

Problem Set 1
The Surface Energy Balance

1. You have an important government position: you control the noontime temperature of a shallow, open pool of water at the White House. You do this by adjusting the effective albedo of the pool. (You do this through some crazy mechanical process involving tiny mirrors at the pool's bottom.)

Assume the following for noon:

$$\text{Downward solar radiation} = 650 \text{ W/m}^2$$

$$\text{Downward longwave radiation} = 330 \text{ W/m}^2$$

$$\text{Emissivity } \epsilon = 1.$$

$$\text{Air temperature at reference level } (T_r) = 15^\circ\text{C}$$

$$\text{Dewpoint temperature at reference level } (T_r) = 14^\circ\text{C}$$

$$\text{Mean air density } \rho = 1.2 \text{ kg/m}^3$$

$$\text{Heat capacity of air } (c_p) = 1010 \text{ J kg}^{-1} \text{ } ^\circ\text{K}^{-1}$$

$$\text{Aerodynamic resistance } (r_a) = 40 \text{ s/m}$$

$$\text{Latent heat of vaporization} = 2.45 \times 10^6 \text{ J/kg}$$

$$\text{Saturated vapor pressure of air (mb) is } e_s(T) = \exp(21.18123 - 5418/T)/0.622,$$

where T is the temperature in $^\circ\text{K}$.

$$\text{Stefan-Boltzmann constant } (\sigma) = 5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ } ^\circ\text{K}^{-4}$$

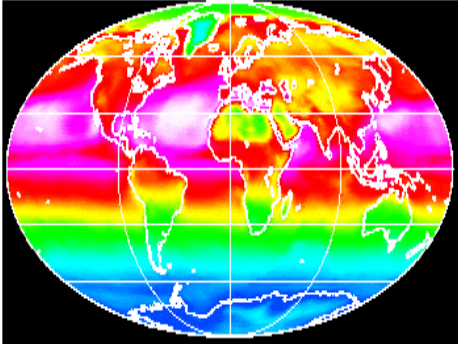
$$\text{Surface pressure } (p) = 1000 \text{ mb}$$

To simplify your calculations, assume the following:

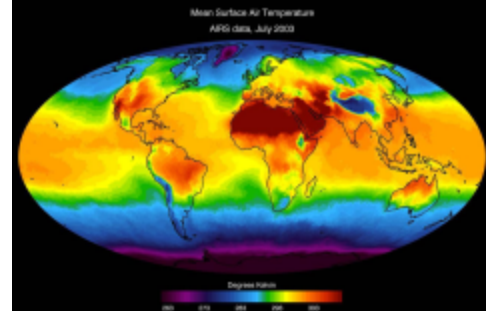
- Ground heating ($C_p\Delta t$ and G) is zero throughout the day. (This is rather unrealistic, but it allows for straightforward solutions.)
 - The aerodynamic resistance doesn't change with air temperature. (This is also unrealistic!)
- a. Suppose your assistant fails to fill the pool with water, and you start out with a dry (empty) pool. What albedo should it have to produce a temperature of 20°C ?
- b. How low can the air temperature go before it is impossible to produce a 20°C temperature in the dry pool by adjusting the albedo?
- c. You point out your assistant's mistake, and he fills the pool with water. The air temperature is still 15°C . What albedo do you need now to produce a temperature of 20°C ?
- d. What percentage of the net radiative energy goes into sensible heat for the dry pool case (a)?
- e. What percentage of the net radiative energy goes into sensible heat for the full pool case (c)?

2. Shown below are several maps of observed geophysical fields. (Don't worry about trying to read numbers off these plots; all answers for this problem can be qualitative.)

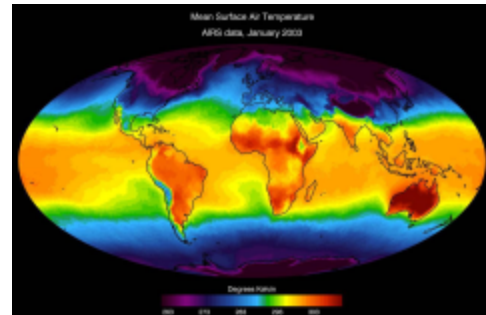
Plot 1



Plot 2



Plot 3



Plot 1: Net radiative flux at the surface of the Earth, for July. Blue denotes low values; red, purple and white denote high values.

Plot 2: Global surface temperature, July,

Plot 3: Global surface temperature, January.

(Note: there may, in fact, be more than one relevant answer to the following questions. The answers we're looking for involve straightforward interpretations of the surface energy balance.

- The Sahara and India are at roughly the same latitude. Why, then, is the net radiative flux in July lower in the Sahara (Plot 1)?
- The July net radiative flux in the rainforests of equatorial Africa is much higher than that in the Sahara (Plot 1). Why, then, does the Sahara have the higher July temperature (Plot 2)?
- Much of Canada is seen to have an air temperature well below 263K during January (Plot 3). Would you expect the soil temperature there to be warmer, cooler, or about the same as the air temperature? Why?

3. Two large regions lie side by side. You know the following:

Region 1:

Reference level air temperature = 287.

Surface temperature = 281.

Region 2:

Reference level air temperature = 290.

Surface temperature = 293.

Both regions:

Mean air density = 1.2 kg/m^3

Heat capacity of air (c_p) = $1010 \text{ J kg}^{-1} \text{ }^\circ\text{K}^{-1}$

Emissivity of surface = 1.

Finally, to make this problem tractable, assume that $r_a = 20 \text{ s/m}$ for unstable air ($T_s > T_r$) and that $r_a = 200 \text{ s/m}$ for stable air ($T_s \leq T_r$). (The actual variation of r_a with temperature, of course, is much more complicated. This is a first order attempt to describe its nonlinearity.)

- a. What is the sensible heat flux in Region 1 and Region 2?
- b. What is the outgoing longwave radiation flux in Region 1 and Region 2?
- c. What is the average sensible heat flux for the two regions combined? Assume they are the same size.
- d. What is the average longwave radiation flux for the two regions combined? Again, assume they are the same size.
- e. Suppose that you consider the two regions together as a single, very large region. Compute the average surface temperature for the region and the average air temperature over the region. Then use these average temperatures to compute the sensible heat flux, using the r_a appropriate for the average surface and air temperatures. (See r_a rule above.) How does it compare with the actual average sensible heat flux (from c)? I.e., what is the error associated with using the average temperatures?
- f. Perform the same analysis for the outgoing longwave flux. Compute the average surface temperature for the region, and use this average temperature to compute the outgoing longwave flux. How does it compare with the actual average flux (from d)? I.e., what is the error associated with using the average temperature?
- g. GCMs typically represent a large grid cell area with a single surface temperature, ignoring variations in forcing and surface properties that can lead to subgrid variations in the surface temperature. Based on the answers to the questions above, which flux (sensible heat or longwave) is more prone to being incorrect because of the neglect of explicitly determined subgrid temperature variations? (No calculations are necessary here; just a sentence or two is needed.)