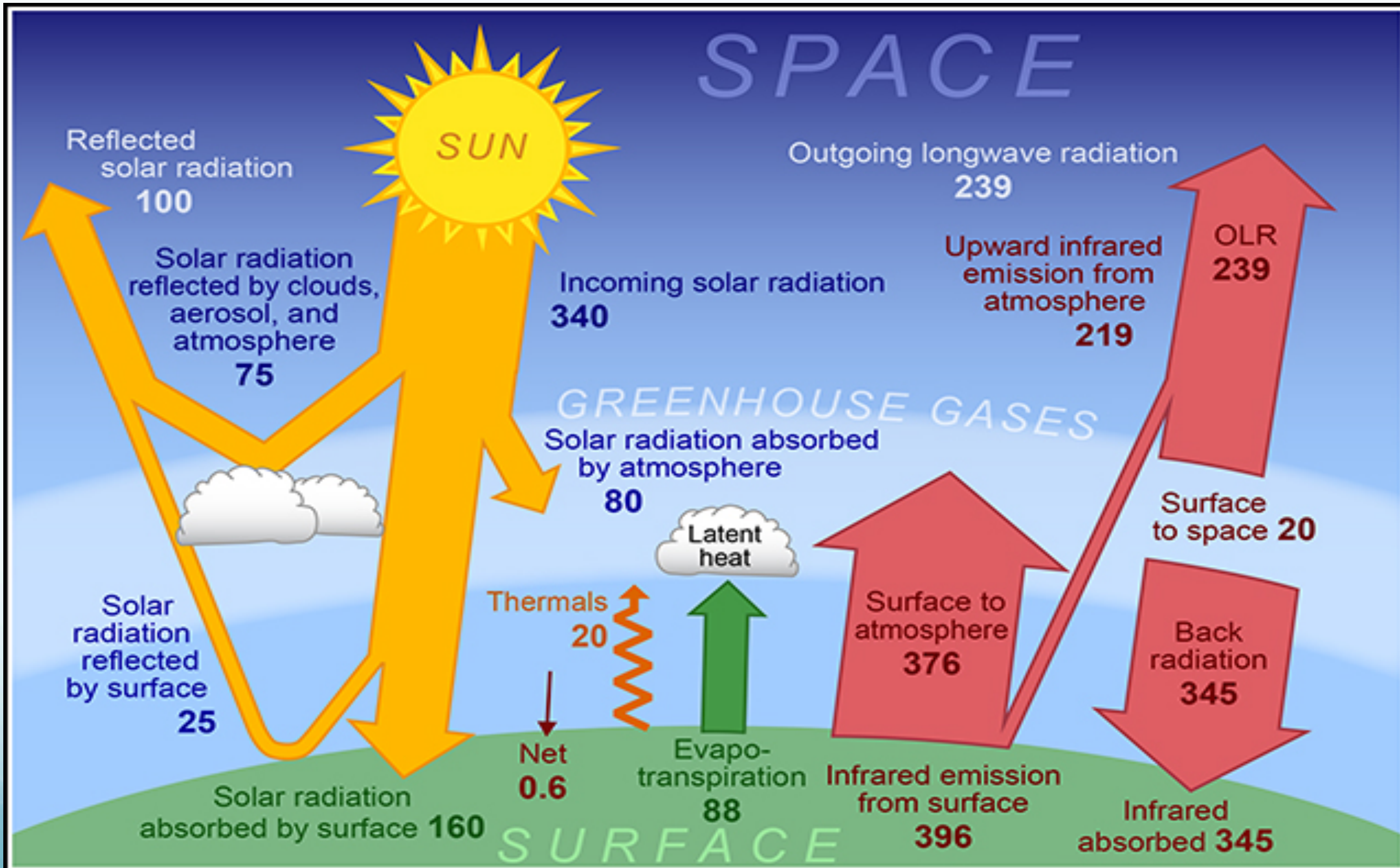
Atmospheric Sciences 321
Science of Climate

Lecture 4: Spatial Energy Balance

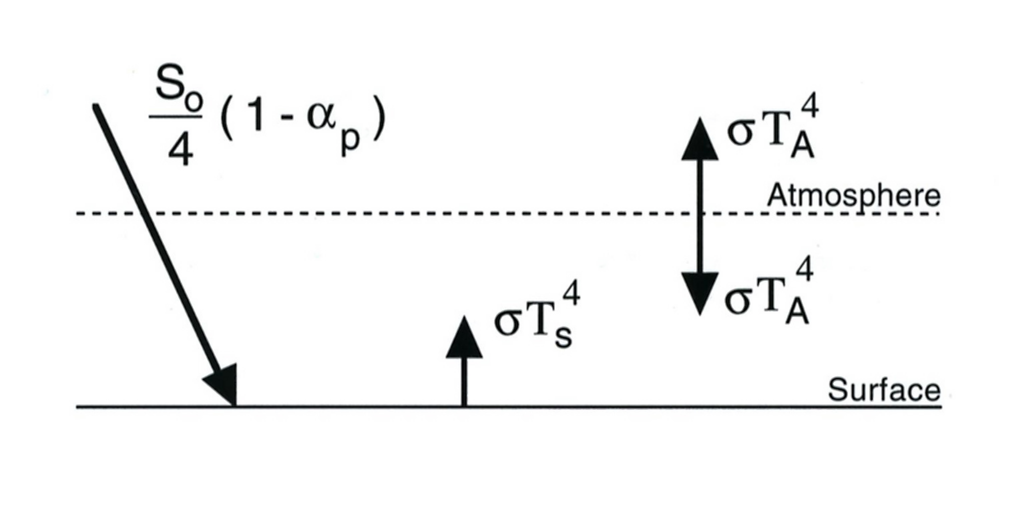
Community Business

- Check the assignments
- You should have read chapters 1 and 2 of book
- First HW #1 due Wednesday in class
- Questions?

Review: Global Energy Balance

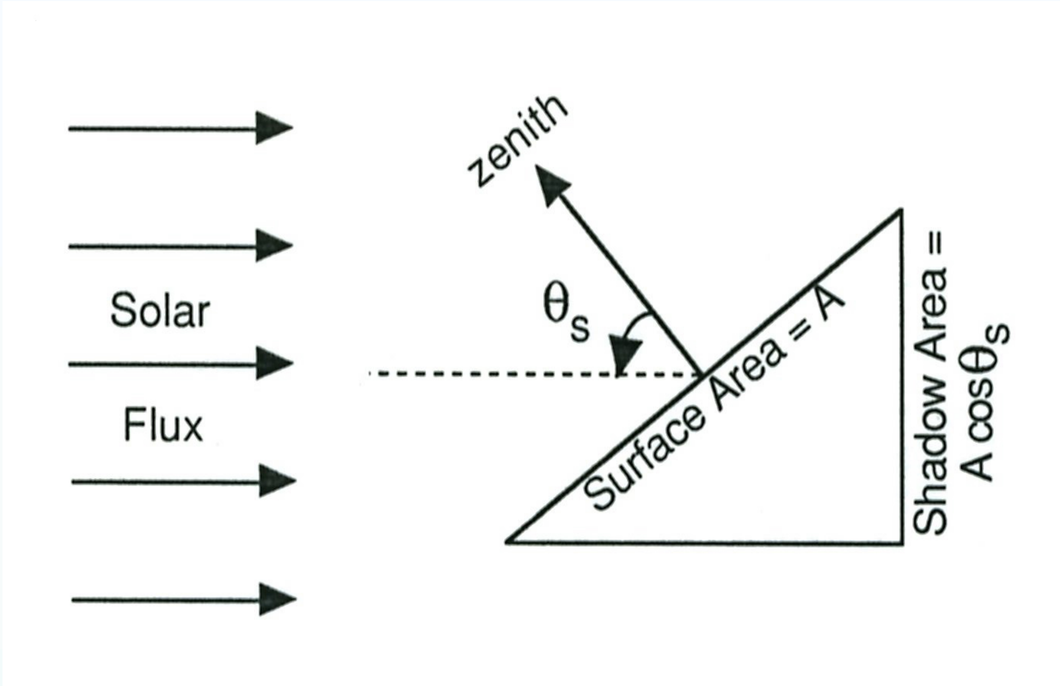


Review: Simplest model of Greenhouse Effect



- TOA $$\frac{S_0}{4}(1-\alpha_p) = \sigma T_A^4 = \sigma T_e^4$$
- Atmosphere $$\sigma T_s^4 = 2\sigma T_A^4$$
- Surface $$\sigma T_A^4 + \frac{S_0}{4}(1-\alpha_p) = \sigma T_s^4$$

Solar Zenith Angle



- A parallel wall of irradiance arrives at Earth from the Sun. The irradiance per unit area depends on the zenith angle.

Solar Zenith Angle

- Insolation at top of atmosphere – TOA

$$Q = S_0 \left(\frac{\bar{d}}{d} \right)^2 \cos\theta_s$$

- Zenith Angle Formula

$$\cos\theta_s = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h$$

- Sunrise/set hour angle

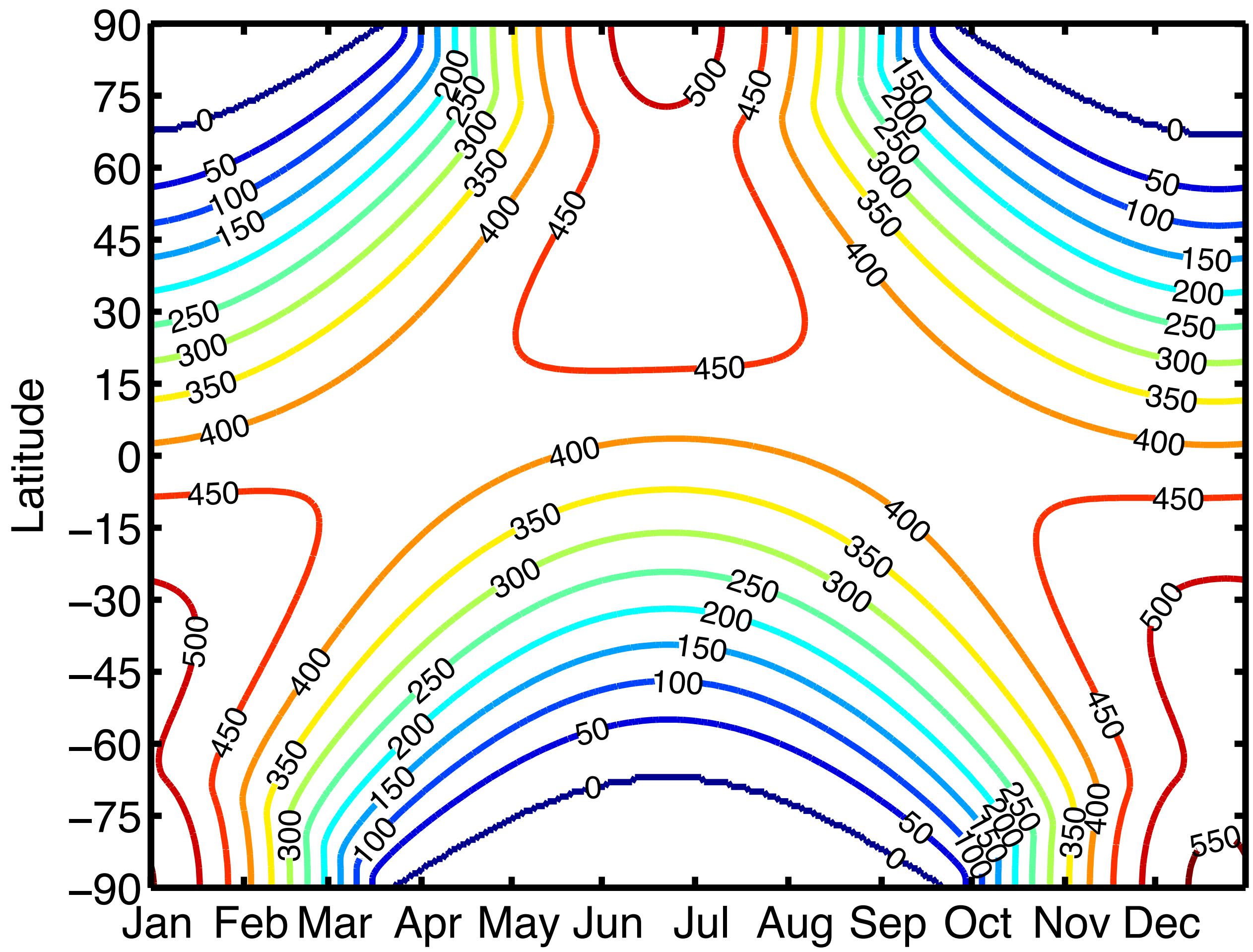
$$\cos h_0 = -\tan\phi \tan\delta$$

Daily Insolation

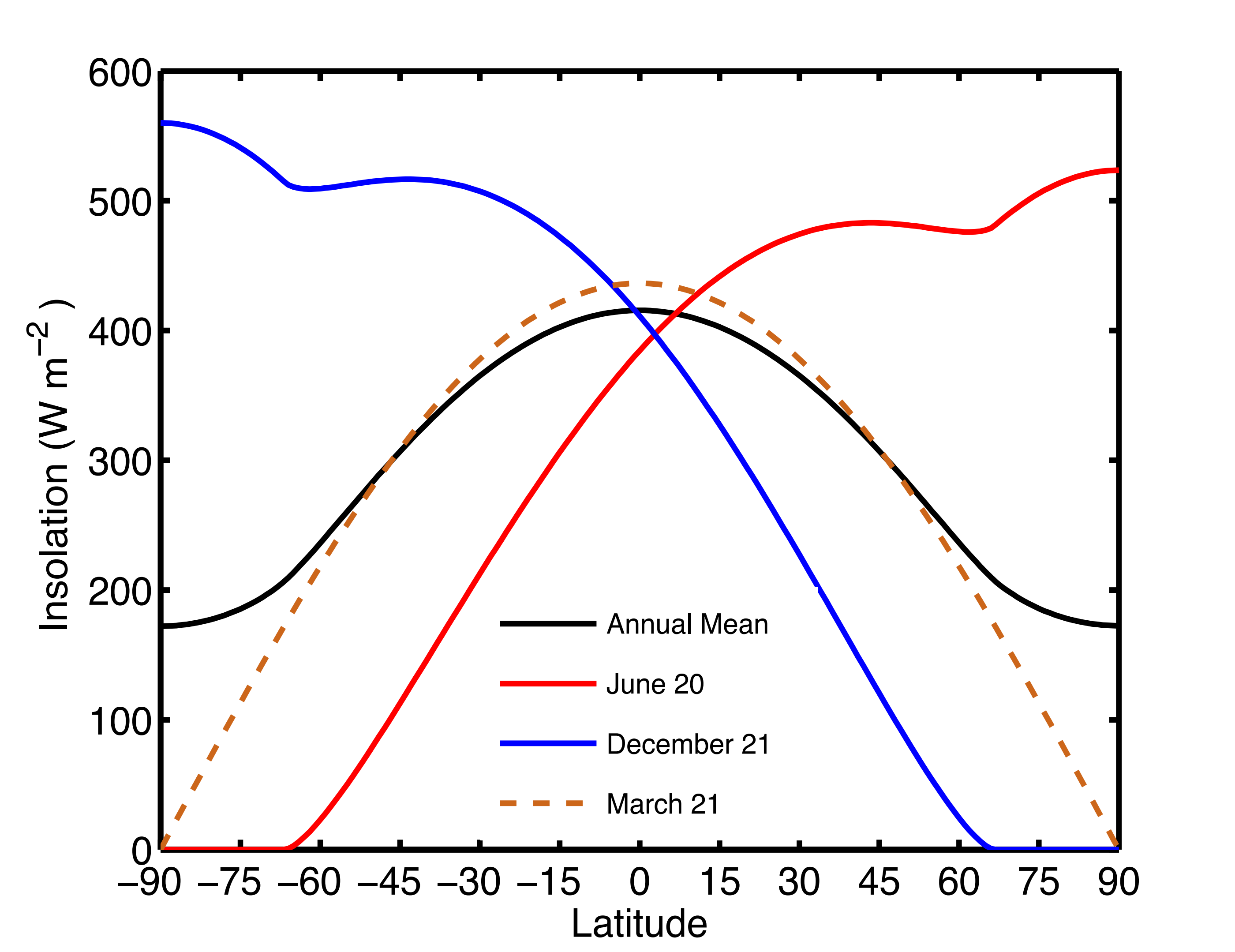
$$\bar{Q}^{day} = \frac{S_0}{\pi}\left(\frac{\bar{d}}{d}\right)^2 \left[h_0 \sin\phi \sin\delta + \cos\phi \cos\delta \sin h_0\right]$$

See class notes for derivation

Daily Insolation Plot in Wm^{-2}



Latitude Distribution of Daily Insolation



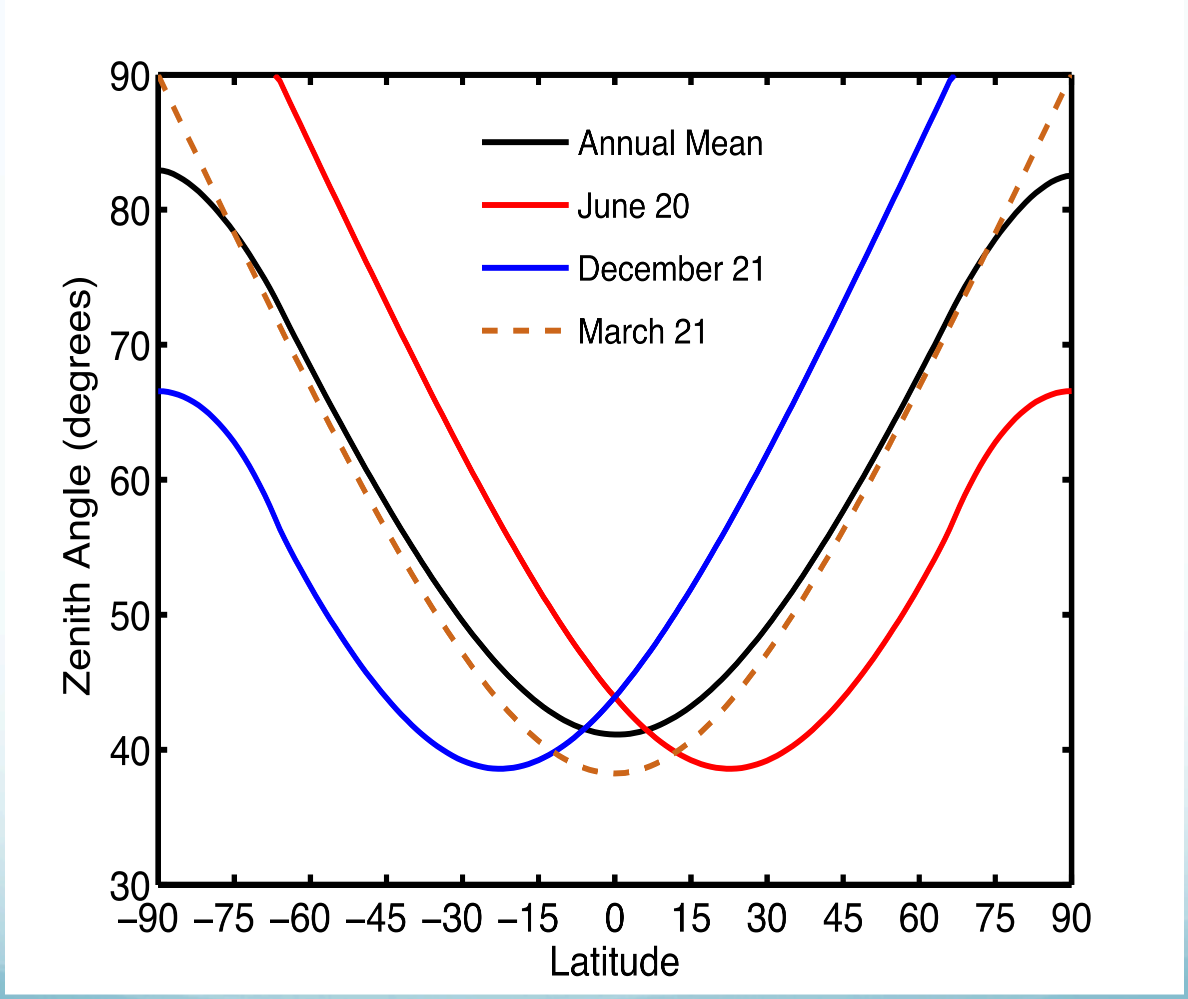
Insolation-Weighted Zenith Angle

- IF you wanted to calculate an average zenith angle, you should weight the average by insolation.
- Of course this would still give the wrong albedo, because the reflection of surfaces depend on zenith angle in complicated ways.

$$\overline{\cos\theta_s}^{day} = \frac{\int_{-h_0}^{h_0} Q\cos\theta_s \, dh}{\int_{-h_0}^{h_0} Q \, dh}$$

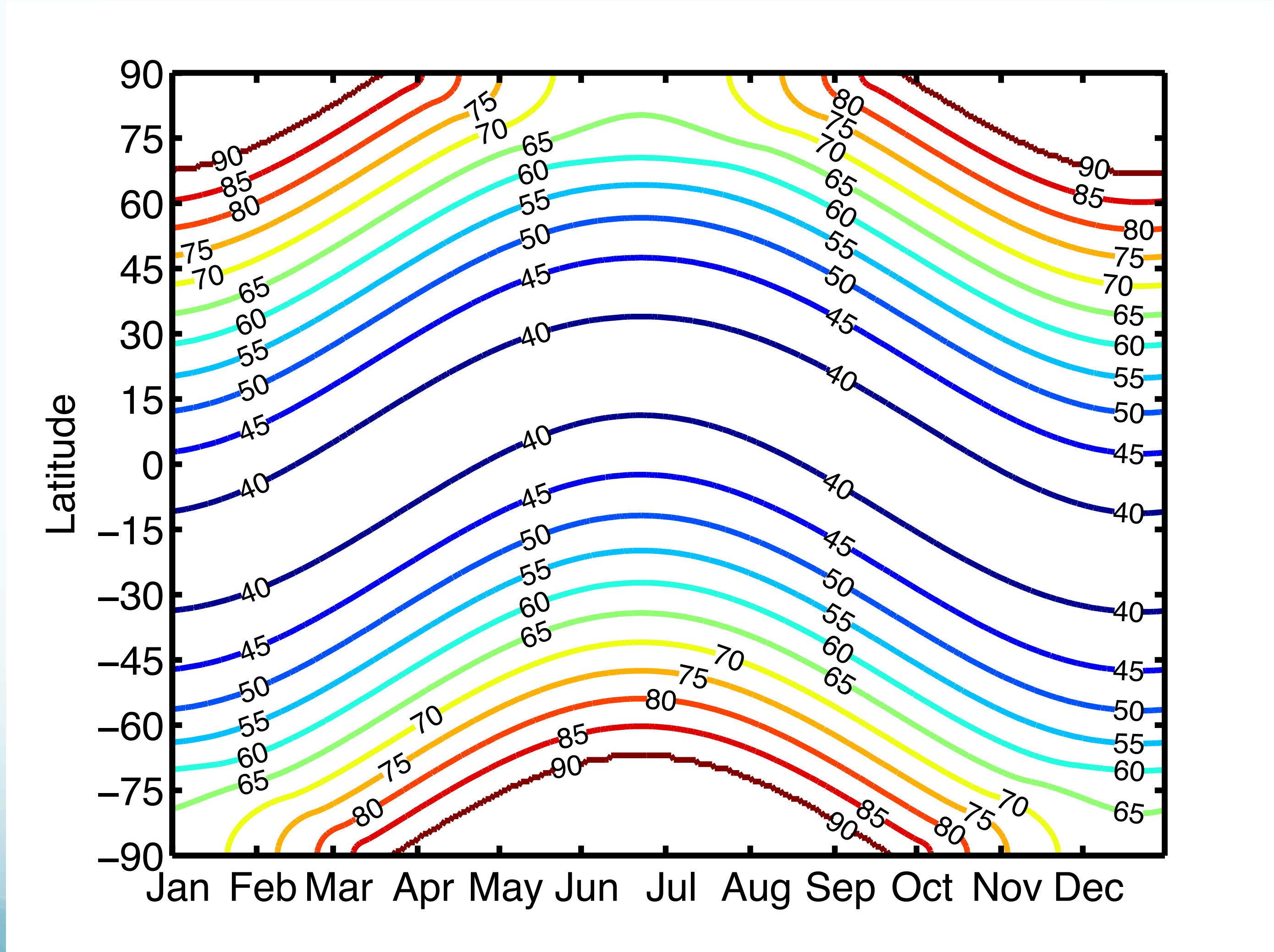
$$Q = S_0 \left(\frac{\bar{d}}{d} \right)^2 \cos\theta_s$$

Solar Zenith Angle Insolation-Weighted over diurnal cycle



Insolation-Weighted Zenith Angle

- is here contoured on Latitude vs Season plot



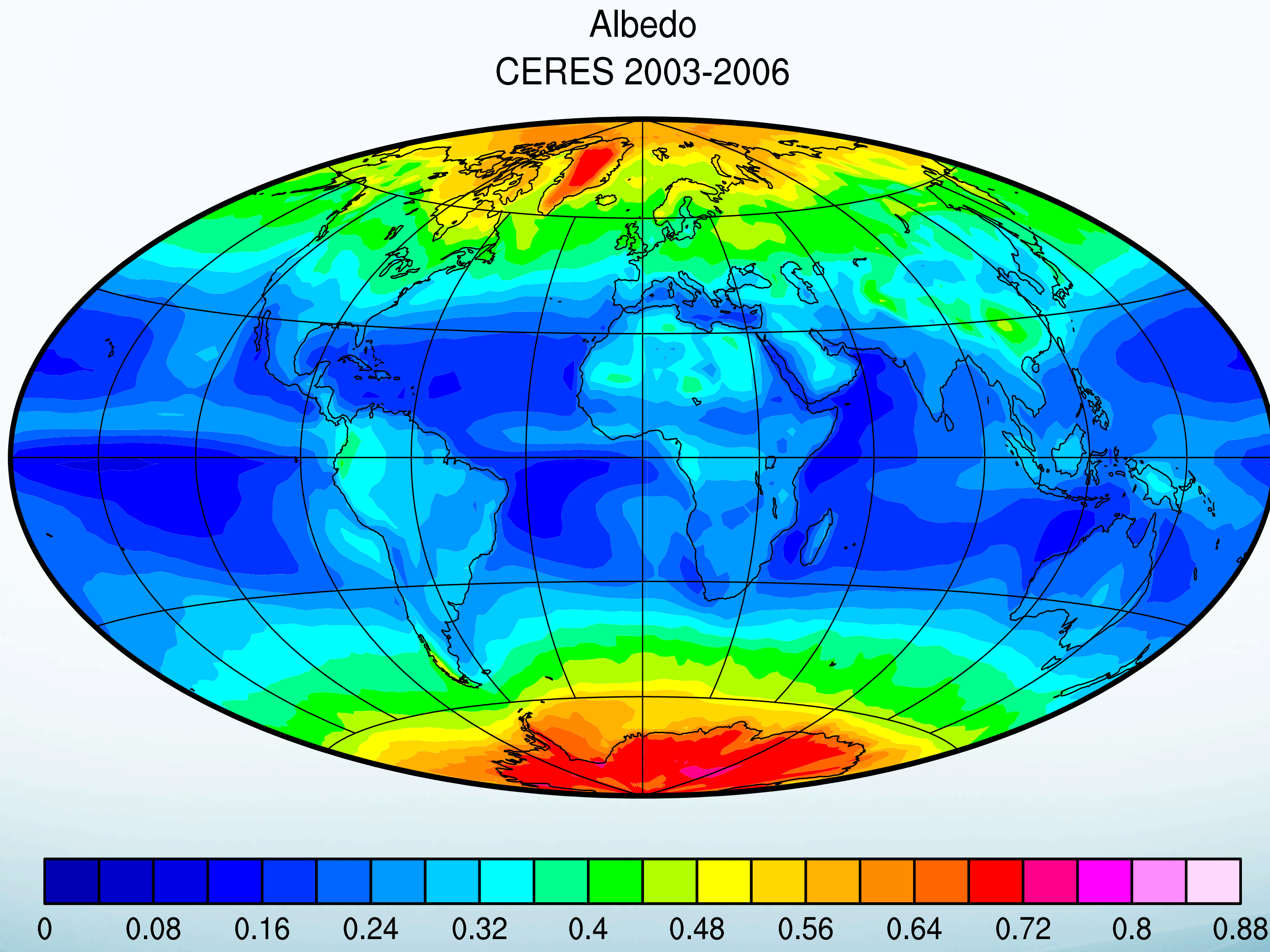
TOA Energy Balance

- Net Radiation = Absorbed Solar - OLR

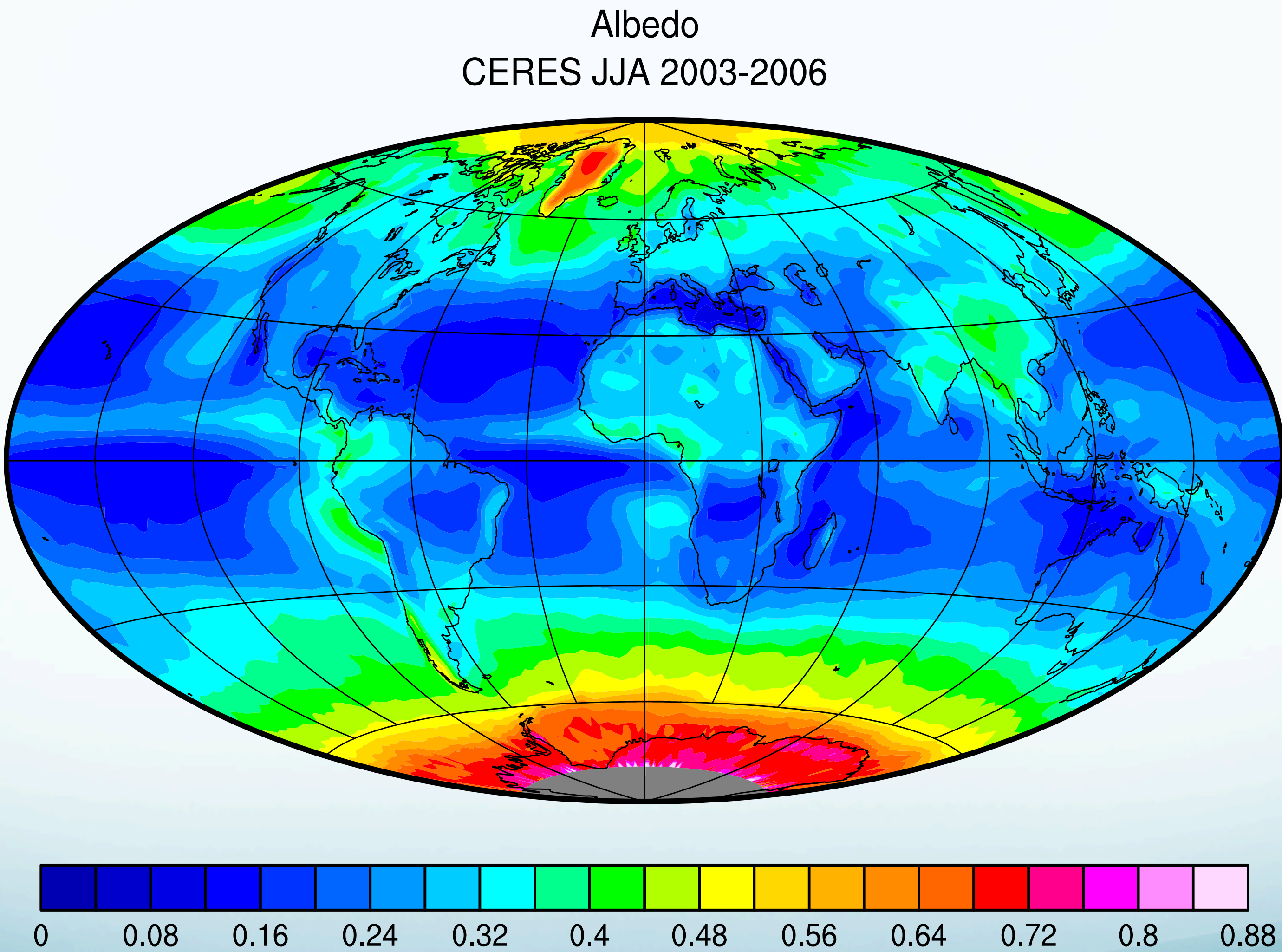
$$R_{TOA} = Q_{abs} - OLR$$

$$Q_{abs} = S_{TOA}(1 - \alpha)$$

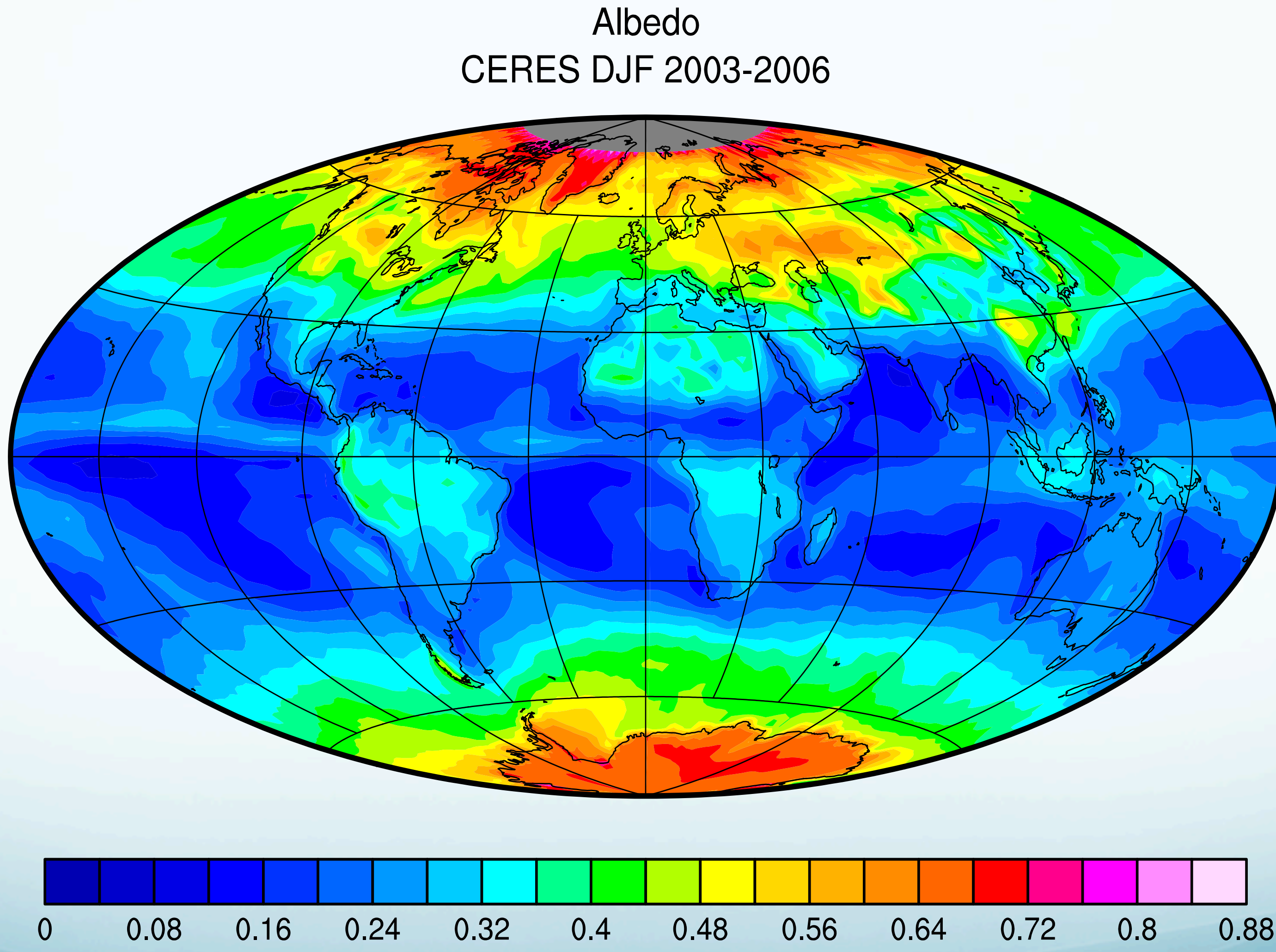
TOA Albedo – annual mean



TOA Albedo – JJA



TOA Albedo – DJF



Albedo

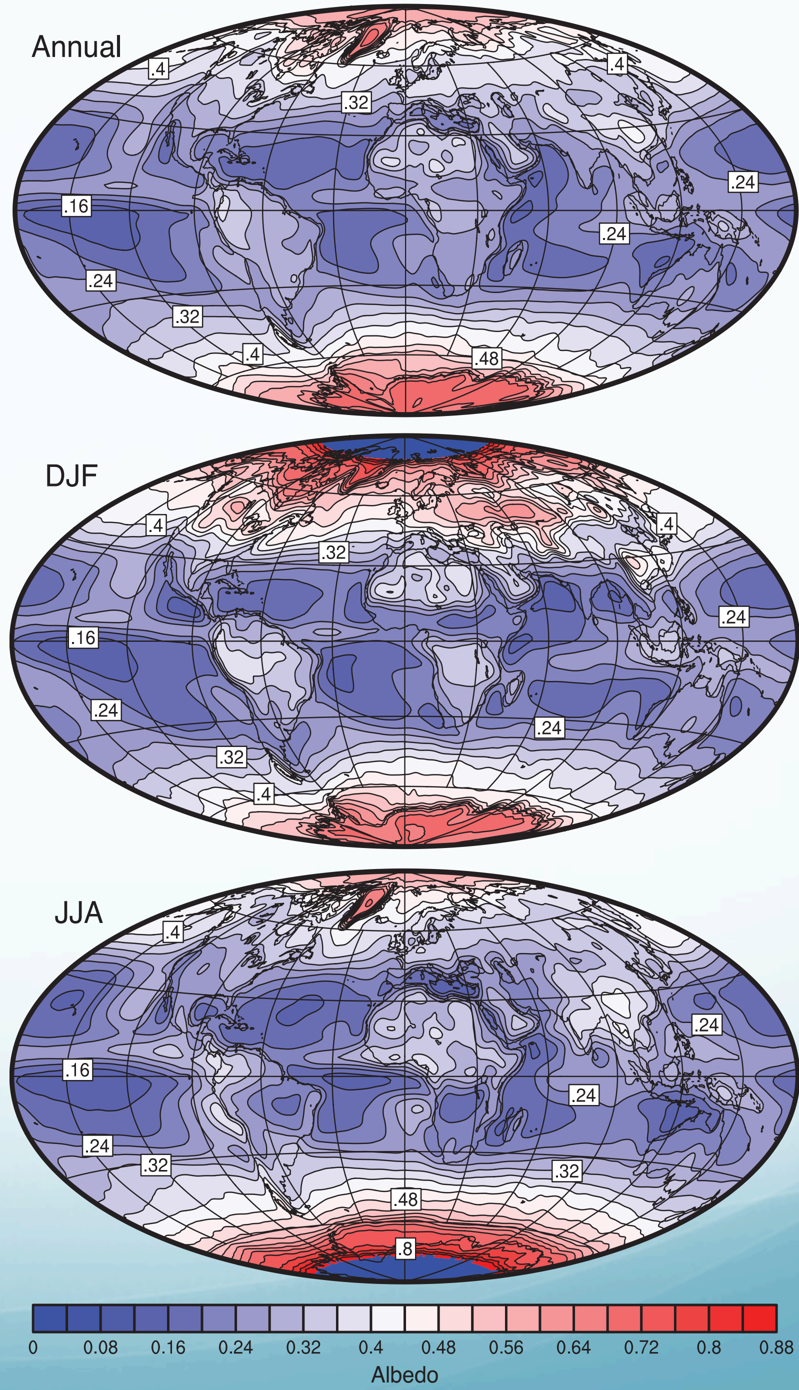
Albedo measured by satellite at top of atmosphere.

Includes effects of surface, clear atmosphere, and clouds

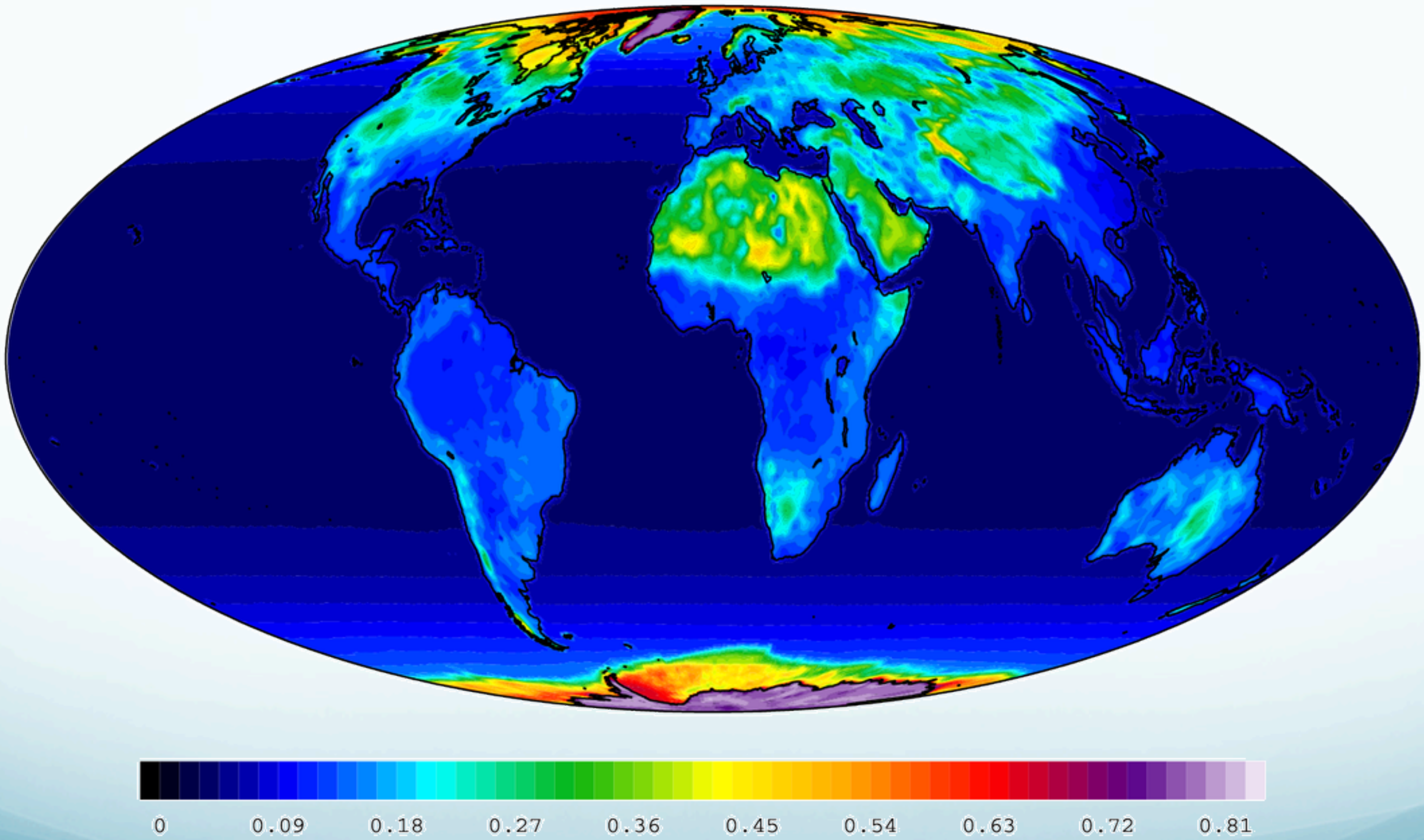
Higher over land than ocean, because of surface albedo.

Higher in high latitudes because of zenith angle, clouds and surface ice.

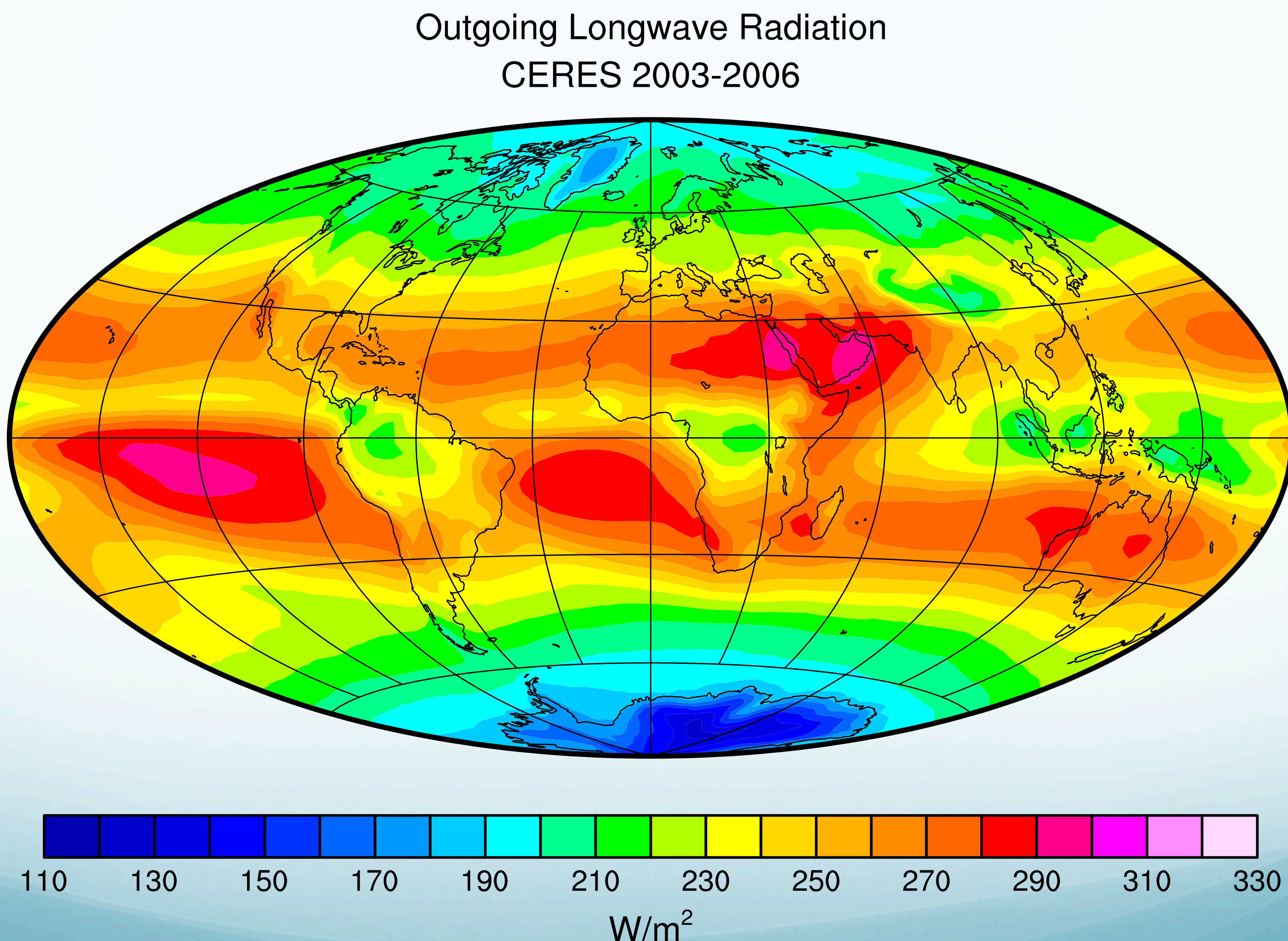
CERES data, 2000-2013.



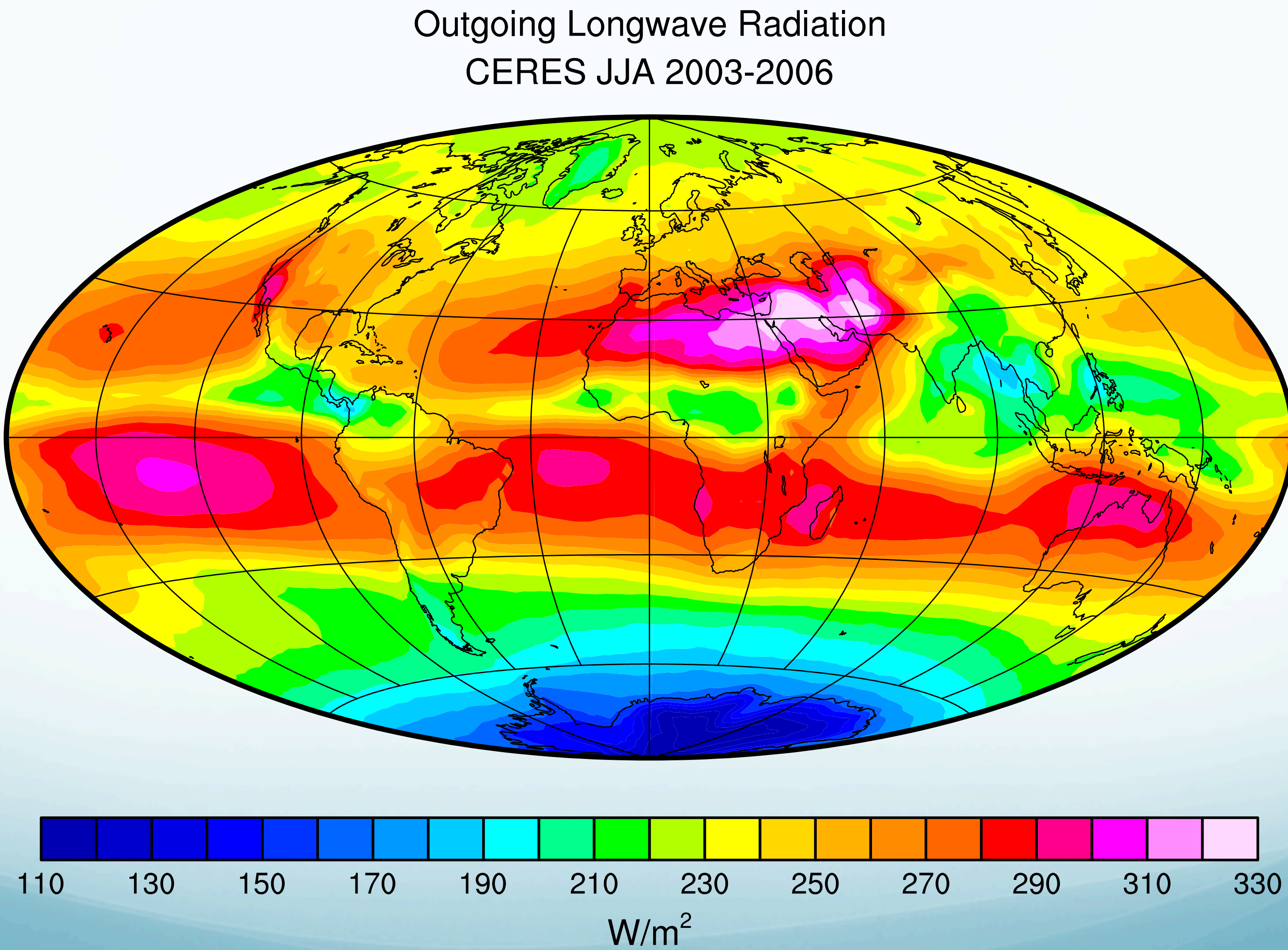
Clear-Sky Albedo



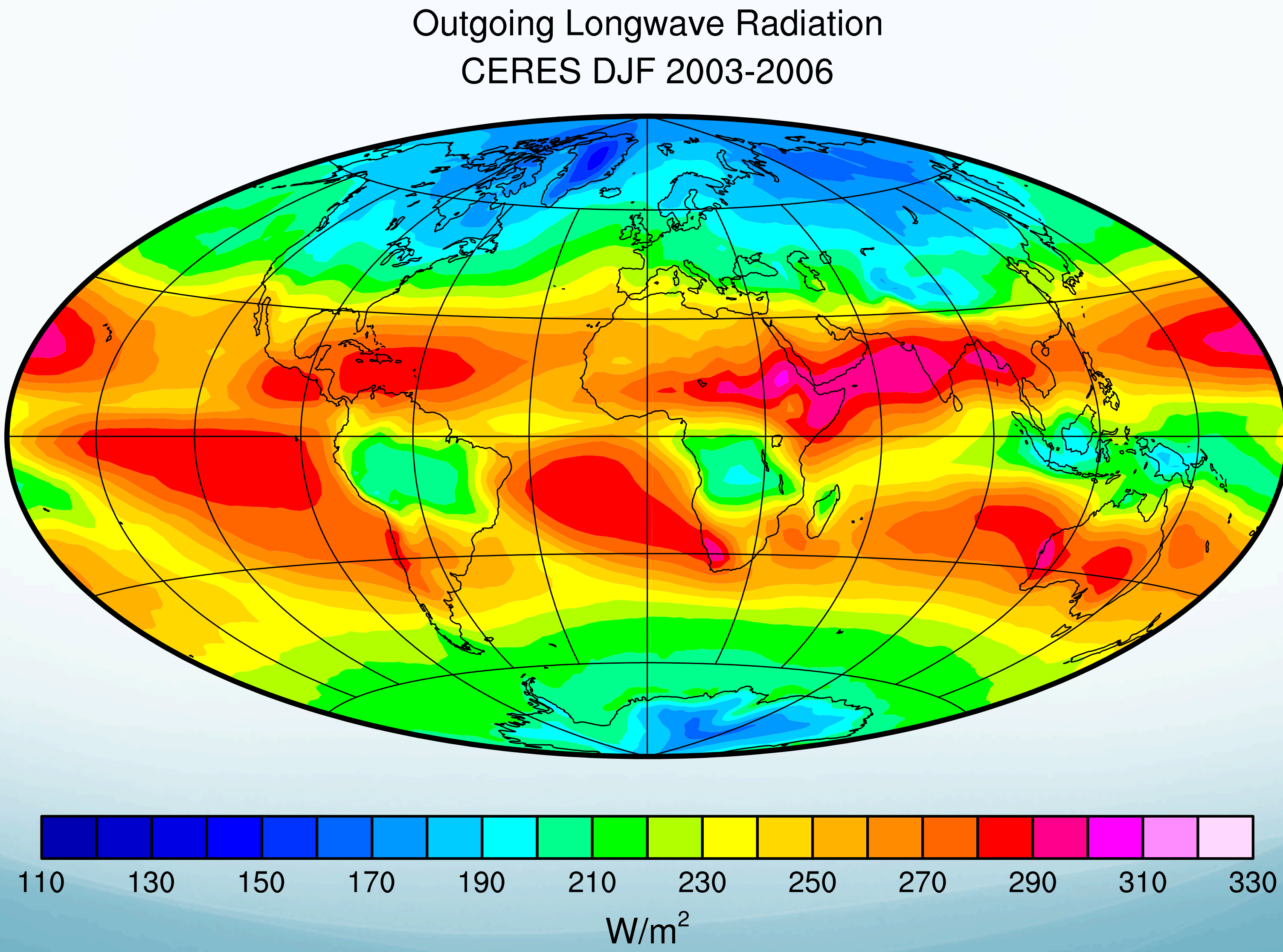
OLR = Outgoing Longwave Radiation



OLR for June, July, August = JJA



OLR for DJF


Outgoing Longwave Radiation
CERES DJF 2003-2006
110
130
150
170
190
210
230
250
270
290
310
330
W/m2

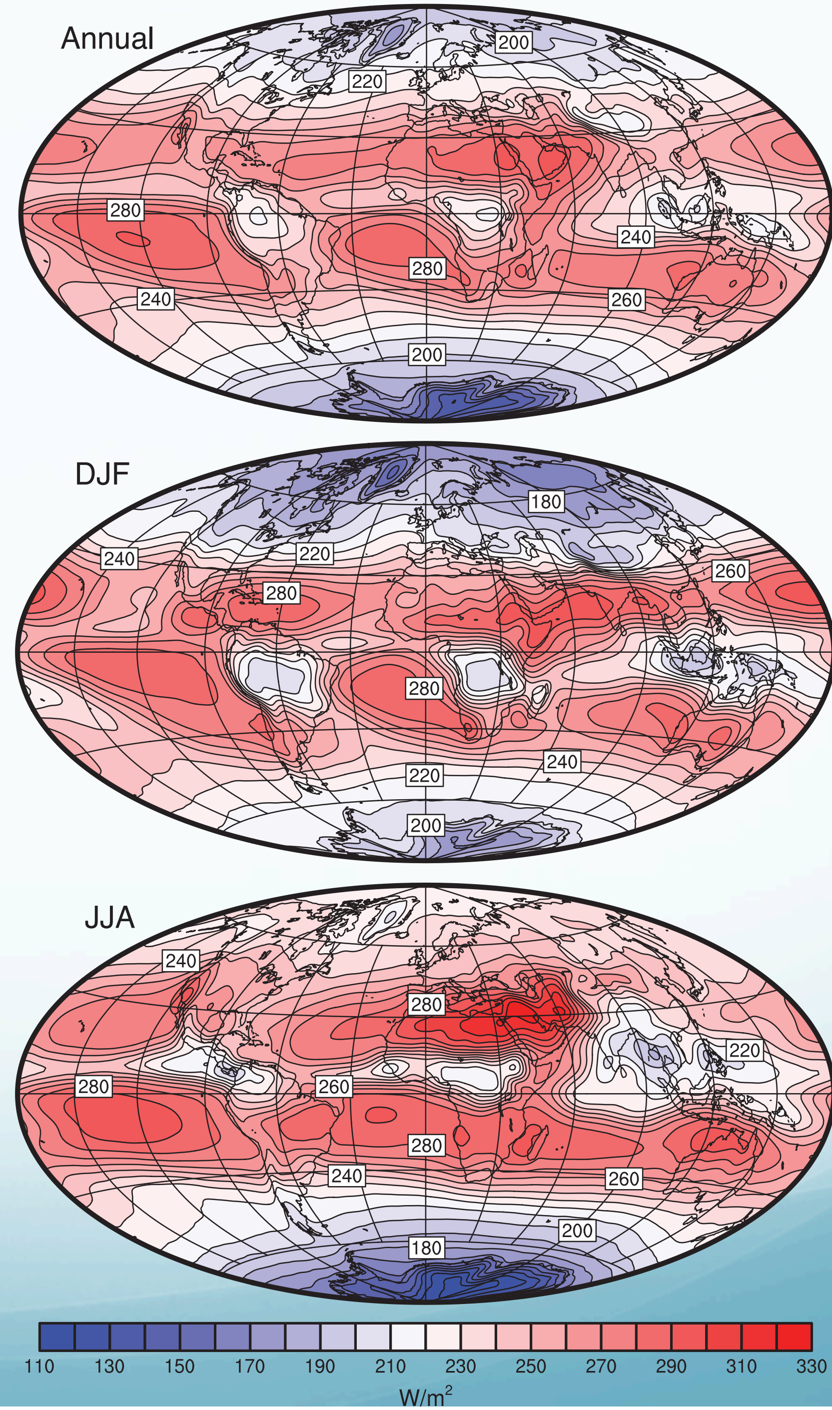
Outgoing Longwave Radiation (OLR)

Greatest in tropical latitudes that have not much cloud, since warm temperatures emit to space there.

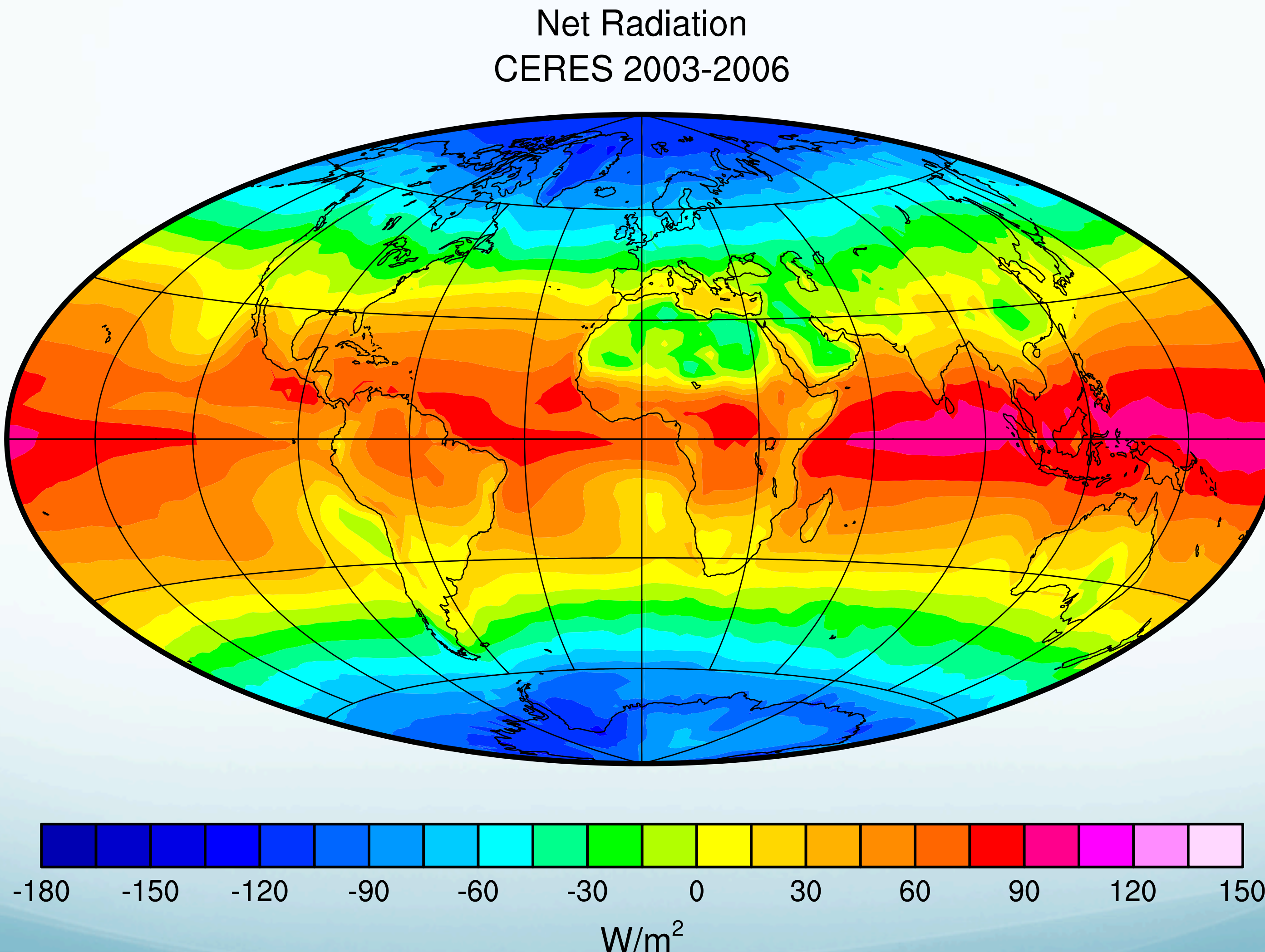
Lower over tropical cloudy regions since clouds are opaque to thermal infrared and their tops are cold.

Lower in high latitudes because it is colder there.

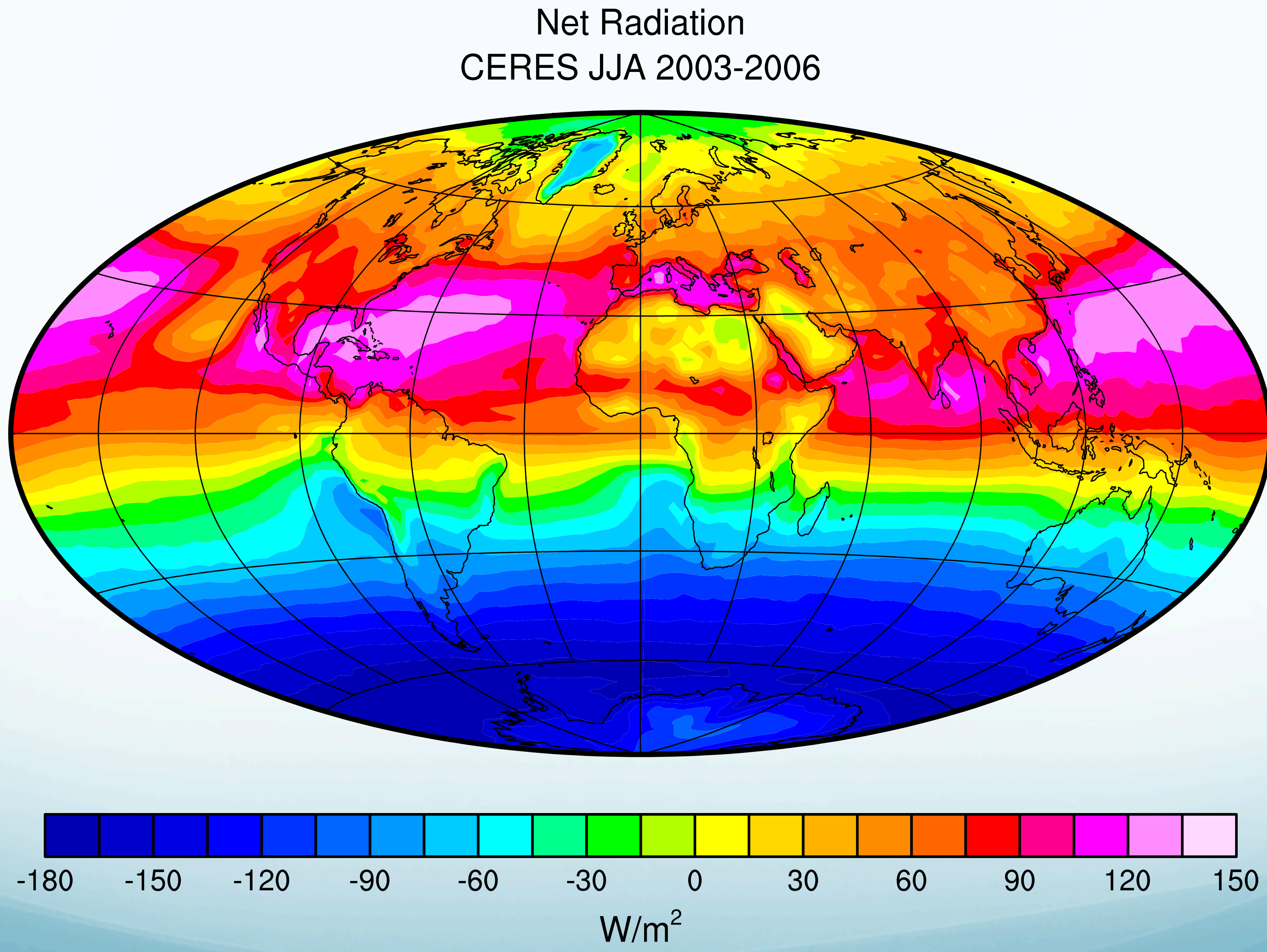
Super high over tropical deserts in summer because the surface is hot and there are few clouds or water vapor to trap IR.



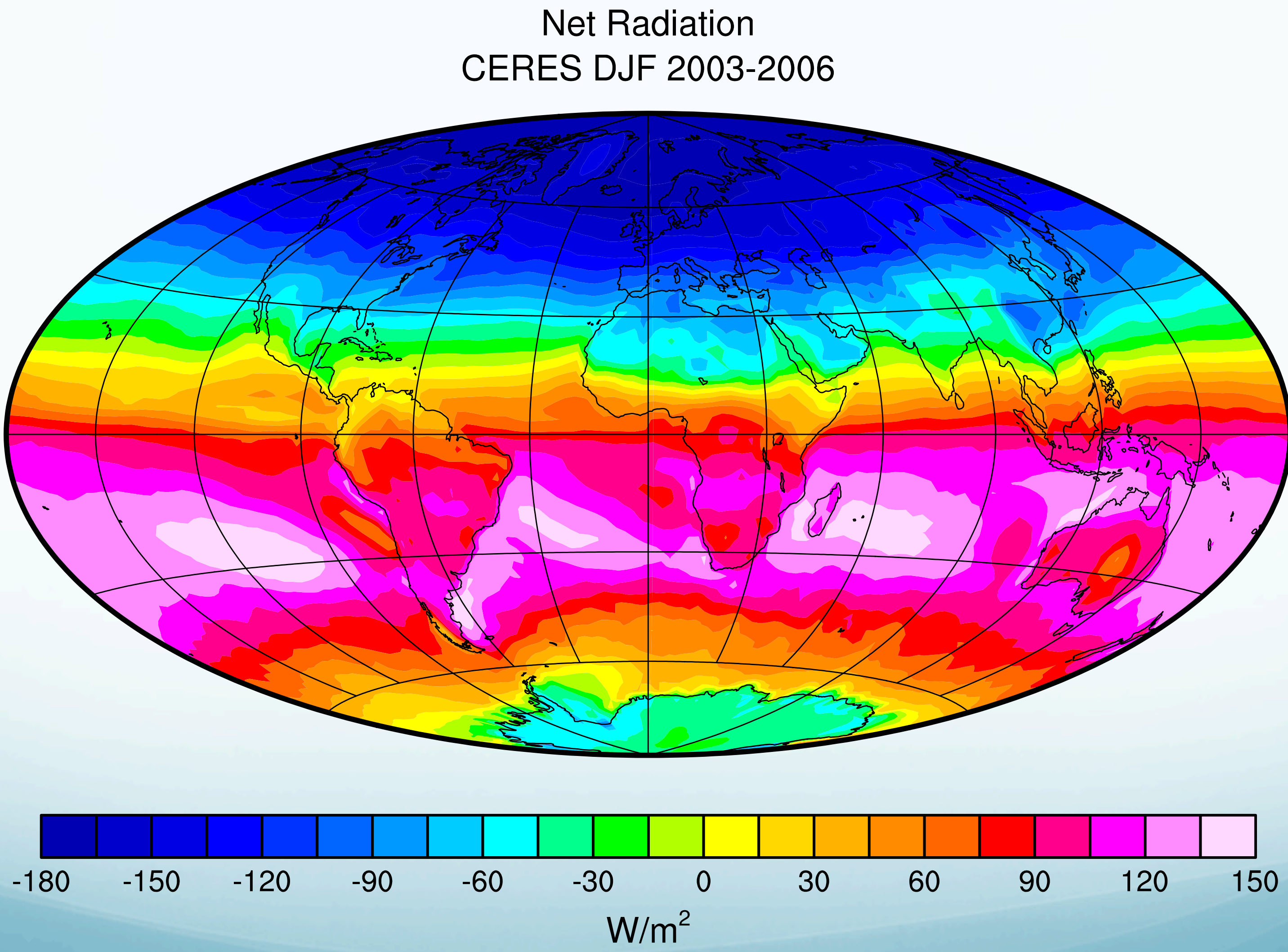
Net Radiation – Annual Mean



Net Radiation – JJA



Net Radiation – DJF

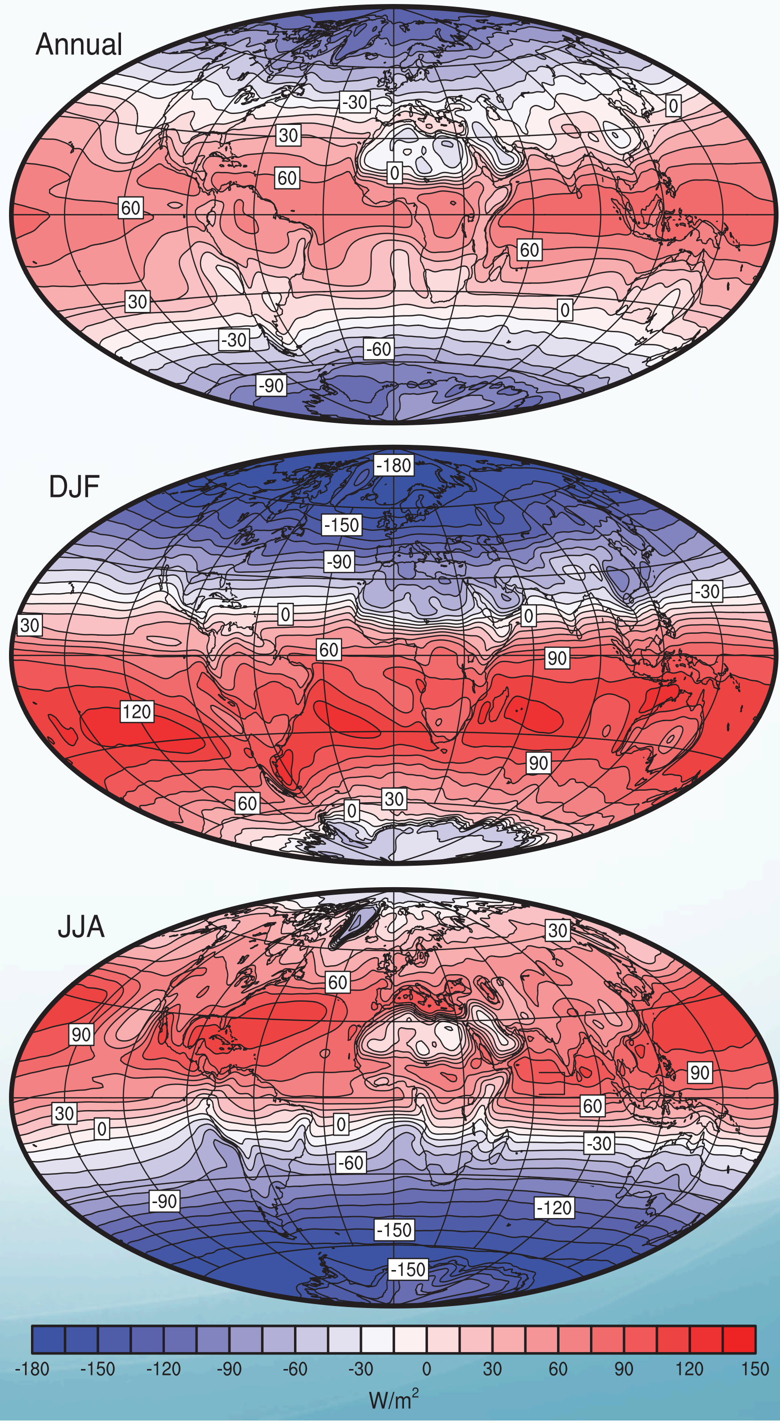


Net Incoming Radiation Absorbed Solar minus OLR

More near equator than in high latitudes

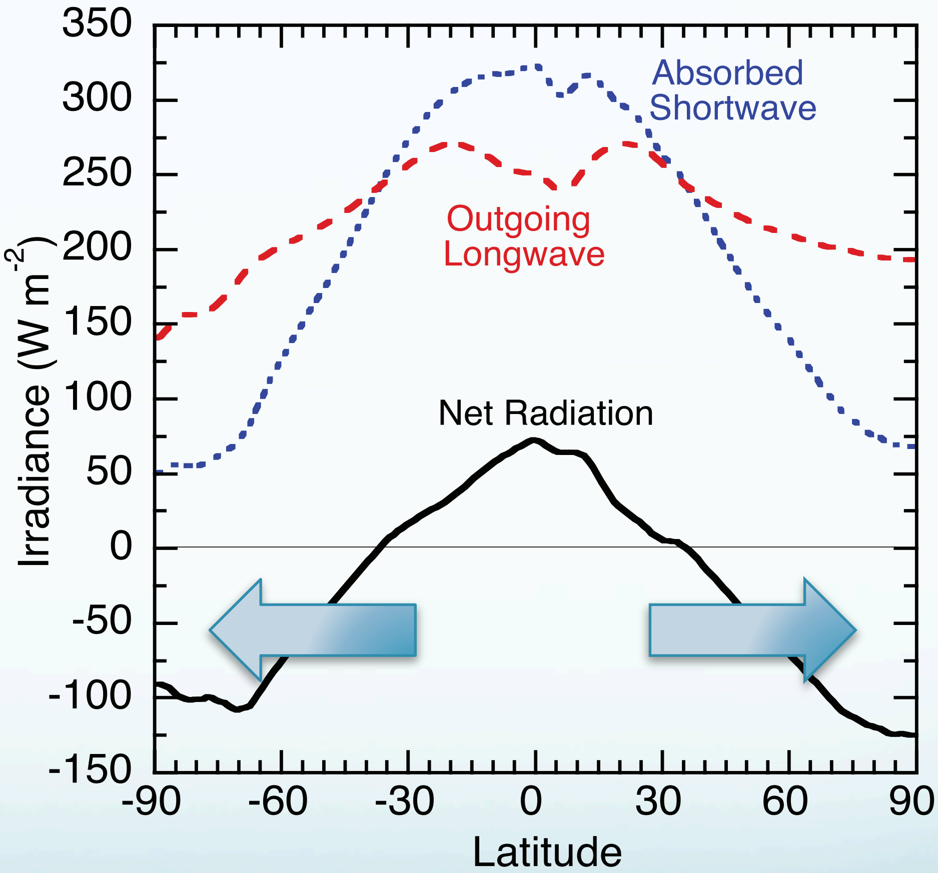
Much more in summer hemisphere than winter hemisphere

Note annual mean is negative over the Sahara/Arabian Desert. How does this support dryness there?



Zonal Average Top-of-Atmosphere (TOA) – Annual mean

Need to move Energy Poleward – in both hemispheres



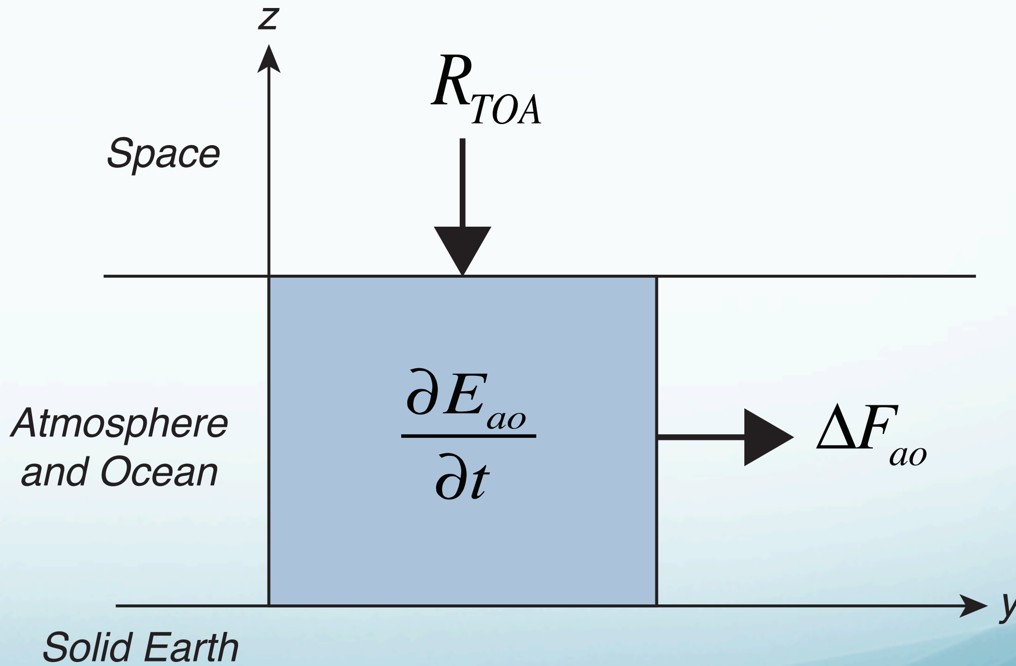
- Net Radiation has a latitude gradient - duh

Computing Poleward Flux

- We can compute the poleward energy flux in the atmosphere and ocean necessary to balance the TOA exchanges: First Law

$$\frac{\partial E_{ao}}{\partial t} = R_{TOA} - \Delta F_{ao}$$

$$R_{TOA} = \Delta F_{ao}$$



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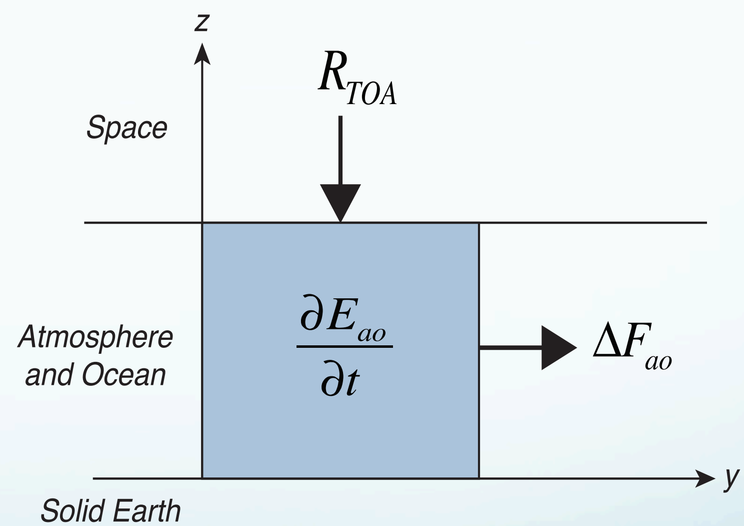


$$F(\phi) = \int_{-\frac{\pi}{2}}^{\phi} \int_{0}^{2\pi} R_{TOA} a^2 \cos\phi \, d\lambda \, d\phi$$

Poleward Energy Flux

- Compute from TOA Balance by integrating over area of polar cap

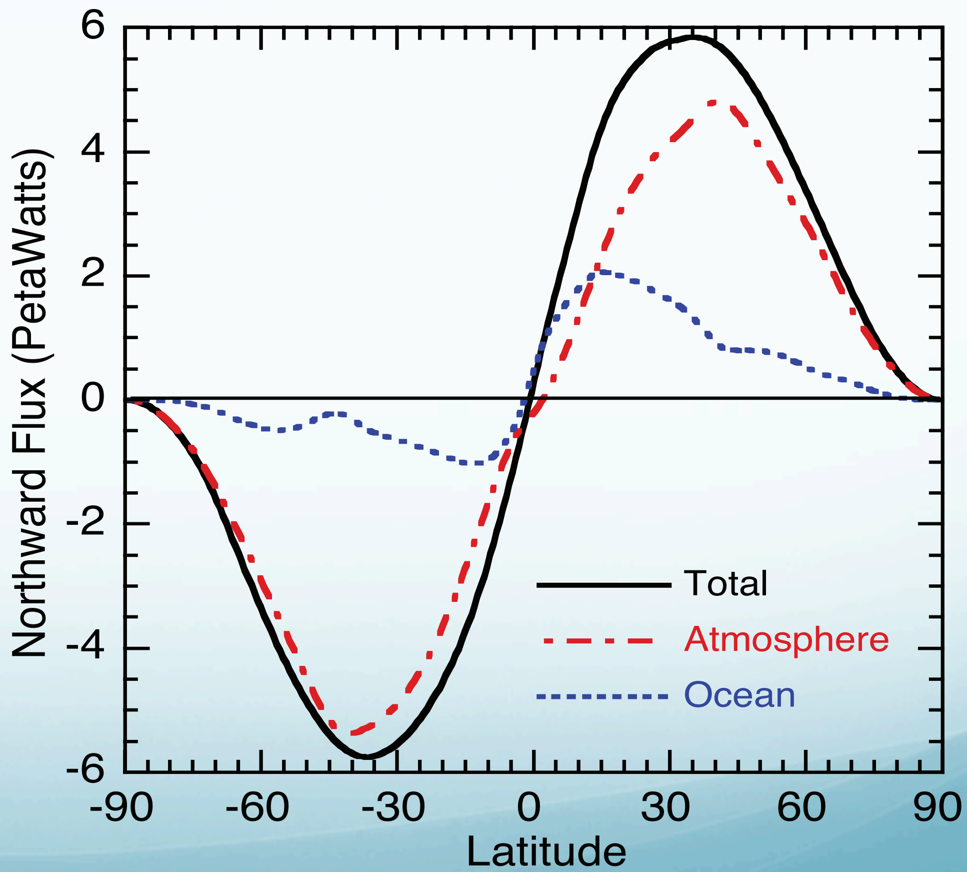
$$F(\phi) = \int_{-\frac{\pi}{2}}^{\phi} \int_{0}^{2\pi} R_{TOA} a^2 \cos\phi \, d\lambda \, d\phi$$

- Use Atmospheric Observations to compute Atmospheric Flux, then Ocean flux is residual

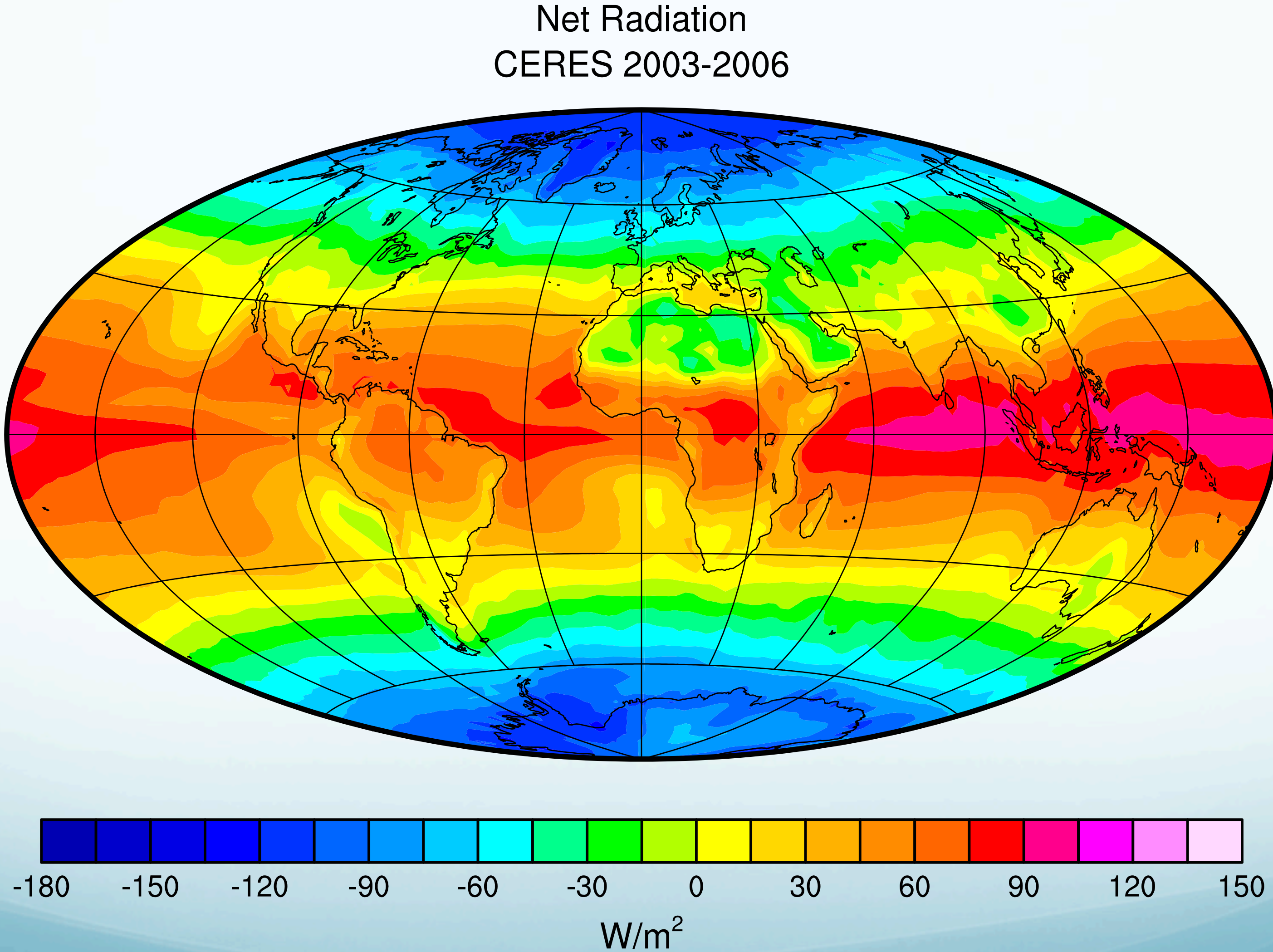
$$F_{Total}(\phi) = F_{Atmosphere}(\phi) + F_{Ocean}(\phi)$$

Poleward Heat Flux

- Contributions of atmosphere and ocean are both important, but are different functions of latitude.
- Total from TOA net radiation satellite data.
- Atmosphere from atmosphere measurements
- Ocean flux is residual in energy budget



Thanks!


Net Radiation
CERES 2003-2006
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
W/m2