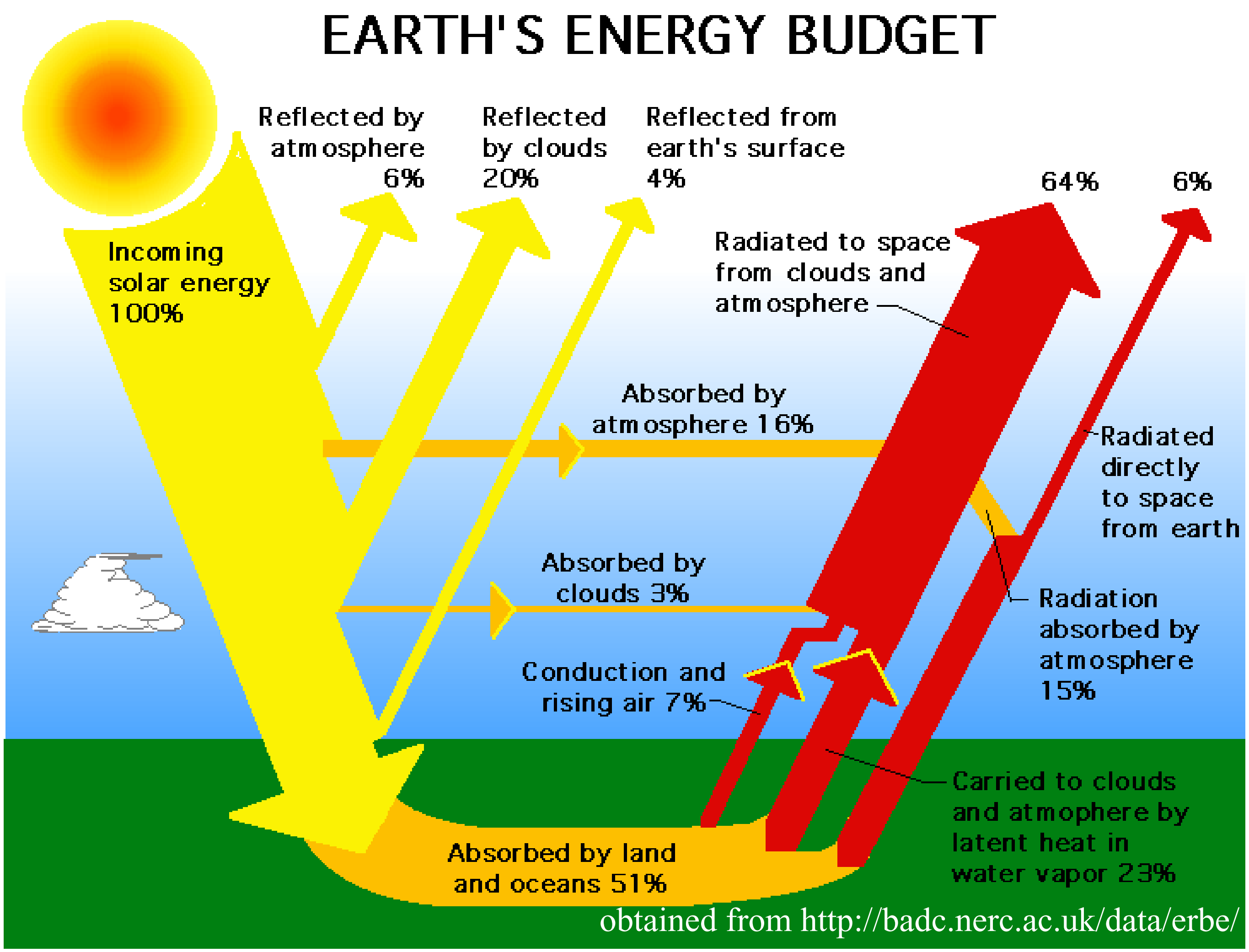
The Earth's Radiation Budget

Material and referenced figures from Chapter 10 of KVH



10.1. Solar Constant

Annual average solar irradiance (flux) received at the TOA on a surface normal to the incident radiation at a mean Earth-Sun distance. Varies ~ ±3.4% through the year

*** See Fig. 10.1

Hard to measure absolute value accurately (i.e., within a few W m^{-2}), but can measure changes to within tenths of a W m^{-2}. Issues:

=> from surface have to correct for atmospheric effects

=> calibration of instruments

=> sunspots

10.2. Top-of-the-Atmosphere (TOA) Radiation Budget

Balance between:

Net incoming shortwave ($\lambda < 5\ \mu m$) = $E_{sun}\mu_{sun} - M_{sw}(t, \theta, \psi)$

Outgoing longwave radiation (OLR, $\lambda > 5\ \mu m$)

$= M_{LW}(t,\theta,\psi)$

E = incoming (irradiance)

M = outgoing (exitance)

μ = cos(solar zenith angle)

t = time

θ = latitude

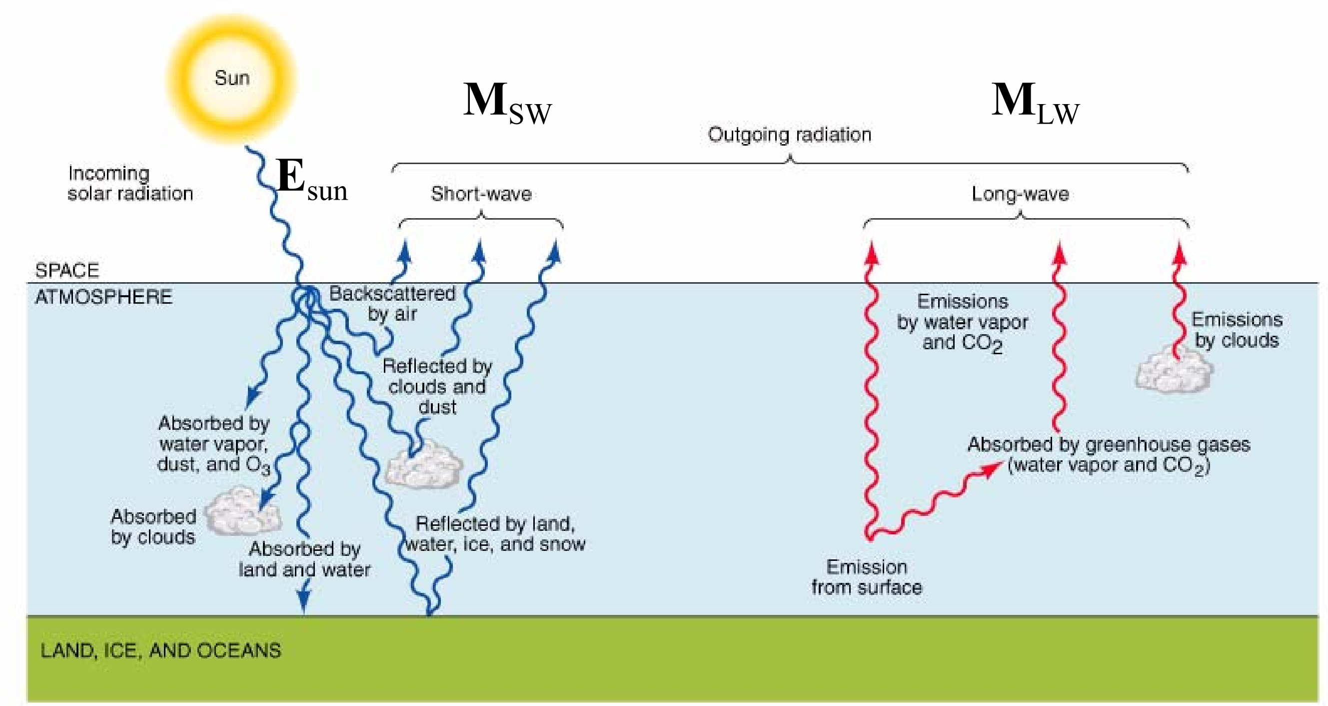
ψ = longitude

λ = wavelength

Shortwave: Net shortwave (absorbed by Earth)

$= E_{sun}\mu_{sun} - A(t,\theta,\psi)E_{sun}\mu_{sun} = (1 - A)E_{sun}\mu_{sun}$

A = albedo



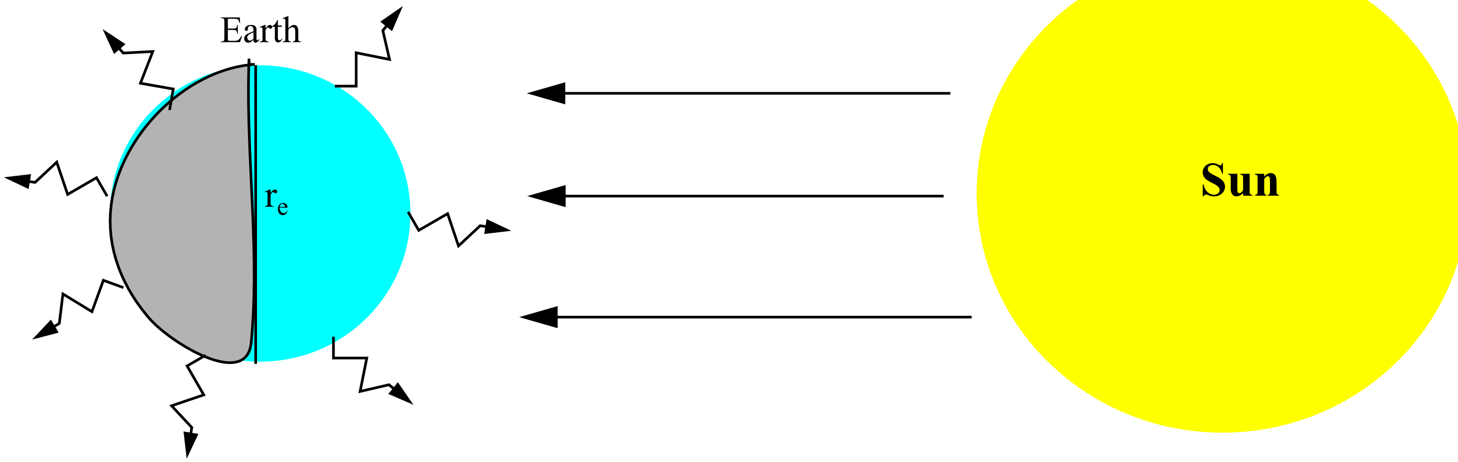
$$A = \frac{M_{SW}}{E_{sun}\mu_{sun}}$$

Measure this with satellite

Total net absorbed radiation = $E_{sun}\mu_{sun} - M_{SW} - M_{LW}$

*** See Fig. 10.4 for examples of measured longwave exitance (OLR) and albedo.

Example:



What is the effective temperature T_e of the Earth? Assume the Earth is a black body in the infrared (emissivity $\varepsilon = 1$); $E_{sun} \sim 1380$ W m^{-2}.

Incoming radiation must equal outgoing radiation for radiative equilibrium.

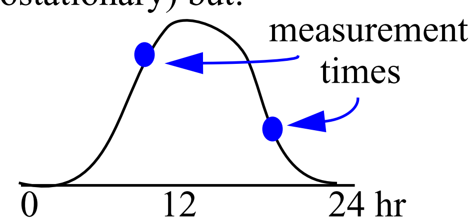
$$\pi r_e^2 (1 - A) E_{sun} = 4\pi r_e^2 \varepsilon\sigma T_e^4$$ solve for $T_e \sim 255$ K

Best way to measure TOA fluxes is with broad-band satellite sensors such as ERBS (Earth Radiation Budget Satellite), otherwise one must estimate broad-band from narrow band measurements across parts of spectrum not measured.

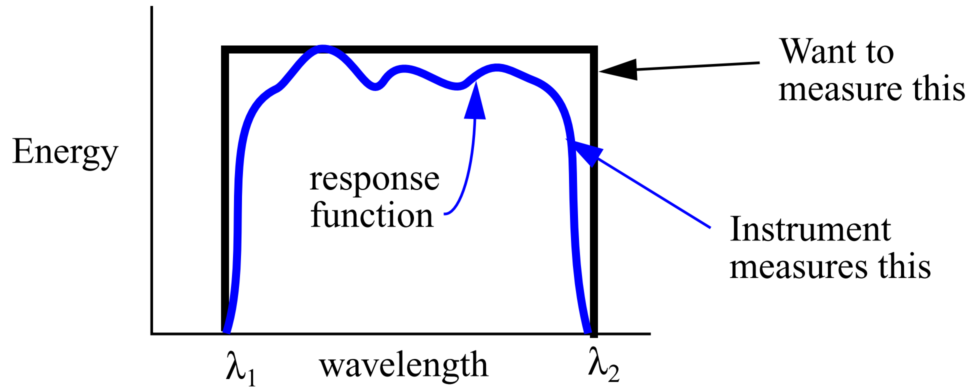
Polar-orbiting platforms best because they cover whole globe (unlike geostationary) but:

=> Must correct for platform not being at the TOA

=> May need model to remove diurnal sampling bias or <u>aliasing</u>



=> Sensors do not measure total energy in wavelength band so need correction for <u>response function</u>



=> Narrow FOV (NFOV) or scanner measures only from 1 angle at a time, but reflectance and/or emission may be angle-dependent. Different surfaces have different angular distributions.

Angular distribution models (also called BRDFs or bidirectional reflection distribution functions)
-- models of reflection (SW) and LW limb darkening. Need ADMs to estimate flux from a location with only single-angle measurements.

isotropic reflectance = incoming SW radiation is reflected equally into all angles

Lambertian surface = surface that reflects isotropically

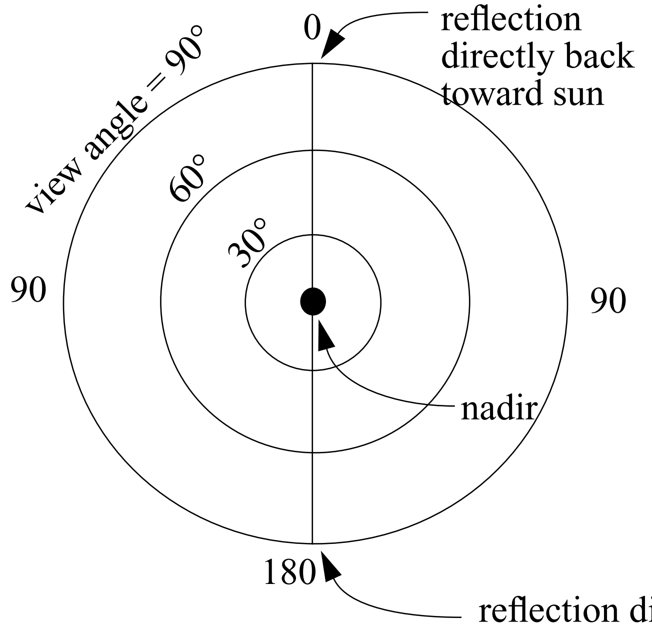
anisotropic reflectance = unequal distribution of reflectances into various angles (most surfaces are anisotropic). Reflected flux M_r =

$$M_r = \frac{\pi L_r}{\xi_r}$$

L_r = flux reflected from Lambertian surface

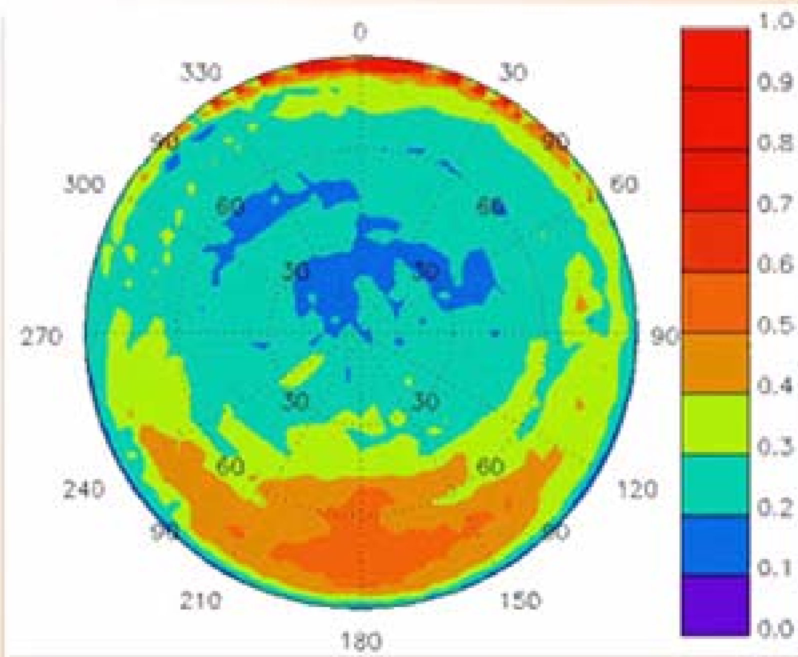
ξ_r = anisotropic factor = ratio reflected flux to that of Lambertian surface with same albedo (= 1 for Lambertian surface)

*** Fig. 3.22



E.g., in Fig. 3.22, overcast:
For solar zenith angle = 70 °
view angle = 60°
Directly away from sun reflectance ~1.75 times brighter than Lambertian surface

Example of measured BRDF over vegetation.



Measurements of BRDF at 0.87 microns over cerrado surface
(18 August 1995) Brasilia, Brazil

Earth Radiation Budget Experiment (ERBE) -- major improvement over previous polar orbiting sensors. Products include clear-sky and all-sky components of TOA fluxes so can investigate effects of clouds and cloud forcing -- effect of clouds on radiation (radiance or flux, R):

Cloud forcing = R(all-sky) – R(clear)

*** Figs. 10.4, 10.5. Make your own ERBE plots at http://earthobservatory.nasa.gov/Observatory. E.g., go to Heat and Energy, Cloud Forcing

Primary sources of uncertainty:

=> diurnal aliasing

=> ADMs (Angular Distribution Models) to correct measured radiance at 1 angle to hemispheric flux

=> cloud identification over bright surfaces

CERES (Clouds and the Earth's Radiant Energy System) instrument is improved version of ERBE: higher resolution, better calibration, more channels

10.3. Surface Radiation Budget

Cannot measure directly from space -- must correct for atmosphere. The following factors are important; affected surface fluxes are listed:

1. surface albedo (SWup, SWnet)
2. cloud fraction (SWdown, LWdown)
3. cloud thickness (SWdown, LWdown)
4. cloud height (LWdown)
5. surface temperature (LWup, LWnet)
6. water vapor (LWdown)
7. solar zenith angle (SWdown)

Surface downwelling shortwave

$$\underbrace{\mu_{sun}E_{sun}}_{\substack{\text{TOA}\\ \text{insolation}}} = \underbrace{A\mu_{sun}E_{sun}}_{\substack{\text{TOA reflected}\\ \text{insolation}}} + \underbrace{E_{atm}}_{\substack{\text{SW}\\ \text{absorbed}\\ \text{by atmosphere}}} + \underbrace{(1 - A_{sfc})E_{sfc}}_{\substack{\text{SW absorbed}\\ \text{by surface}}}$$

$$\underbrace{E_{sfc}}_{\substack{\text{insolation}\\ \text{at surface}}} = \frac{\mu_{sun}E_{sun} - A\mu_{sun}E_{sun} - E_{atm}}{1 - A_{sfc}}$$

hard to measure

Assume isotropic reflection: $A\mu_{sun}E_{sun} = \pi L$ L = satellite-measured radiance

$$E_{sfc} = \frac{\mu_{sun}E_{sun} - \pi L - E_{atm}}{1 - A_{sfc}}$$

Things people have tried:

1. Justus et al (1986) use incoming solar and satellite-measured radiance in regression to get E_{sfc}
2. Gautier et al (1980) use climatological absorption and scattering properties of the atmosphere, surface measurements of surface dewpoint to estimate E_{atm}, and satellite-measured L to estimate albedo and cloud detection
3. More sophisticated models and cloud detection methods used in SARB (Surface and Atmosphere Radiation Budget) dataset

Reflected Shortwave Radiation: Need albedo and SWdown

Downwelling Longwave Radiation: LWdown depends on T(z), q(z), and cloud fraction/base height/thickness, all of which can be estimated from satellite data. Large uncertainties with base height and cloud thickness. Cloud fraction difficult to ascertain over bright surfaces and for low clouds within near-surface inversion at night.

Upward Longwave Radiation: Only need surface temperature and emissivity with Stephan-Boltzmann Law:

$$M_{sfc} = \sigma\varepsilon T_{sfc}^4 \quad \sigma = \text{Stephan-Boltzmann constant}$$

Net Surface Radiation = SWdown – SWup + LWdown – LWup

Errors accumulate.

Cloud Radiative Forcing: Difference between flux in all-sky conditions and clear-sky conditions. Positive (negative) value means cloud warm (cool) the system.