Introduction to Heat Transfer in Soils and Other Materials

ME 7710
Spring 2013

Surface/Skin Temperature

- T_s - The temperature at the air-soil interface. For an "ideal" surface which varies in time in response to energy fluxes at the surface
  - Depends on:
    - *Radiation Balance*
    - *Surface exchange processes*
    - *Vegetative cover*
    - *Thermal properties of the subsurface*
  - Difficult to Measure (very large temperature gradients near the surface both in the air & soil)
    - Extrapolate air/soil temps
    - Radiometer – uses $R_L \uparrow \sim -\varepsilon\sigma T_s^4$

Diurnal Soil & Air Temperatures

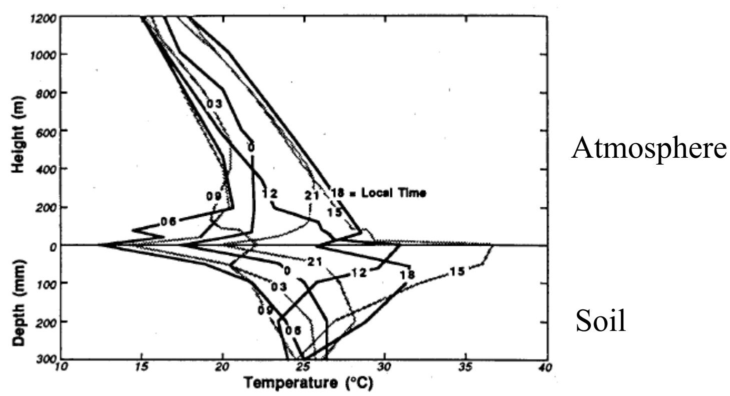


Fig. 7.17 Three day average of temperature profiles at indicated hours for the Koorin field program, days 7-9. Note the scale difference between height and depth. (After Lettau, personal communication).

Fig from Stull, 1988
An Introduction to Boundary Layer Meteorology

Surface/Skin Temperature

- Diurnal Range
  - In dry desert ~ 40-50 ^{o}C
  - Surface & subsurface moisture moderate range
    - Increased evaporation from the surface
    - Increased heat capacity (*c*) & conductivity of the soil (*k*)
      - Wet soils may dry changing the temperature response
  - Vegetation moderates diurnal range
    - Intercepts incoming solar – lower surface temps during the day
    - Intercepts outgoing longwave
    - Enhanced latent heat flux due to evapotranspiration (ET)
    - Increased Turbulence

Sub-surface Soil Temperature

- Much easier to measure – thermocouple
- Amplitude of the temperature fluctuations decrease exponentially with depth
- Depends on –
  - Latitude
  - Time of year
  - Net radiation
  - Soil texture (porosity) and moisture content
  - Ground cover
  - Surface weather conditions

Thermal Properties of Soil

- Specific Heat – c (J kg^{-1} K^{-1}) – the amount of heat absorbed by a material to raise the temperature of a unit mass of material by 1^{o}
- Thermal Conductivity – k (W m^{-1} K^{-1}) – material property; the ability of a material to conduct heat
- Thermal Diffusivity – α_h (m^2 s^{-1}) Ratio of thermal conductivity to heat capacity

1D Thermal Conduction

$$\frac{\partial}{\partial t}(\rho c T) = -\frac{\partial H_G}{\partial z}$$

$$\frac{\partial}{\partial t}(\rho c T) = k\frac{\partial^2 T}{\partial z^2}$$

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

Fourier's conduction law

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

$$\alpha_h = \frac{k}{\rho c} = \frac{k}{C}$$

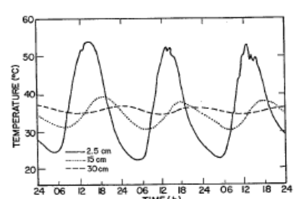
Soil heat capacity

Solutions

- Analytical – multiple methods
- Numerical (e.g.) – e.g. finite difference
- Force Restore – 2 Layer Slab Model (See Stull Ch. 7, Backadar, 1976)

Diurnal & Annual Soil Temperature Temporal Variability

Diurnal Wave



re 4.1 Observed diurnal course of subsurface soil temperatures at various depths in a ly loam soil with bare surface. [From Deacon (1969); after West (1952).]

Annual Wave

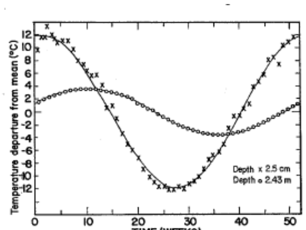


Figure 4.2 Annual temperature waves in the weekly averaged subsurface soil temperatures at two depths in a sandy loam soil. Fitted solid curves are sine waves. [From Deacon (1969); after West (1952).]

Soil Heat Transfer

- 1D Thermal Conduction

$$\int_{z=0}^{z=D} \left\{ \frac{\partial}{\partial t}(CT) = -\frac{\partial H}{\partial z} \right\} dz$$

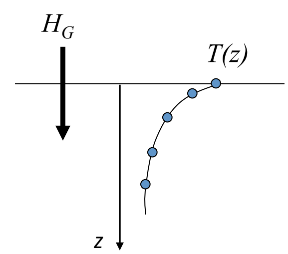
$$H(z=0) - H(z=D) = \int_{z=0}^{z=D} \frac{\partial}{\partial t}(CT)\, dz$$

$$H_G = H_D + \int_{z=0}^{z=D} \frac{\partial}{\partial t}(CT)\, dz$$

Surface Heat Flux — H_G

Reference depth — H_D

Storage — $\int_{z=0}^{z=D} \frac{\partial}{\partial t}(CT)\, dz$



Governing Parameters

- Thermal conductivity - k
- Heat Capacity - C_s
- Thermal Diffusivity – α (sometime κ)
- Thermal Admittance - μ

Governing Parameters

- Thermal conductivity – k (W m^{-1} K^{-1})
  - Def. - the ability of a material to conduct heat
  - Depends on:
    - Soil particles
    - Porosity
    - Moisture content

Governing Parameters

- Heat Capacity – $C_s = \rho\ c$ (J m^{-3} K^{-1})
  - c specific heat of the soil (J kg^{-1} K^{-1})
  - Relates to the ability of a material to store heat
  - Def. The amount of heat (J) necessary to increase a unit volume (m^3) of a substance by 1 K.
  - Water (~5 J m^{-3} K^{-1}) has a very high heat capacity, air is quite low
  - Depends on porosity, mineral content, organic content, air, etc.

Governing Parameters

- Thermal Diffusivity – $\alpha = k/C_s$ (m^2 s^{-1})
  - Controls the speed at which temperature waves move through the soil & the depth of thermal influence of an active surface
  - Water (~5 x 10^6 J m^{-3} K^{-1}) has a very high heat capacity, air is quite low

Let's Look at example Data from Sage Brush at DPG

Governing Parameters

- Thermal Admittance – Surface Property (not a "soil property"
- $\mu = (kC_s)^{1/2}$ (J m^{-2} $s^{-1/2}$ K^{-1})
  - Def. The ability of a surface to accept or release heat
  - High µ – metals
  - low µ – wood
  - High µ materials feel cooler to the touch even though they have the same surface temperature

Typical Values

Table 2.1 Thermal properties of natural materials

Material	Remarks	ρ Density (kg m^{-3} × 10^{3})	c Specific heat (J kg^{-1} K^{-1} × 10^{3})	C Heat capacity (J m^{-3} K^{-1} × 10^{6})	k Thermal conductivity (W m^{-1} K^{-1})	κ Thermal diffusivity (m^{2} s^{-1} × 10^{-6})	μ Thermal admittance (J m^{-2} s$^{-1/2}$ K^{-1})
Sandy soil (40% pore space)	Dry	1·60	0·80	1·28	0·30	0·24	620
	Saturated	2·00	1·48	2·96	2·20	0·74	2550
Clay soil (40% pore space)	Dry	1·60	0·89	1·42	0·25	0·18	600
	Saturated	2·00	1·55	3·10	1·58	0·51	2210
Peat soil (80% pore space)	Dry	0·30	1·92	0·58	0·06	0·10	190
	Saturated	1·10	3·65	4·02	0·50	0·12	1420
Snow	Fresh	0·10	2·09	0·21	0·08	0·10	130
	Old	0·48	2·09	0·84	0·42	0·40	595
Ice	0°C, pure	0·92	2·10	1·93	2·24	1·16	2080
Water*	4°C, still	1·00	4·18	4·18	0·57	0·14	1545
Air*	10°C, still	0·0012	1·01	0·0012	0·025	21·50	5
	Turbulent	0·0012	1·01	0·0012	~125	~10 × 10^{6}	390

* Properties depend on temperature, see Appendix A3.
Sources: van Wijk and de Vries (1963), List (1966).

From Oke, 1988

Effect of Soil Moisture on Thermal Properties

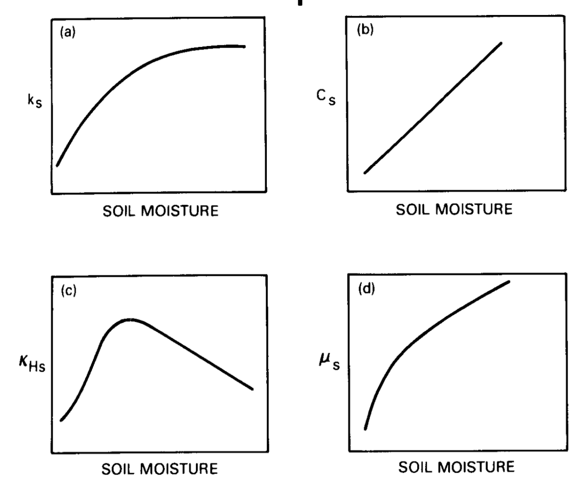
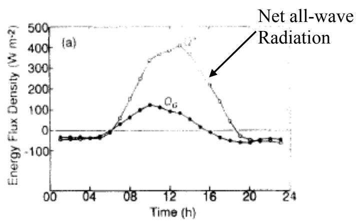


Figure 2.5 Relationship between soil moisture content: (a) thermal conductivity, (b) heat capacity, (c) thermal diffusivity and (d) thermal admittance for most soils.

From Oke, 1988

Hysteresis



$$\Delta H_S = \int \frac{\partial}{\partial t}(\rho C T)dz$$

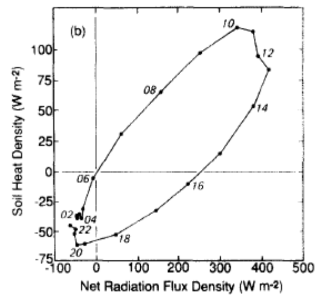
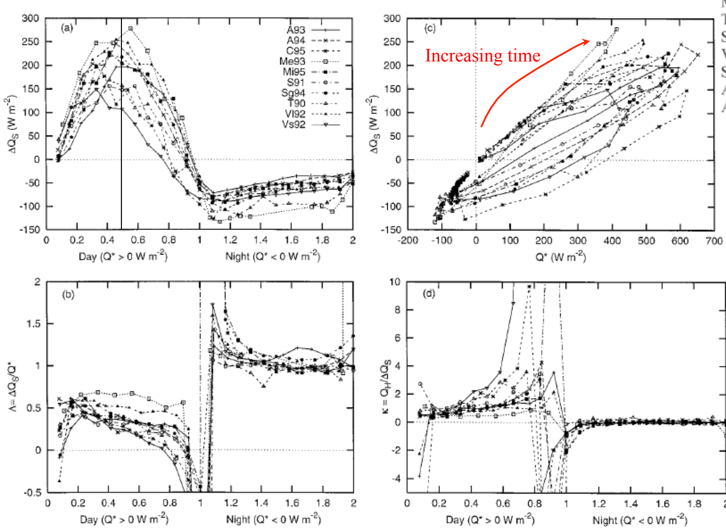


Fig. 1. (a) Time series and (b) hysteresis loop relations between soil heat flux and net all-wave radiation for short grass near St Louis, MO calculated from the data of Doll *et al.* (1985) for a single day. Best fit statistics give the equation: $Q_G = 0.32Q^* + 0.54(\partial Q^*/\partial t) - 27.4$.

Urban Areas

Site	Code
Mexico City, D.F.	Me93
Vancouver, BC	VI92
Chicago, IL	C95
Miami, FL	Mi95
Tucson, AZ	T90
San Gabriel, LA, CA	Sg94
Vancouver, BC*	Vs92
Sacramento, CA	S91
Arcadia, LA, CA	A94
Arcadia, LA, CA	A93



More Energy is transferred to the "urban fabric" in the morning - Asymmetry

FIG. 1. Mean diurnal patterns of observed (a) ΔQ_S (W m^{-2}), (b) $\Delta Q_S/Q^*$, (c) ΔQ_S vs Q^*, and (d) $Q_H/\Delta Q_S$ for each of the datasets (see details in Table 1).

Grimmond & Oke 1990