Lecture 4: The Energy Balance of the Surface

Chapter 4: The Energy Balance of the Surface
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- Surface Energy Balance
- Heat Storage
- Surface Heat Fluxes
- Atmospheric Boundary Layer

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The surface of Earth

- The surface of Earth is the boundary between the atmosphere and the land or ocean.
- Defining the location of this boundary can be difficult over a highly disturbed sea or over land surfaces with a variable plant canopy.
- In considering the important energy exchange processes we must include the atmosphere and oceanic boundary layers and the first few meters of soil.
- The surface energy balance determines the amount of energy available to evaporate surface water and to raise or lower the temperature of the surface.
- The energy budget at the surface is more complex than the budget at the top of the atmosphere because it requires consideration of fluxes of energy by conduction and by convection of heat and moisture through fluid motion, as well as by radiation.

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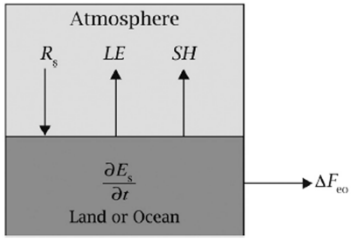
The Surface Energy Budget



energy storage in surface water and soil

net radiative flux into surface

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

latent heat flux from sfc to atmos

sensible heat flux from sfc to atmos

horizontal flux out of the column of land–ocean below the surface

the storage of energy below the surface is equal to the net radiative input minus the heat lost from the surface by evaporation, sensible heat flux, and horizontal heat transport to other latitudes or longitudes.

*** Steady-state conditions**

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

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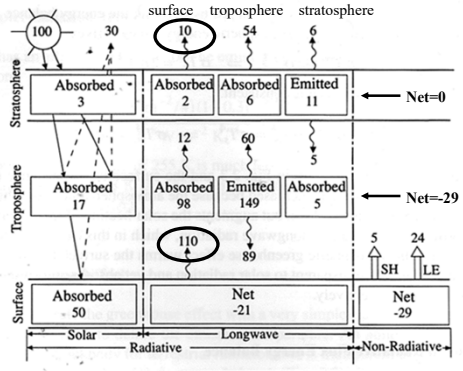
Vertical Distribution of Energy



(from *Global Physical Climatology*)

Outgoing radiation (70 units)

- 10 units by the surface
- 60 units by the atmosphere

  54 units by troposphere

  6 units by stratosphere
- Greenhouse effect (89 units) from the atmosphere back to the surface
- Water vapor and cloud provide 80% of the greenhouse effect

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The Energy Budget at TOA

(Top Of the Atmosphere)

$$R_{\text{TOA}} = Q_{\text{abs}} - \text{OLR} \qquad Q_{\text{abs}} = S_{\text{TOA}}(1-\alpha)$$

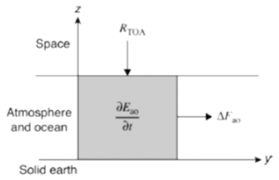


FIGURE 2.13 Diagram of the energy balance for a vertical column of the climate system in some latitude interval.

$$R_{\text{TOA}} = \Delta F_{\text{ao}}$$

If we average over a year, then the storage term becomes small, and we have an approximate balance between net flux at the top of the atmosphere and horizontal transport.

Storage of Heat in the Surface

amount of energy in the surface — **effective heat capacity of the land or ocean**

$$E_s = \overline{C}_{co} T_{co}$$

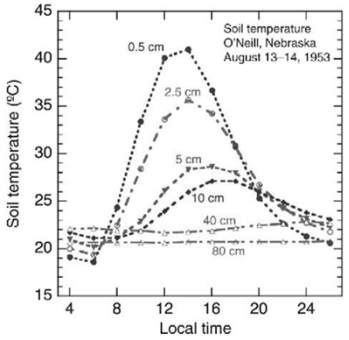
effective temperature of the land or ocean

- The heat capacity depends on the physical properties of the surface materials and the depth of the surface layer that communicates with the atmosphere on the time scale of interest.
- It is generally only the first few meters of soil that respond to seasonal forcing of the surface energy balance, but the temperature of the top 50–100 m of ocean changes with the seasons.
- On the seasonal time scale the thermal capacity of the ocean is about 30 times that of the atmosphere.
- The heat capacity of a land surface is typically slightly smaller than that of the atmosphere.

Heat Storage in Soil

soil temperature — **thermal diffusivity**

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



(from Global Physical Climatology)

- Because the surface is solid, it does not have the efficient heat transport by fluid motions that occurs in the atmosphere and ocean.
- Heat is transferred through the soil mostly by the less efficient process of conduction.
- Only the top 1-2 m of the soil is affected by seasonal variations, while about the top 70 m of ocean interact with the atmosphere on the time scale of a year.
- The penetration depth of soil is about 10 cm for diurnal forcing.

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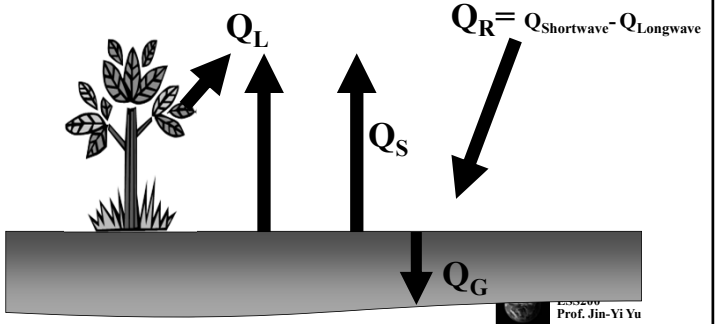
Surface Energy Balance

$$Q_{\text{Radiative}} = Q_{\text{Sensible}} + Q_{\text{Latent}} + Q_{\text{Ground}}$$



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Radiative Heating of the Surface

$$R_s = \underline{S^{\downarrow}(0) - S^{\uparrow}(0)} + \underline{F^{\downarrow}(0) - F^{\uparrow}(0)}$$

albedo

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

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

emissivity

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Bowen Ratio

$$B_o \equiv \frac{SH}{LE} = B_e \qquad B_e^{-1} \equiv \frac{L}{c_p}\frac{\partial q^*}{\partial T}\bigg|_{T=T_s}$$

- The *Bowen ratio* is the ratio of the sensible cooling to the latent cooling of the surface.
- The Bowen ratio is an indicator of the type of surface. The Bowen ratio, is less than one over surfaces with abundant water supplies.

Type of surface	Range of Bowen ratios
Deserts	>10.0
Semi-arid landscapes	2.0-6.0
Temperate forests and grasslands	0.4-0.8
Tropical rainforests	0.1-0.3
Tropical oceans	<0.1

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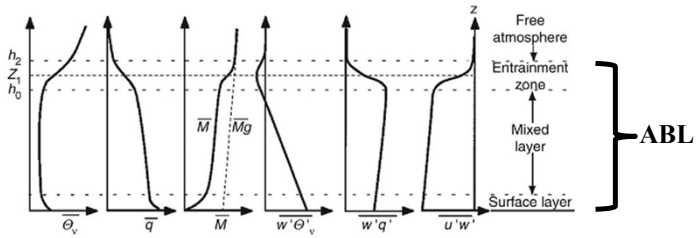
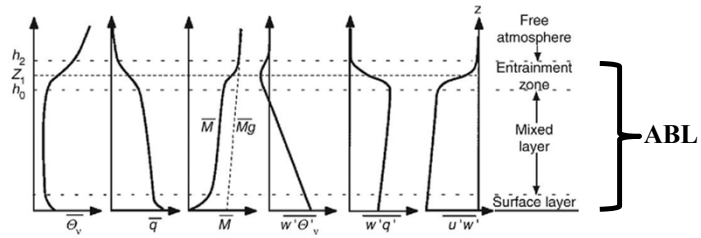
Atmospheric Boundary Layer (ABL)



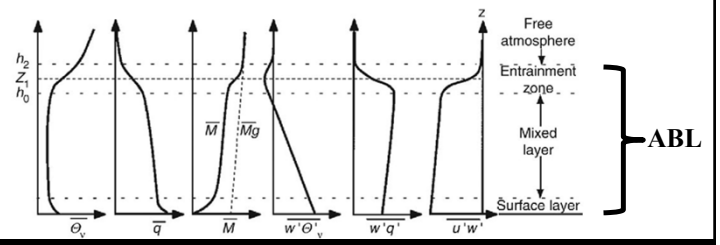
- The ABL is the lowest part of the troposphere, where the wind, temperatures, and humidity are strongly influenced by the surface.
- The wind speed decreases from its value in the free atmosphere to near zero at the surface.
- Fluxes of momentum, heat, and moisture by small-scale turbulent motions in the boundary layer communicate the presence of the lower boundary to the atmosphere.
- A characteristic of the atmospheric boundary layer is its quick response to changes in surface conditions.

Depth of the ABL



- The depth of the atmospheric boundary layer can vary between about 20 m and several kilometers, depending on the conditions, but a typical boundary-layer depth is about 1 km.
- The boundary layer is generally deeper when the surface is **being heated**, when the **winds are strong**, when **the surface is rough**, and when the **mean vertical motion in the free troposphere is upward**.
- Transports of mass, momentum, and energy through the boundary layer are accomplished by **turbulent motions**.
- Turbulence can be generated **thermally or mechanically**.

Structure of the ABL



- **Surface layer:** where the vertical fluxes of momentum, heat, and moisture are almost constant with height. (constant fluxes)
- **Mixed layer:** where buoyancy drives turbulent motions that maintain the potential temperature, v, the humidity, q, and the momentum, M, at values that are almost independent of height. (constant/well-mixed properties)
- **Entrainment zone**: which is the top of the boundary layer and is a transition zone between the boundary layer and the free atmosphere. Across this transition, the air properties change rapidly from those of the mixed layer to those of the free atmosphere above, generally marked by a **decrease in humidity**, an **increase in potential temperature**, and a **decrease in the magnitude of the vertical fluxes** of heat, moisture, and momentum by turbulent motions
- **Entrainment** is the process whereby air from the free atmosphere is incorporated into the boundary layer.

Clouds in ABL

The Neutral Boundary Layer

Stratified Boundary Layers

SH and LH in the Boundary Layer