



*A micrometeorology / energy balance site in a tidal wetland in Puget Sound, Washington (Photo: F. Anderson)*

## 11 Soil heat transfer

# Learning objectives

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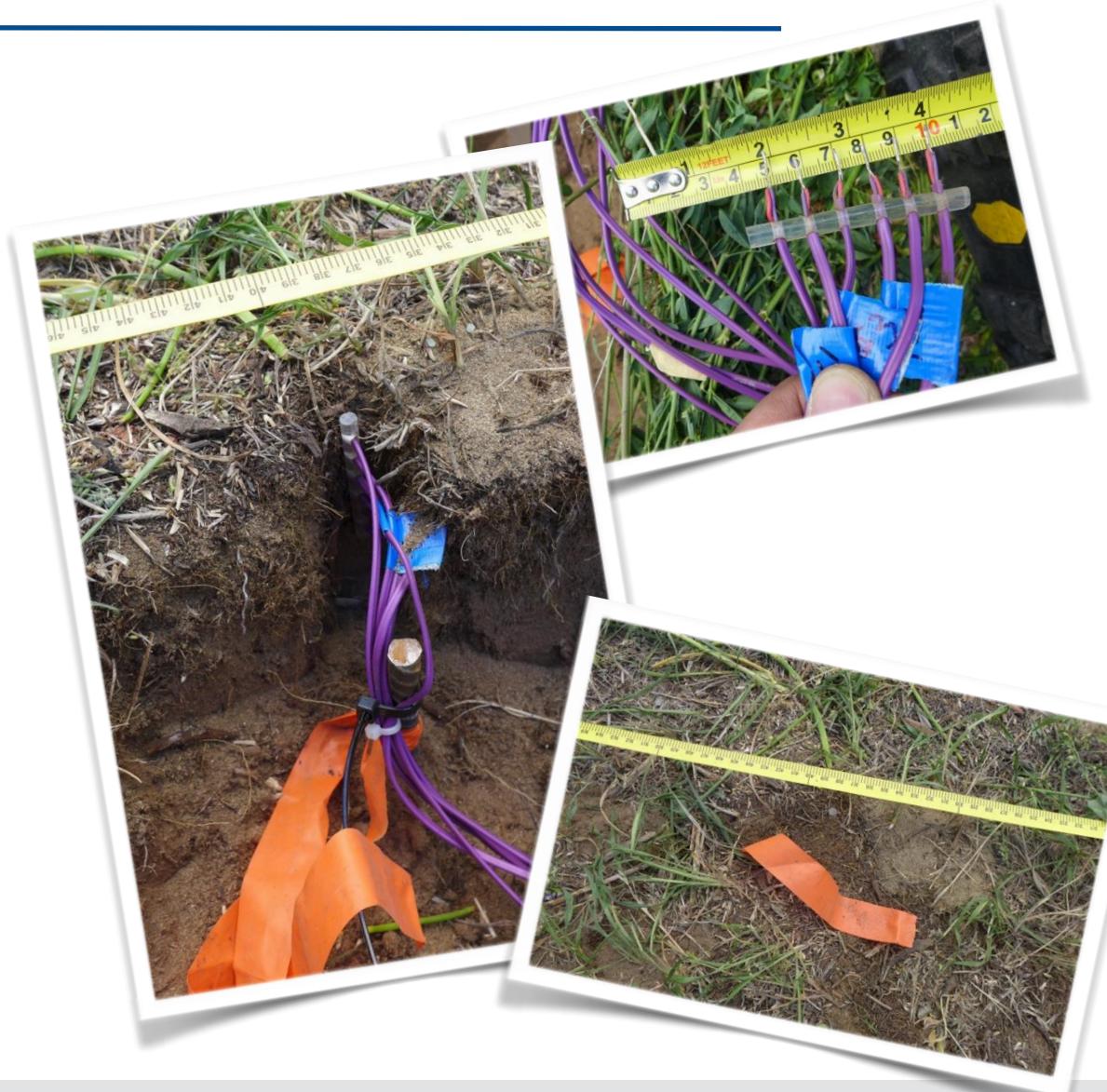
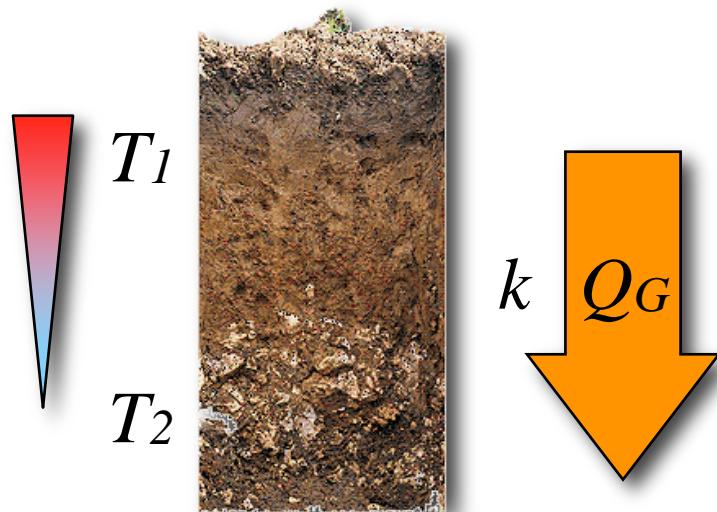
- Explain how we **measure** heat storage changes, and transfer in and out of soils.
- Describe how we **predict** and model heat storage changes, and transfer in and out of soils.
- Explain how heat storage in soils changes on diurnal and annual scales.



Installation of soil sensors in an organic soil of the Low Arctic (Illiisarvik)  
Photo: W. Skeeter (UBC Geography)

# Measurement of $Q_G$

Theoretically, soil heat flux could be simply measured using a vertical array of thermocouples using Fourier's law



# Measuring soil heat flux using a temperature profile

Soil heat flux  
at a given  
depth  
in  $\text{W m}^{-2}$

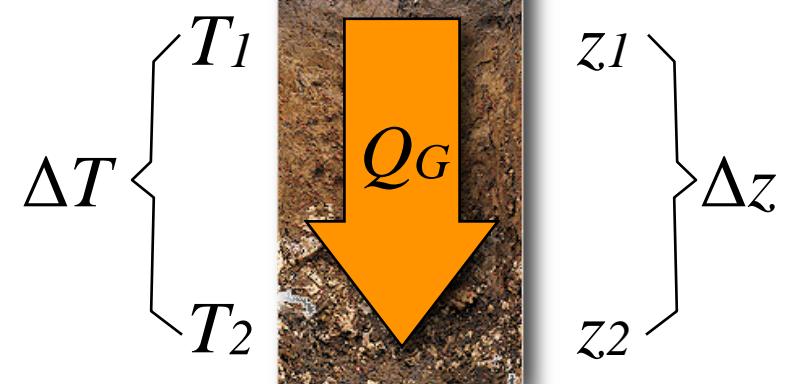
$$Q_G = -k \frac{\partial T}{\partial z} \approx -k \frac{T_2 - T_1}{z_2 - z_1}$$

Thermal conductivity  
in  $\text{W m}^{-1} \text{K}^{-1}$

Temperature  
gradient (change  
with depth)  
in  $\text{K m}^{-1}$

Difference between  
two temperatures...

... measured at two  
different depths



# The role of soil water content

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Practically, the problem is the variably  $k$  with water content. Requires continuous measurements of soil volumetric water content  $\theta_w$ .

A UBC Geography undergraduate measures the volumetric water content of a soil using a TDR.



# The role of soil water content

$\theta_w$  can be measured in the lab using the gravimetric method or using time domain reflectometry (TDR) (i.e. an indirect measure of soil water content based on the travel time of a high frequency electromagnetic pulse through the soil)

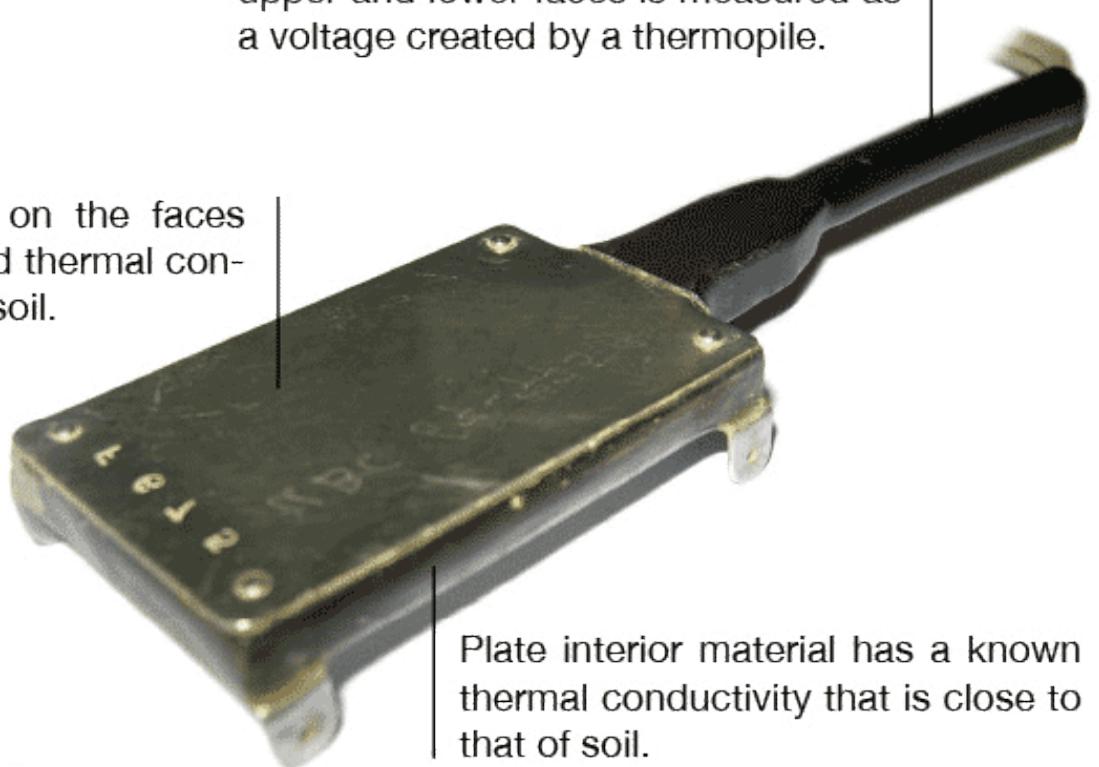


# Soil heat flux density - direct measurement

More useful are **soil heat flux plates**:



Metal plates on the faces ensure a good thermal contact with the soil.



The temperature difference across the upper and lower faces is measured as a voltage created by a thermopile.

Plate interior material has a known thermal conductivity that is close to that of soil.



A floating flux tower in  
Burns Bog, Delta, BC  
operated by UBC Geography



# Soil heat flux plates - correction

Soil heat flux plates are inserted in undisturbed soil, not at the surface but in a few cm depth.

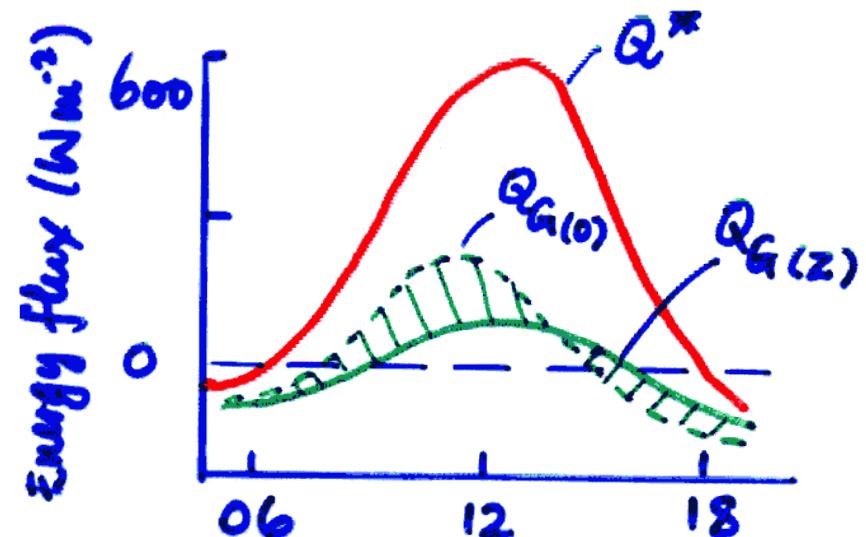
We have to consider the soil heat flux divergence / convergence in the topmost layer.

$$Q_{G(0)} = Q_{G(z)} + \Delta Q_{G(0-z)}$$

Using heat capacity:

$$\Delta Q_{G(0-z)} = C_s \left( \frac{\Delta T}{\Delta t} \right) \Delta z_{0-z}$$

Measured using a temperature profile.



Typical effect of correction during a clear-sky day for bare soil.

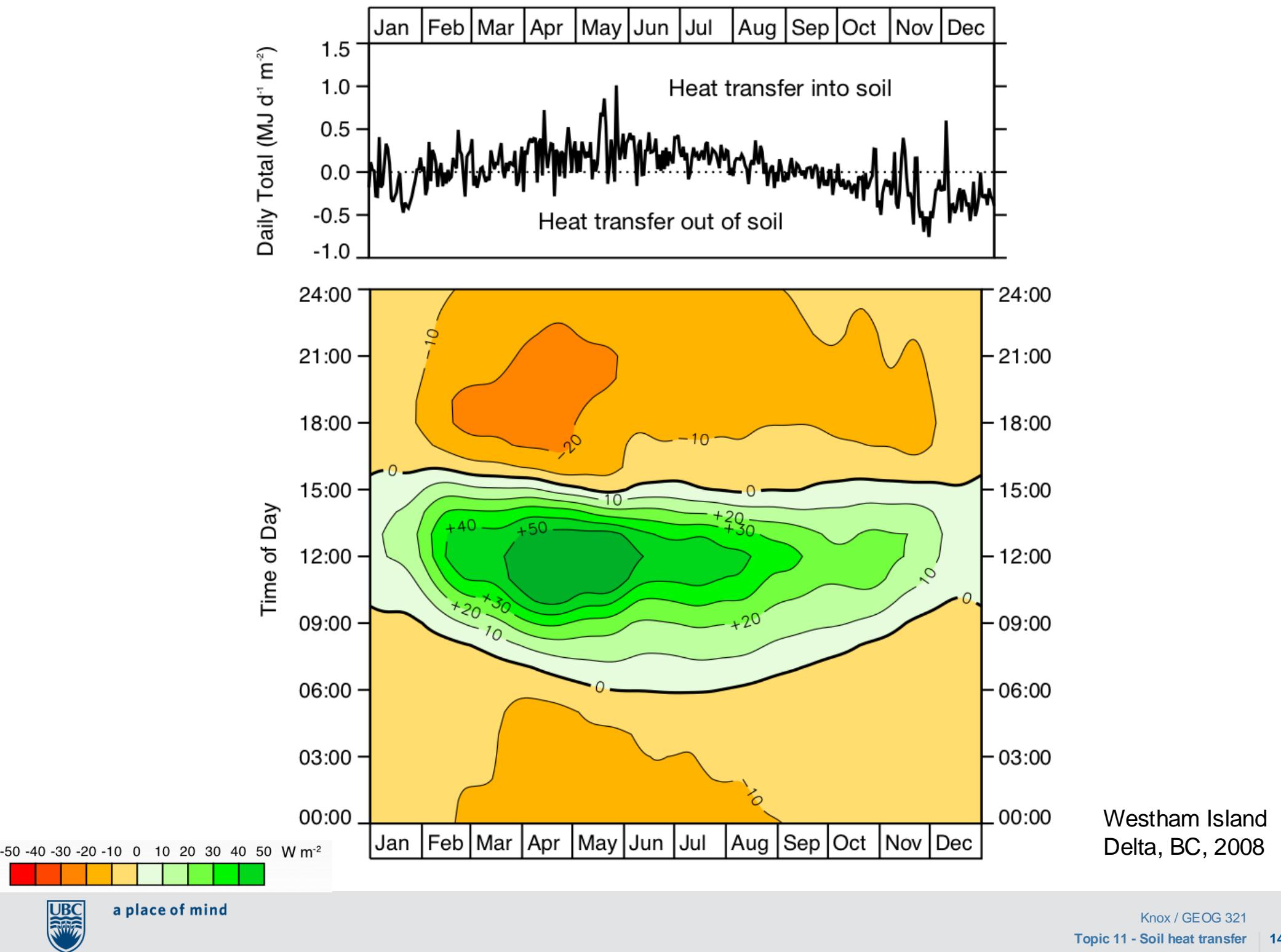


## Test your knowledge (Class activity)

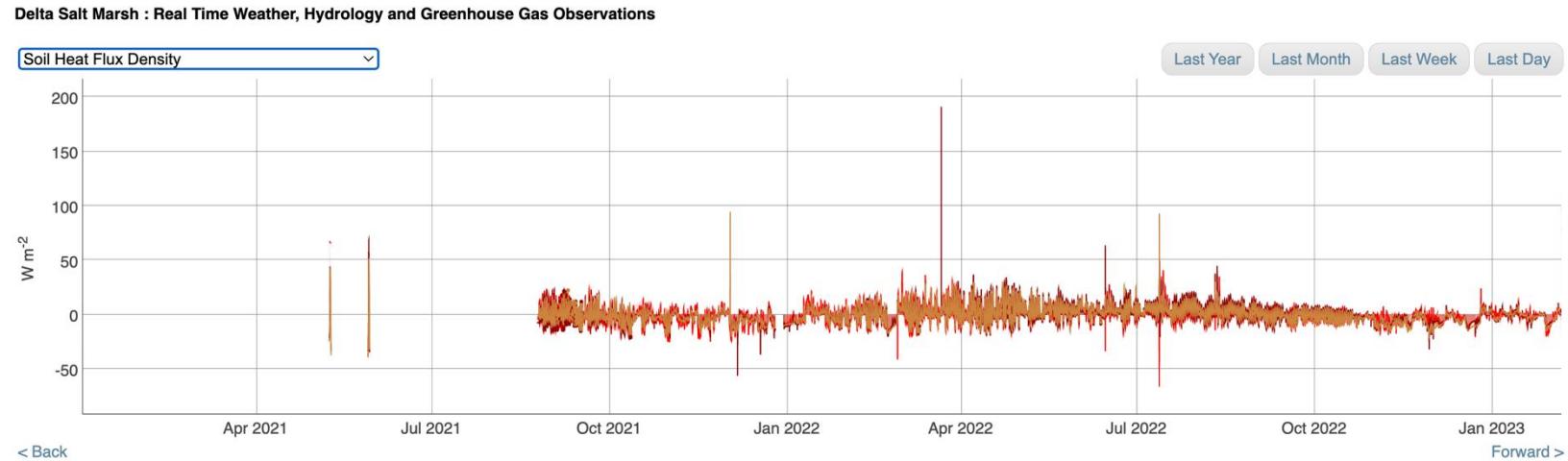
At 11:30 in the morning, we measure a soil heat flux density  $Q_G(5\text{cm})$  of  $25 \text{ W m}^{-2}$  using a heat flux plate installed at 5 cm depth. Calculate the soil heat flux density at the surface  $Q_G(0)$ , if the soil's heat capacity in the layer from 0 to 5 cm depth is  $2 \text{ MJ m}^{-3} \text{ K}^{-1}$  and the temperature in the same layer changed from  $24.8^\circ\text{C}$  at 11:00 to  $25.3^\circ\text{C}$  at 12:00.

$$Q_{G(0)} = Q_{G(z)} + \Delta Q_{G(0-z)}$$

$$\Delta Q_{G(0-z)} = C_s \left( \frac{\Delta T}{\Delta t} \right) \Delta z_{0-z}$$



# Data from a tidal marsh in Delta – questions for discussion

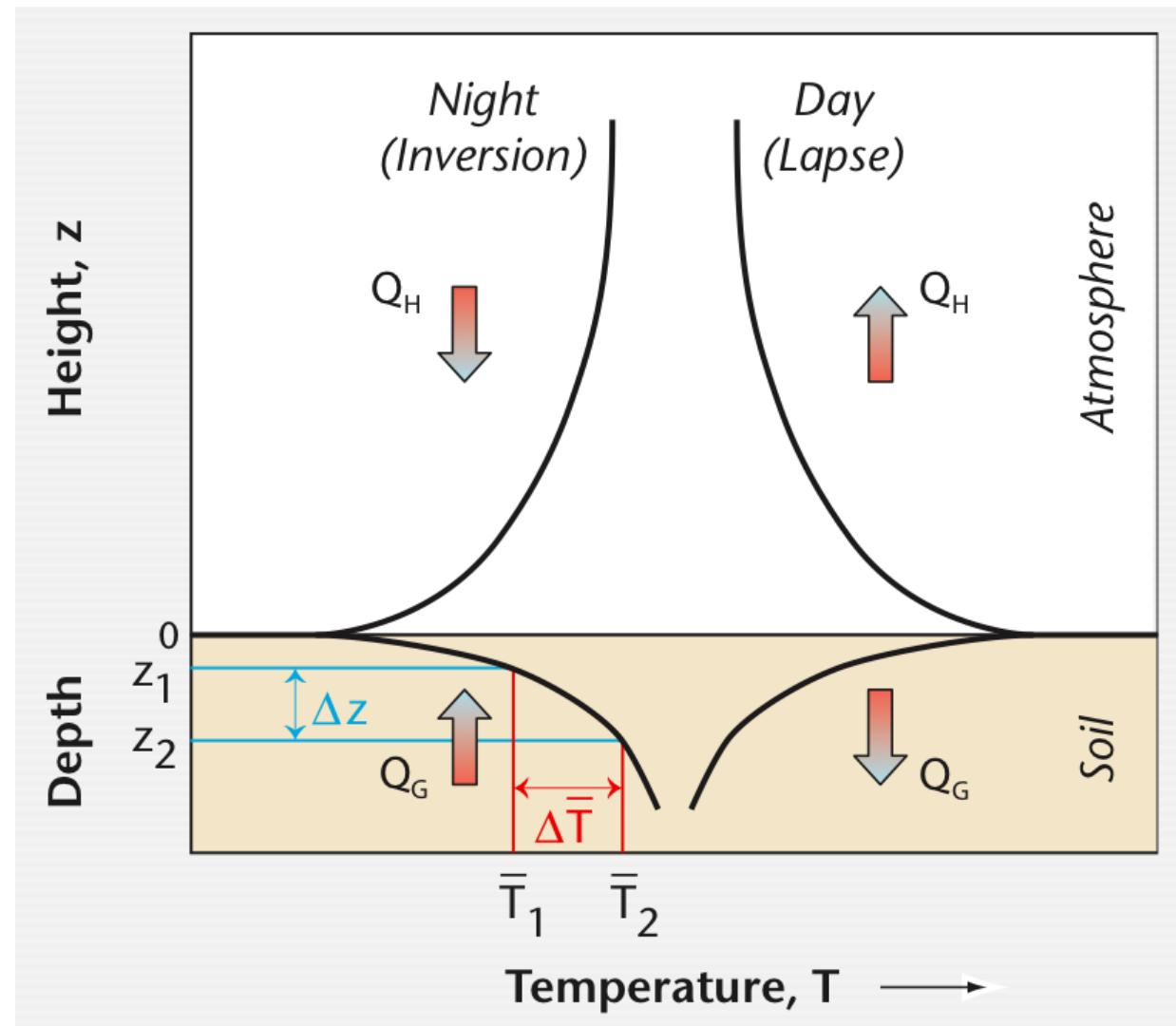


- How does G vary between daytime and nighttime?
- Can you say anything about the spatial variability at the site?

<https://ibis.geog.ubc.ca/~micromet/data/DeltaSaltMarsh.html#>



# Soil temperatures and heat flux profiles



# The heat conduction equation.

$$\frac{\partial Q_G}{\partial z} = C_s \frac{\partial T}{\partial t}$$

$$Q_G = -k \frac{\partial T}{\partial z}$$

Second law of thermodynamics  
(Eq. 1)

Fourier's law of heat conduction (Eq. 2)

$$\frac{\partial T}{\partial t} = -\frac{k}{C_s} \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) = -\kappa_s \frac{\partial^2 T}{\partial z^2}$$

## Solving the heat conduction equation.

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$$\frac{\partial T}{\partial t} = -\kappa_s \frac{\partial^2 T}{\partial z^2}$$

This is a **partial differential equation**, for which **no general analytic solution** exists. There are solutions for selected boundary conditions (see Lecture 12).

Often we approximate the equation with **multi-level soil models** (e.g. in numerical weather forecasting or climate models).

Alternatively one can neglect the variation with depth and look at **heat sharing** between air and soil.

## Thermal admittance

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The **thermal admittance  $\mu$**  is the ability of a surface or system to accept or release heat following a change in (soil) heat flux  $\partial Q_G / \partial t$ .

$$\mu = \sqrt{kC} \quad *$$

Units are:  $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$ .

## Thermal admittance

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For a given change in  $\Delta Q_G$  the change in surface temperature  $\Delta T_s$  is inversely proportional to  $\mu$ .

$$\frac{\partial T_s}{\partial t} \propto \frac{1}{\mu} \frac{\partial Q_G}{\partial t}$$

## **Test your knowledge**

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Surface temperature fluctuations for soils with **low thermal** admittance are:

- a) Small
- b) Large

$$\frac{\partial T_s}{\partial t} \propto \frac{1}{\mu} \frac{\partial Q_G}{\partial t}$$

## **Test your knowledge**

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Surface temperature fluctuations for soils with **low thermal** admittance are:

- a) Small
- b) Large

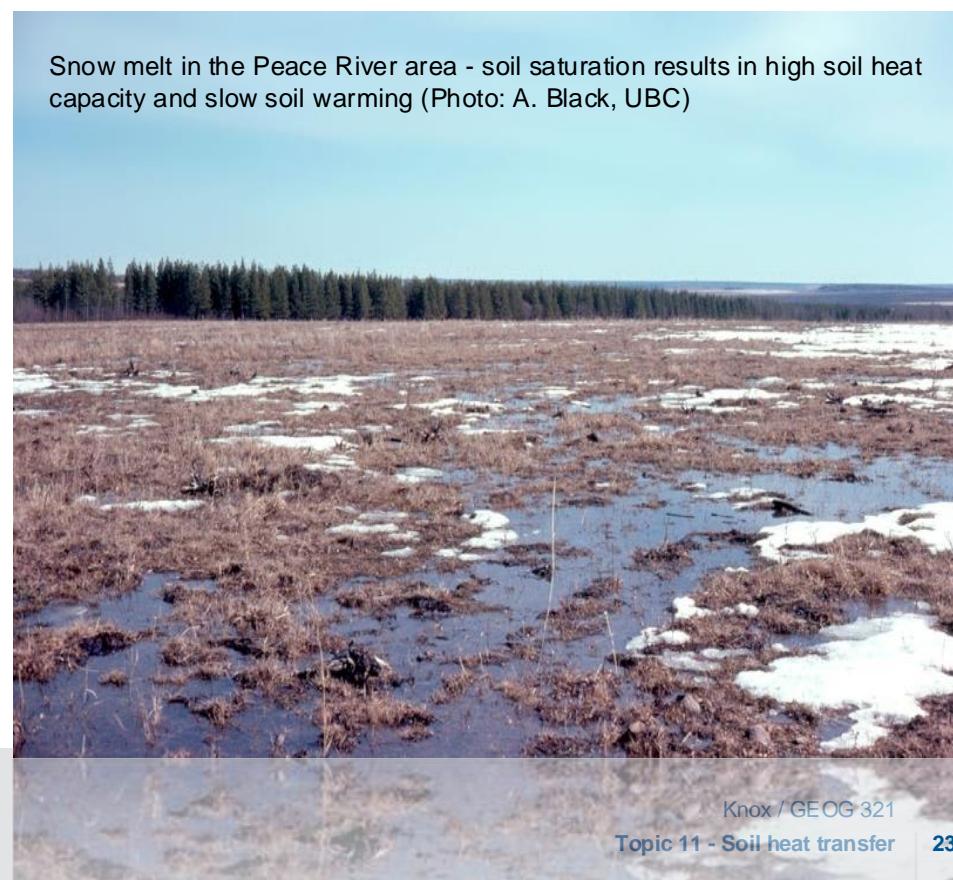
$$\frac{\partial T_s}{\partial t} \propto \frac{1}{\mu} \frac{\partial Q_G}{\partial t}$$

# Thermal admittance of soils

**High  $\mu$  environments** - relatively small  $T$  range (wet areas, clay, bare rock)

**Low  $\mu$  environments** - large daily  $T$  range (dry areas, sandy, organic soils, vegetation cover, snow)

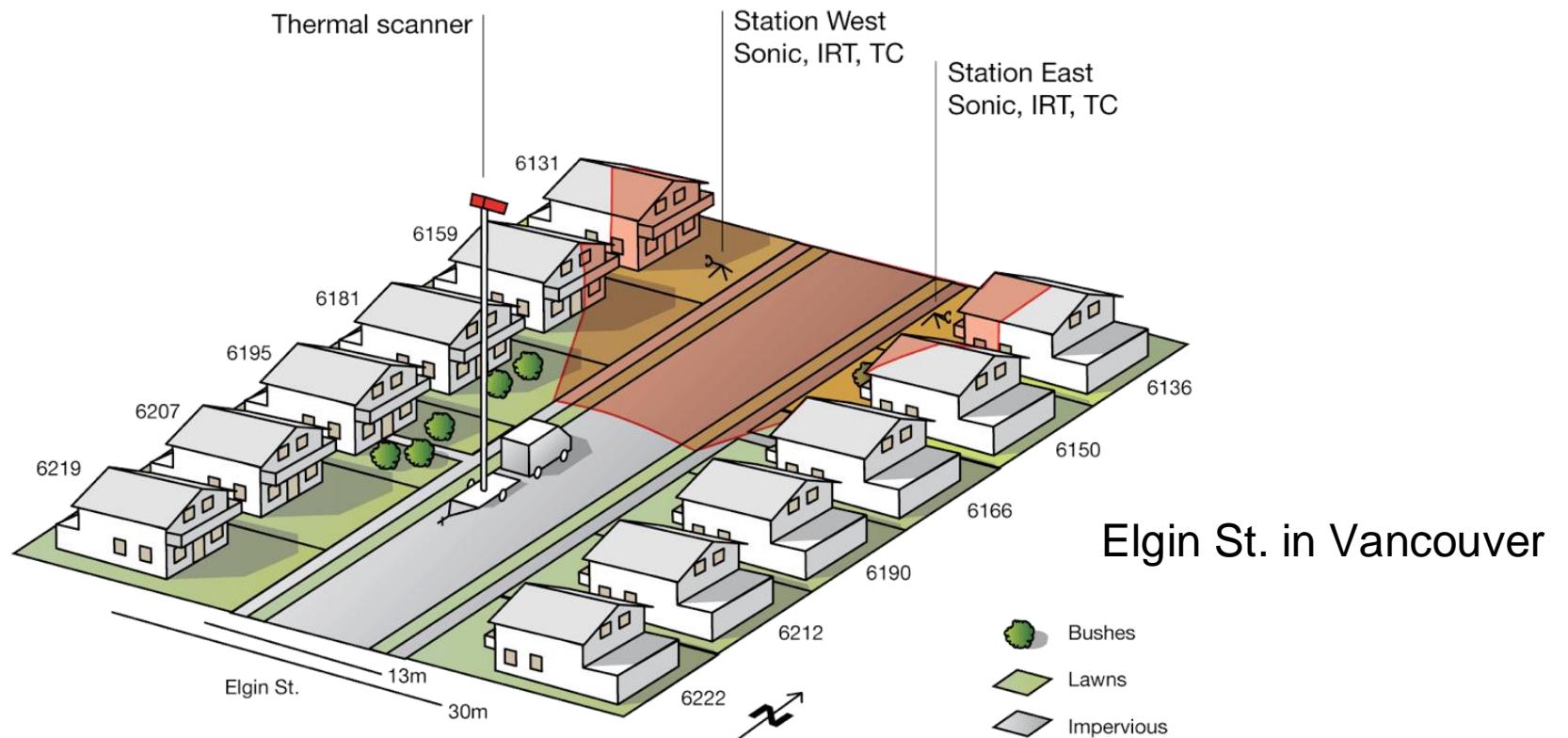
All forcing being equal soil with high  $\mu$  will have a smaller surface temperature wave. Low  $\mu$  produces a larger surface temperature wave.



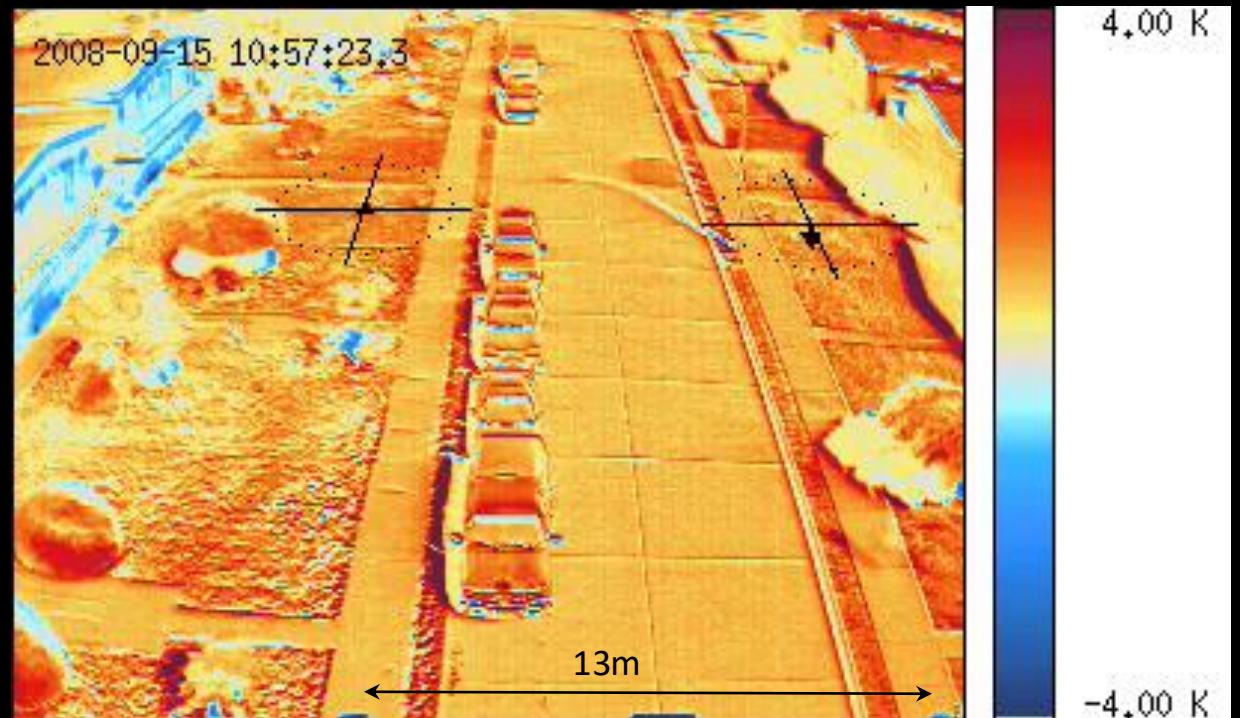
Snow melt in the Peace River area - soil saturation results in high soil heat capacity and slow soil warming (Photo: A. Black, UBC)

# Visualizing the effect of thermal admittance

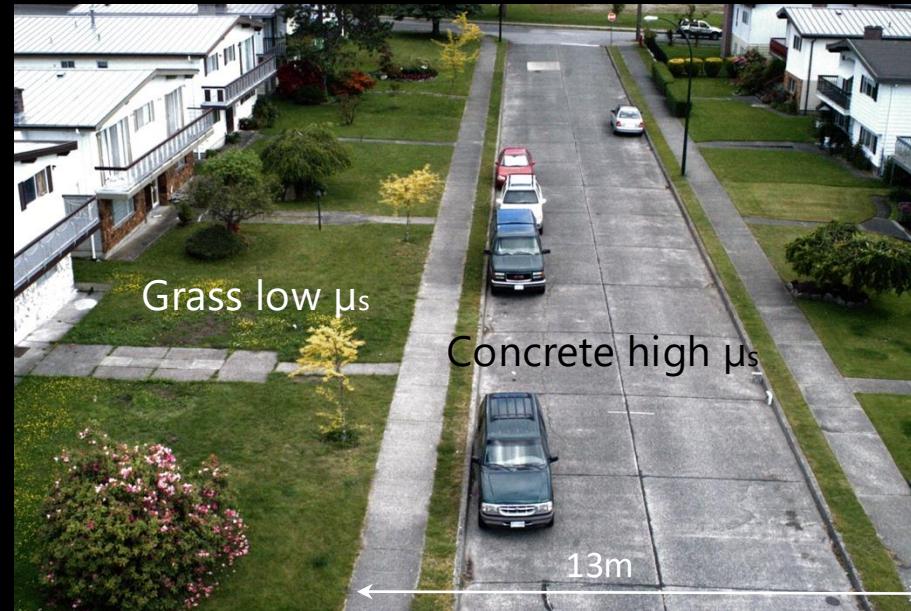
Thermal admittance controls how quickly the surface accepts heat, i.e. how much temperature fluctuation a surface is experiencing.



Fast thermal infrared thermography of temperature fluctuations at the surface with wind vectors overlaid

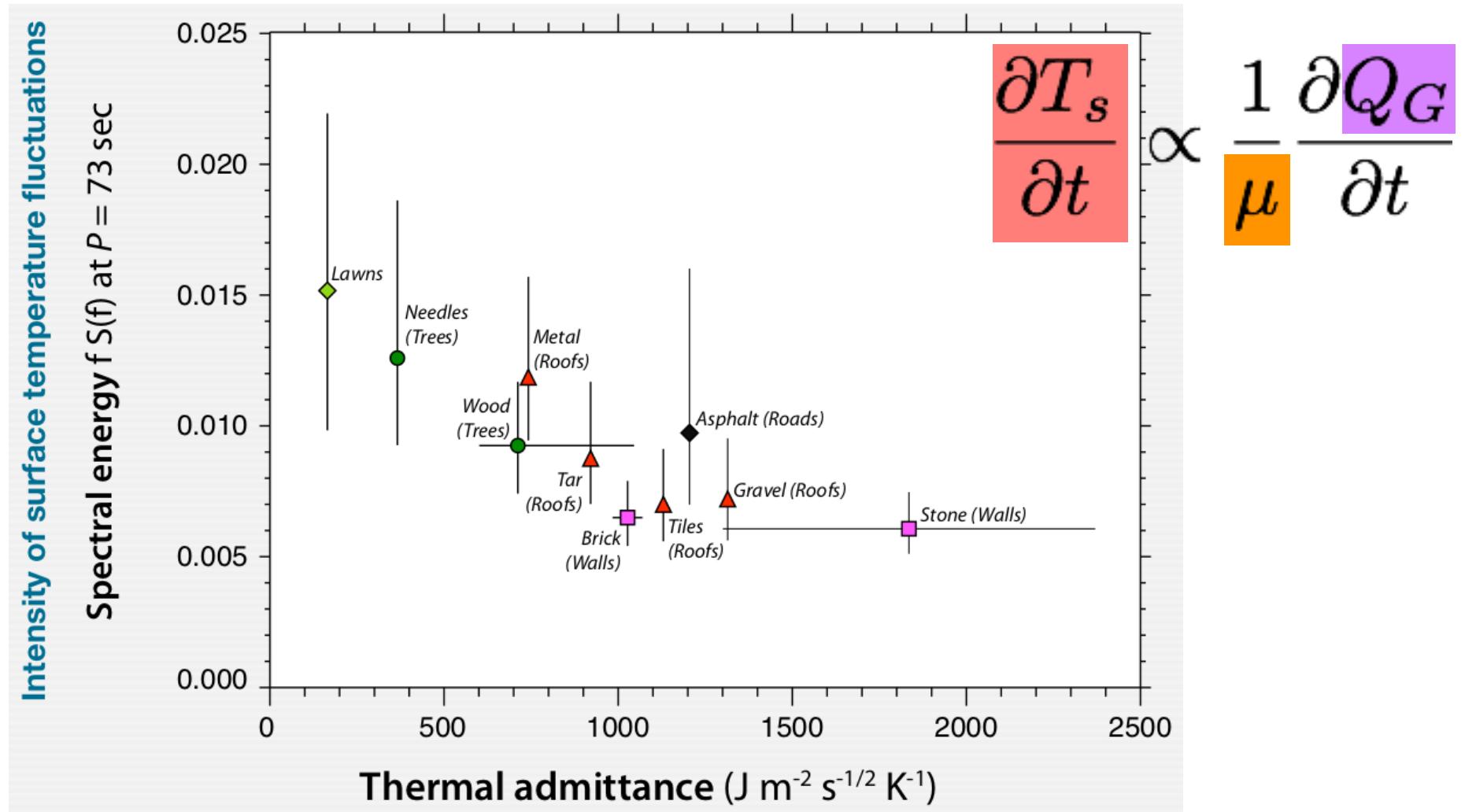


Approximate visible field of view



A.. Christen, J. A., Voogt (2010): 'Inferring turbulent exchange processes in an urban street canyon from high-frequency thermography', *19th Symposium on Boundary Layers and Turbulence*, Keystone CO, USA.

# Surface temperature fluctuations correlate with thermal admittance.



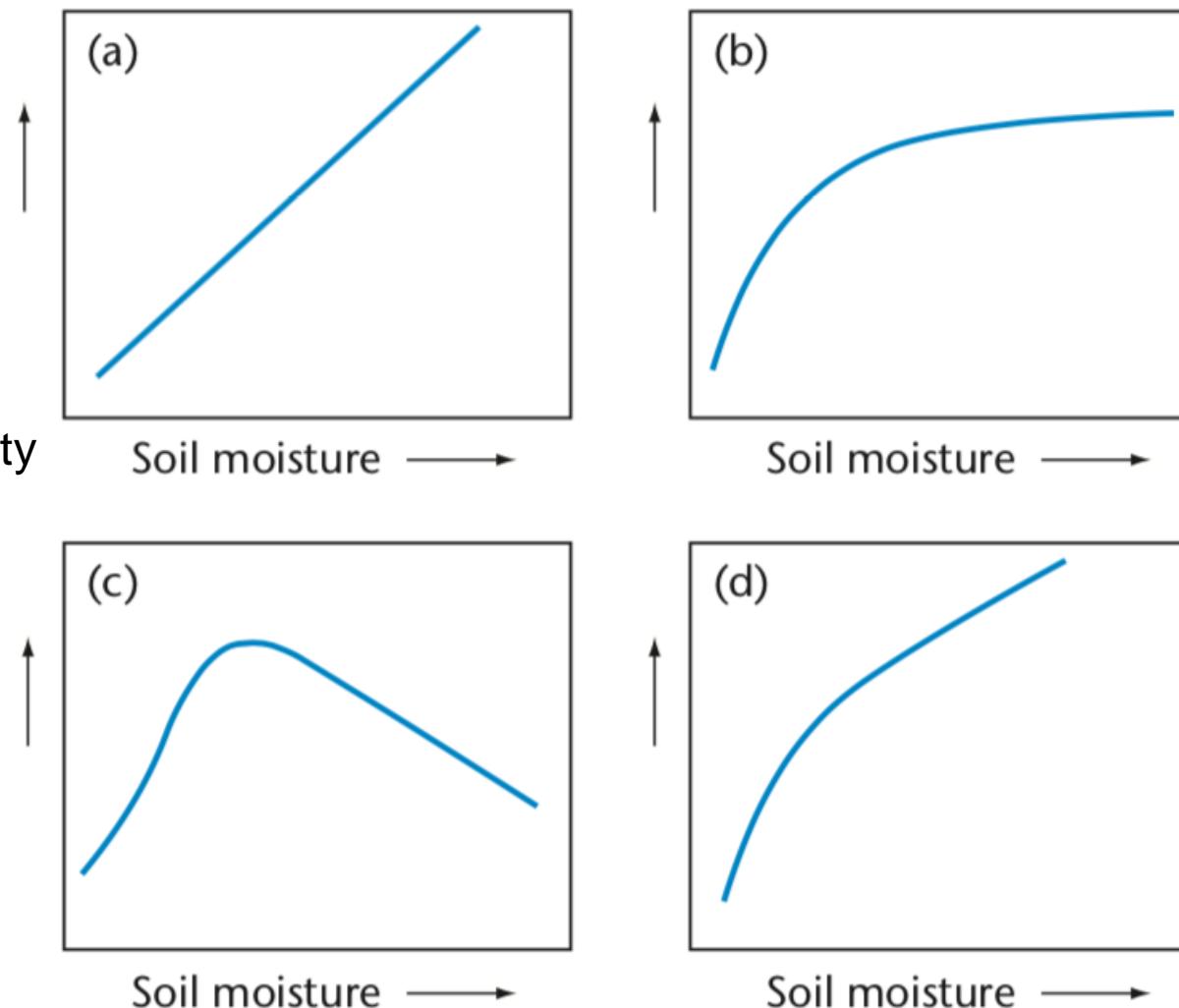
# Effect of soil water content on thermal properties

Thermal  
admittance

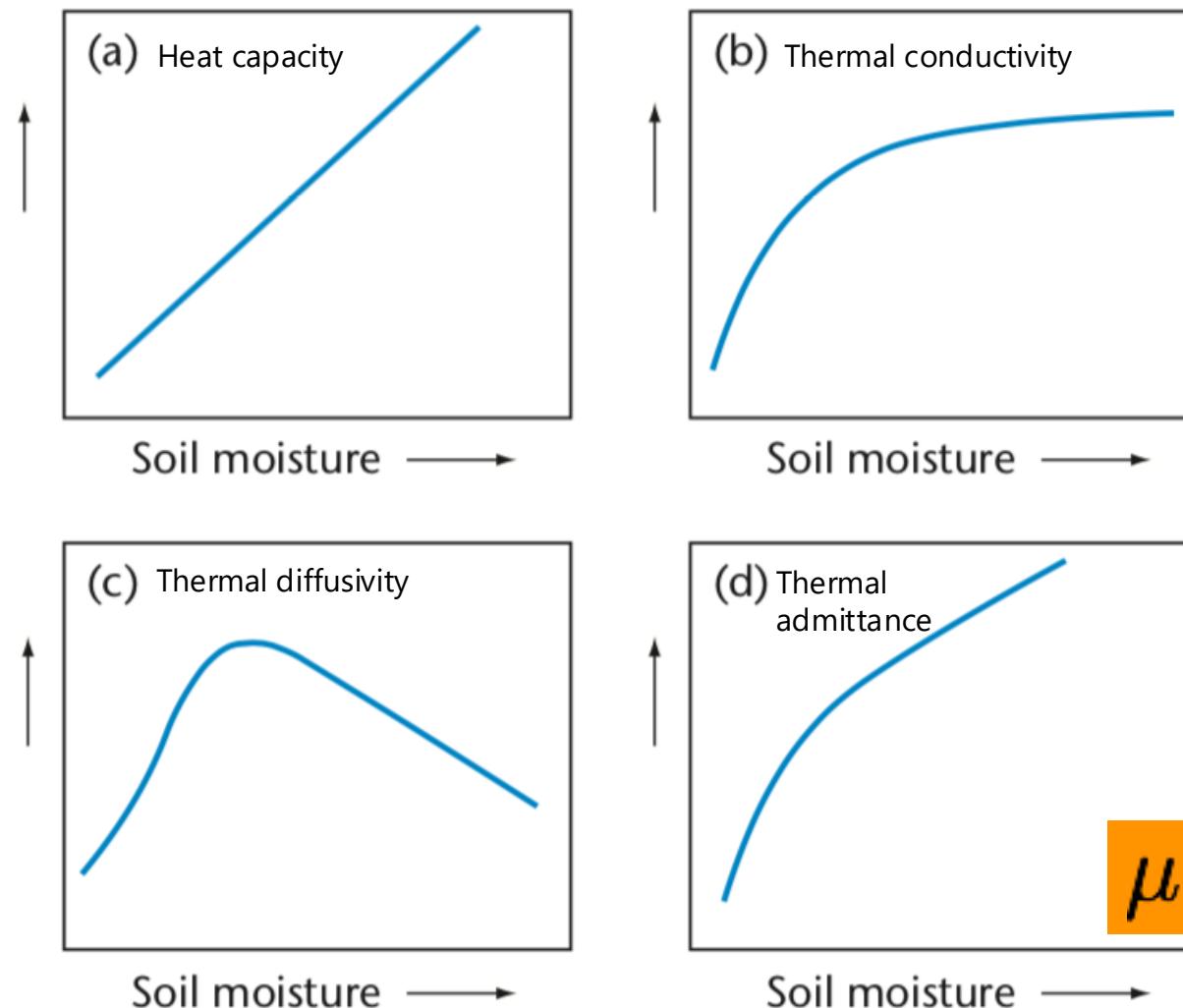
Heat capacity

Thermal diffusivity

Thermal conductivity



# Effect of soil water content on thermal properties



$$\mu = \sqrt{kC} \quad *$$

## Heat sharing

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Refers to partitioning of total sensible heat flux (heat for warming  $Q^*$  -  $Q_E$ ) between soil ( $Q_G$ ) and atmosphere ( $Q_H$ ).

Both share in accepting heat during daytime (warming) and share in releasing heat at night (cooling):

$$\frac{Q_G}{Q_H} = \frac{\mu_s}{\mu_a}$$

where  $\mu_a$  is the atmospheric thermal admittance, which increases with wind speed and free convection as result of surface heating.

## Take home points

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- Soils heat fluxes can be measured using **heat flux plates** inserted into some depth below the surface. Need to be corrected for divergence of heat above measurement level.
- The general **equation for heat conduction** describes how soil temperatures change over time and with depth. It has no general analytical solution, but we can approximate it or solve for selected boundary conditions.
- **Thermal admittance  $\mu$**  can be used to describe the heat sharing between soil and atmosphere.