
Photo: S. Knox

13 Radiation and heat transfer in water, snow and ice

Today's learning objectives

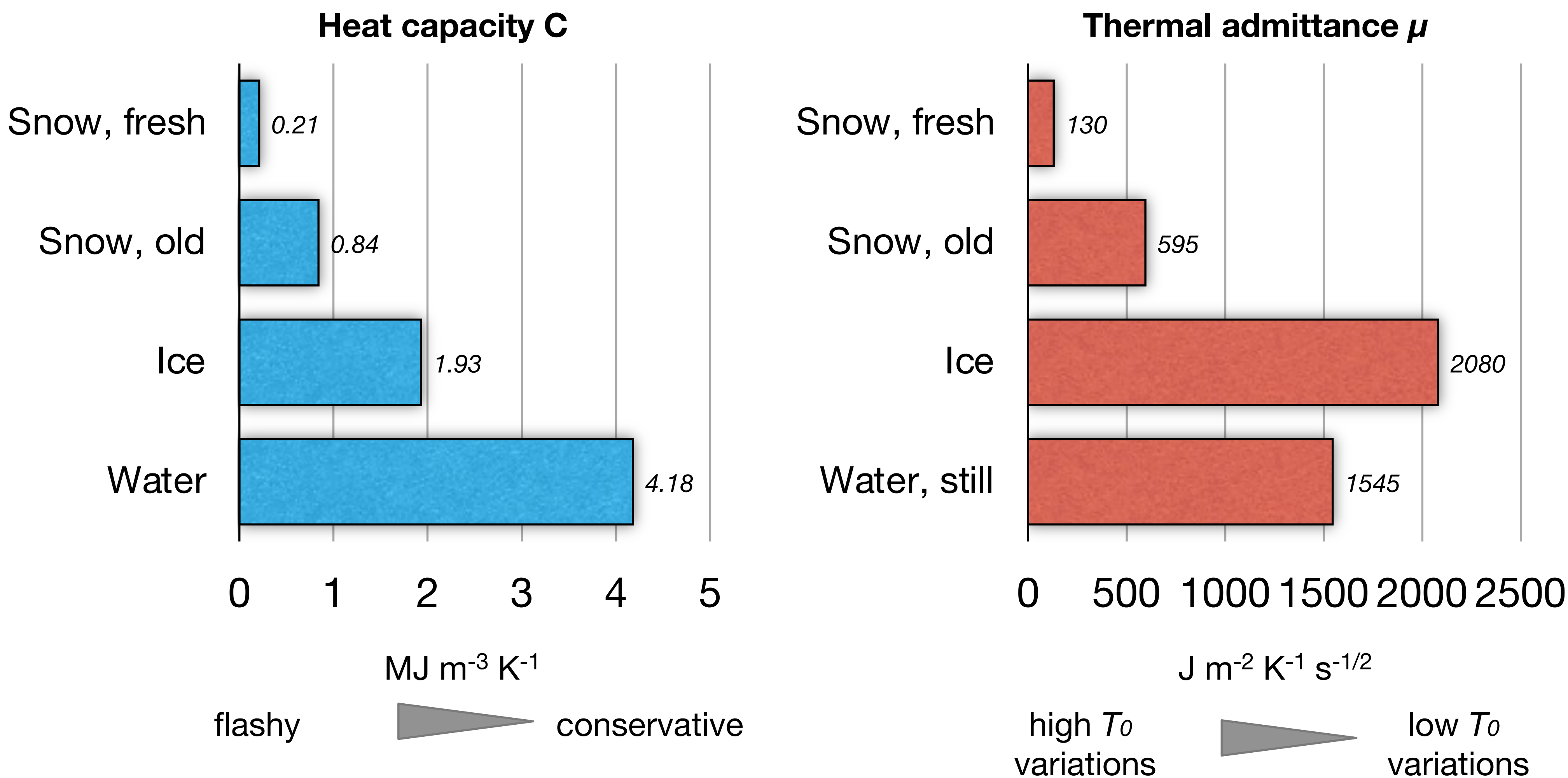
- Explain what makes snow and water different compared to most other surface-atmosphere interfaces.
- Describe the transmission, absorption and reflection of radiation in water and snow.
- Describe how we can define the energy budget of a snow-pack or water body.

Photo: A. Christen

Properties of snow and water surfaces?

Photo: A. Christen

Thermal properties of snow, water and ice.



Treating snow and water as volume interfaces

▲ Transmission of short-wave radiation through a glacier (Photo: USGS Webpage)

In contrast to opaque land surfaces, land-atmosphere interfaces of liquid and solid water transmit radiation into lower layers.

This means we must know the transmission (and absorption, reflection and emission) of radiation in those media in order to predict energy exchange.

As a consequence, we must treat water, snow and ice 'surfaces' as **3D-volume interfaces**.

Transmission in a homogeneous medium.

Beer's Law describes the reduction in flux density of a parallel beam of monochromatic radiation through a homogeneous medium.

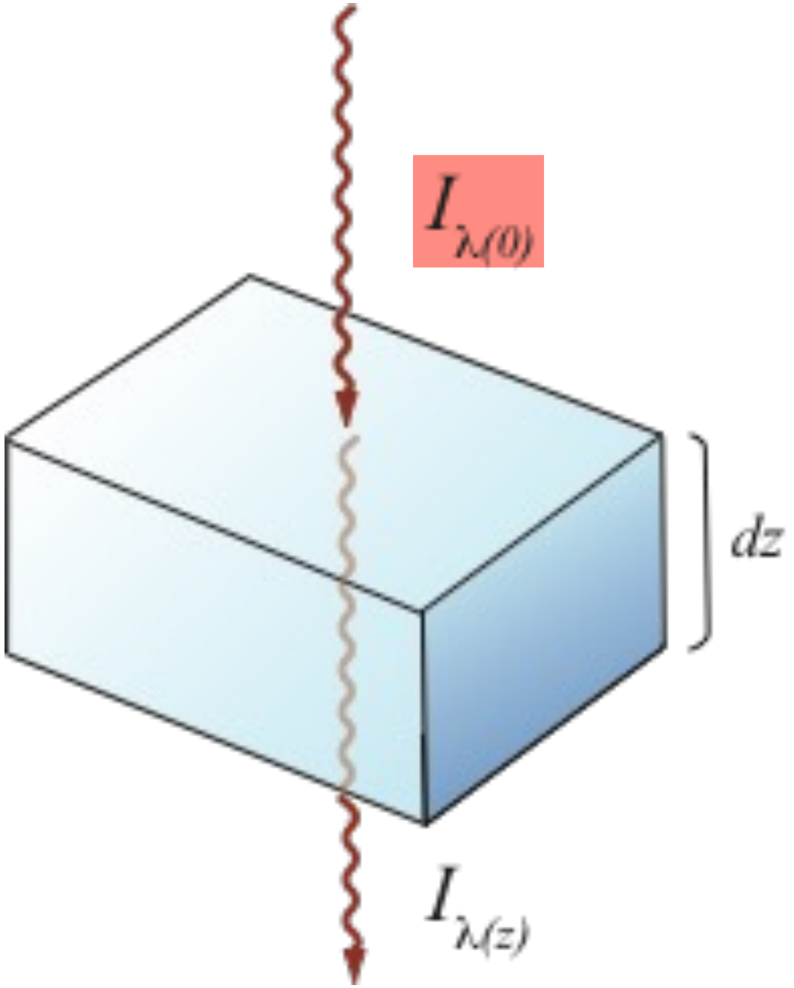
In each layer the absorptivity (and hence transmissivity) stays constant:

$$dI_\lambda = -k I_{\lambda(0)} dz$$

change in radiative flux in an infinite thin layer *dz* (i.e. absorption)

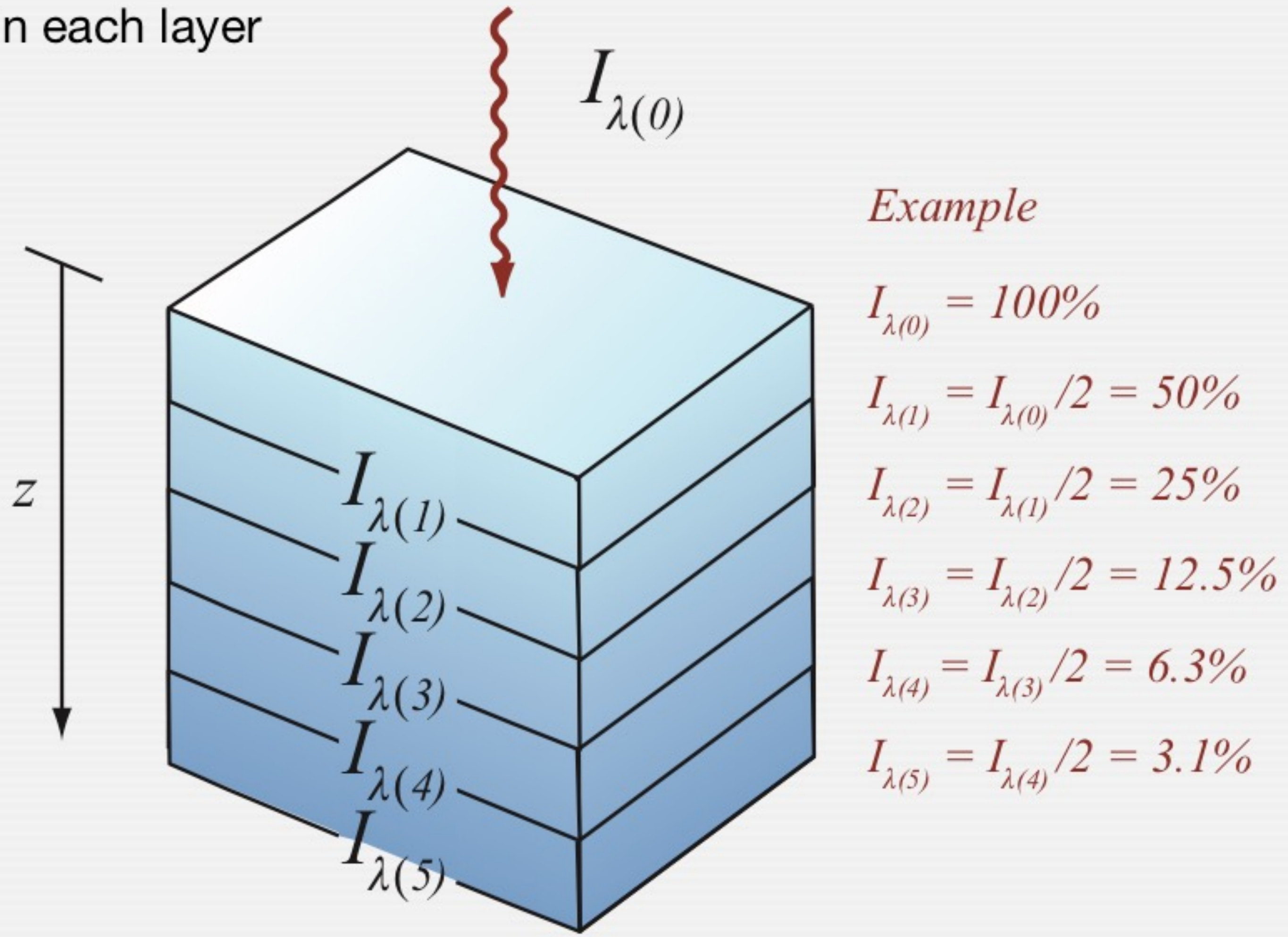
incoming radiative flux density

k Extinction coefficient

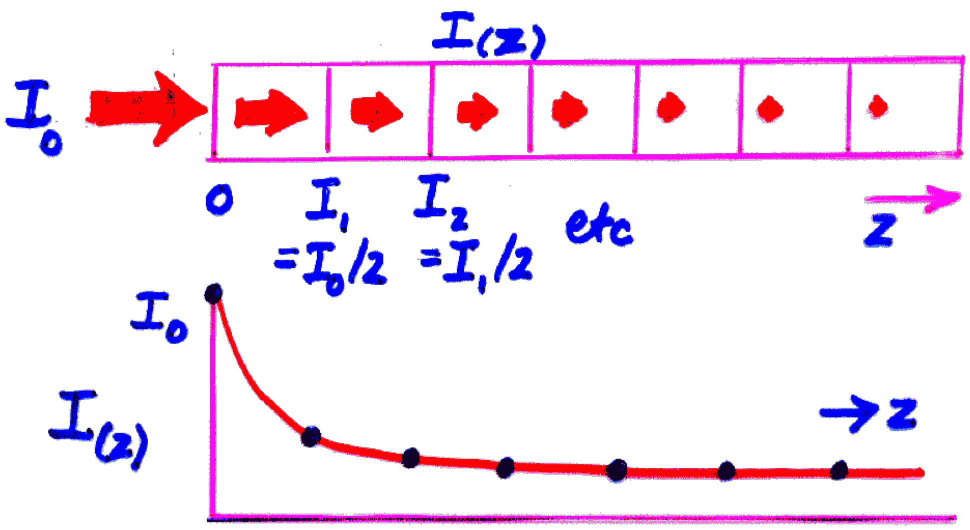


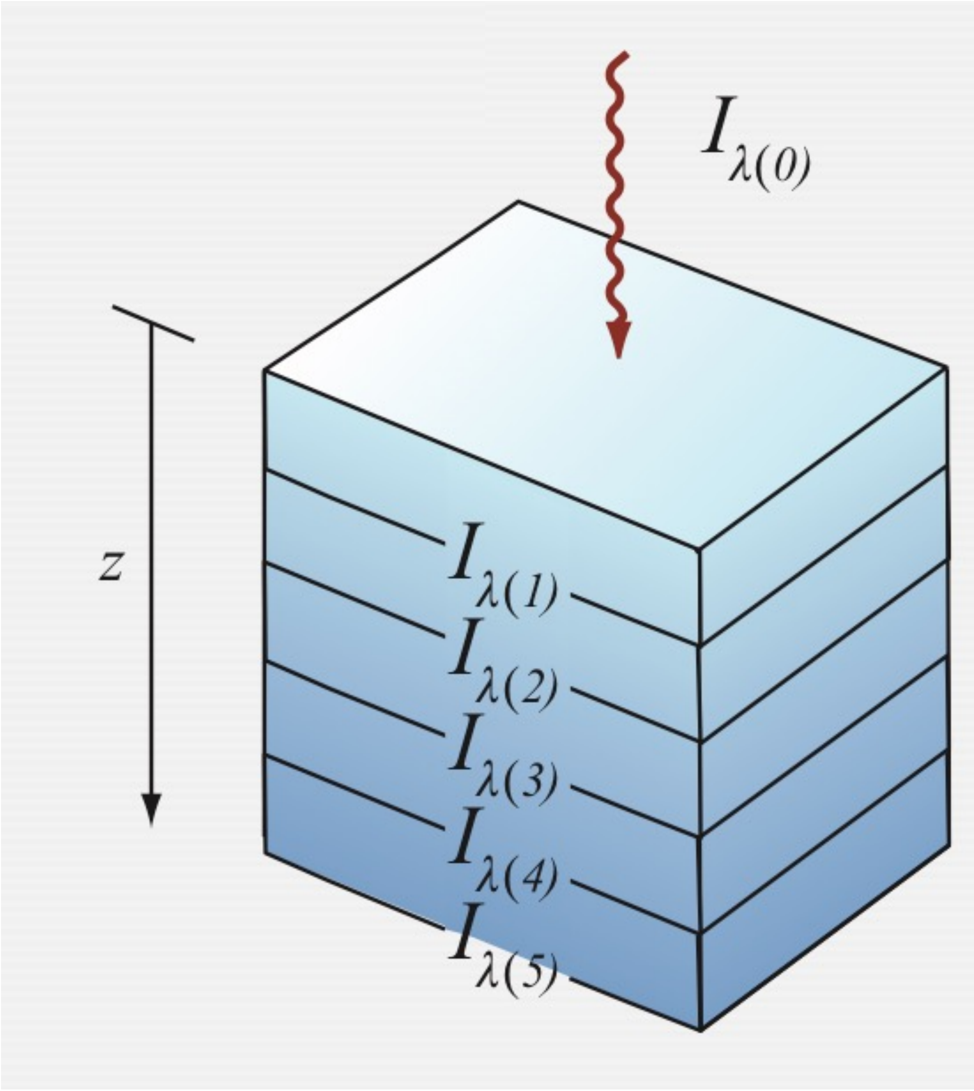
Beer's Law - Approximation with finite layers

Assume 50% absorption in each layer



Beer's Law - Approximation with finite layers





Integration of Beer's Law.

Integration if Beer's law gives us:

$$\int_0^z \frac{\mathrm{d}I_\lambda}{I_{\lambda(0)}} \mathrm{d}z = \ln\left(I_{\lambda(z)}\right) - \ln\left(I_{\lambda(0)}\right) = -k\, z$$

Rearranging the logarithmic terms:

$$\ln\left(\frac{I_{\lambda(z)}}{I_{\lambda(0)}}\right) = -k\, z$$

Eliminating the logarithm (take exponent):

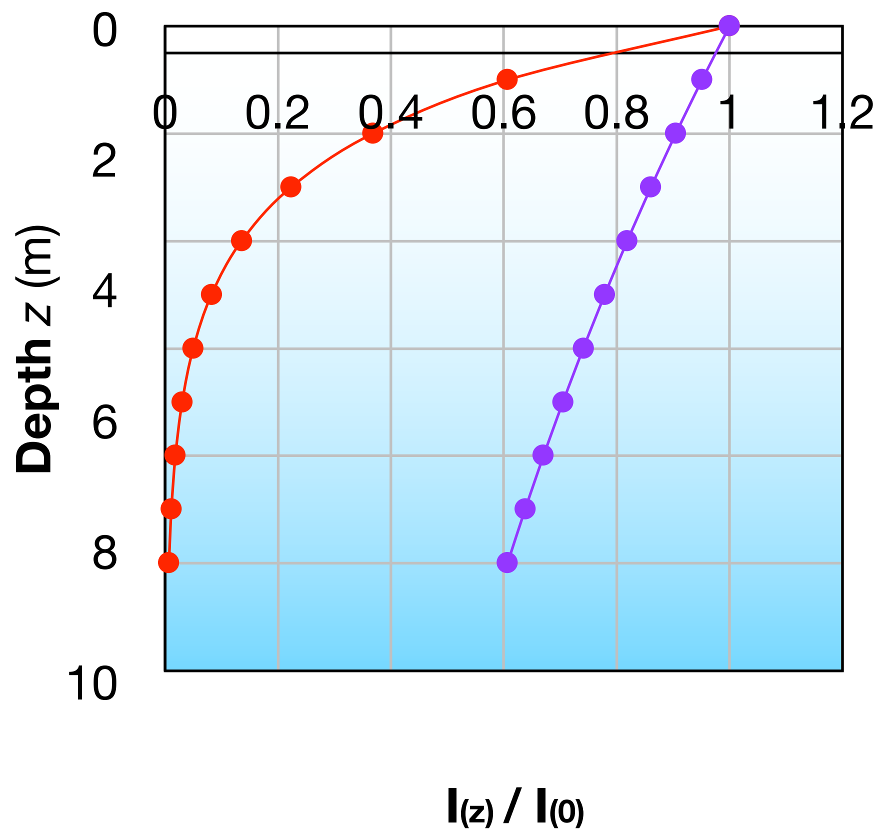
$$\boxed{I_{\lambda(z)} = I_{\lambda(0)}\ e^{-k\, z} \quad \star}$$

The radiative flux density decays **exponentially** with depth.

Extinction coefficient.

The constant of proportionality k is called **extinction coefficient** (m^{-1}). It depends on

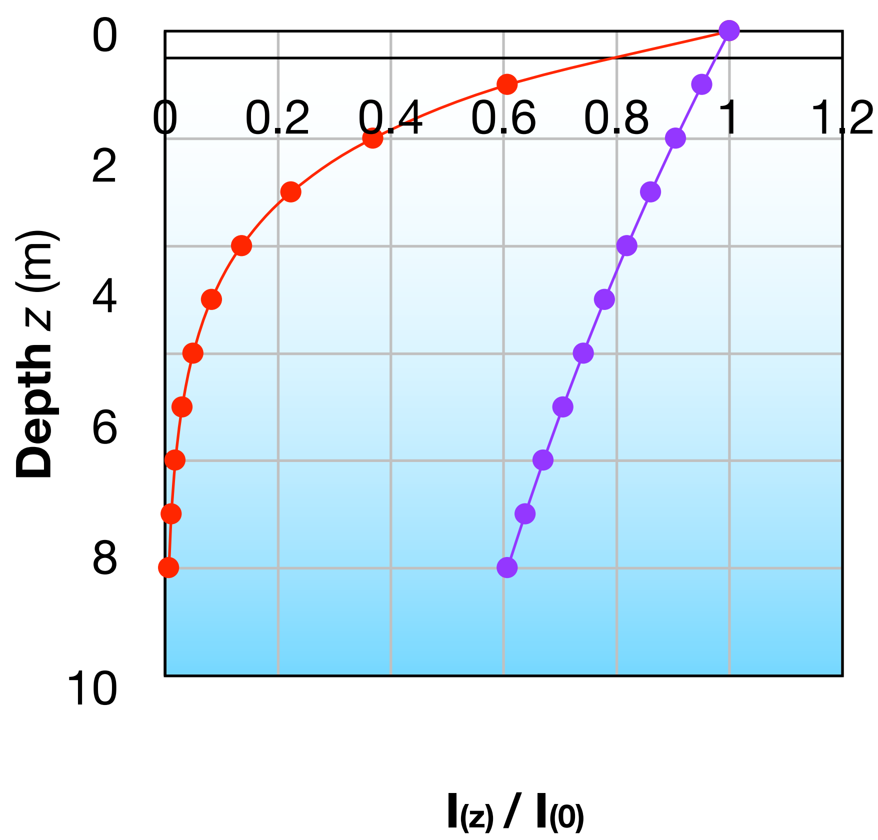
- Wavelength.
- Nature of the medium.
- Impurities (e.g. turbidity of water, i.e. algae, plankton, chemicals).



Which line has the greater extinction coefficient? (Slido)

The constant of proportionality k is called **extinction coefficient** (m^{-1}). It depends on

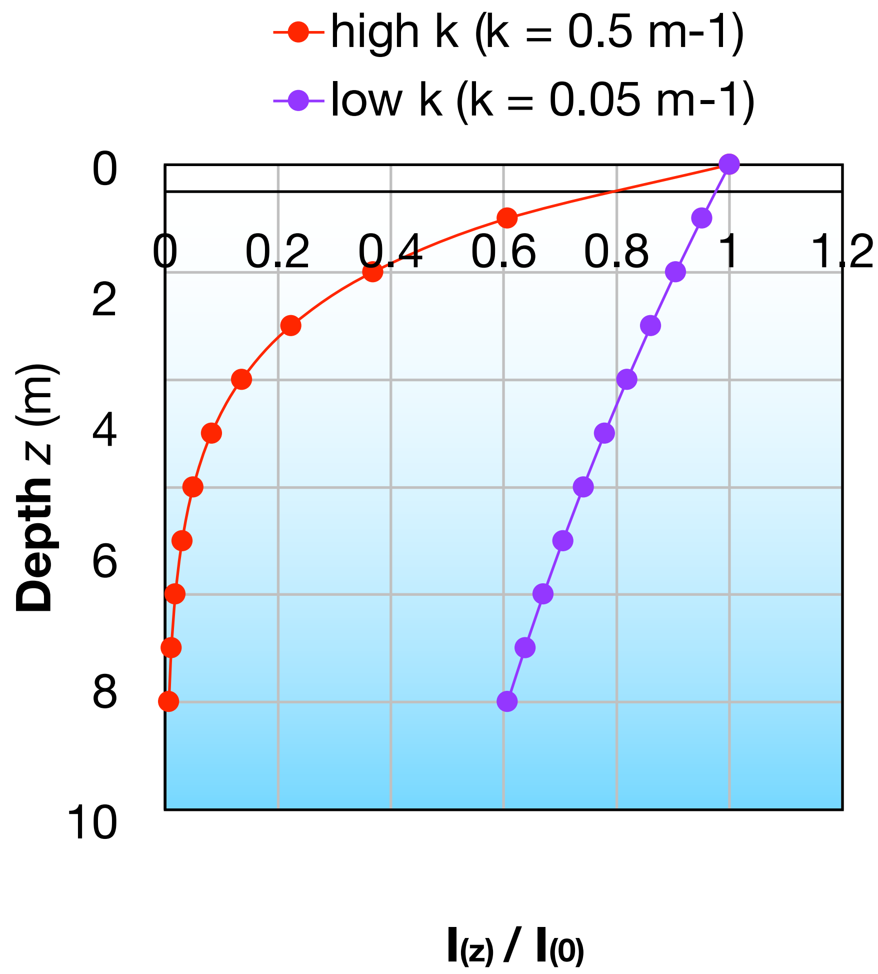
- Wavelength.
- Nature of the medium.
- Impurities (e.g. turbidity of water, i.e. algae, plankton, chemicals).



Extinction coefficient.

The constant of proportionality k is called **extinction coefficient** (m^{-1}). It depends on

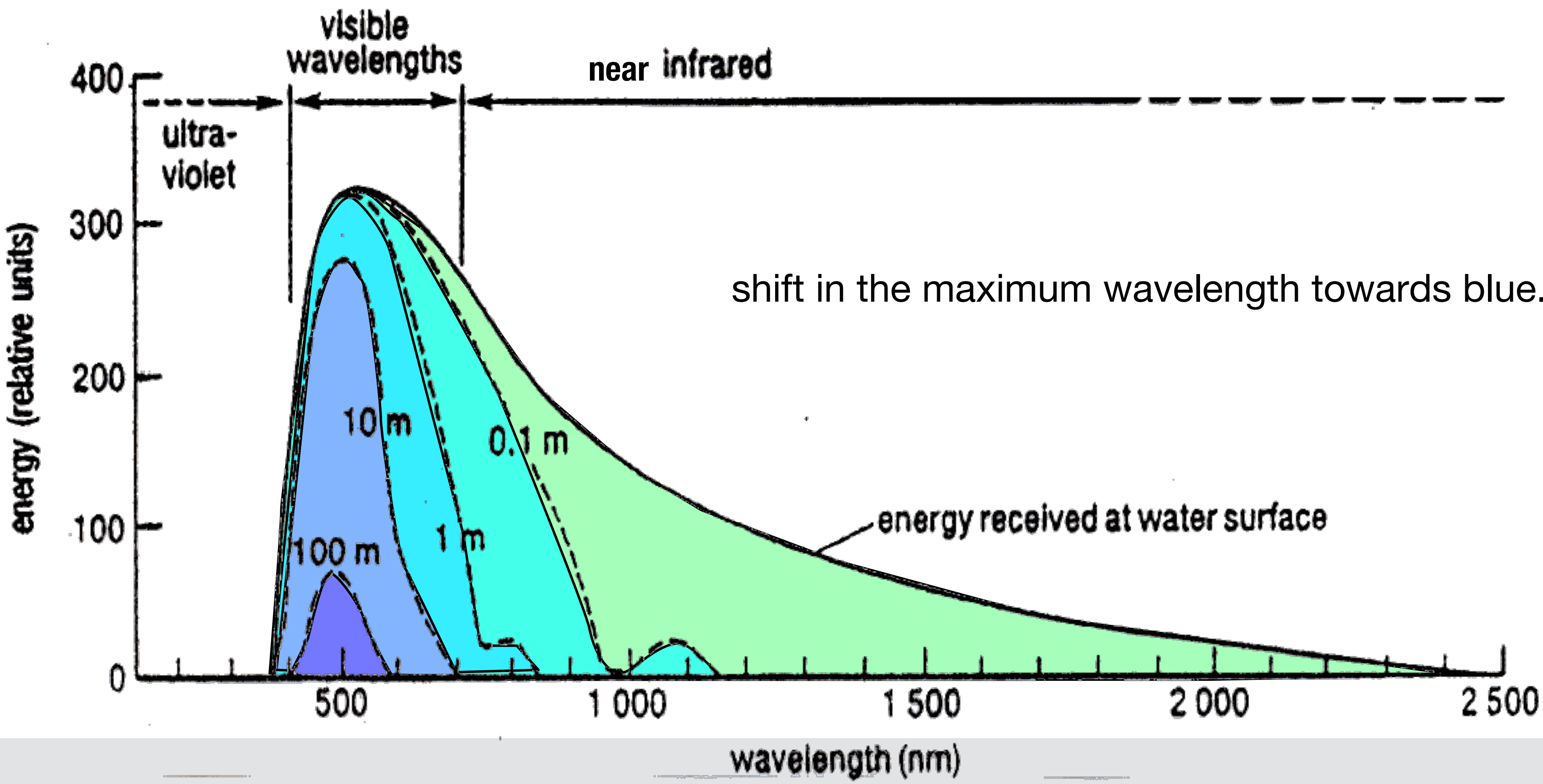
- Wavelength.
- Nature of the medium.
- Impurities (e.g. turbidity of water, i.e. algae, plankton, chemicals).




Why do light and objects appear bluish underwater?

Extinction in water

k of water depends strongly on wavelength λ. Absorption is very high in near infrared (NIR, 0.7 to 3 µm), and lowers in the visible range (0.4 to 0.7 µm).



shift in the maximum wavelength towards blue.

Extinction coefficients of liquid water and ice

We can use Beer's law to describe the decay of radiation with depth z in water bodies, snow or ice for different wavelengths.

The liquid and solid state of water have very similar extinction coefficients k, except for the region between 1350-1750 nm.

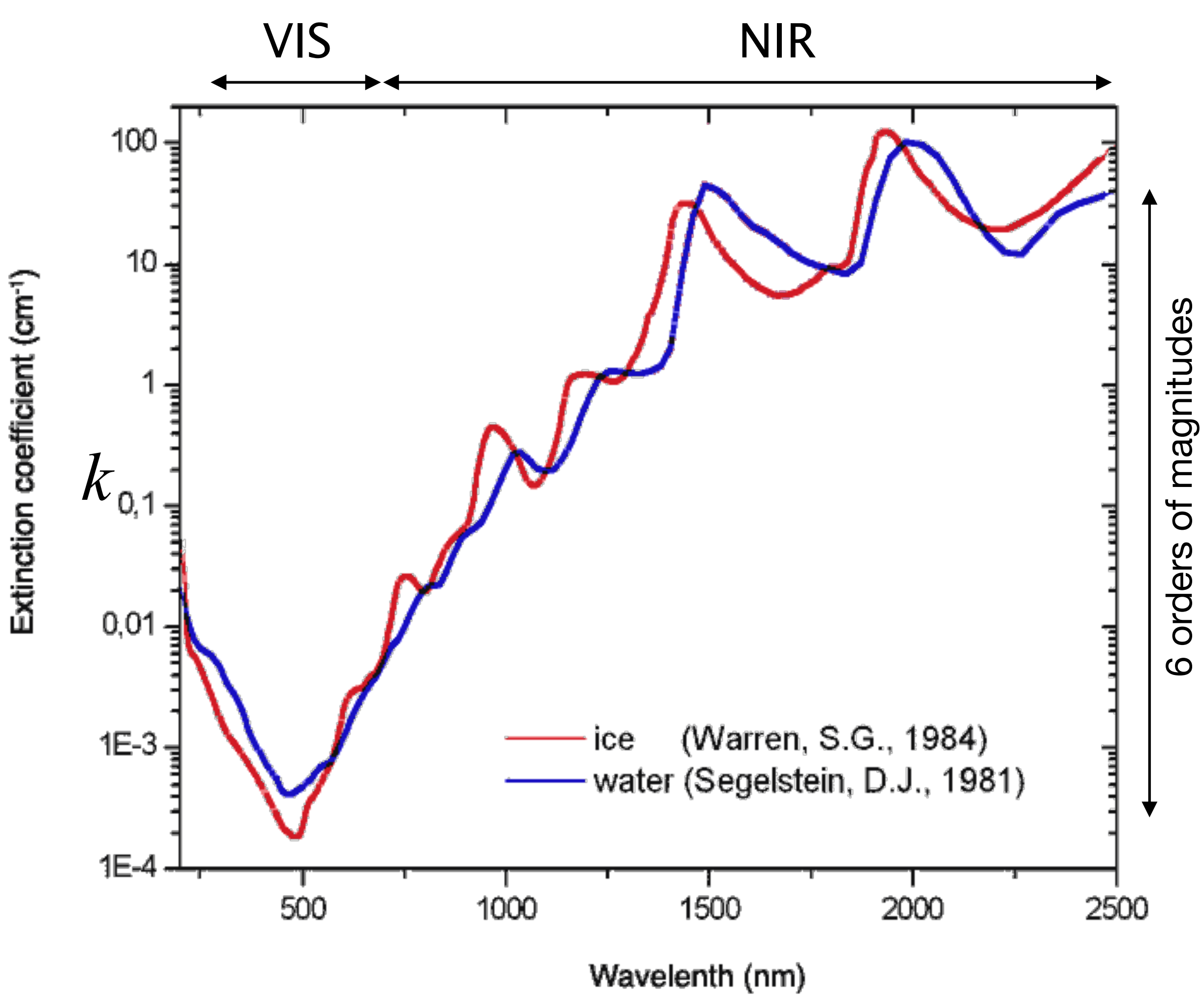
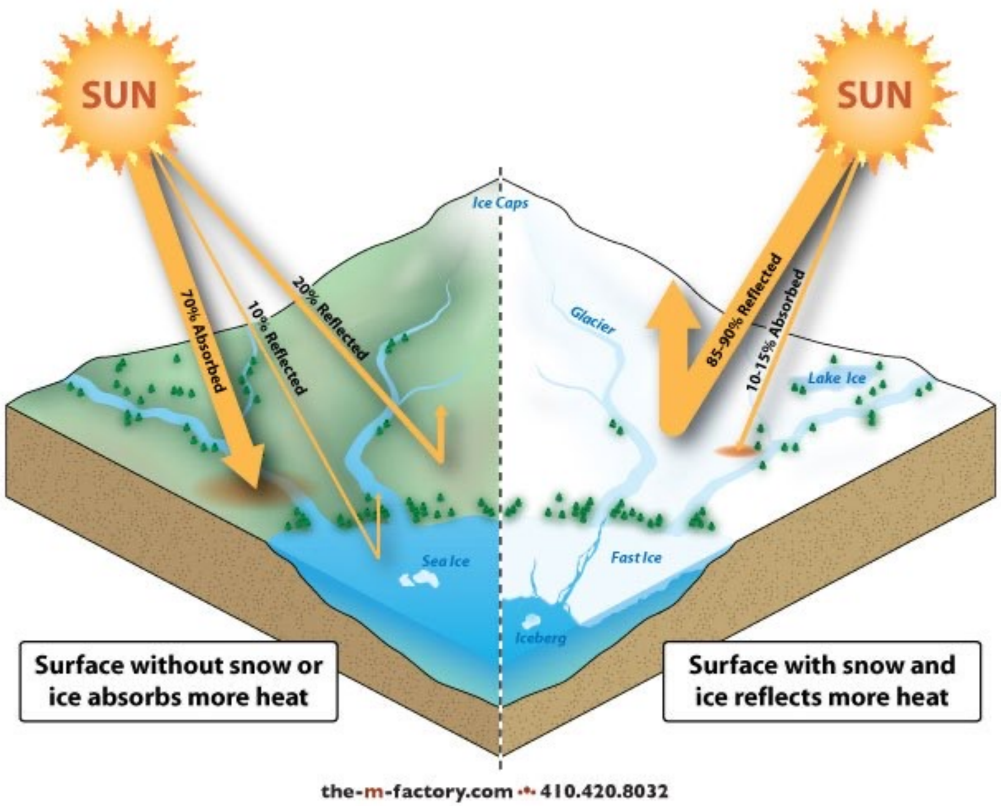



Photo: A. Christen

The radiation balance of snow and ice - reflectance

One of the most important characteristics of snow and ice is their **high albedo**



Source: https://i0.wp.com/oceanbites.org/wp-content/uploads/2014/12/albedo_2.jpg

Photo: S. Knox

The radiation balance of snow and ice – example over Antarctica

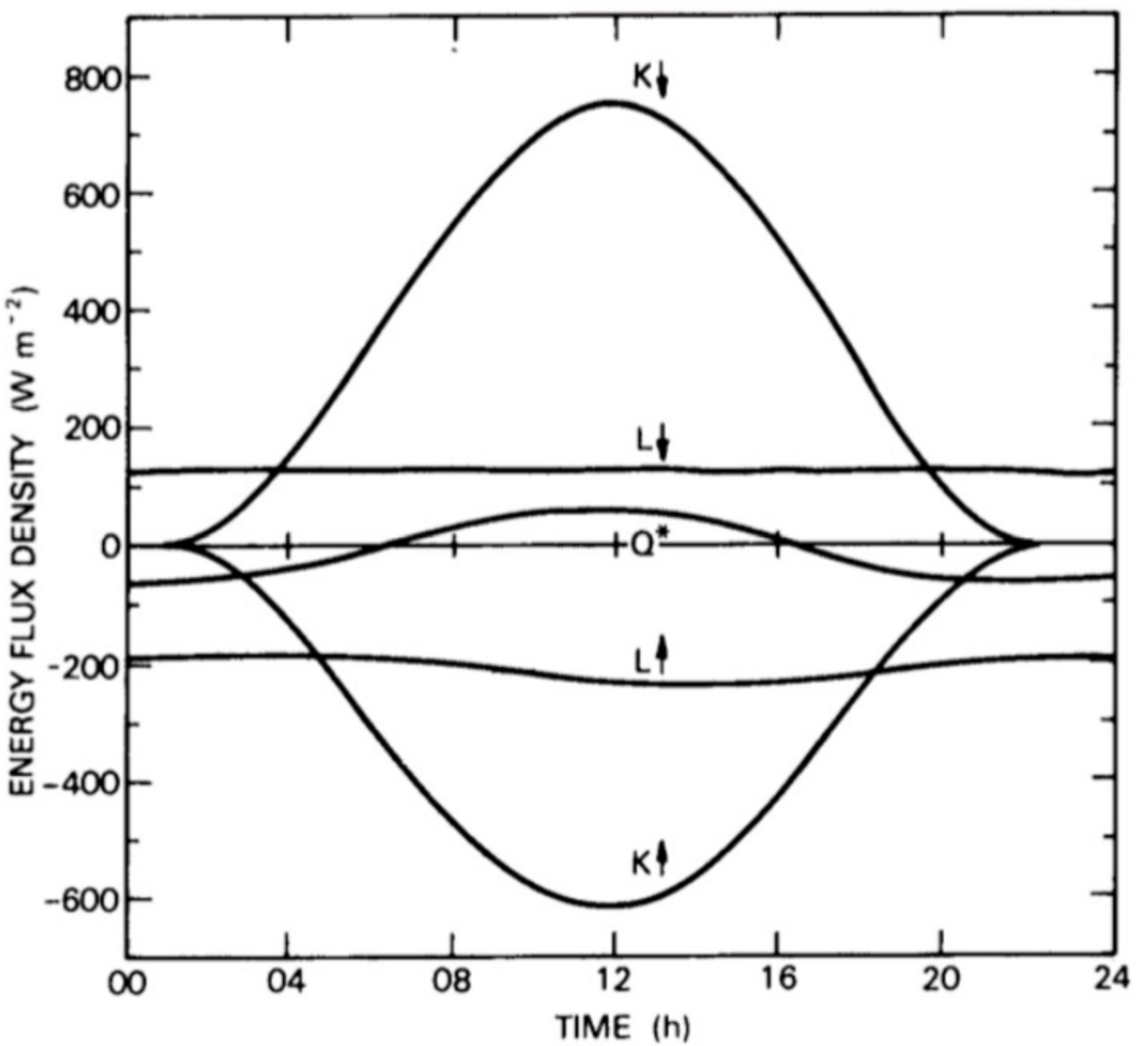


Photo: Joe Shea (UBC Geography)

The energy balance of snow and ice

Beside the 3D framework, also the **phase changes of water** play an important role in the energy balance of a snow and ice volumes.

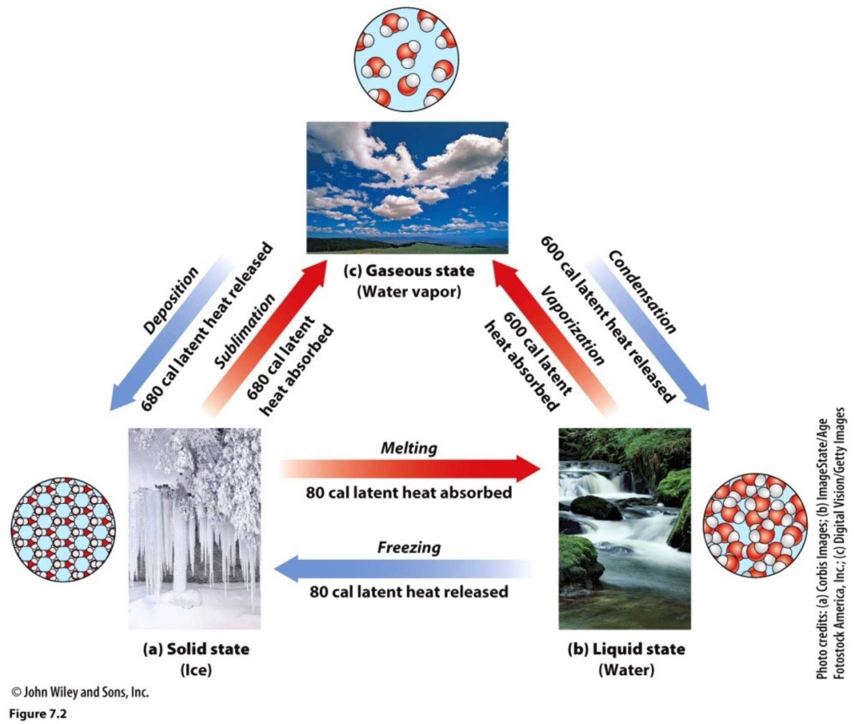


Photo: A. Christen

The energy balance of snow and ice

Beside the 3-d framework, also the **phase changes of water** play an important role in the energy balance of a snow and ice volumes.

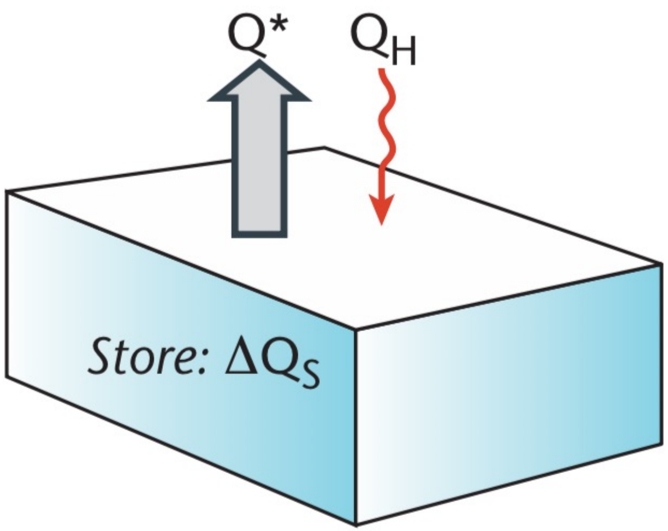
Phase changes of water are accounted by a special term in the energy balance, ΔQ_M, which is the energy flux density put into (or released by) the **latent heat of fusion** of ice (L_f = 0.334 MJ kg^{-1} at 0°C)

$$Q^* = Q_H + Q_E + \Delta Q_S + \boxed{\Delta Q_M}$$

Photo: A. Christen

The state of a snow pack

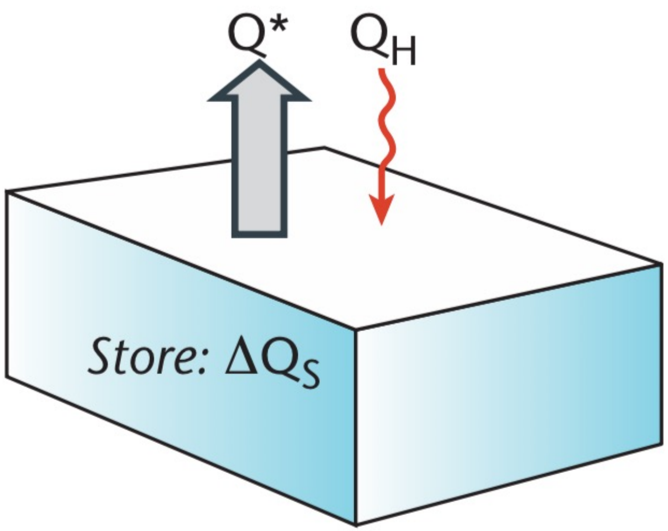
‘Cold’ snow pack



T_S well below 0°C.
Only solid state of water.
No water available for Q_E or ΔQ_M.

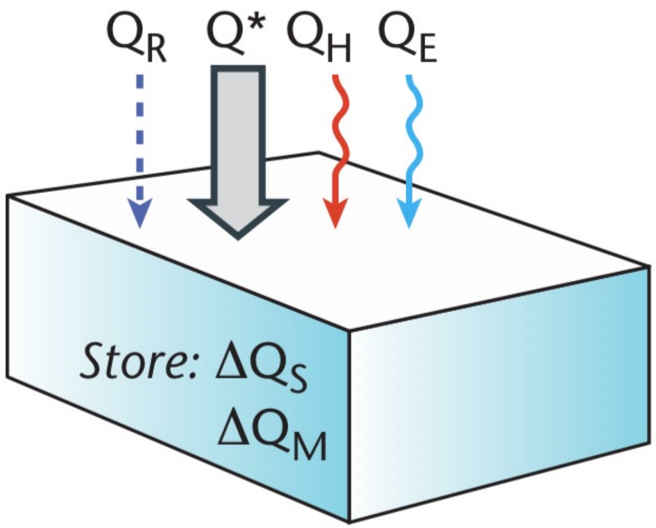
The state of a snow pack

‘Cold’ snow pack



T_S well below 0°C.
Only solid state of water.
No water available for Q_E or ΔQ_M.

‘Wet’ snow pack



T_S at 0°C and often isothermal.
Both, solid and liquid state of water makes Q_E or ΔQ_M important.
Q_R is the heat input by rain (i.e. $T_R > T_S$)

Energy balance of a melting snow volume

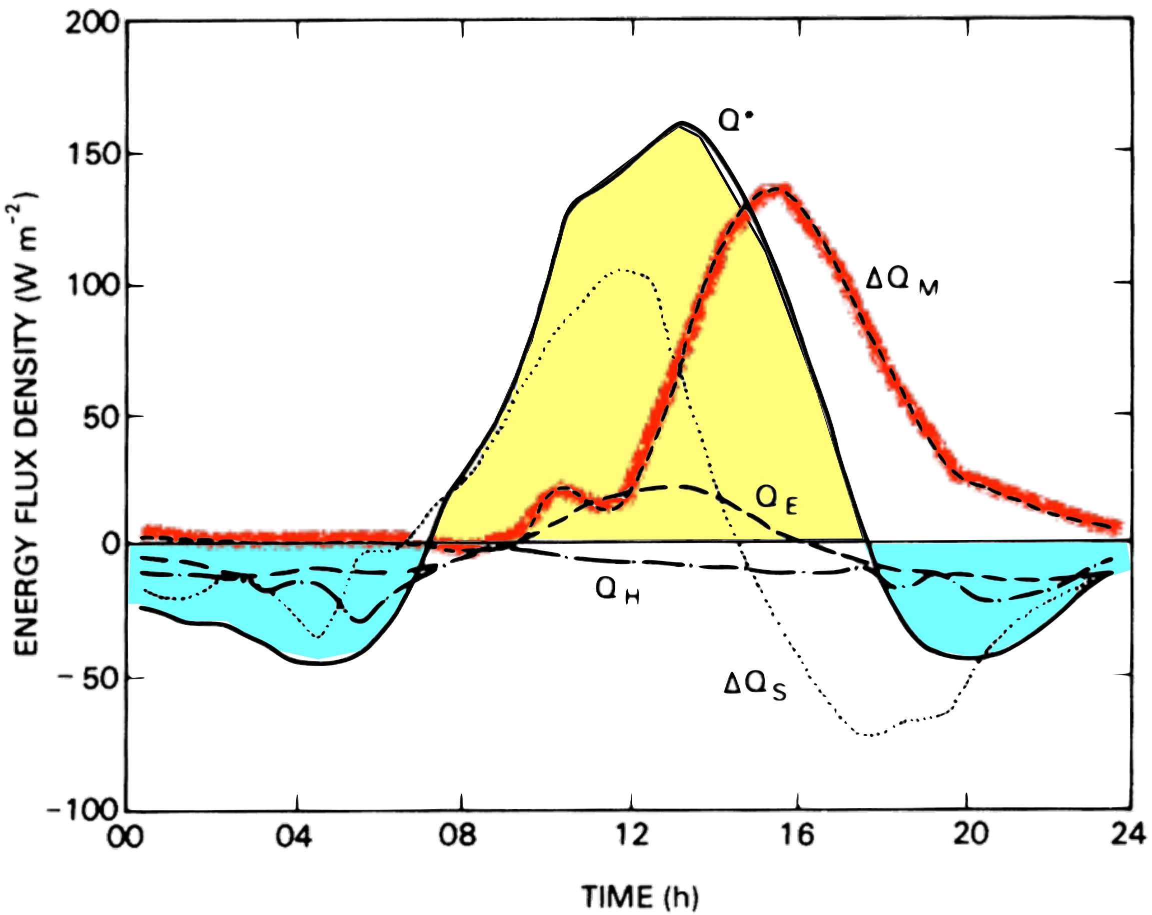


Figure 3.7 Energy balance components for a melting snow cover at Bad Lake, Saskatchewan (51°N) on 10 April 1974 (modified after Granger and Male, 1978).

Albedo of a water surface

Albedo of liquid water strongly depends on the angle at which the direct solar beam hits the water surface.

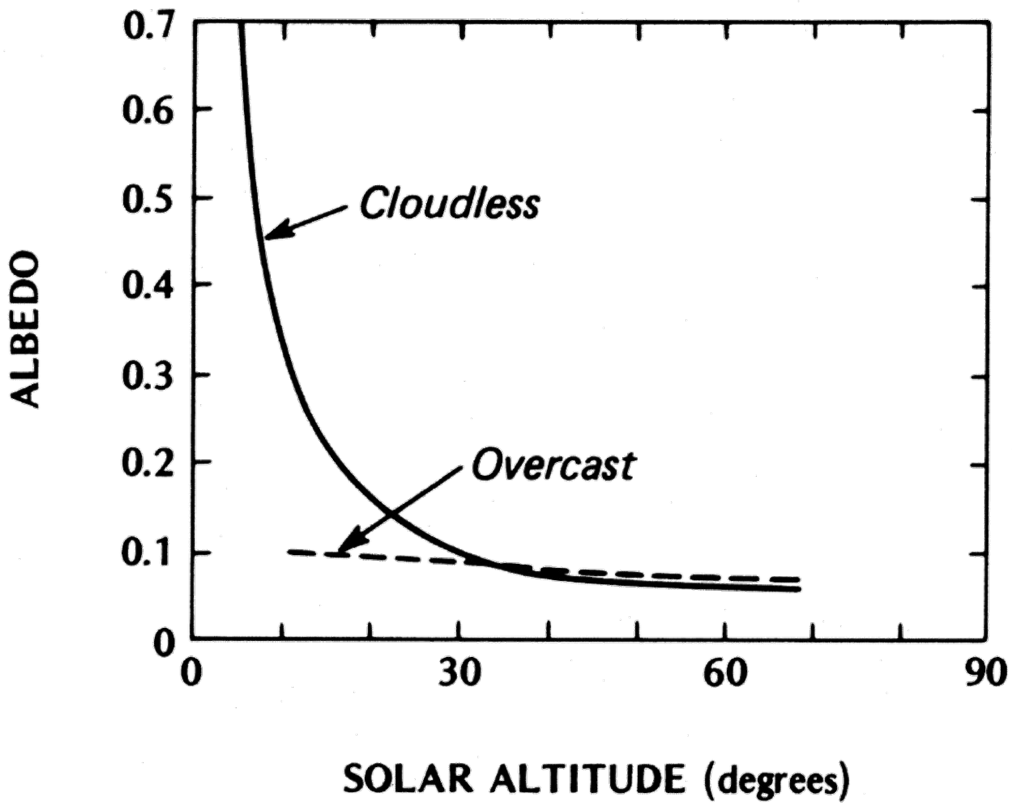


Figure 3.12 Relation between solar altitude and the albedo of lake water for clear and cloudy days over Lake Ontario (after Nunez *et al.*, 1972).

T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition.

The radiation balance of an open water surface

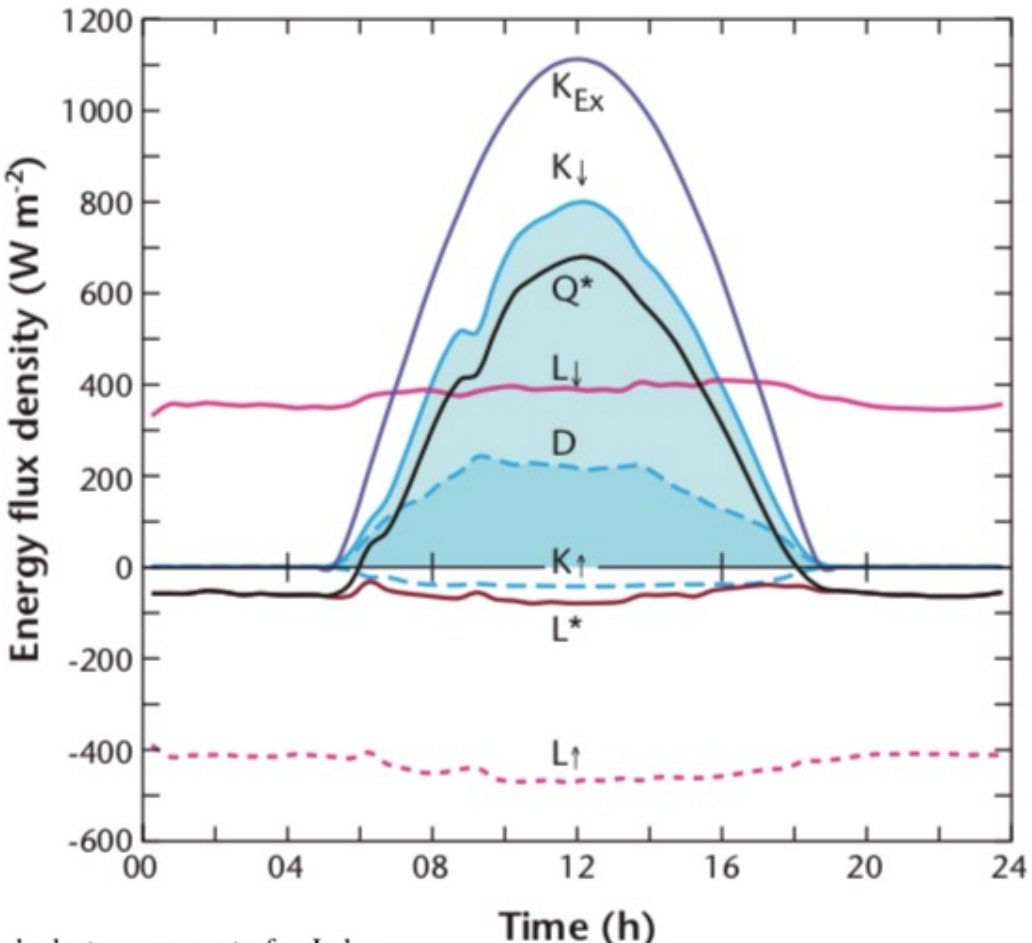


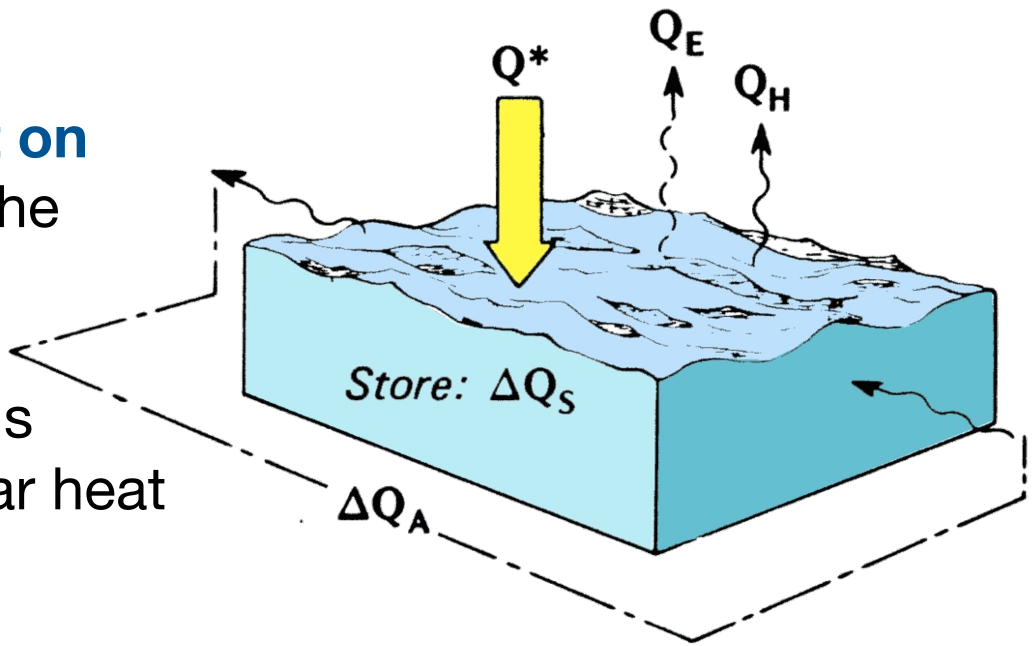
Figure 8: Variation of the radiation budget components for Lake Ontario near Grimsby, Ontario (43°N) on 28 August 1969, with cloudless skies (after Davies et al., 1970).

The energy balance of an open water surface

Open water surfaces (rivers, lakes, oceans) have the unique feature compared to land surfaces, that **turbulent exchange is important on both sides**, the atmosphere and the hydrosphere.

Similar to air, turbulent exchange is much more efficient than molecular heat conduction in water.

Further **advective energy flux densities** (ΔQ_A) are almost all the time significant.



T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition.

Take home points

- **Beer's law** describes the transmission of radiation through a medium (snow, water) at a given wavelength. Extinction coefficient *k* for water is changing from low (VIS, blue) to high (NIR).
- The energy balance for a snow-pack or ice volume needs to consider the **latent heat of fusion**. Depending on snow/ice temperature we distinguish between dry 'cold' and melting 'warm' snowpacks.