Today's Topics

General Introduction to Radiative Energy Budget

- Key characteristics
  - Key considerations in a radiation budget
  - Types of radiation
  - Annual cycle
  - Examples of the global budget

Considerations in the Radiative Budget

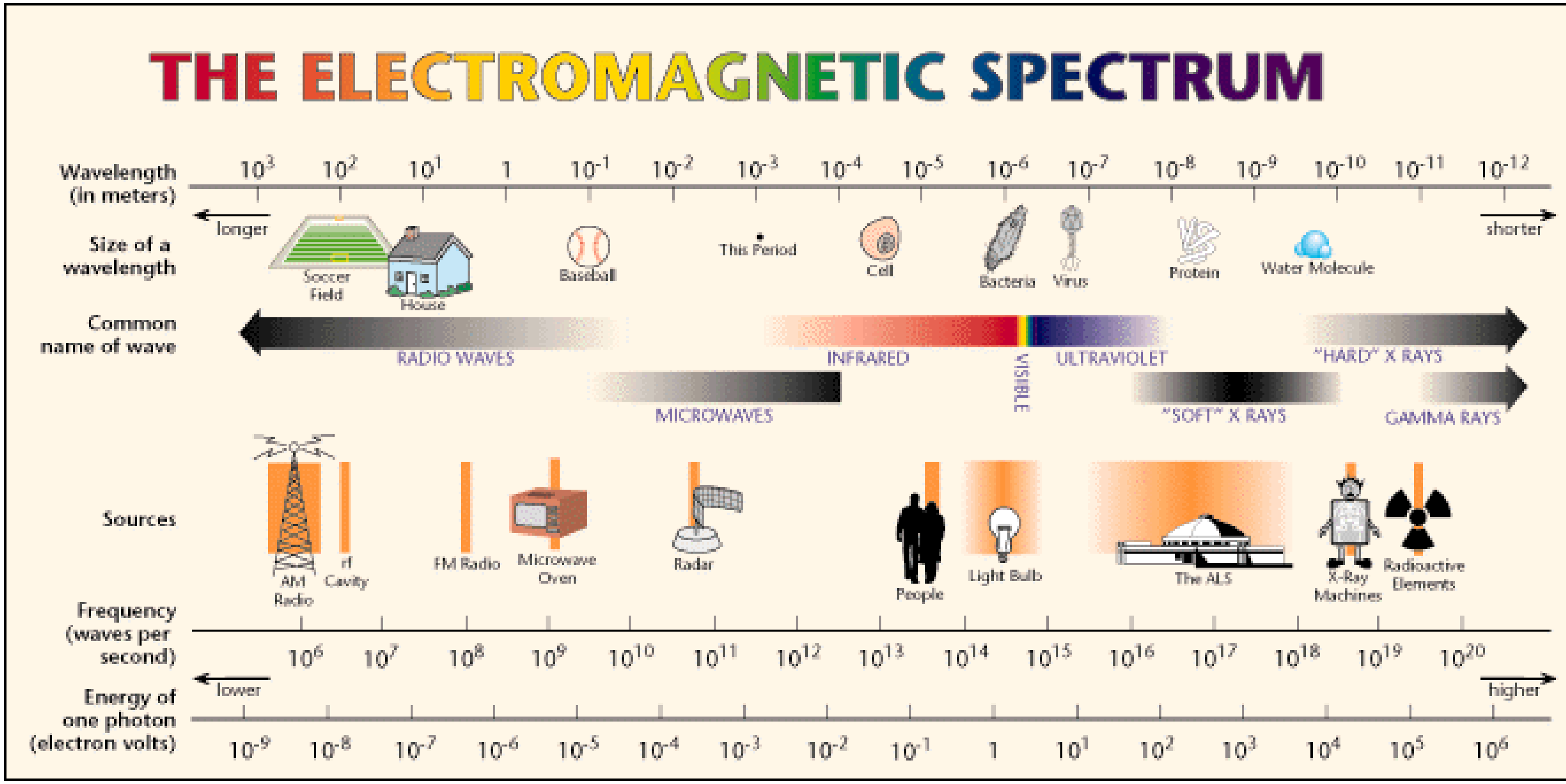
- Components of ‘Net’ radiative transfer
  - Long wave (terrestrial) vs. Short wave (solar)
  - Upwelling vs. downwelling
- Radiative flux through the top of the atmosphere
  - Variability in solar radiation reaching the earth
  - Impact of atmospheric constituents
- Radiative flux at the planet’s surface
  - Passage through the atmosphere, and emission by the atmosphere
  - Direct vs. Diffusive Radiation
  - Reflectivity and Albedo
- Net energy budget.

Components of Net Radiative Transfer

- Solar Radiation
  - Emitted from very hot bodies (e.g., the sun, red or white hot objects)
  - Relatively energetic (short wavelength) photons
  - Spectrum includes visible light and shorter wavelengths
- Terrestrial Radiation
  - Emitted from objects at typical earth-like temperatures
  - Relatively non-energetic (long wavelength) photons
  - Spectrum includes infra-red and longer wavelengths

- $E = h\ \nu$ — E = Energy per photon;
- $c = \lambda\ \nu$ — h = constant; ν = frequency
- $E = h\ c / \lambda$ — c = speed of light; λ = wavelength

The Spectrum



Note: 1eV (electron volt) = $1.6 * 10^{-19}$ J

Acquired from

http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

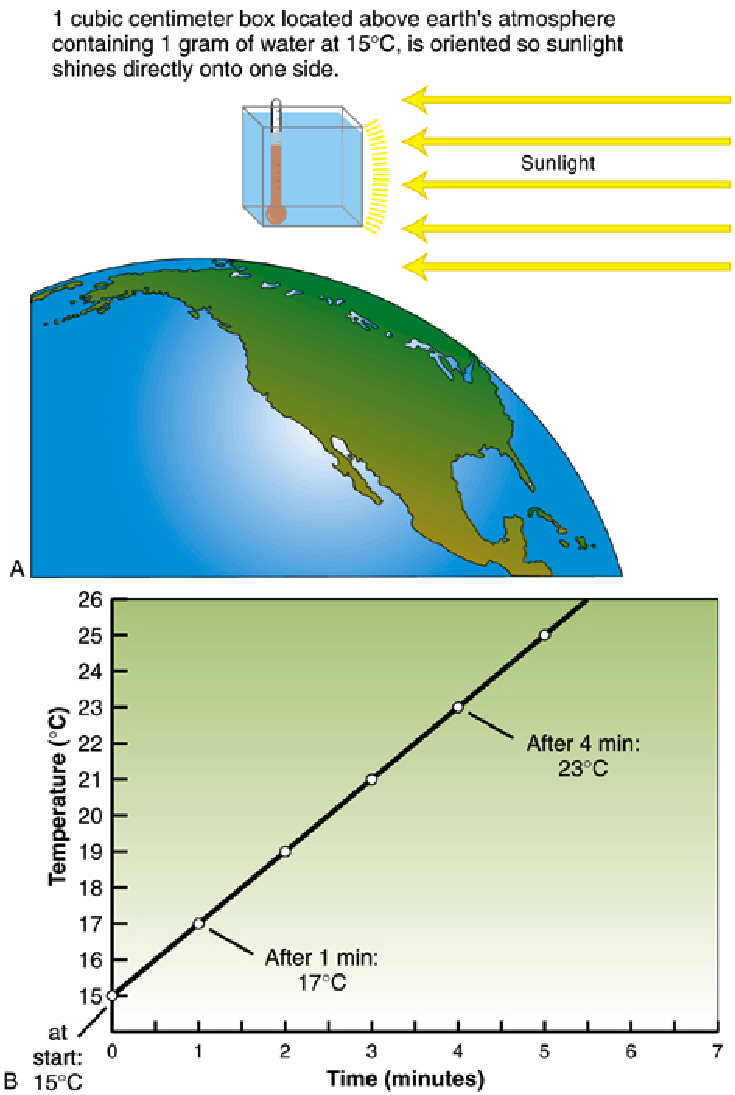
(I recommend this site for more information)

Upwelling and Downwelling

- We are usually interested in the flux density of radiative energy through a surface that is parallel to the mean surface.
  - A flux density (often referred to as flux in meteorology and oceanography) is the rate of energy that passes through an area or surface.
  - The units of fluxes are usually $J\,m^{-2}\,s^{-1}$ or $W\,m^{-2}$.

- Electromagnetic energy can pass through the above surface from either side.
  - From an Earth-centric point of view:
    - Solar radiation is typically moving down (downwelling)
    - Terrestrial radiation has substantial components moving up and down
  - Net radiative flux includes: upwelling short-wave (assumed to be small), downwelling short-wave, upwelling long-wave, and downwelling long-wave.

Conversion of Solar Radiation to Heat



- Consider a cube of water ($1cm^3$), floating is space at the same distance from the sun as the earth.
- Assume that $1cm^2$ surface area is exposed to the sun's energy.
- Assume that the sun's radiations (intercepted by the cube) are moving parallel.
  - The flux of energy is about 1365 Wm^{-2}
- Assume that no energy escapes.
- Using our knowledge of thermodynamics, we can estimate the rate at which the thermal energy of the cube increases.
  - 1.96°C increase per minute!

Graphic from *Meteorology* by Danielson, Levin and Abrams

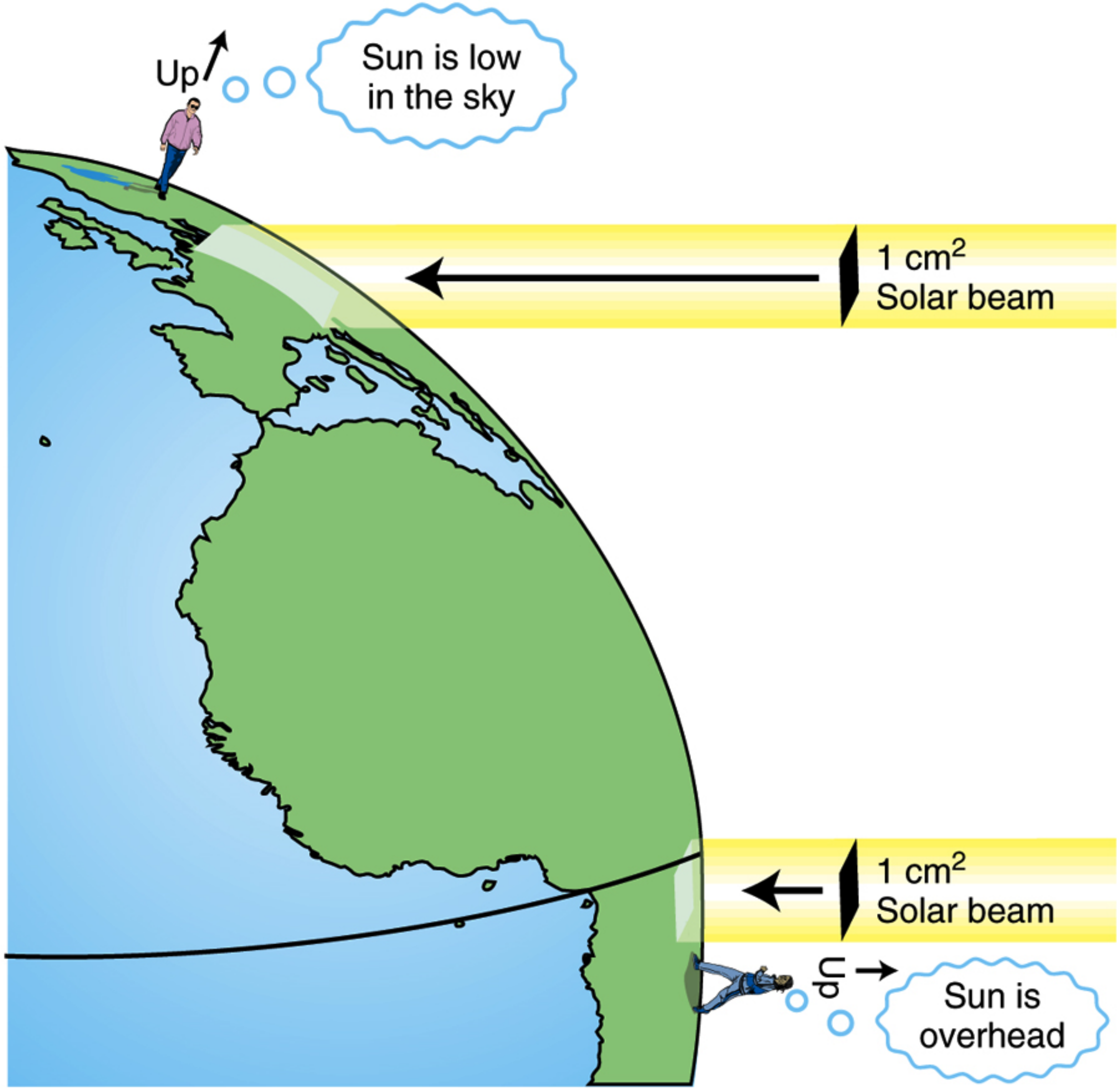
Insolation (Incoming Solar Radiation)

- Insolation is the incoming solar radiation at the top of the atmosphere.
- It is the amount of energy, per unit area (perpendicular to surface) per unit time.
  - At solar noon, the value of insolation is approximately 1365 Wm^{-2}.
    - This term is also know as the solar constant.
  - There are a small range of published values near this value: there is some uncertainty in the average.
- Energy [J] per unit time [s] is also know as Power [W].
- The rate at which something (e.g., energy) passes through or into something is called a flux (units of the quantity being input per unit time, e.g., Js^{-1}).
- The flux per unit area is correctly called a flux density. A good example is the insolation.
  - Caution: most meteorology and oceanography texts use the term flux when referring to a flux density.

What Influences Surface Temperature?

- There are many things that influence the surface atmospheric temperature.
  - Two obvious considerations are the input of energy into the earth system, and the output of energy from this system.
  - In the long-term (multiple years) these must be approximately balanced for a nearly steady state system. Why?
    - The amount that is input is a function of the fraction that is reflected (reflectivity) back into space.
    - The amount that is emitted (output) into space is a strong function of the **temperature** of the 'exposed' emitters (the surface, clouds, and constituents of the atmosphere).
- The atmosphere's temperature (at all levels) is also modified by how much energy can be kept within a layer.
  - This consideration is particularly complicated in areas with rapidly changing cloud cover!

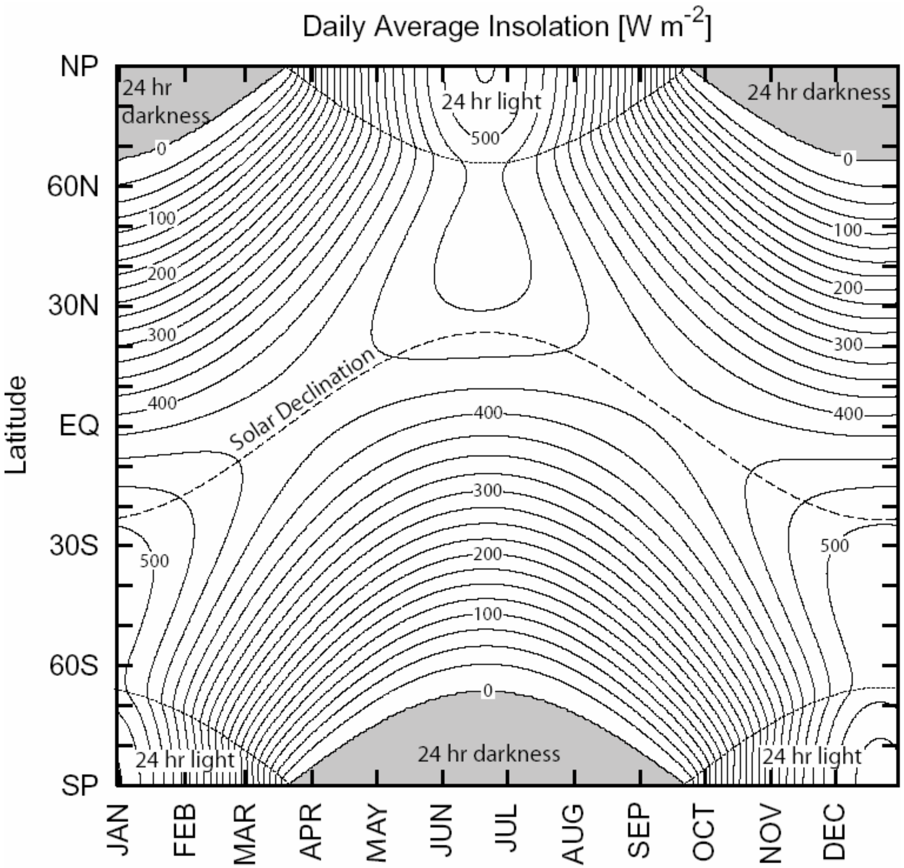
Solar Incidence Angle (round earth perspective)



- Recall that solar radiation reaching the top of earth's atmosphere can be thought of as moving in parallel.
- The surface of the earth, and the top of the atmosphere are curved.
- Solar radiation, passing though a unit area perpendicular to it's direction of travel, is projected onto the earth's surface.
- The angle at which the sunlight strikes the earth depends on latitude and season.

Graphic from *Meteorology* by Danielson, Levin and Abrams

Incoming Solar Radiation at the Top of the Atmosphere

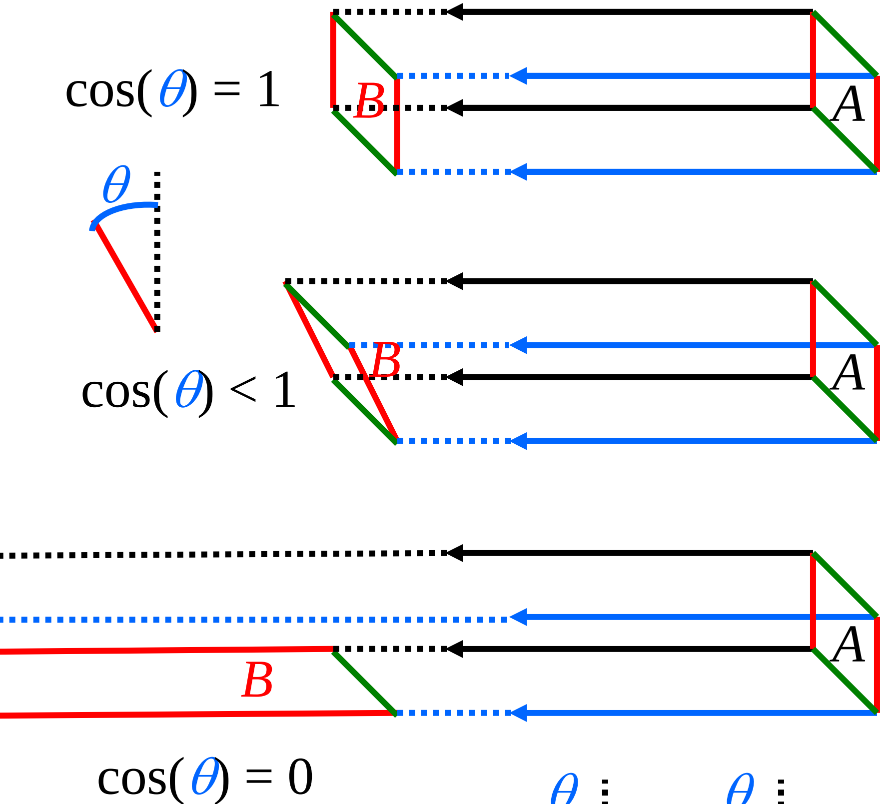


- Function of Latitude and season
  - Distance from the sun (season)
  - Tilt of the surface (season and latitude)
- Value of solar radiative flux density, at the mean orbit of the Earth is ~1365 $W m^{-2}$

Solar irradiance on a horizontal surface outside the Earth's atmosphere [$W m^{-2}$] from Smithsonian Meteorology Tables (1966). The values are 24 hour means – why do I say this?

Graphic from A First Course in Atmospheric Radiation by G. W. Petty

Flux Density of Solar Radiation at the Top of the Atmosphere



A = Area perpendicular to direction the radiation is moving.

B = Area on a surface intersecting the radiation.

θ = Difference between the angle normal to the surface and the direction the radiation is moving

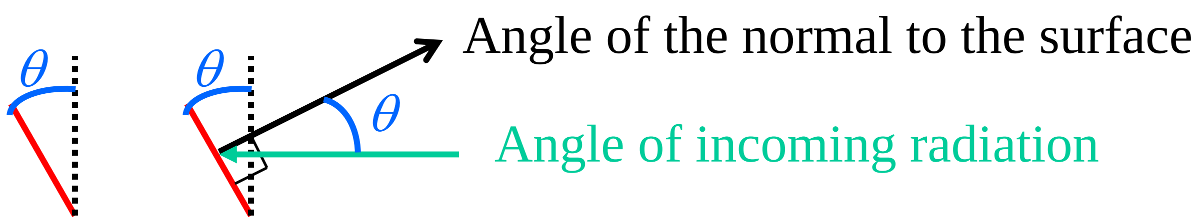
$B = A / \cos(\theta)$

- If R is the radiative flux through A, then the flux on the surface (F) is

  $F = R$

- For Flux densities (F' and R')

  $F' = F / B = (R / A)\ \cos(\theta)\ = R'\ \cos(\theta)$



Seasonal Change

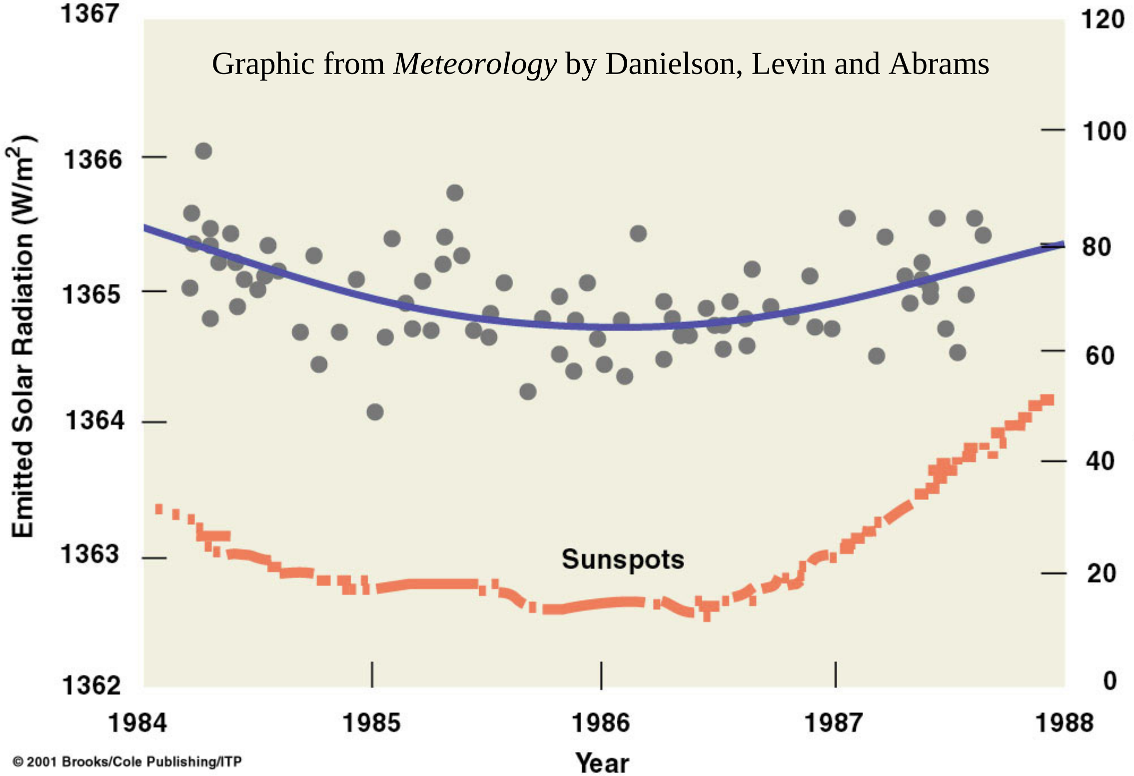
- The energy flux (F) from the sun can be estimated by multiplying the flux density (S, aka the solar constant) at a mean radius (R) by the surface area of a sphere at that radius. Note that this value of S applies only to the mean distance from the earth to the Sun. The insolation varies as a function of distance (R) from the Sun.

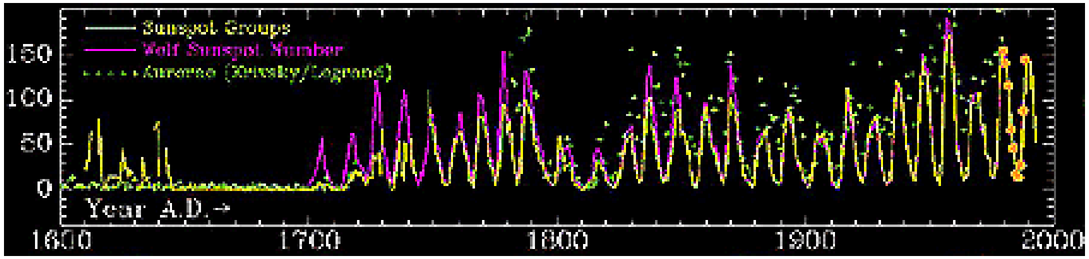
  $$F = S\, 4\, \pi\, R^2$$

- F is constant – it does not depend on R.

Solar Activity and the Solar 'Constant'

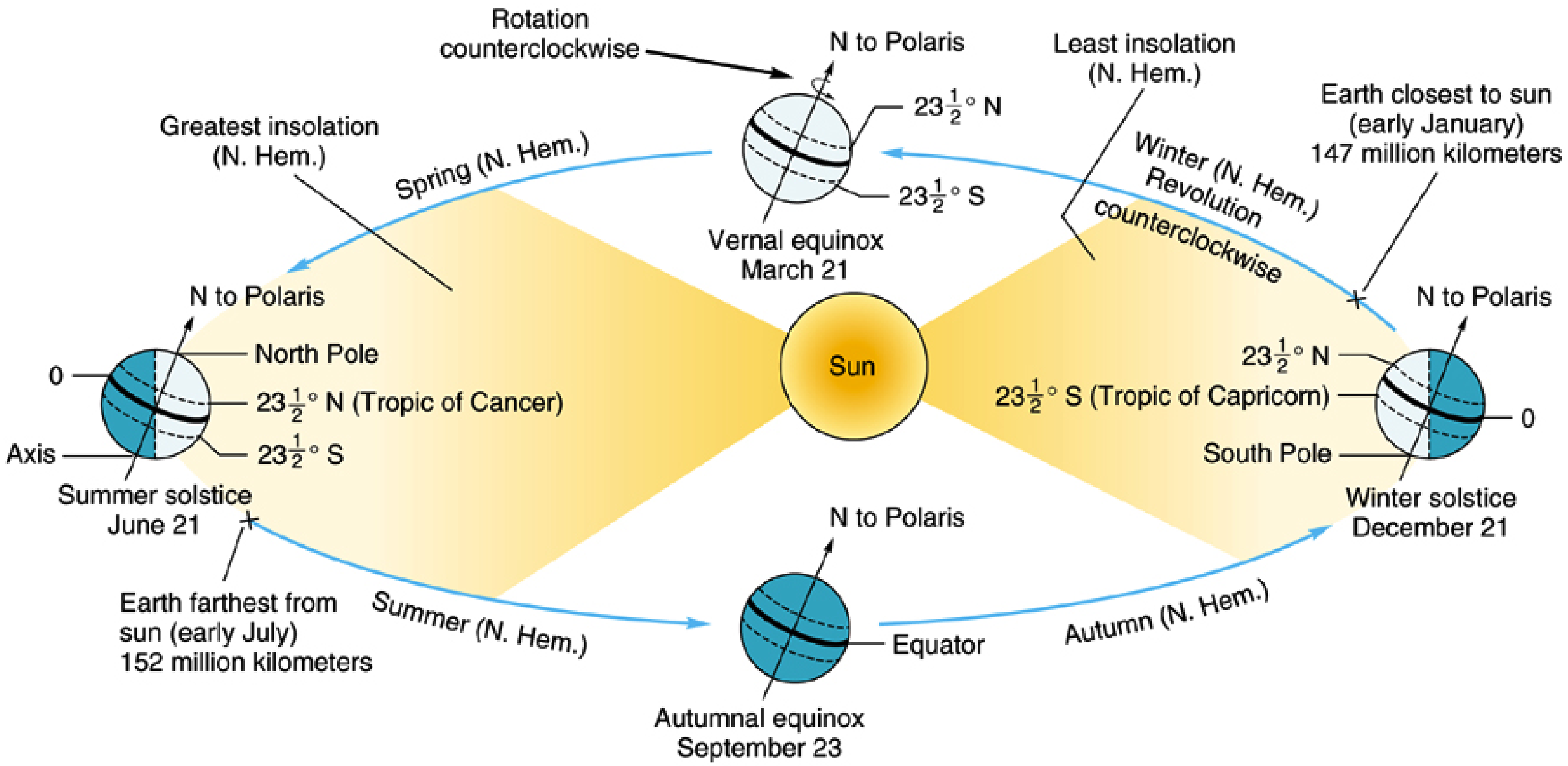
- Sunspots are huge magnetic storms on the sun that show up as (cool) dark spots
- Sunspots change the solar energy output
  - Bright areas around spots make up for lost energy
  - Change is around 0.1% (1 Wm^{-2})
- Sunspot cycle is 11 years long
- Long periods with few observed sunspots match long cold periods.





Graphic from http://astro.uni-tuebingen.de/groups/time/slide17.gif

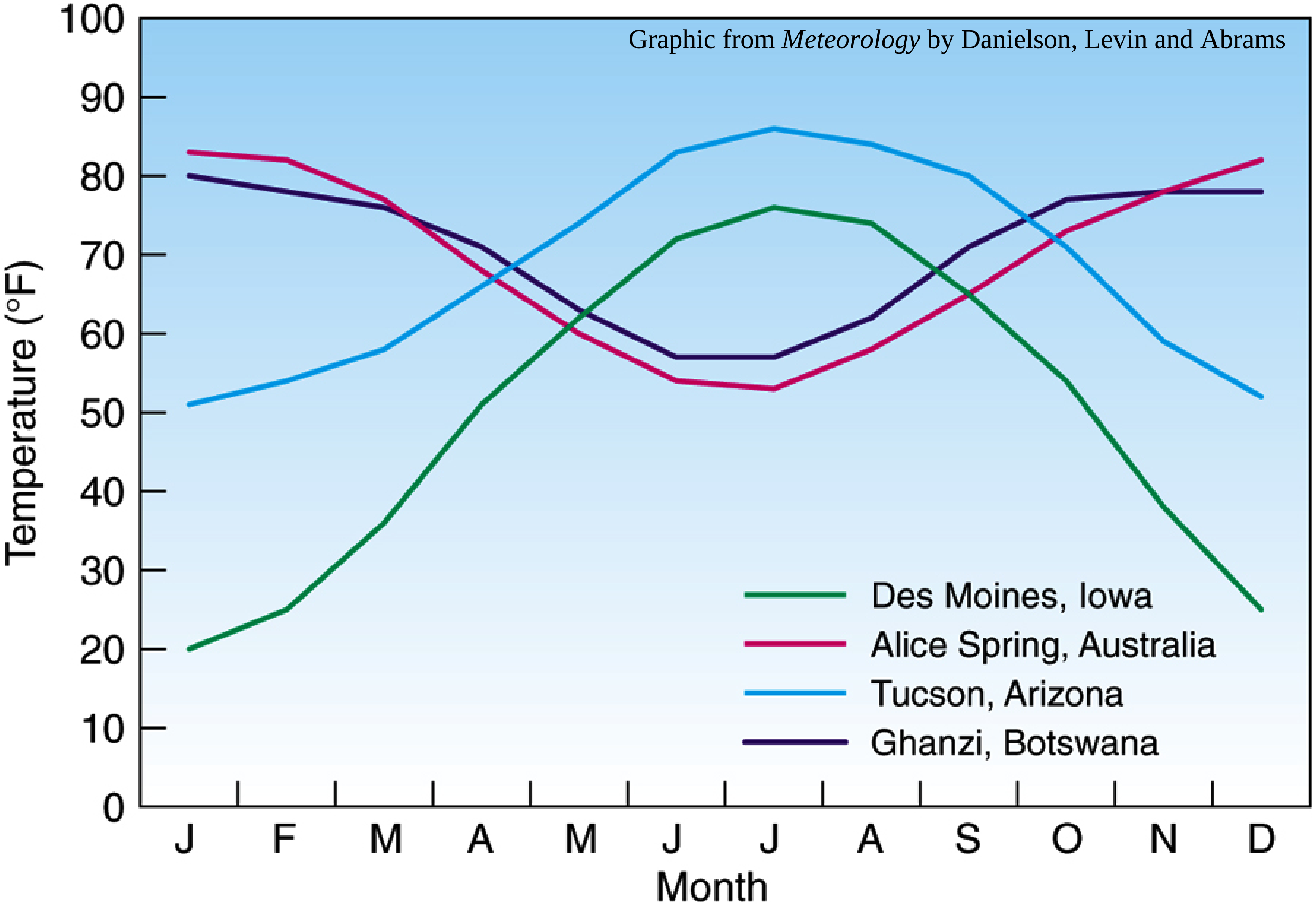
Seasonal Changes in Solar Radiation



- There are two considerations for seasonal change:
  - Distance from the sun (orbits are elliptical rather than circular), and
  - Tilt of the earth's orbit with respect to the direction of incoming solar energy.

Graphic from *Meteorology* by Danielson, Levin and Abrams

Examples of Seasonal Changes in Temperature



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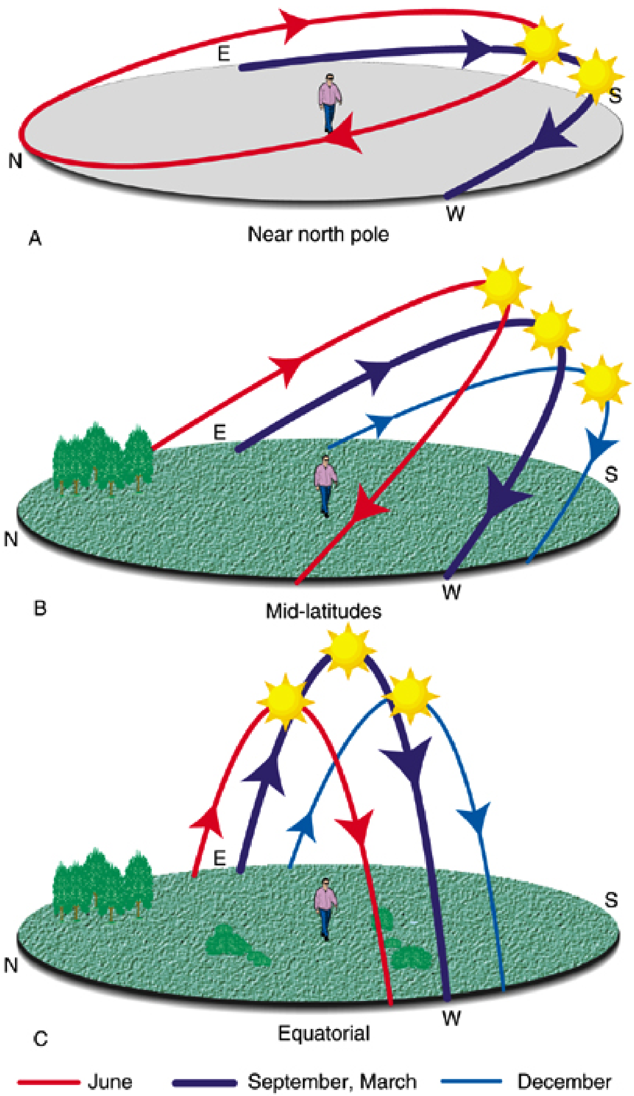
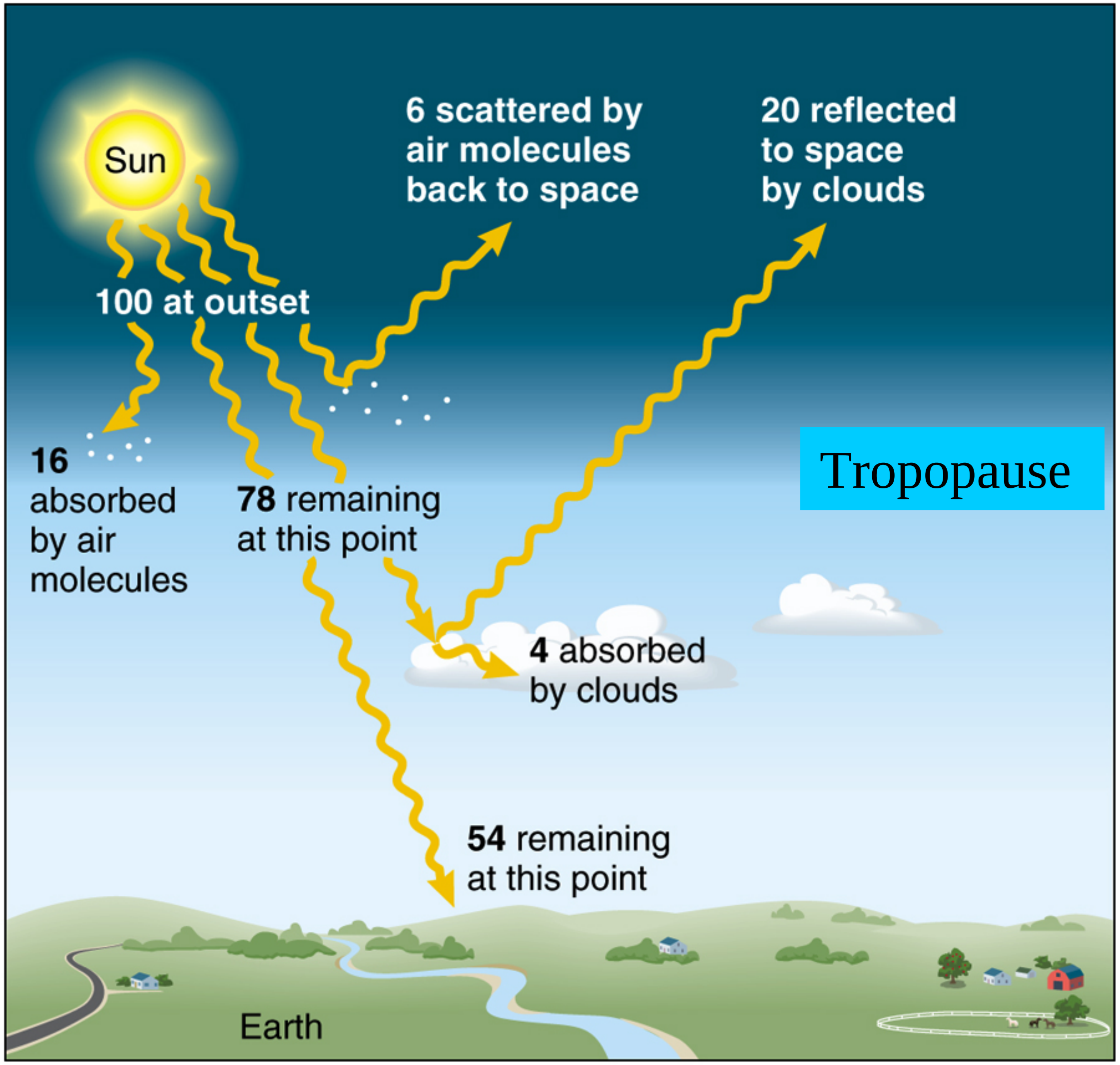
Directions of Sunrise and Sunset



- Does the sun always rise in the East and set in the West?
  - No! Extreme contrary examples occur near the poles, where the sun does not set in Summer or rise in Winter.
  - In mid-latitude Winters, the sun always appear to be somewhat to the South.
- Even at the equator, the sun moves around the East-West axis as a function of season.

Graphic from *Meteorology* by Danielson, Levin and Abrams

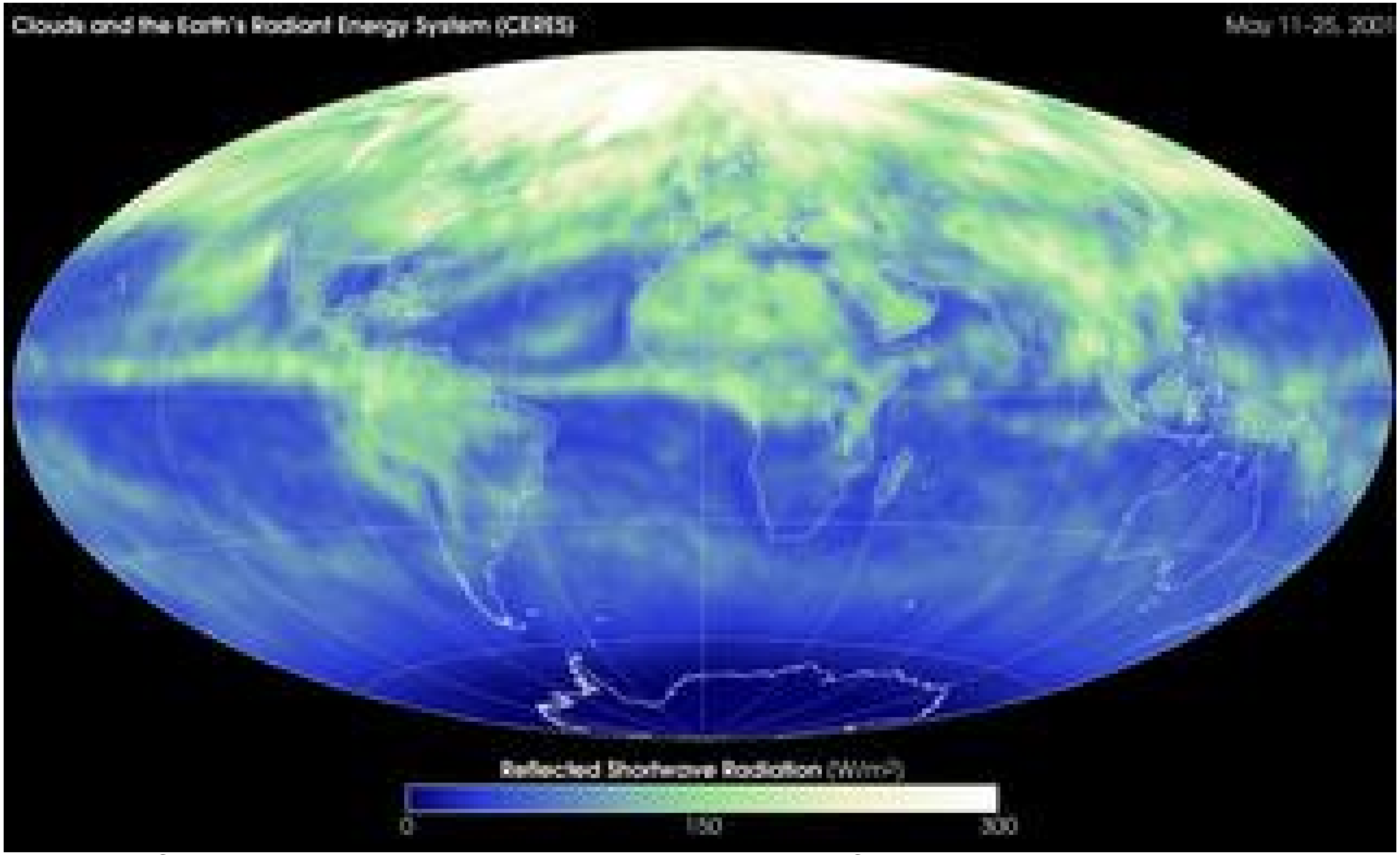
The Earth's Energy Balance, Part I
Solar Energy Fluxes



Graphic from *Meteorology* by Danielson, Levin and Abrams

- Radiation (electromagnetic or otherwise) pass through something is either
  - Transmitted
    - directly or indirectly
  - Reflected
    - Perhaps many times.
    - Afterwards returning to space
  - Absorbed
    - Later reemitted

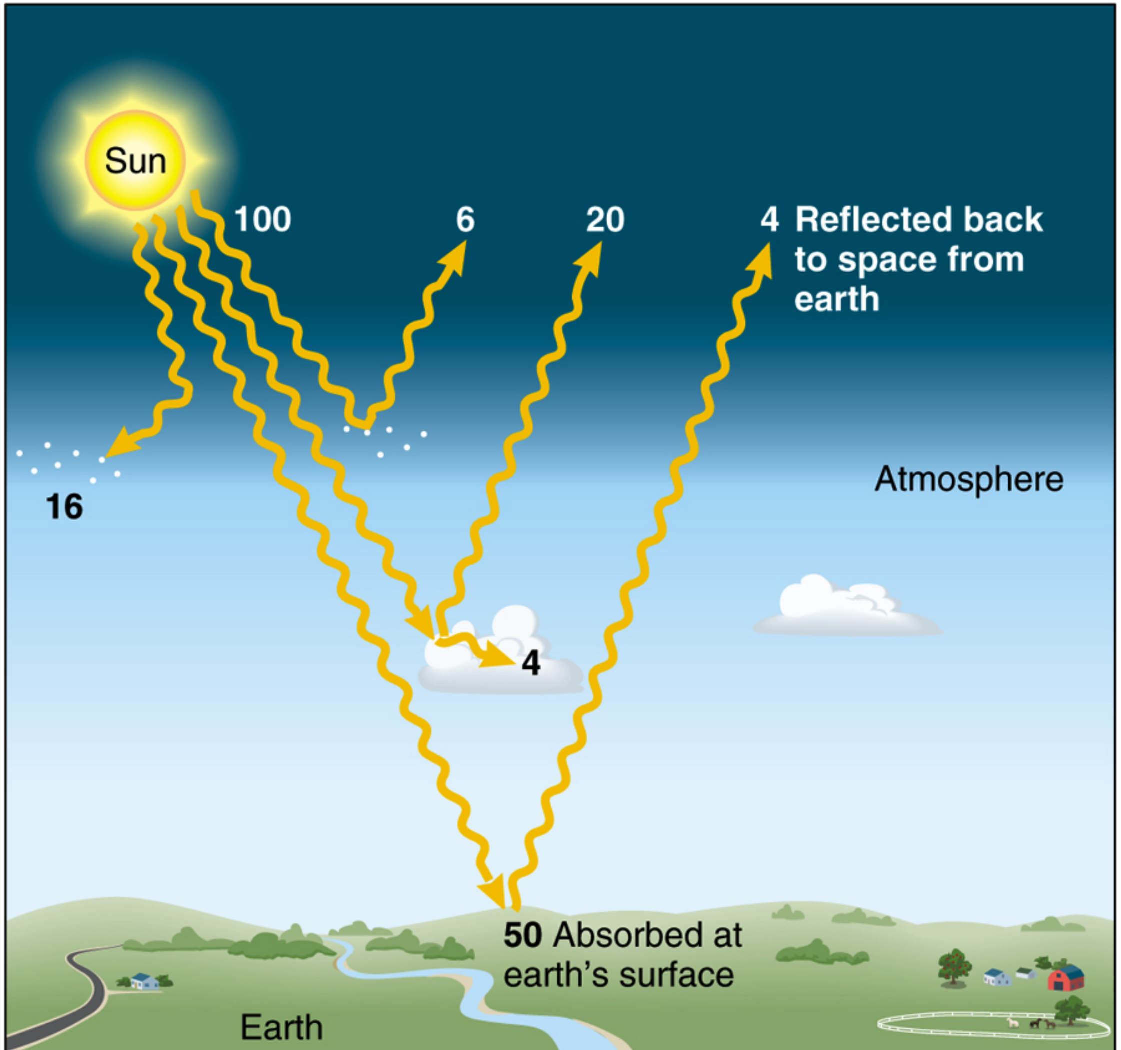
Satellite Estimates of Reflected Solar Radiation



Why does this pattern occur?

- Reflected Solar Radiation, May 25, 2000, from the CERES instrument on the TERRA Satellite (scale from 0 to 300 Wm^{-2}).
- http://svs.gsfc.nasa.gov/vis/a000000/a002300/a002328/

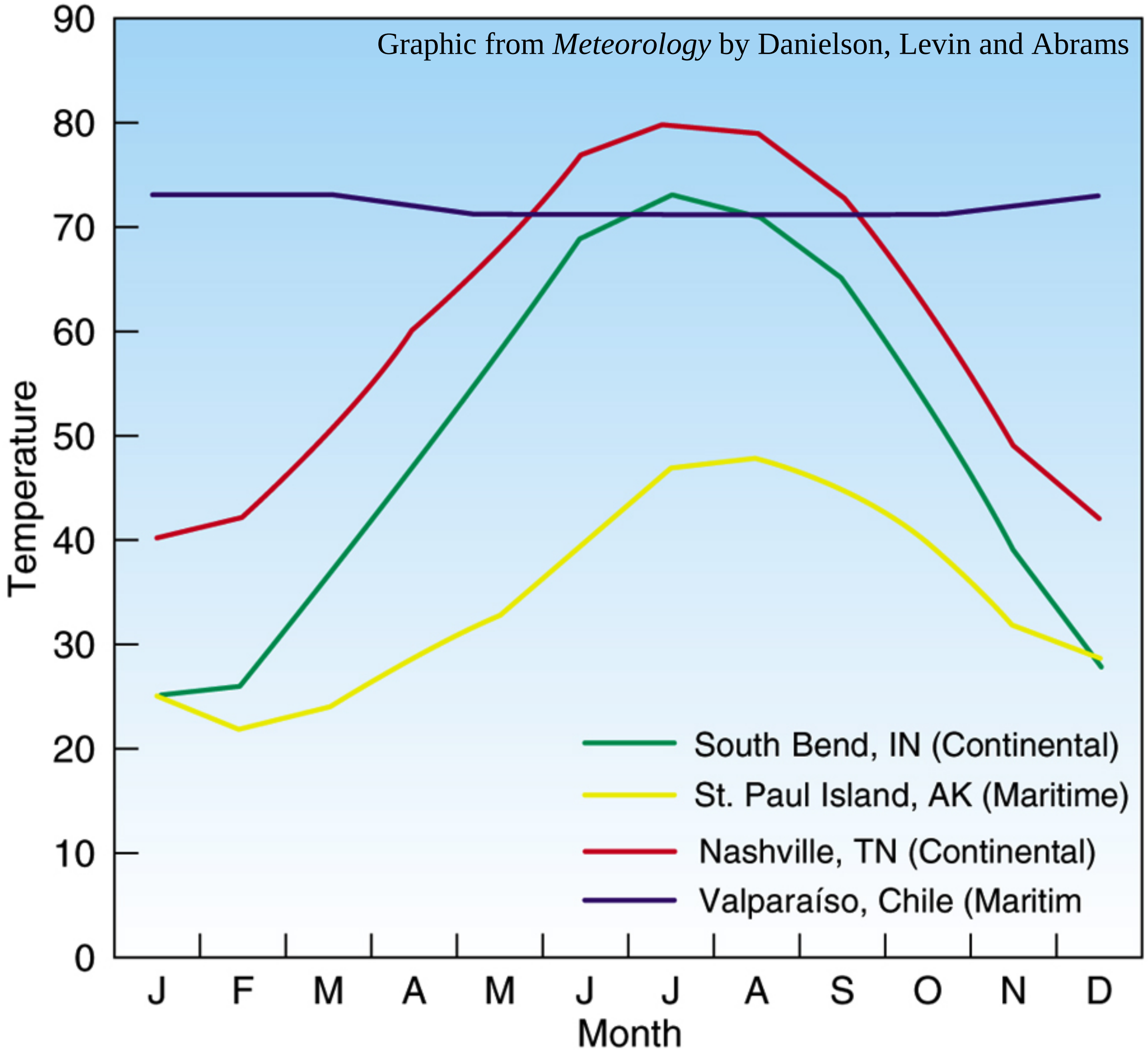
Solar Radiation Reaching The Earth



Graphic from *Meteorology* by Danielson, Levin and Abrams

- Quantify the interactions between radiation and the earth/atmosphere system in terms of the percentage of incoming solar radiation.
- You can also think of the incoming solar radiation as having a quantity of 100 units, where each unit in approximately 13.65 Wm^{-2}.
- 30% of solar radiation is reflected back into space.
- 20% is absorbed by the atmosphere.
- 50% is absorbed by the earth.

Maritime & Continental Temperatures



- Large bodies of water moderates the local and nearby air temperatures.
  - Except when the body of water becomes ice covered!
  - The water has enormous thermal inertia. It can absorb or release great amounts of heat.
- Water cooled to heat the air is usually more dense than surrounding water.
- Wind and night time cooling mix the water.

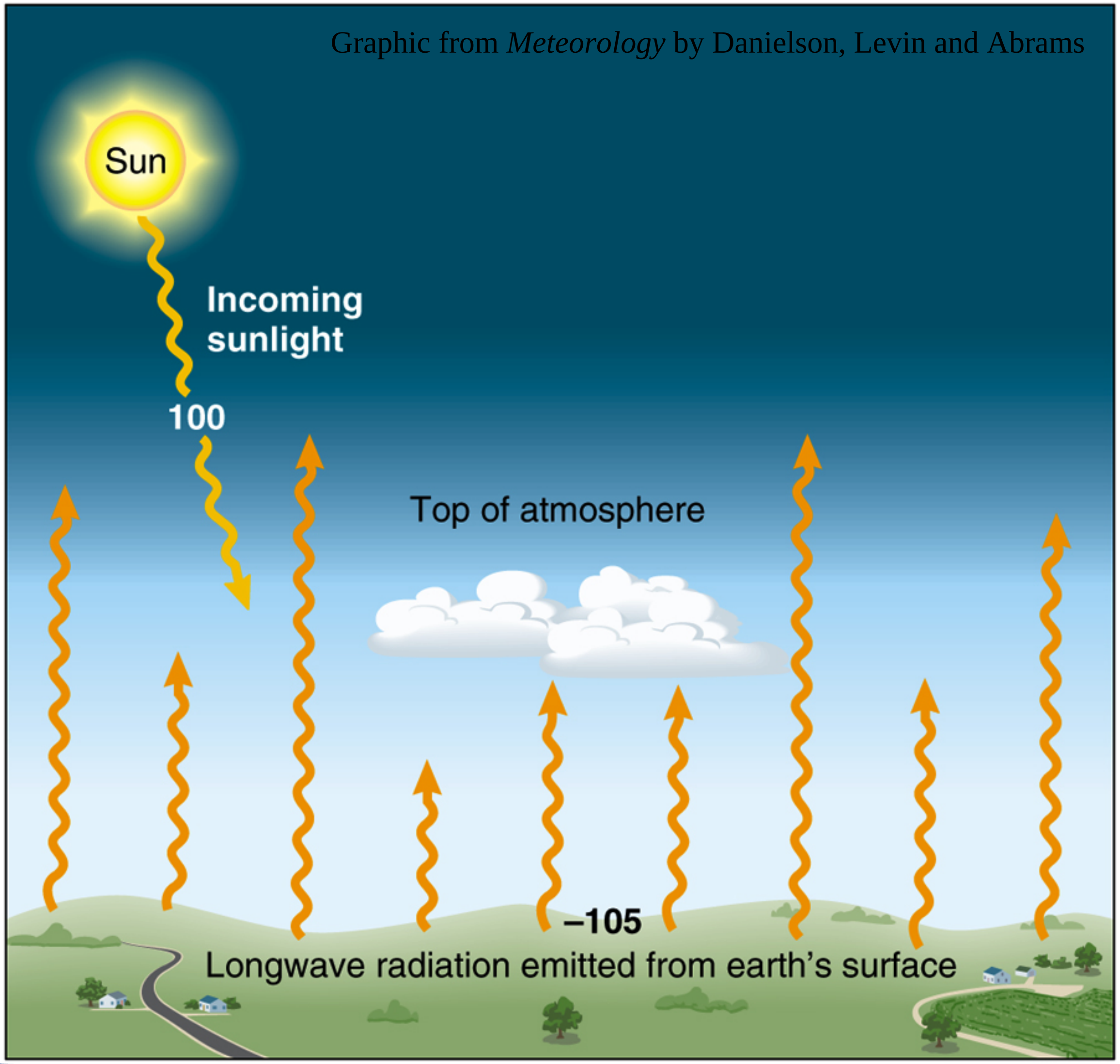
Terrestrial Radiation

Terrestrial radiation can be approximated as being emitted

- If a radiometer (set for the IR band) was pointed up from the surface, it would measure the temperature of emitters (mostly water):
  - Cloud bottoms
  - Cloud sides
  - ‘clear’ sky

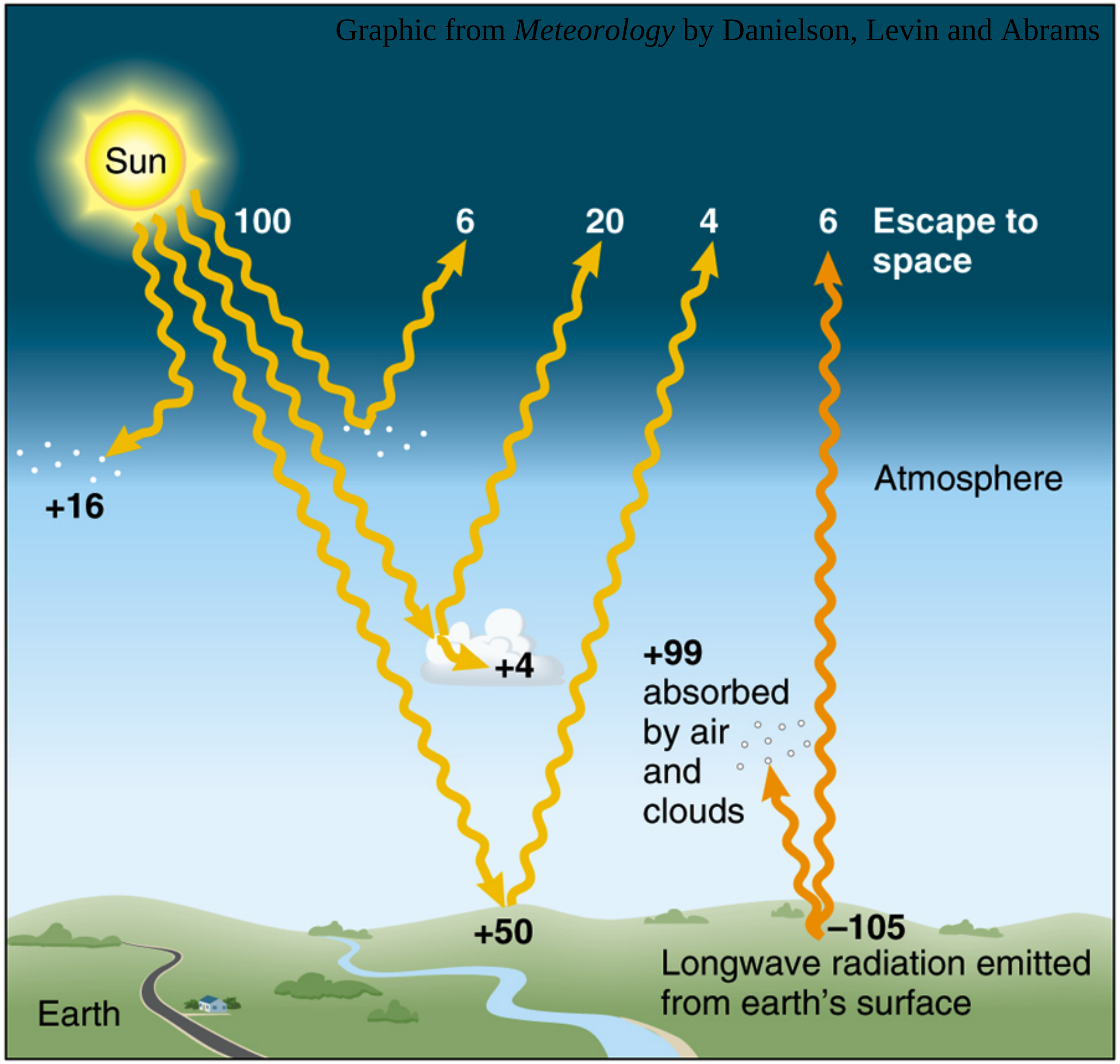
- The radiative flux of a black body is proportional to the fourth power of the temperature of that body (in degrees Kelvin).
  - $I = \sigma T^4$, where σ is the Stephan-Boltzmann constant
    - $\sigma = 5.67 \times 10^{-8}$ $Wm^{-2}K^{-4}$.
  - Clouds can reasonably be approximated as gray bodies, with 90 to 95% the irradiance of a black body. This percentage is called the emissivity (ε).

Long Wave Radiation Emission



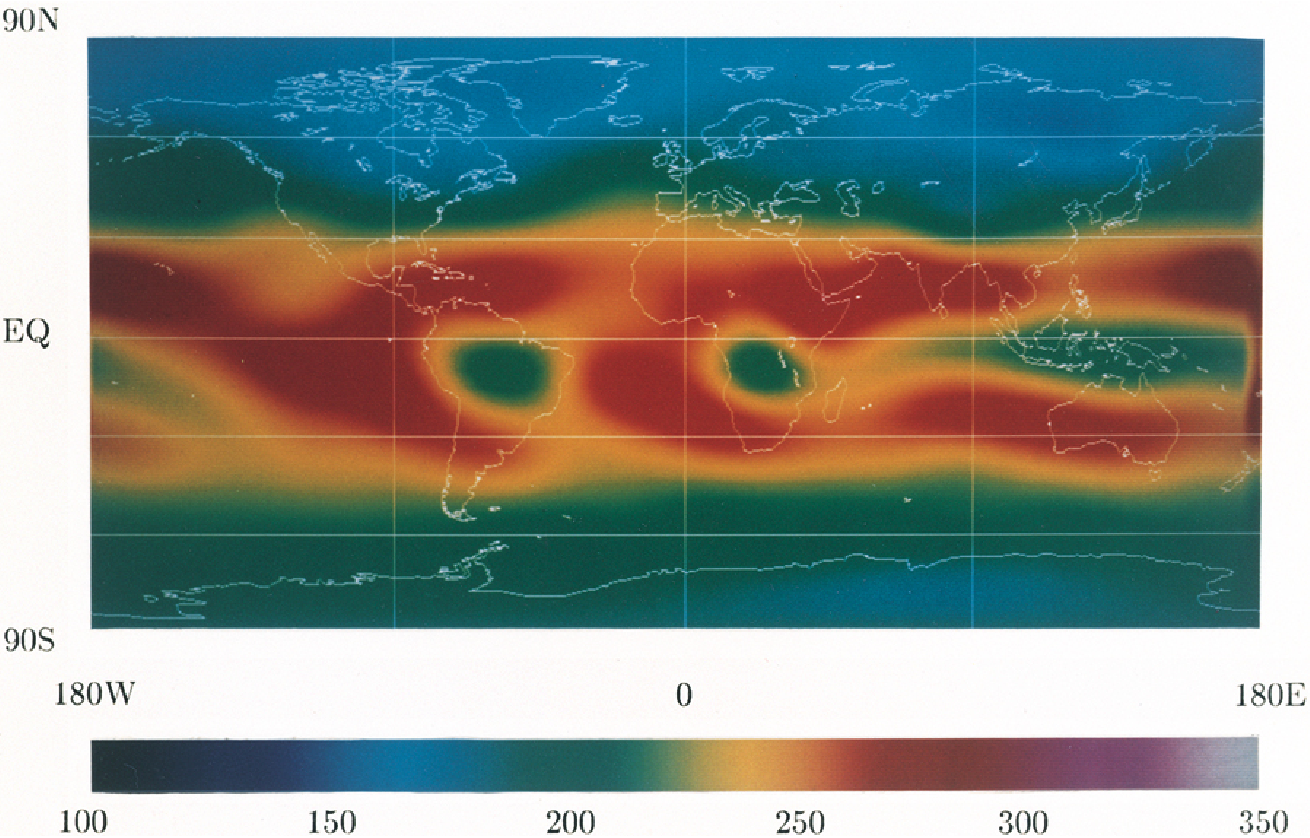
- The long wave emission from the surface can be estimated from the temperature and the emissivity of the material.
- There will be great regional variability.

Updated Energy Budget



- On average 99 of the 105 units emitted from the surface are absorbed in the atmosphere; 6 of the 105 units escape to space.
- This will vary regionally and on the local weather.
- Cloud cover is the key factor. Recall that water is a great absorber of IR radiation.

Satellite-based Longwave Radiation Emission Into Space

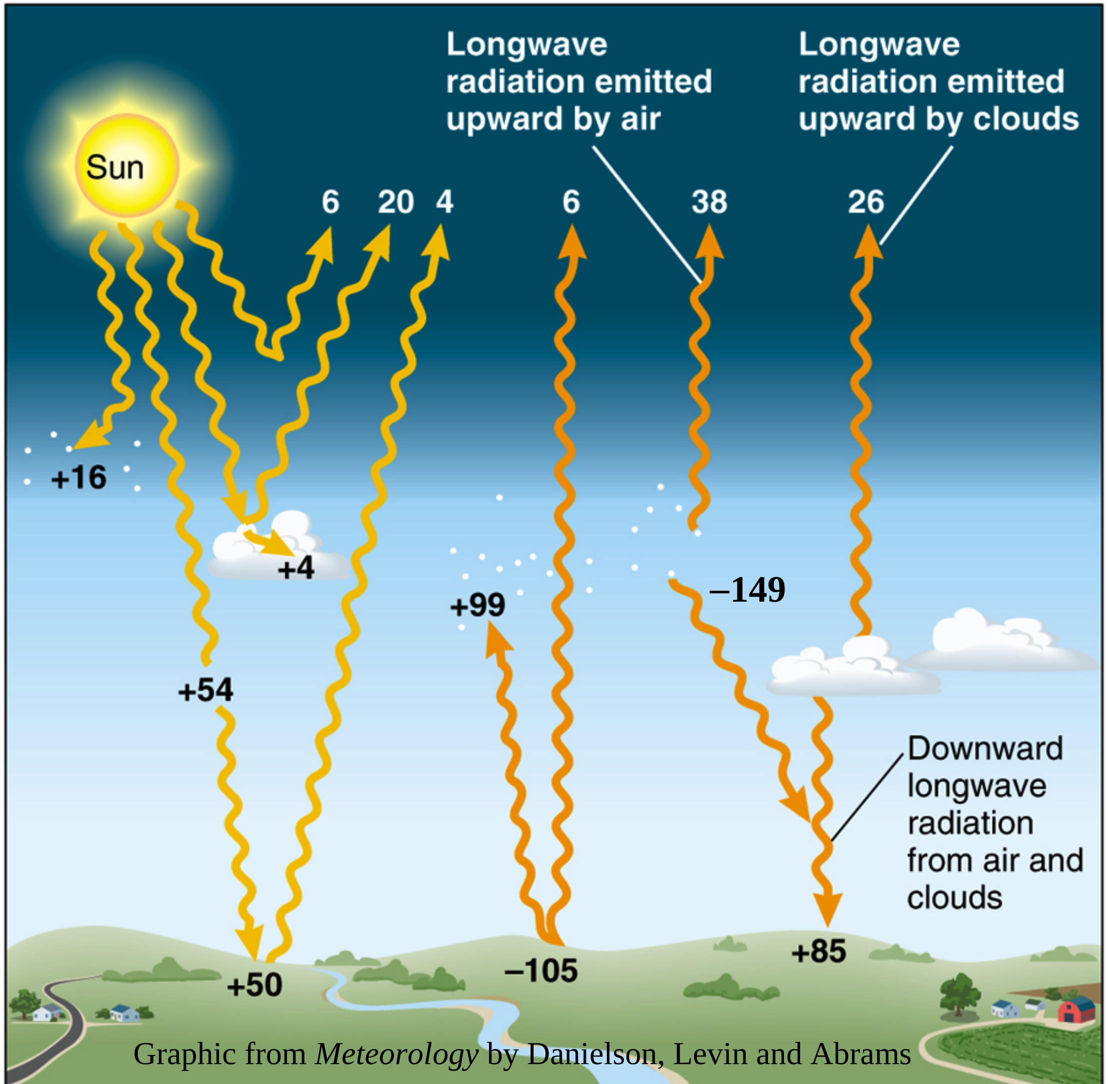


- Satellites can measure the outgoing longwave radiation (OLR).
- Given enough satellites in reasonable orbits, an average can be determined.
- This example is for January, averaged over several years.
- Units are Wm^{-2}

What does this picture appear to tell you?

Graphic from *Meteorology* by Danielson, Levin and Abrams

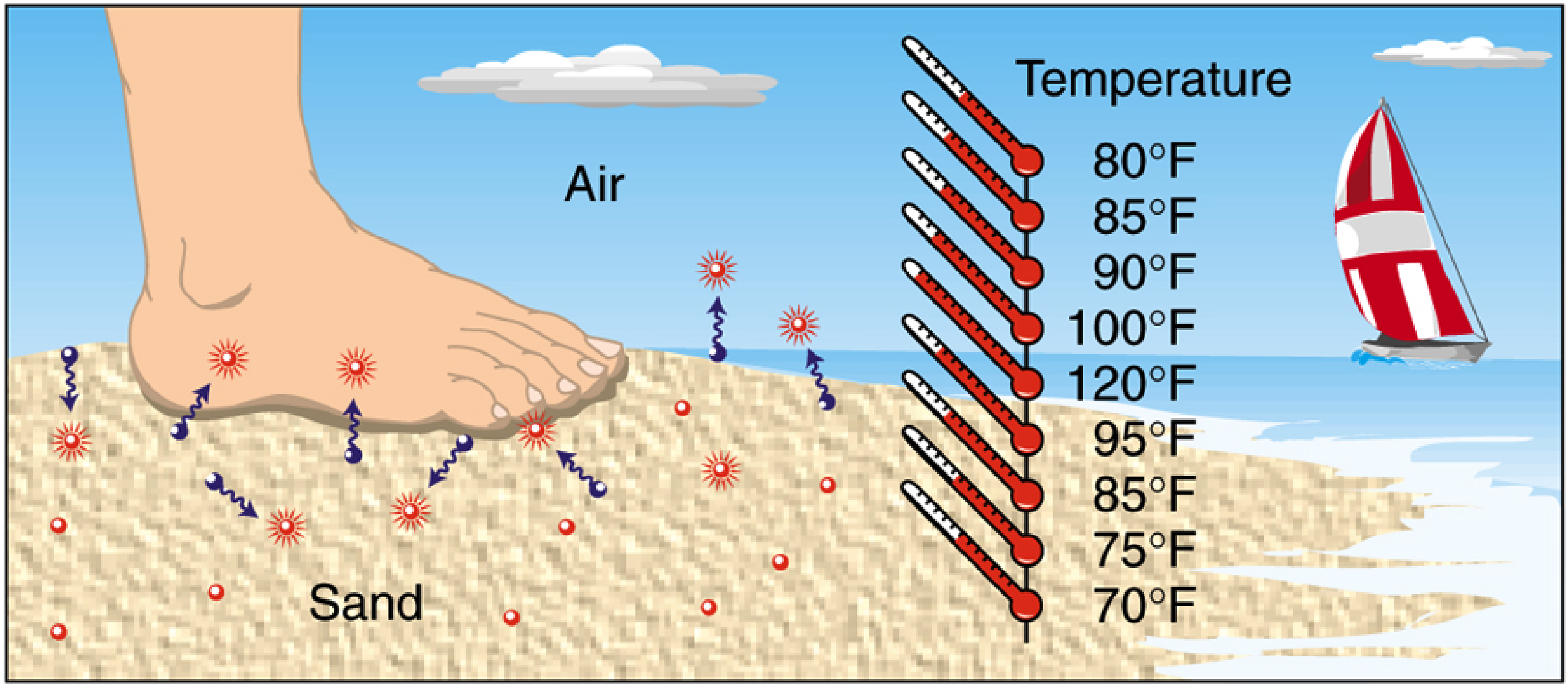
Earth's Radiation Budget



Graphic from *Meteorology* by Danielson, Levin and Abrams

- The vast majority of long wave radiation emitted by the surface is absorbed in the atmosphere (including clouds).
- It is re-radiated in all directions.
- More returns to the surface than is emitted to space.
- The atmosphere (including clouds) plays a key role in warming the surface.
- Budgets:
  - TOA: 0 Net
  - Atmosphere: –410 Wm^{-2}
  - Surface: +410 Wm^{-2}

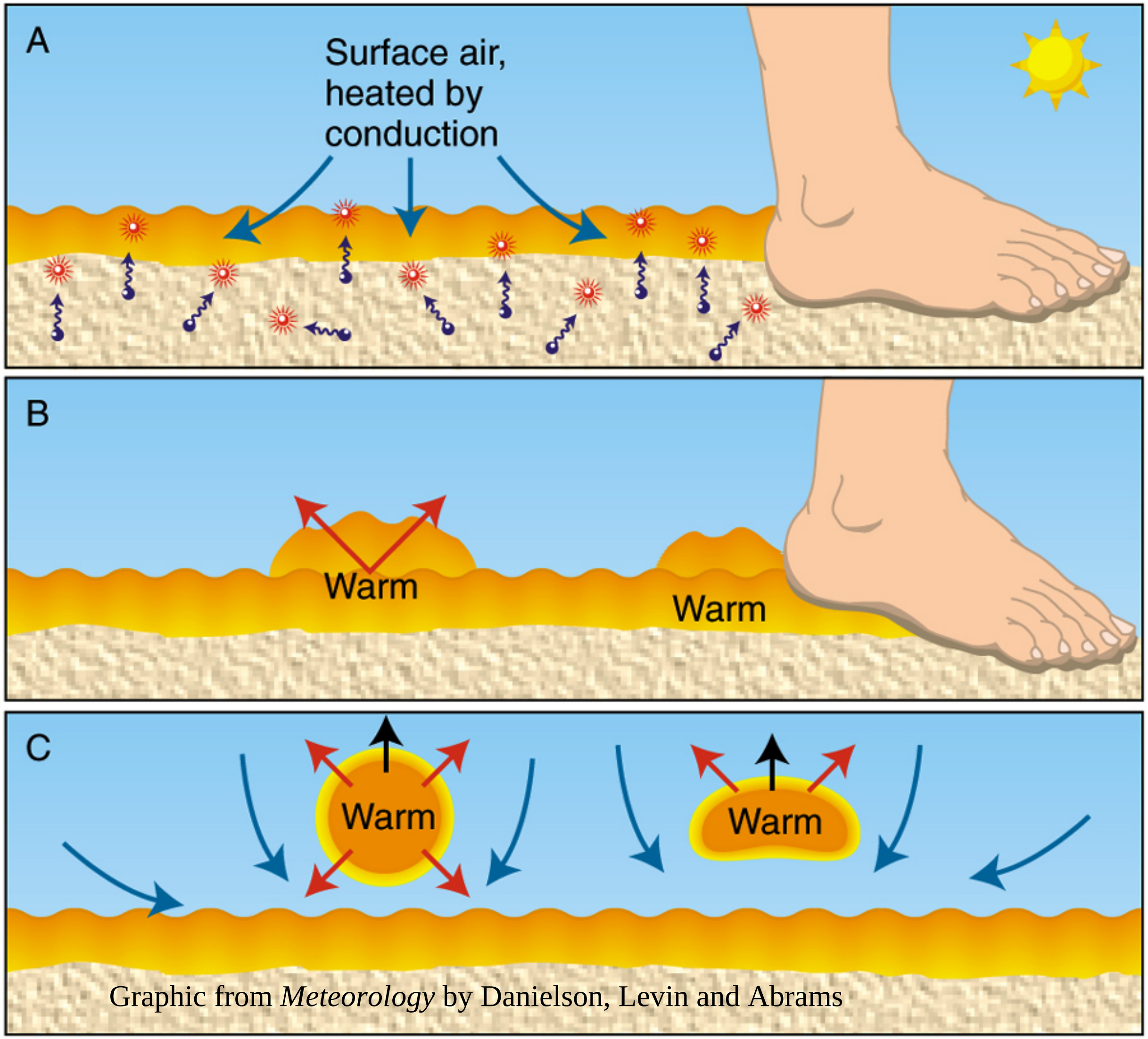
Inefficiency of Conduction Over Distances



- How does the energy leave the surface? Inside solid matter, conduction is sometimes an efficient mechanism for transferring energy.
- Conduction is a very poor process in most surface materials and in the atmosphere.

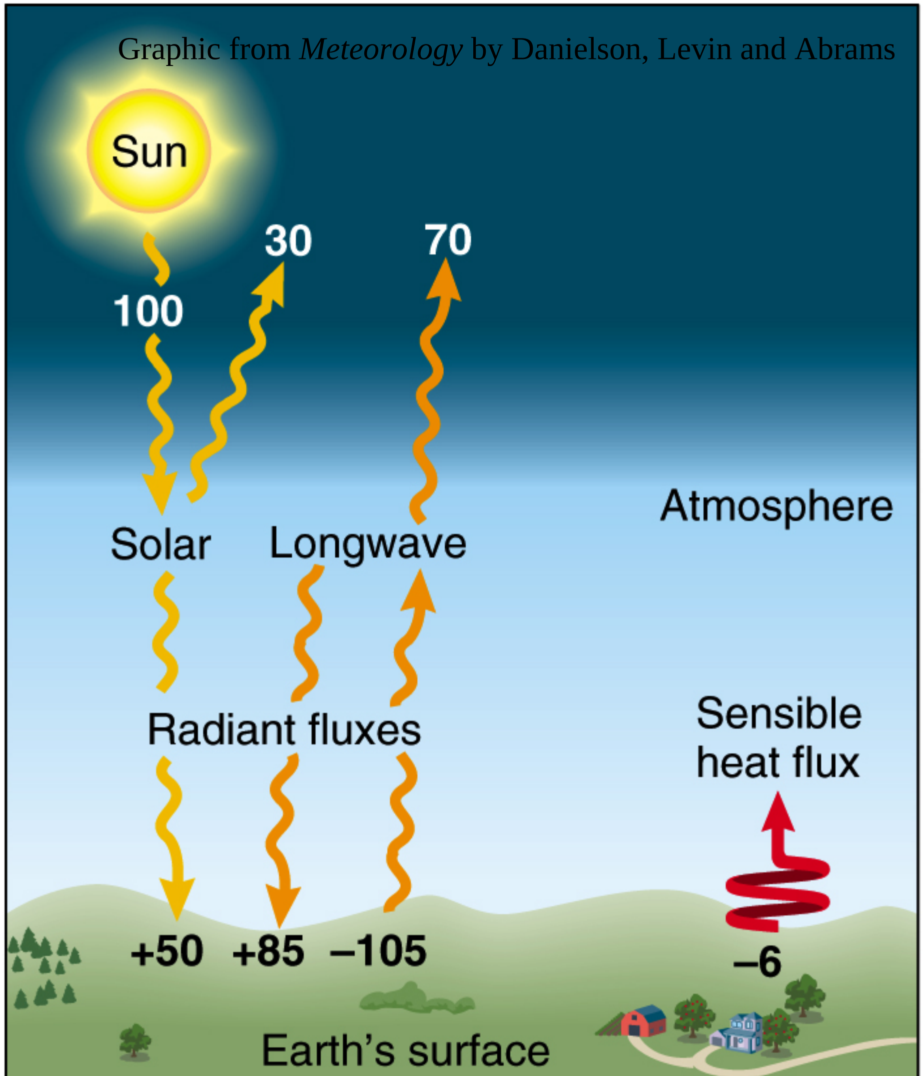
Graphic from *Meteorology* by Danielson, Levin and Abrams

Heat Transfer by Convection



- Conduction is effective only near the surface (A).
- Heated air expands, and becomes less dense (B).
- The warm, less dense air rises (C), allowing cooler air to replace it.
- This process (convection) results in motion, where relatively warm air rises, and relatively cool air sinks.

Energy Budget with Sensible Heat Flux



- Radiative transfer is NOT the only mechanism for transferring energy.
- Convection contributes to another process, know as the sensible heat flux.
  - For light winds (w_{10} < 3 ms^{-1}), convection can be very important.
  - For stronger winds, turbulent mixing processes are far more important.
- Factors that contribute to large sensible heat fluxes are
  - Large temperature differences between the surface and the nearby air, and
  - Large wind speeds.
- SHF ⇔ 82Wm^{-2} of the imbalance.

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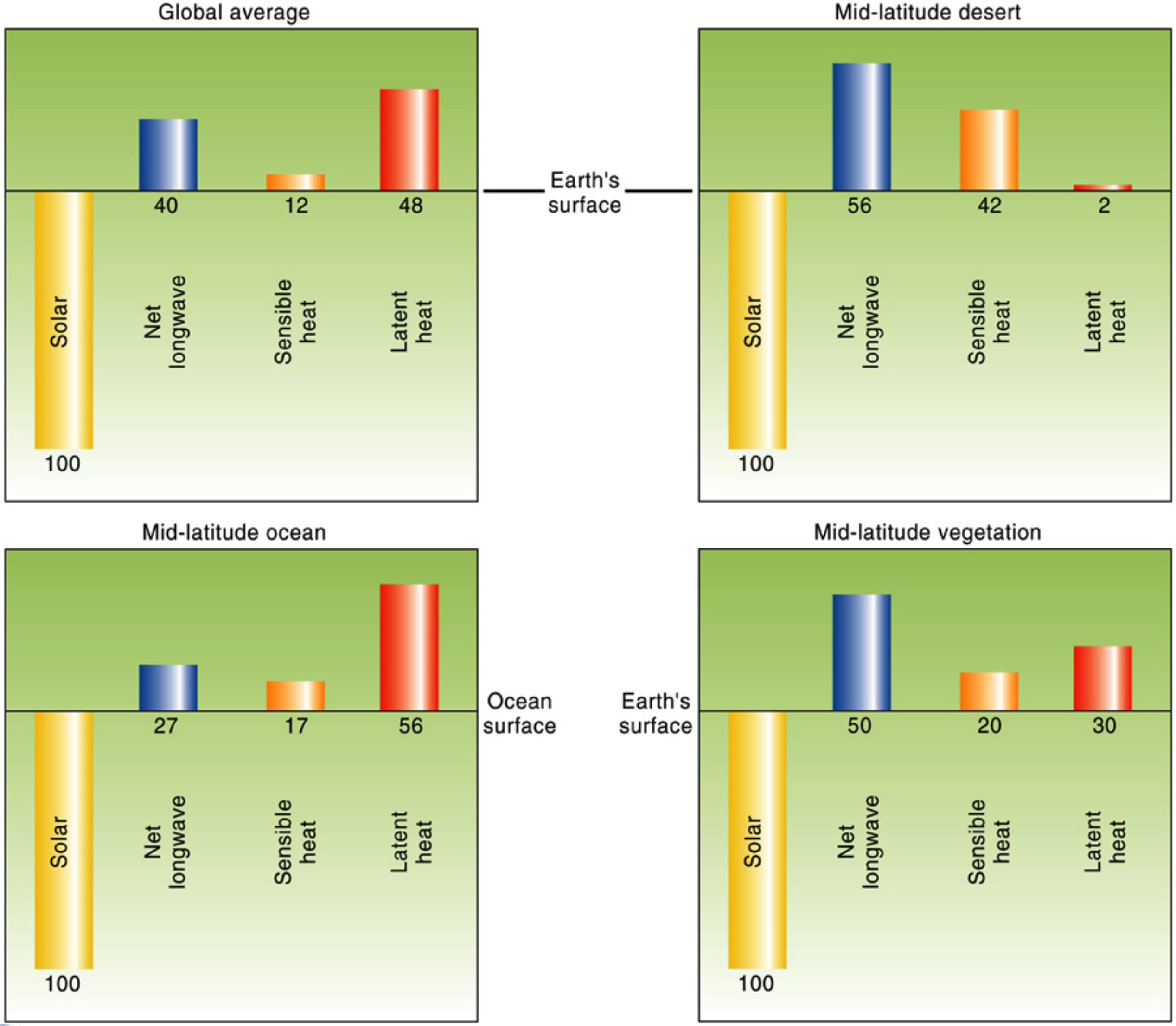
Latent Heat Flux

- The latent heat flux is similar to the sensible heat flux, except that it applies to moisture rather than heat.
  - The energy transfer come from the change of phase, from ice or water to water vapor.
  - The water vapor is then transported in the same manner as warm parcels of air in the sensible heat flux.
- Factors that contribute to large latent heat fluxes are
  - Large humidity differences between the surface and the nearby air, and
  - Large wind speeds.
- Note that like the radiative fluxes, both sensible and latent heat fluxes are vertical (upward or downward) fluxes of energy.
- Accounts for the remaining 328Wm^{-2} imbalance between the surface and the atmosphere.

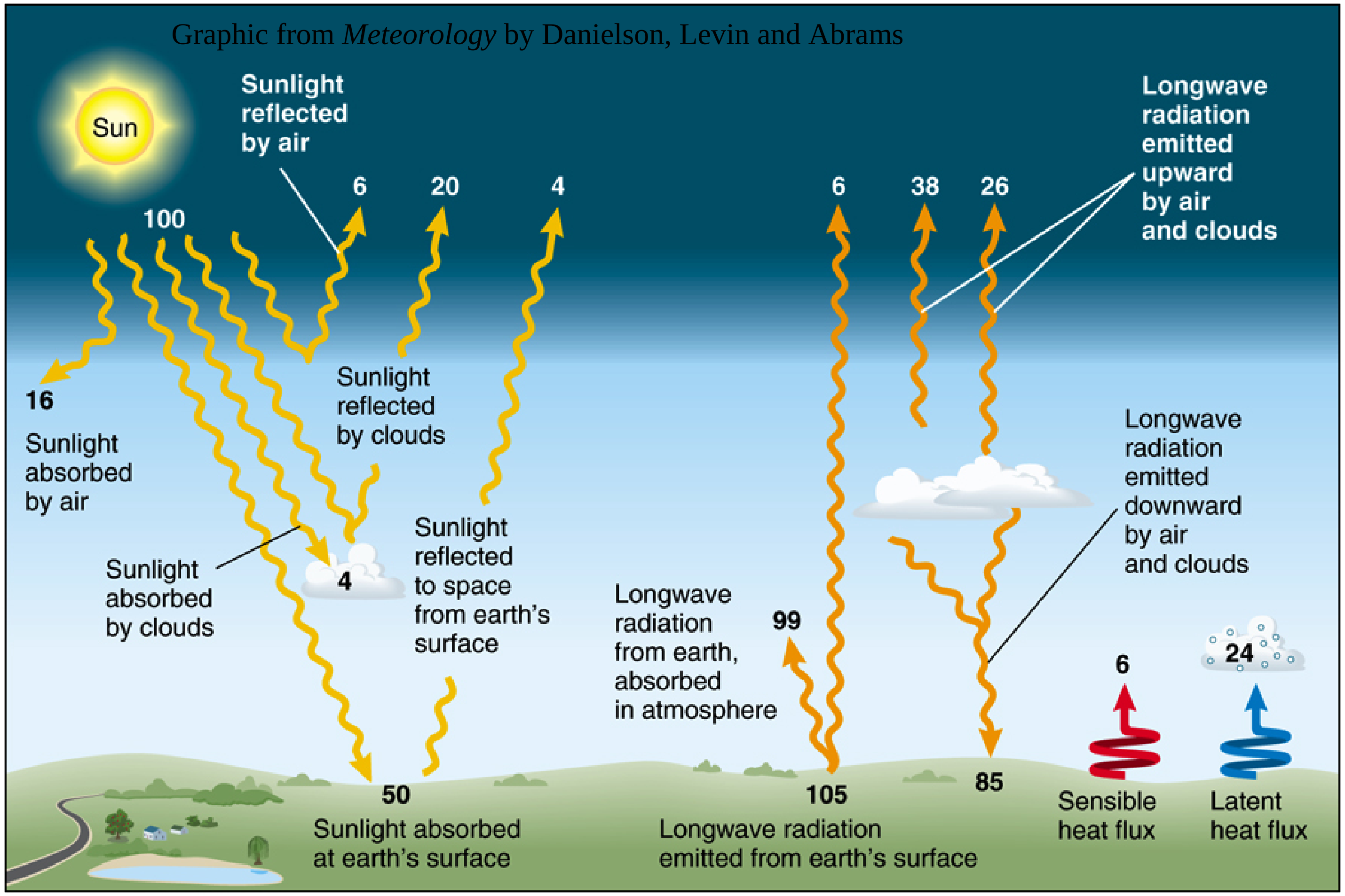
Energy Fluxes vs. Midlatitude Locations



- Examples of how surface fluxes change with difference types of surfaces.
- 100 units of solar radiation is assumed.

Graphic from *Meteorology* by Danielson, Levin and Abrams

Concept Map:
Mean Global Energy Budget



- TOA
  - Down
    - 100 Solar
  - Up
    - 30 Solar
    - 70 LW
- Atmosphere
  - Absorbed
    - 20 Solar
    - 99 LW
    - 6 Sensible
    - 24 Latent
  - Emitted
    - 149 LW
- Surface
  - Absorbed
    - 50 Solar
    - 85 LW
  - Emitted
    - 105 LW
    - 6 Sensible
    - 24 Latent

The net flux through every layer is zero. This is true only as a long term, global average (assuming no global change).