Community Business

- Check the assignments
  HW #4 is out there
- Questions?
Chapter 4: The Surface Energy Balance

- New Topic
- Study Chapter 4
- Surface Energy Balance
- Storage = radiation – latent – sensible – horizontal

$$\frac{\partial E_s}{\partial t} = G = R_s - LE - SH - \Delta F_{eo}$$
Chapter 4: The Surface Energy Balance

- **In equilibrium**, the storage is zero and the radiative heating of the surface is balanced by three terms.

- Storage = radiation – latent – sensible – horizontal

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

- becomes

\[
R_s = LE + SH + \Delta F_{eo}
\]
Heat Capacity

- The amount of energy it takes to heat up the surface by 1 °K
- Energy in surface is heat capacity \( \bar{C}_{eo} \) (J m\(^{-2}\) K\(^{-1}\)) times bulk surface temperature

\[
E_s = \bar{C}_{eo} T_{eo}
\]
Heat Capacity: Atmosphere

- The amount of energy it takes to heat up the surface by 1 °K

- Heat Capacity of Atmosphere = total mass times specific heat at constant pressure

\[
\overline{C}_a = c_p \frac{p_s}{g} = \frac{1004 \text{ J K}^{-1} \text{ kg}^{-1} \cdot 10^5 \text{ Pa}}{9.81 \text{ ms}^{-2}} = 1.02 \times 10^7 \text{ J K}^{-1} \text{ m}^{-2}
\]

- So, if you apply 100 Wm\(^{-2}\) it heats up at rate of nearly one degree per day.

\[
\frac{dT_a}{dt} = \frac{F}{C_a} = \frac{100 \text{ Wm}^{-2}}{1.02 \times 10^7 \text{ J K}^{-1} \text{ m}^{-2}} = 10^{-5} \text{ K s}^{-1} \times 86400 \text{ s day}^{-1} = 0.86 \text{ °K day}^{-1}
\]
Heat Capacity: Ocean

- Heat Capacity of Ocean = total mass times specific heat for some depth of ocean $d_w$

\[ \overline{C}_o = \rho_w c_w d_w = 10^3 \text{kg m}^{-3} \cdot 4218 \text{ J K}^{-1} \text{ kg}^{-1} \cdot d_w \]

\[ = d_w \cdot 4.2 \times 10^6 \text{ J K}^{-1} \text{ m}^{-2} \text{ m}^{-1} \]

- So, to have the same heat capacity as the atmosphere, you a little over two meters of ocean.

\[ \overline{C}_a = 1.02 \times 10^7 \text{ J K}^{-1} \text{ m}^{-2} = d_w \cdot 4.2 \times 10^6 \text{ J K}^{-1} \text{ m}^{-2} \text{ m}^{-1} \]

- when \[ d_w = 2.43 \text{ m} \]
The Ocean Heat Capacity

- Covers the Earth to an average depth of 2650 meters, so about 1000 times the heat capacity of the atmosphere,

- But only about the first 70 meters of the ocean is well-mixed on time scales of seasons,

- So on time scales of seasons, the ocean mixed-layer has about 30 times the heat capacity of the atmosphere

- But the ocean has another longer time scale that it takes to heat the entire 2650 meters equivalent of global ocean heat capacity.
Ocean Mixed Layer

- From Chapter 7
- There’s always a layer on top that has almost the same temperature – well-mixed layer
- This is shallower in summer and deeper in winter
Ocean Mixed Layer

- From profile data

Chu and Fan, 2011
ARGO Floats

6-12 hours at surface to transmit data to satellite

Descent to depth 
~10 cm/s (~6 hours)

1000 db (1000m) 
Drift approx. 9 days

Total cycle time 10 days

Salinity & Temperature profile recorded during ascent 
~10 cm/s (~6 hours)

Float descends to begin profile from greater depth 
2000 db (2000m)
Surfaced to report
ARGO Floats

Started deployment in about 2000
in 2010 pretty good coverage of the world ocean

Our best shot at measuring warming of deep ocean, but rather late
being established, in about the year 2000. Before that, sparse
and infrequent measurements.
Multi-National Contributions to ARGO
Land Heat Capacity

• Although the land is the most massive part of the climate system, because it is a solid, it can only transfer heat through conduction.

• As a result of its low thermal transmissivity, the effective heat capacity of the land is generally less than that of the atmosphere.
Land Heat Capacity

- Diffusive heat flux goes down the gradient of temperature.
  \[ F_s = -K_T \frac{\partial T}{\partial z} \]

- The convergence of this heat flux drives a temperature tendency.
  \[ C_s \frac{\partial T}{\partial t} = -\frac{\partial}{\partial z}(F_s) = \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right) \]

- Define the thermal diffusivity of the surface material, and assume it is a constant
  \[ D_T = K_T / C_s \]
Land Heat Capacity

- Assuming that the thermal diffusivity is a constant
  \[ D_T = \frac{K_T}{C_s} \]

- we get,
  \[ \frac{\partial T}{\partial t} = D_T \frac{\partial^2 T}{\partial z^2} \]

- Do a little scale analysis
  \[ \frac{\Delta T}{\tau} = D_T \frac{\Delta T}{h_T^2} \]

- to get a characteristic depth
  \[ h_T = \sqrt{D_T \tau} \]

- Which depends on the square root of diffusivity and characteristic time scale
Characteristic Depth

- The characteristic depth of penetration is

\[ h_T = \sqrt{D_T \tau} \]

- For a diffusivity of \( D_T = 5 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \)

- And a time period of one year

- We get a characteristic penetration depth of

\[ h_T = \sqrt{D_T \tau} = \sqrt{5 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \times 86400 \text{ s day}^{-1} \times 365 \text{ days} / 2\pi} = 1.6 \text{ m} \]

- for a diurnal variation of temperature this would be about 8 cm or 3 inches.
Heat Diffusion into soil

- For a grass field in Nebraska
- Signal amplitude is about $e^{-1}$ by 10cm depth.
- Signal is delayed with depth
Surface Radiation

- The primary variable here is the surface albedo, which varies a lot.
- Surface emissivity is mostly high for natural surfaces.
- $S = \text{solar}$, and $F = \text{longwave}$

\[
R_s = S_{\downarrow}(0) - S_{\uparrow}(0) + F_{\downarrow}(0) - F_{\uparrow}(0)
\]

\[
S_{\downarrow}(0) - S_{\uparrow}(0) = S_{\downarrow}(0)(1 - \alpha_s)
\]
**Table 4.2 Albedos for various surfaces in percent.**

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Range</th>
<th>Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep water: low wind, low altitude</td>
<td>5-10</td>
<td>7</td>
</tr>
<tr>
<td>Deep water: high wind, high altitude</td>
<td>10-20</td>
<td>12</td>
</tr>
<tr>
<td><strong>Bare surfaces</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moist dark soil, high humus</td>
<td>5-15</td>
<td>10</td>
</tr>
<tr>
<td>Moist gray soil</td>
<td>10-20</td>
<td>15</td>
</tr>
<tr>
<td>Dry soil, desert</td>
<td>20-35</td>
<td>30</td>
</tr>
<tr>
<td>Wet sand</td>
<td>20-30</td>
<td>25</td>
</tr>
<tr>
<td>Dry light sand</td>
<td>30-40</td>
<td>35</td>
</tr>
<tr>
<td>Asphalt pavement</td>
<td>5-10</td>
<td>7</td>
</tr>
<tr>
<td>Concrete pavement</td>
<td>15-35</td>
<td>20</td>
</tr>
<tr>
<td><strong>Vegetation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short green vegetation</td>
<td>10-20</td>
<td>17</td>
</tr>
<tr>
<td>Dry vegetation</td>
<td>20-30</td>
<td>25</td>
</tr>
<tr>
<td>Coniferous forest</td>
<td>10-15</td>
<td>12</td>
</tr>
<tr>
<td>Deciduous forest</td>
<td>15-25</td>
<td>17</td>
</tr>
<tr>
<td><strong>Snow and Ice</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest with surface snow cover</td>
<td>20-35</td>
<td>25</td>
</tr>
<tr>
<td>Sea ice, no snow cover</td>
<td>25-40</td>
<td>30</td>
</tr>
<tr>
<td>Old, melting snow</td>
<td>35-65</td>
<td>50</td>
</tr>
<tr>
<td>Dry, cold snow</td>
<td>60-75</td>
<td>70</td>
</tr>
<tr>
<td>Fresh, dry snow</td>
<td>70-90</td>
<td>80</td>
</tr>
</tbody>
</table>
Ocean surface albedo depends on zenith angle, unless overlying clouds diffuse solar radiation.
Wavelength dependence of plant absorption of solar radiation

- Green plants have a very special absorption and reflection spectrum.
- They like to absorb photosynthetically active radiation (by chlorophyll), but reject near IR.
Surface Albedo – “Observed”

SFC Albedo - All-Sky
CERES 2000-2013
SFC Albedo - All-Sky
CERES Jan 2000-2013
Surface Albedo:

- Higher over land than ocean
- Higher for deserts than forests.
- Higher for snow and ice than for most things.
## Surface Emissivities

Table 4.4 Infrared emissivities (percent) of some surfaces.

<table>
<thead>
<tr>
<th>A. Water and Soil Surfaces</th>
<th>C. Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Alfalfa, dark green</td>
</tr>
<tr>
<td>Snow, fresh fallen</td>
<td>Oak leaves</td>
</tr>
<tr>
<td>Snow, ice granules</td>
<td>95</td>
</tr>
<tr>
<td>Ice</td>
<td>91-95</td>
</tr>
<tr>
<td>Soil, frozen</td>
<td>Leaves and plants</td>
</tr>
<tr>
<td>Sand, dry playa</td>
<td>0.8 μ</td>
</tr>
<tr>
<td>Sand, dry light</td>
<td>1.0 μ</td>
</tr>
<tr>
<td>Sand, wet</td>
<td>2.4 μ</td>
</tr>
<tr>
<td>Gravel, coarse</td>
<td>10.0 μ</td>
</tr>
<tr>
<td>Limestone, light gray</td>
<td>97-98</td>
</tr>
<tr>
<td>Concrete, dry</td>
<td></td>
</tr>
<tr>
<td>Ground, moist, bare</td>
<td></td>
</tr>
<tr>
<td>Ground, dry plowed</td>
<td></td>
</tr>
<tr>
<td>B. Natural Surfaces</td>
<td>D. Miscellaneous</td>
</tr>
<tr>
<td>Desert</td>
<td>Paper, white</td>
</tr>
<tr>
<td>Grass, high dry</td>
<td>89-95</td>
</tr>
<tr>
<td>Field and shrubs</td>
<td>Glass pane</td>
</tr>
<tr>
<td>Oak woodland</td>
<td>87-94</td>
</tr>
<tr>
<td>Pine forest</td>
<td>Bricks, red</td>
</tr>
<tr>
<td></td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Plaster, white</td>
</tr>
<tr>
<td></td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Wood, planed oak</td>
</tr>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Paint, white</td>
</tr>
<tr>
<td></td>
<td>91-95</td>
</tr>
<tr>
<td></td>
<td>Paint, black</td>
</tr>
<tr>
<td></td>
<td>88-95</td>
</tr>
<tr>
<td></td>
<td>Paint, aluminum</td>
</tr>
<tr>
<td></td>
<td>43-55</td>
</tr>
<tr>
<td></td>
<td>Aluminum foil</td>
</tr>
<tr>
<td></td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>Iron, galvanized</td>
</tr>
<tr>
<td></td>
<td>13-28</td>
</tr>
<tr>
<td></td>
<td>Silver, highly polished</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Skin, human</td>
</tr>
<tr>
<td></td>
<td>95</td>
</tr>
</tbody>
</table>

(Data from Sellers, 1965. Reprinted with permission from the University of Chicago Press.)
Mylar film, gold foil

- Emissivity of gold and aluminum is small.
Net Longwave at the ground

- The upward longwave flux at the surface is
  \[ F^\uparrow(0) = (1 - \varepsilon) F^\downarrow(0) + \varepsilon \sigma T_s^4 \]

- where \( \varepsilon \) is the emissivity of the surface

- The net downward longwave at the surface is
  \[ F^\downarrow(0) - F^\uparrow(0) = \varepsilon(F^\downarrow(0) - \sigma T_s^4) \]

- Usually the emissivity is nearly one
Non-Radiative Fluxes

- Turbulence transports sensible and latent heat vertically in the boundary layer and above.

- The upward sensible heat flux is
  \[
  \text{Upward sensible heat flux} = c_p \rho w T
  \]

- Decompose variables into time mean and deviations.
  \[
  w = \bar{w} + w', \quad T = \bar{T} + T'
  \]

- then,
  \[
  \bar{w}T = \bar{w}\bar{T} + \bar{w}'T'
  \]
  Total = mean + eddy
Sensible and Latent Heat Fluxes

- Physically, turbulent motions move warm, moist parcels upward and cold, dry ones downward, most of the time.

\[
\begin{align*}
\text{SH} &= c_p \rho w'T', \\
\text{LE} &= L \rho w'q'
\end{align*}
\]
An inversion-capped boundary layer might look like

Stuff tends to be well-mixed with small gradients in the vertical, but fluxes of stuff tend to be linear. Much changes at the top of the mixed layer.
Richardson Number critical value is $1/4$

- Richardson Number measures stability to buoyancy and shear instabilities.

$$ Ri = \left( \frac{g}{T_0} \right) \frac{\partial \Theta / \partial z}{\left( \partial U / \partial z \right)^2} $$

- If vertical shear of wind $\partial U / \partial z$ is large, Richardson number is small and flow is less stable.

- If static stability $\partial \Theta / \partial z$ is large, then $Ri$ is large and flow is stable. Theta is potential temperature, $U$ is wind speed.
Nighttime Boundary Layer is highly stratified

- Richardson number is large at 1.2km because, static stability is large and shear is small. Heat and momentum fluxes are DOWNWARD! Opposite to usual
Daytime Boundary layer over land in summer is unstable. Heated strongly from below.

Inversion at night, super adiabatic lapse rate during the early afternoon.
Oklahoma City TV Tower Data

- Explain the wind speed variations on the tower with time of day.