Soil Temperature and the Energy Cycle

Energy Balance (Day): \[ R_n = SH + ET + G + SS \]
Energy Balance (Night): \[ -R_n = -SH - G + SS \]

Biological Processes

Organic molecule from photosynthesis

\[ CO_2 + H_2O \rightarrow CH_2O + O_2 \]
\[ CH_2O + O_2 \rightarrow CO_3 + H_2O \]

Oxygen is needed to carry out this reaction (aerobic systems). In the absence of O2, other reactions take place.

Soil Air

- In general, soil air contains more CO2 and less O2 than the atmosphere. These differences are seasonal and increase with depth.
- Soil air is almost saturated with water vapor (relative humidity ~100%). It may also contain variable amounts of volatile contaminants.
The process of diffusion between gases in a soil pore and the atmosphere. The total gas pressure is the same on both sides of the boundary. The partial pressure of oxygen is greater, however, in the atmosphere. Therefore, oxygen tends to diffuse into the soil pore where fewer oxygen molecules per unit volume are found. The carbon dioxide molecules, on the other hand, move in the opposite direction owing to the higher partial pressure of this gas in the soil pore. This diffusion of O\textsubscript{2} into the soil pore and of CO\textsubscript{2} into the atmosphere will continue as long as the respiration of root cells and microorganisms consumes O\textsubscript{2} and releases CO\textsubscript{2}.

**Air Movement in Soils**

- Diffusion of gases through water is **very** slow.
- In saturated/wet soils O\textsubscript{2} is depleted and CO\textsubscript{2} accumulates.

In the presence of water, soil temperature controls biological activity.

**Outcome:** more weathering and organic matter decomposition in temperate and tropical regions than in colder regions.

**Relationship between CO\textsubscript{2} and Soil Temperature**
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Weathering Profiles Across Climatic Regions

Network of Soil Temperature Measurements

Soil Temperature

- At least 50% of the land in the northern hemisphere is seasonally frozen (i.e., for more than 15 days/year), and between 12 and 18% contain permafrost (below 0 ºC for at least 2 years).
- Frozen ground in northern latitudes are typically covered with boreal forest. About 1/3 of soil carbon is stored at high latitudes.
- Permafrost is not stable and it often exists near its melting point.

Source: National Snow and Ice Data Center
Building on Permafrost

Construction on permafrost will cause the underlying ice to melt. This house in Fairbanks Alaska has insulated and melted the ice lense in the underlying permafrost.

Building on Permafrost

Special construction techniques are required to build on permafrost.

Avoiding Frost Heave
Frost Susceptible Soils (Heave)

- Wet soils rich in silt are the most susceptible soils:
  - With enough water ice lenses are formed.
  - Ice moves upward while water is supplied from the unfrozen soil below the freezing front.

Source: http://www.maths.ox.ac.uk/~fowler/pictures/gallery.html

Infrastructure and Thawing Permafrost
Environmental Consequences of Thawing Permafrost

- Permafrost in Siberia is a sediment (yedoma) rich in grass roots and animal bones that has the potential of releasing large amounts of carbon dioxide and methane upon thawing. Both carbon dioxide and methane are potent greenhouse gases.
- Methane is produced at the bottom of present lakes (anaerobic decomposition of organic matter) and it is also trapped in permafrost when a lake migrates and the ground refreezes.

Energy Balance and Heat Conduction


Soil Surface Temperature

- Soil surface temperature is dominated by external forcing: (the energy flux reaching the surface is more than 4000 greater than the energy flux from the interior of the Earth).
- Soil surface temperature is a function of $R_n$ modified by:
  - surface albedo
  - Topography
  - Vegetation
  - Hydrological and climatological processes.
Distribution of Annual Average Soil Temperatures


Subsurface Temperature

- Subsurface temperature is determined by:
  - Surface temperature
  - Energy flow from the interior of the Earth
- Temperatures close to the surface (few meters deep) are mainly influenced by changes at the surface.
- Soil acts as a filter damping the periodic fluctuations while preserving the overall trend.

### Subsurface Temperature Profiles

**Figure 1** Temperature measurements at various depths in three boreholes in central Canada. The extreme in the upper parts of the profiles is a response, at least in part, to temperature changes at the surface. The linear increase of temperature with depth in the deeper sections of the holes is the so-called parabolic gradient.


### Annual Temperature

**New Brunswick 1984**


### Daily Temperature

Soil Temperature Profiles: **Dry Soil**

Source: [http://soilphysics.okstate.edu/software/index.html](http://soilphysics.okstate.edu/software/index.html)

Soil Temperature Profiles: **Wet Soil**

Source: [http://soilphysics.okstate.edu/software/index.html](http://soilphysics.okstate.edu/software/index.html)

**Summary of Observations**

- Energy transport through soil results in:
  - Decrease in the range of temperature (amplitude) with depth.
  - At any depth, maximum and minimum temperatures occur at a later time than at the surface (the lag increases with depth).
- The depth of penetration of energy is a function of:
  - The duration of the input: annual cycle penetrates 19 times deeper than daily cycle.
  - Soil type and soil water content.
Heat Transport

- Heat transport in soils is mainly through conduction.
- Two properties of the material are important:
  - Thermal conductivity, \( \lambda \)
  - Heat (storage) capacity, \( C_H \)
- The components of soils (i.e., mineral and organic matter, water and air) have very different \( \lambda \) and \( C_H \).

Thermal Conductivities of Soil Components

Volumetric Heat Capacity
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Transport of Energy by Individual Soil Components

Soil: Mix of Components

- Dry soils are poor conductors.
- Saturated soils have the highest potential for conducting heat, but require more energy to increase their temperature.
- Soils at intermediate water contents conduct energy better than dry soils and are warmer than saturated soils.

Fourier’s Law

\[ H_G = -\lambda \frac{\Delta T}{\Delta z} \]

For example: assuming \( \lambda = 1.1 \text{ W/m}^2\text{K} \), then

\[ \left\{ \frac{\Delta T}{\Delta z} \right\} = \frac{288 \text{ K} - 295 \text{ K}}{3\text{ m} - 1\text{ m}} = \frac{-7 \text{ K}}{2\text{ m}} \]

\[ H_G = -1.1 \text{ W/m}^2\text{K} \cdot \left\{ \frac{-7 \text{ K}}{2\text{ m}} \right\} \]

\[ H_G = 3.9 \text{ W/m}^2 \]
How about Heat Flow from the Earth?


Applications

- Frost heave and its prevention (soil freezing is similar to soil drying!).
- Thermal signatures can be used to detect buried objects (e.g., land mines).

Soil Temperature and Mine Detection

- More than 110 million buried mines in 70 countries kill or mutilate 15,000 people/year.
- The concept of using thermal properties to locate buried mines:

Some Results

- Very small differences in temperature.
- Temperature differences enhanced in wet soils.


More Results