



Photo: S. Knox

## 13 Radiation and heat transfer in water, snow and ice

# Today's learning objectives

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- 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.

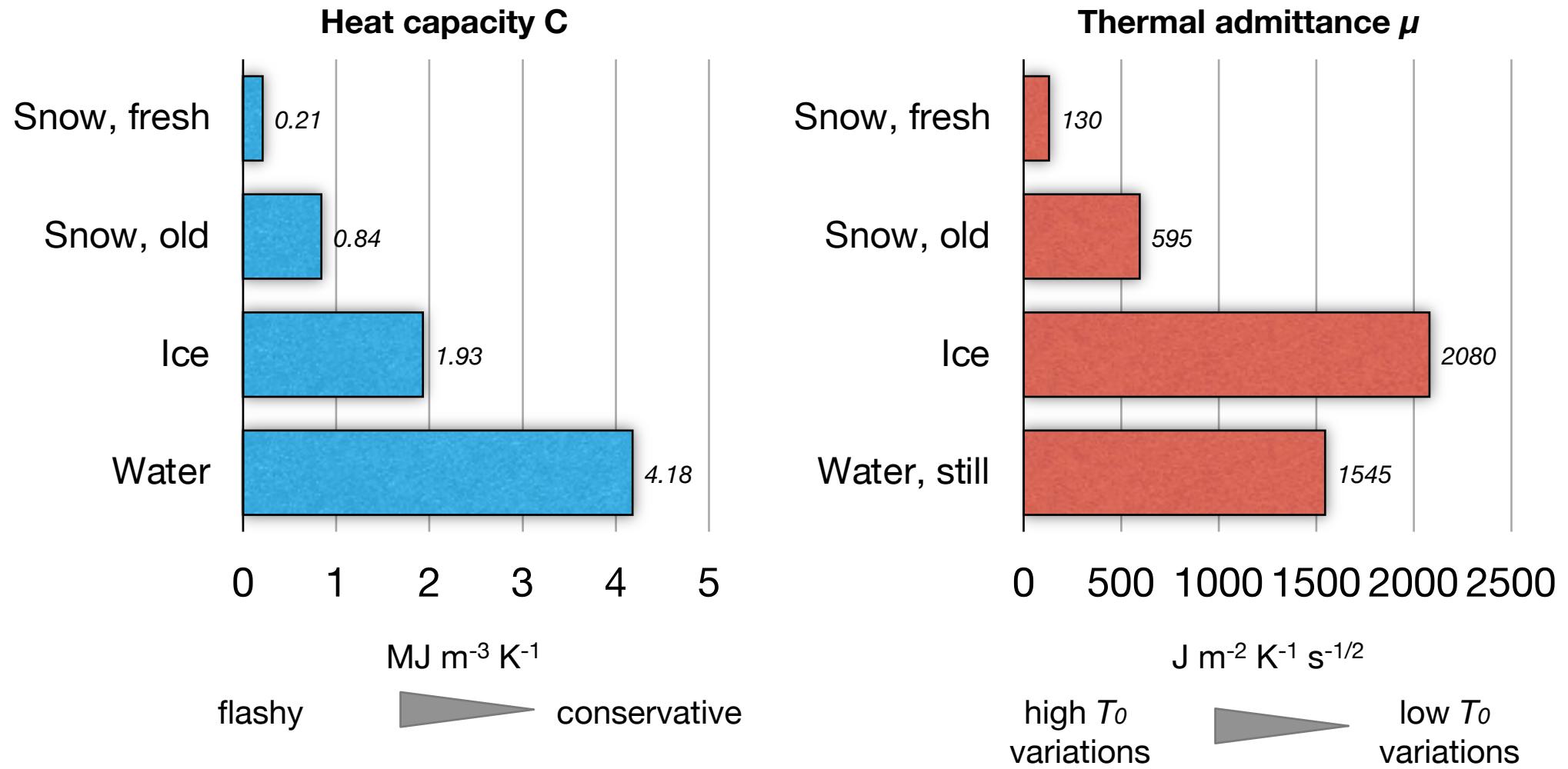


*Photo: A. Christen*



# Properties of snow and water surfaces?

# Thermal properties of snow, water and ice.



# Treating snow and water as volume interfaces

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▲ 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.

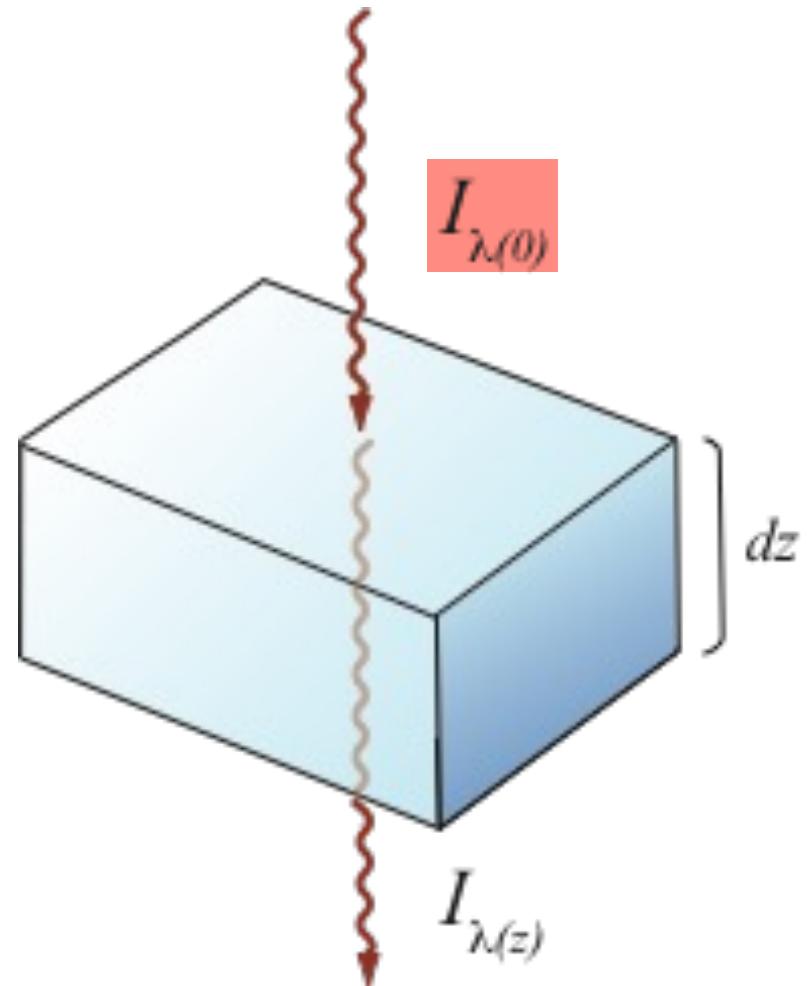
In each layer the absorptivity (and hence transmissivity) stays constant:

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

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

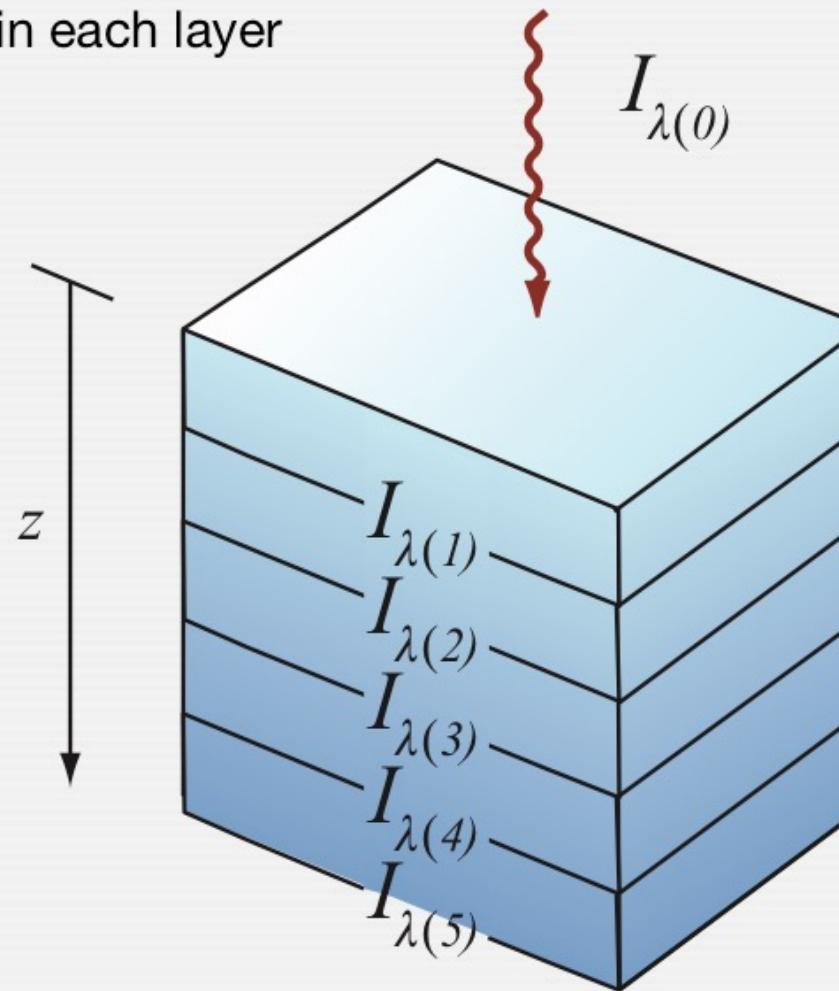
$k$  Extinction coefficient

incoming  
radiative flux  
density



## Beer's Law - Approximation with finite layers

Assume 50% absorption in each layer



*Example*

$$I_{\lambda(0)} = 100\%$$

$$I_{\lambda(1)} = I_{\lambda(0)}/2 = 50\%$$

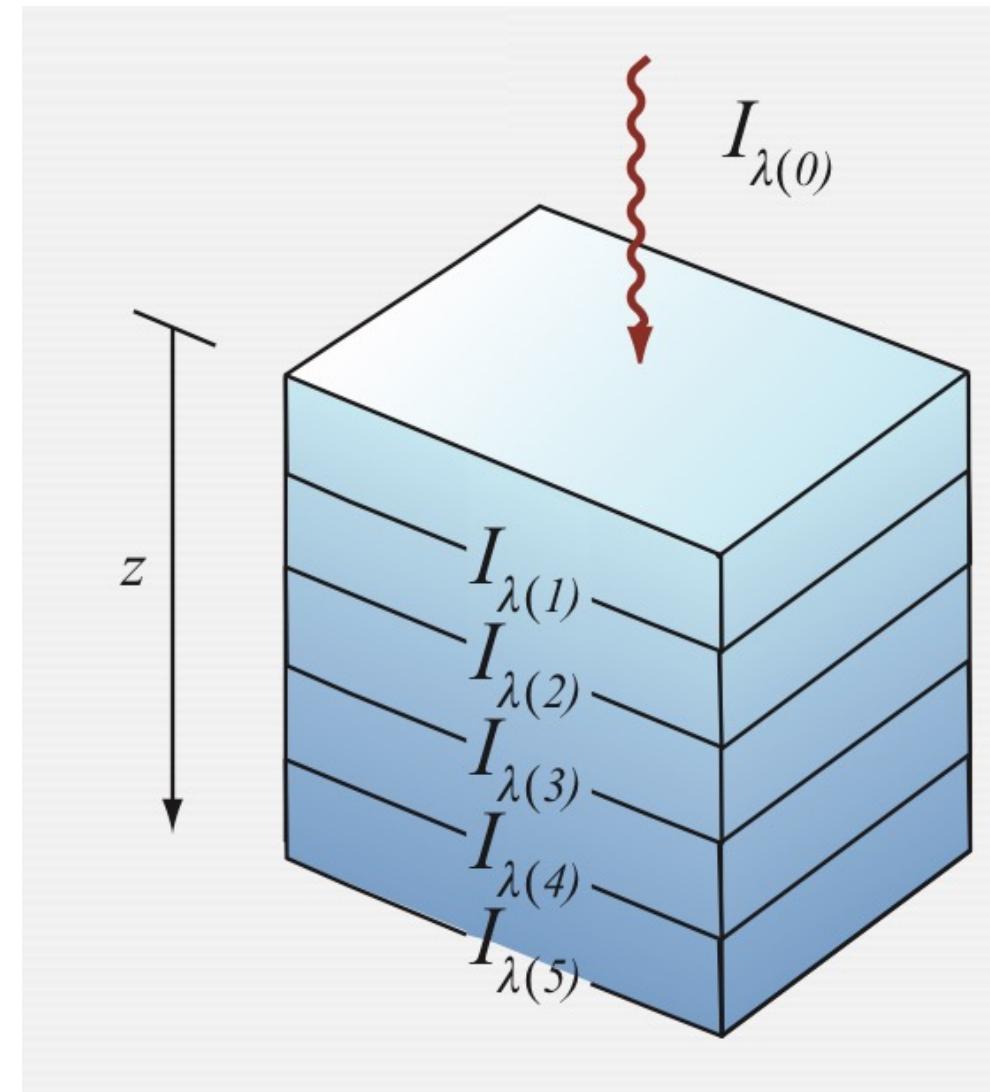
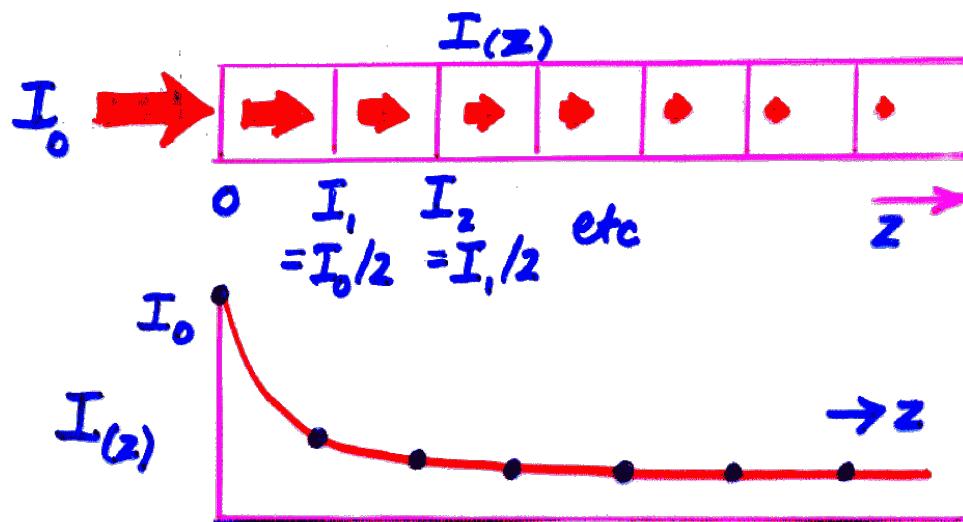
$$I_{\lambda(2)} = I_{\lambda(1)}/2 = 25\%$$

$$I_{\lambda(3)} = I_{\lambda(2)}/2 = 12.5\%$$

$$I_{\lambda(4)} = I_{\lambda(3)}/2 = 6.3\%$$

$$I_{\lambda(5)} = I_{\lambda(4)}/2 = 3.1\%$$

# Beer's Law - Approximation with finite layers



## Integration of Beer's Law.

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Integration of Beer's law gives us:

$$\int_0^z \frac{dI_\lambda}{I_{\lambda(0)}} dz = \ln(I_{\lambda(z)}) - \ln(I_{\lambda(0)}) = -k z$$

Rearranging the logarithmic terms:

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

Eliminating the logarithm (take exponent):

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

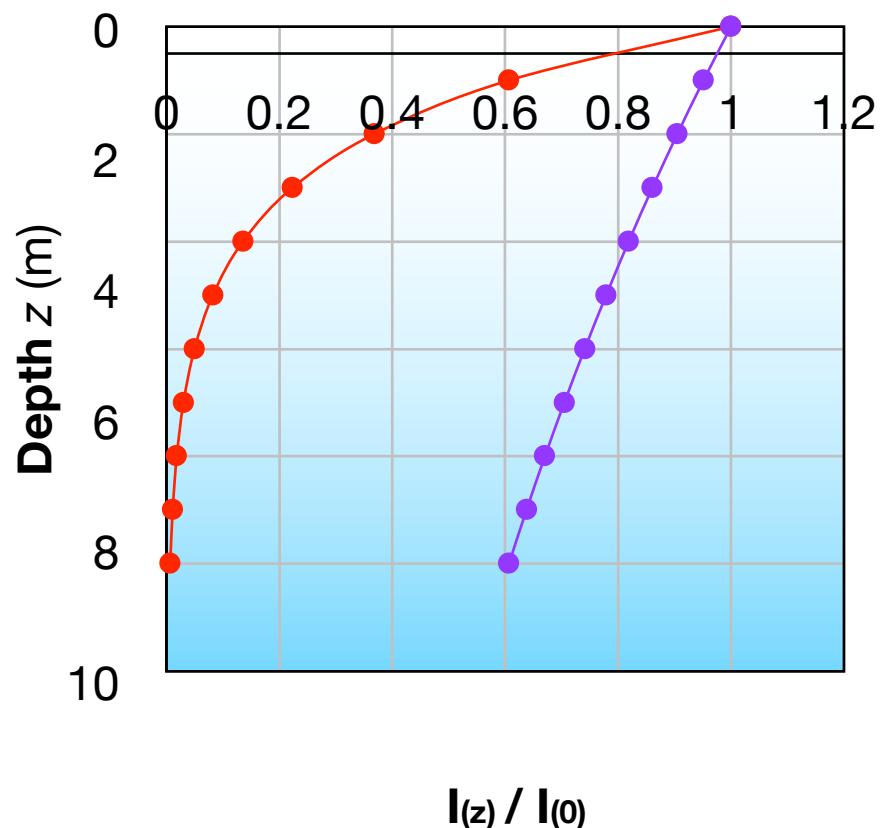
The radiative flux density decays **exponentially** with depth.

# Extinction coefficient.

The constant of proportionality  $k$  is called **extinction coefficient**

( $\text{m}^{-1}$ ). It depends on

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



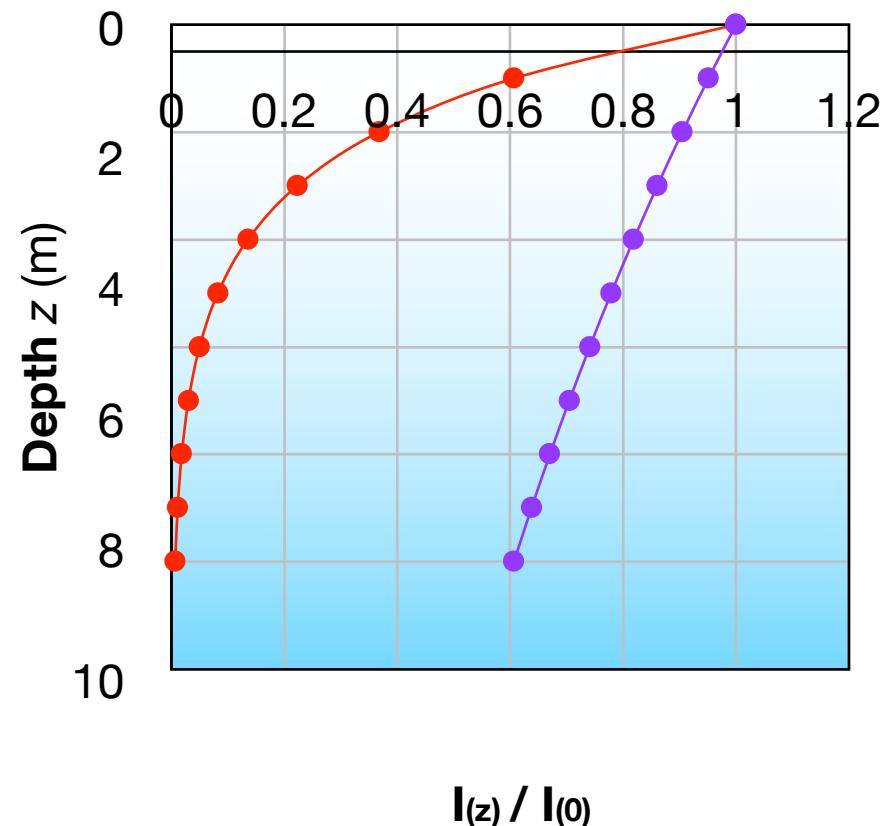
# Which line has the greater extinction coefficient? (Slido)

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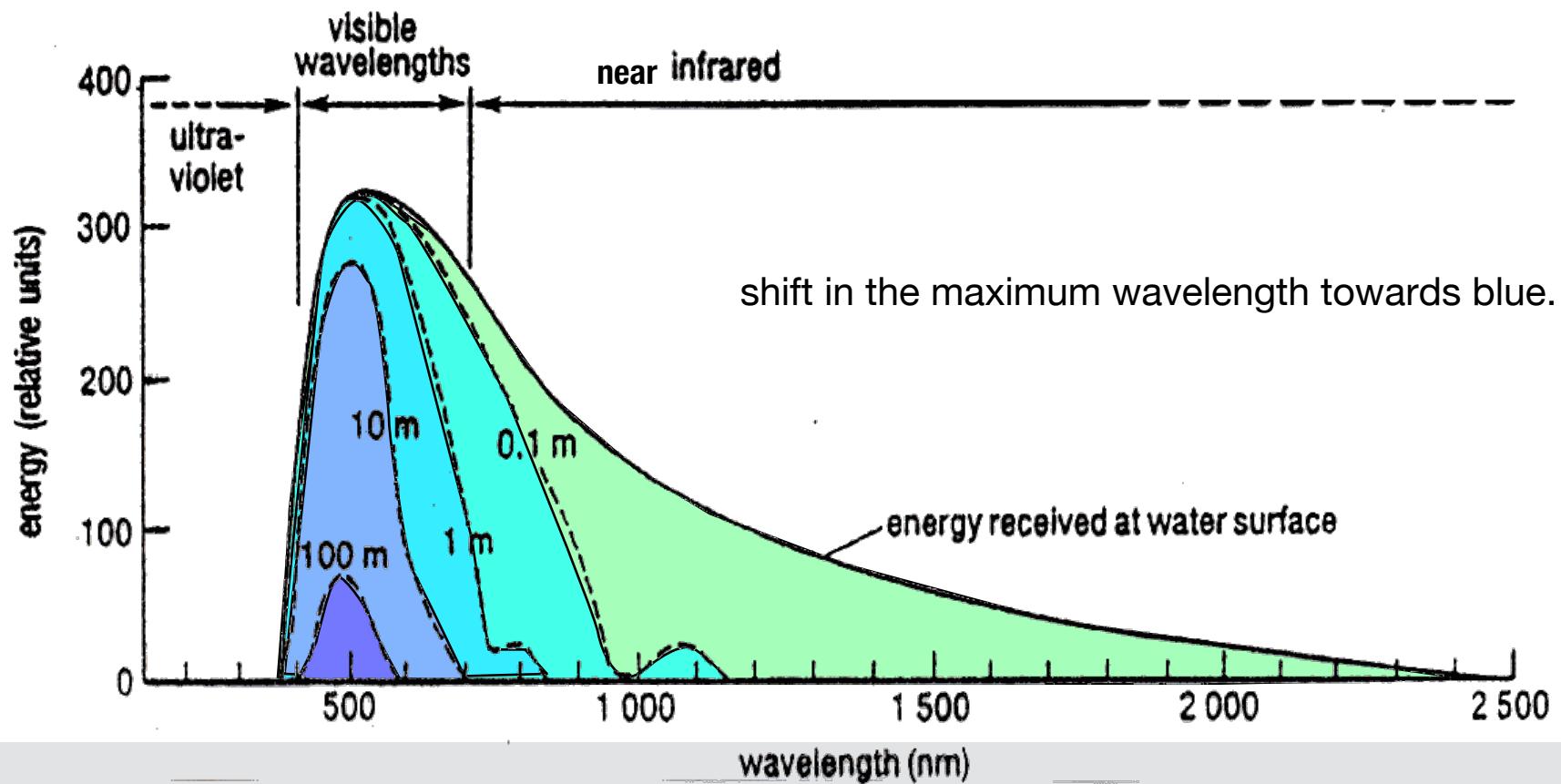


A photograph of an underwater environment, likely a coral reef or kelp forest. The water is a deep, clear blue. Sunlight filters down from the surface in bright rays, creating a dappled light effect on the marine life and plants below. Various species of fish are visible, some swimming gracefully and others resting among the rocks and vegetation. The overall atmosphere is serene and mysterious, typical of a deep-sea ecosystem.

**Why do light and objects appear bluish underwater?**

# Extinction in water

$k$  of water depends strongly on wavelength  $\lambda$ . Absorption is very high in near infrared (NIR, 0.7 to 3  $\mu\text{m}$ ), and lowers in the visible range (0.4 to 0.7  $\mu\text{m}$ ).



# 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.

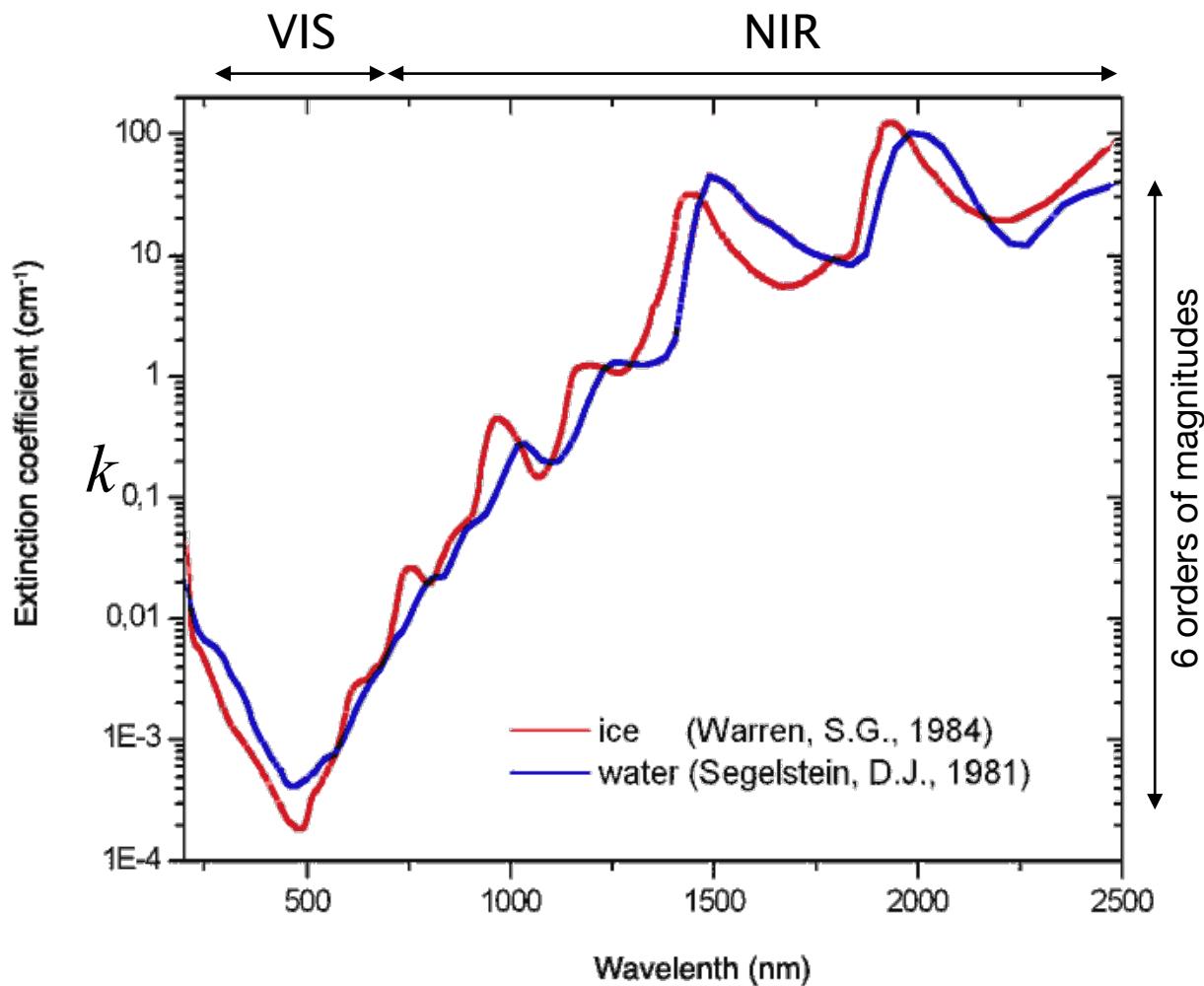
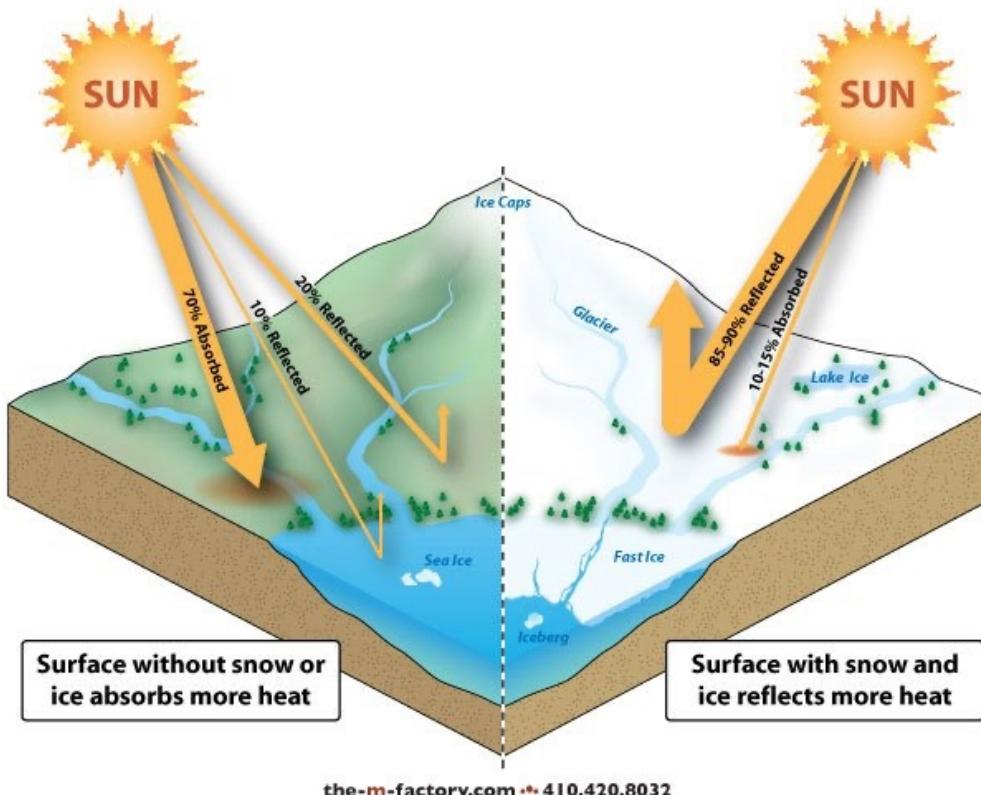




Photo: A. Christen

# 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](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

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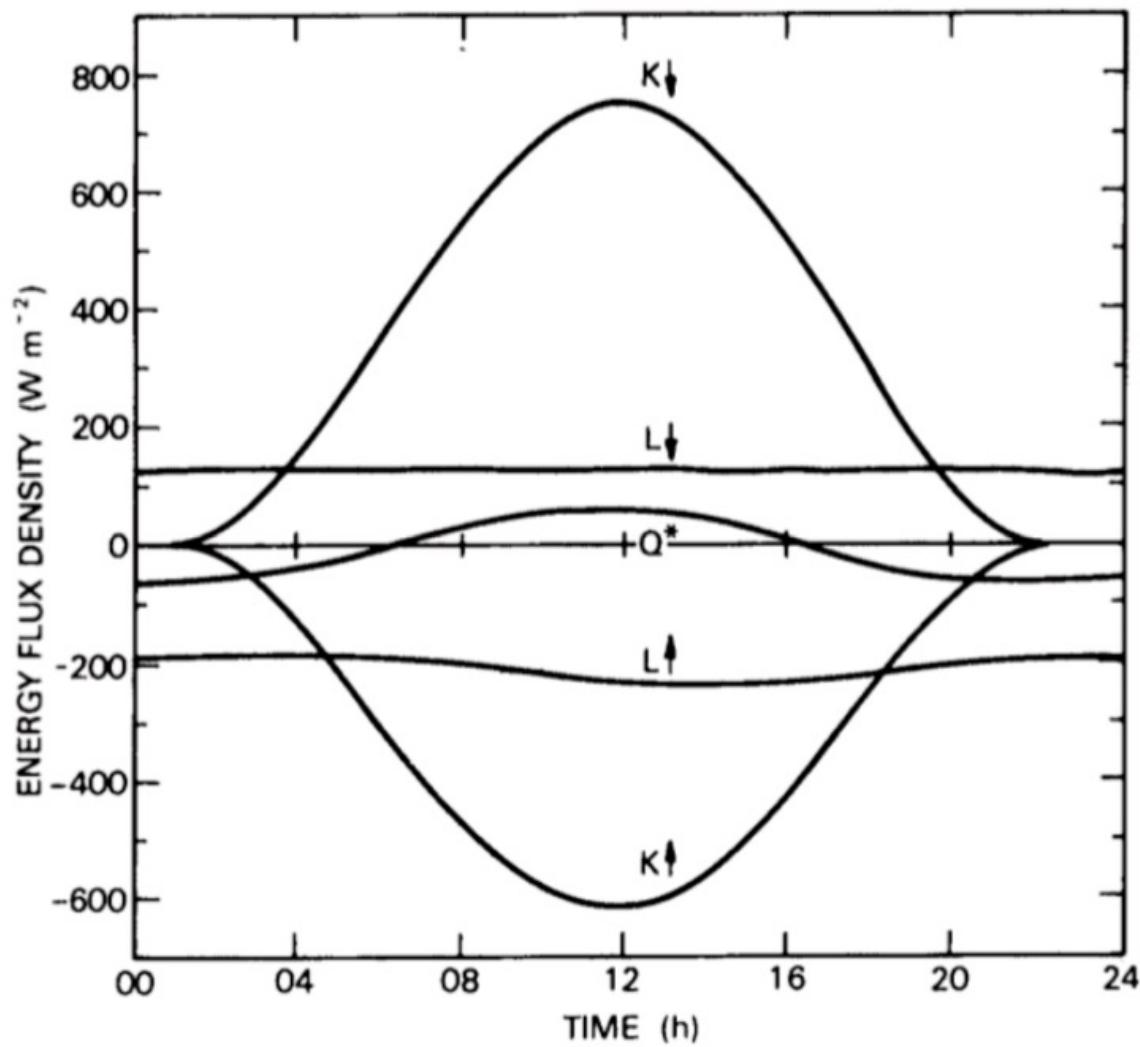
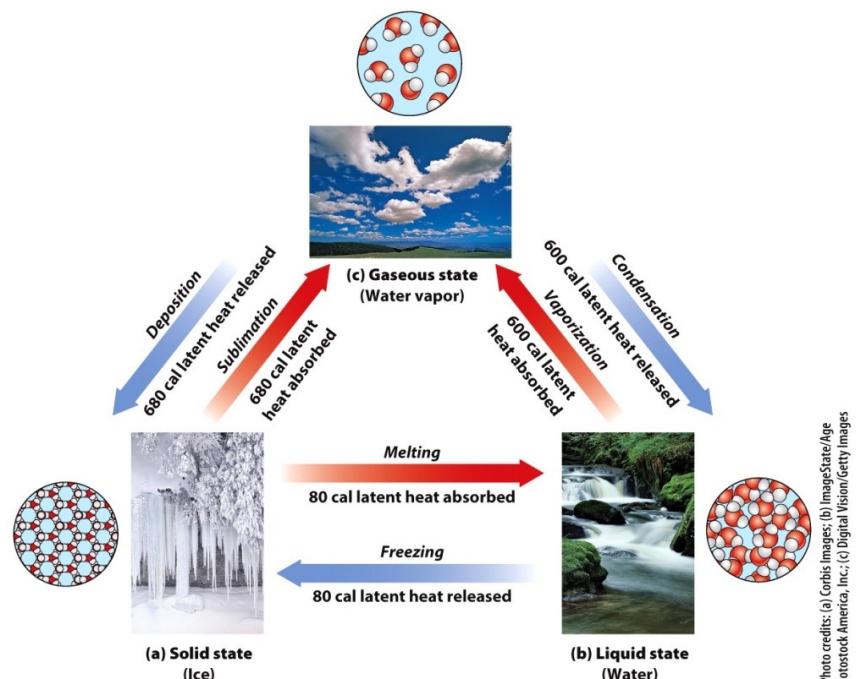




Photo: Joe Shea (UBC Geography)

# The energy balance of snow and ice

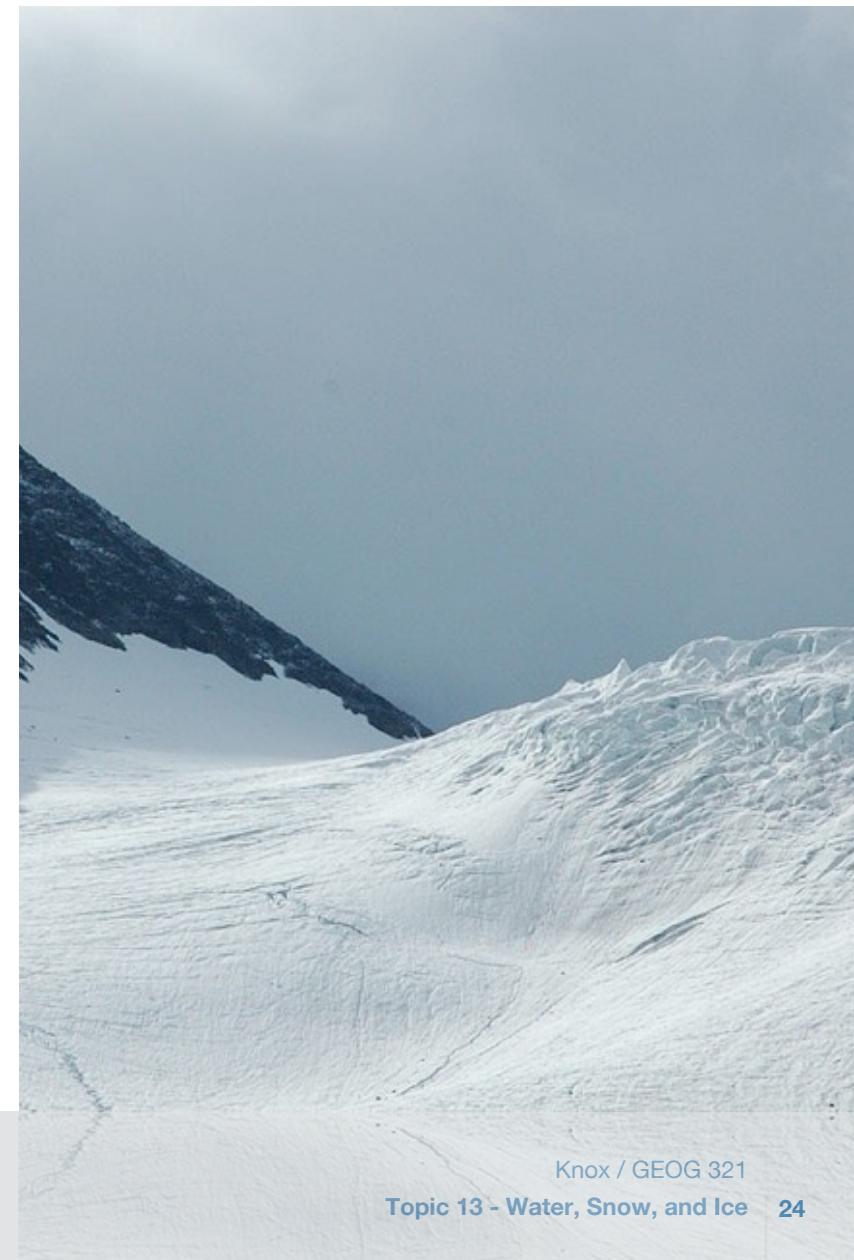
Beside the 3D framework, also the **phase changes of water** play an important role in the energy balance of a snow and ice volumes.



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Figure 7.2

Photo: A. Christen



# The energy balance of snow and ice

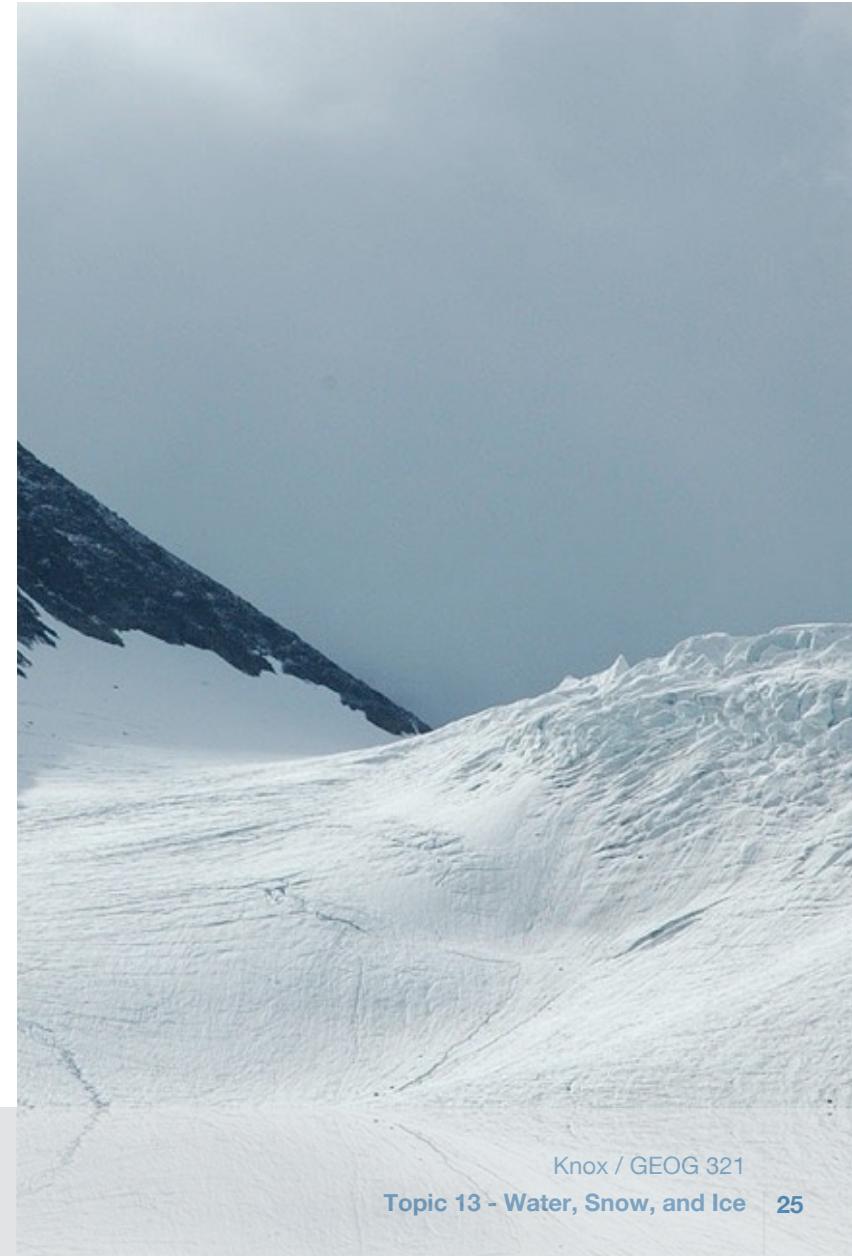
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Beside the 3-d framework, also the **phase changes of water** play an important role in the energy balance of a snow and ice volumes.

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

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

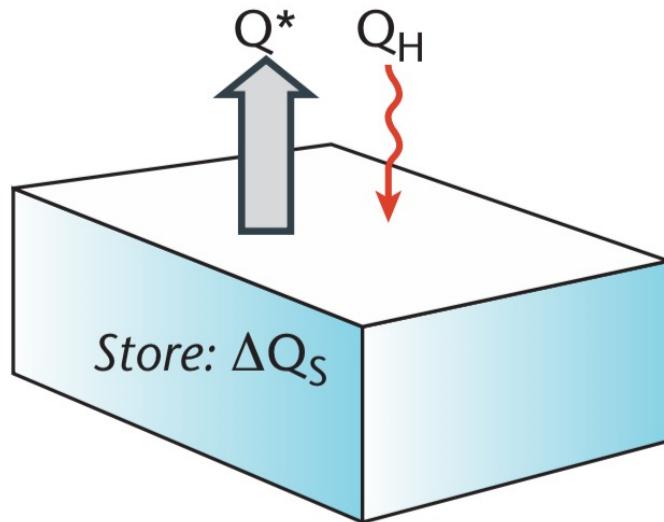
*Photo: A. Christen*



# The state of a snow pack

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## 'Cold' snow pack



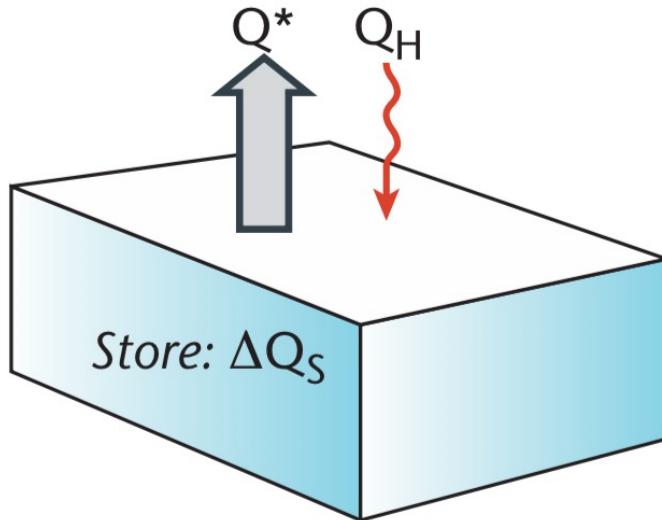
$T_s$  well below 0°C.

Only solid state of water.

No water available for  $Q_E$  or  $\Delta Q_M$ .

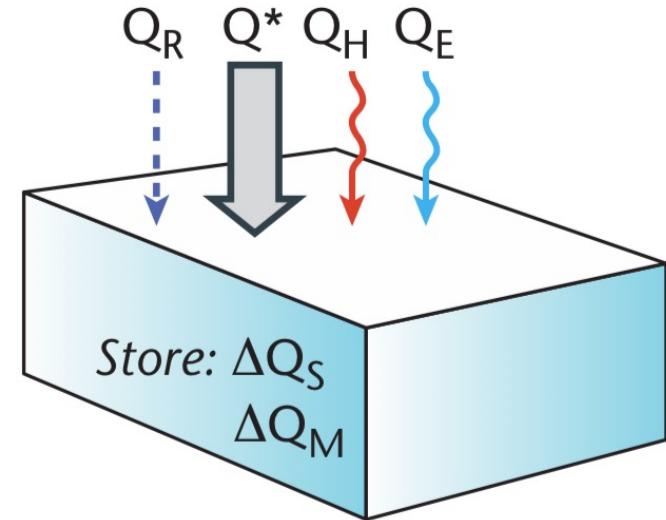
# The state of a snow pack

‘Cold’ snow pack



$T_s$  well below 0°C.  
Only solid state of water.  
No water available for  $Q_E$  or  $\Delta Q_M$ .

‘Wet’ snow pack



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

# Energy balance of a melting snow volume

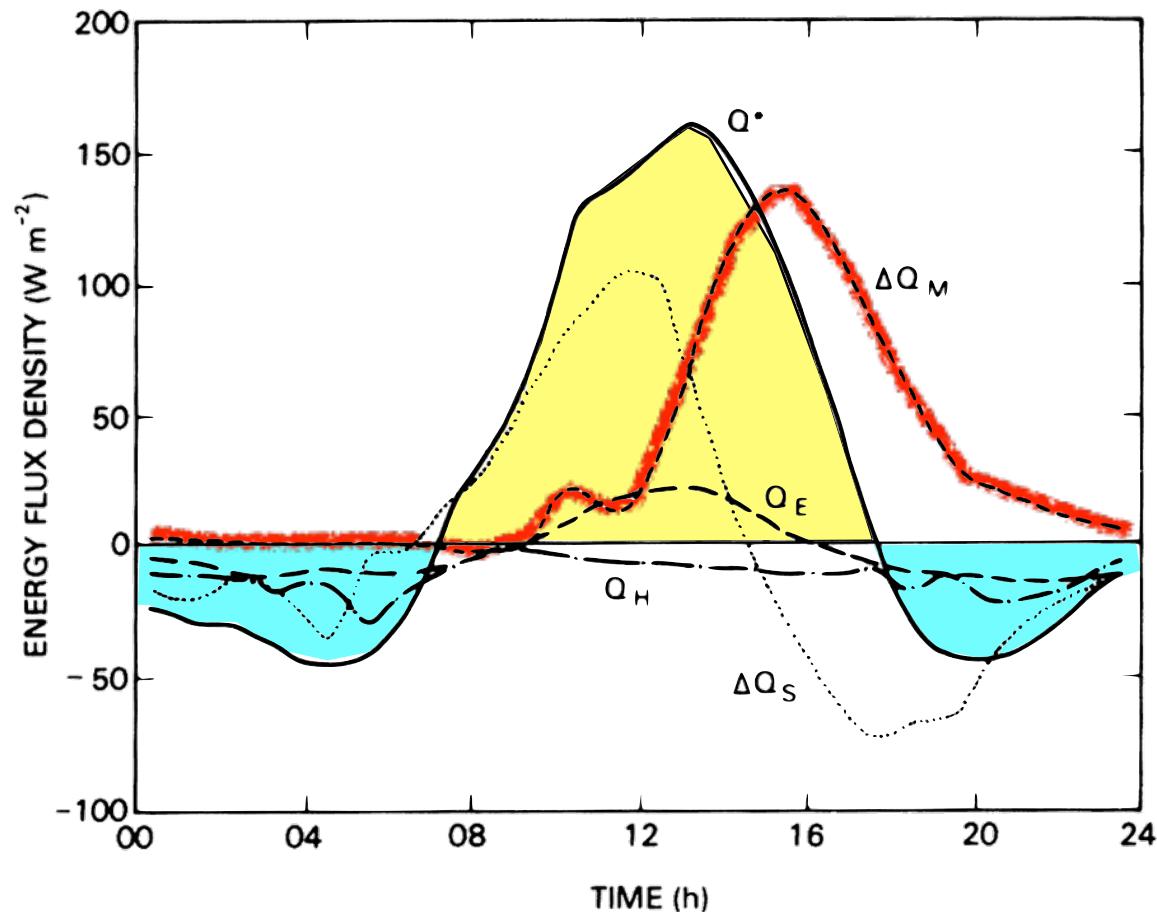


Figure 3.7 Energy balance components for a melting snow cover at Bad Lake, Saskatchewan ( $51^\circ\text{N}$ ) on 10 April 1974 (modified after Granger and Male, 1978).



# Albedo of a water surface

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

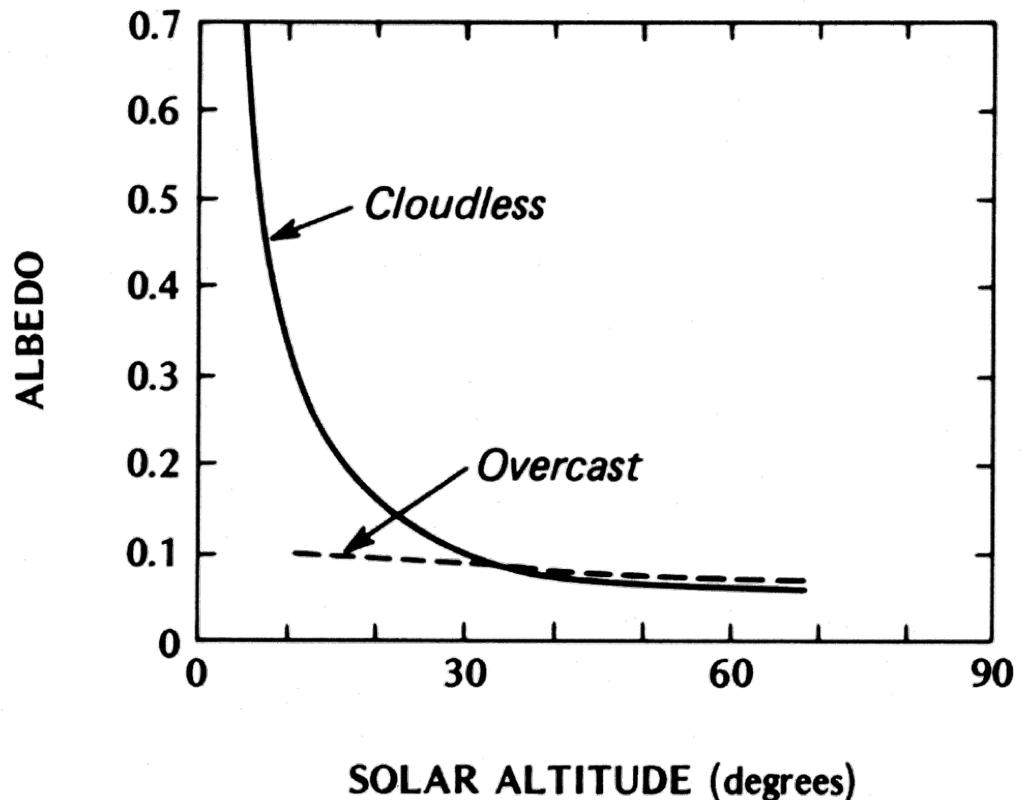


Figure 3.12 Relation between solar altitude and the albedo of lake water for clear and cloudy days over Lake Ontario (after Nunez *et al.*, 1972).

T.R. Oke (1987): 'Boundary Layer Climates' 2<sup>nd</sup> Edition.



# The radiation balance of an open water surface

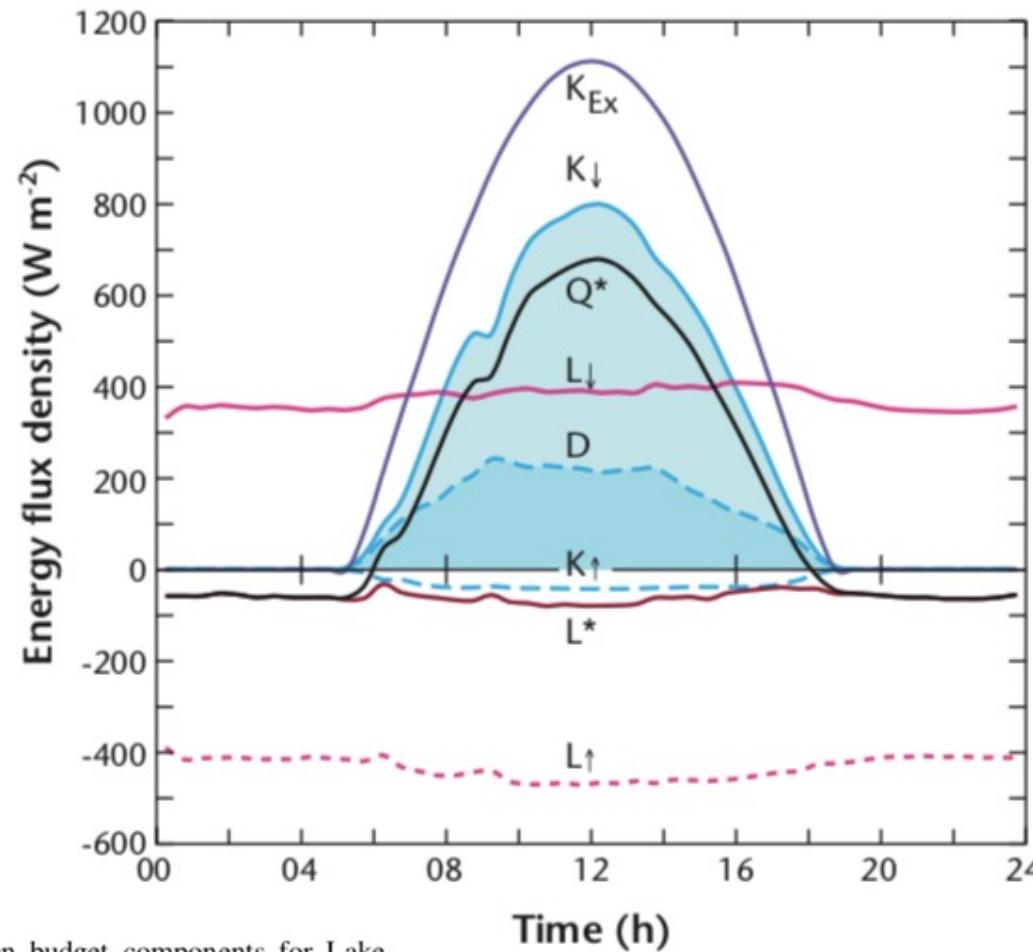
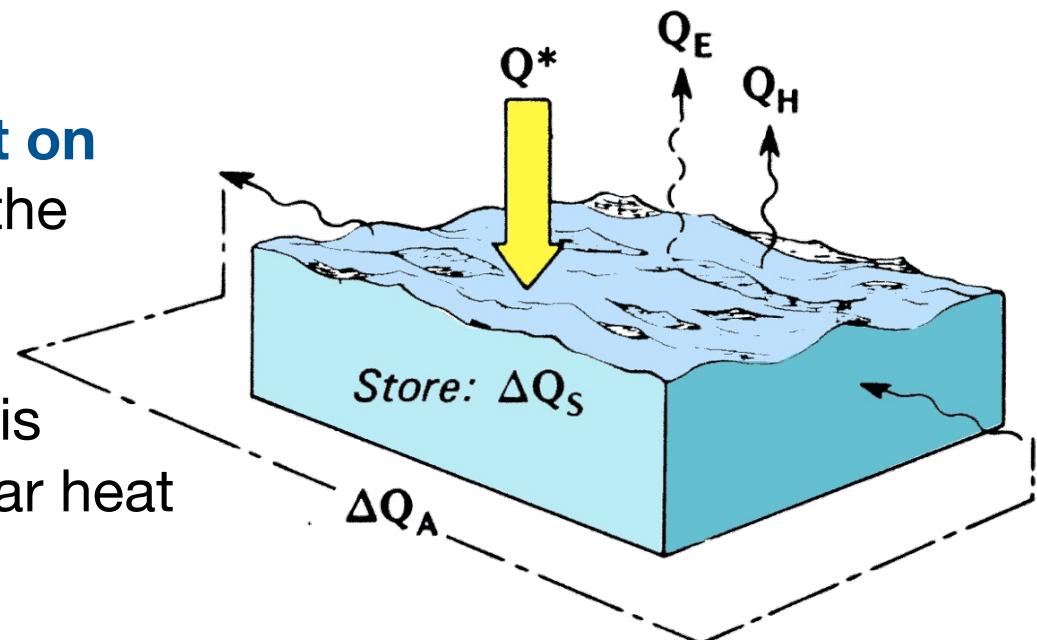


Figure 8: Variation of the radiation budget components for Lake Ontario near Grimsby, Ontario (43°N) on 28 August 1969, with cloudless skies (after Davies et al., 1970).

# 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** ( $\Delta Q_A$ ) are almost all the time significant.

T.R. Oke (1987): 'Boundary Layer Climates' 2<sup>nd</sup> Edition.

## Take home points

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- **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.