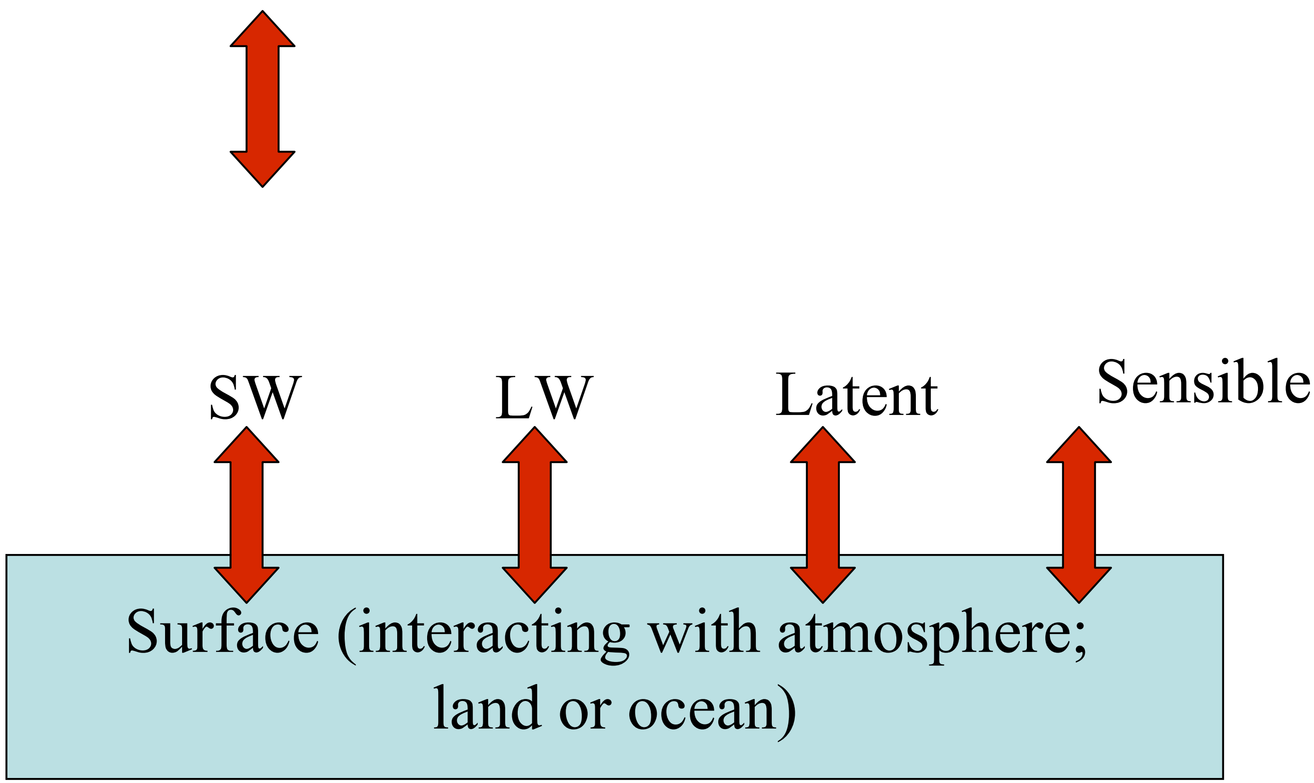
Surface energy balance I

Reading: GPC Ch4

Outline:

- Surface energy budget
- Surface heat storage, penetration depth
- Radiative flux at the surface - SW and LW

The energy balance at the surface



4.2 Surface energy budget

$$\frac{\partial E_s}{\partial t} = G = R_s - \mathrm{LE} - \mathrm{SH} - \Delta F_{eo}$$

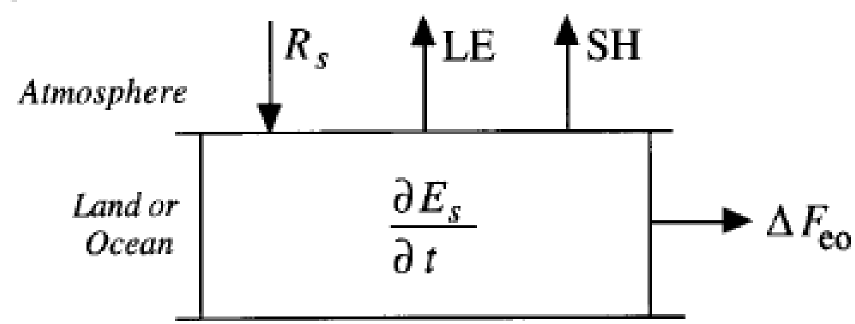
Horizontal energy flux

Total radiation

Sensible heat flux

Latent heat flux

Storage of energy in surface



Energy balance

$$R_s = \mathrm{LE} + \mathrm{SH} + \Delta F_{eo}$$

Heat storage at the surface

It is important for the seasonal cycle of T over the oceans and for the diurnal cycle over land and oceans.

The amount of energy in the surface box ($/m^2$) may be written as $E_s = C_e T_e$ where C_e is the effective heat capacity of the medium and T_e is the effective temperature of the energy storing medium.

Comparison between atmosphere and ocean

Thermal capacity of atmosphere, C_a

$= c_p$ x mass of atm. per unit area

$= c_p \, p_s/g = 1.02 \times 10^7 \text{ J K}^{-1}\text{m}^{-2}$

Thermal capacity of ocean depth d_w, C_o

$= c_w$ x mass of ocean per unit area

$= c_w \, \rho_w \, d_w = \mathbf{d_w \times} \, 4.2 \times 10^6 \text{ J K}^{-1}\text{m}^{-2}\text{m}^{-1}$

(so thermal capacity of atmosphere ~ 2m of water)

Soil: no motions, conduction (less efficient). Typically C_s slightly smaller than that of the atmosphere. Shallow penetration depth.

Table 4.1

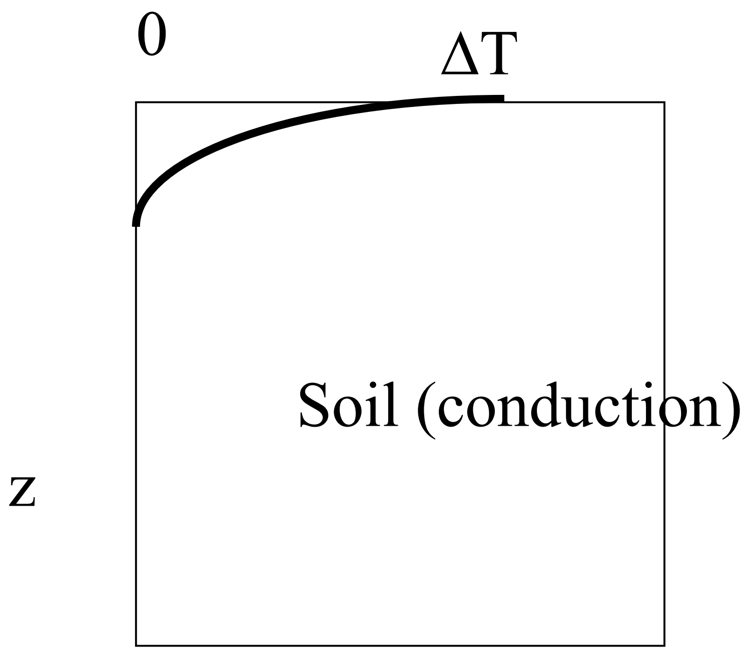
Properties of Soil Components at 293 K

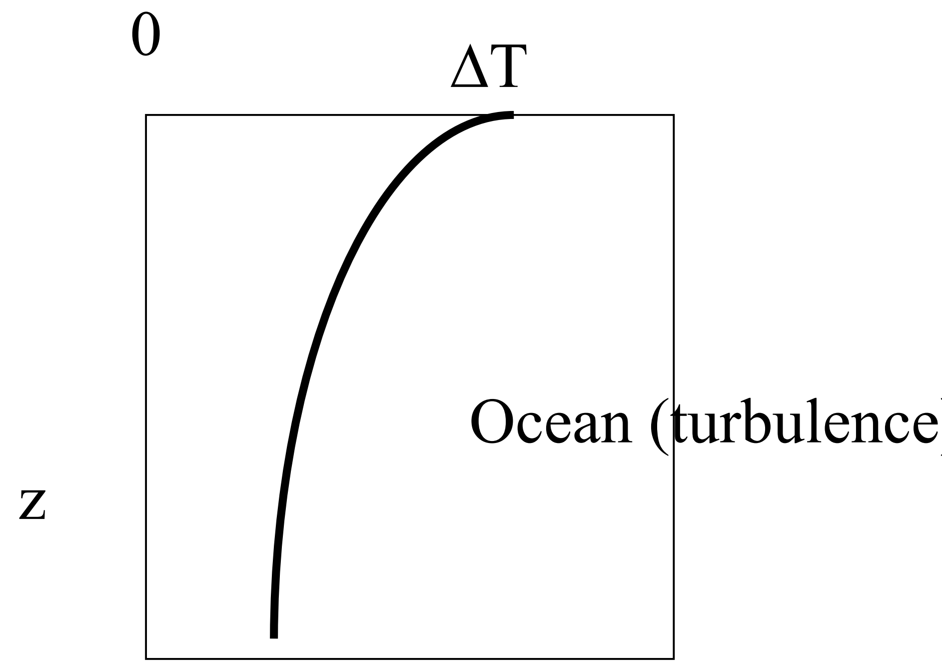
	Specific heat (c_p) ($J\ kg^{-1}\ K^{-1}$)	Density (ρ) ($kg\ m^{-3}$)	ρc_p ($J\ m^{-3}\ K^{-1}$)
Soil inorganic material	733	2600	1.9×10^6
Soil organic material	1921	1300	2.5×10^6
Water	4182	1000	4.2×10^6
Air	1004	1.2	1.2×10^3

[After Brutsaert (1982). Reprinted with permission from Kluwer Academic Publishers.]

When water replaces air in the open spaces of the soil (porosity) c_p increases.
ρc_p = volumetric heat capacity

Heat storage in the soil





Land has a smaller overall heat capacity relative to ocean mainly because the penetration depth is shallower. Heat is transferred downwards by ***conduction*** over land and turbulent mixing (convection) in the ocean surface layer.

The **penetration depth** determines what depth of ocean/land is relevant to climate. Penetration depth (here denoted h_T) depends on ***time and thermal diffusivity***

$$h_T = \sqrt{D_T \tau}$$

D_T = ***thermal diffusivity*** of surface material

τ = characteristic time of periodic forcing at the surface

Typical soil diffusivity: $D_T = 5 \times 10^{-7} m^2 s^{-1}$
e.g. for diurnal cycle $\tau \sim 1$ day, so $h_T \sim 0.2$ m
for seasonal cycle $\tau \sim 1$ year, so $h_T \sim 4$ m

For ocean on seasonal timescales $h_T \sim 70$ m.

An important point is that penetration depth goes as the time$^{1/2}$.

Because of poor conduction properties, horizontal transport of energy in the soil is negligible.

How did we get this function for penetration depth?

$$F_s = -K_T \frac{\partial T}{\partial z}$$

Energy flux into soil proportional to temperature gradient

$$C_s \frac{\partial T}{\partial t} = -\frac{\partial}{\partial z}(F_s) = \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right)$$

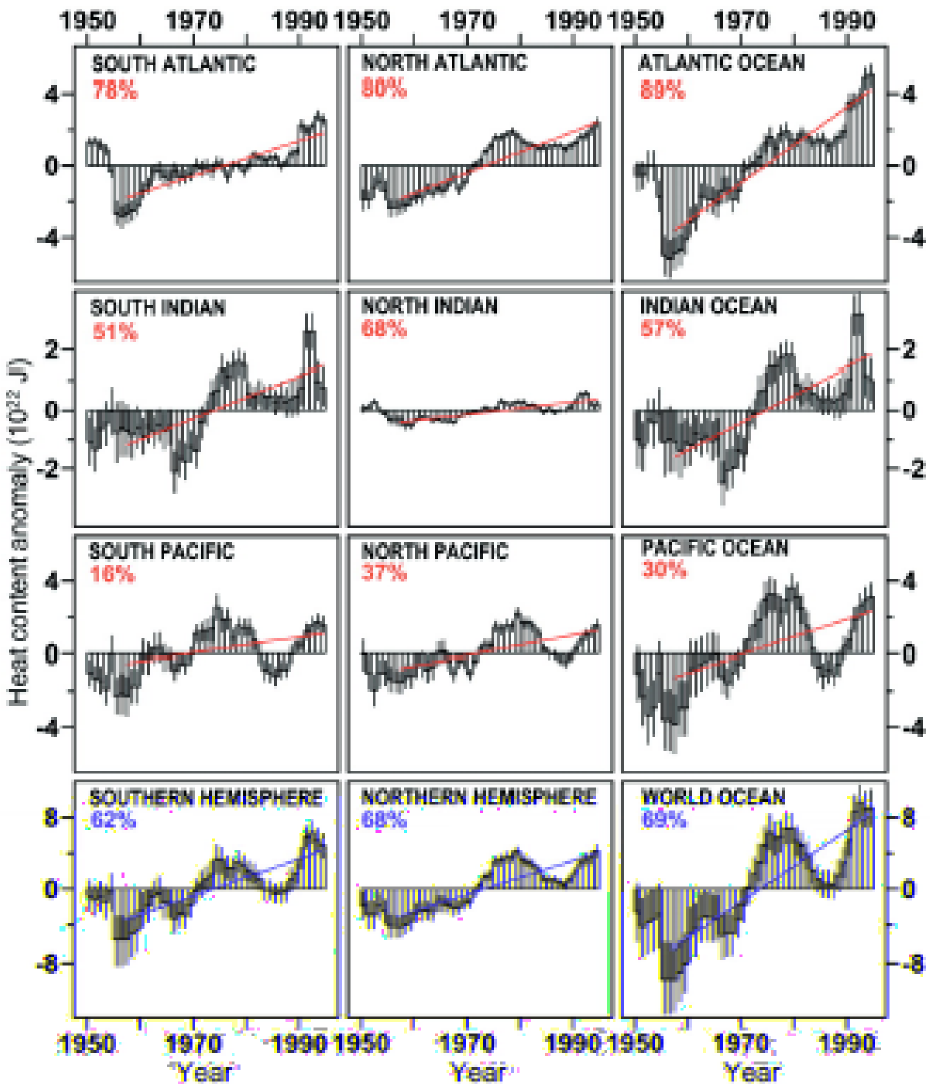
Rate of temperature change proportional to flux convergence - you've seen this before!

or

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

where $D_T = K_T/C_S$

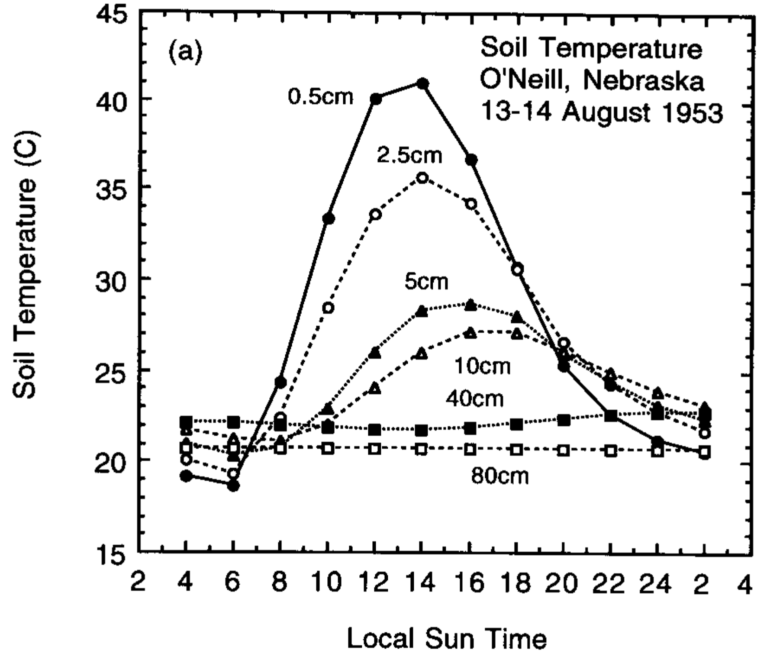
This turns out the be the heat equation, whose solution is beyond the course (you'll need to solve for the semi-infinite case with boundary conditions at the surface, and specified initial conditions). However, a scale analysis shows that the typical depth for penetration of a surface temperature anomaly is as given as $(D_T \tau)^{1/2}$



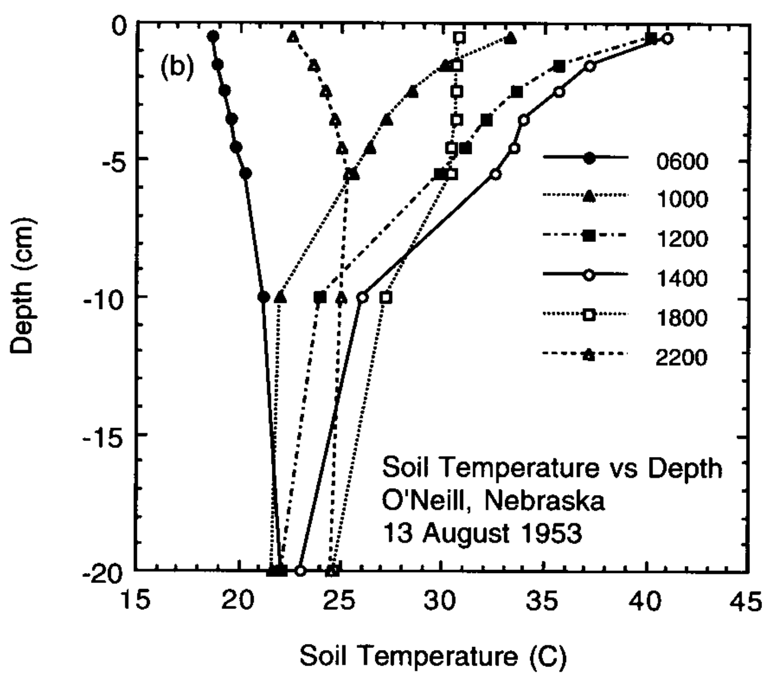
Levitus et al. 2000 - observed heat content in the upper 3km of the world's oceans 1955-1996.

Notice the increase.

Clear summer day – grass field



Soil temperatures at various depths vs. local sun time. The amplitude of the diurnal cycle decreases of ~1/e of the surface value at a depth of ~10 cm and is very small below 40 cm.



Vertical profiles of soil temperature at various times of the day.

Radiative heating of the surface

Net input of radiative energy to the surface:

$$R_s = \underbrace{S^{\downarrow}(0) - S^{\uparrow}(0)}_{\text{Net solar radiation}} + \underbrace{F^{\downarrow}(0) - F^{\uparrow}(0)}_{\text{Net LW radiation}} \qquad \text{(flux densities)}$$

$$S^{\downarrow}(0) - S^{\uparrow}(0) = S^{\downarrow}(0)(1-\alpha_s)$$

α_s= surface albedo.
Varies widely depending on
surface type and conditions

$$F^{\downarrow}(0) - F^{\uparrow}(0) = \varepsilon\left(F^{\downarrow}(0) - \sigma T_s^4\right)$$

ε= LW emissivity of the surface ~absorptivity
because abs. and emitt. LW have about the same ν.
A fraction ε of $F^{\downarrow}(0)$ is absorbed and $(1-\varepsilon)F^{\downarrow}(0)$ is re-emitted
→ $F^{\uparrow}(0)=(1-\varepsilon)F^{\downarrow}(0)+\varepsilon\sigma T_s^4$

Table 4.2
Albedos for Various Surfaces in Percent

Surface type	Range	Typical value
Water		
Deep water: low wind, low altitude	5–10	7
Deep water: high wind, high altitude	10–20	12
Bare surfaces		
Moist dark soil, high humus	5–15	10
Moist gray soil	10–20	15
Dry soil, desert	20–35	30
Wet sand	20–30	25
Dry light sand	30–40	35
Asphalt pavement	5–10	7
Concrete pavement	15–35	20
Vegetation		
Short green vegetation	10–20	17
Dry vegetation	20–30	25
Coniferous forest	10–15	12
Deciduous forest	15–25	17
Snow and ice		
Forest with surface snowcover	20–35	25
Sea ice, no snowcover	25–40	30
Old, melting snow	35–65	50
Dry, cold snow	60–75	70
Fresh, dry snow	70–90	80

Albedos for various surfaces - vary from 70-90% for fresh snow to 5-10% for oceans in low wind speed situations

Highly variable→ strong effect on absorbed LW, hence on surface T

↑ Depends on solar zenith angle too

Albedo depends on solar zenith angle

BUT: ***under overcast skies, solar zenith angle matters less and less.***

Clouds scatter radiation, so that SW under a cloud is no longer a parallel beam but is scattered in all directions. Therefore as cloudiness increases the albedo becomes less and less sensitive to solar zenith angle. The amount of SW reaching the surface under overcast skies is sensitive to solar zenith angle, however, because the albedo ***of clouds*** depends on it.

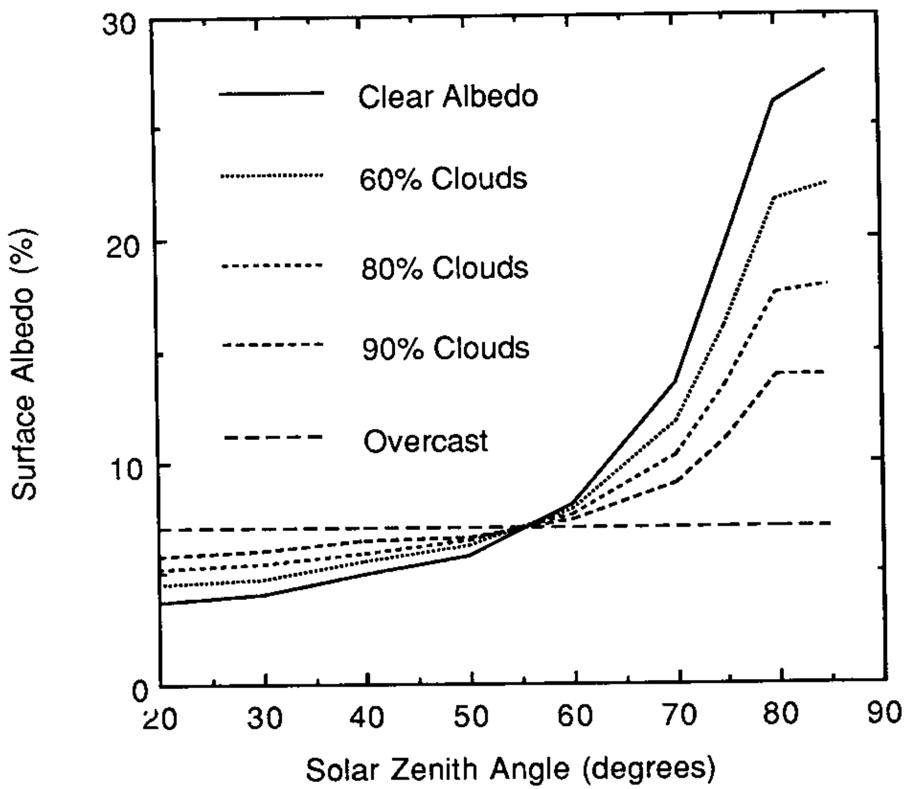


Fig. 4.4 Dependence of the albedo of a water surface on solar zenith angle and cloud cover. [Data n Mirinova (1973).]

Water surface

Albedo also depends on wind speed and impurities in the water

Albedo also depends on frequency of SW radiation:

More reflective

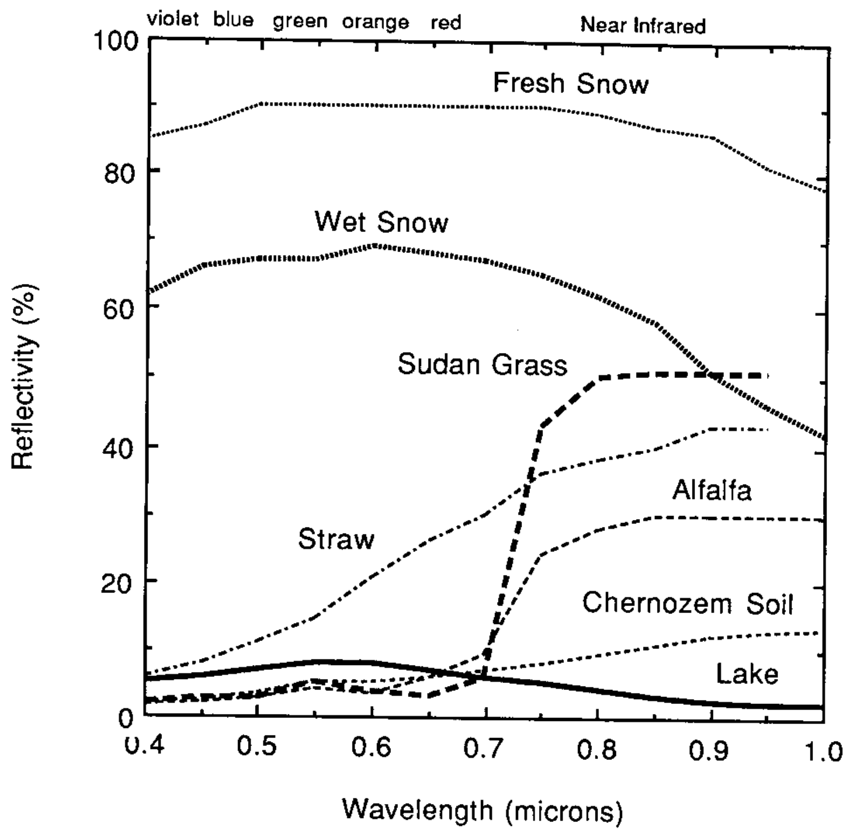


Fig. 4.5 Surface reflectivity as a function of wavelength of radiation for a variety of natural surfaces. Human eyesight is sensitive to wavelengths from 0.4 μm (violet) to 0.7 μm (red). Alfalfa and sudan grass appear green because their albedo is higher for green light (~0.55 μm) than for other visible wavelengths. [Data from Mirinova (1973).]

Note the dip around 0.7 microns for grass and alfalfas: green plants have a very low albedo for photosynthetically-active radiation. The increase for $\lambda > 0.7\ \mu m$ helps the leaves to stay cool.

Moist ground is generally darker than dry ground and therefore has a lower albedo.

Table 4.3

Albedos for Dry and Moist Soil Surfaces

	Even surface		Tilled surface	
	Dry	Moist	Dry	Moist
Chernozem of dark gray color	13	8	8	4
Light chestnut soil of gray color	18	10	14	6
Chestnut soil of grayish red color	20	12	15	7
Gray sandy soil	25	18	20	11
White sand	40	20	—	—
Dark blue clay	23	16	—	—

[From Mironova (1973).]

Net LW heating at the surface

$$F^{\uparrow}(0) = (1-\varepsilon)F^{\downarrow}(0) + \varepsilon\sigma T_s^4$$

or

$$F^{\downarrow}(0) - F^{\uparrow}(0) = \varepsilon\left(F^{\downarrow}(0) - \sigma T_s^4\right)$$

Table 4.4

Infrared Emissivities (percent) of Some Surfaces

Water and soil surfaces		Vegetation	
Water	92–96	Alfalfa, dark green	95
Snow, fresh fallen	82–99.5	Oak leaves	91–95
Snow, ice granules	89	Leaves and plants	
Ice	96	0.8 μm	5–53
Soil, frozen	93–94	1.0 μm	5–60
Sand, dry playa	84	2.4 μm	70–97
Sand, dry light	89–90	10.0 μm	97–98
Sand, wet	95	Miscellaneous	
Gravel, coarse	91–92	Paper, white	89–95
Limestone, light gray	91–92	Glass pane	87–94
Concrete, dry	71–88	Bricks, red	92
Ground, moist, bare	95–98	Plaster, white	91
Ground, dry plowed	90	Wood, planed oak	90
Natural surfaces		Paint, white	91–95
Desert	90–91	Paint, black	88–95
Grass, high dry	90	Paint, aluminum	43–55
Field and shrubs	90	Aluminum foil	1–5
Oak woodland	90	Iron, galvanized	13–28
Pine forest	90	Silver, highly polished	2
		Skin, human	95

[Data from Sellers (1965). Reprinted with permission from the University of Chicago Press.]

ε is the emissivity - generally high for earth surfaces (90%+)

ε inaccuracies do not play a key role in determining the surface climate because $\varepsilon F^{\downarrow}(0)$ and $\varepsilon\sigma T_s^4$ are both large and tend to offset each other.