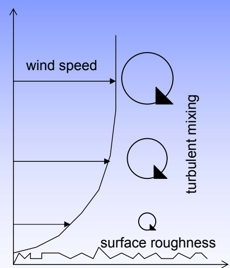
Latent heat flux

- **Function of vapour pressure gradient**
- **Function of wind speed**

Fluxes also affected by
- **Surface roughness**
- **Atmospheric stability**



Turbulent exchange



Momentum (τ)	$\rho_a K_M \frac{\partial u}{\partial z}$
Heat (H)	$\rho_a C_p K_H \frac{\partial \theta}{\partial z}$
Water vapor (E)	$\rho_a L_v K_W \frac{\partial q}{\partial z}$

ρ_a is air density
u is wind velocity (m s^{-1})
θ is potential temperature (K)
q is the specific humidity (dimensionless)
C_p is the specific heat of air (1.005 x 10^3 J kg^{-1} deg K^{-1})
L_v is the latent heat of vaporization
K_M is the eddy diffusivity for momentum (m^2 s^{-1})
K_H is the eddy diffusivity for heat in air (m^2 s^{-1})
K_W is the eddy diffusivity for water vapor in air (m^2 s^{-1})

Melt physics

- To melt 1 kg snow/ice requires 334 000 J kg^{-1} **Latent heat of fusion**
- To sublimate 1 kg of snow requires 2 600 000 J kg^{-1} **Latent heat of sublimation (8x L_f !!!)**
- To warm 1 kg of snow 1 K requires 2009 J kg^{-1} K^{-1}; ice: 2097 J kg^{-1} K^{-1} **Specific heat capacity**

Refreezing of 1 g water → warms 160 g snow by 1 K

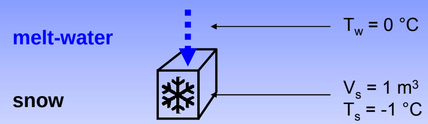
Dry conditions:
Sublimation of snow occurs
$L_s = 8 * L_f$ → 8x less ablation than under wet conditions

Melt physics

- To melt 1 kg snow/ice requires 334 000 J kg^{-1} **Latent heat of fusion**
- To sublimate 1 kg of snow requires 2 600 000 J kg^{-1} **Latent heat of sublimation (8x L_f !!!)**
- To warm 1 kg of snow 1 K requires 2009 J kg^{-1} K^{-1}; ice: 2097 J kg^{-1} K^{-1} **Specific heat capacity**

Refreezing of 1 g water → warms 160 g snow by 1 K

Removing cold content



Condition for melt: snow must be at melting temperature, otherwise refreezing will occur

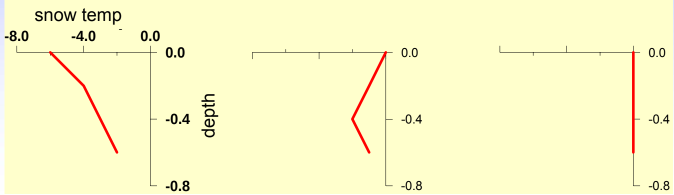
Cold content = energy needed to bring the snow / ice to 0 °C.

In the given example, refreezing of 2.5 l melt-water is needed to compensate for the cold content of the snow pack (snow density, ρ_s=400 kg m^{-3}).

Cold content

$$Q_{cc} = C_i \, \rho_s \, h_s \, (T_s - T_m)$$

Q_{cc} is the cold content
ρ_s is the density of snow
h_s is the snow height
C_i is the specific heat of ice
T_s is average snow temperature in K or C
T_m is the melting temperature of ice in K or C



Precipitation…

- Heat Advected by Rain on Snow (Q_p)
  - First Case
  - Rainfall on a melting snow pack, where the rain does not freeze
    - $Qp = 4.2 T_r P_r$ (kJ/m²·d)
      - where T_r is the temperature of the rain (°C)
      - and P_r is the depth of rain (mm/day)
    - If $T_r = 2°C$ and $P_r = 2$ mm, then $Q_p = 16.8$ kJ/m²·d or 0.19 Wm⁻²
      - Very small compared to 800 Wm⁻² Incident Solar Radiation!

$A = C_w \, \rho_w \, P \, (T_r - T_s)$

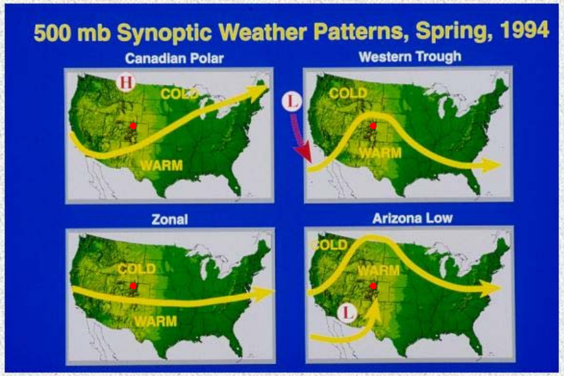
A is the advected energy, usually rain on snow, in J m^{-2} day^{-1}
C_w is the specific heat of liquid water
ρ_w is the density of liquid water
T_s is average snow temperature in K or C
T_r is the temperature of the rain
P is the precipitation amount (m day^{-1})

Energy partinioning

TABLE 5-3
Energy-Balance Components (in cal cm⁻¹) for Six Seasons at the U.S. National Weather Service–U.S. Agricultural Research Service Snow Research Station, Danville, VT

	68–69	69–70	70–71	71–72	72–73	73–74	Average	in [%]	out [%]
Accumulation Season									
Net shortwave radiation, K	4011	4096	4664	4053	2750	4580	4026	58	
Net long-wave radiation, L	−6317	−6201	−6756	−5707	−4165	−5394	−5757		92
Net radiation, $K + L$	−2306	−2105	−2092	−1654	−1415	−814	−1731		
Heat from rain, R	2	20	6	9	17	24	13	0.2	
Heat from ground, G	735	1287	770	597	628	710	788	11	
$K + L + R + G$	−1569	−798	−1316	−1048	−770	−80	−930		
Turbulent exchange, sensible, H	2311	2015	2697	2209	1562	1955	2125	31	
Turbulent exchange, latent, LE	−286	−618	−648	−584	−384	−487	−501		8
H + LE	2025	1397	2049	1625	1178	1468	1624		
Net heat input	456	599	733	577	408	1388	694		
Melt Season									
Net shortwave radiation, K	4585	3081	3889	3600	3575	4031	3794	70	
Net long-wave radiation, L	−2415	−1612	−1846	−1786	−2208	−2627	−2082		76
Net radiation, $K + L$	2170	1469	2043	1814	1367	1404	1711		
Heat from rain, R	11	15	17	30	16	28	20	0.4	
Heat from ground, G	125	85	121	102	228	222	147	3	
$K + L + R + G$	2306	1569	2181	1946	1611	1654	1878		
Turbulent exchange, sensible, H	1590	1030	1603	1573	1345	1452	1432	27	
Turbulent exchange, latent, LE	−677	−427	−565	−689	−836	−762	−659		24
H + LE	913	603	1038	884	509	690	773		
Net heat input	3219	2172	3219	2830	2120	2344	2651		

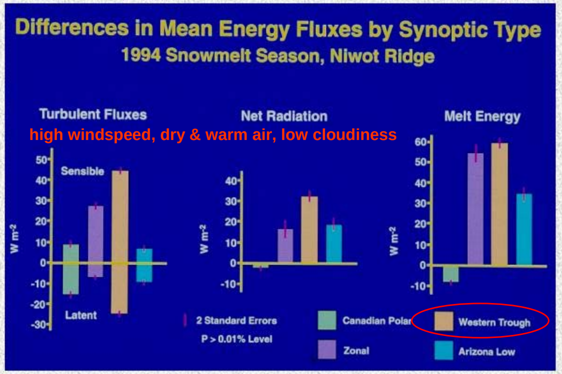
Energy Flux Partitioning



NOHRSC

Niwot Ridge, Colorado, USA

Energy Flux Partitioning

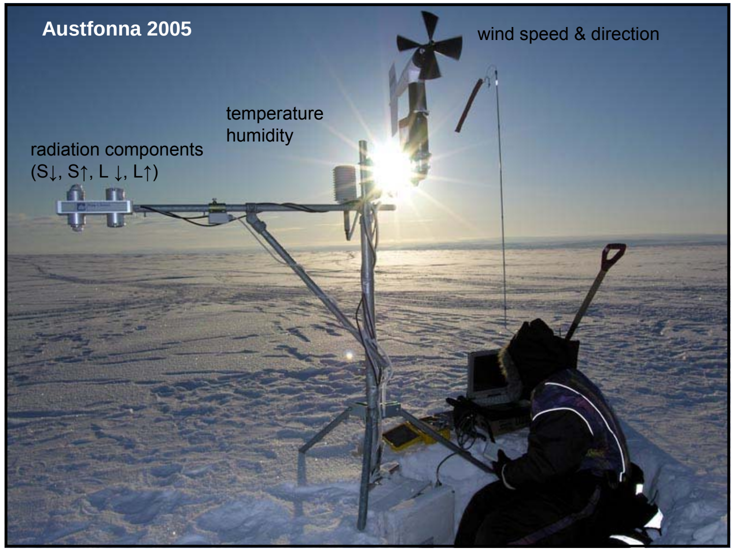


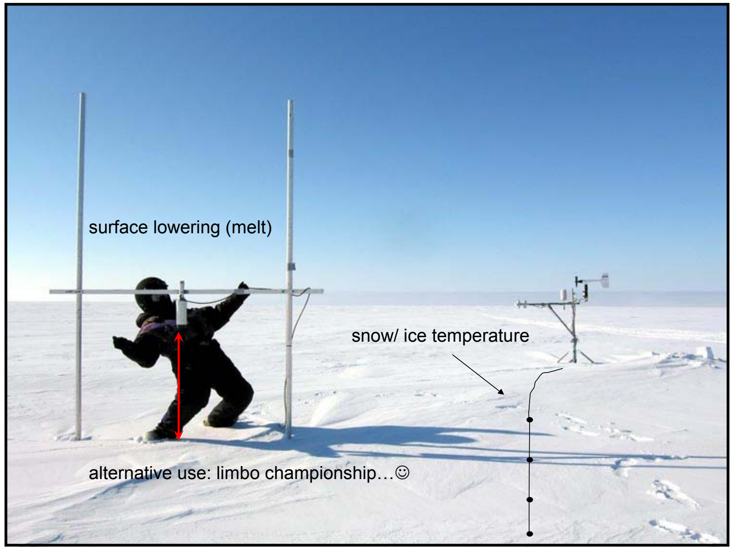
Energy partitioning (%)

Glacier	Q_R	Q_H	Q_L	Q_G	Q_M
Aletschgletscher, Switzerland	92	8	-6	0	-94
Hintereisferner, Austria	90	10	-2	0	-98
Peytoglacier, Canada	44	48	8	0	-100
Storglaciären, Sweden	66	30	5	-3	-97

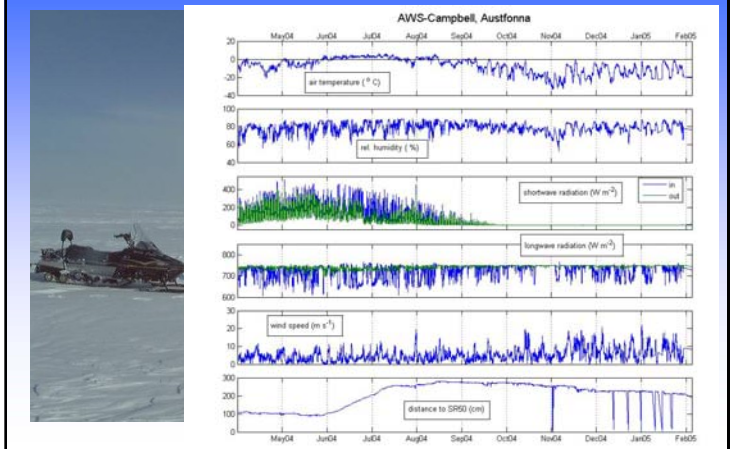
Summary

- *Ice and snow melt are determined by the energy balance*
  → Do not necessarily melt at air temperature >= 0° C
- *Snow/ice surface temperature must be raised to 0°C before melting can occur (2 steps: warming, melting)*
- *Fixed maximum surface temperature (0°C)*
  → under melting conditions: constant L↑ = 316 Wm^2, surface vapour pressure = 611 Pa
- *Often net radiation dominant source of energy*
- *Sublimation reduces energy available for melt*




surface lowering (melt)
snow/ ice temperature
alternative use: limbo championship…☺

Meteo data


AWS-Campbell, Austfonna
May04 Jun04 Jul04 Aug04 Sep04 Oct04 Nov04 Dec04 Jan05 Feb05
air temperature (° C)
rel. humidity (%)
shortwave radiation (W m-2)
in
out
longwave radiation (W m-2)
wind speed (m s-1)
distance to SR50 (cm)