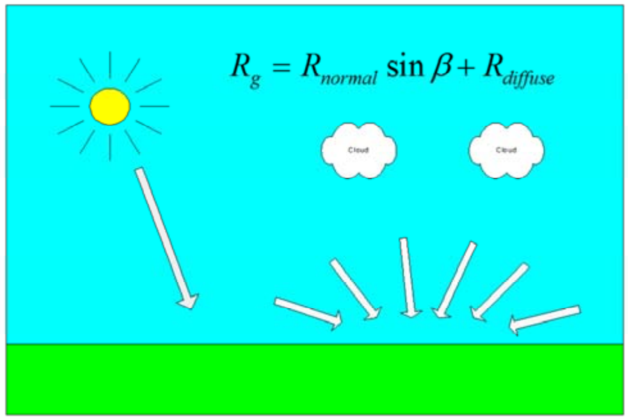
Lecture 6
Solar Radiation: Principles, part 2

- Global Shortwave Radiation
  - Direct
  - Diffuse
- Terrestrial Radiation
- Long wave radiation
  - Stefan-Boltzmann Law
  - Kirchoff's Law
  - Emissivity
- Net Radiation Balance

Global Radiation

$$R_g = R_{beam} + R_{diffuse}$$



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We also can break up solar radiation into two dominant streams. One is directional and is beam radiation from the sun. The other is isotropic and is diffuse radiation emitted by the sky. Obviously the fraction of clouds and amount of cloud cover will alter the ratio between direct and diffuse radiation. Directional radiation needs to be quantified as it has trigonometric relationships with the angle of the surface it is hitting.

Solar Spectra with Direct and Diffuse Light

24,364 MEYWERK AND RAMANATHAN: SPECTRAL AEROSOL FORCING

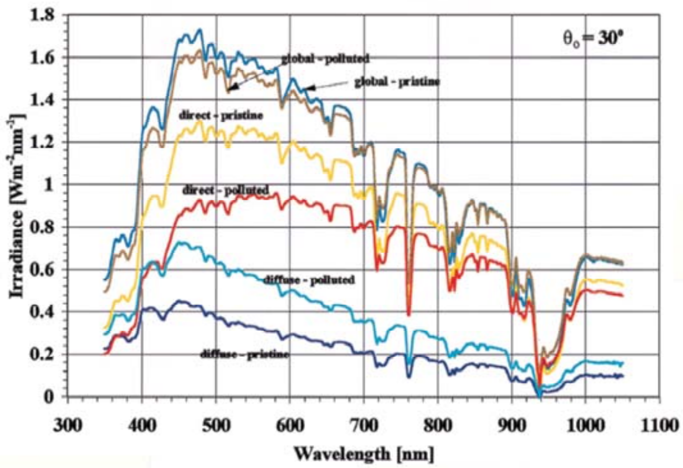

Plate 2. Global, direct, and diffuse portion of the spectral irradiance for the most pristine day, day 78 (March 19, 1998) at ~12°S, and the most polluted day, day 85 (March 28, 1998) at ~8°N. Solar zenith angle for both samples was 30°.

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As photons pass through a clear or cloudy sky there can be changes in the spectrum. Here is an example

Wave-length Dependent Radiation Attenuation through the Atmosphere

$$R_g(\tau,\lambda) = R_g(0,\lambda)\exp(-\tau(\lambda)\cdot m)$$

$$m = \frac{P}{101.3(kPa)\cos\theta}$$

m, atmospheric thickness
τ, transmissivity
R_g, flux density of global radiation, W m^{-2}

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Sunlight from the sun is attenuated as it passes through the atmosphere, in line with Beers law. Here the path is denoted by m which is a function of the solar zenith angle and the ratio of the pressure of the atmosphere to that at sea level…assuming the observer is at sea level. Tau is the transmissivity and is a function of the wavelength. Light is scattered differently by gases and particles

Optical Thickness of the Atmosphere

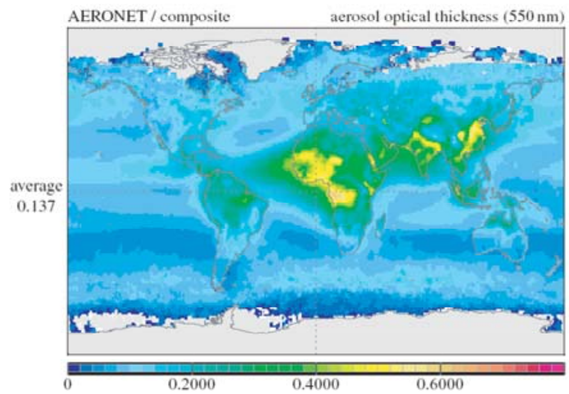

Figure 2. Global distribution of atmospheric aerosols represented as aerosol optical thickness, i.e. the extinction of sunlight by atmospheric aerosols. The image was obtained by merging data from several satellite sensors with ground-based sun photometer measurements (figure courtesy of Kinne 2006, personal communication).

Andreae, 2007, Phil Tran Roy Soc A

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What is the value of tau? Globally it is about 0.137 for light in the 550 nm wavelength. Maps show spatial variation as aerosols from biomass burning, air pollution, moisture can alter tau.

The transmissivity, τ, is determined by integrating the mass absorption (k) and scattering coefficients (s) across the depth of the atmosphere

$$\tau(\lambda) = \int_0^Z \rho(k(\lambda) + s(\lambda))dz$$

$$\tau(\lambda) = \tau_{o_3}(\lambda) + \tau_{h_2o}(\lambda) + \tau_{Rayleigh}(\lambda) + \tau_{aerosols}(\lambda)$$

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What affects transmissivity? If photons are absorbed or scattered by media in the path tau will change. Smaller numbers allow more light to pass. Larger numbers attenuate light more.

Light Scattering

$$s = \frac{2\pi r}{\lambda}$$

- Rayleigh Scattering
  - photons strike gas molecules in the atmosphere
    - s ratio is much less than one

- Mie Scattering
  - proportional to the ratio of the molecular diameter
  - Inversely proportional to wavelength, d/l.

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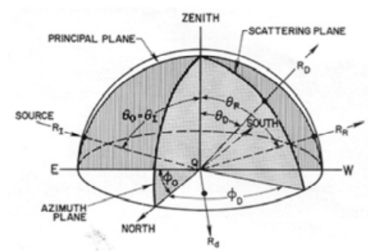
Two types of scattering are dominant, Rayleigh and Mie. Rayleigh is associated with gas molecules. Mie tends to be associated with aerosols and dust

Diffuse Radiation, Energy Integrated over the Hemisphere

$$E = \int_0^{2\pi} \int_0^{\pi/2} R(\phi, \theta) \cos\theta \sin\theta d\theta d\phi$$



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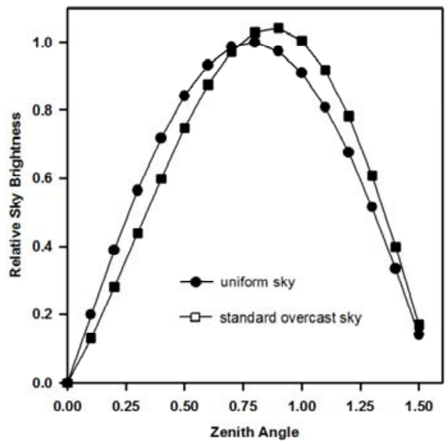
How to assess isotropic diffuse radiation. It is simply the integral across the hemisphere of light coming from each sky sector. Here theta is elevation angle and phi is azimuth angle sky brightness for a uniform and standard overcast sky

$$\frac{R_d(\gamma)}{R_d} = \frac{6}{5}(1+\sin\gamma)\cos\gamma\sin\gamma$$



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It is not perfectly isotropic, so there will be differences in sky brightness.

Global Dimming

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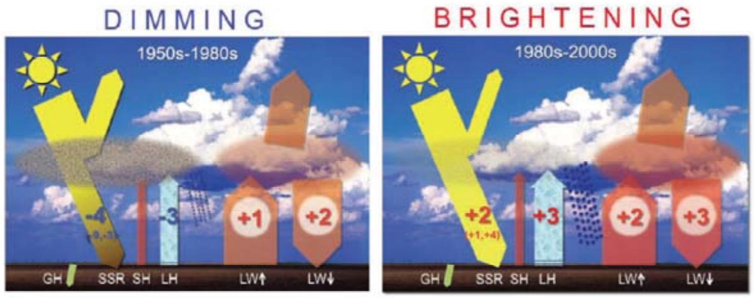
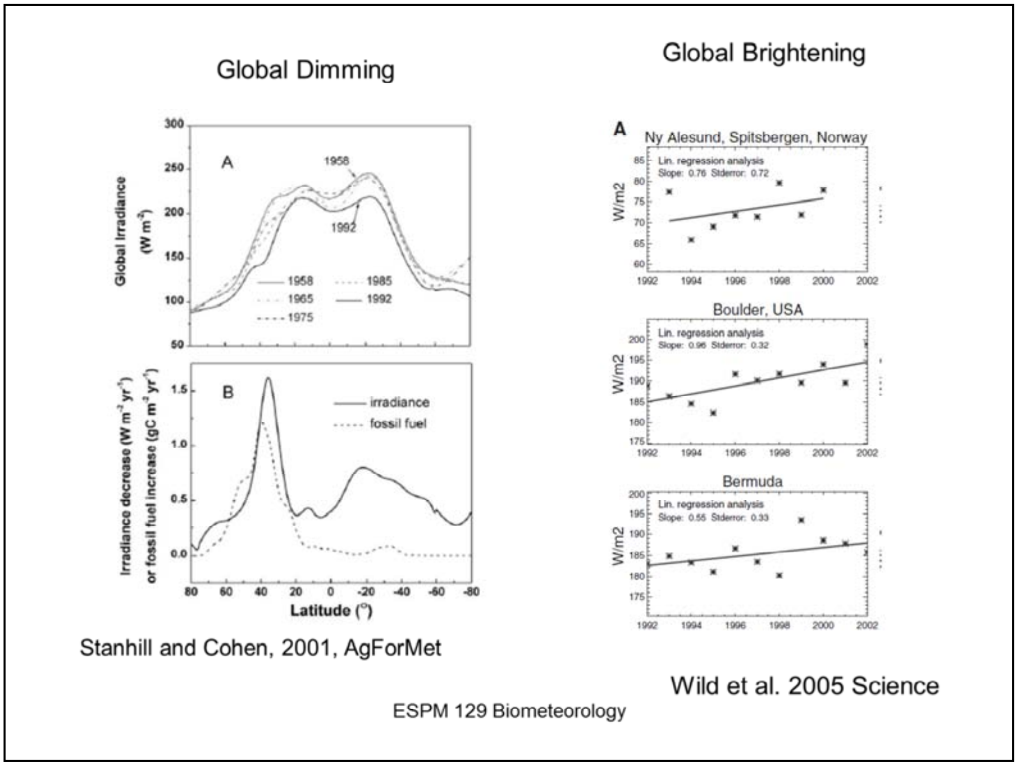
Global dimming has been a topic of interest in recent decades. As pollution levels increased there was a dimming observed. Yet, with the clean air act and attempts to reduce pollution, there has been a recent reverse.



Wild 2012 BAMS

Cartoon showing the relative flows of energy under a dimming and brightening sky.
Wild 2012 BAMS



Stanhill and Cohen and Omura et al were among the first to detect global dimming. It was clear associated with large emission of sulfur from fossil fuel combustion. The brightening is good news from the standpoint that pollution is lessening. On the other hand, more solar radiation at the surface is a warming agent, in step with greenhouse gas effect.

Infrared Radiation:
Kirkoff's Law

A black body radiator is defined as a surface that perfectly absorbs, α, and emits, ε, radiation

$$\alpha(\lambda) = \varepsilon(\lambda)$$ Absorptivity equals emissivity

$$\rho(\lambda) = 1 - \varepsilon(\lambda)$$ Reflectivity equals 1 minus emissivity

$$\tau(\lambda) = 0$$ Transmissivity is zero

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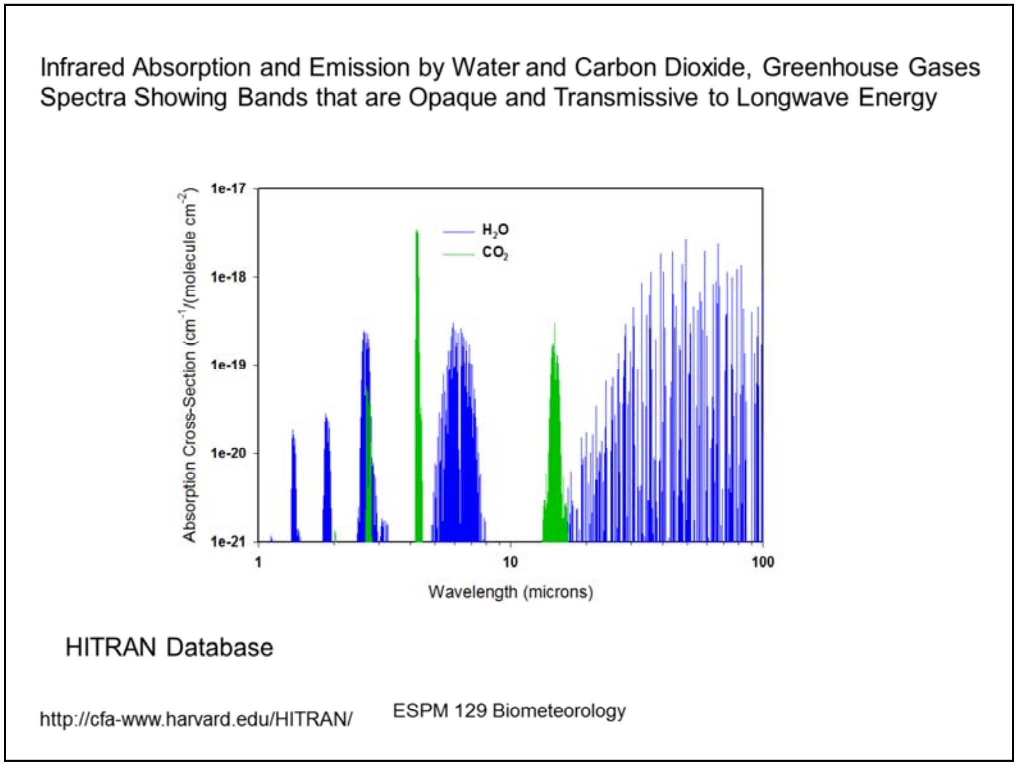
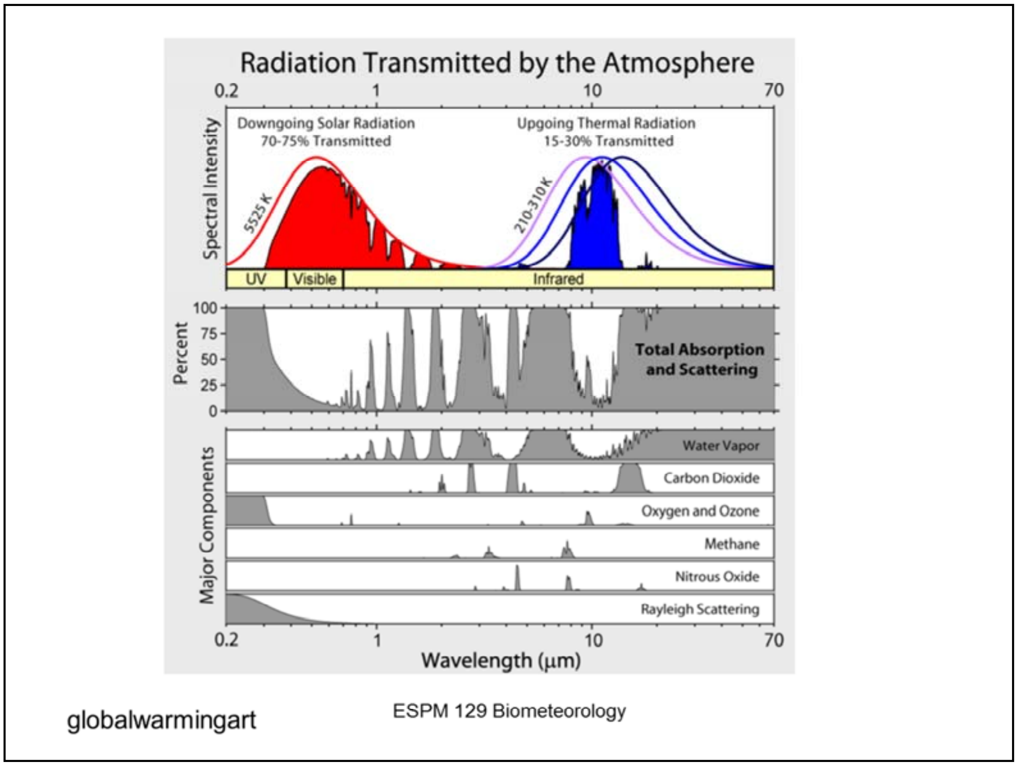
Next we focus on Longwave, infrared or terrestrial energy. This is energy whose spectrum ranges between 3 and 100 microns. It is the energy emitted by the earth, the sky and clouds. Surfaces are dark in the IR band so radiation is only absorbed and emitted. Typically the amount of energy absorbed equals that emitted..Kirkoff's law

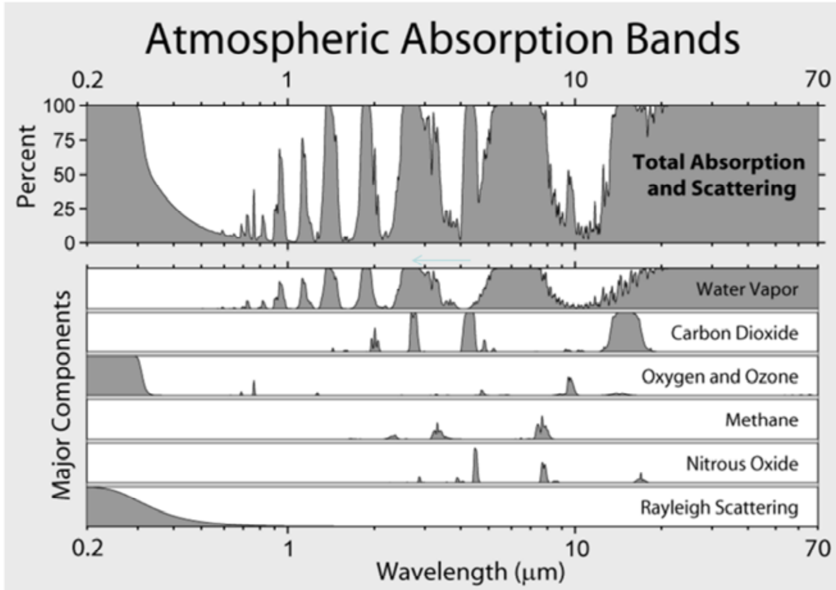


Many trace gases, known as greenhouse gases absorb and emit radiation in the bands of the longwave or infrared radiation



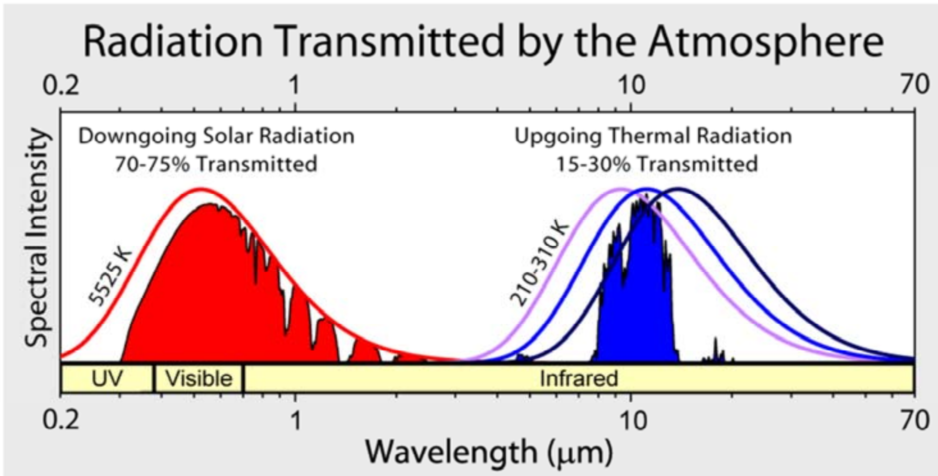
This figure shows the spectral bands where infrared radiation is lost to the sky and the bands where gases like water vapor, carbon dioxide, methane, ozone and nitrous oxide absorb and re-emit radiation.

Atmospheric Windows and Absorption Bands



Globalwarmingart

Longwave Energy is Transmitted through Windows.
More Greenhouse gases, with absorption properties in those wavebands
Will act to absorb and re-radiate energy to the Surface, thereby Warming the Surface



www.GlobalwarmingArt.com

Stefan-Boltzmann Redefined:

Longwave Energy Emitted is a function of Surface Temperature to the 4th power

$$L\uparrow = \varepsilon \sigma T^4$$

Energy emitted is a function of emissivity, ε, 0–1

Not all surfaces are perfect black bodies. Hence we must multiply the Stefan Bolzmann relation by emissivity. Emissivity is unitless and ranges from 0 to one.

List of Infrared Emissivities

Surface	Emissivity
Plant leaves	0.94-0.99
Glass	0.90-0.95
Aluminum	0.06
Aluminum paint	0.30
Soil	0.93-0.96
Water	0.96

Campbell and Norman, 1998

Surfaces like aluminum have a low emissivity. Note on a sunny day, they feel ‘cool’ compared to other surfaces. Yet, once they do warm, it takes longer for them to cool down and radiate to the sky. Most biometeorological surfaces are close to being black bodies and have emissivities greater than 0.9.

Outgoing Longwave Energy of Surface Energy Budget

$$L\uparrow = \varepsilon\sigma T_s^4 + (1-\varepsilon)L\downarrow$$

radiated reflected

Energy emitted by the Surface Plus that Reflected
if Emissivity is less than one

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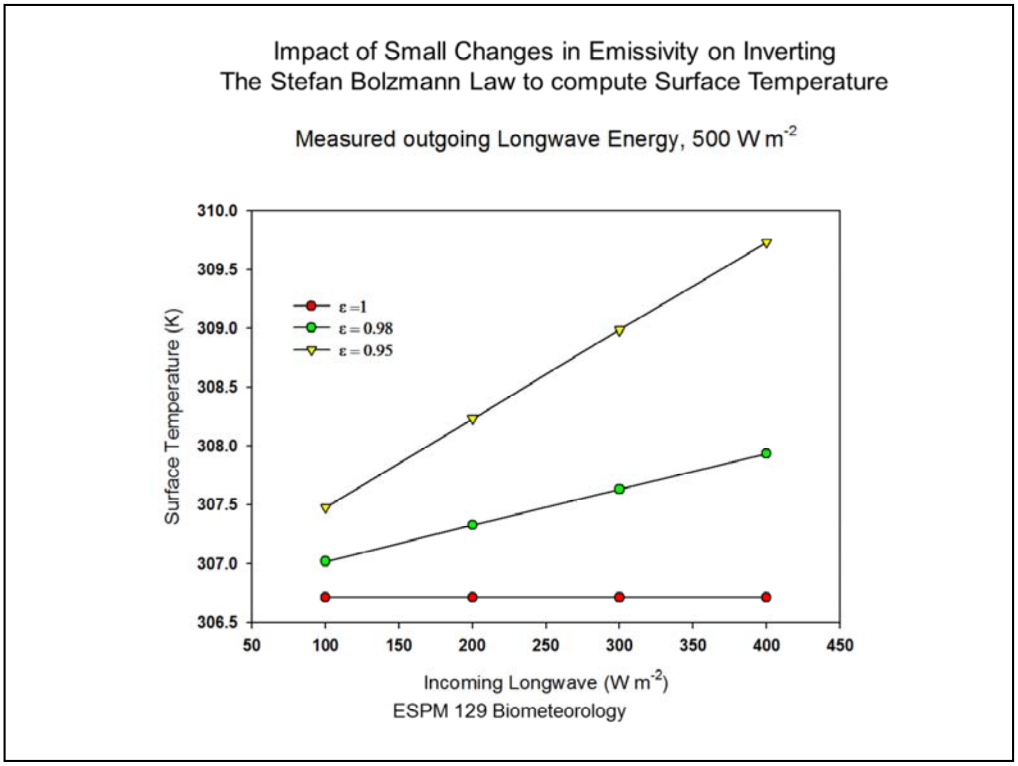
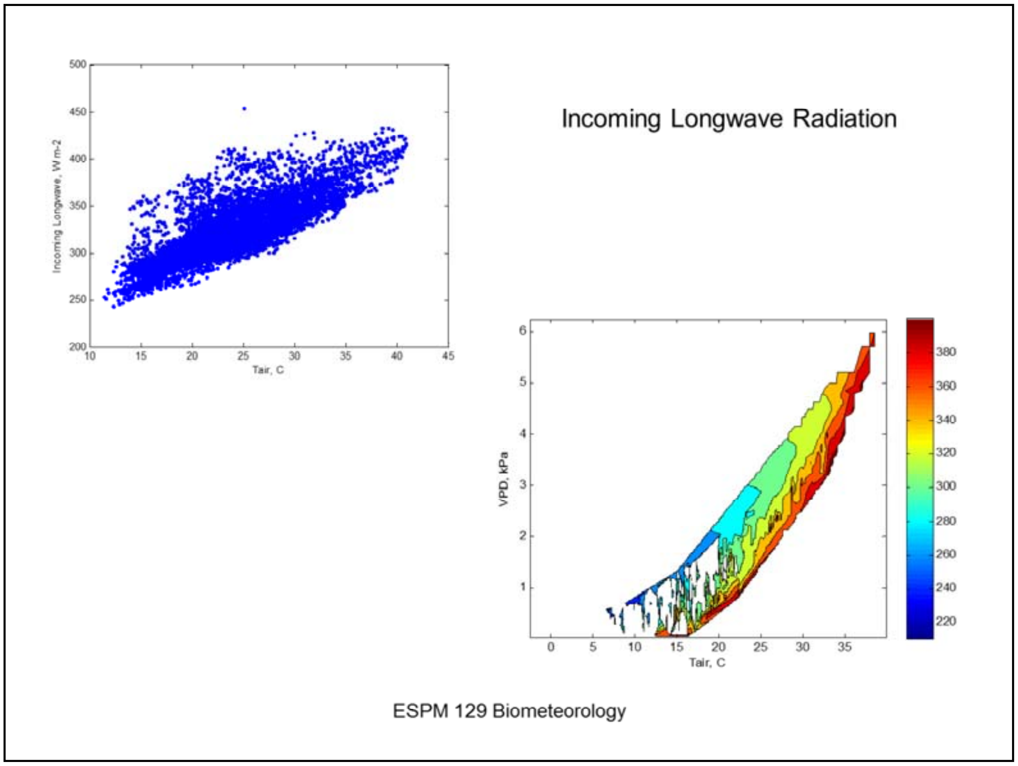
If a surface is not perfectly black, the longwave energy lost is the sum of that emitted, as a function of surface temperature to the fourth power, plus that reflected. This equation is very important if one wants to estimate the surface temperature by measuring its infrared signal.



Science is an art, too. Sometimes small differences in a key parameter can magnitude the effect of the desired quantity you want to measure or infer. This is truly the case with measuring the radiative temperature of the surface. A 3 K error in radiative temperature can occur through differences in emissivity between 0.95 and 1.0

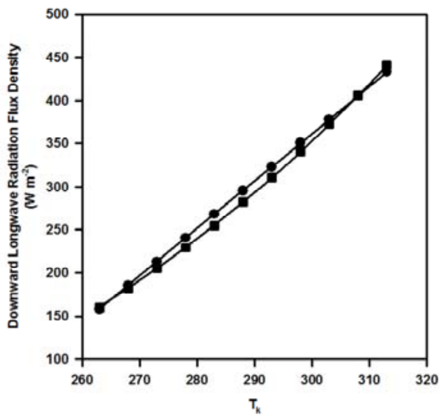


Here are measurements of incoming longwave radiation measured in eastern California, near Ione.

Computations of infrared flux density as a function of temperature

$$L\downarrow = -119 + 1.06\sigma T_a^4$$

Monteith and Unsworth, 1990



$$L\downarrow = 5.31 \cdot 10^{13} T_a^6$$

Swinbank

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For energy balance estimations we want to know how much longwave energy is being emitted by the sky to the ground. This can be inferred with some simple temperature dependent equations.

Brunt Equation

$$L\downarrow = \varepsilon_a \sigma T_a^4$$

Sky emissivity is f() vapor pressure, ea, temperature, T, and Precipatable water, p

$$\varepsilon_{sky} = 1.72\left(\frac{e_a}{T_a}\right)^{1/7}$$

$$\varepsilon_a = a + b(\ln(p) + 0.5)$$

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Empirical models for sky emissivity are a function of humidity and air temperature

Net Radiation Balance!!!

$$R_n = R^{\downarrow} - R^{\uparrow} + L^{\downarrow} - L^{\uparrow}$$

Net Radiation Equals
Incoming Solar Radiation Minus Reflected
(or Incoming Solar radiation times One minus Albedo, ρ),
plus Longwave In, minus Longwave Out

$$R_n = (1 - \overline{\rho})R_g + L \downarrow - L \uparrow$$

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Here is where the rubber meets the road. We pull all the ideas together of short and longwave energy and that incoming, outgoing and reflected to define the surface energy balance.

Net Radiation Budget

$$R_n = (1 - \overline{\rho})R_g + \varepsilon L \downarrow - \varepsilon \sigma T_s^4$$

The Net Radiation Budget is a function of Surface Temperature, Ts, to the fourth power

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Simplified version of the net radiation balance.

Summary

- Longwave emission of energy is proportional to its emissivity, as defined by Kirkoff's Law
- The net radiation balance is a equal to the sum of incident solar radiation minus the fraction reflected (albedo times incoming solar radiation) plus incoming longwave energy minus the energy emitted from the surface that is proportional to its temperature to the fourth power.
  - The Net Radiation Balance is one of the Most Important Concepts Taught, and Learned, this semester. Later We will study how this energy is Used