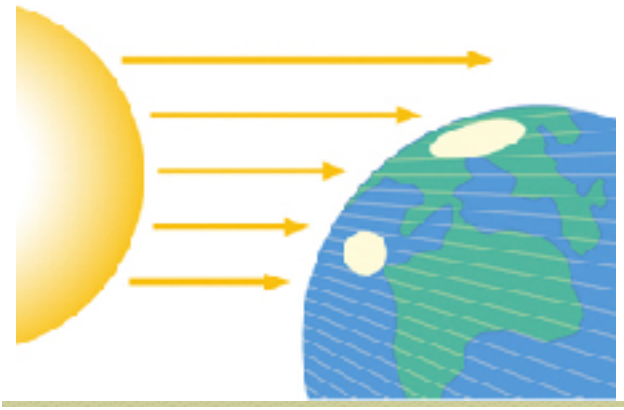
第二章:

大气环流的外部强迫（II）



授课教师：张洋

2022.9.29

第二章:

大气环流的外部强迫（II）

Reference reading: PO Chapter 6.7-6.8

2022.9.29

Outline

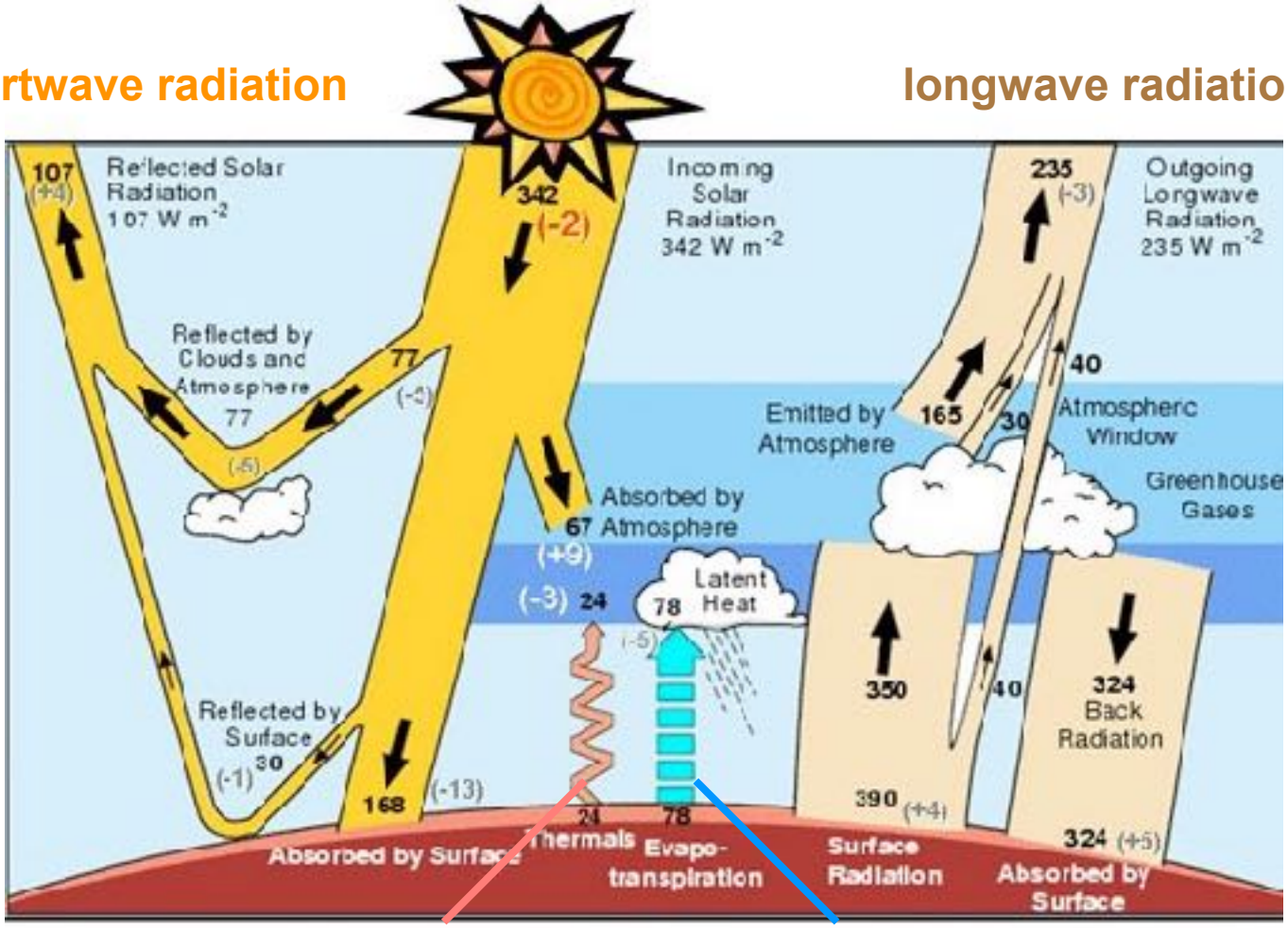
- Global averaged feature
  - TOA (Top of the atmosphere)
  - Surface
- Latitudinal distribution (zonal averaged feature)
  - TOA
  - Surface
- Zonal distribution
  - TOA
  - Surface

From the solar radiation…

Review

shortwave radiation

longwave radiation



TOA

energy budget

surface

sensible heat

latent heat

From the solar radiation…

Review

Incident solar radiation	340 W/m^2
Planetary albedo	0.3
Absorbed solar radiation	240 W/m^2
Outgoing longwave radiation	240 W/m^2

Table: globally and annually averaged TOA radiation budget

$$SW \sim LW$$

$$S(1-\alpha)$$

← TOA

Absorbed solar radiation (240 - 176)	64 W m^{-2}
Net emitted terrestrial radiation (-240 + 73)	-167 W m^{-2}
Net radiative heating	-103 W m^{-2}
Latent heat input	79 W m^{-2}
Sensible heat input	24 W m^{-2}

Table: globally and annually averaged atmosphere energy budget

energy budget

Absorbed solar (SW)	176 W m^{-2}
Downward infrared (LW↓)	312 W m^{-2}
Upward infrared (LW↑)	-385 W m^{-2}
Net longwave (LW)	-73 W m^{-2}
Net radiation (SW + LW)	103 W m^{-2}
Latent heat (LH)	-79 W m^{-2}
Sensible heat (SH)	-24 W m^{-2}

Table: globally and annually averaged surface energy budget

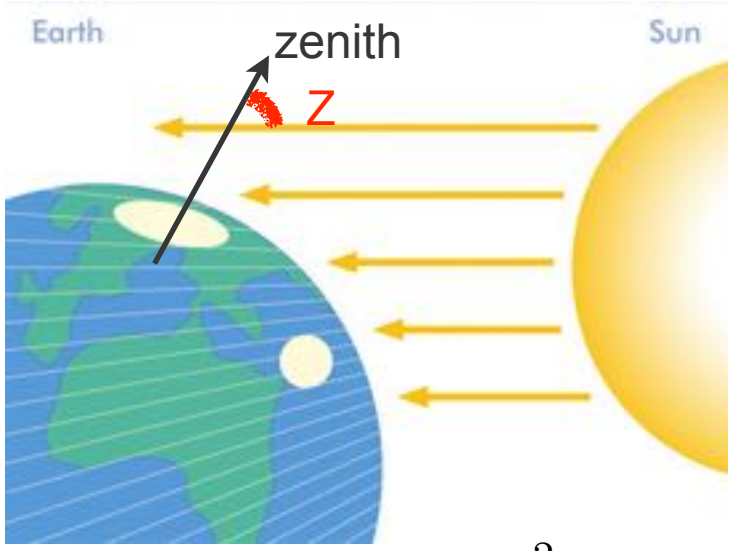
e: $SW(net) + LW(net) + LH + SH \sim 0$ ← surface

Outline

- Global averaged feature
  - TOA (Top of the atmosphere)
  - Surface
- Latitudinal distribution (zonal averaged feature)
  - TOA
  - Surface
- Zonal distribution
  - TOA
  - Surface

From the solar radiation…

- At TOA

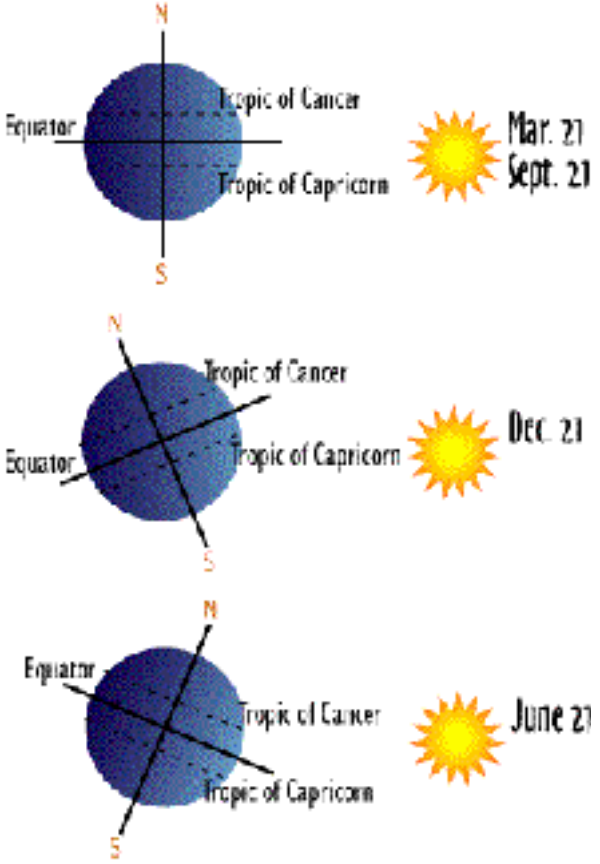


$$SW = S\,(d_m/d)^2\,cosZ$$

d -- earth-sun distance

d_m -- mean earth-sun distance

Z -- zenith angle



Solar radiation varies with latitude and season

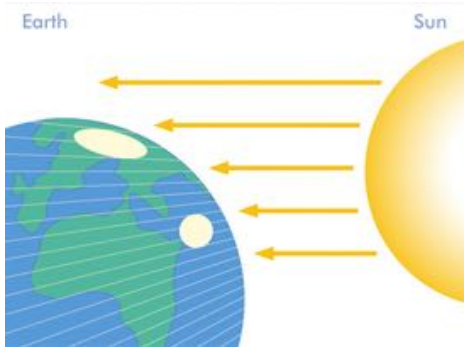
From the solar radiation…

$$SW = S\,(d_m/d)^2\,cosZ$$

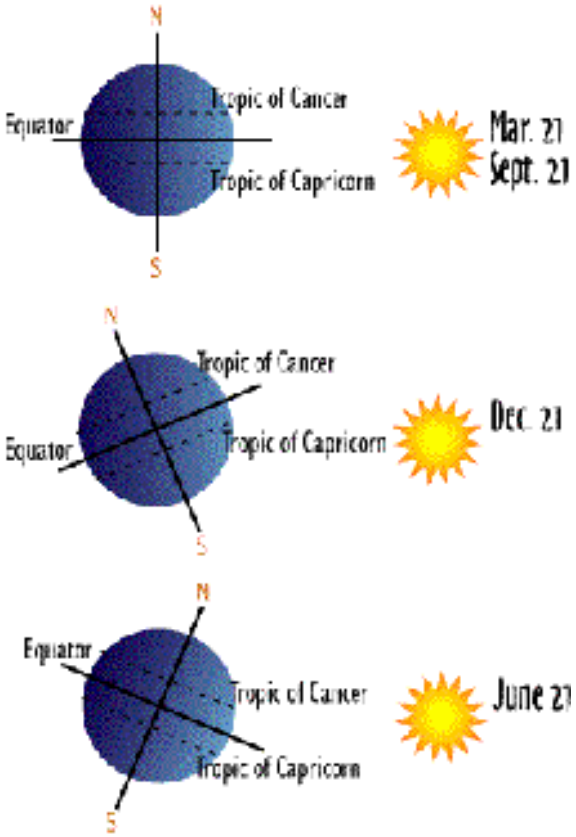
d -- earth-sun distance

d_m -- mean earth-sun distance

Z -- zenith angle



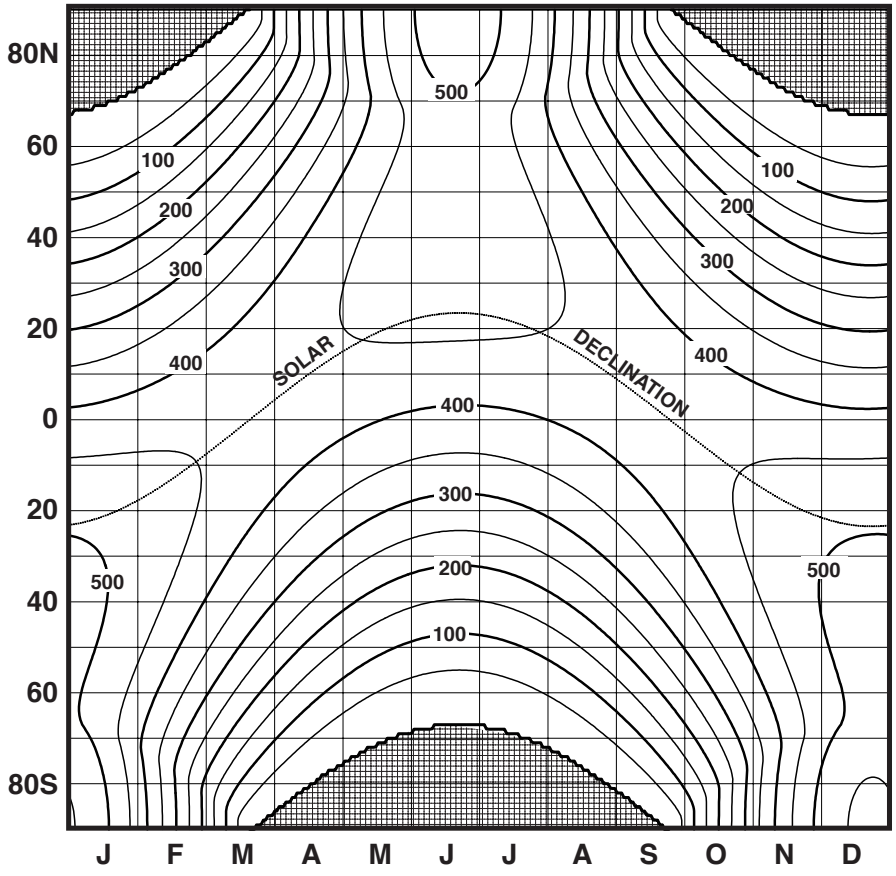
$$Q = S\,(d_m/d)^2 \int_{\text{time of sunrise}}^{\text{time of sunset}} \cos Z\, dt$$

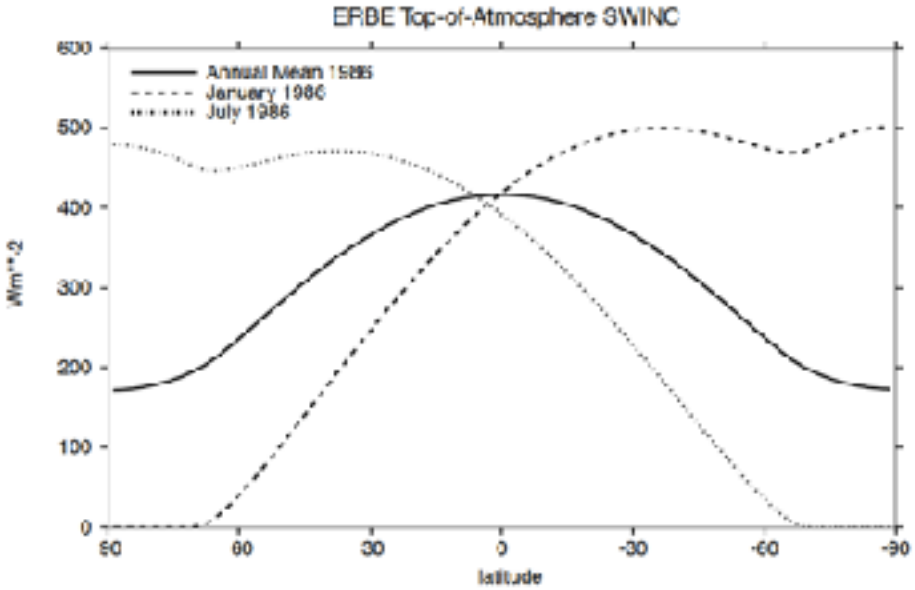


- solar radiation depends on:
  - earth-sun distance
  - length of the day
  - zenith

From the solar radiation…

- At TOA

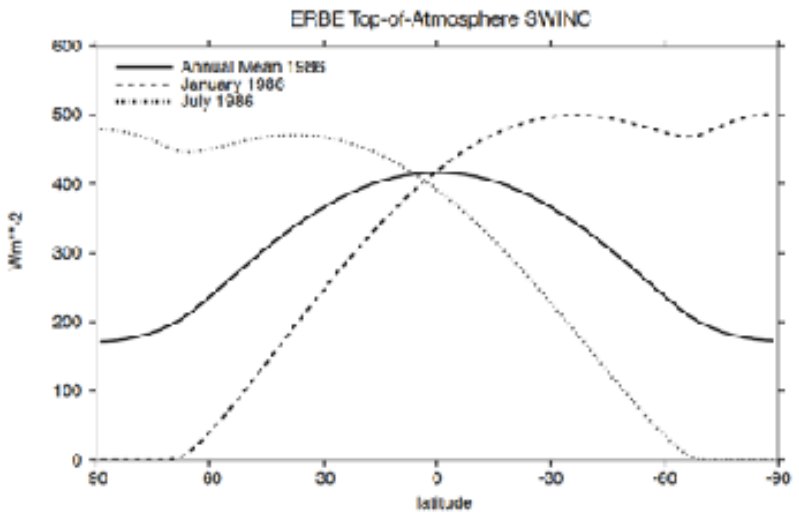


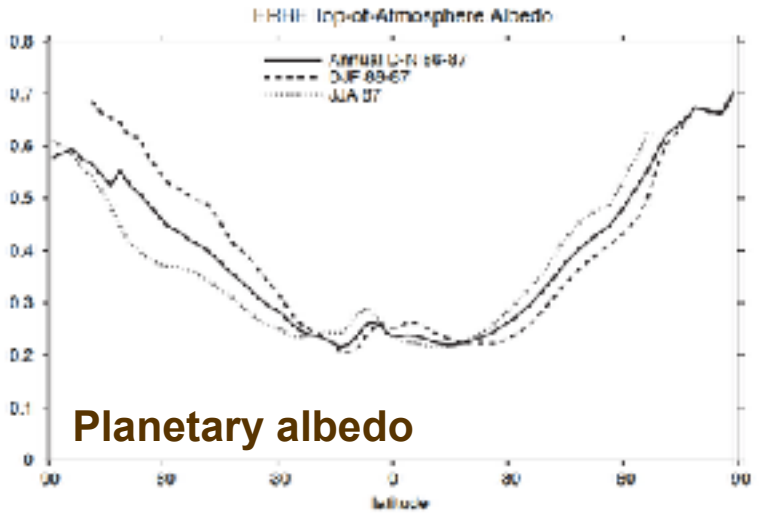


Figures: the zonally averaged incident solar radiation, observed in the Earth Radiation Budget Experiment (ERBE). (from Randall 2009)

From Peixoto and Oort, 1992

Radiation budget at TOA

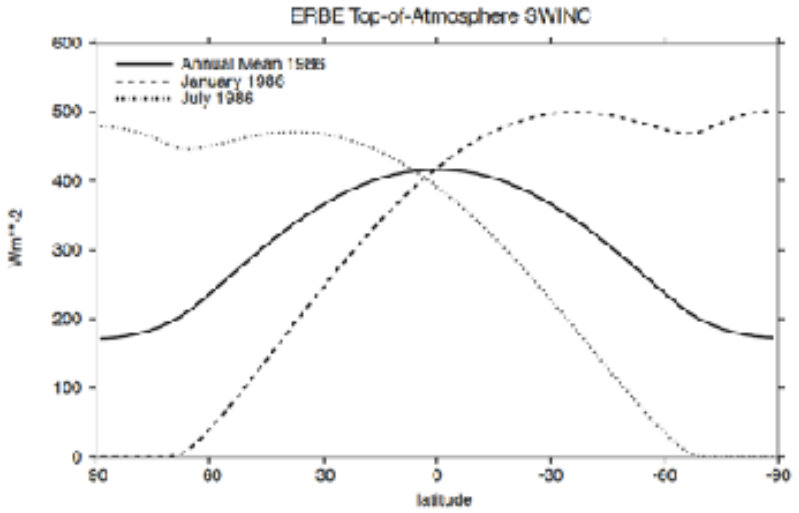


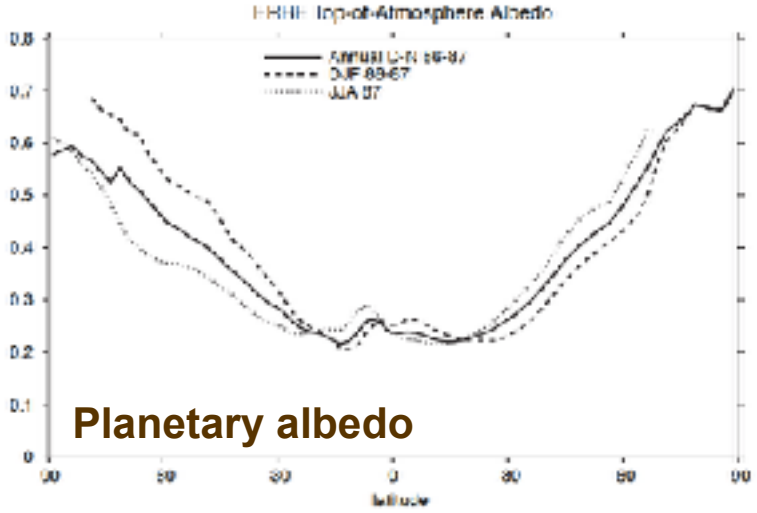


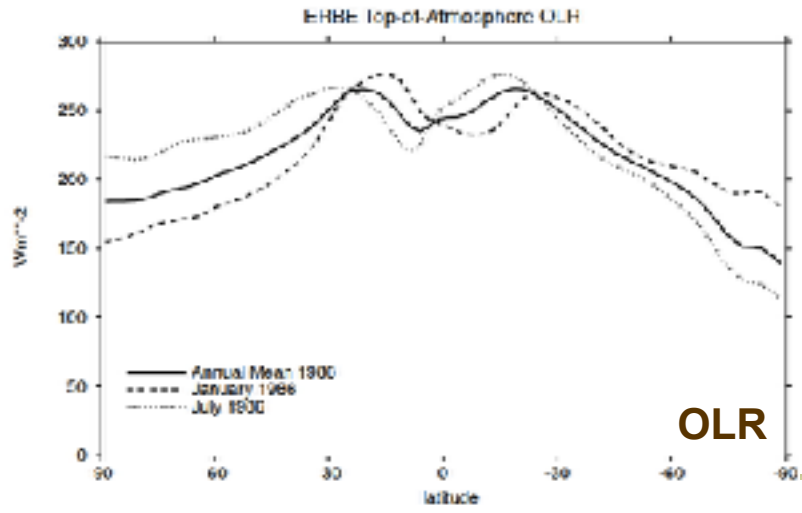
Planetary albedo

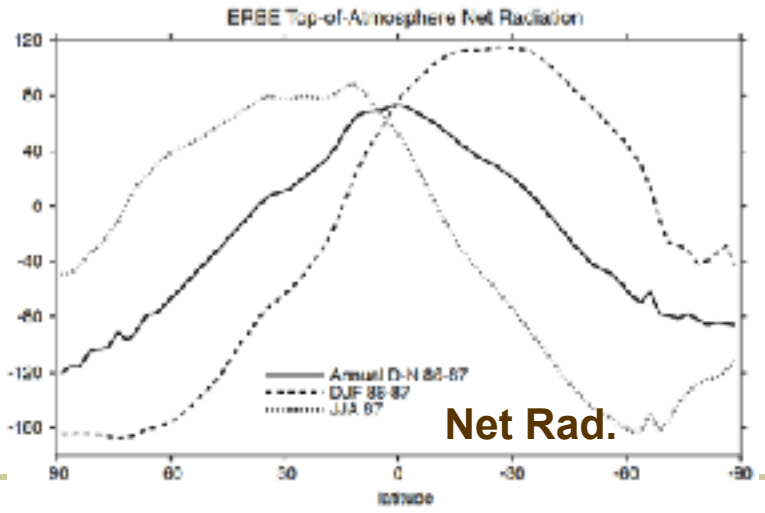
From Randall, 2009

Radiation budget at TOA



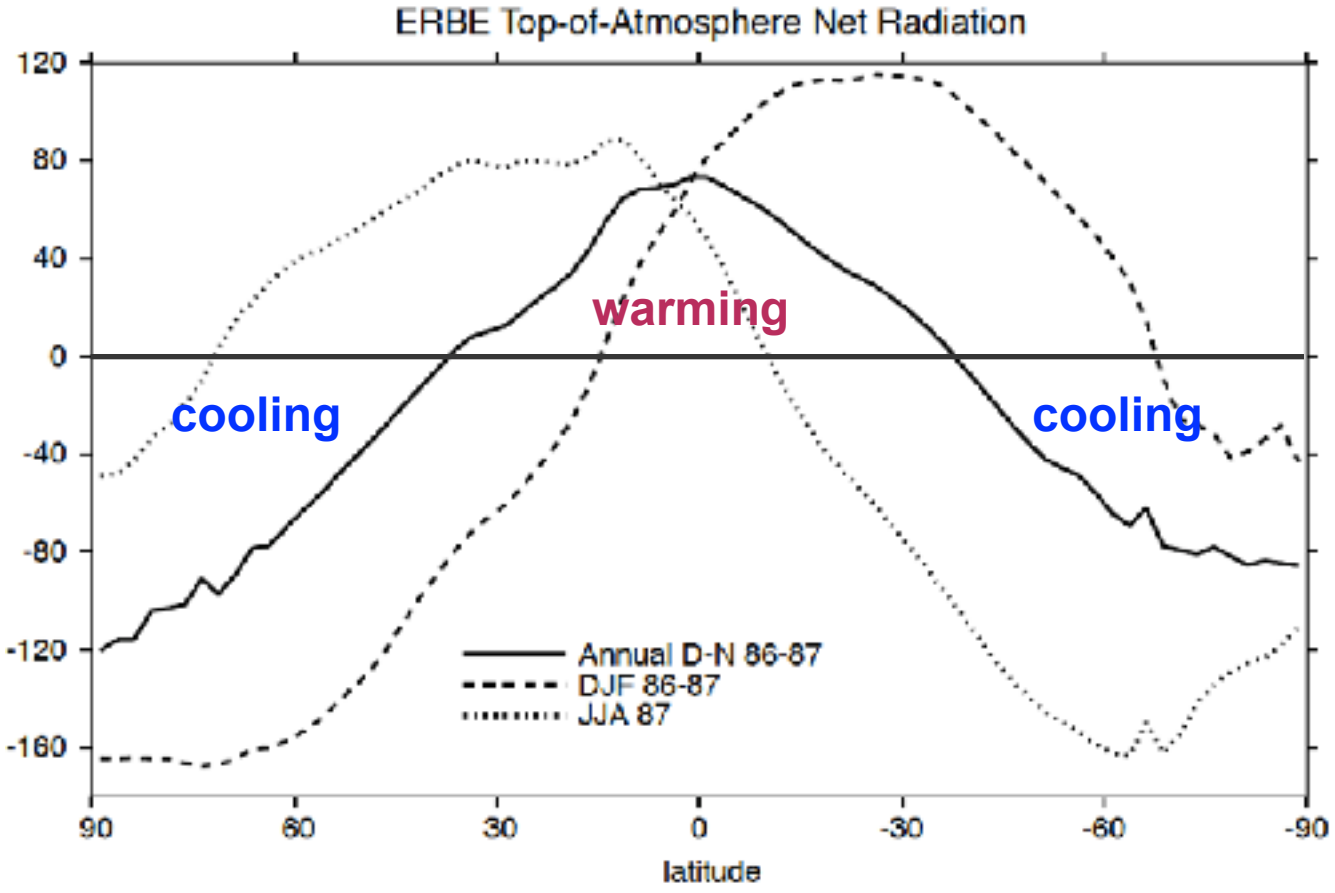






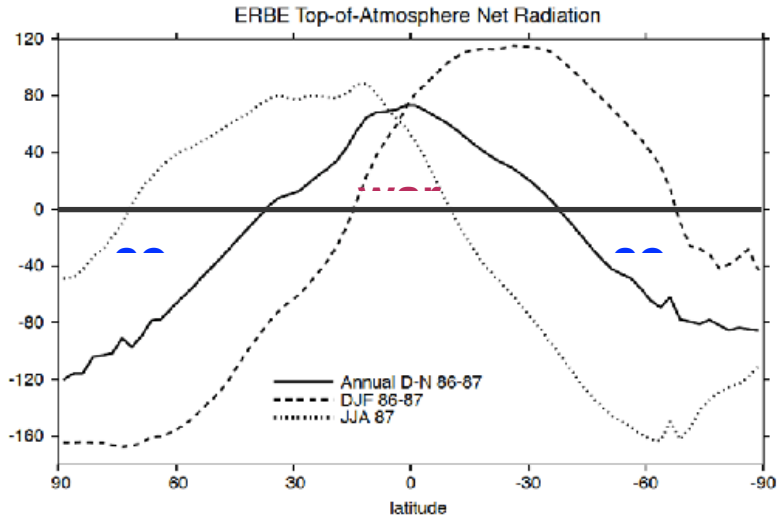
From Randall, 2009

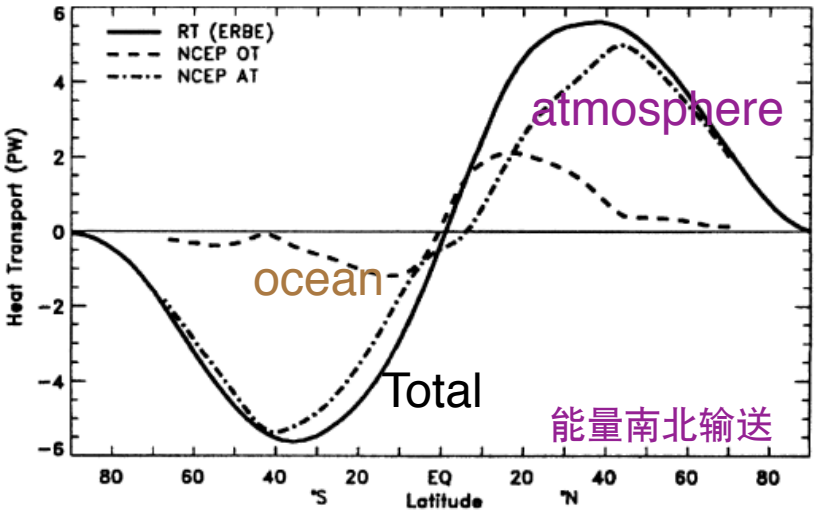
Radiation budget at TOA



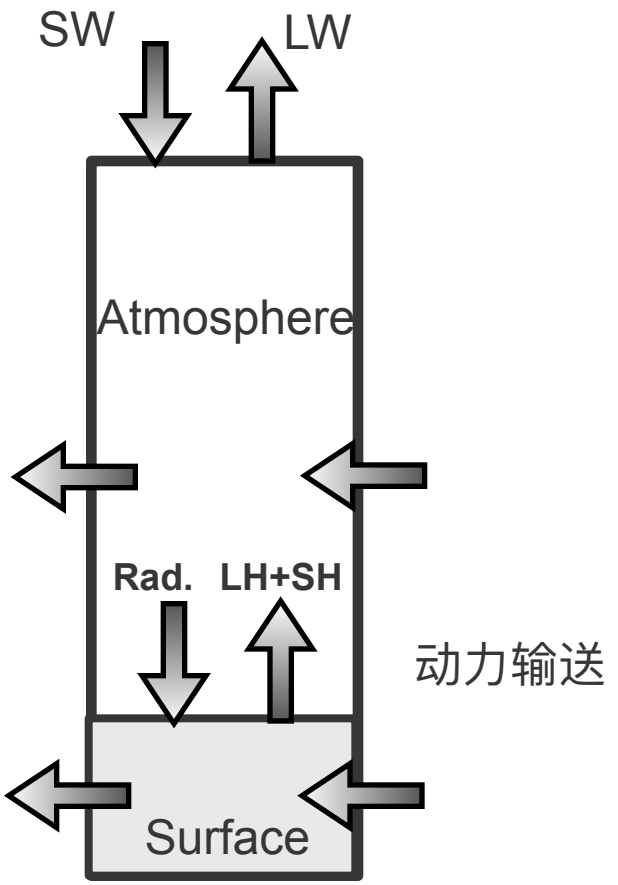
From Randall, 2009

Radiation budget at TOA





Wunsch (2005), J. Climate



Energy budget at SURFACE

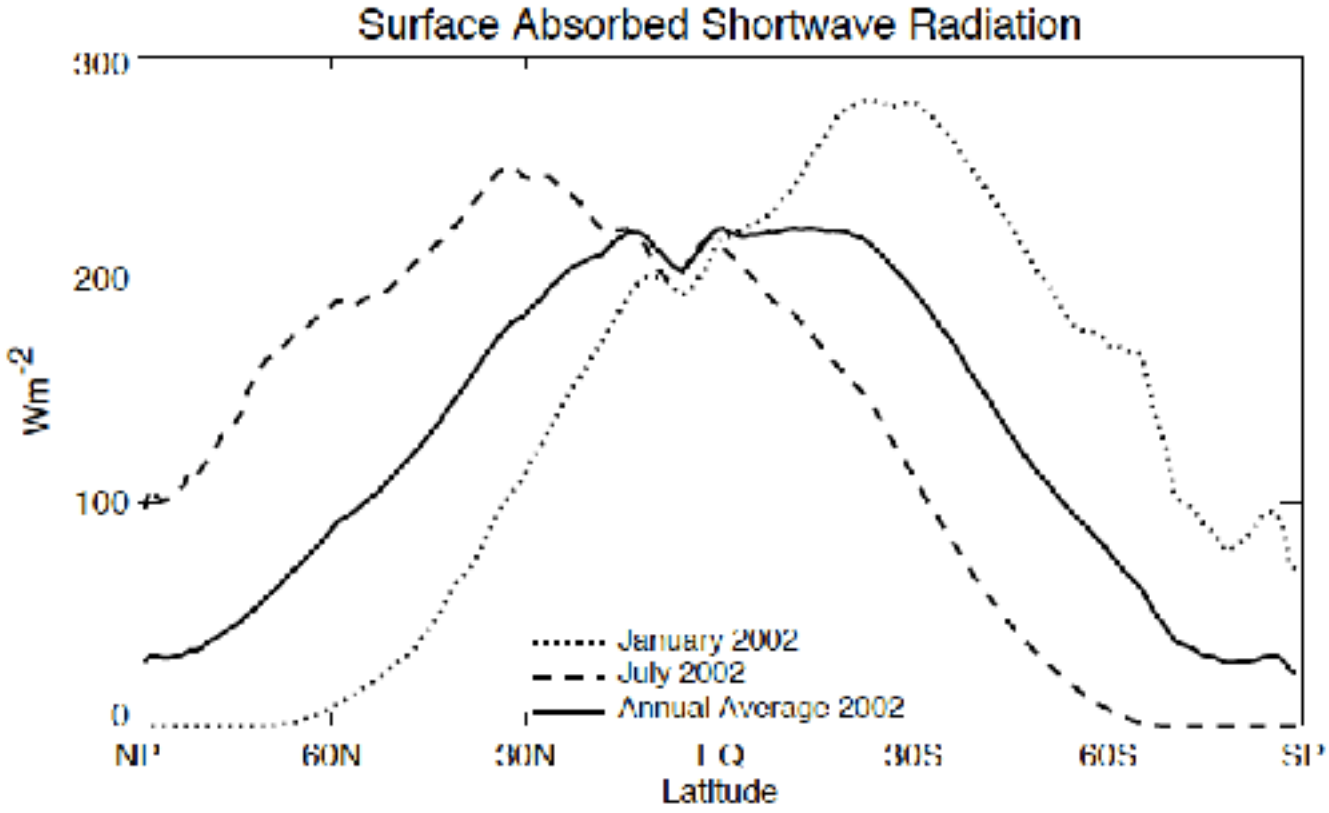


Figure: zonally averaged net surface shortwave radiative flux, positive upward (from Randall 2009).

Energy budget at SURFACE

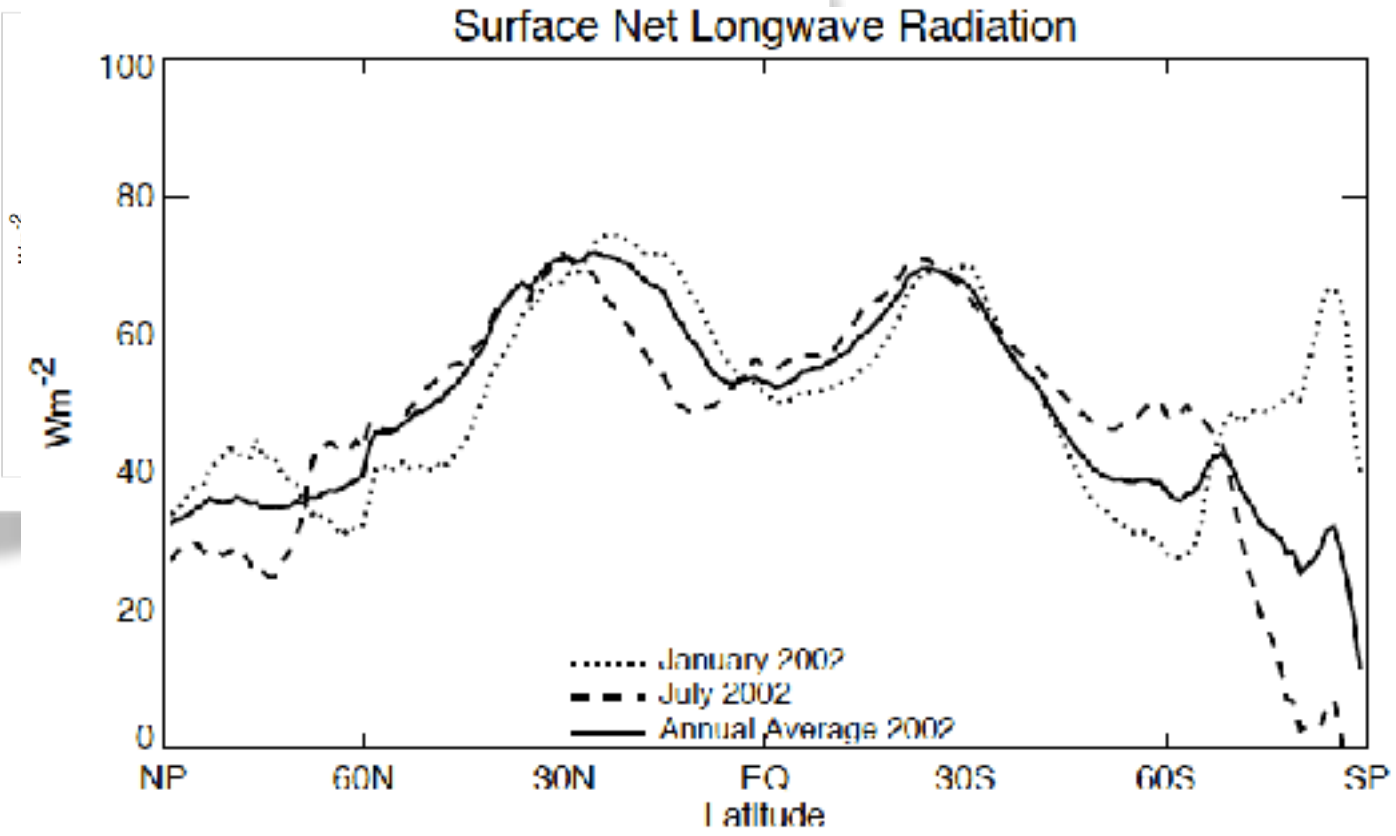


Figure: zonally averaged net surface longwave radiative flux, positive upward (from Randall 2009).

Energy budget at SURFACE

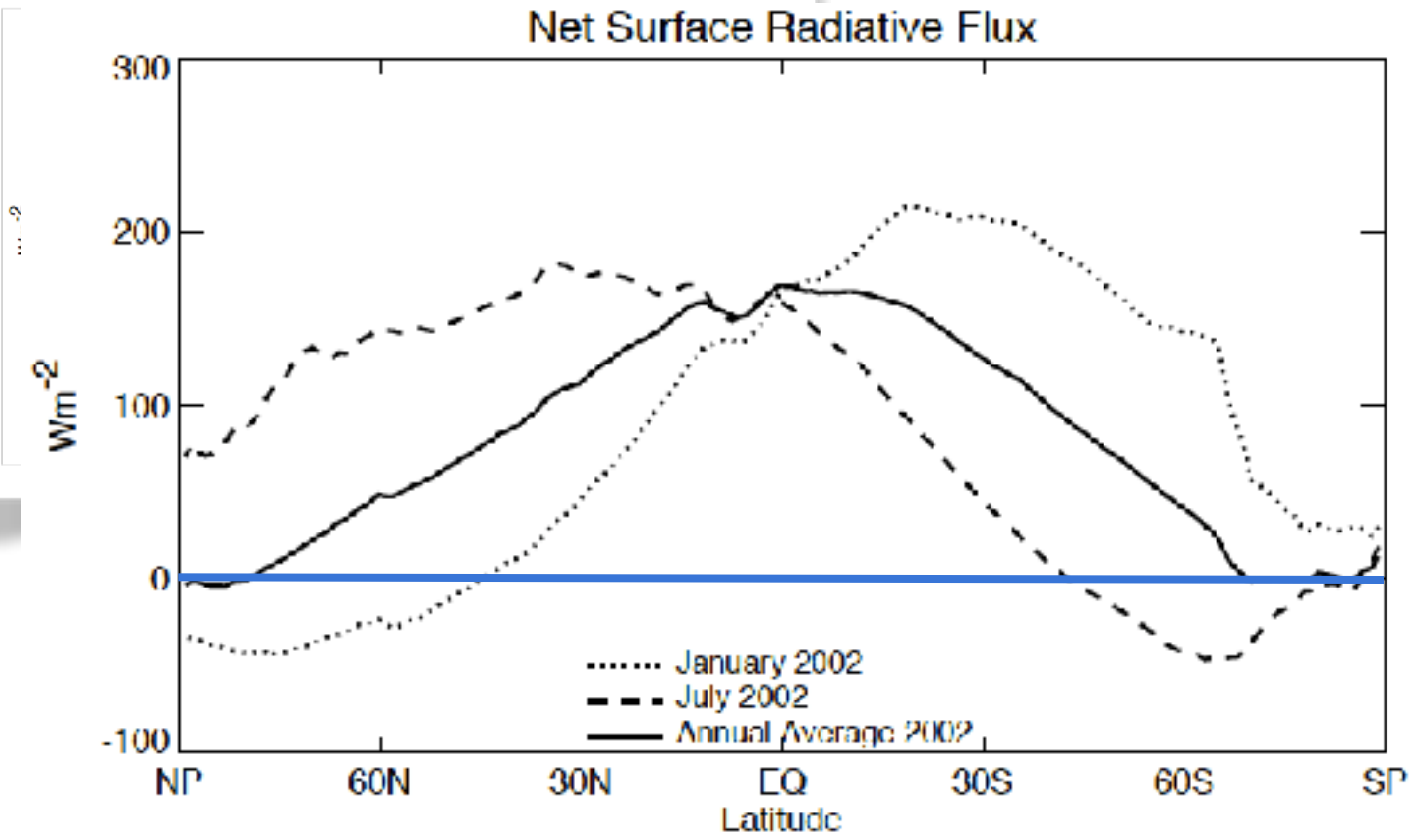
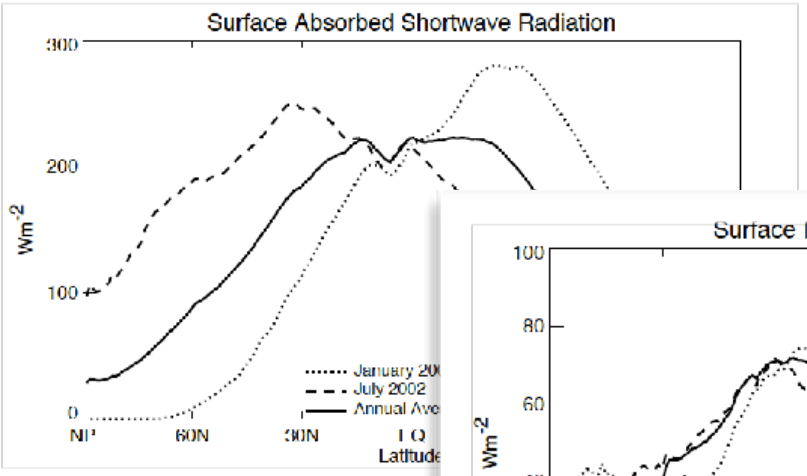
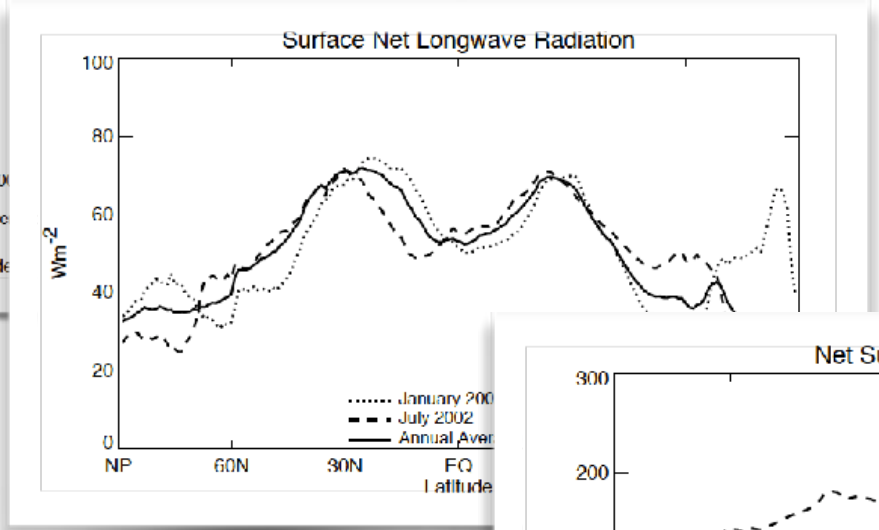
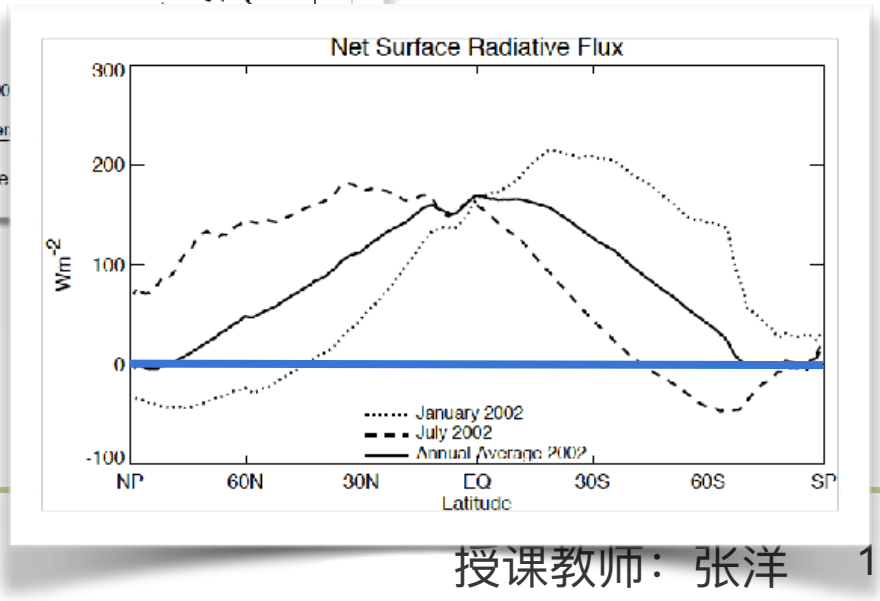


Figure: zonally averaged net surface radiative flux, positive upward (from Randall 2009).

Energy budget at SURFACE







Energy budget at SURFACE

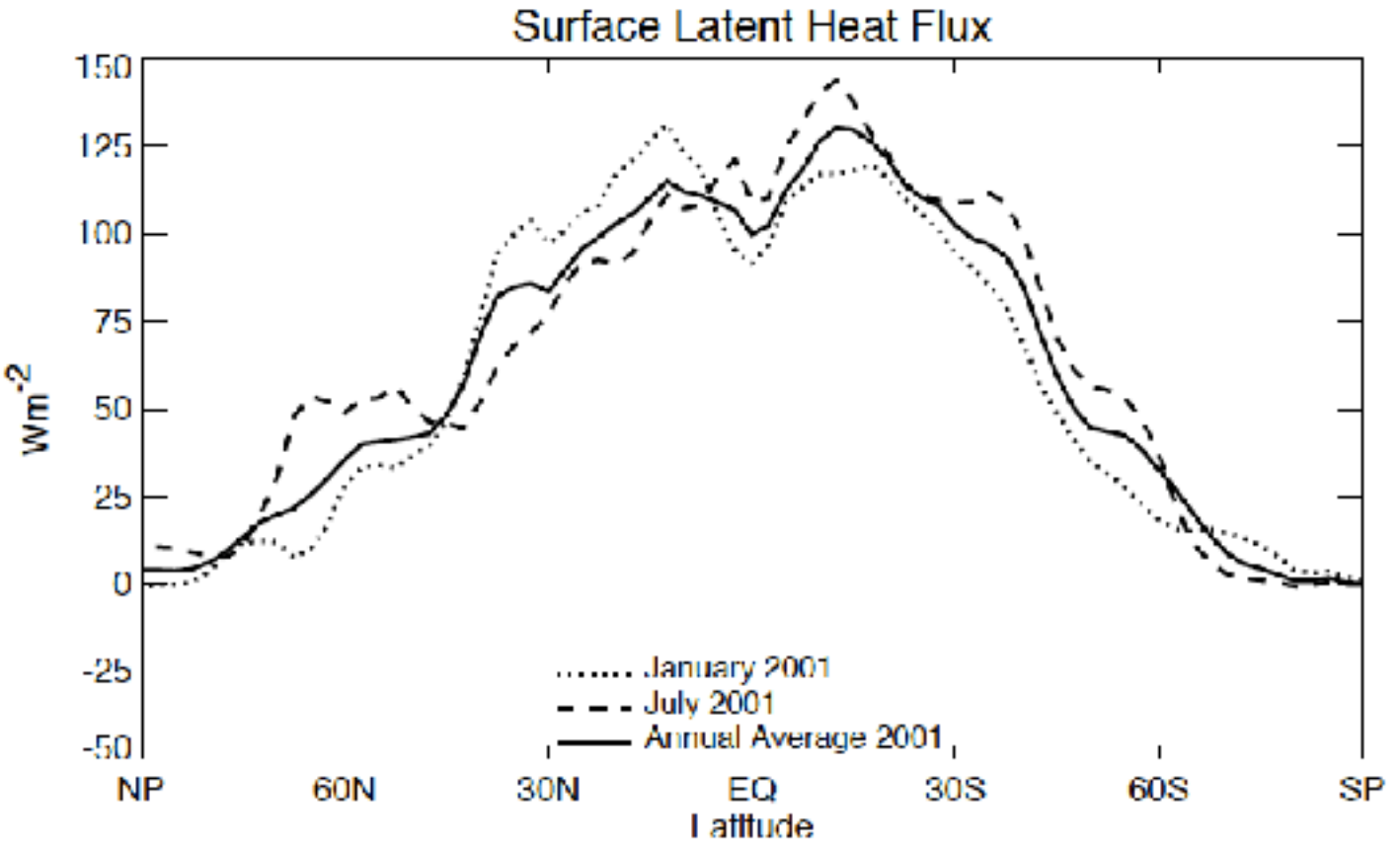


Figure: zonally averaged surface latent heat flux, positive upward, based on ECMWF (from Randall 2009).

Energy budget at SURFACE

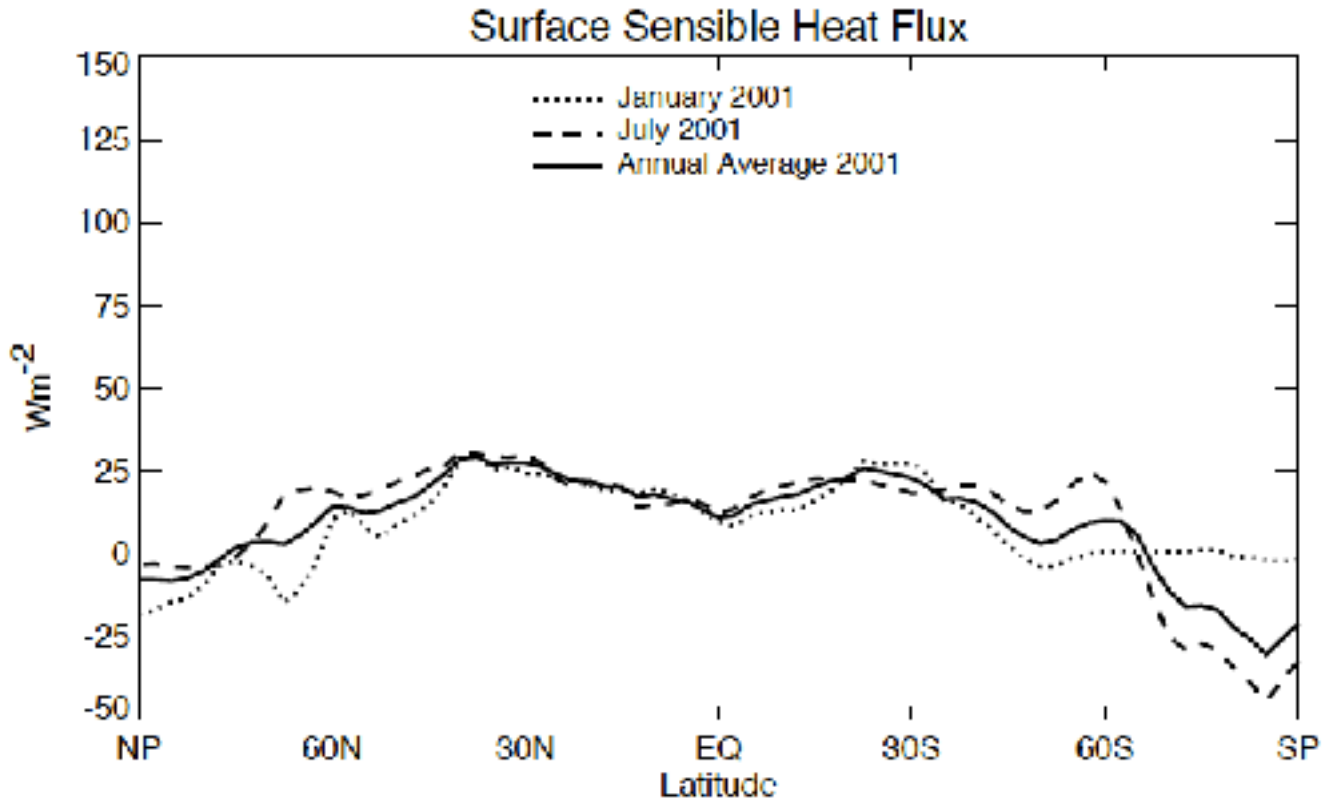
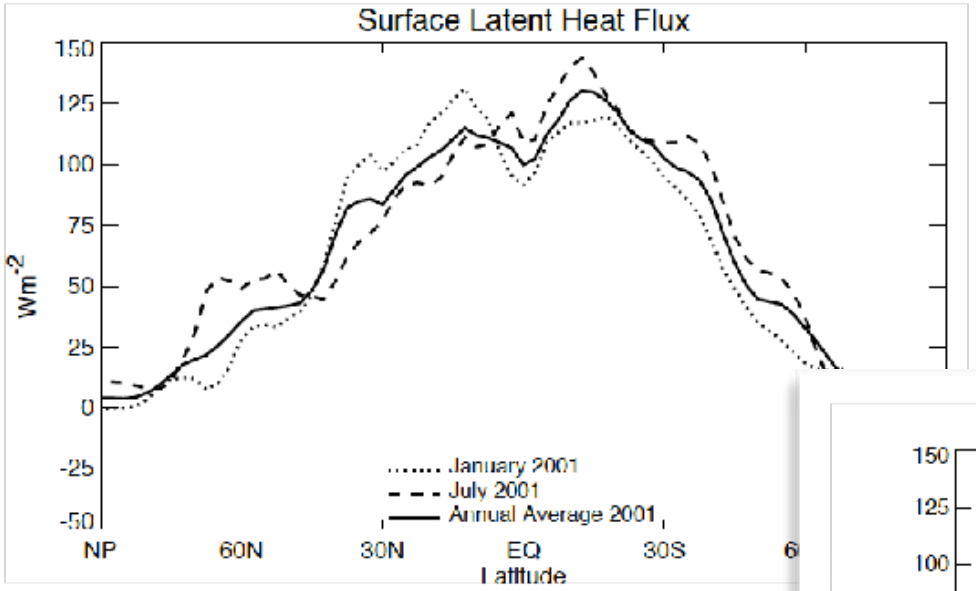
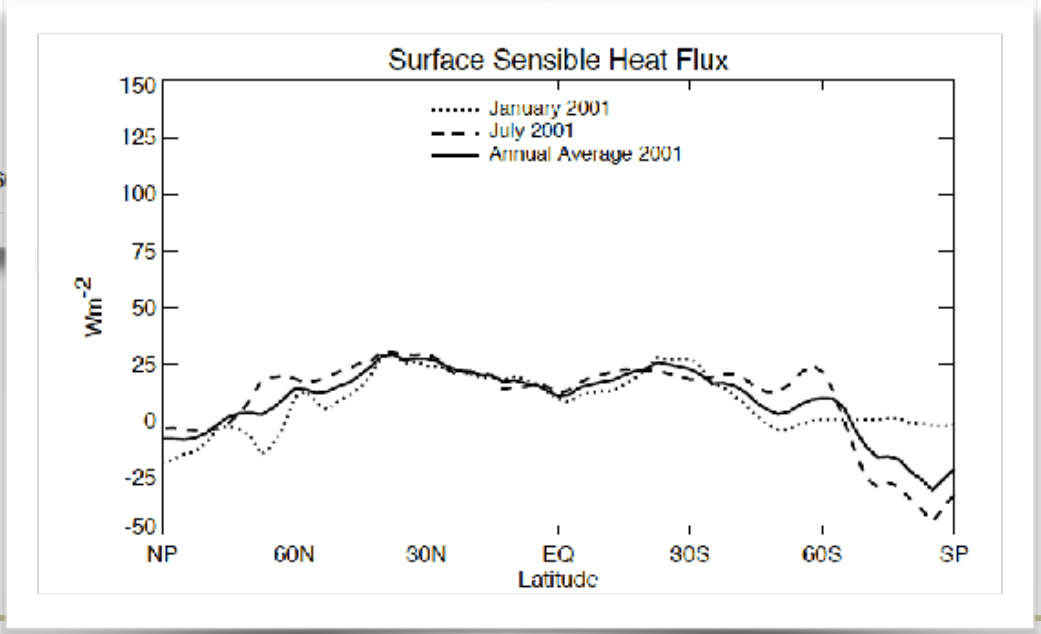


Figure: zonally averaged surface sensible heat flux, positive upward, based on ECMWF (from Randall 2009).

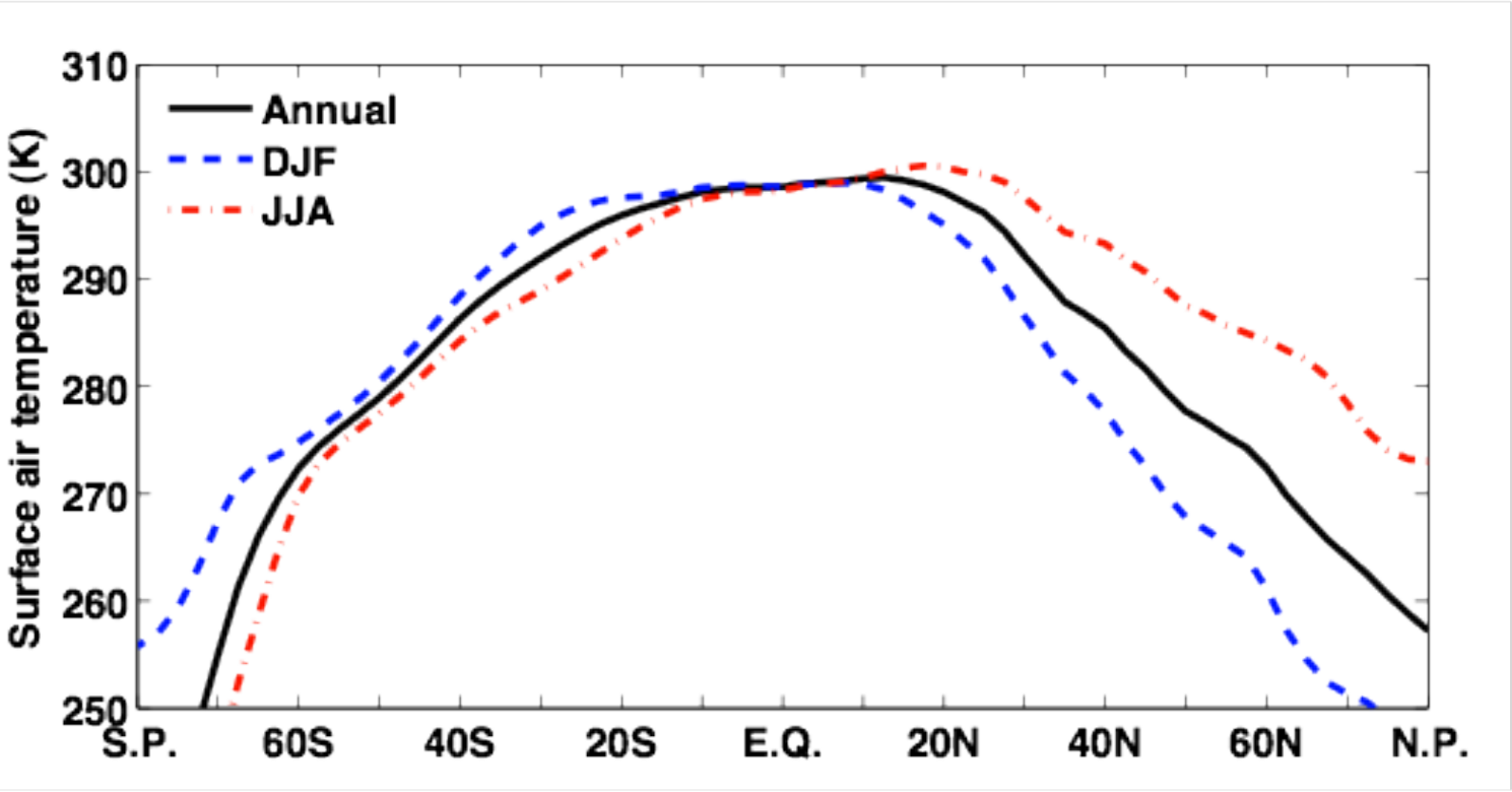
Energy budget at SURFACE





Energy budget at SURFACE

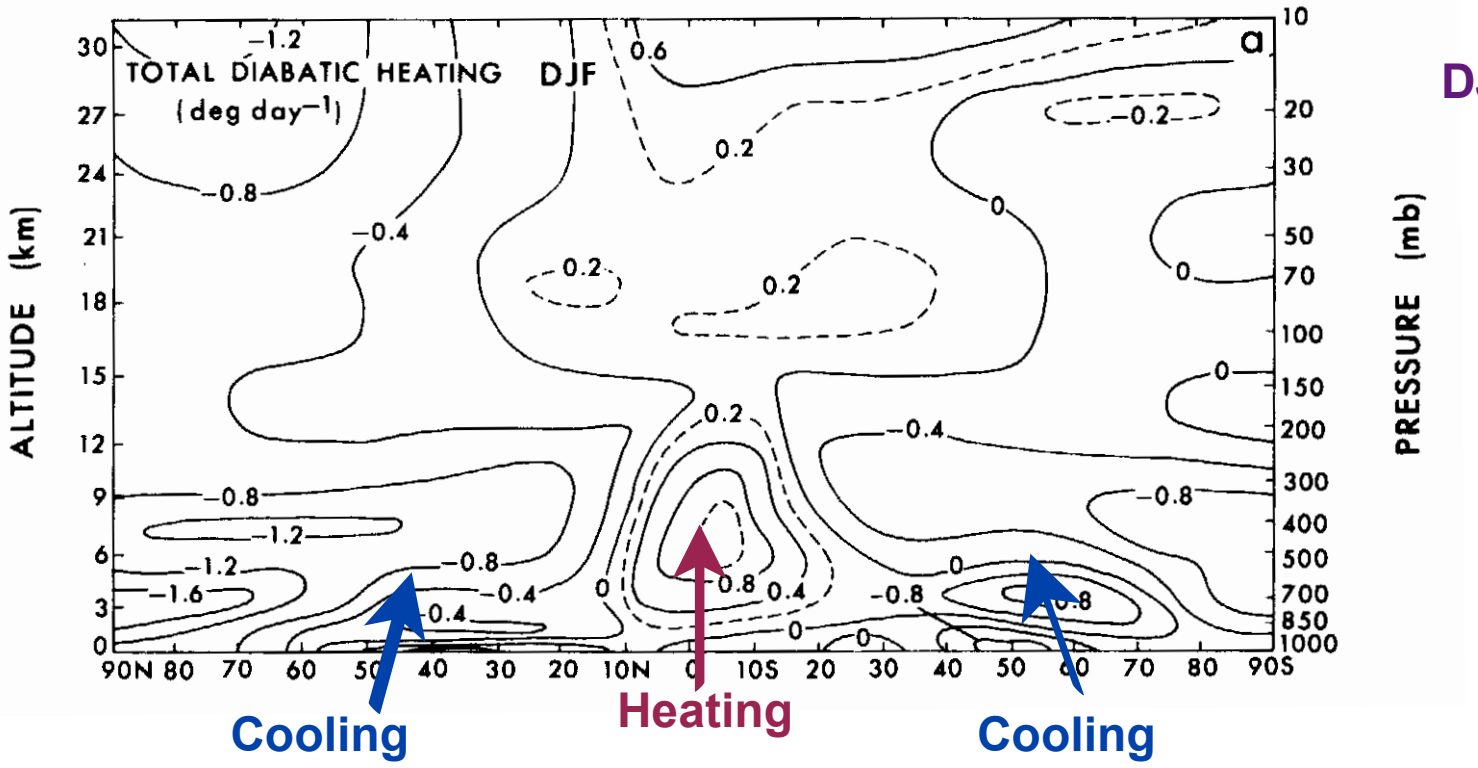
- Surface air



Energy budget at SURFACE

- Strong meridional variation in SW, LH and surface temperature
  - temperature: 250 - 310 K, strong seasonal variation in N.H.
  - absorbed solar radiation: 0 - 280 W/m^2, strong seasonal variation
  - latent heat: 0 - 150 W/m^2

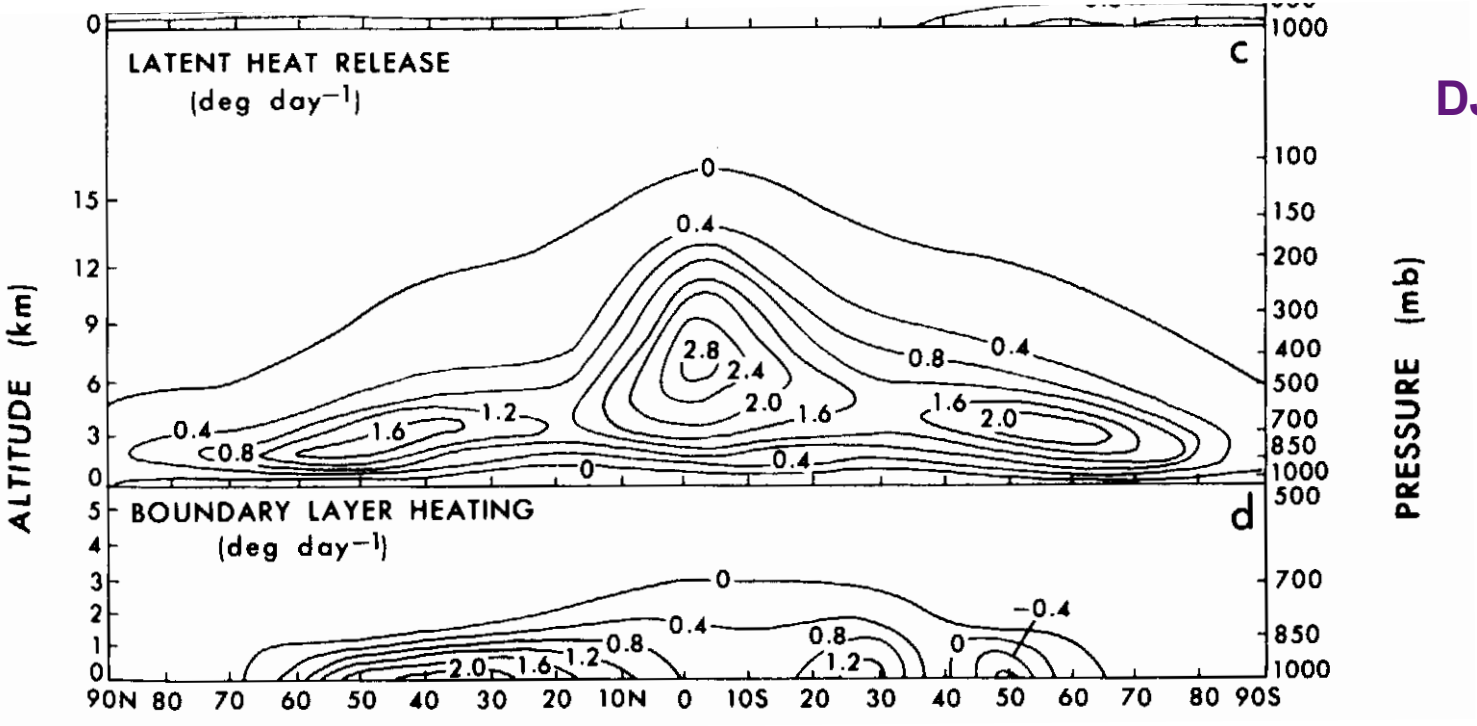
Diabatic heating in atmosphere
estimated as residual



DJF

from Peixoto and Oort, 1992

Diabatic heating in atmosphere
estimated as residual

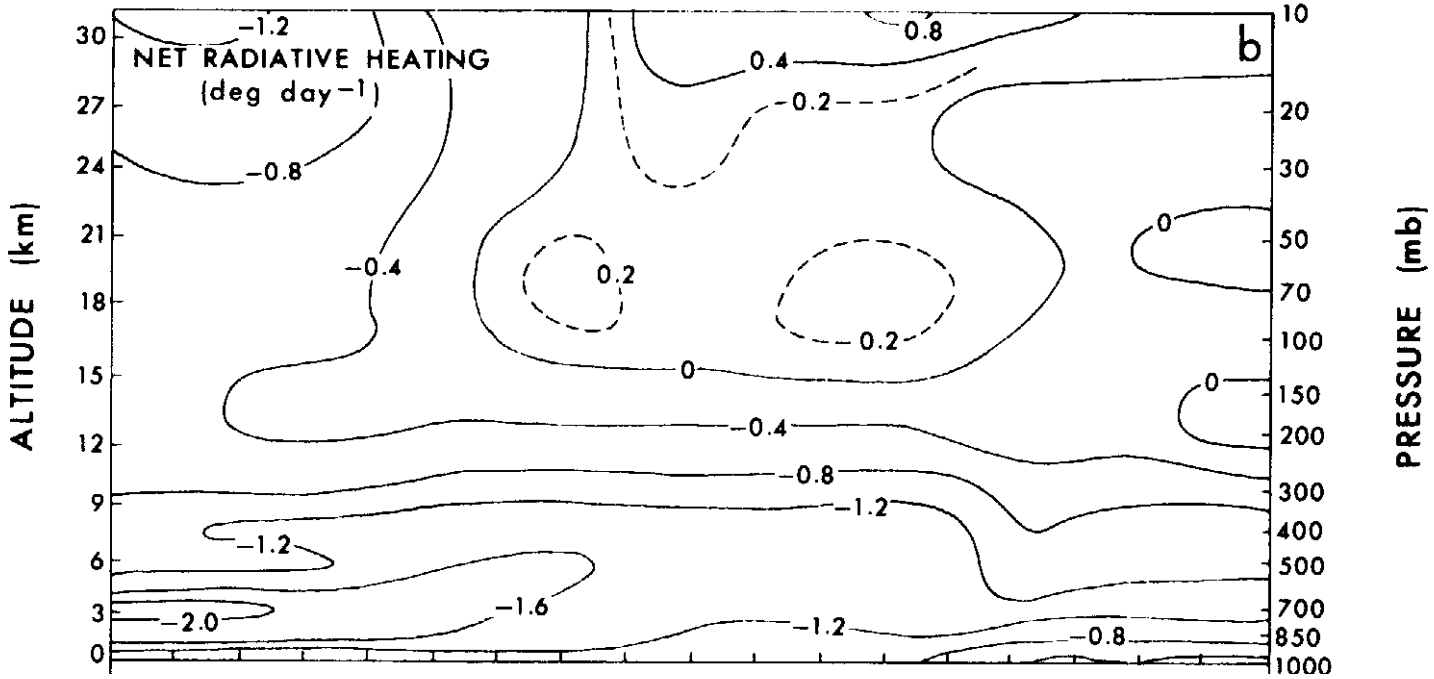


DJF

Latent heating: strongest in the tropics, penetrating over the who troposphere; in the extratropics,confined in the lower levels;
Sensible heating: in the boundary layer and strongest in the extratropics.

from Peixoto and Oort, 1992

Diabatic heating in atmosphere
estimated as residual



DJF

Cooling over the troposphere
Small latitudinal variation

from Peixoto and Oort, 1992

Outline

- Global averaged feature
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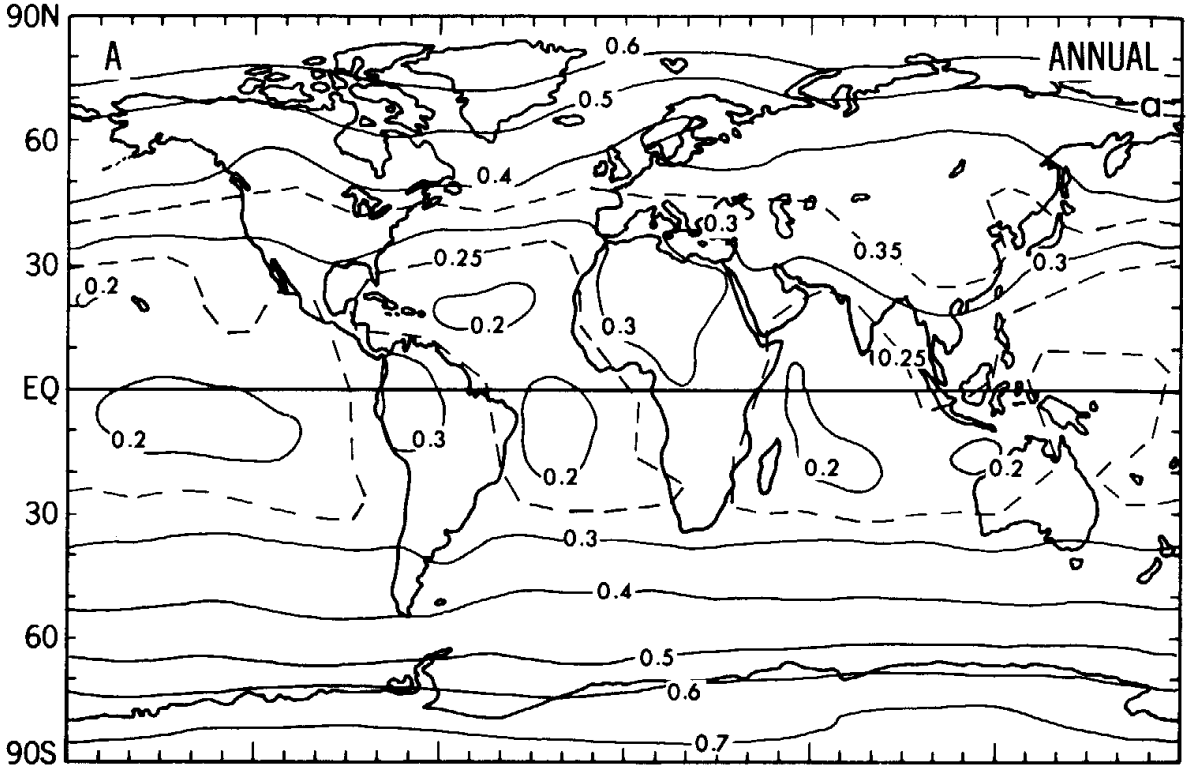
  - TOA
  - Surface
- Zonal distribution
  - TOA
  - Surface

Zonal variation of TOA energy flux

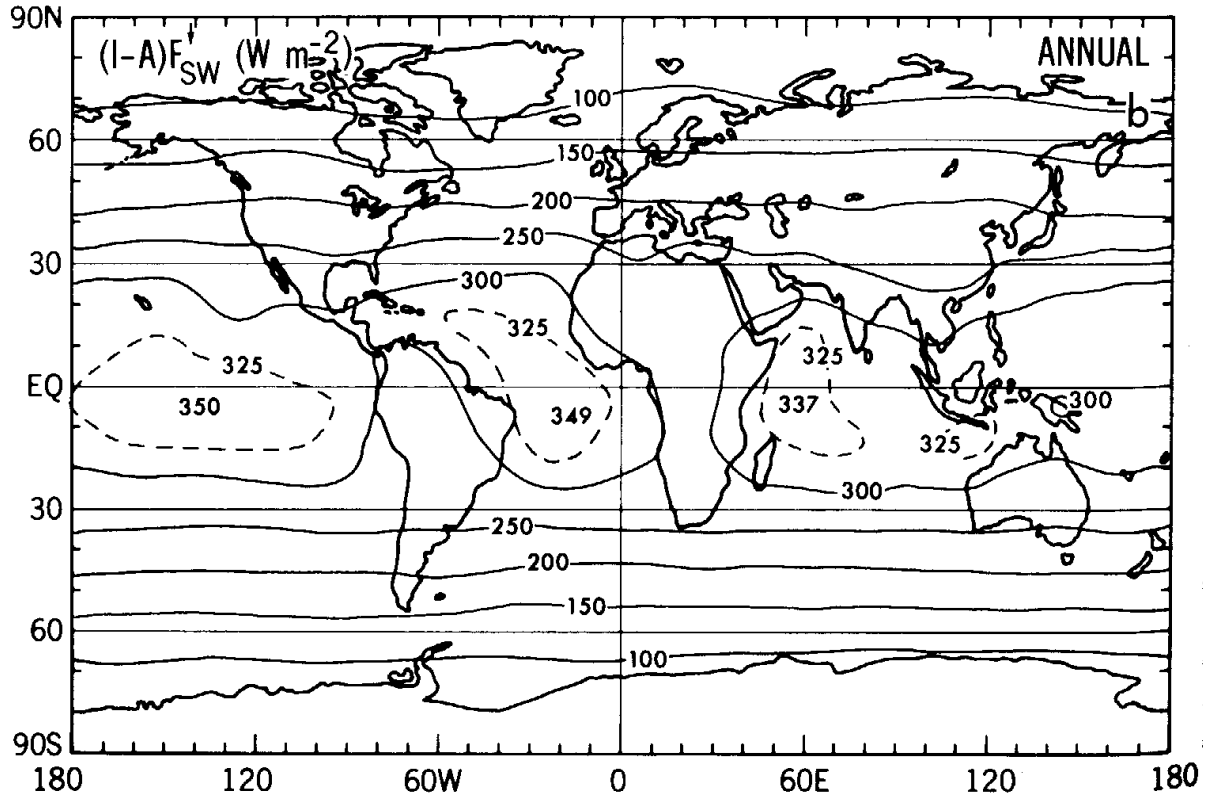
- Planetary albedo



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

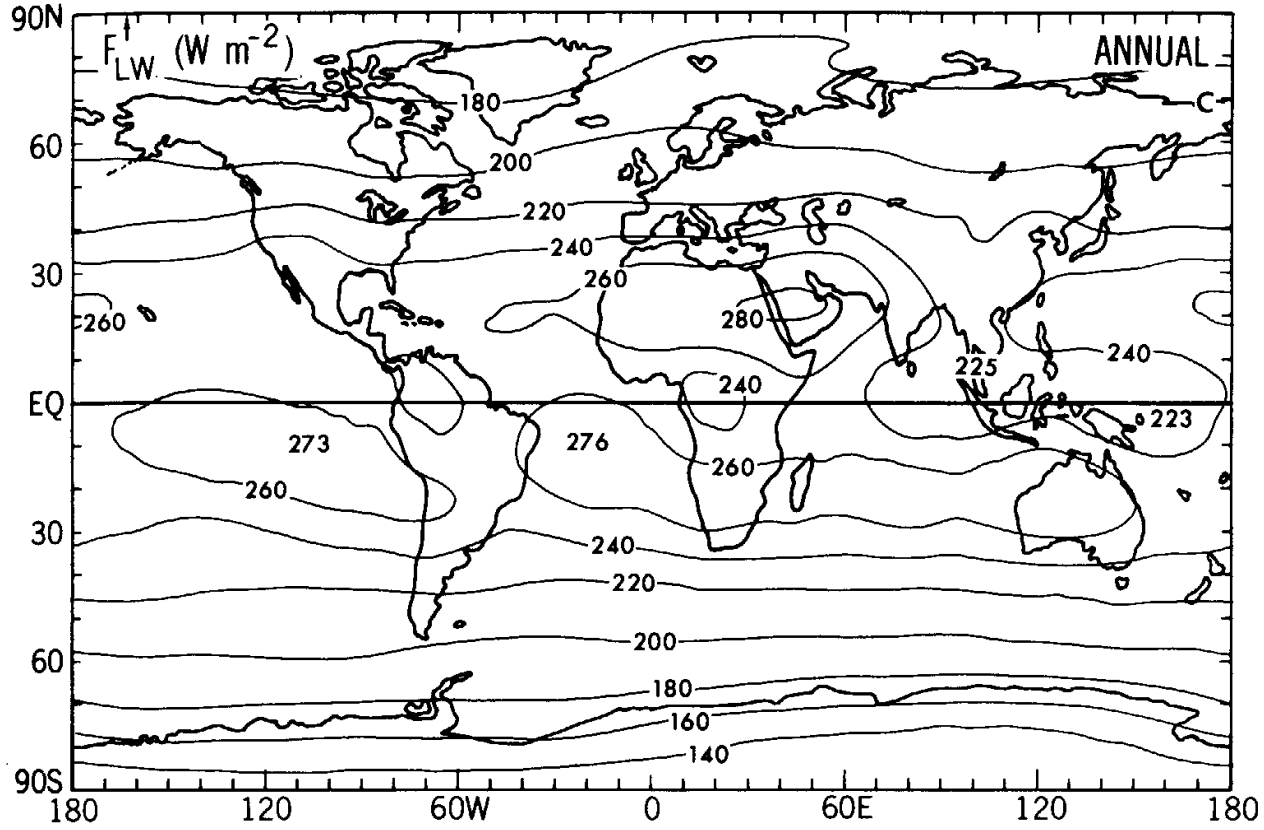
- Net short wave radiation



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

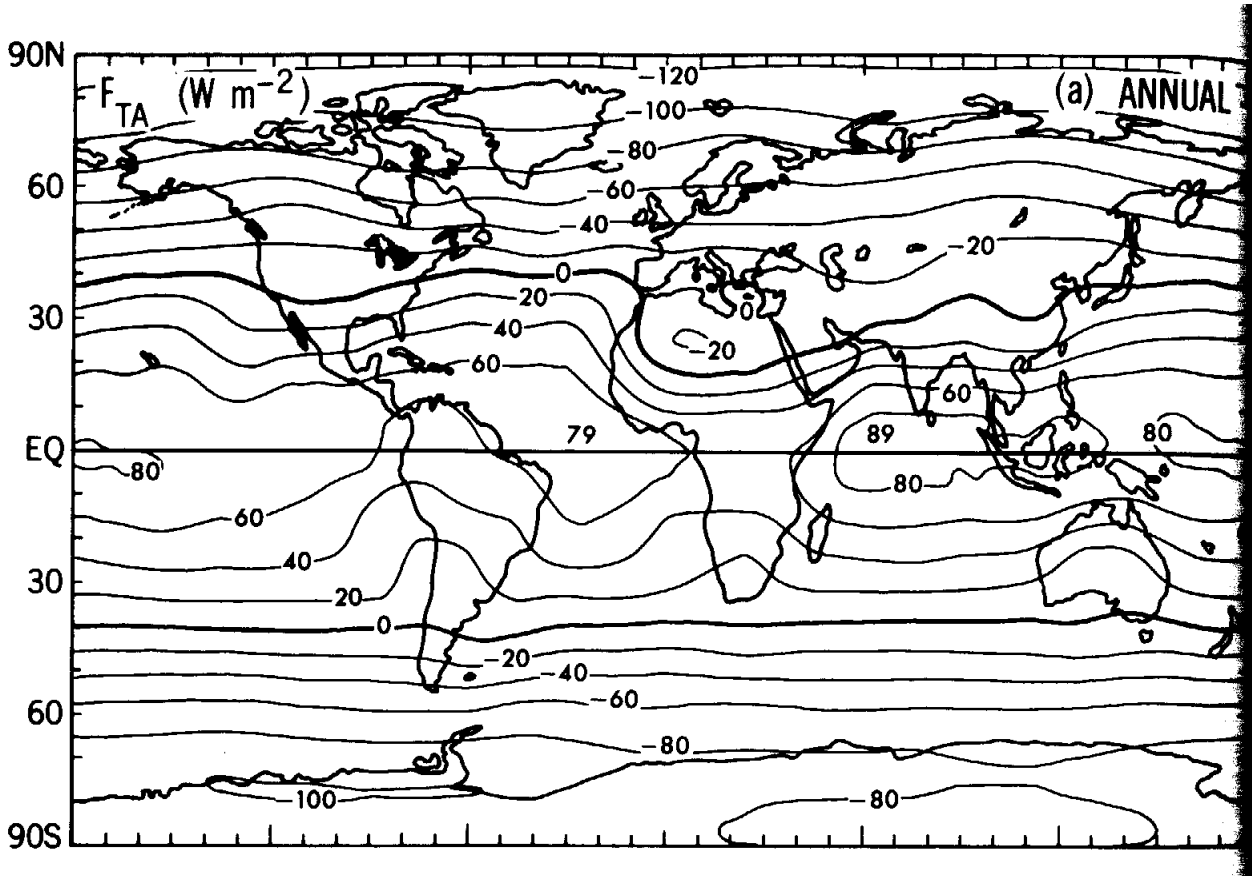
- Net longwave radiation



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

- Net radiation at TOA



From Peixoto and Oort, 1992

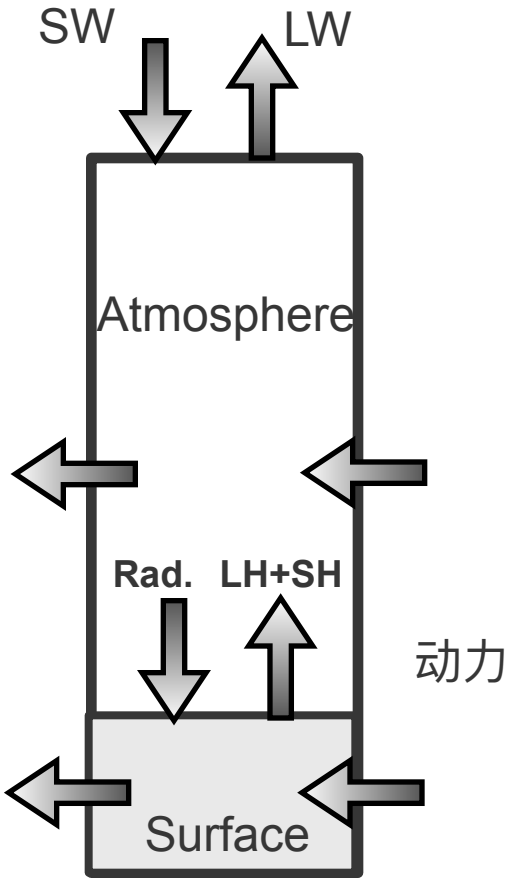
Zonal variation of TOA energy flux

- Relatively small zonal variation in solar radiation, planetary albedo and OLR;
- Ocean regions generally gain more energy than the land regions.
- Strong latitudinal variation:
  - planetary albedo: 0.2 to 0.6
  - absorbed solar radiation: 350 to 100 W/m^2
  - outgoing longwave radiation: 270 to 160 W/m^2

Energy budget at SURFACE

$$\rho_g C_{pg} H_{sur} \frac{\partial T_g}{\partial t} = F_{sur} + D_{fx},$$

$$F_{sur} = F_{rad} - F_{sh} - F_{lh}$$



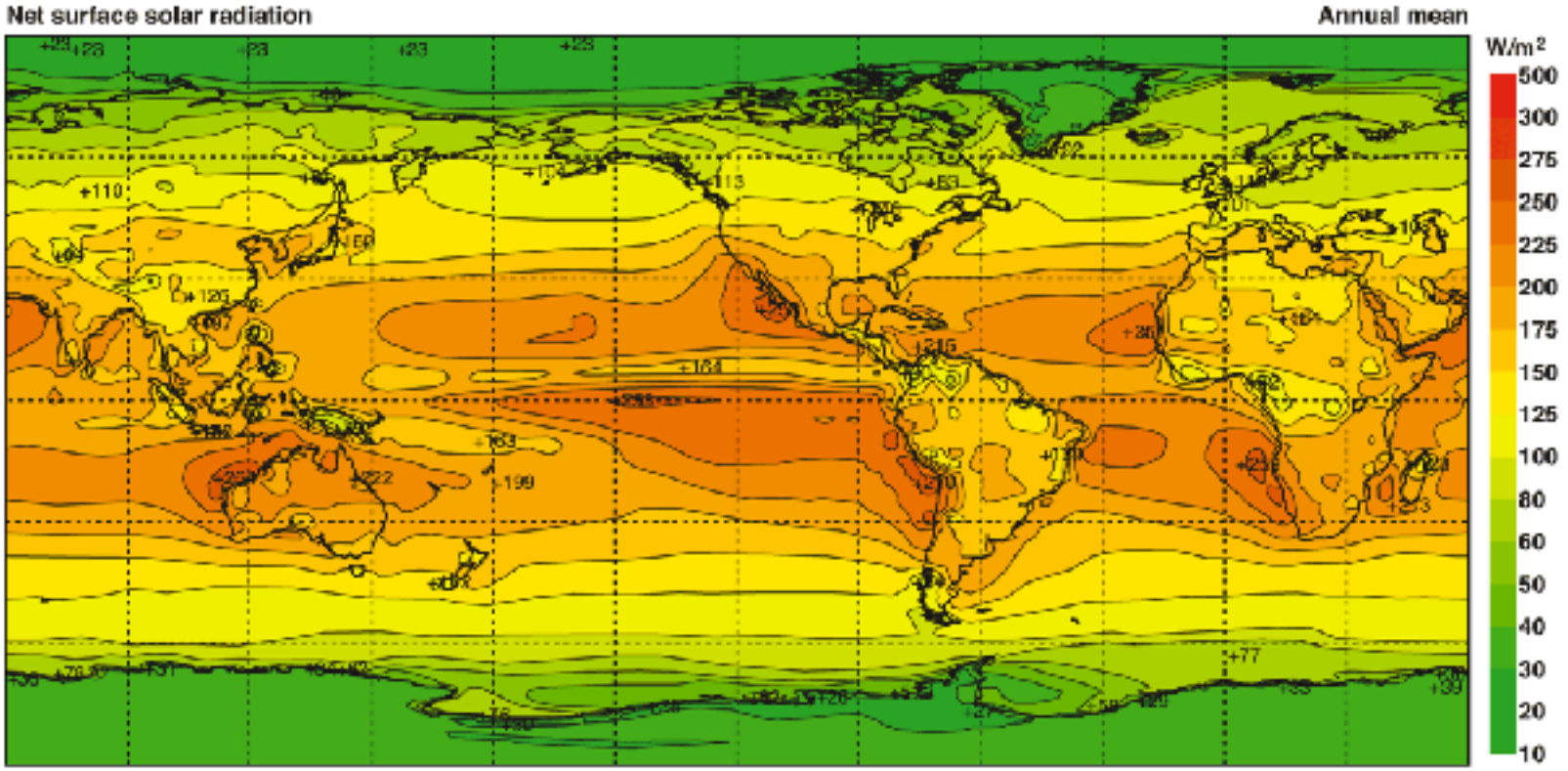
specific heat of ocean water: 4187 J/(kg* K)

specific heat of land: 840 J/(kg* K)

specific heat of ice at 273K: 2106 J/(kg* K)

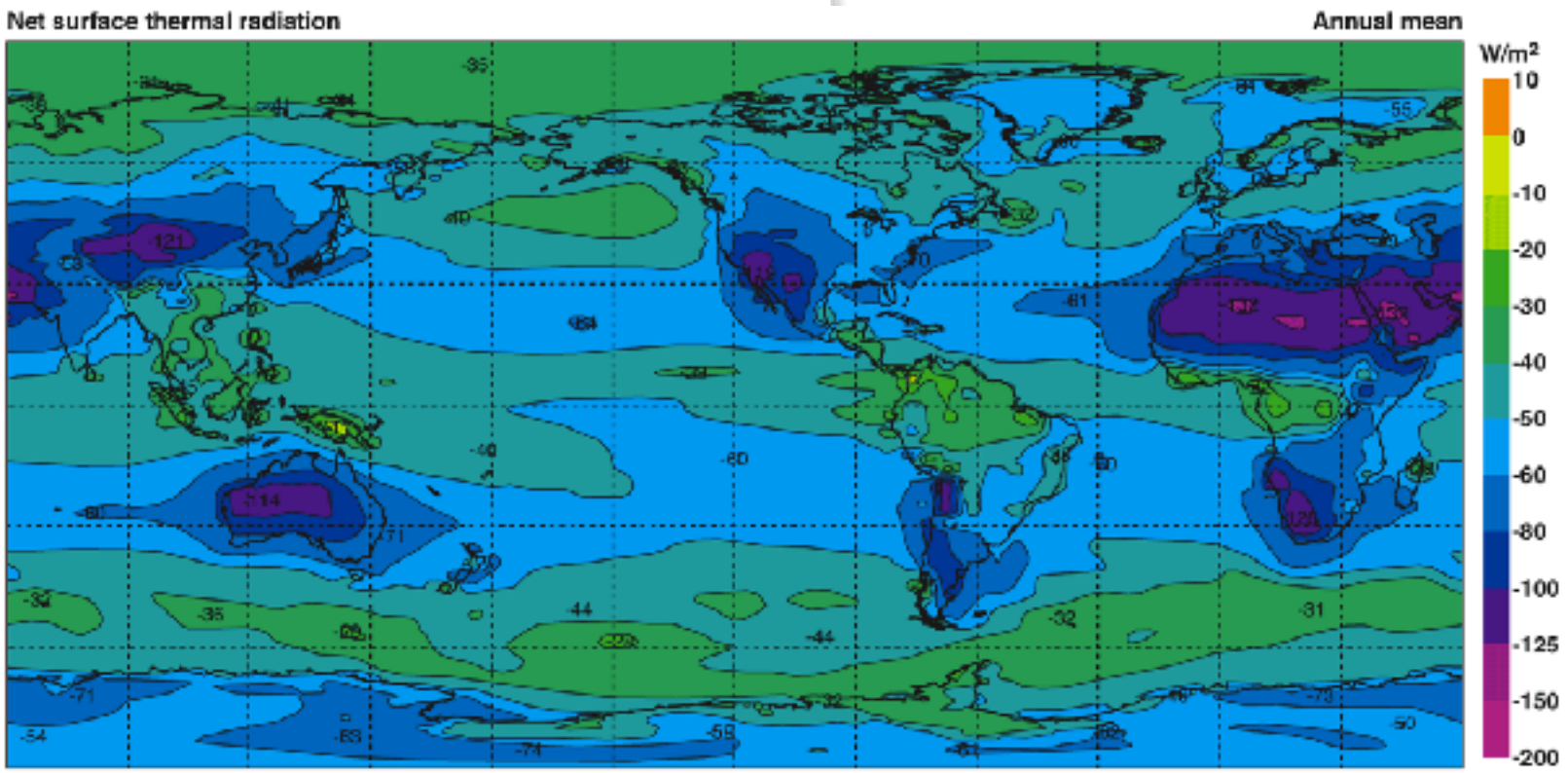
specific heat of atmosphere at constant pressure: 1004 J/(kg* K)

Zonal variation of surface energy flux - SW radiation



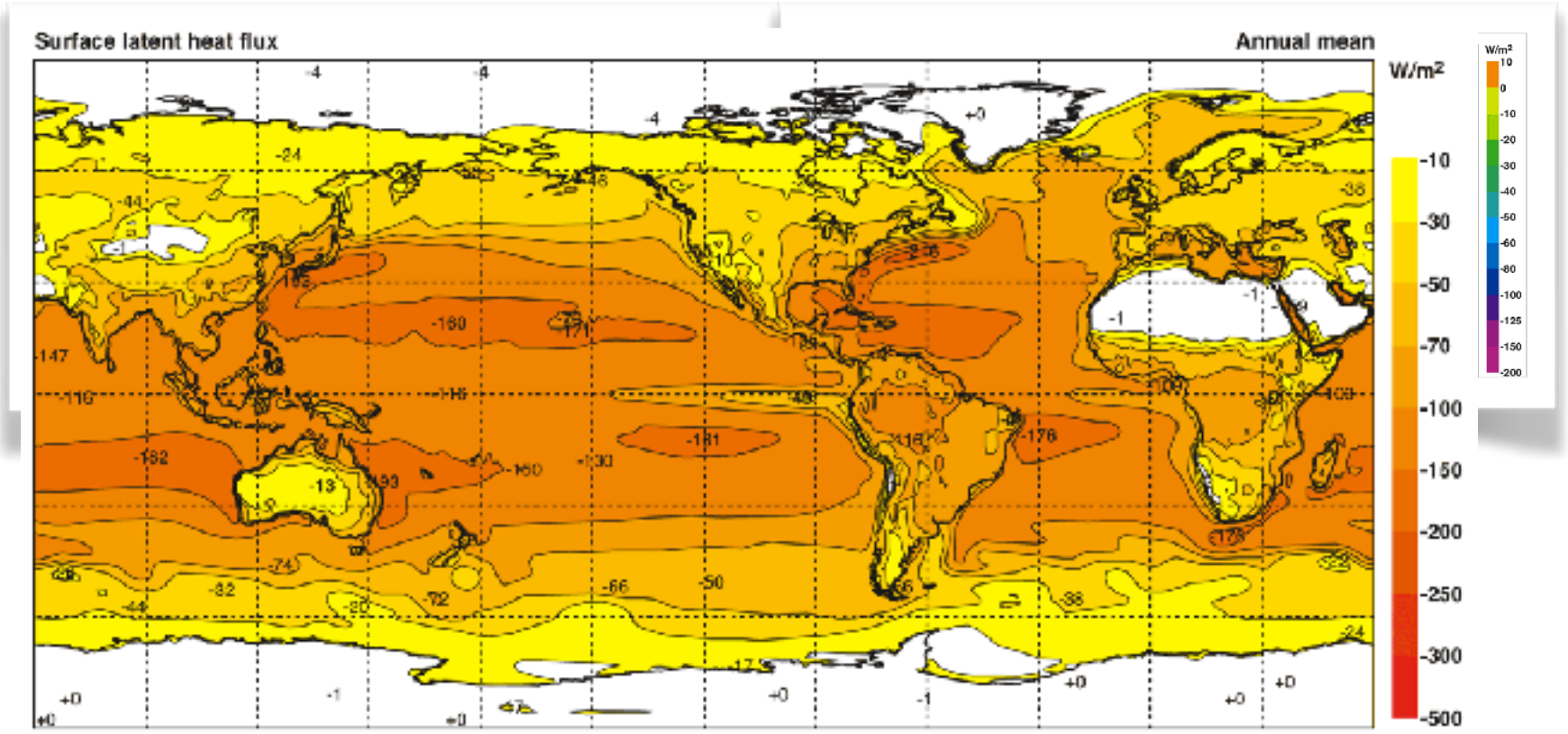
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux - LW radiation



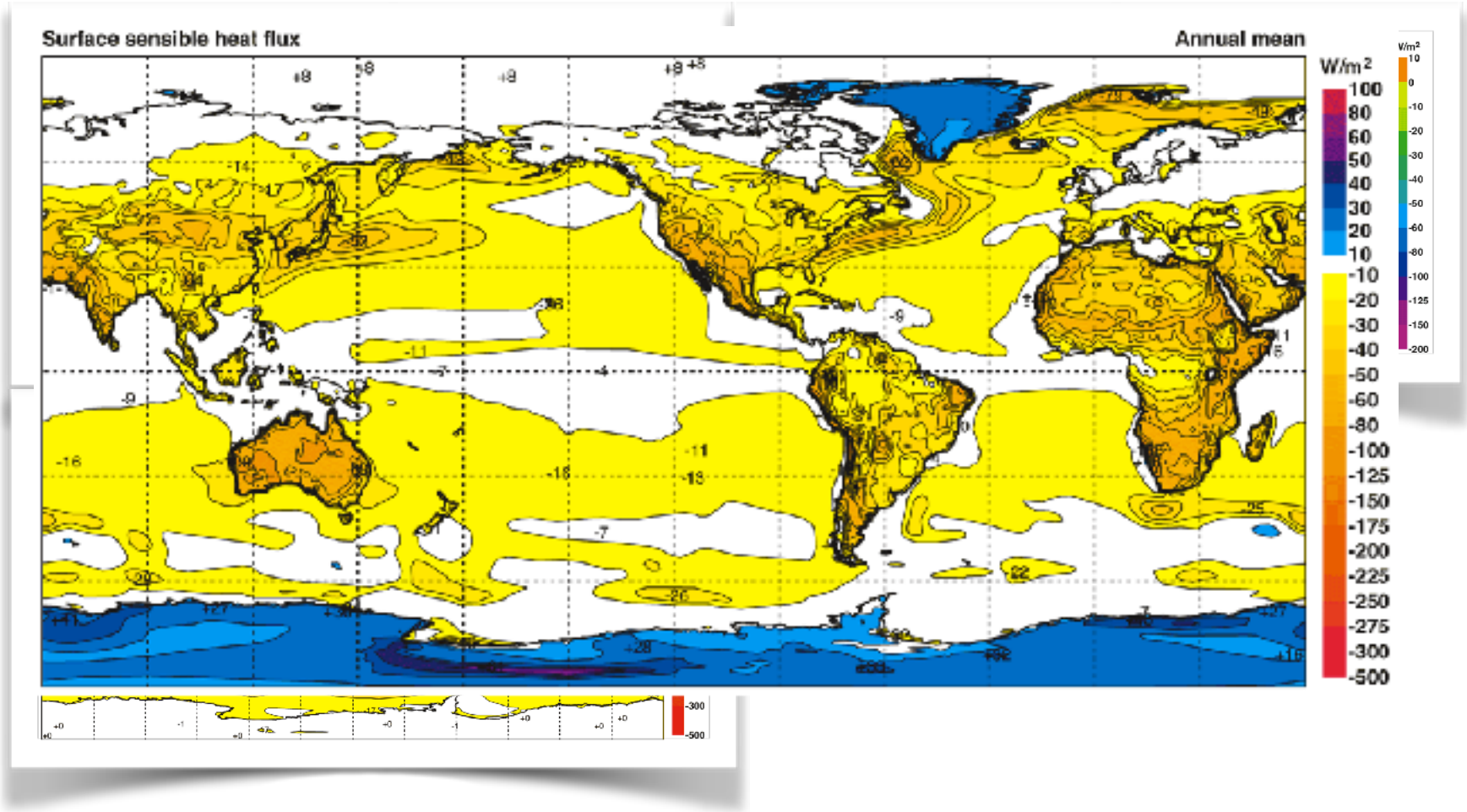
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux – latent heat



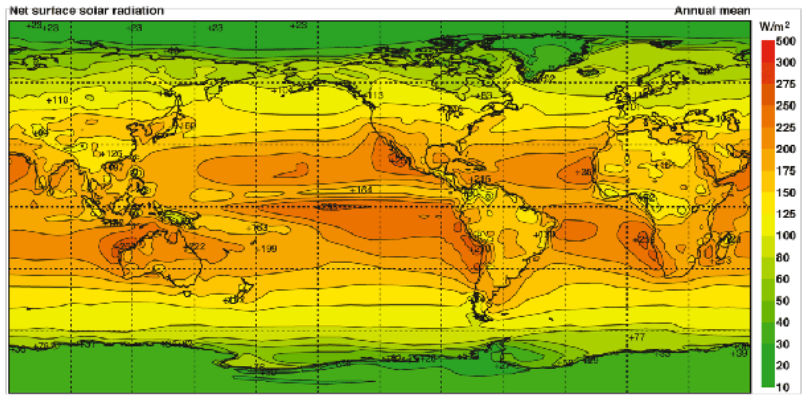
From Stewart, 2005
Introduction to Physical Oceanography

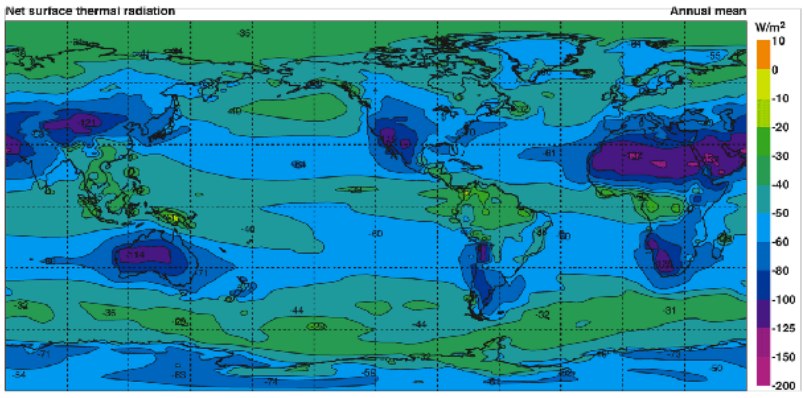
Zonal variation of surface energy flux – Sensible heat

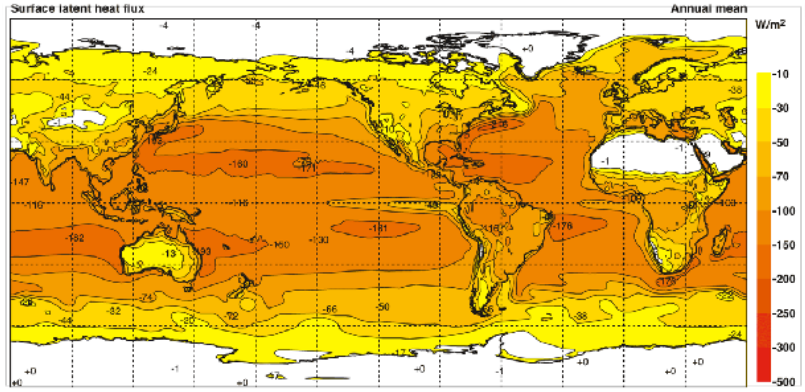


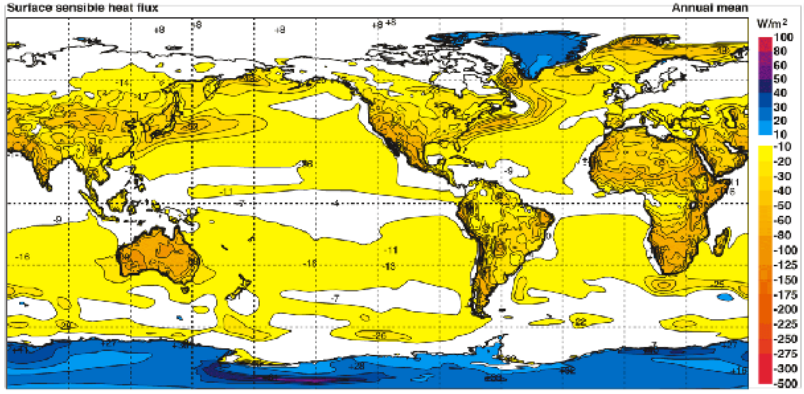
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux





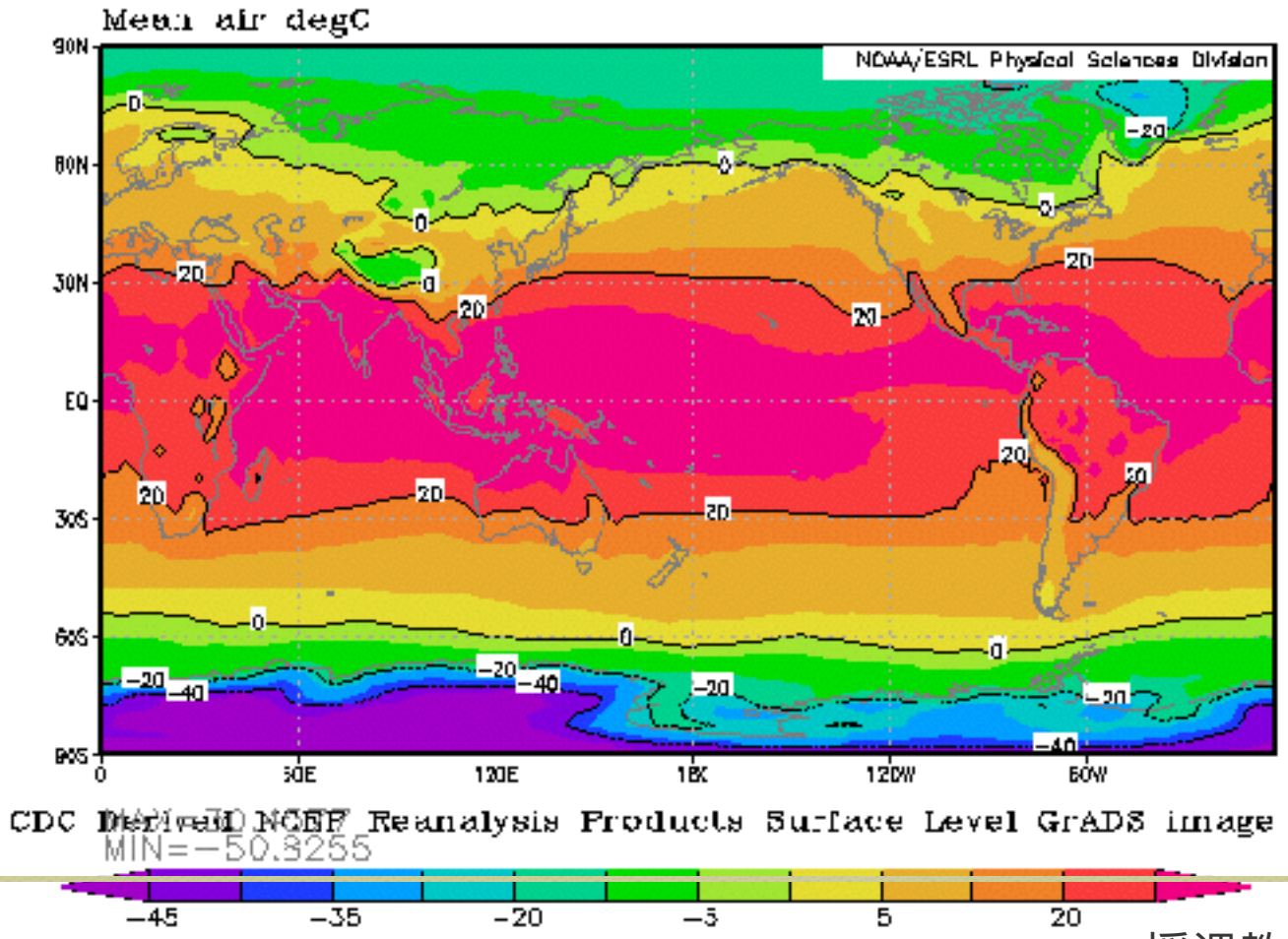




From Stewart, 2005
Introduction to Physical Oceanography

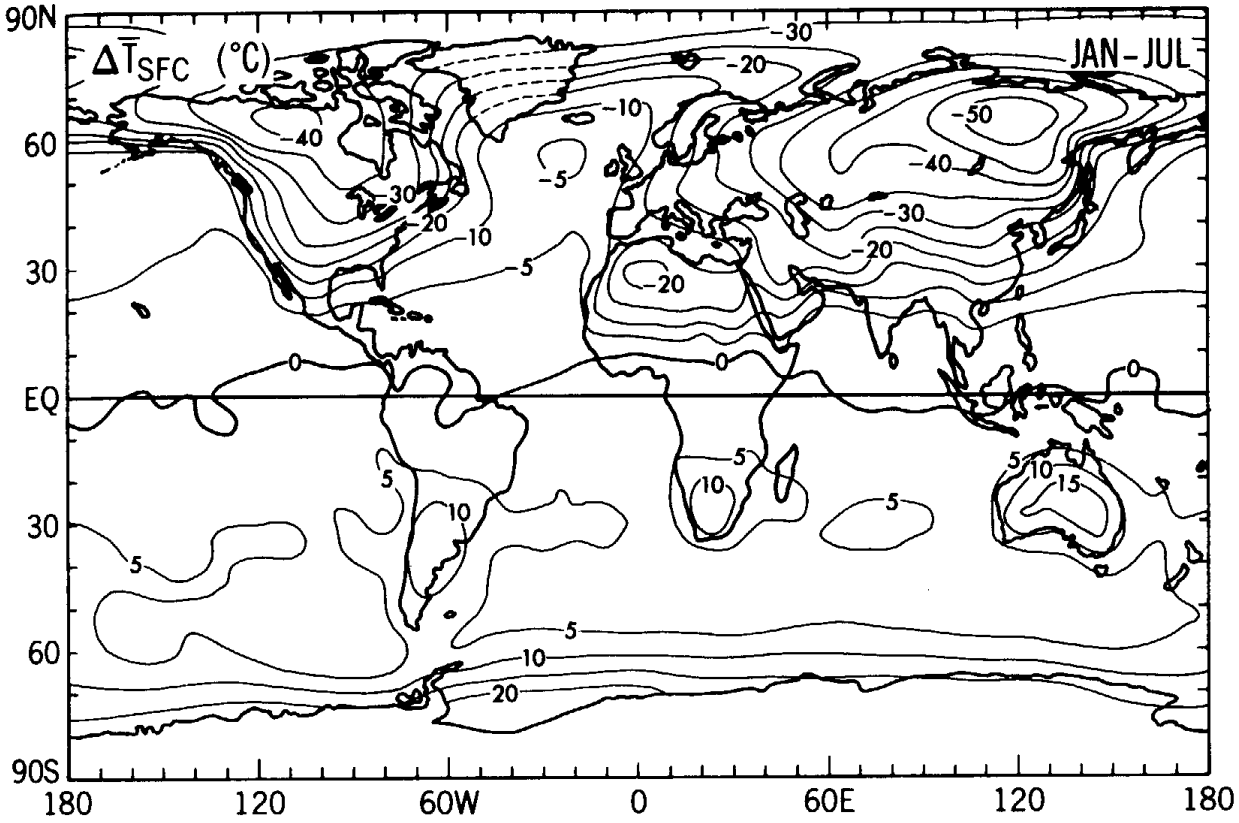
Zonal variation of surface energy flux

- Surface air



Zonal variation of surface energy flux

- Seasonal variation of surface temperature



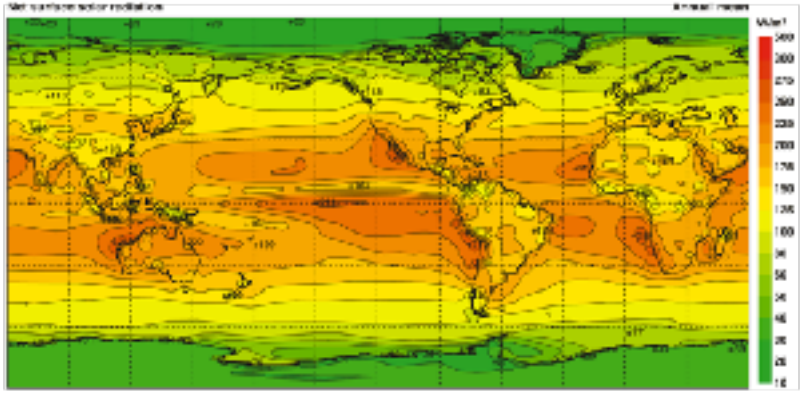
From Peixoto and Oort, 1992

Zonal variation of surface energy flux

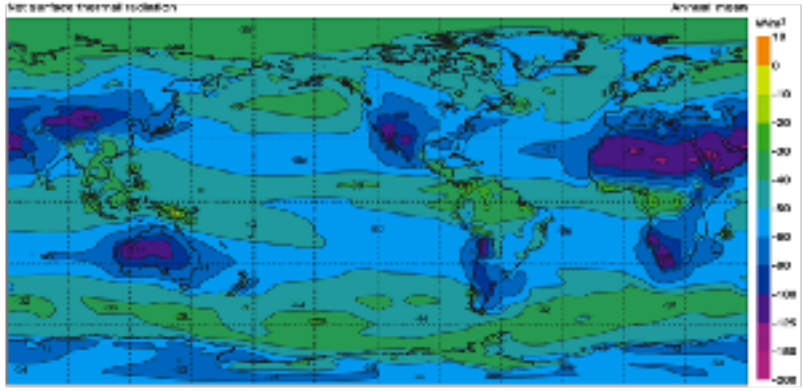
- Stronger zonal variation in surface LW, LH, SH and surface temperature
  - LW: stronger infrared cooling over land.
  - LH: stronger over ocean surface but weak over land
  - SH: stronger over land surface but weak over ocean
  - surface air temperature: stronger meridional temperature gradient and seasonal variation over land.

Zonal variation of surface energy flux

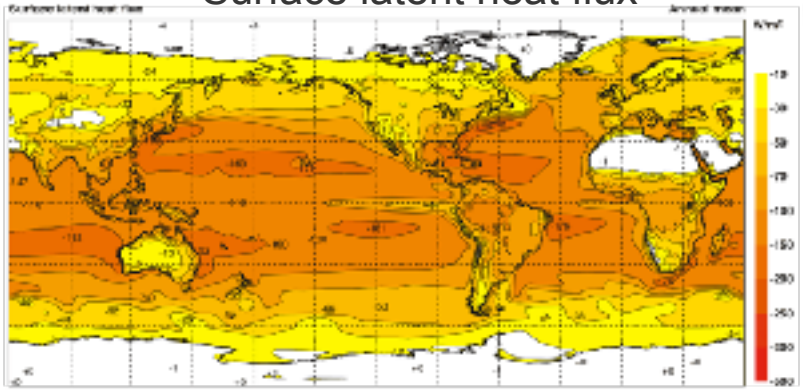
Net surface solar radiation



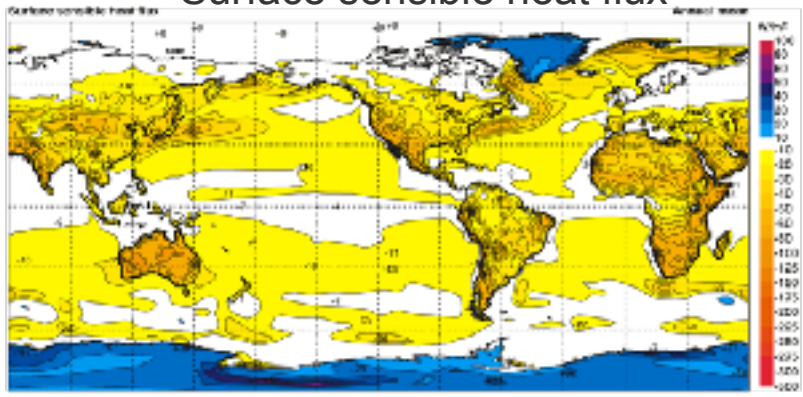
Net surface infrared radiation



Surface latent heat flux



Surface sensible heat flux



From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux

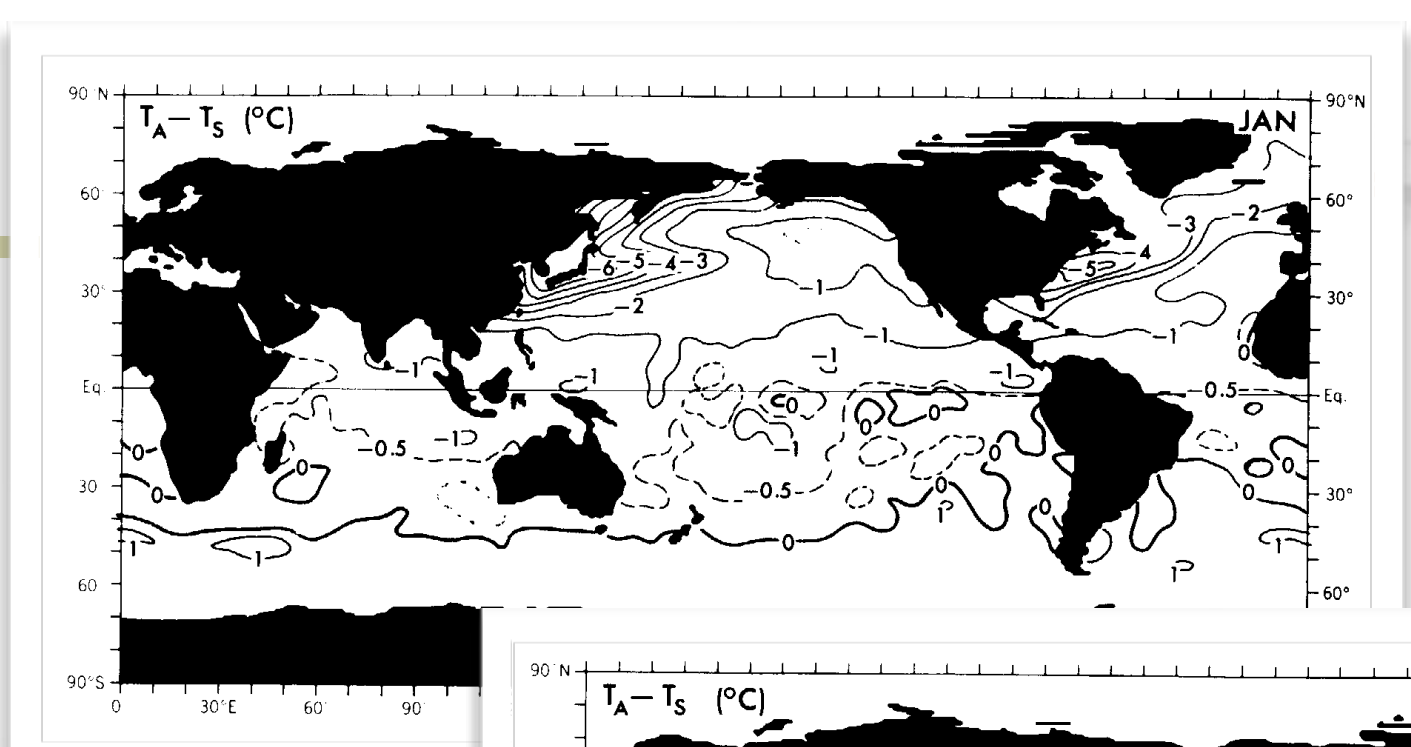
Surface sensible heat flux:

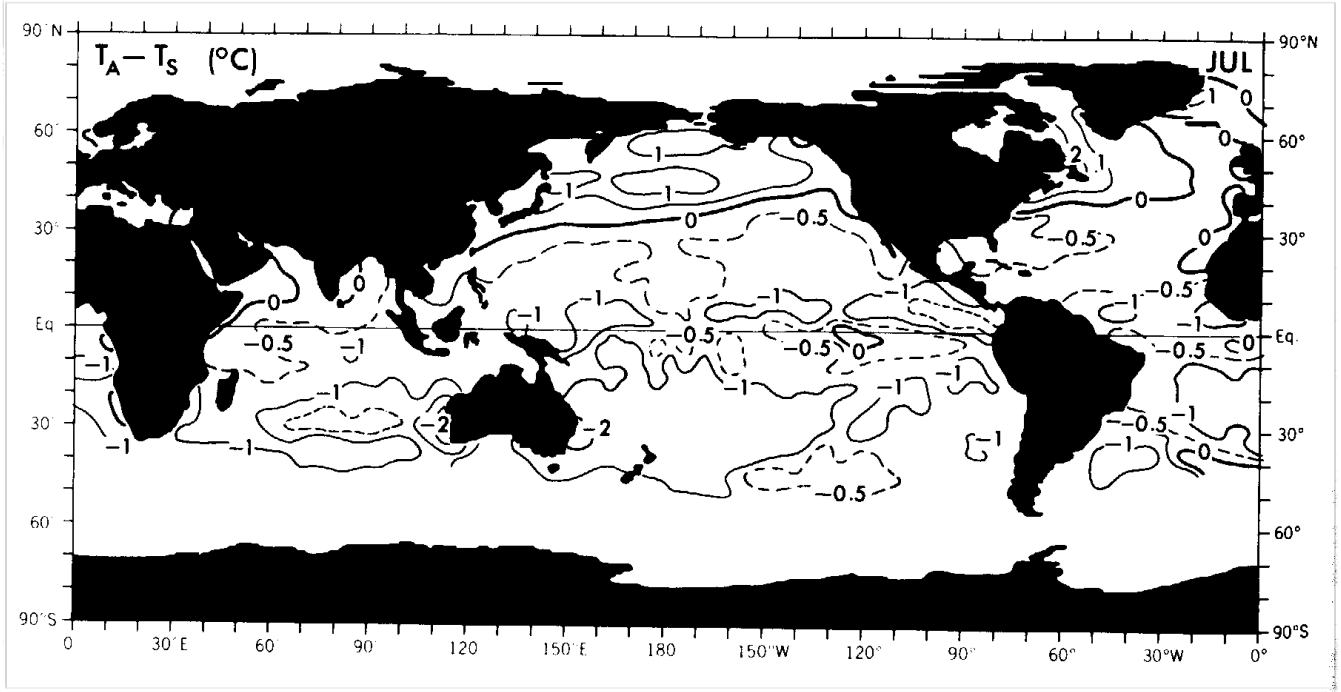
$$SH = c_p \rho \, \overline{\omega T} \approx c_p \rho \, C_d |\mathbf{v}| (T_s - T_a)$$

Ts - surface temperature

Ta - surface air temperature

Surface latent heat flux:


$T_A - T_S$ (°C)
JAN
90°N
60°
30°
Eq.
30
60
90°S
0
30°E
60°
90°


$T_A - T_S$ (°C)
JUL
90°N
60°
30°
Eq.
30
60
90°S
0
30°E
60°
90°
120
150°E
180
150°W
120°
90°
60°
30°W
0°

Zonal variation of surface energy flux

Surface sensible heat flux:

$$SH = c_p \rho \, \overline{\omega T} \approx c_p \rho \, C_d |\mathbf{v}| (T_s - T_a)$$

Ts - surface temperature

Ta - surface air temperature

Surface latent heat flux:

$$LH = L\rho \, \overline{\omega q} \approx L\rho \, C_d |\mathbf{v}| (q_s - q_a)$$

qs - specific humidity at surface

qa - specific humidity of surface air

For ocean surface,

$$q_s = q^*(T_s)$$

$$q_a = RH \cdot q^*(T_a) = RH \cdot \left[q^*(T_s) + \frac{\partial q^*}{\partial T}(T_a - T_s) \right]$$

$$\begin{aligned} q_s - q_a &= q^*(T_s) - RH \cdot \left[q^*(T_s) + \frac{\partial q^*}{\partial T}(T_a - T_s) \right] \\ &= q^*(T_s)(1 - RH) + RH \cdot \frac{\partial q^*}{\partial T}(T_s - T_a) \end{aligned}$$