Atmospheric Sciences 321

Science of Climate

Lecture 13: Surface Energy Balance
Chapter 4

Community Business

- Check the assignments

  HW #4 due Wednesday

  Quiz #2 Wednesday

- Mid Term is Wednesday May 6
  - Practice exams on assignment page (I think)
- We're now on Chapter 4: Surface Energy Balance
- Questions?

Reynolds Averaging

- A time average is signaled with an overbar.

$$\overline{w} = \frac{1}{T}\int_0^T w\,dt$$

- A deviation from the time average is signified with a prime.

$$w' = w - \overline{w}$$

- By definition, then, the time average of a deviation from a time average is zero

$$\overline{w'} = \frac{1}{T}\int_0^T (w - \overline{w})\,dt = \frac{1}{T}\int_0^T w\,dt - \frac{1}{T}\int_0^T \overline{w}\,dt = \overline{w} - \overline{w} = 0$$

Reynolds Averaging: Covariance

- If I am interested in the upward transport of temperature by fluid motion, I am interested in the product of vertical velocity w with temperature T, averaged over time, say.

$$\overline{wT}$$

- Let's use a decomposition into time averages and deviations therefrom.

$$w = \bar{w} + w' \qquad T = \bar{T} + T'$$

- So,

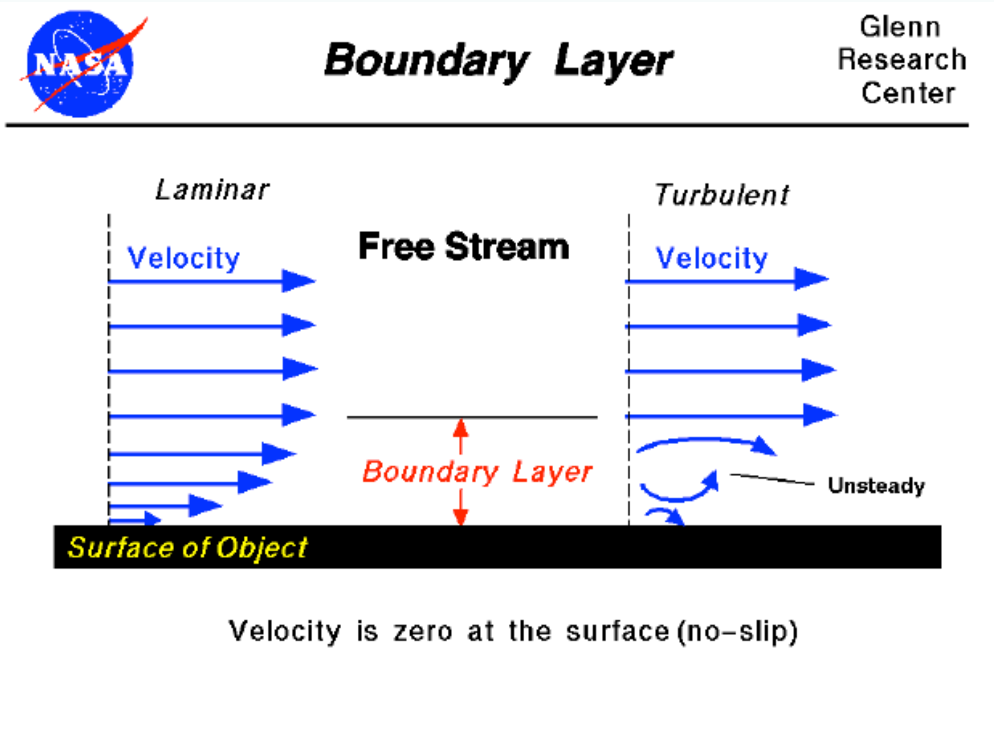
$$\overline{wT} = \overline{(\bar{w} + w')(\bar{T} + T')} = \bar{w}\bar{T} + \overline{w'T'}$$

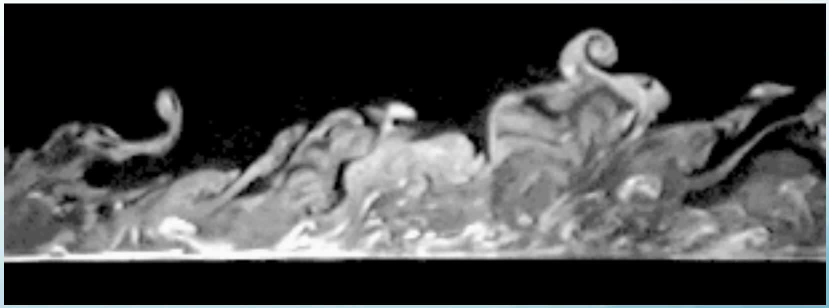
- The mean vertical velocity is smaller than the deviation from the time mean, also called the 'eddy' part.

Sensible and Latent Heat Fluxes

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

$$\mathrm{SH} = c_p \rho \overline{w' T'}, \quad \mathrm{LE} = L \rho \overline{w' q'}$$





Sometimes you can see turbulence in PBL Clouds

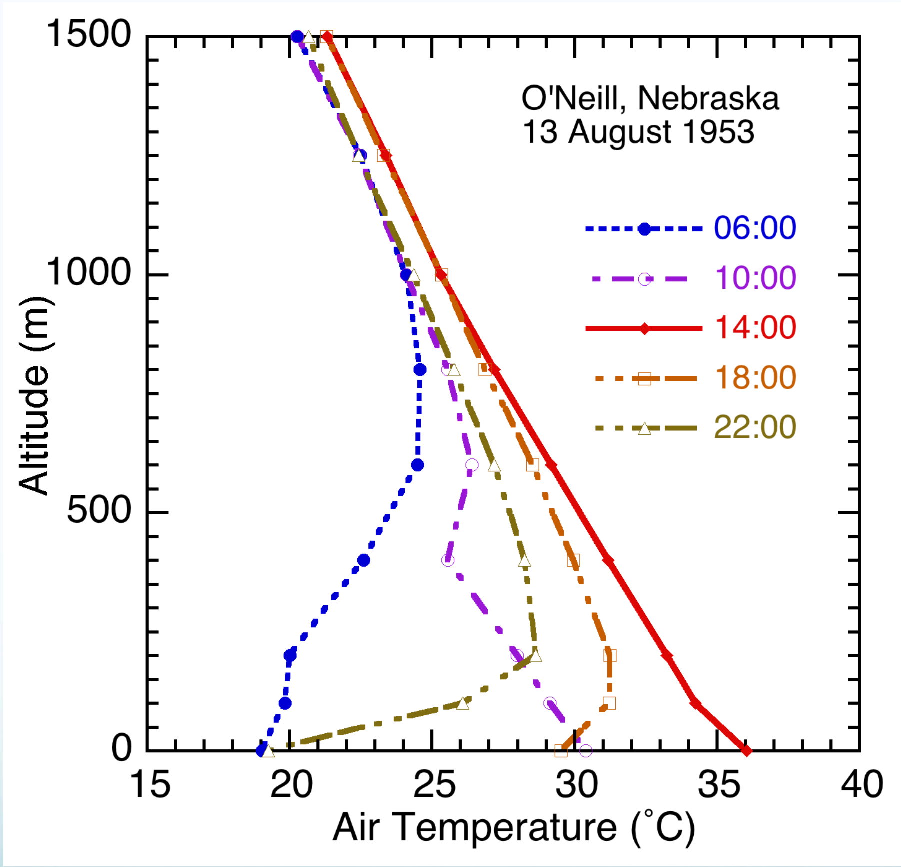
Richardson Number critical value is 1/4

- Richardson Number measures stability to buoyancy and shear instabilities.

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

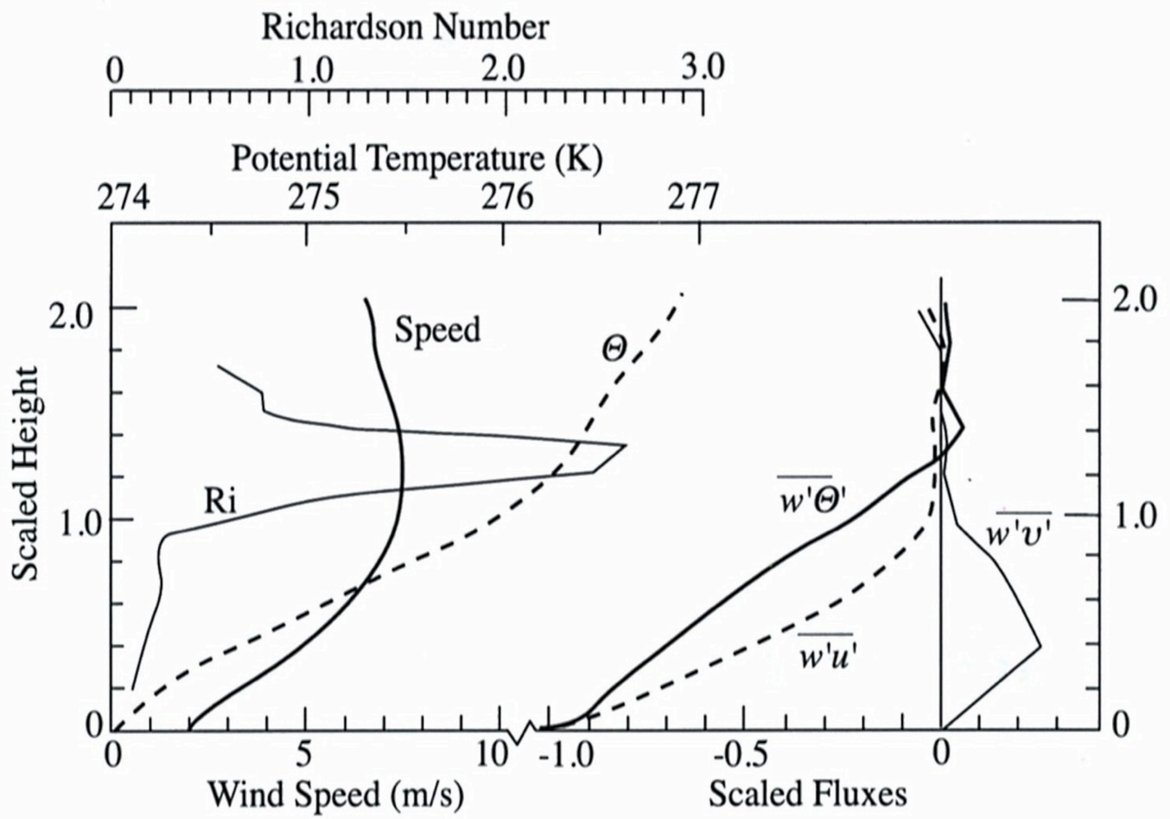
- If vertical shear of wind $\partial U / \partial z$ is large, Richardson number is small and flow is less stable
- If static stability $\partial\Theta / \partial z$ is large, then Ri is large and flow is stable. Theta is potential temperature, U is wind speed.

Daytime Boundary layer over land in summer is unstable. Heated strongly from below



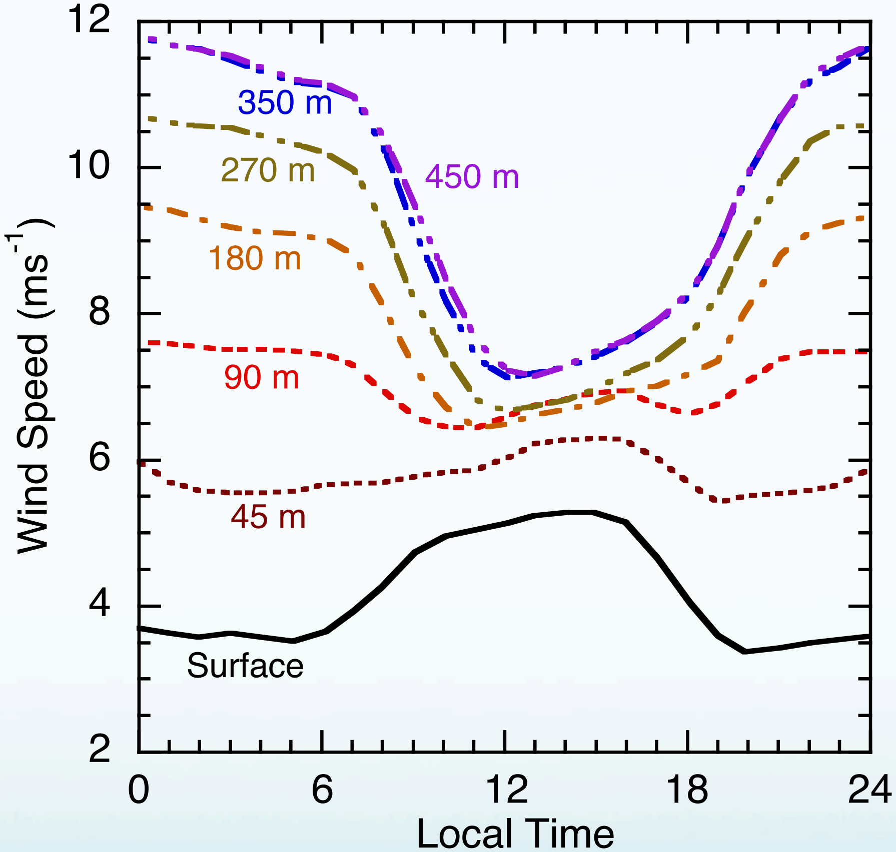
Inversion at night, super adiabatic lapse rate during the early afternoon.

Nightime Boundary Layer is highly stratified



- Richardson number is large at 1.2km because, static stability is large and shear is small. Heat fluxes are DOWNWARD! Opposite to usual

Oklahoma City TV Tower Data



- Explain the wind speed variations on the tower with time of day. Note mixing is stronger during the day.

Planetary Boundary Layer (PBL) Facts

- Stability is important
- When the surface is heated, turbulence is generated by buoyancy and mixing is enhanced
- When the surface is cooled, turbulence is suppressed. If strong winds are present in the free troposphere, shear increases to produce mechanical turbulence in the PBL. Otherwise very stable and still boundary layer (you get fog and bad air quality then)

Drag Laws
Aerodynamic Formulas

- Vertical fluxes of heat and moisture in the boundary layer are accomplished by small-scale high-frequency turbulence that is not measured by the normal climate observations.

$$\mathrm{SH} = c_p \overline{\rho w' T'}, \quad \mathrm{LE} = L \overline{\rho w' q'}$$

- So we have come up with formulas that allow us to estimate the fluxes from time mean observations

$$SH = c_p \rho C_{DH} U_r \left(T_s - T_a \left(z_r \right) \right)$$

$$LE = L \rho C_{DE} U_r \left(q_s - q_a \left(z_r \right) \right)$$

Drag Laws
Aerodynamic Formulas

We have come up with formulas that allow us to estimate the fluxes from time mean observations

$$
\begin{aligned}
SH &= c_p \rho C_{DH} U_r \left(T_s - T_a \left(z_r \right) \right) \\
LE &= L \rho C_{DE} U_r \left(q_s - q_a \left(z_r \right) \right)
\end{aligned}
$$

We use mean values measure at the surface s and at a reference height z_r often 2 or 10 meters.

These formulas are also used in global climate models, which represent variables only on a coarse grid.

Equilibrium Bowen Ratio

- The Bowen ratio is the ratio of the sensible heat flux to the latent heat flux

$$B_o = \frac{SH}{LE}$$

- We can estimate the Equilibrium Bowen Ratio, which is the Bowen ratio under equilibrium conditions when the air is saturated.

Equilibrium Bowen Ratio

- Start by expanding the saturation mixing ration of the air as a Taylor series about the surface saturation value

$$q_s = q^*\left(T_s\right)$$

$$q_a^* = q_s^*(T_s) + \left.\frac{\partial q^*}{\partial T}\right|_{T_s} \cdot (T_a - T_s) + \cdots$$

- Define the Relative Humidity = RH $\quad \mathrm{RH} = \dfrac{q}{q^*}$
- and write the surface mixing ratio this way

$$q_a \cong \mathrm{RH} \cdot (q_s^*(T_s) + \frac{\partial q^*}{\partial T} \cdot (T_a - T_s))$$

Equilibrium Bowen Ratio - II

- Go back to our bulk aerodynamic formula and put in our approximation for q_a

$$LE = L\rho C_{DE} U_r \left(q_s - q_a \left(z_r \right) \right)$$

$$\mathrm{LE} \cong \rho L C_{\mathrm{DE}} U \left(q_s^* (1 - \mathrm{RH}) + \mathrm{RH}\ B_e^{-1} \frac{c_p}{L} (T_s - T_a) \right)$$

- where

$$B_e^{-1} \equiv \frac{L}{c_p} \frac{\partial q^*}{\partial T}$$

- Is the inverse equilibrium Bowen Ratio

Equilibrium Bowen Ratio - II

- Take our estimate of LE, assume the air is saturated, then compute the Bowen ratio

$$\mathrm{LE} \cong \rho L C_{\mathrm{DE}} U \left(q_s^*(1-\mathrm{RH}) + \mathrm{RH}\; B_e^{-1} \frac{c_p}{L}(T_s - T_a) \right)$$

- For RH = 1 this is $\mathrm{LE} \cong \rho L C_{\mathrm{DE}} U \left(B_e^{-1} \frac{c_p}{L}(T_s - T_a) \right)$
- and

$$B_o = \frac{c_p \rho C_{DH} U_r \left(T_s - T_a\left(z_r\right)\right)}{\rho L C_{\mathrm{DE}} U \left(B_e^{-1} \frac{c_p}{L}(T_s - T_a) \right)} \simeq B_e$$

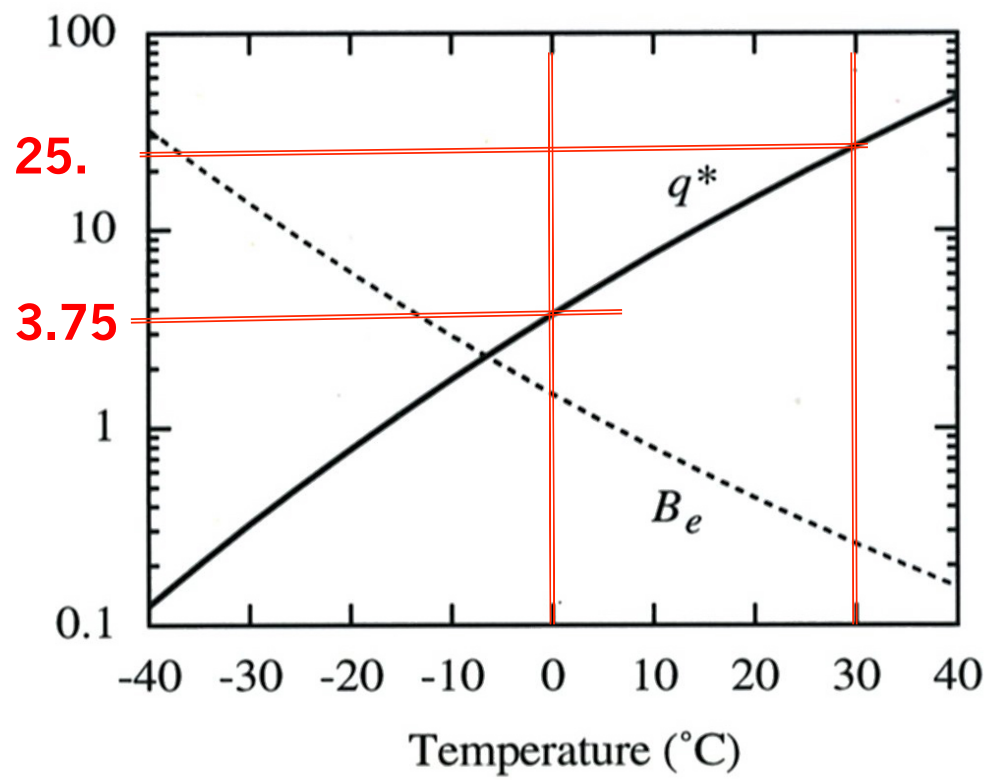
- with the proviso that the drag coefficients for heat and vapor are equal

Equilibrium Bowen Ratio III

- The dependence of saturation mixing ratio on temperature is approximately exponential

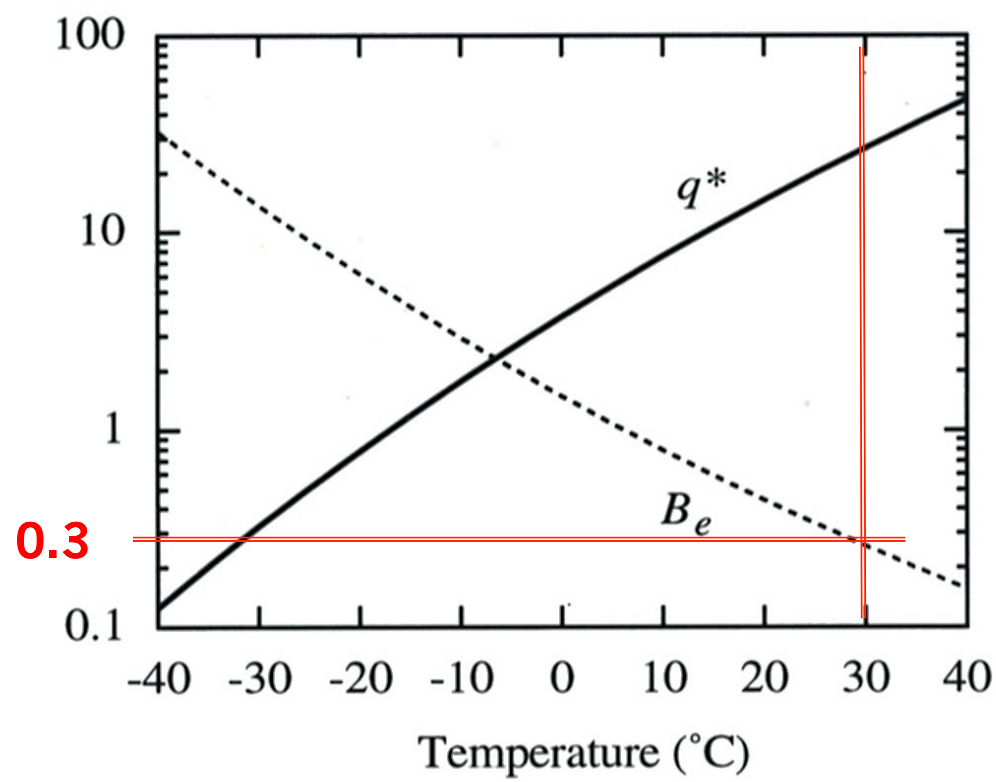
$$\frac{\partial q^*}{\partial T} \approx q^*(T) \cdot \left(\frac{L}{R_v T^2} \right)$$

$$\frac{\partial \ln q^*}{\partial T} \approx \left(\frac{L}{R_v \overline{T}^2} \right)$$



Equilibrium Bowen Ratio III

- Equilibrium Bowen Ratio is large at low temperatures, like high latitudes
- and would be very low in the tropics, assuming the surface is wet and the air not too dry, like over the ocean.

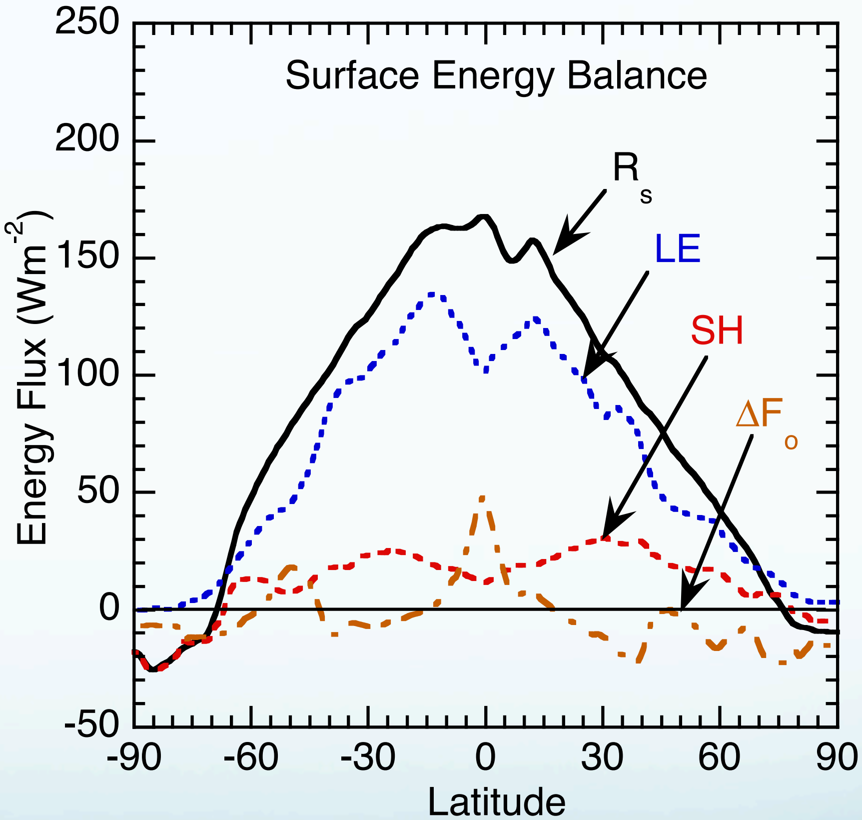


What does this mean?

Over the tropical oceans, most of the cooling is by evaporation, rather than by sensible heat flux!

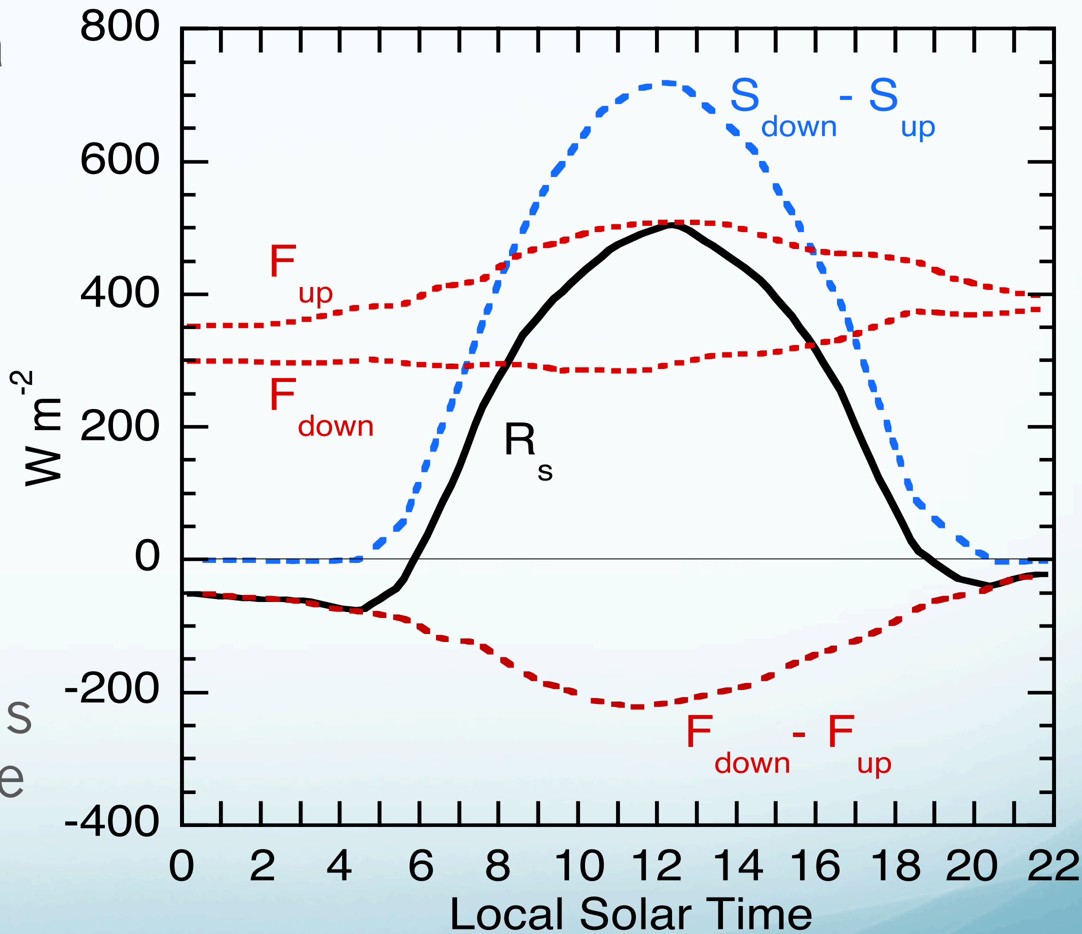
Surface Energy Balance Zonal, Annual Mean

- Radiation and Evaporative cooling are big in the tropics and the biggest terms almost everywhere except poleward of about 60 degrees.



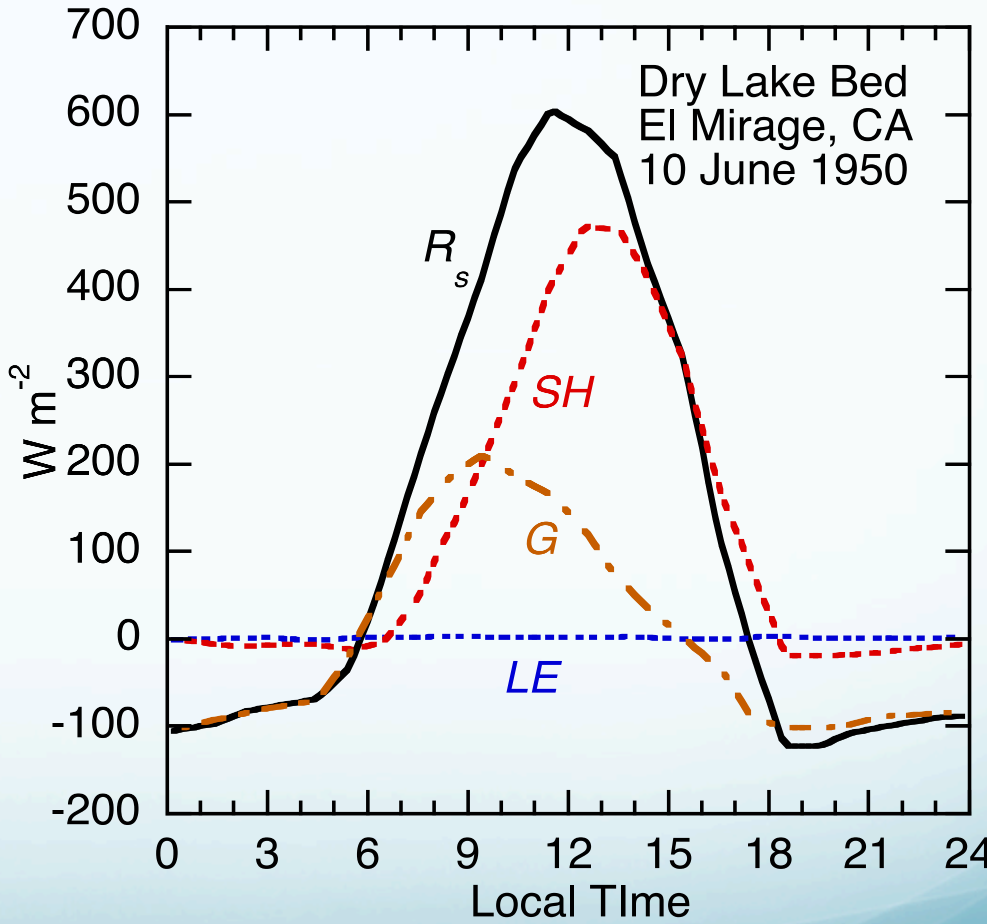
The Diurnal Variation

- The sun rising and setting every day is a big deal
- The radiative driving from this is huge.
- The solar part goes from zero to a big value.
- The longwave part does not vary quite as much, because of the strong infrared opacity of the atmosphere



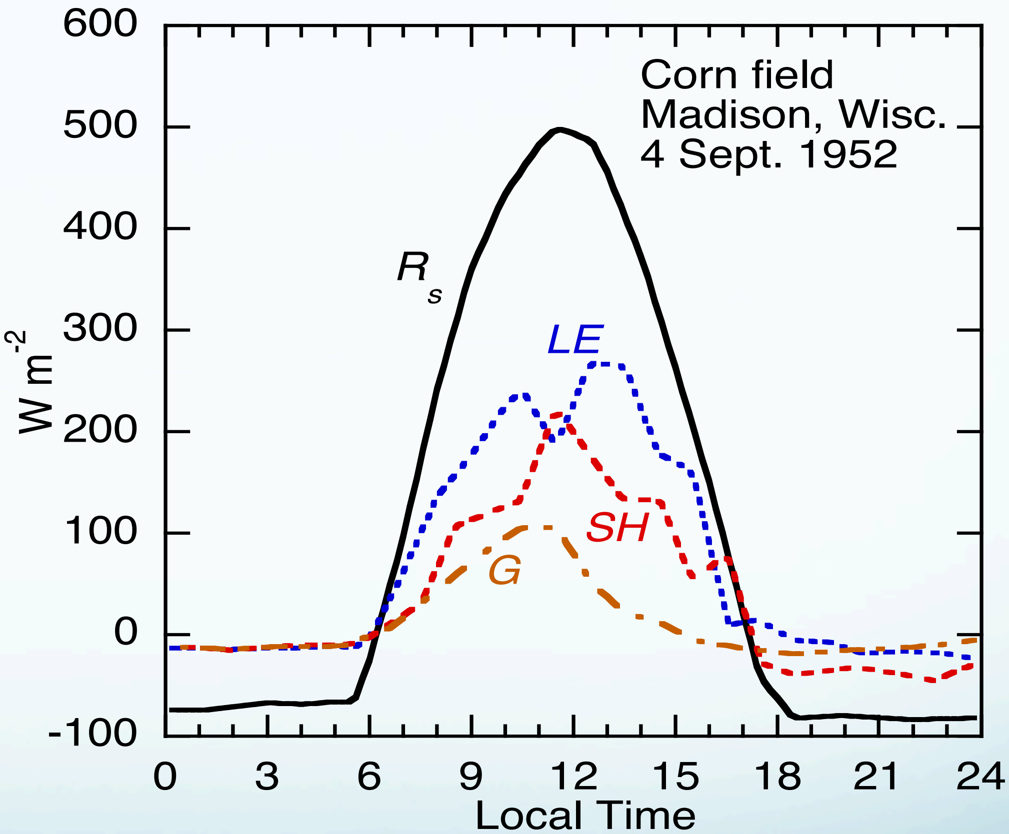
The Diurnal Variation

- Over a dry lake bed in the CA desert
- The radiative driving is huge
- First the surface stores heat G by warming up
- Then sensible cooling, turbulent transfer of sensible heat c_pT Takes over



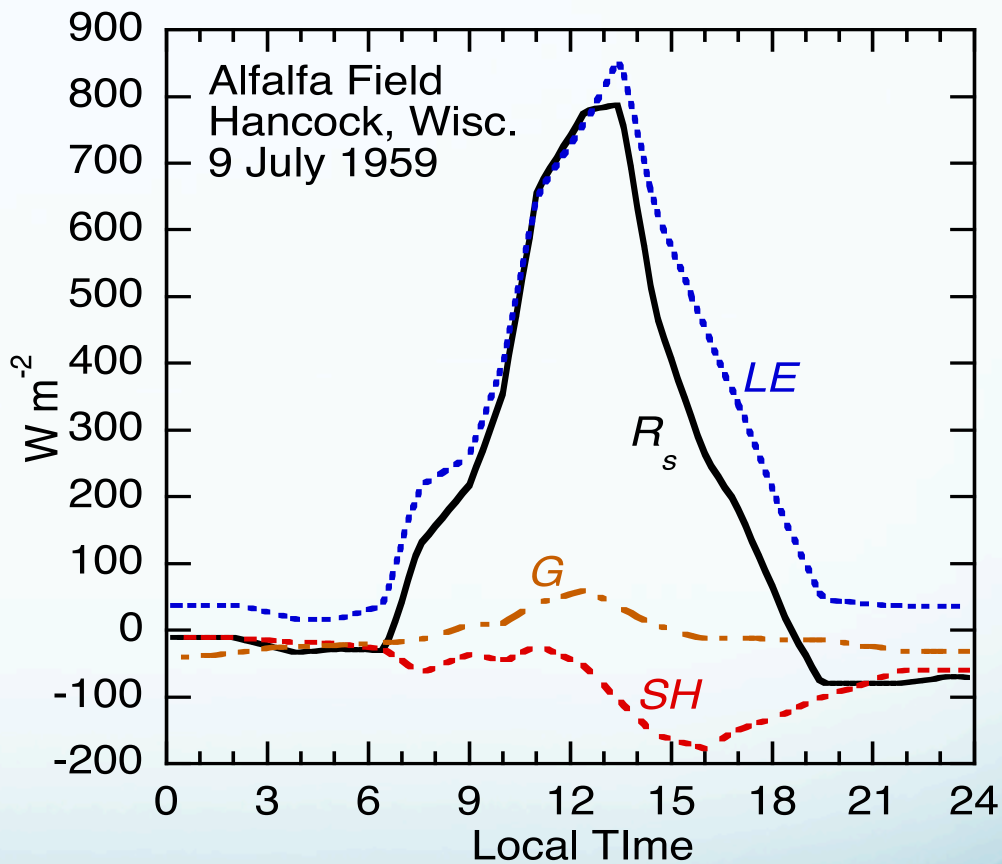
The Diurnal Variation

- Over a cornfield in Wisconsin in September
- The radiative driving is huge
- First the evaporation starts
- Then storage and sensible cooling, kick in later.



The Diurnal Variation

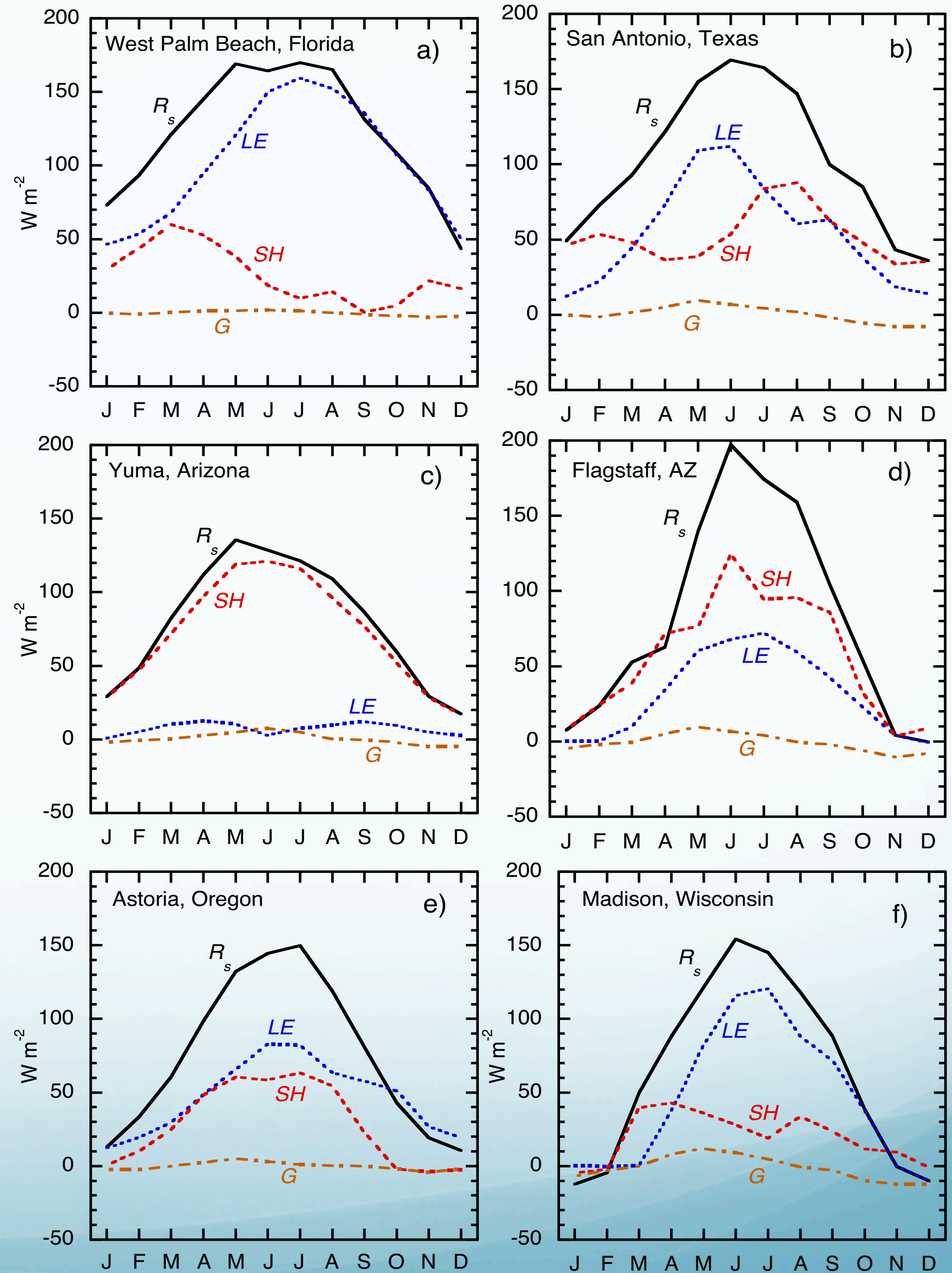
- Over a alfalfa field in Wisconsin in July
- Something weird
- The evaporation is bigger than the radiation
- The sensible heat flux is downward and the storage is mostly negative.
- Why?



Dry air, irrigated field

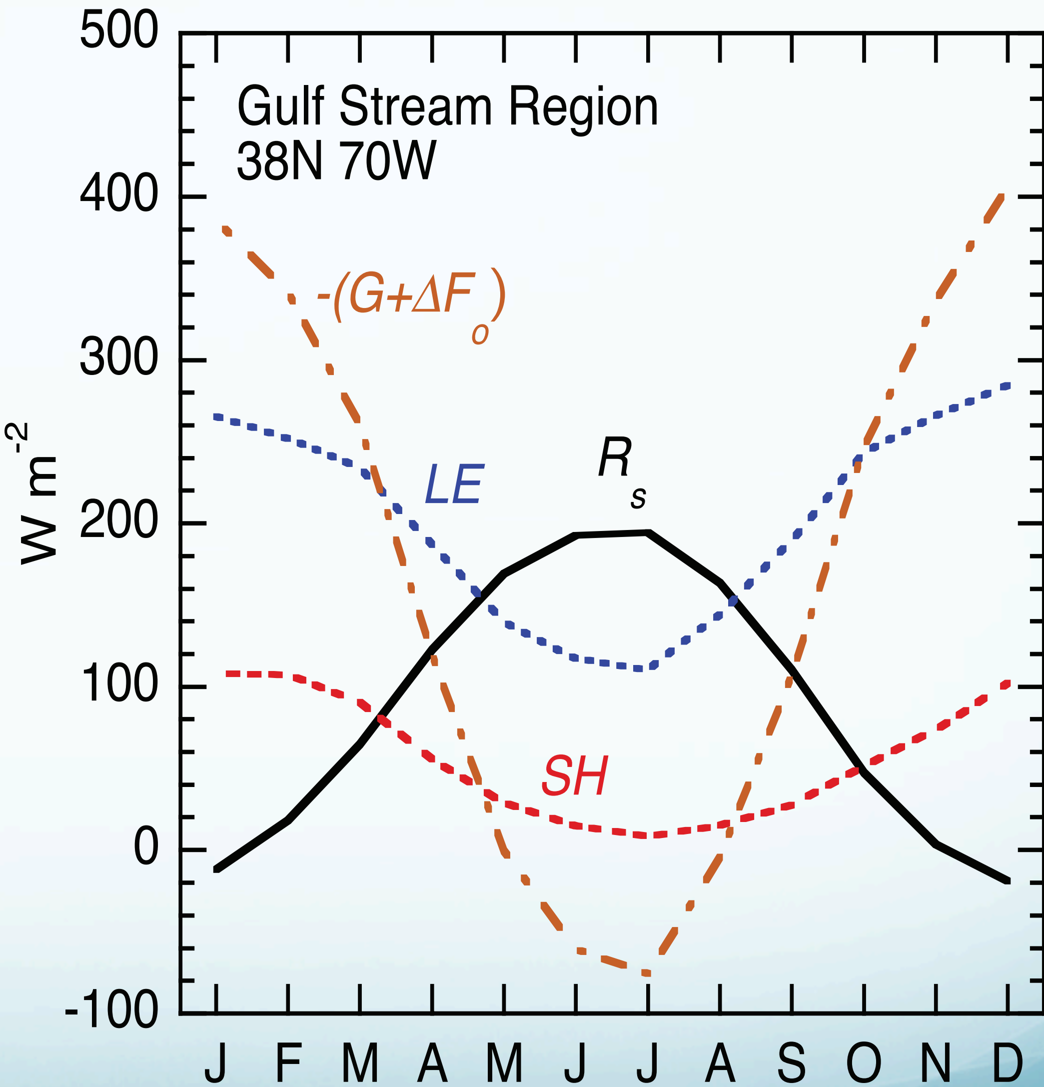
Seasonal Variations

- Discuss among yourselves.
- Difference between West Palm Beach and San Antonio
- Difference between Yuma and Flagstaff
- Difference between Astoria and Madison



Seasonal Variations

- The ocean, especially in the Gulf Stream region, is different.
- Horizontal transport and storage are the biggest terms.
- Radiation is smaller than LE

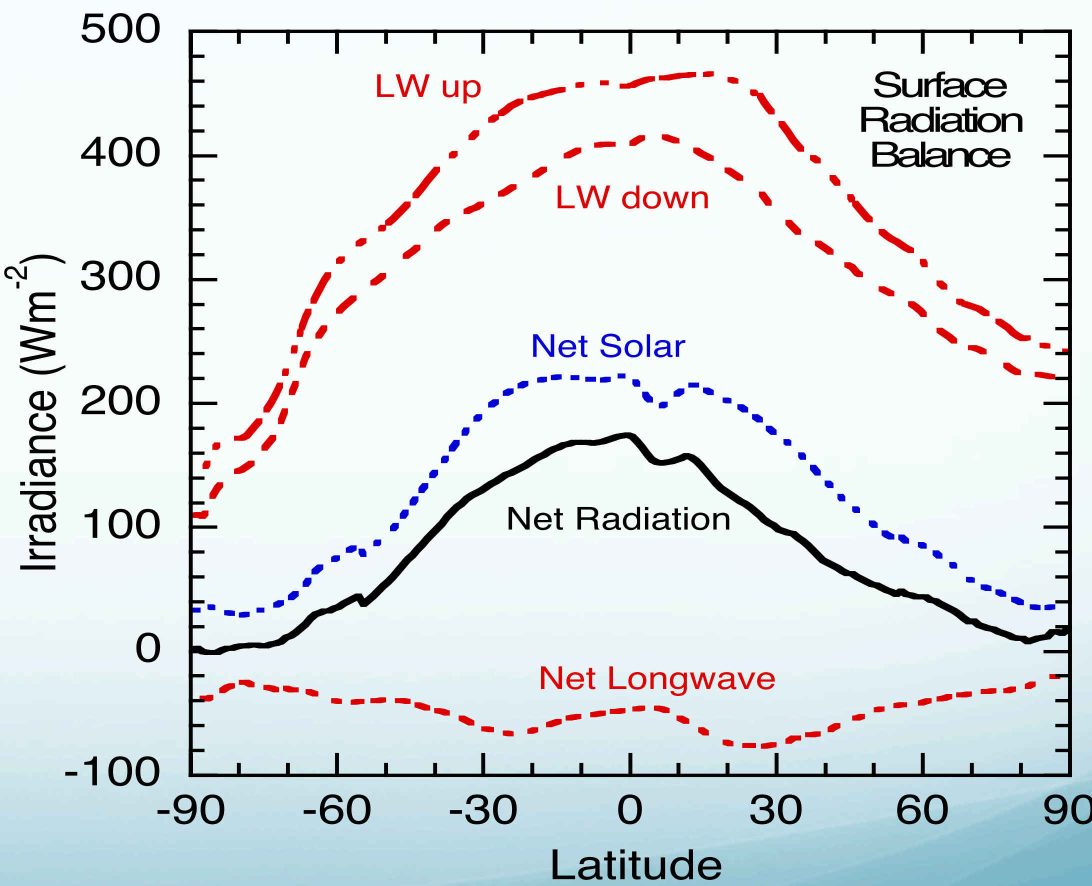


Surface Radiation Balance

LW up and LW down are close together, with smaller net longwave loss

Net solar peaks at about 200 Wm^{-2} in the Tropics

Net radiation peaks at about 150 Wm^{-2} in the Tropics and is about zero at the poles

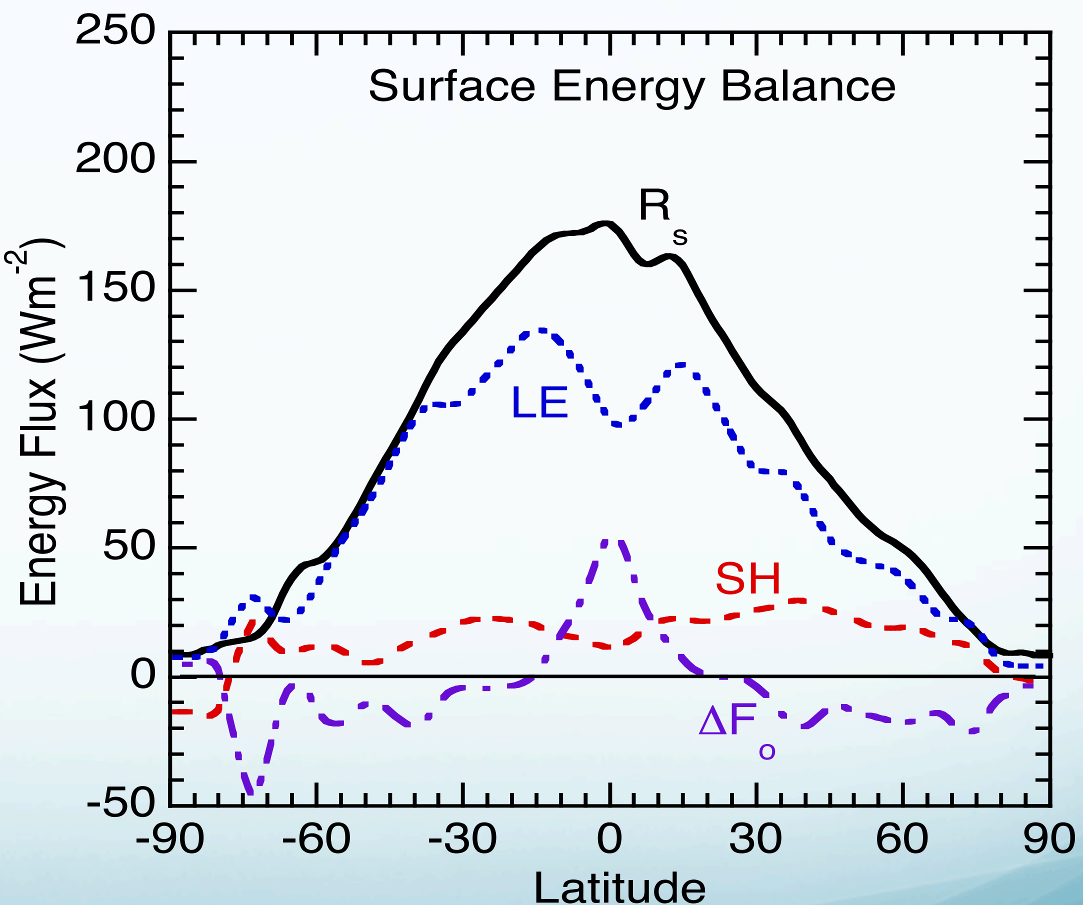


Surface Energy Balance

Net radiative input is mostly balanced by evaporative cooling

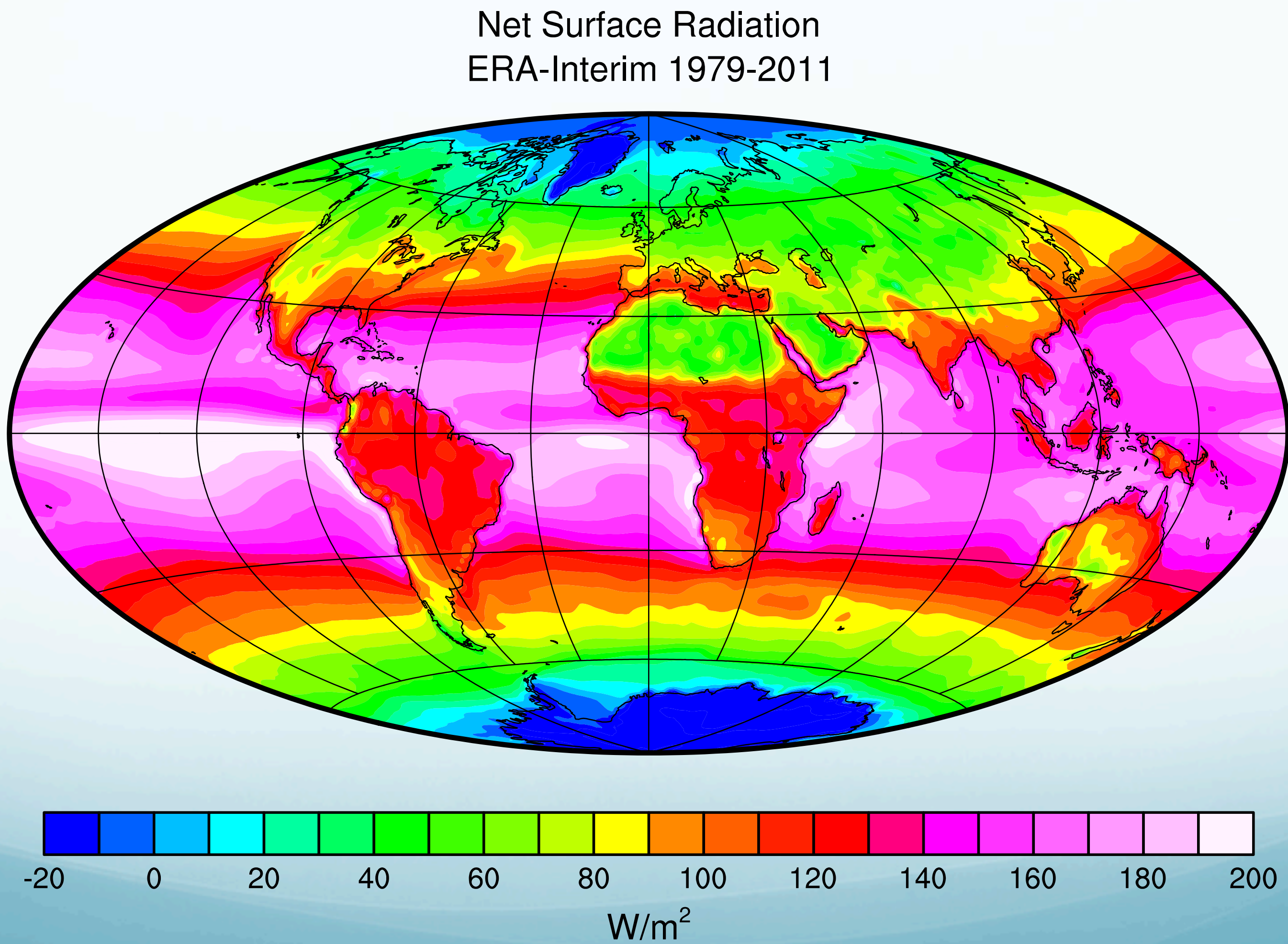
Sensible heating is less than about 25 Wm-2

The ocean transports heat poleward.



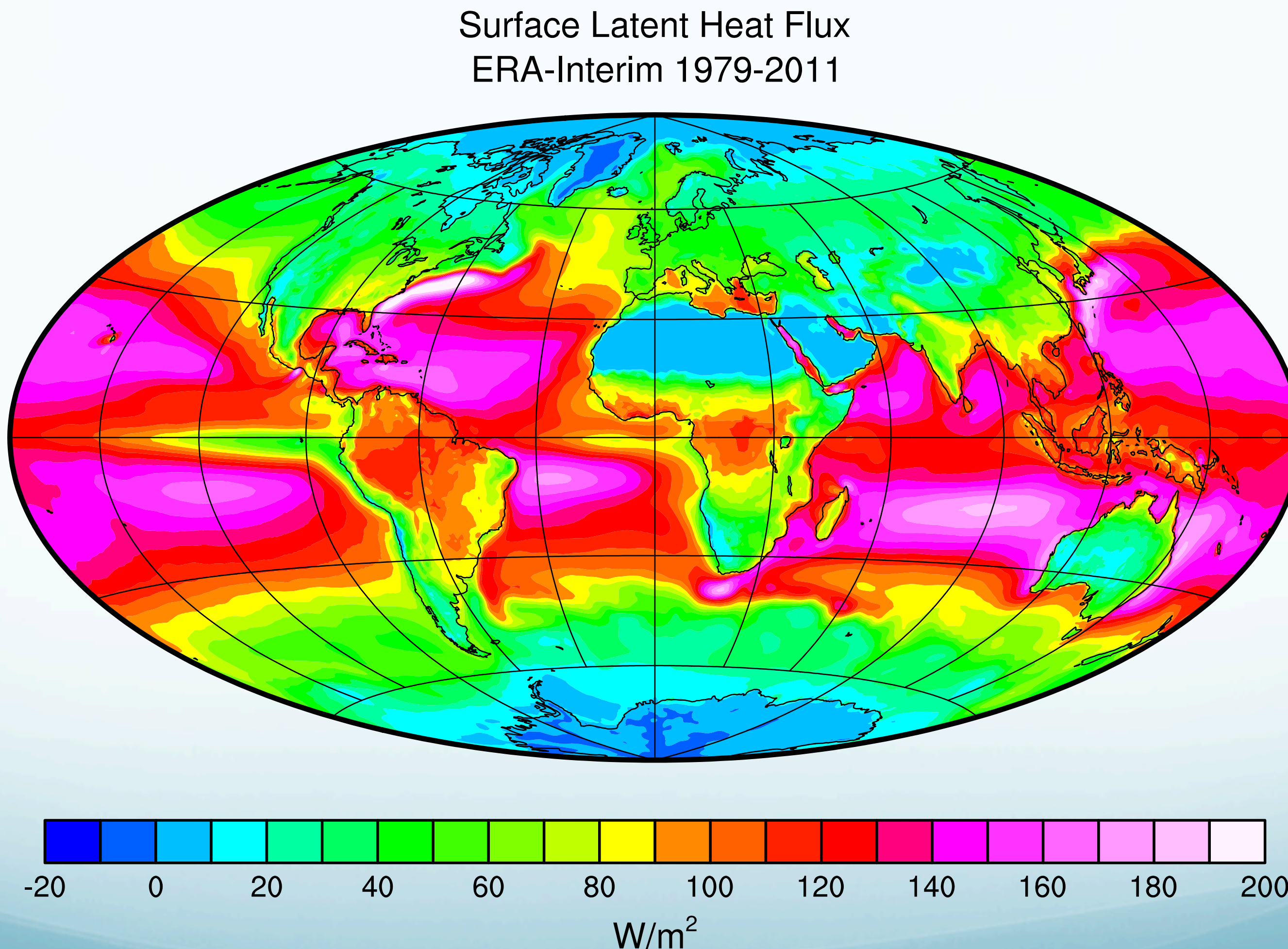
Global Maps of Annual Means

- Net Surface Radiation



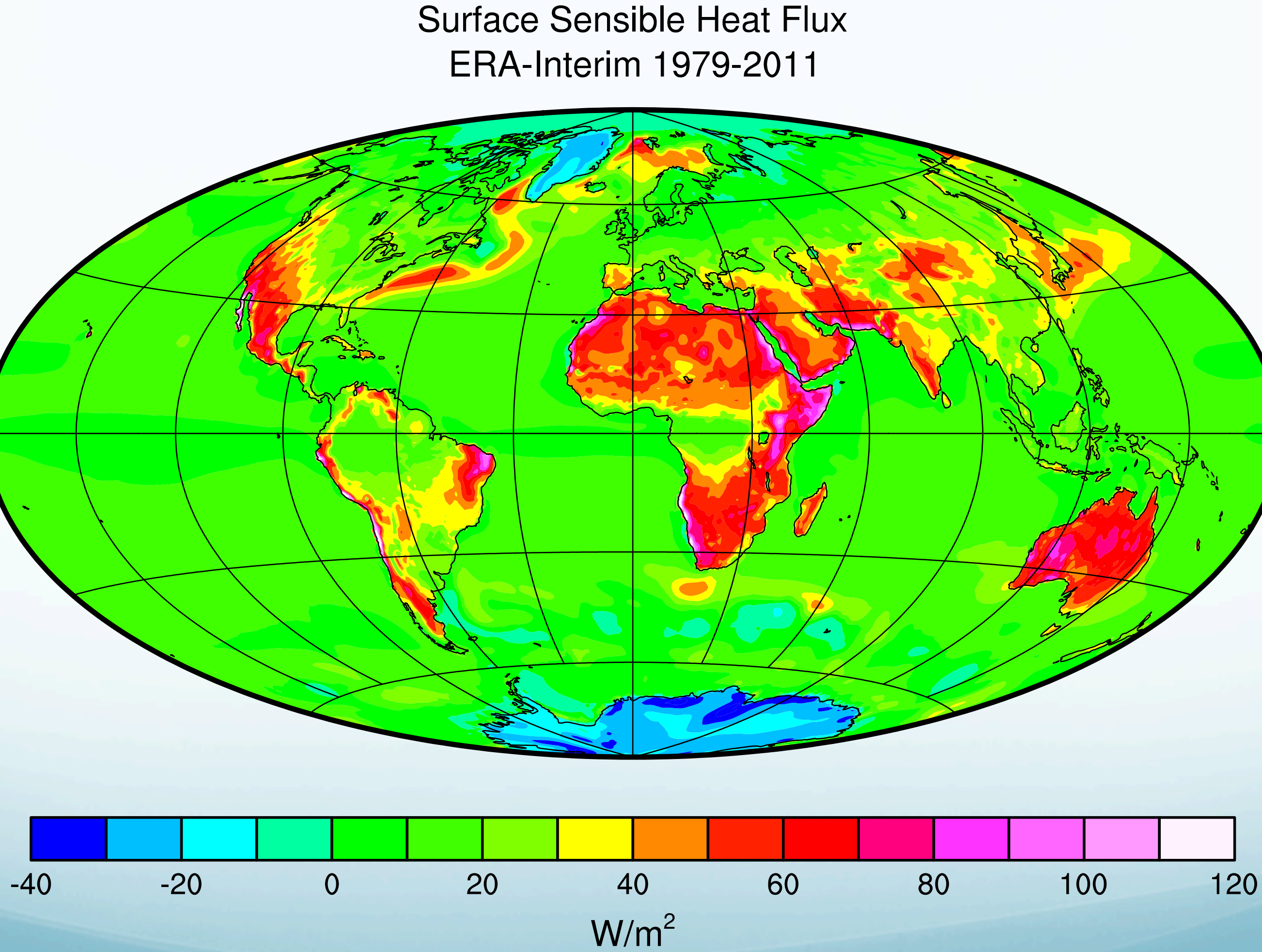
Global Maps of Annual Means

- Evaporation Cooling



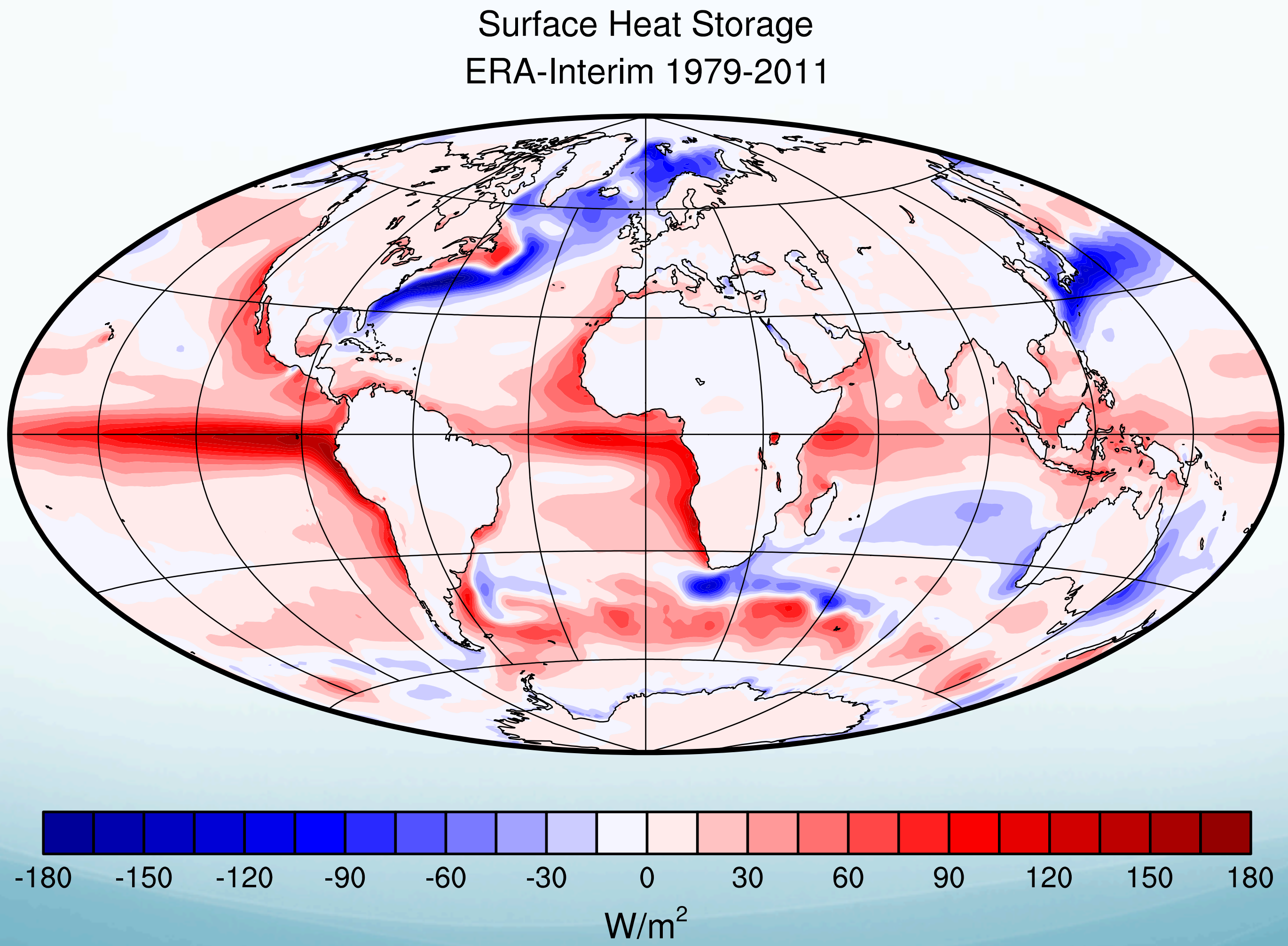
Global Maps of Annual Means

- Sensible Heat Cooling



Global Maps of Annual Means

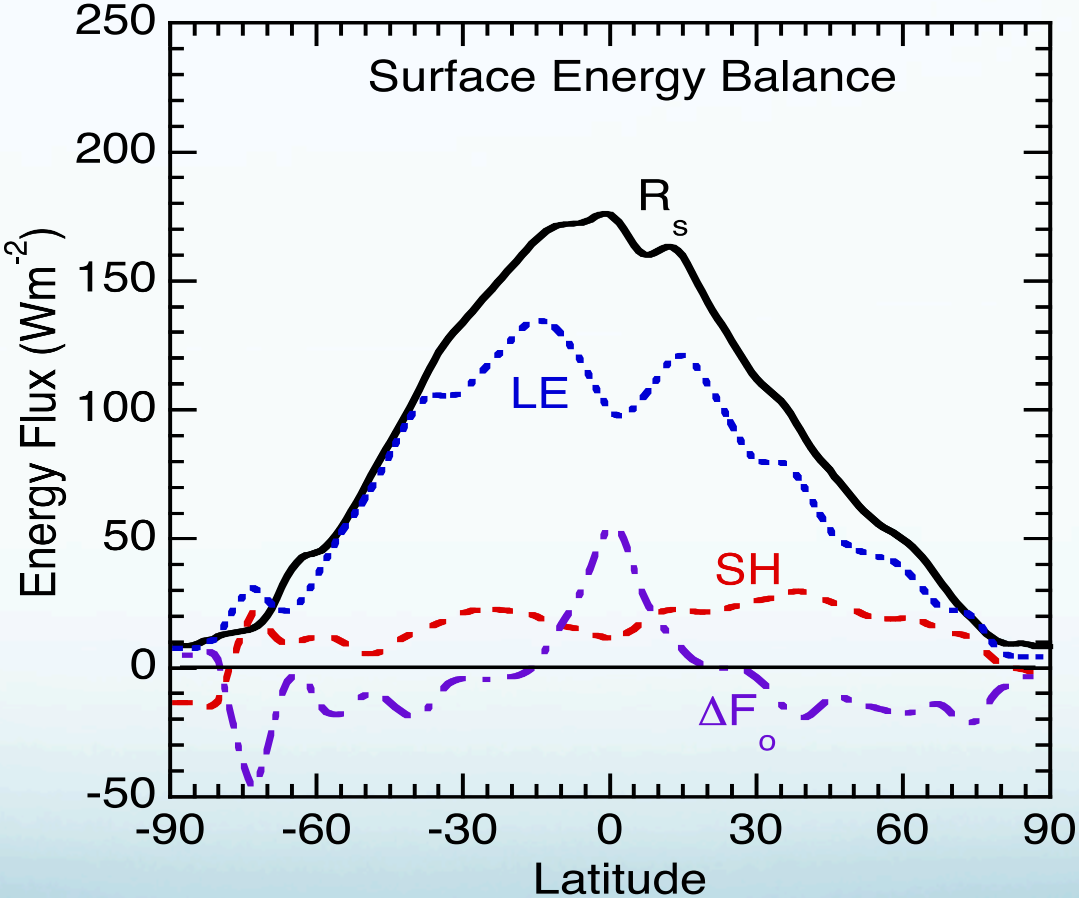
- Surface Heat Storage, or flux into the ocean



Summary Chapter 4

- Basic surface balance is net radiation, mostly solar, is balanced by mostly evaporative cooling
- Over land sensible heat is important locally
- Over ocean heat flux into (in equatorial region, mostly) and out of (mostly in western boundary current regions) is important.
- On land diurnal and seasonal variations depend on land moisture, very different in deserts and rain forests.

Thanks!


Surface Energy Balance
Energy Flux (Wm-2)
Latitude
Rs
LE
SH
ΔFo
250
200
150
100
50
0
-50
-90
-60
-30
0
30
60
90