Chapter 8 - Soil Temperature

- **Factors affecting soil temperature**
- **Heat transfer processes**
- **Thermal conductivity and diffusivity**
- **Measurement of temperature**
- **Diurnal and annual cycles**
- **Heat capacity**
- **Heat flow**
- **Determining K_T in field**
- **Simultaneous transport of water and heat**

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Temperature affects several processes

- assimilation
- respiration
- transpiration
- chemical reactions in soil and plants
- diffusion of gases and solutes
- water flow in soil
- translocation
- microbial activity
- availability of water to plants

Factors that influence temperature

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of surface soil
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- radiation from sun
- slope of land
- water content of soil
- vegetative cover
- albedo

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of subsurface soil
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- heat flux from surface
- water content
- bulk density
- heat capacity of soil

Radiation

See Fig. 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, and 5.7 in the book (Jury et al., 1991)

- Radiation from sun is mostly short wave.
- Earth absorbs short wave - some reflected
- Earth radiates energy nearly like a black body (primarily long wave)

- H_2O vapor, CO_2, N_2O, CH_4, synthetic industrial gases, and dust absorb long wave

Heat Transfer Processes

1. Radiative

   - Any surface radiates energy

   - What is mostly felt as heat coming from fireplace

   - Stefan's Law

Radiation from blackbody

$$\Sigma = \varepsilon\ \sigma\ T^4$$

Σ - $\frac{\text{cal}}{\text{cm}^2\ \text{min}}$ - Energy flux, integrated over all wavelengths

$\varepsilon = 1$ for blackbody
$\varepsilon < 1$ for other bodies
$\sigma = 8\text{x}10^{-11}$ cal cm min^{-1} $^{\circ}\text{K}^{-4}$
T - $^{\circ}$K

2. Convection

   - Hot air rises causing mixing and transport

3. Conduction

   - Net molecular exchange of kinetic energy which takes place from more energetic molecules (hot regions) to less energetic molecules (cool regions)

Within soil, radiative and convection are very small in relation to conduction

Measurement of Temperature

- Glass thermometers
    - high heat capacity
    - may conduct heat along thermometer
- Thermocouples & Thermistors
    - response good
    - small size
- Radiation Thermometer
    - measures surface temperature
    - measures infrared

Diurnal and annual cycles

See 5.14 and 5.15 in the textbook (Jury et al., 1991).

- Soil heats up during day, cools at night
- Diurnal variations damped with depth
- Peak shifts

Heat Capacity

Heat capacity = $\frac{\Delta Q}{\Delta T}$ (cal /^{o} K)

ΔQ is quantity of heat

ΔT is associated T change

Heat capacity is dependent upon size of the system. Heat capacity per unit mass is

$$c = \frac{\Delta Q}{m\Delta t} \quad \frac{cal}{g\,{}^{\circ}K}$$

c is called specific heat

- independent of system size

	Soil Minerals	H_2O	Humus
c	0.2	1.0	0.5
	$\frac{cal}{g\,{}^{\circ}K}$	$\frac{cal}{g\,{}^{\circ}K}$	$\frac{cal}{g\,{}^{\circ}K}$

Volumetric heat capacity

$C_{soil} = S\ X_i\ \rho_i\ c_i$

$$C_{soil} = \frac{\Delta Q}{V\Delta T} \qquad \frac{cal}{cm^3\ °K}$$

X_i - volume fraction of particular soil constituent

$C_{soil} = X_m\ \rho_m\ c_m + X_o\ \rho_o\ c_o + X_w\ \rho_w\ c_w + X_a\ \rho_a\ c_a$

- X_m, X_o, X_w, & X_a are volume fractions of mineral matter, organic matter, water, & air

- ρ are respective densities
- c are respective specific heats

$$\rho_a = \frac{\rho_w}{1000} \text{ therefore } \rho_a \approx 0$$

$C_{soil} = X_m\ \rho_m\ c_m + X_o\ \rho_o\ c_o + X_w\ \rho_w\ c_w$

$\rho_m = 2.6\ g/cm^3$
$\rho_o = 1.3\ g/cm^3$
$\rho_w = 1.0\ g/cm^3$

$C_{soil} = X_m\ (2.6)\ (0.2) + X_o\ (1.3)\ (0.5) + X_w\ (1)\ (1)$

$= 0.52\ X_m + 0.65\ X_o + X_w$

Volumetric heat capacity has units of cal cm^{-3} soil $°K^{-1}$
Since X_w is just volumetric water content, $X_w = \theta_v$.

The equation using slightly different values for ? and c given by Jury et al. (1991) is

$$C_{soil} = 0.46\ (1 - \phi - X_o) + 0.6\ X_o + \theta_v$$

In California soils the $X_o \approx 1\%$, so this term has little influence.

In all problems, assume X_o=0 if not specified.

Heat Flow

Steady State

$$J_H = -\lambda_e \frac{dT}{dz}$$

J_H = heat flux density $\dfrac{\text{cal}}{\text{cm}^2\,\text{sec}}$

λ_e - effective thermal conductivity $\dfrac{\text{cal}}{\text{cm soil sec °K}}$

T - temperature °K

z - distance (cm)

Transient State

$$C\frac{\partial T}{\partial t} = \frac{-\partial J_H}{\partial z}$$

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[\lambda_e \frac{\partial T}{\partial z}\right]$$

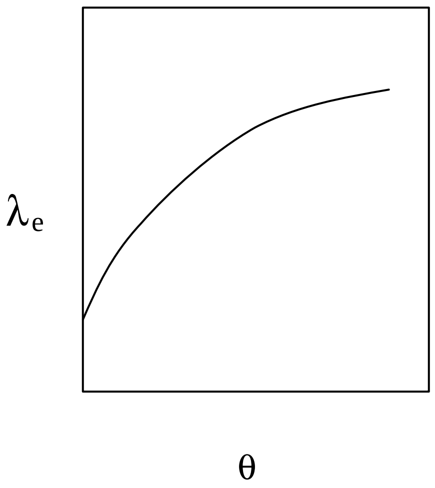
If l_e constant with z

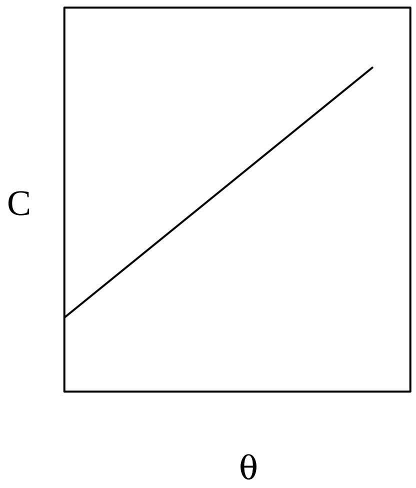
$$C\frac{\partial T}{\partial t} = \lambda_e \frac{\partial^2 T}{\partial z^2}$$

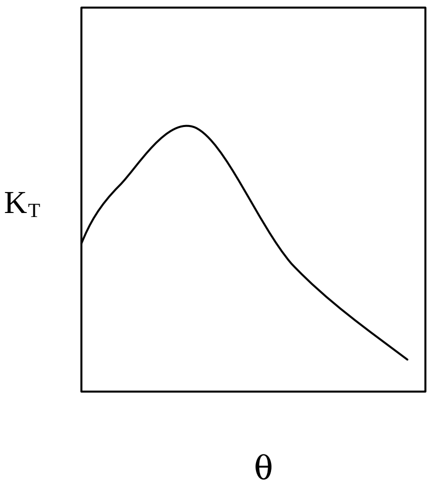
$$\frac{\partial T}{\partial t} = K_T \frac{\partial^2 T}{\partial z^2}$$

$$K_T = \frac{\lambda_e}{C}$$

K_T - Soil thermal diffusivity





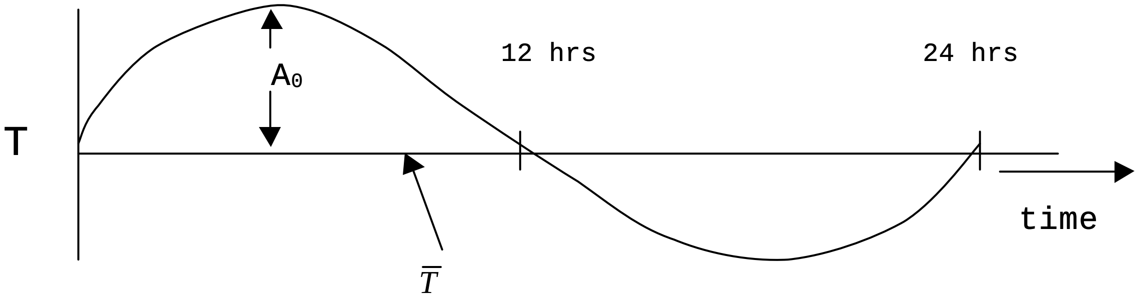


Also, see Fig. 5.10 and 5.11 in Jury et al., 1991 book.

<u>Thermal conductivities for several materials</u>

dry soil	1.5×10^{-3}	$\frac{\text{cal}}{\text{cm sec °K}}$
H_2O	1.4×10^{-3}	"
air	6×10^{-5}	"
copper	0.918	"
steel	0.108	"
cardboard	5×10^{-4}	"
glass	1.7×10^{-3}	"
quartz	26.3×10^{-3}	"
clay minerals	8.7×10^{-3}	"

Determining K_T in field



$T(o,t) = \bar{T} + A_o \sin \omega t$

$T(o,t)$ - Temperature at z=o (soil surface)
$\bar{T}$ - Average daily temperature at soil surface
A_o - Amplitude of surface temperature fluctuation
ω - radial frequency

$\omega = \frac{2\pi}{\tau}$ τ - period = 86,400 s (=24 hours)

$$\omega = \frac{2\pi \text{ radians}}{86{,}400 \text{ s}}$$

Also assume that $T(\infty,t) = \bar{T}$

$\bar{T}$ assumed to be same at all depths

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

Solution with above conditions is

$$T(z,\ t) = \overline{T} + A_o\, e^{-z/d}\,[\sin\,(\omega t - \frac{z}{d})]$$

d is "damping depth" at which the T amplitude decreases to 1/e of A_o

d is usually 20-30 cm for diurnal temperature fluctuations

$$d = \sqrt{2K_T/\omega}$$

Å **Calculate d for the annual wave using** t **for one year.**

Amplitude Equation

amplitude at z=o is A_o
amplitude at $z=z_1$ is $A_1 = A_o \exp(-z_1/d)$
amplitude at $z=z_2$ is $A_2 = A_o \exp(-z_2/d)$

$$\frac{A_1}{A_2} = \frac{\exp(-z_1/d)}{\exp(-z_2/d)} = \exp\,[(z_2 - z_1)/d]$$

$$\ln(A_1/A_2) = \frac{z_2 - z_1}{d}$$

$$d = \frac{z_2 - z_1}{\ln(A_1/A_2)}$$

$$\sqrt{2K_T/\omega} = \frac{z_2 - z_1}{\ln(A_1/A_2)}$$

$$K_T = \frac{\omega}{2}\left[\frac{z_2 - z_1}{\ln(A_1/A_2)}\right]^2$$

Determine A_1 at z_1 and A_2 at z_2. Calculate K_T.

Phase Equation

$$T(z,\ t) = \overline{T} + A_o e^{-z/d}\left[\sin\left(\omega t - \frac{z}{d}\right)\right]$$

When T is maximum at each depth, the sin ( ) must be maximum.

The sin ( ) is maximum when the ( ) = $\frac{\pi}{2}$, $\sin\frac{\pi}{2} = 1$.

$$\therefore \omega t_1 - \frac{z_1}{d} = \frac{\pi}{2}$$

and

$$\omega t_2 - \frac{z_2}{d} = \frac{\pi}{2}$$

Thus, can equate the 2 terms

$$\omega t_1 - \frac{z_1}{d} = \omega t_2 - \frac{z_2}{d}$$

$$\frac{-z_1}{d} + \frac{z_2}{d} = \omega t_2 - \omega t_1$$

$$\frac{1}{d}(z_2 - z_1) = \omega(t_2 - t_1)$$

$$d = \frac{1}{\omega}\left[\frac{z_2 - z_1}{t_2 - t_1}\right]$$

$$\sqrt{2K_T/\omega} = \frac{1}{\omega}\left[\frac{z_2 - z_1}{t_2 - t_1}\right]$$

$$\frac{2K_T}{\omega} = \frac{1}{\omega^2}\left[\frac{z_2 - z_1}{t_2 - t_1}\right]^2$$

$$K_T = \frac{1}{2\omega}\left[\frac{z_2 - z_1}{t_2 - t_1}\right]^2$$

Thus, K_T can be determined by measuring the time at which the maximum temperature is observed at two depths. K_T is the diffusivity of the soil between two depths.

Simultaneous Transport of Water and Heat

- Temperature gradients affect soil-water potential which induces both liquid and vapor movement.
- Soil-water potential gradients move water, which consequently carries heat.
- Combined transport generally ignored in very wet systems and in very dry systems. Temp. gradient effect on water flow small in relation to soil-water potential grad. in wet range. Little water is moved in very dry range.
- Two approaches
  - Mechanistic
  - Irreversible thermodynamics

Mechanistic

For water

$$\frac{\partial \theta_v}{\partial t} = \frac{\partial}{\partial z}\left(D_T \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial z}\left(D_w \frac{\partial \theta_v}{\partial z} \right) - \frac{\partial K}{\partial z}$$

For heat

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_e \frac{\partial T}{\partial z} \right) - L\frac{\partial}{\partial z}\left(D_{w,v} \frac{\partial \theta}{\partial z} \right)$$

D_T - water diffusivity under temperature gradient
D_w - water diffusivity under water potential gradient
L - Latent heat of vaporization
$D_{w,v}$- Diffusivity for heat conveyed by water movement

Problems with mechanistic approach

- Difficult to measure or calculate diffusivities

- Two flow mechanisms are not strictly additive since they interact

Irreversible thermodynamics

For water
$$q_w = - L_{ww} \frac{1}{T} \frac{dP}{dz} - L_{wh} \frac{1}{T^2} \frac{dT}{dz}$$

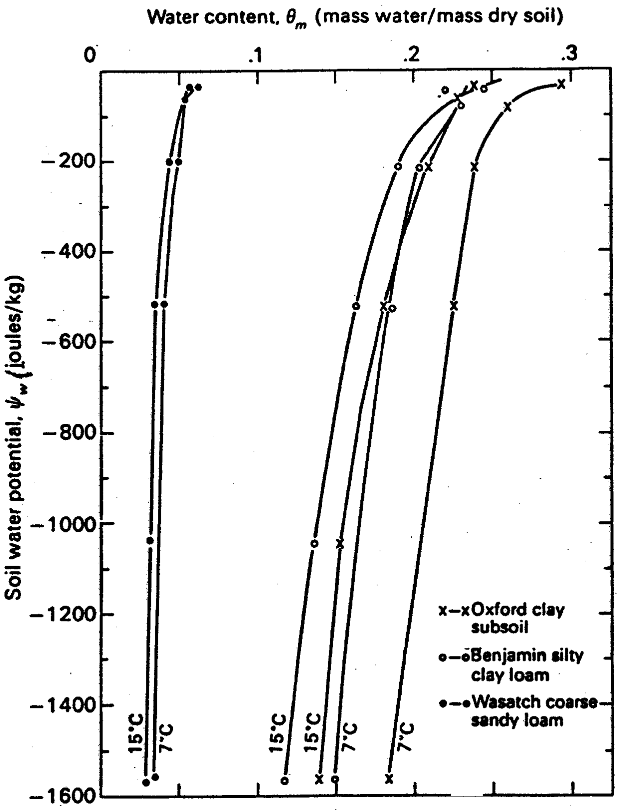
For heat
$$q_h = - L_{hw} \frac{1}{T} \frac{dP}{dz} - L_{hh} \frac{1}{T^2} \frac{dT}{dz}$$

P - Soil-water potential

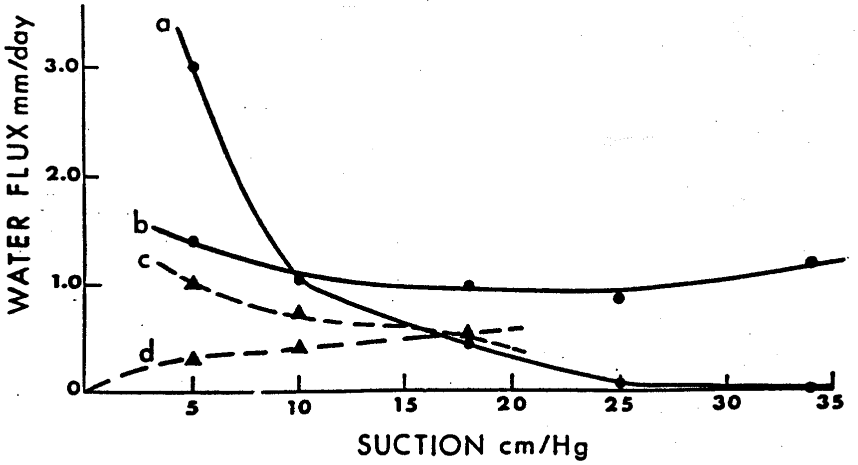
$L_{i,j}$- Coefficients which are unknown functions of P and T

Makes no assumptions about mechanisms

Figures on simultaneous transport of water and heat follow:



1 joule/Kg
= 0.01 bar



–Water flow components in Columbia loam. Curve a represents flow from a pressure head gradient of 5 cm H_2O cm^{-1}. Curve b is the water flow caused by a thermal gradient of 0.8 C cm^{-1}. The liquid and vapor components of curve b are given by c and d, respectively. (Cary, 1965. Copyright 1965 by the Williams & Wilkins Co., Baltimore, Md.)