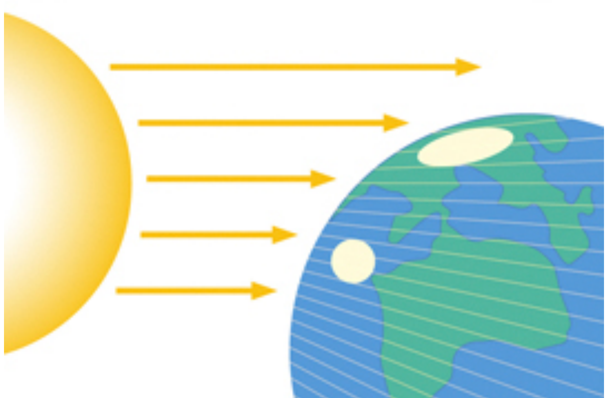
第二章:

大气环流的外部强迫



授课教师: 张洋

2023.10.07

第二章:

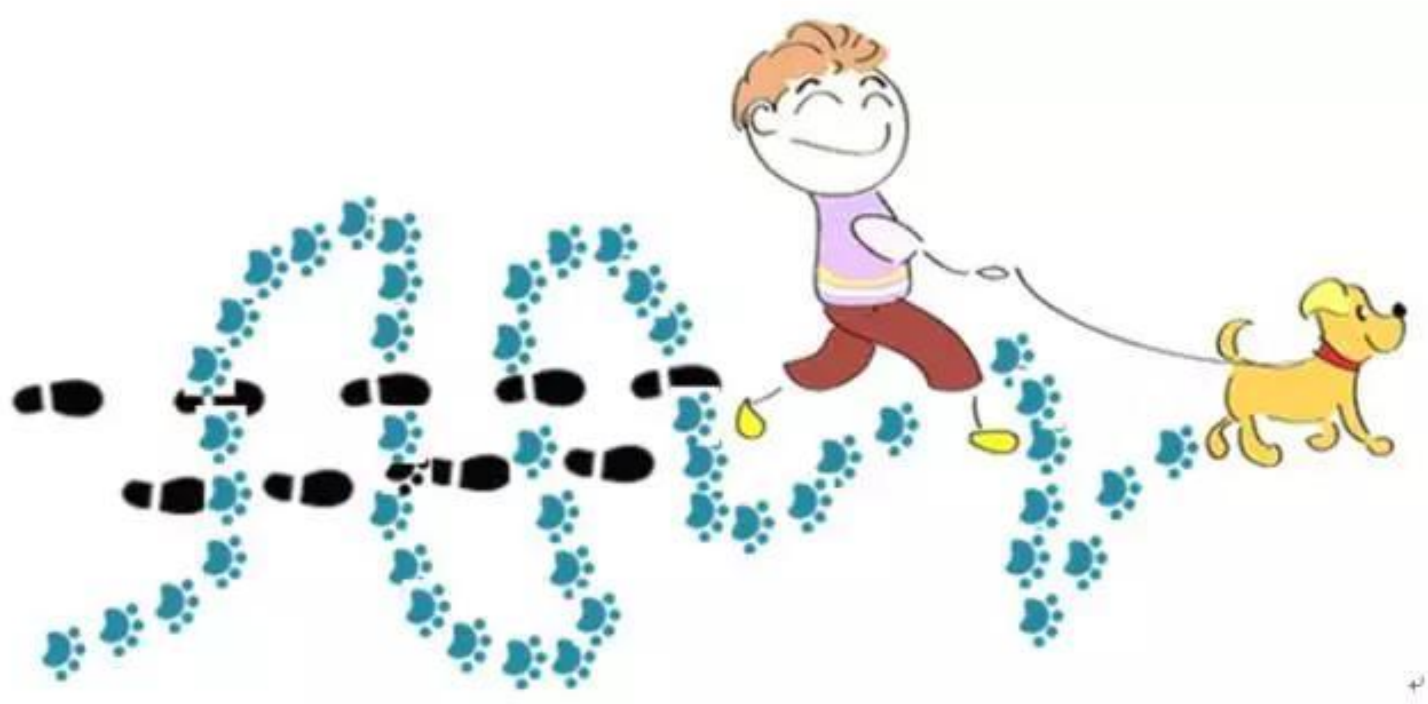
大气环流的外部强迫

Reference reading: PO Chapter 6.3, 6.7–6.8

2023.10.07

大气环流的外部强迫

外部强迫与大气内部变率

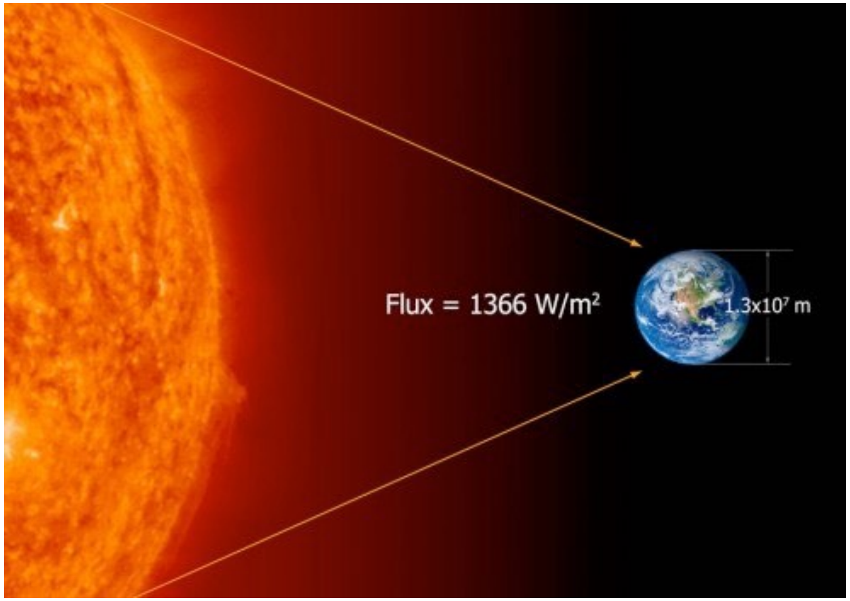


选自谢尚平等
《揭开汛期降水变化的奥秘：厄尔尼诺回响曲》

Outline

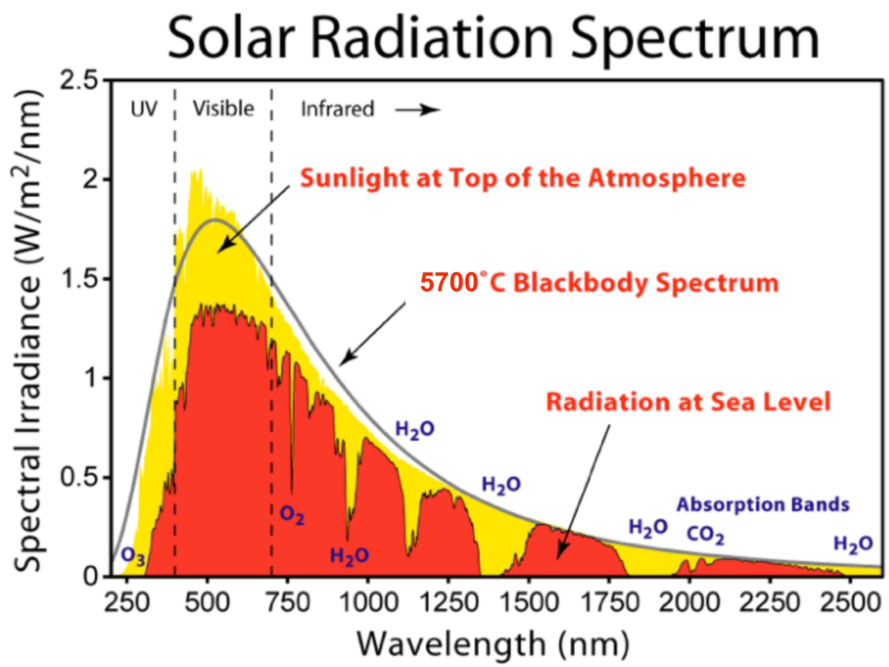
- Global averaged feature
  - TOA (Top of the atmosphere)
  - Surface
- Latitudinal distribution (zonal averaged feature)
  - TOA
  - Surface
- Zonal distribution
  - TOA
  - Surface

From the solar radiation…



S_o -- solar constant (1360~1370 W/m^2) ,
太阳辐射通量

$$S = S_o \left(\frac{\pi a^2}{4\pi a^2} \right) \approx 340\ Wm^{-2}$$，辐射率

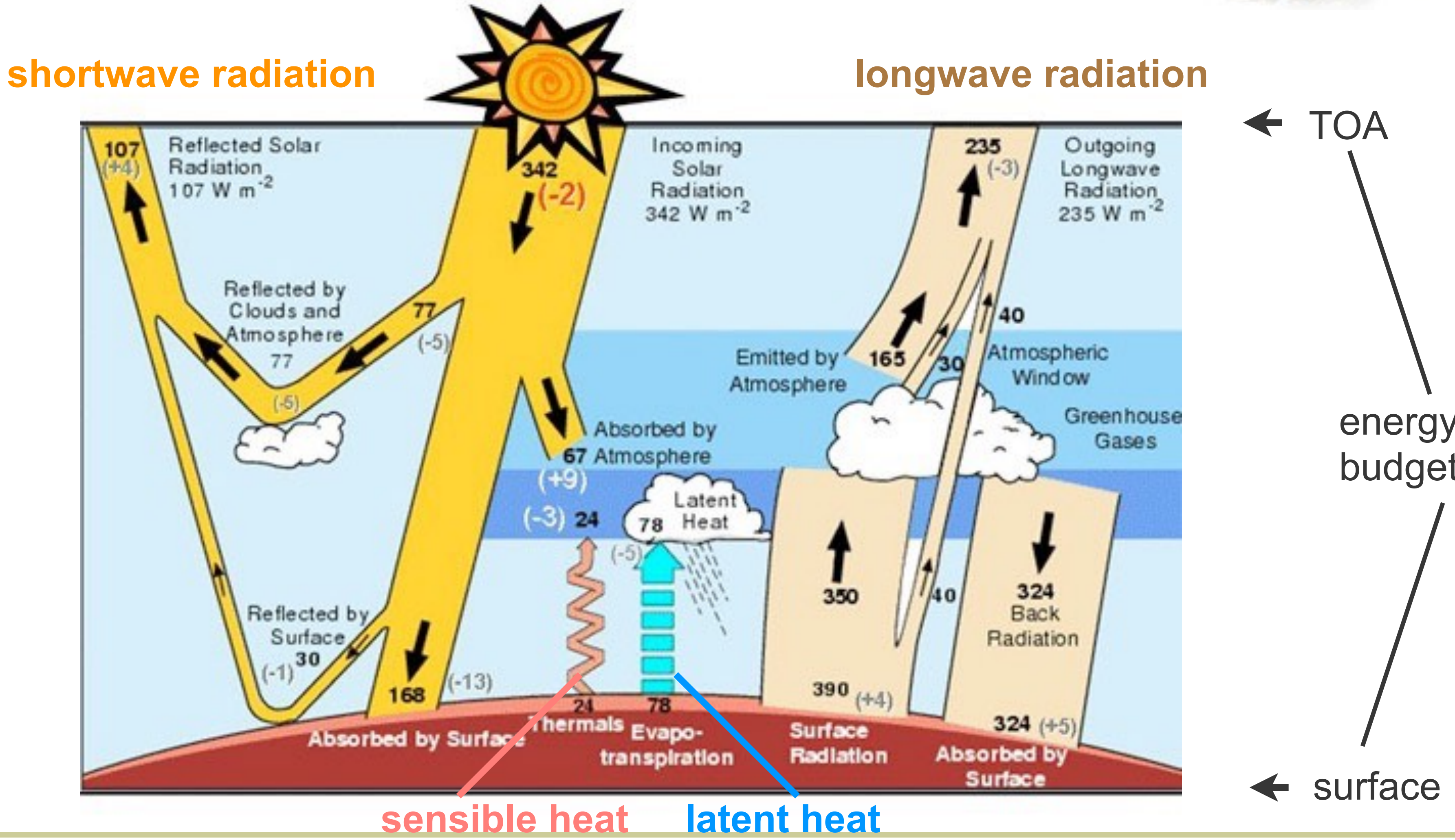


Effective emission temperature:

$$\sigma T_e^{\,4} \equiv \frac{S_0}{4}\left(1 - a_p\right)$$

Earth: $T_e = 255K = -18°C$ 实际大气：288K

From the solar radiation…



From the solar radiation…

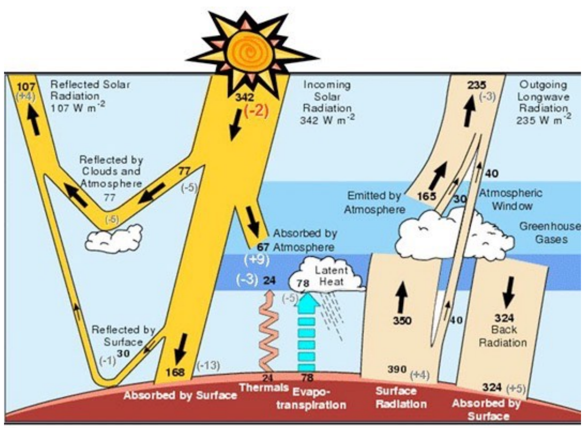
Incident solar radiation	340 W/m^2
Planetary albedo	0.3
Absorbed solar radiation	240 W/m^2
Outgoing longwave radiation (OLR)	240 W/m^2

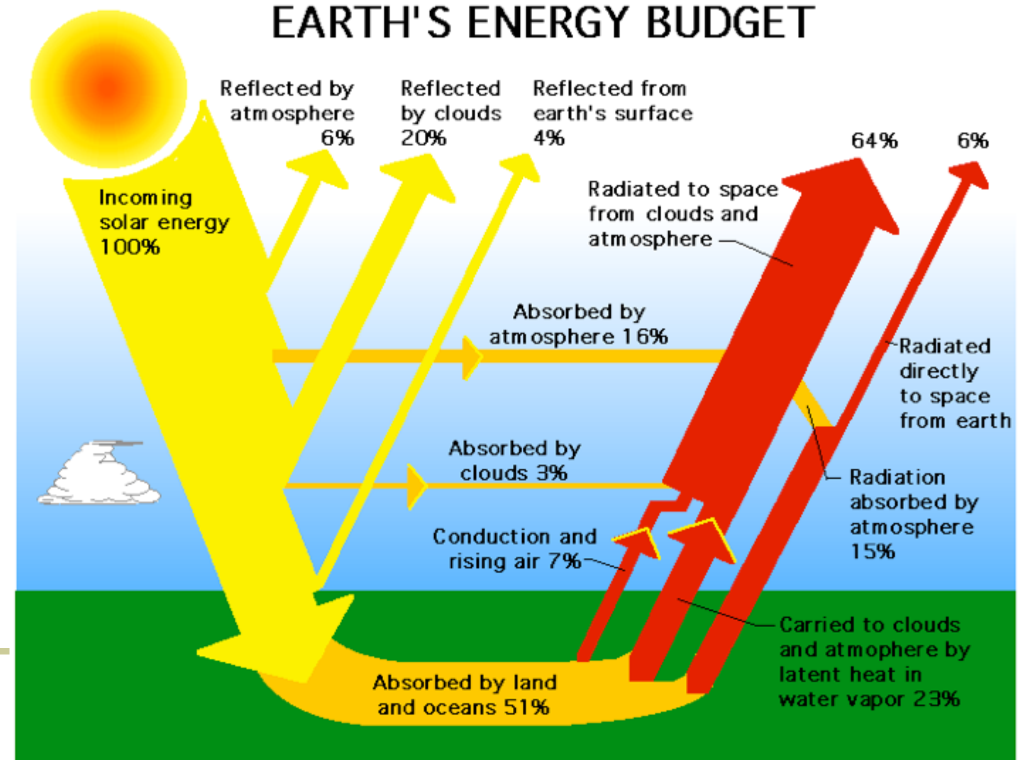
Table: globally and annually averaged TOA radiation budget

SW ~ LW

$S(1-\alpha)$

← TOA



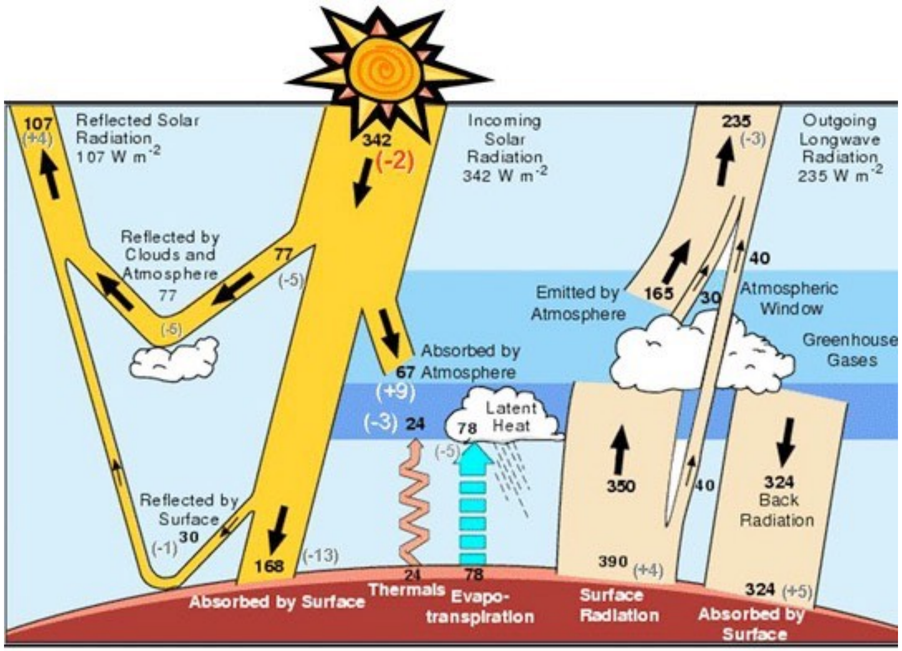


From the solar radiation...

- Planetary albedo （TOA总反射辐射与总入射辐射的比值）
  - penetrate into the atmosphere, absorbed and scattered by:
    - atmospheric gases: H20, O3, CO2...
    - aerosols: direct injection, chemical reactions
    - clouds: albedo 30% thin stratus, 60-70% thick stratus
  - at the earth’s surface -- surface albedo, strongly depends on the nature of the surface, vegetation cover, snow cover...

Sand	Grassland	Green crops	Forest	Dense Forest	Fresh snow	Old snow	Cities
18-28	16-20	15-25	14-20	5-10	75-95	40-60	14-18

From the solar radiation...



SW ~ LW

$S(1-\alpha)$ ← TOA

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

Long term, global average: SW(net) + LW(net) + LH +SH ~0 ← surface

From the solar radiation…

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 ~ LW

$S(1-\alpha)$

← TOA

energy budget

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

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}

e: SW(net) + LW(net) + LH +SH ~0 ← surface

Table: globally and annually averaged surface energy budget

Outline

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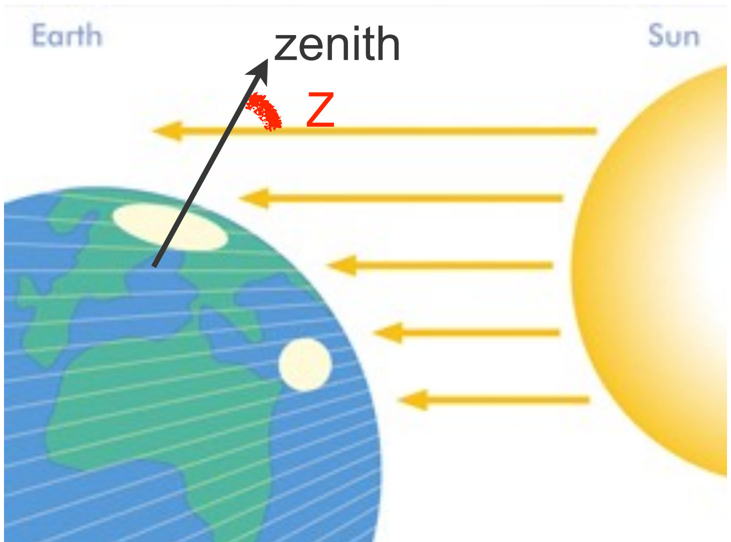
- Latitudinal distribution (zonal averaged feature)
  - TOA
  - Surface
- Zonal distribution
  - TOA
  - Surface

From the solar radiation…

- At TOA

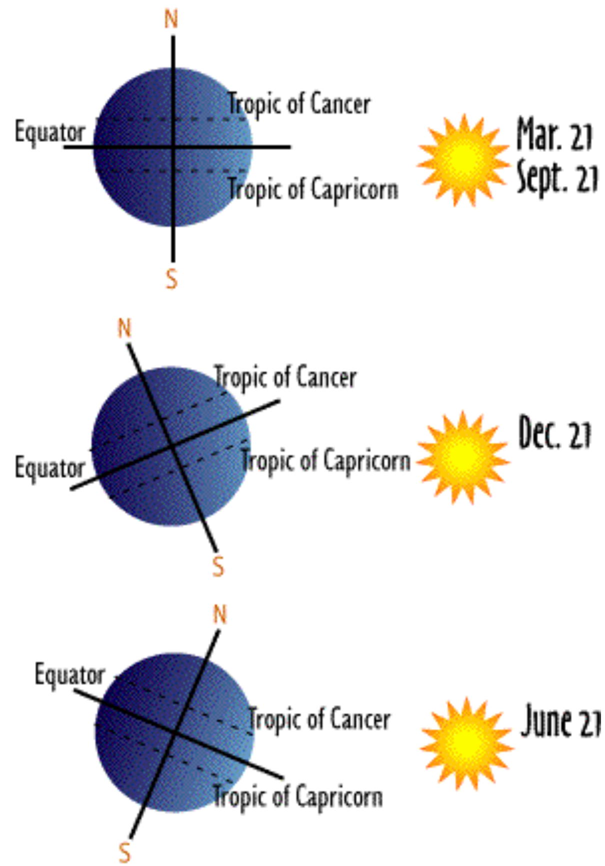


$$SW = S\left(d_m/d\right)^2 cosZ$$

d -- earth-sun distance

d_m -- mean earth-sun distance

Z -- zenith angle



Solar radiation varies with latitude and season

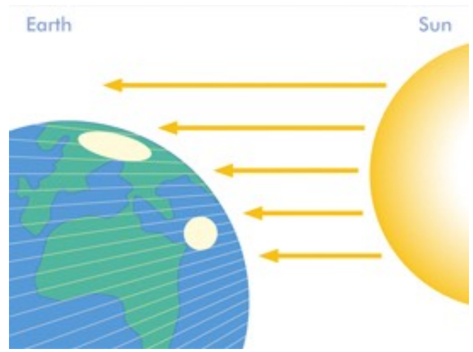
From the solar radiation...

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

d -- earth-sun distance

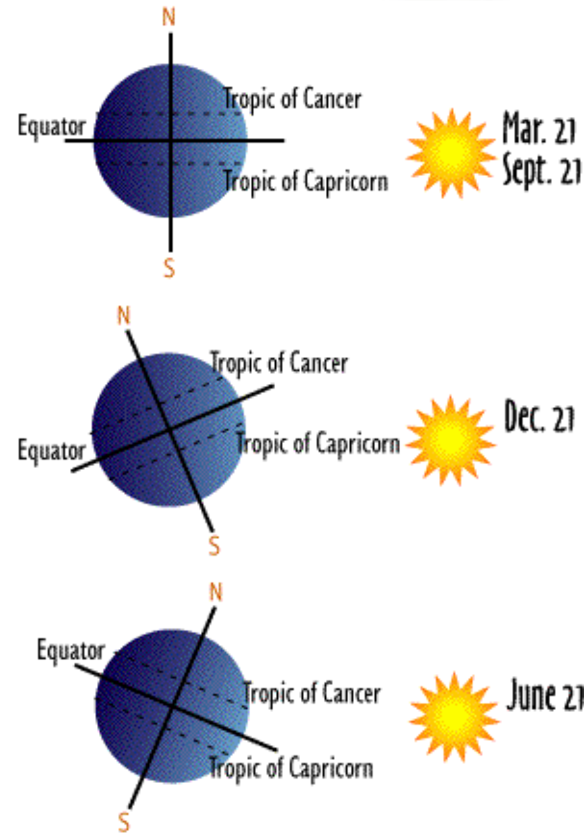
d_m -- mean earth-sun distance

Z -- zenith angle



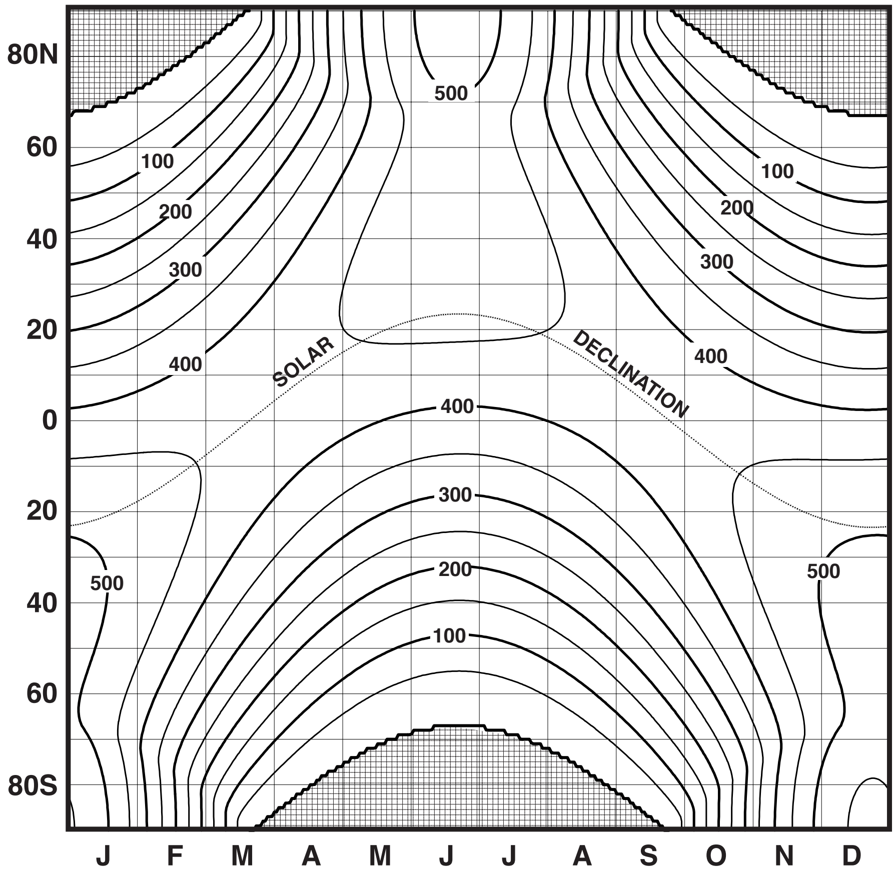
$$Q = S\,(d_m/d)^2 \int_{\text{time of sunrise}}^{\text{time of sunset}} \cos Z\, dt$$

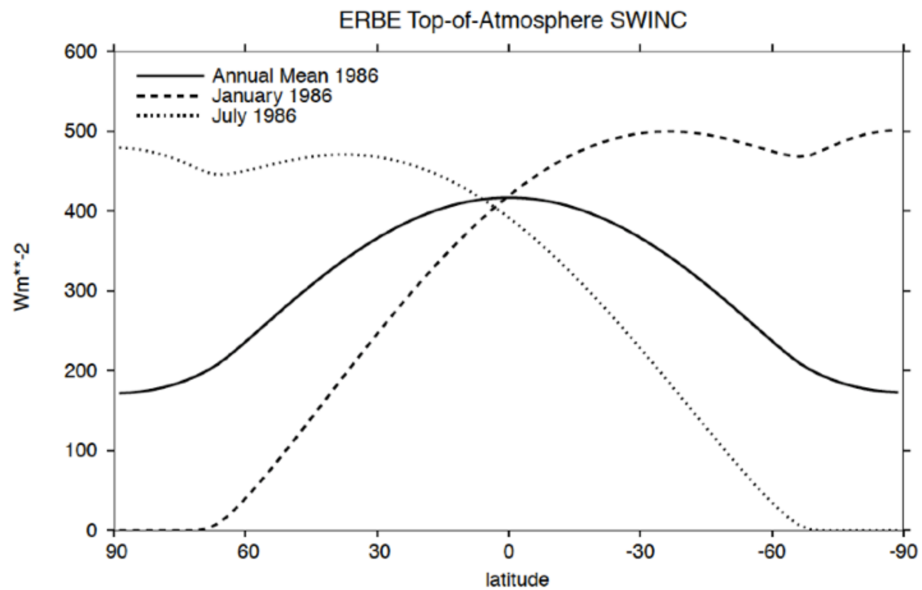
- solar radiation depends on:
  - earth-sun distance
  - length of the day
  - zenith



From the solar radiation…

- At TOA

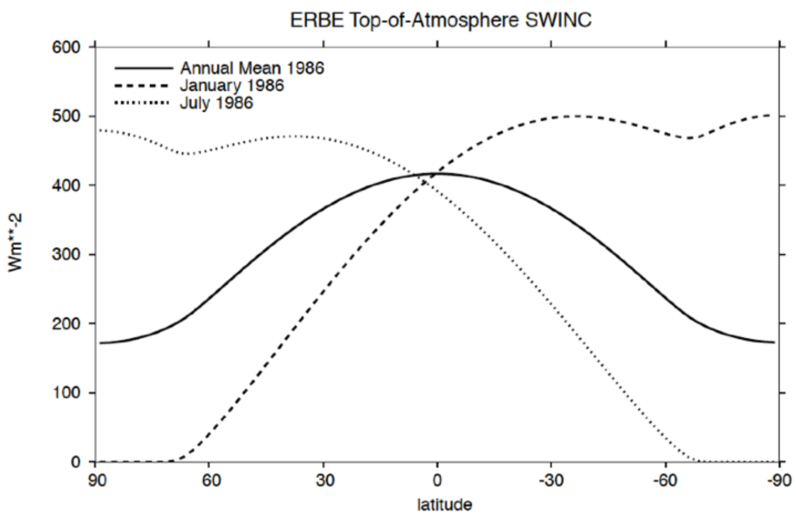


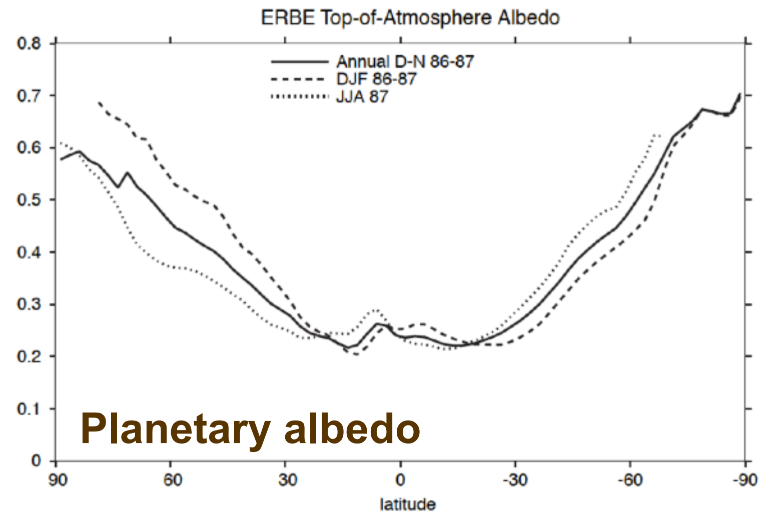


Figures: the zonally averaged incident solar radiation, observed in the Earth Radiation Budget Experiment (ERBE). (from Randall 2009)

From Peixoto and Oort, 1992

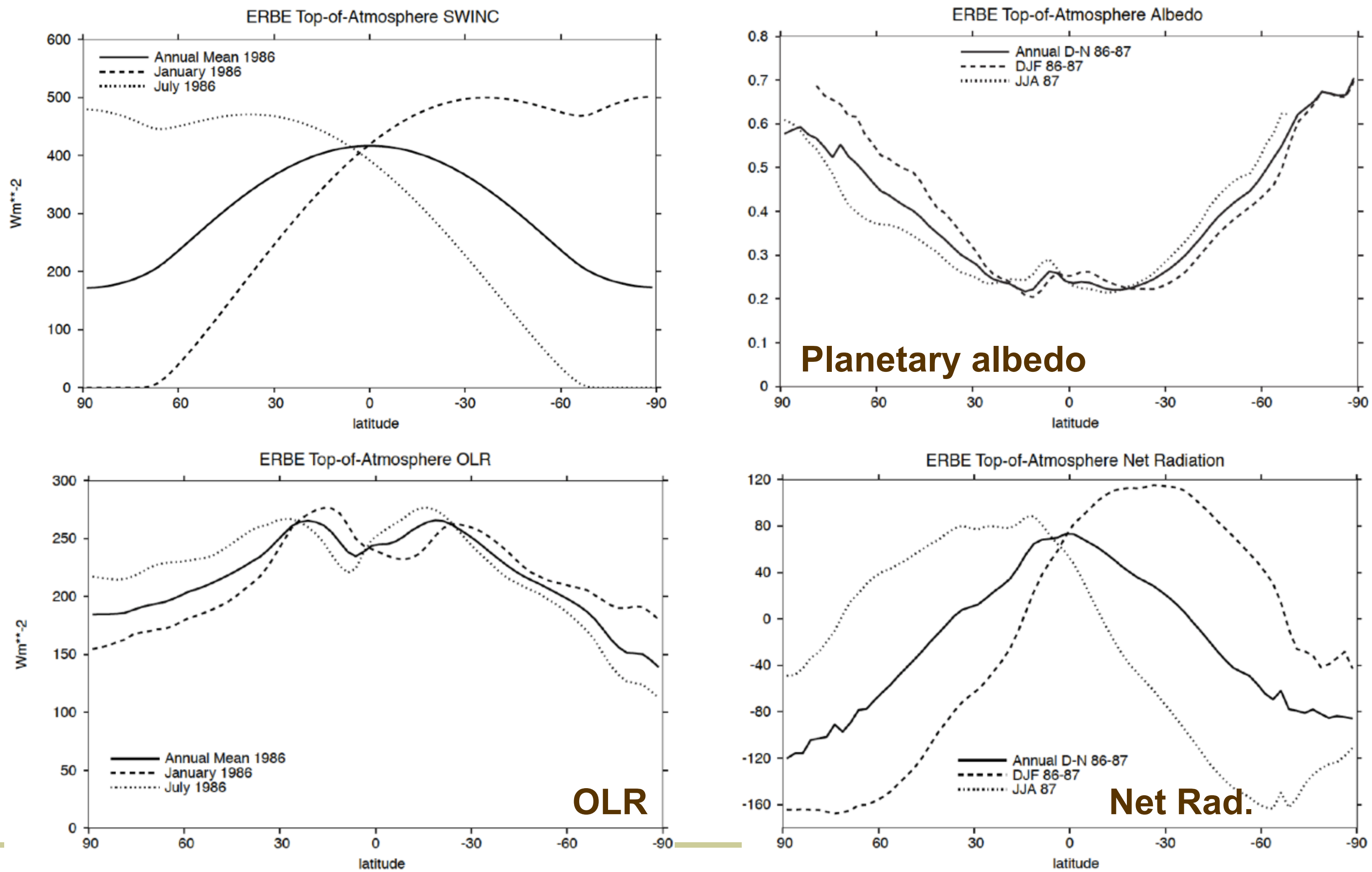
Radiation budget at TOA





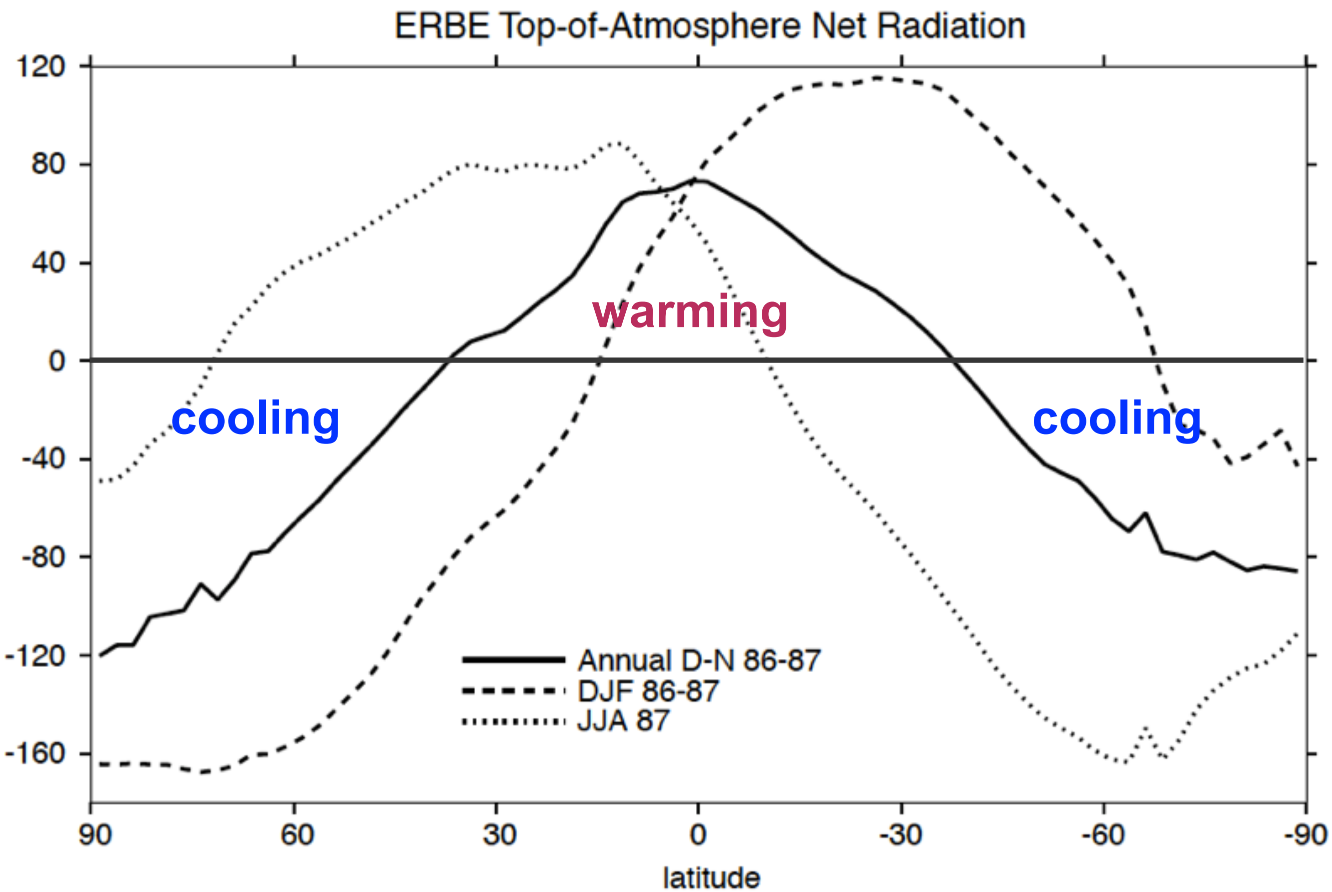
From Randall, 2009

Radiation budget at TOA



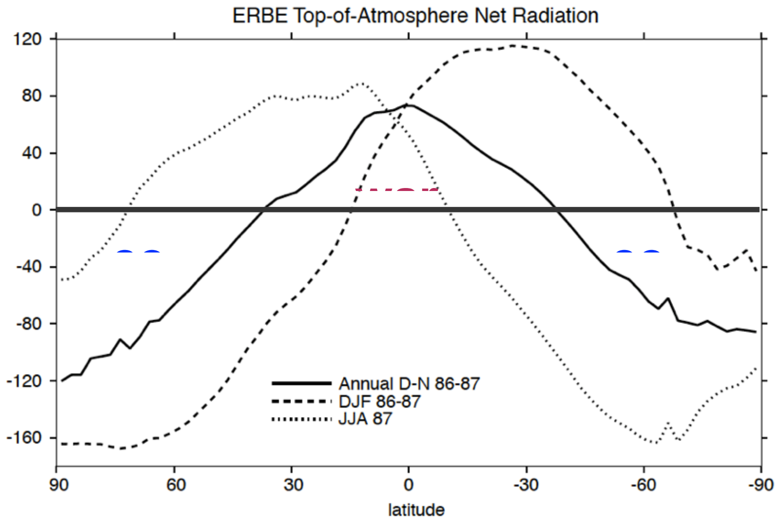
From Randall, 2009

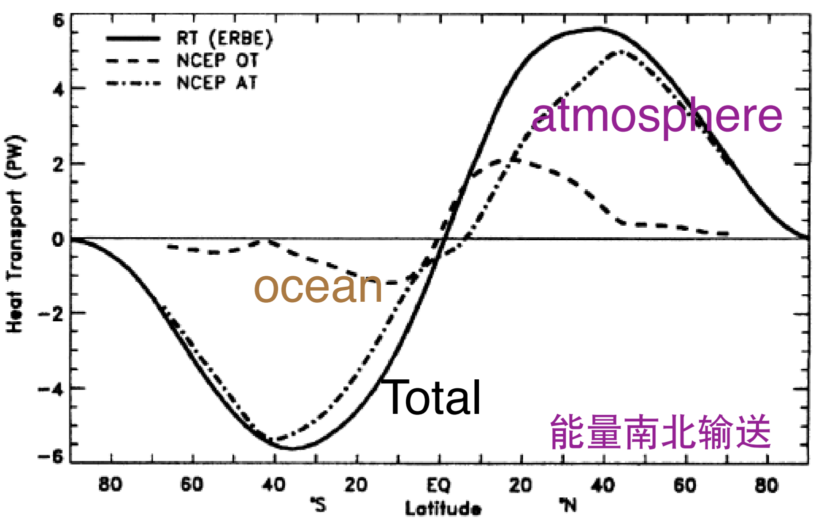
Radiation budget at TOA



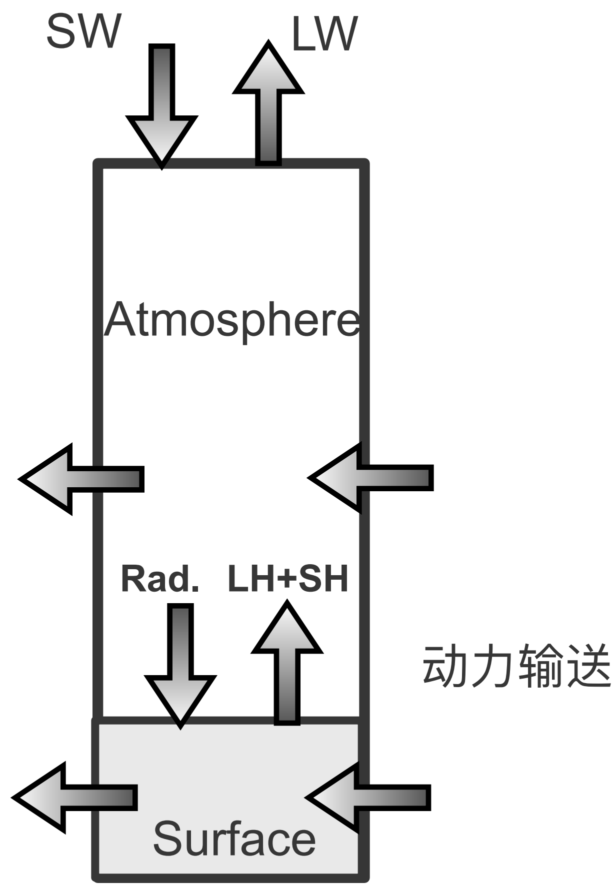
From Randall, 2009

Radiation budget at TOA





Wunsch (2005), J. Climate



Energy budget at SURFACE

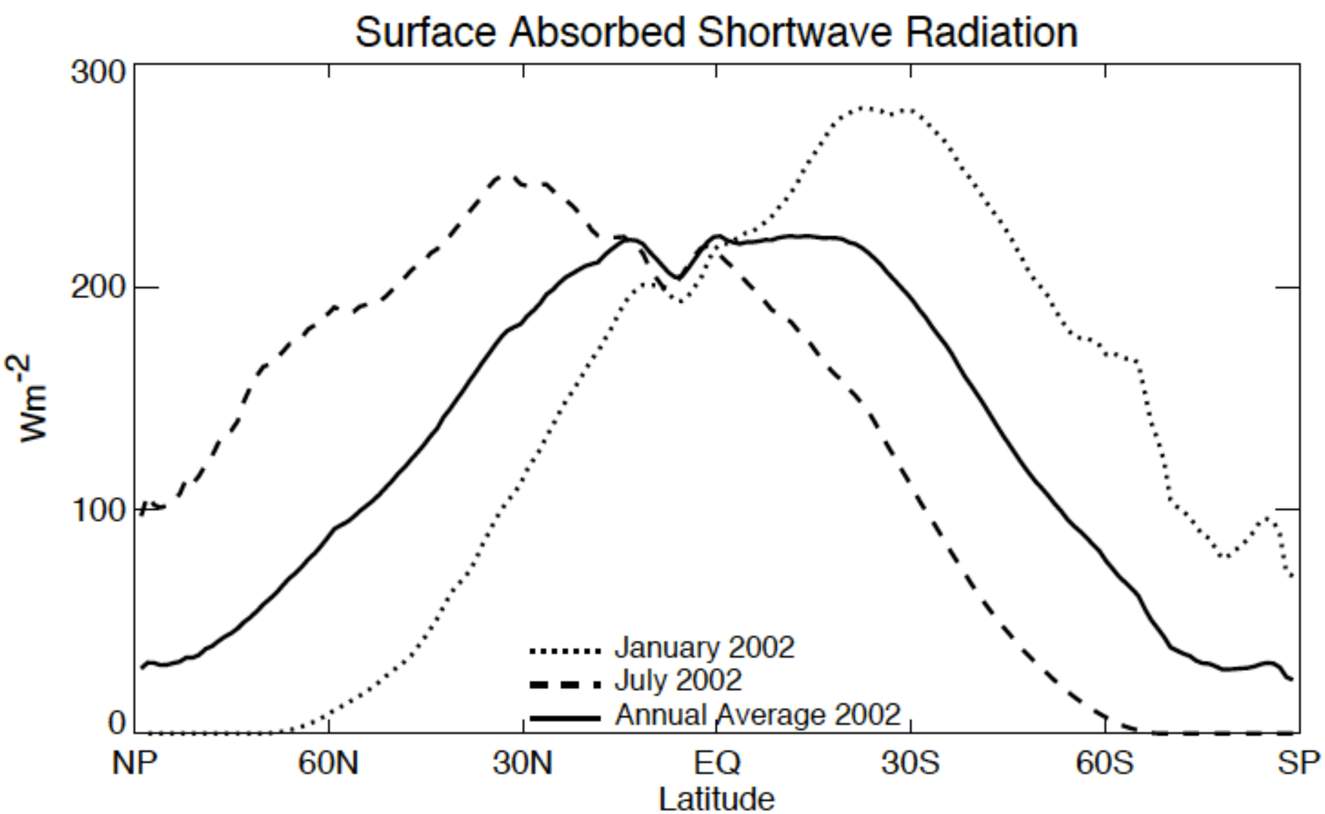


Figure: zonally averaged net surface shortwave radiative flux, positive upward (from Randall 2009).

Energy budget at SURFACE

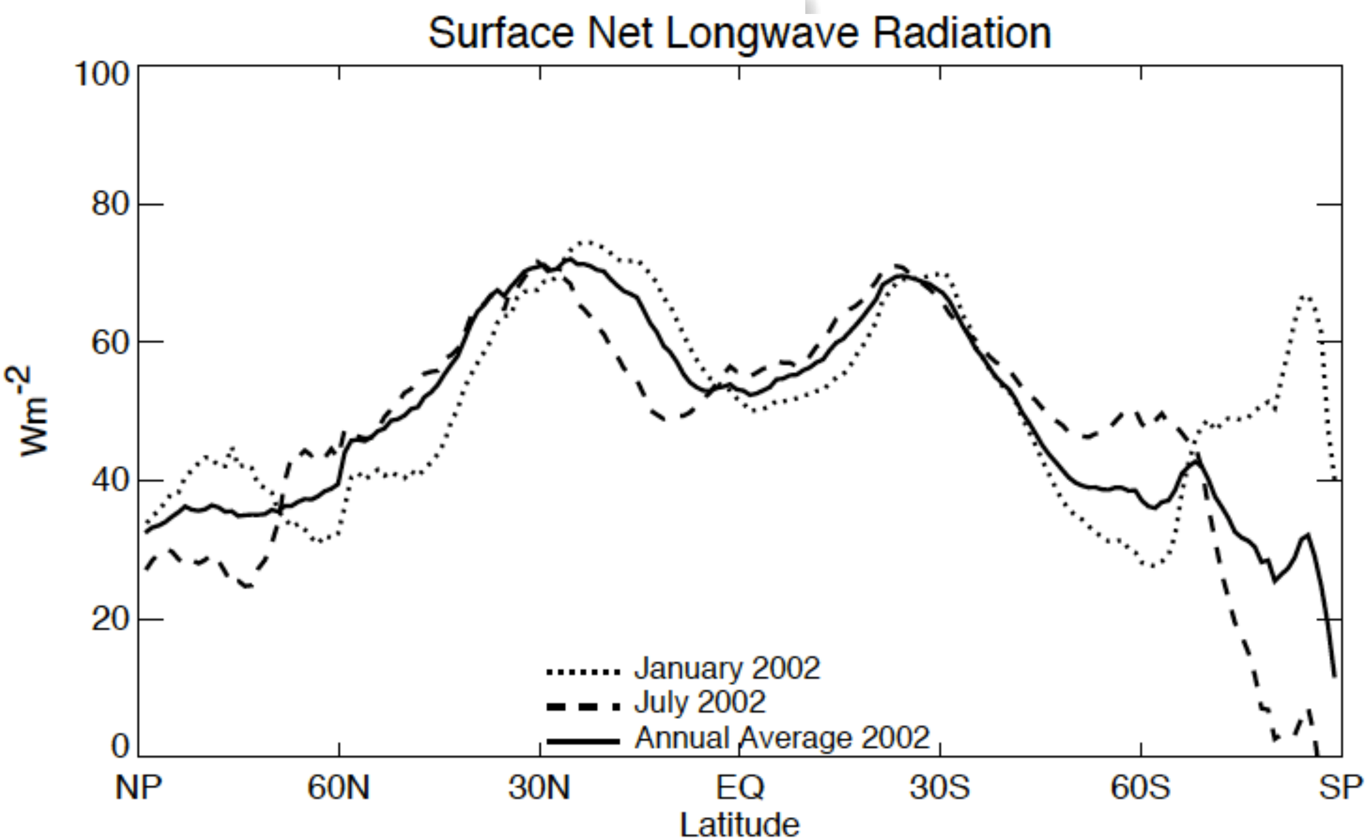


Figure: zonally averaged net surface longwave radiative flux, positive upward (from Randall 2009).

Energy budget at SURFACE

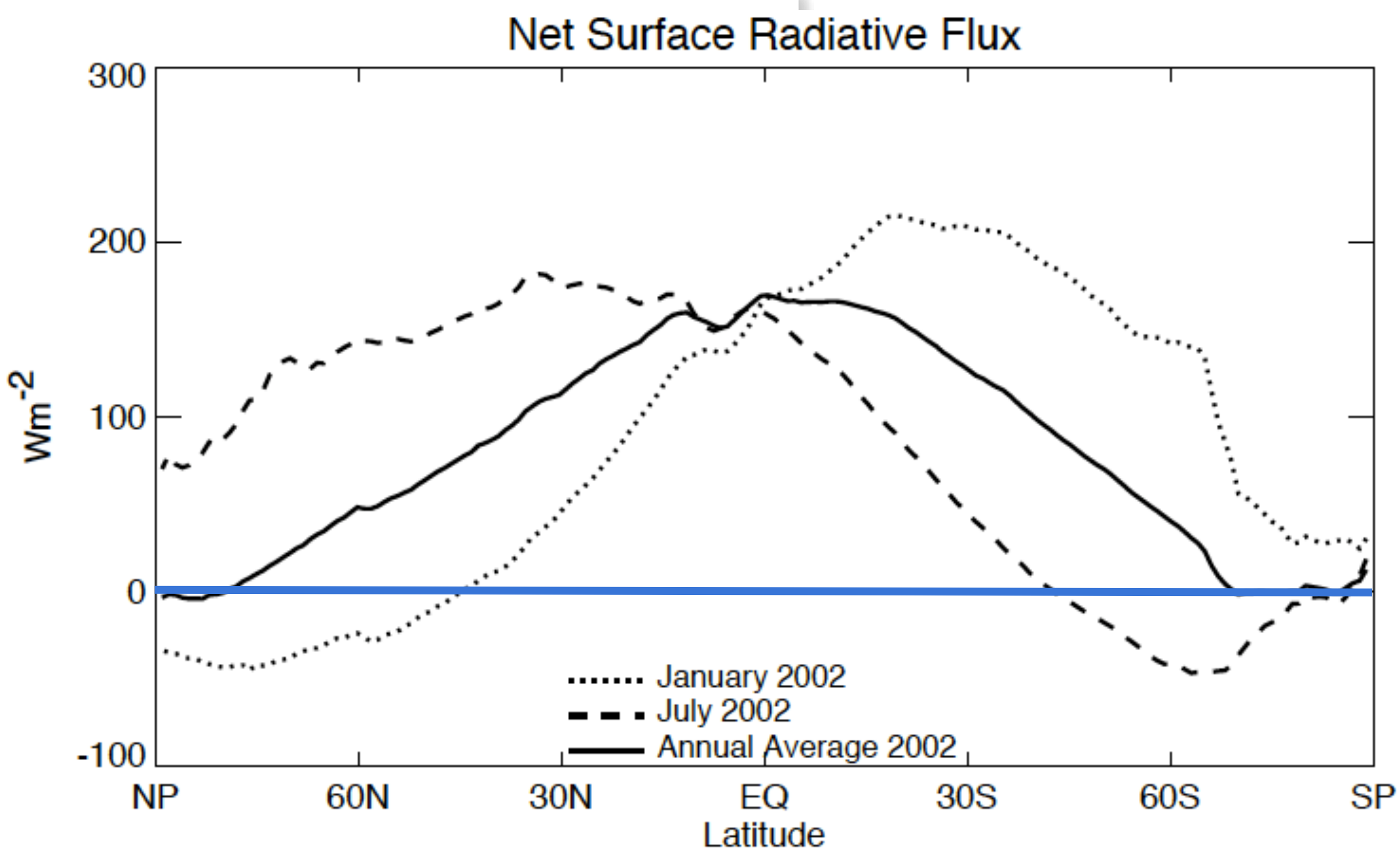
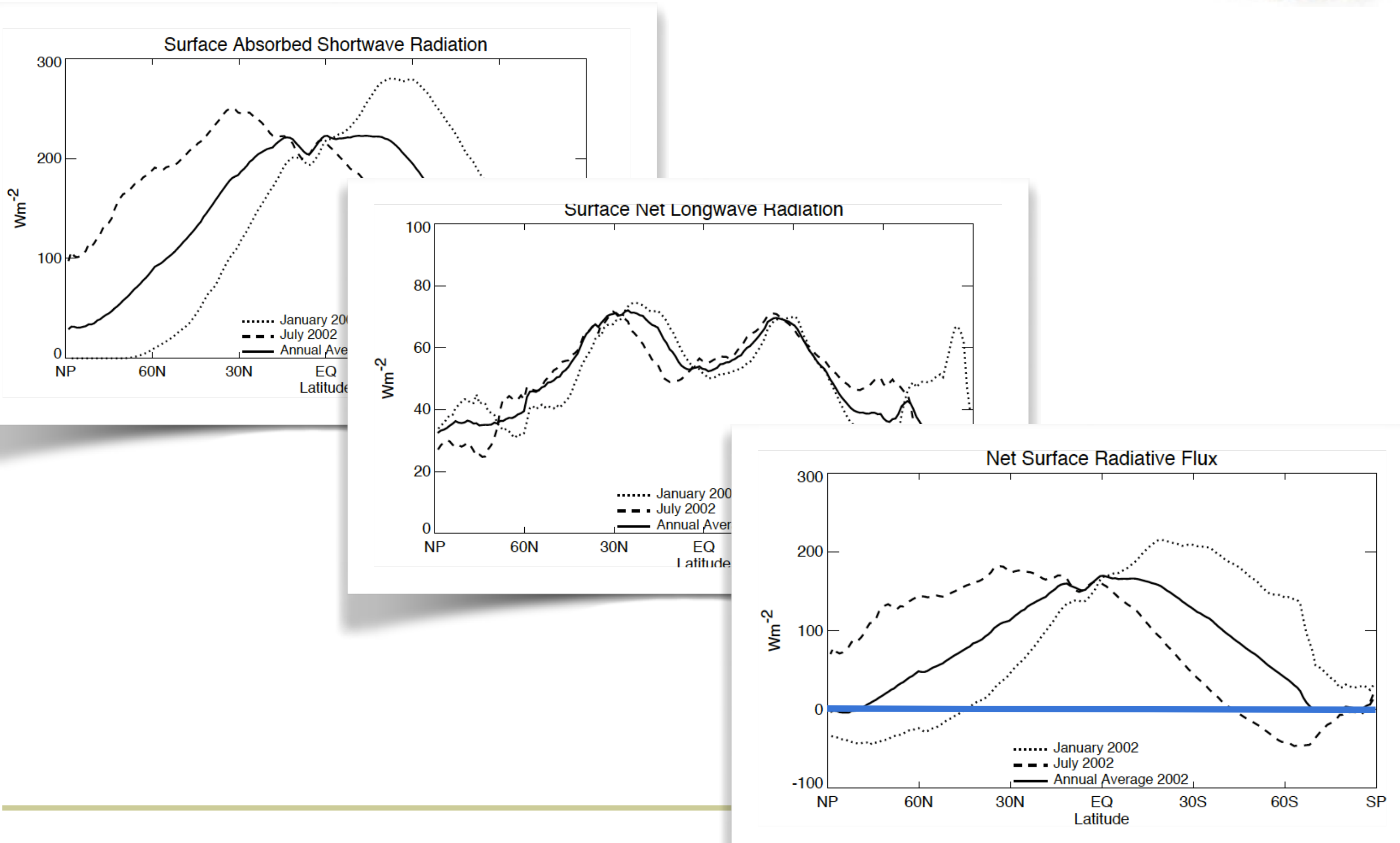


Figure: zonally averaged net surface radiative flux, positive upward (from Randall 2009).

Energy budget at SURFACE



Energy budget at SURFACE

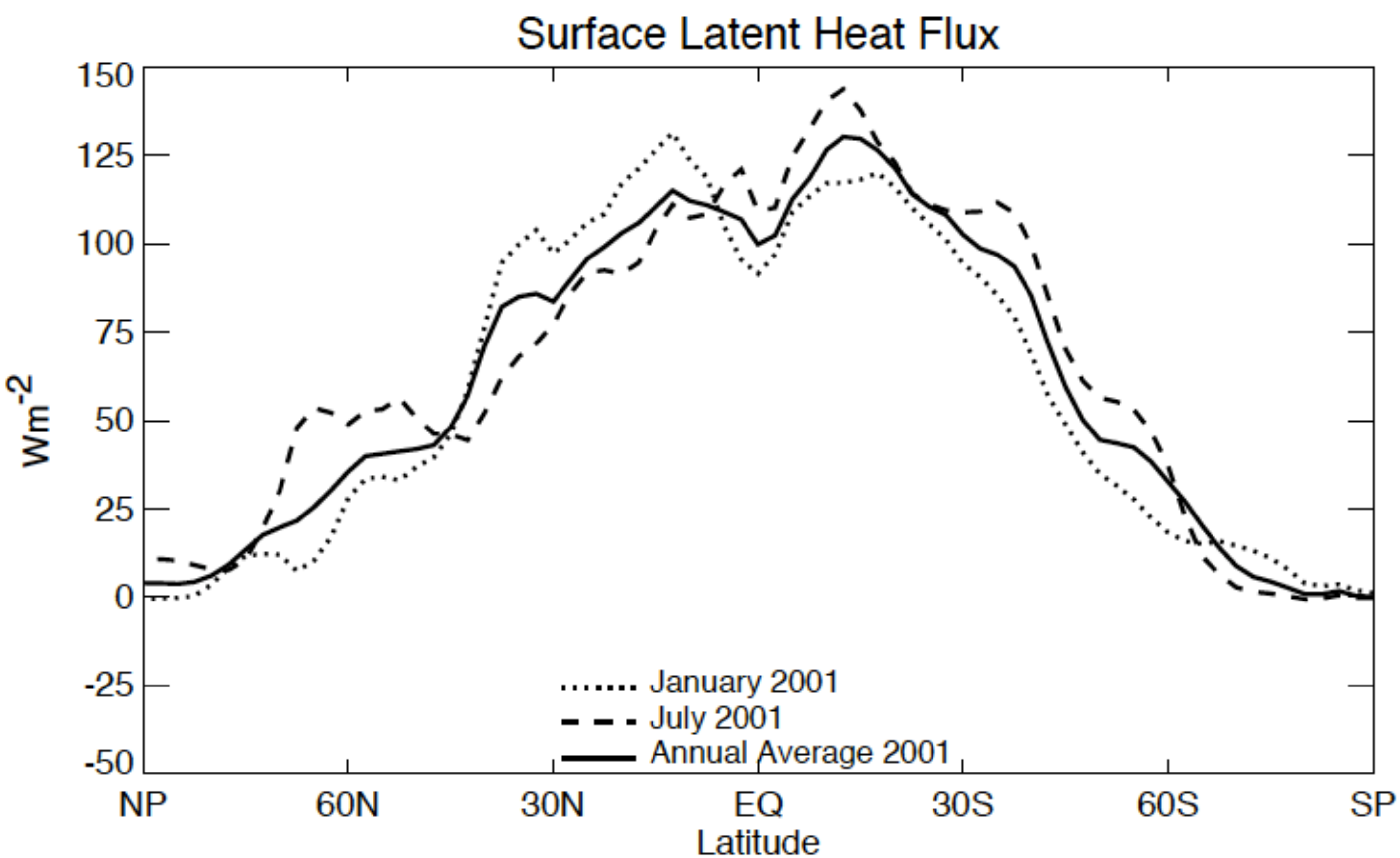


Figure: zonally averaged surface latent heat flux, positive upward, based on ECMWF (from Randall 2009).

Energy budget at SURFACE

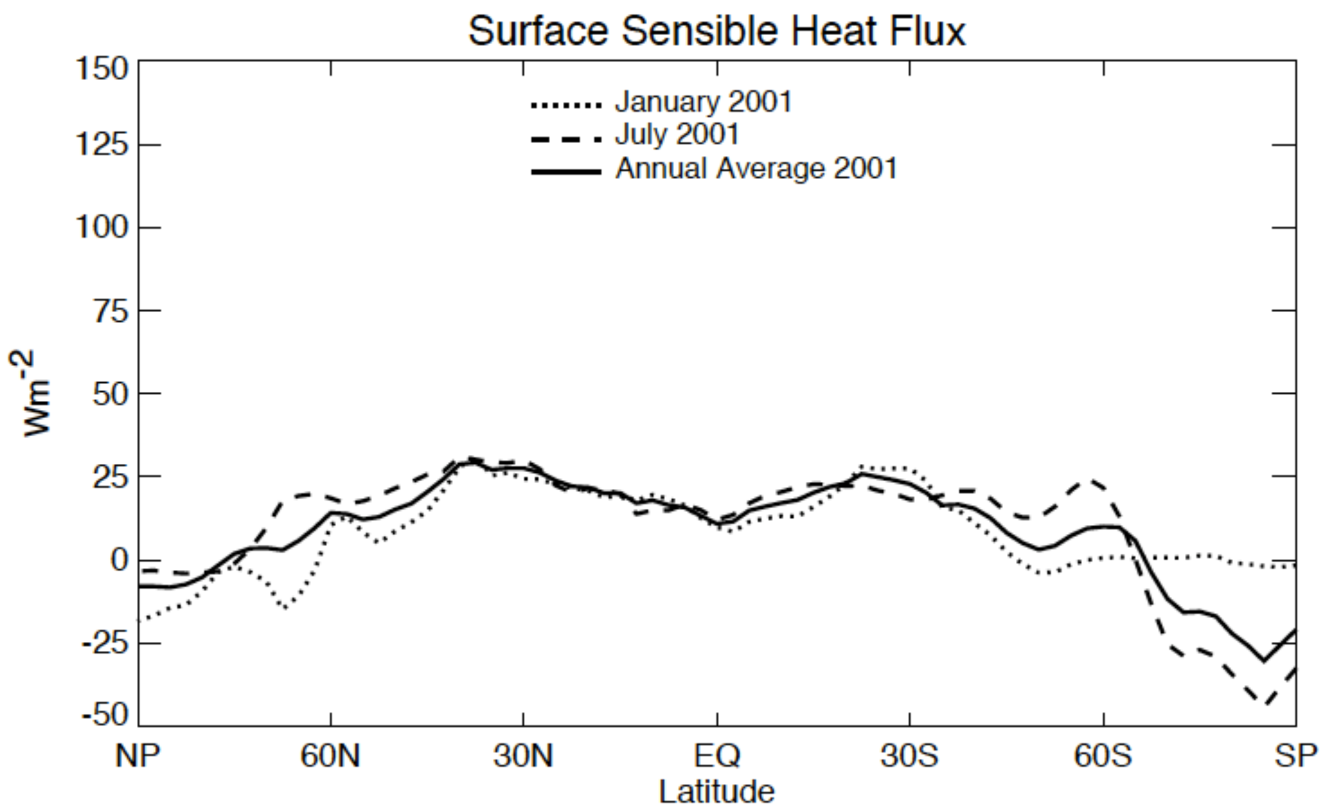
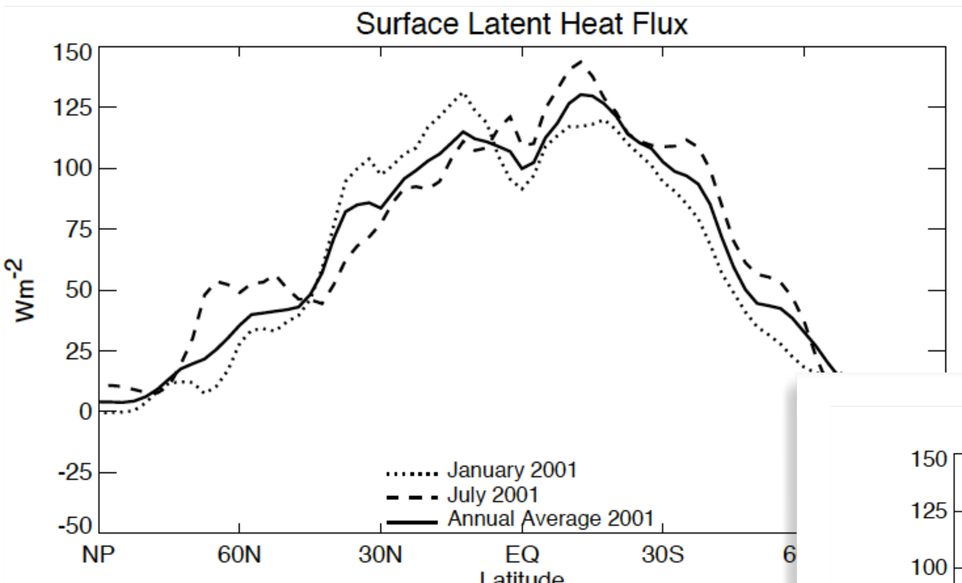
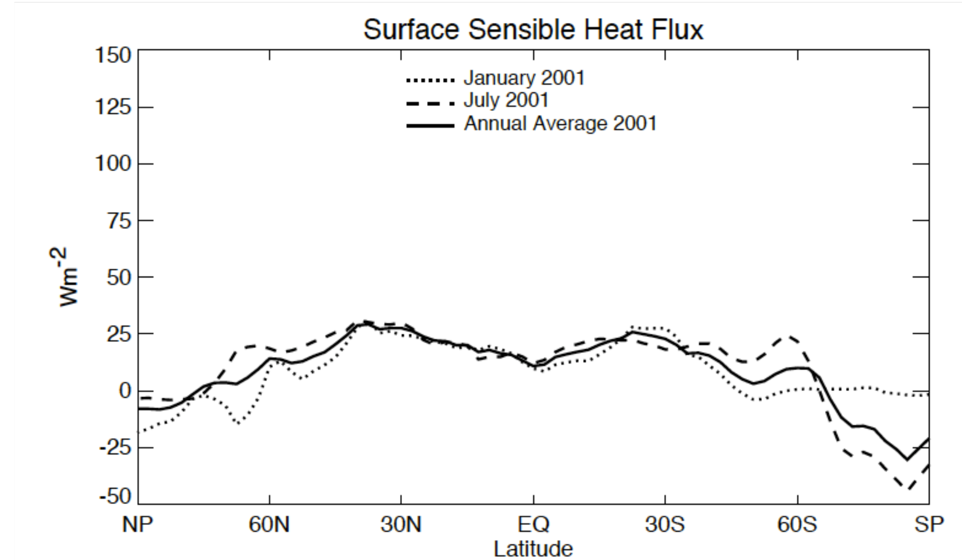


Figure: zonally averaged surface sensible heat flux, positive upward, based on ECMWF (from Randall 2009).

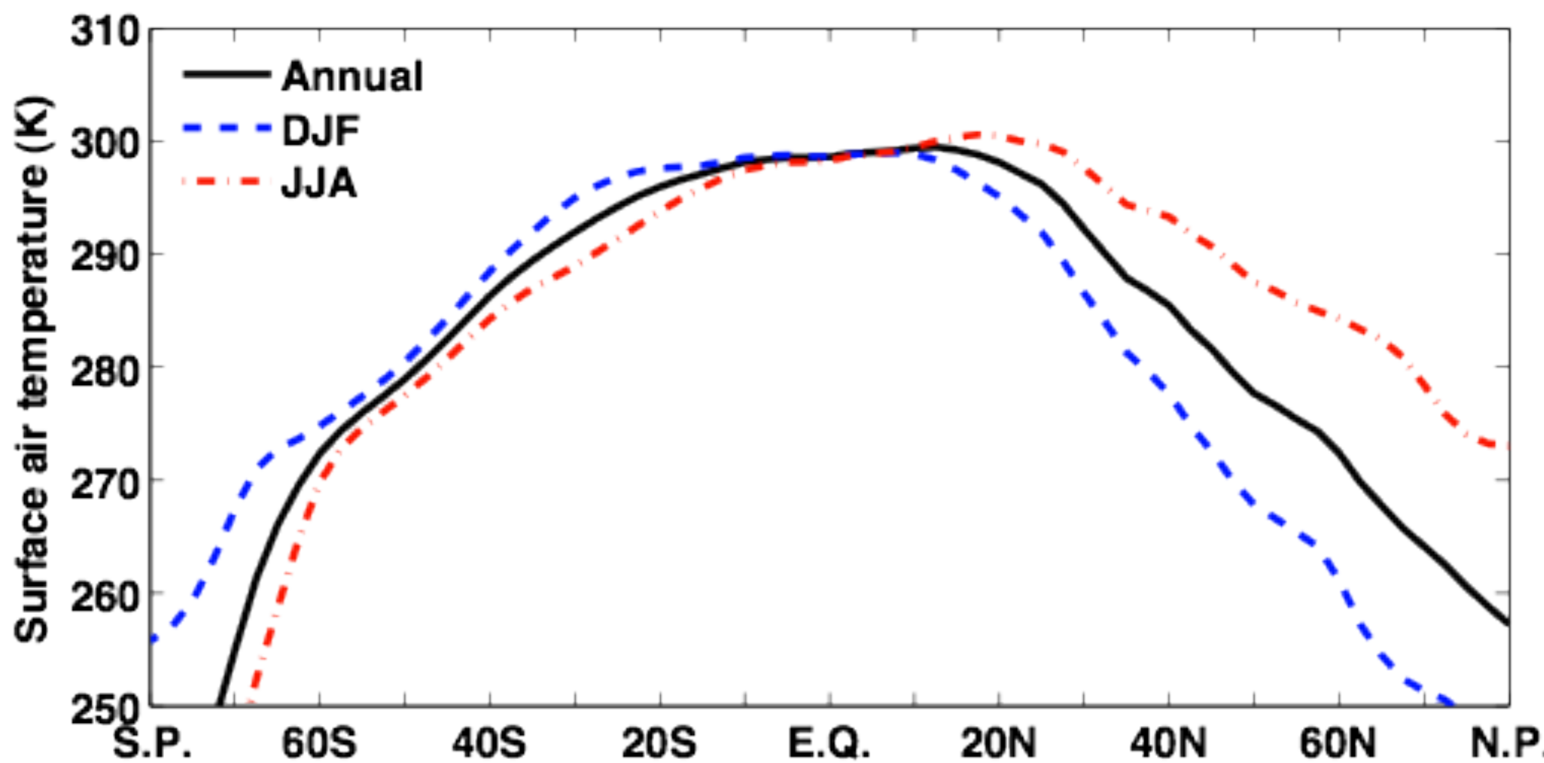
Energy budget at SURFACE





Energy budget at SURFACE

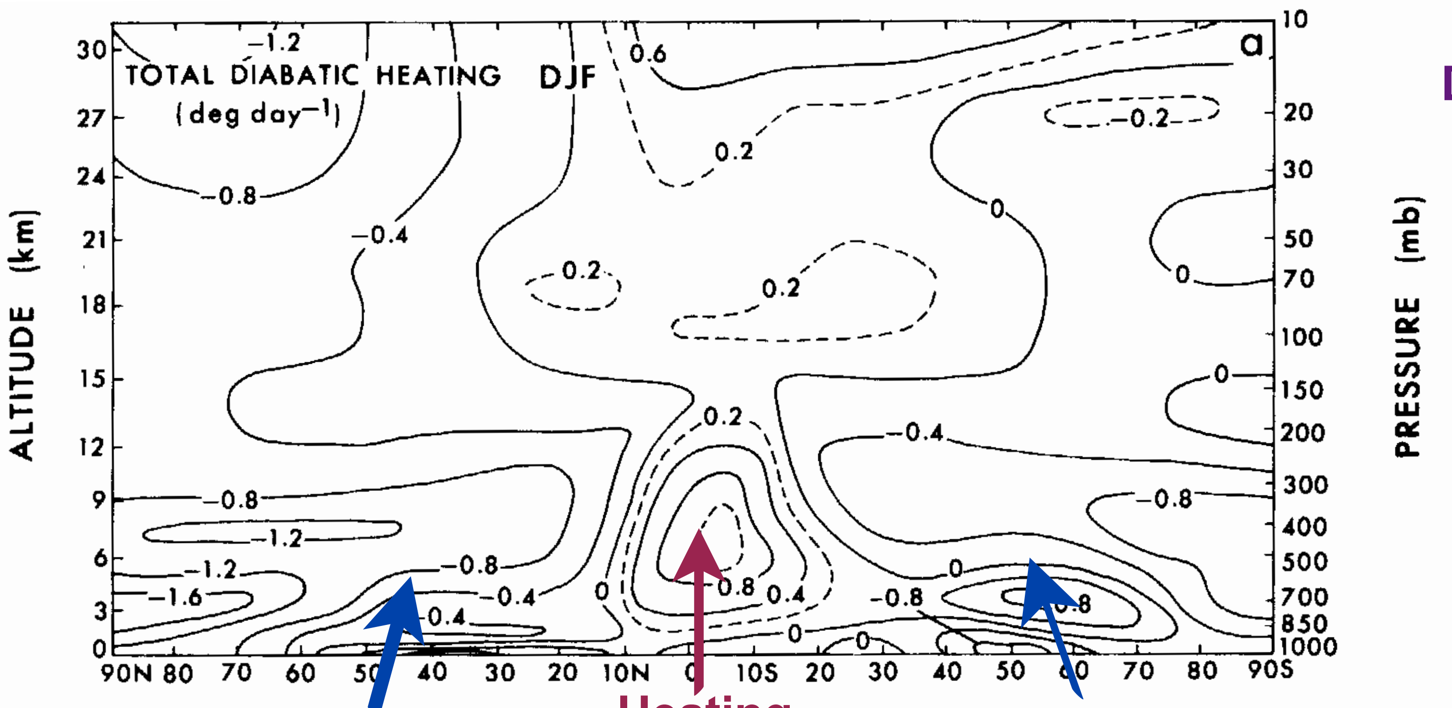
- Surface air



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



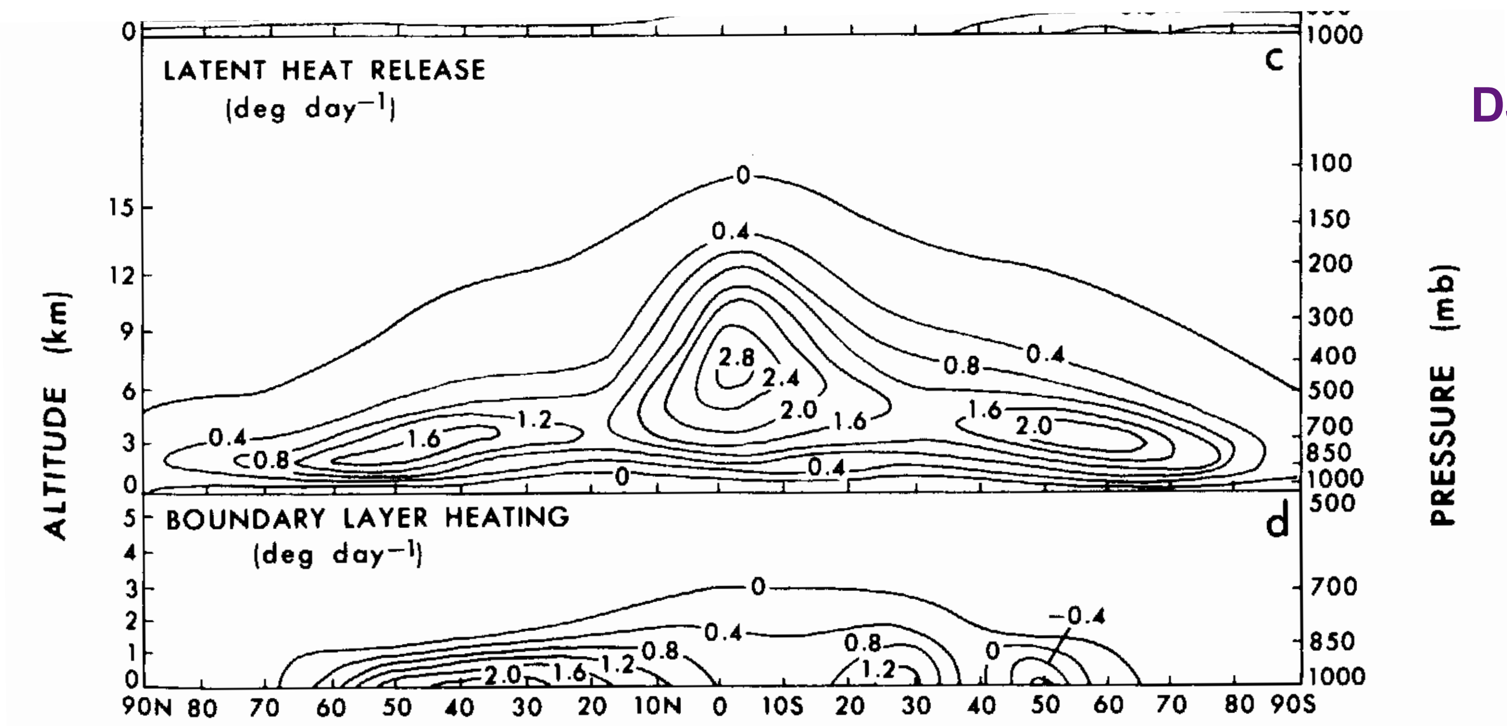
DJF

Cooling Heating Cooling

from Peixoto and Oort, 1992

Diabatic heating in atmosphere

estimated as residual



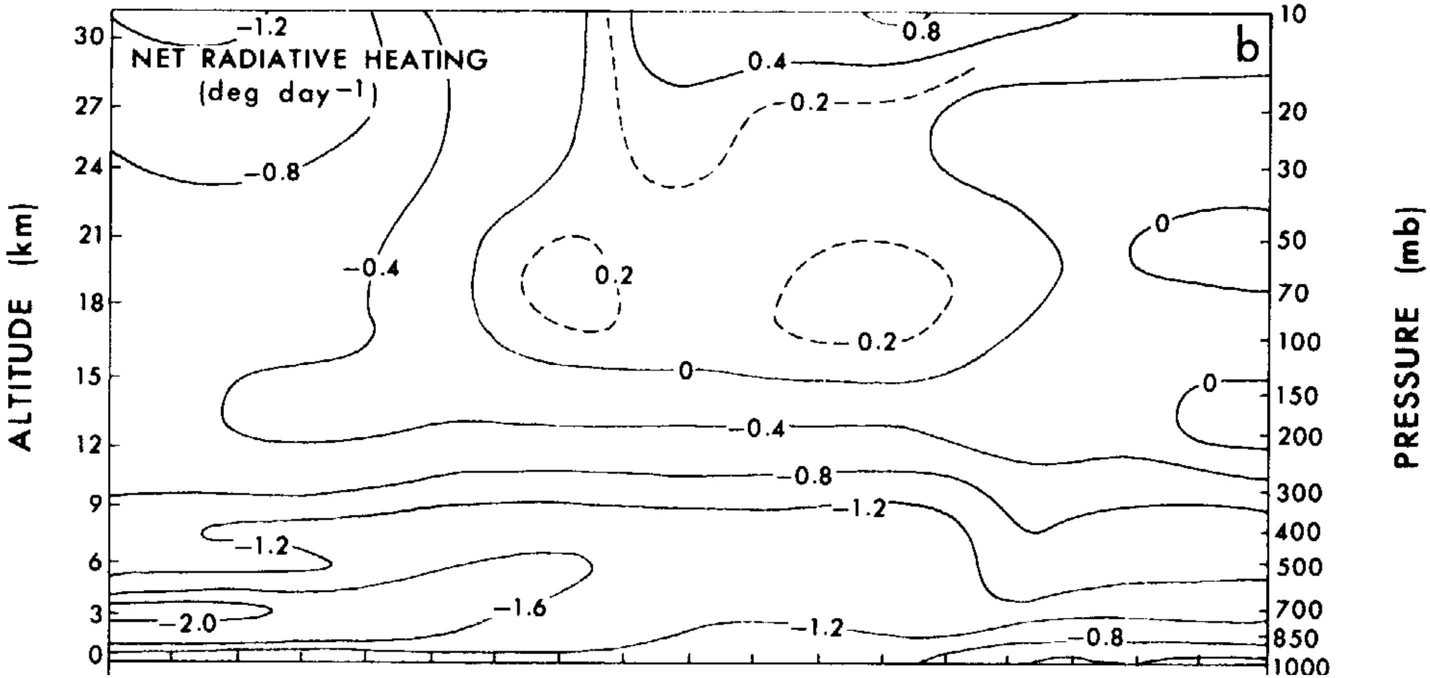
DJF

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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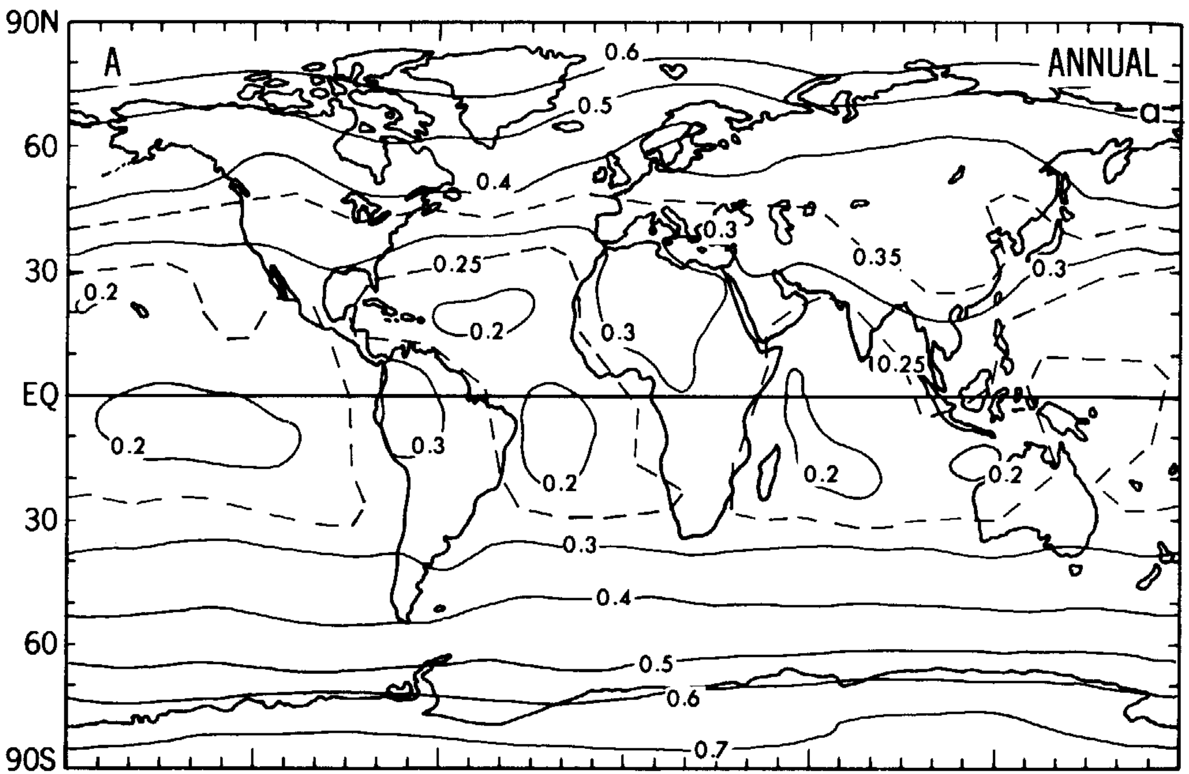
Zonal variation of TOA energy flux

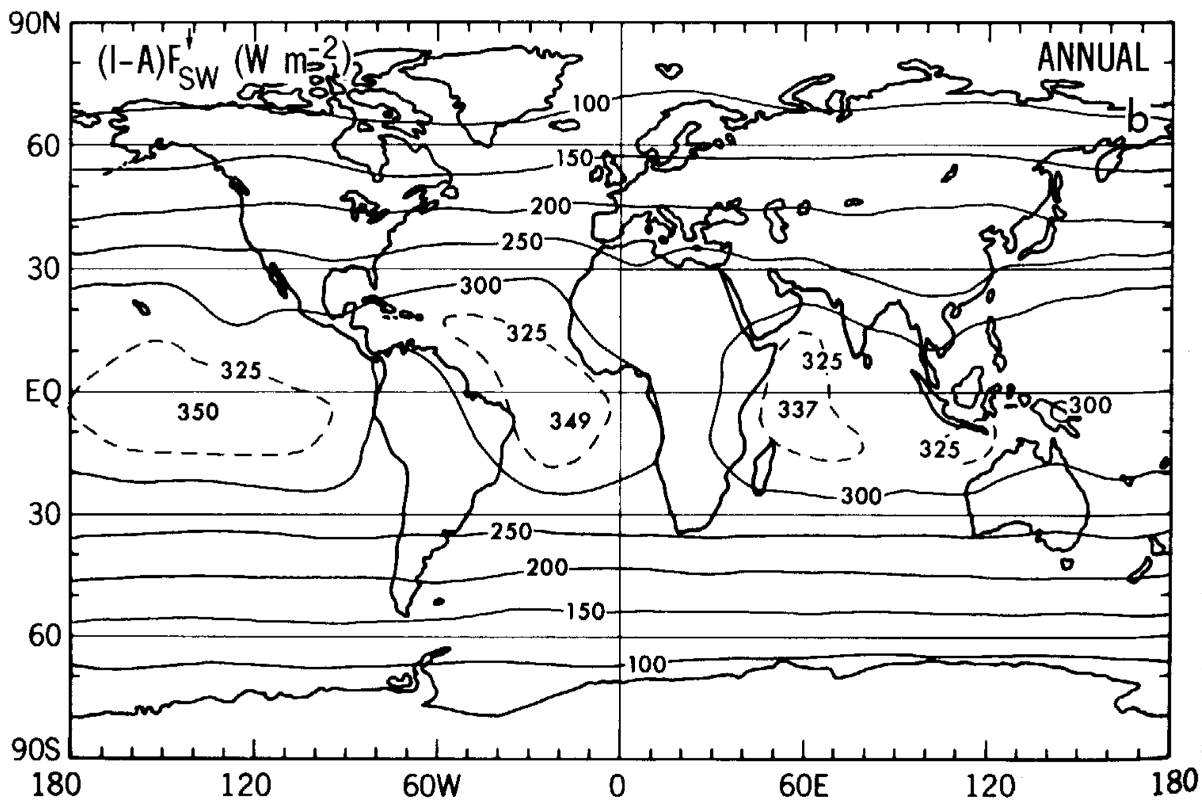
- Planetary albedo



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

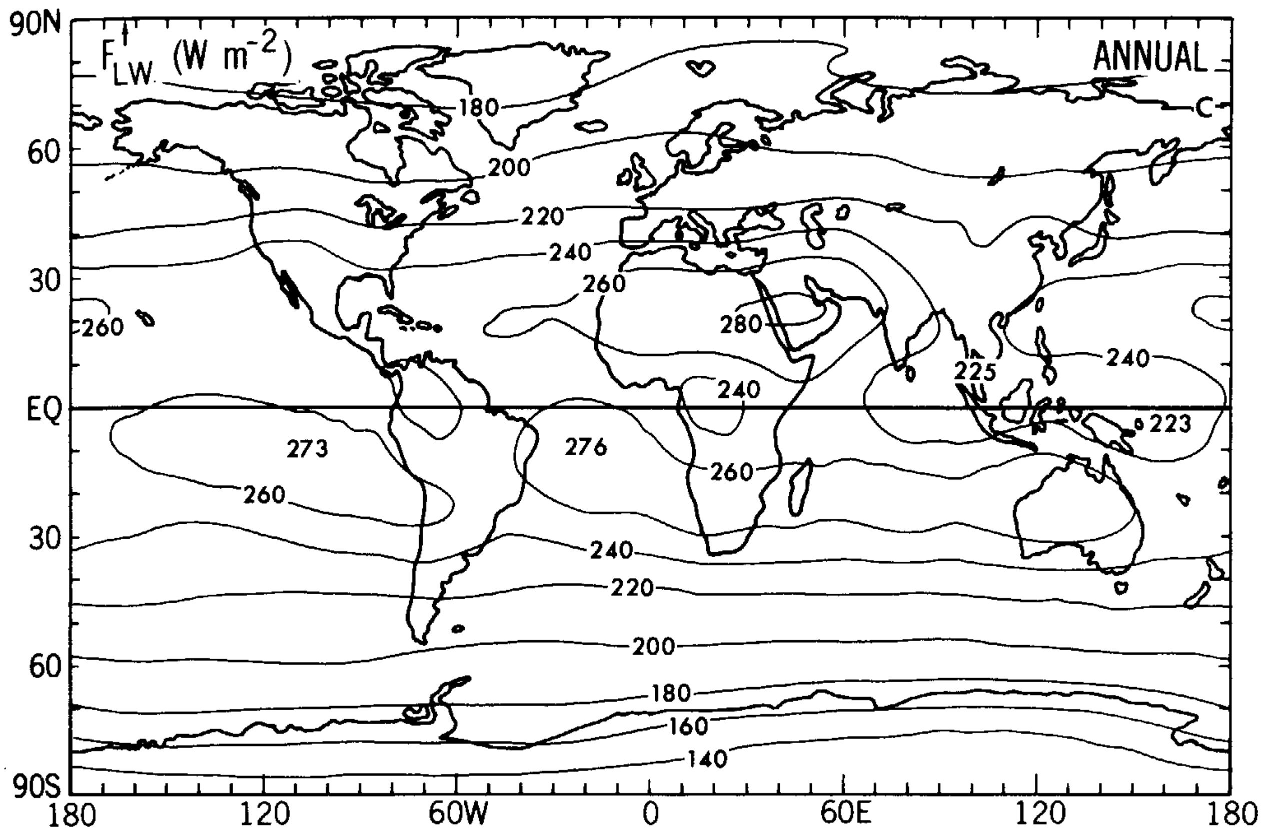
- Net short wave radiation



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

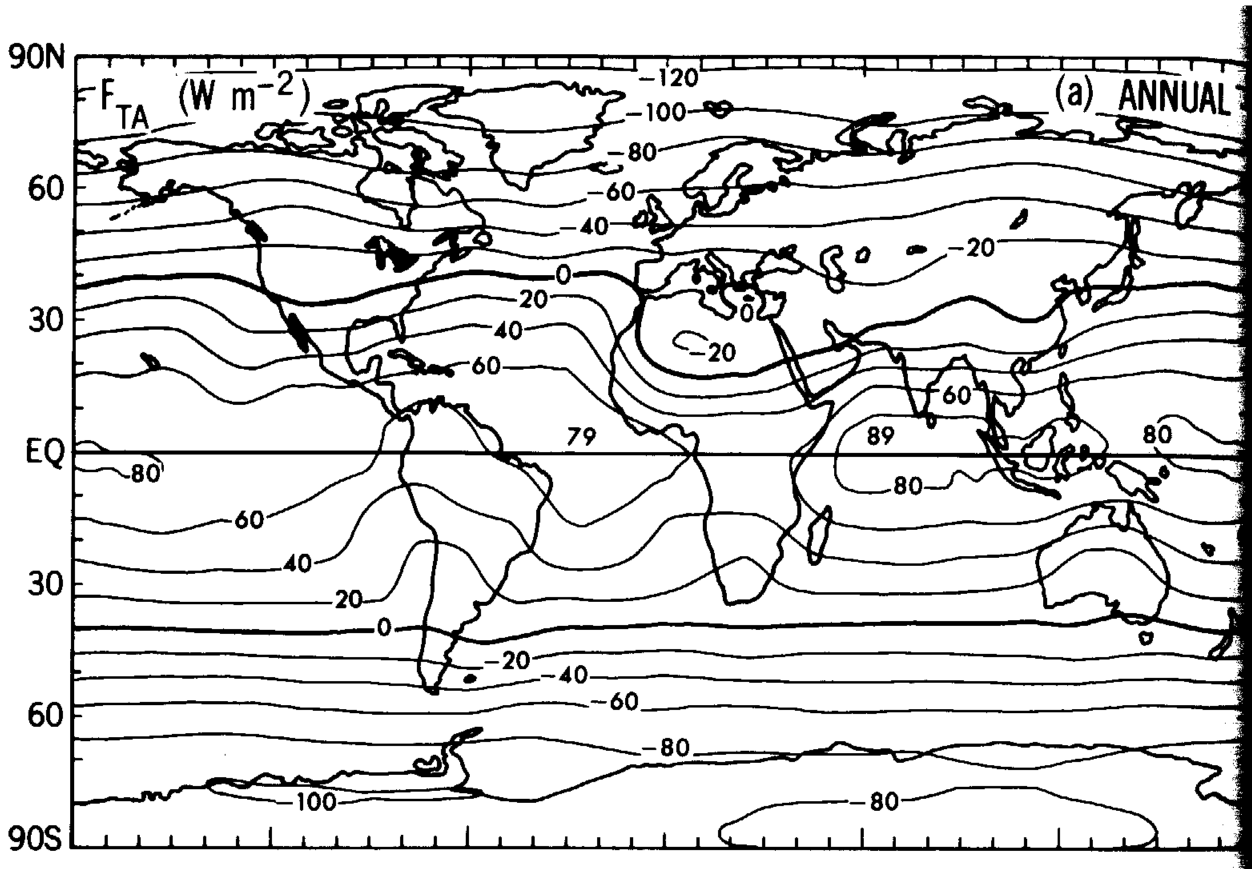
- Net longwave radiation



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

- Net radiation at TOA



From Peixoto and Oort, 1992

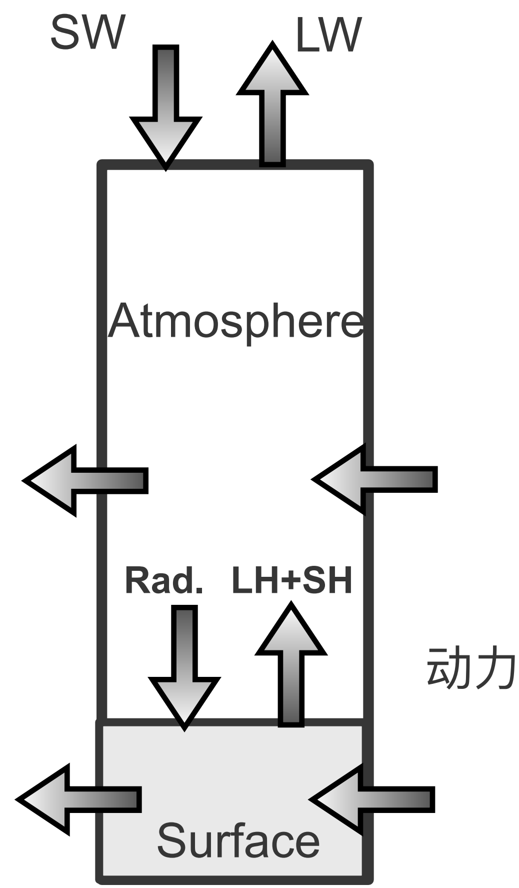
Zonal variation of TOA energy flux

- 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

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

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



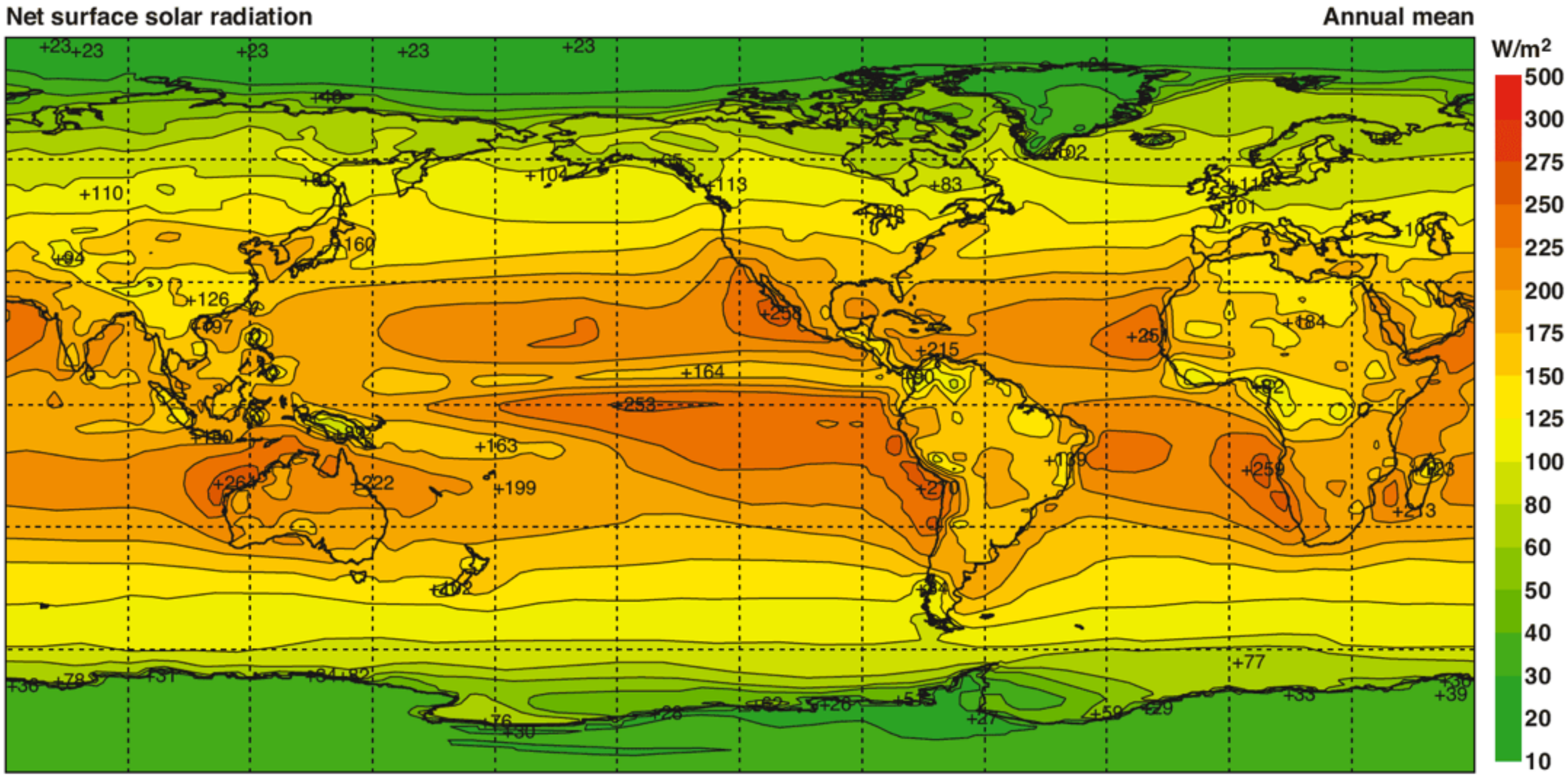
specific heat of ocean water: 4187 J/(kg* K)

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

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

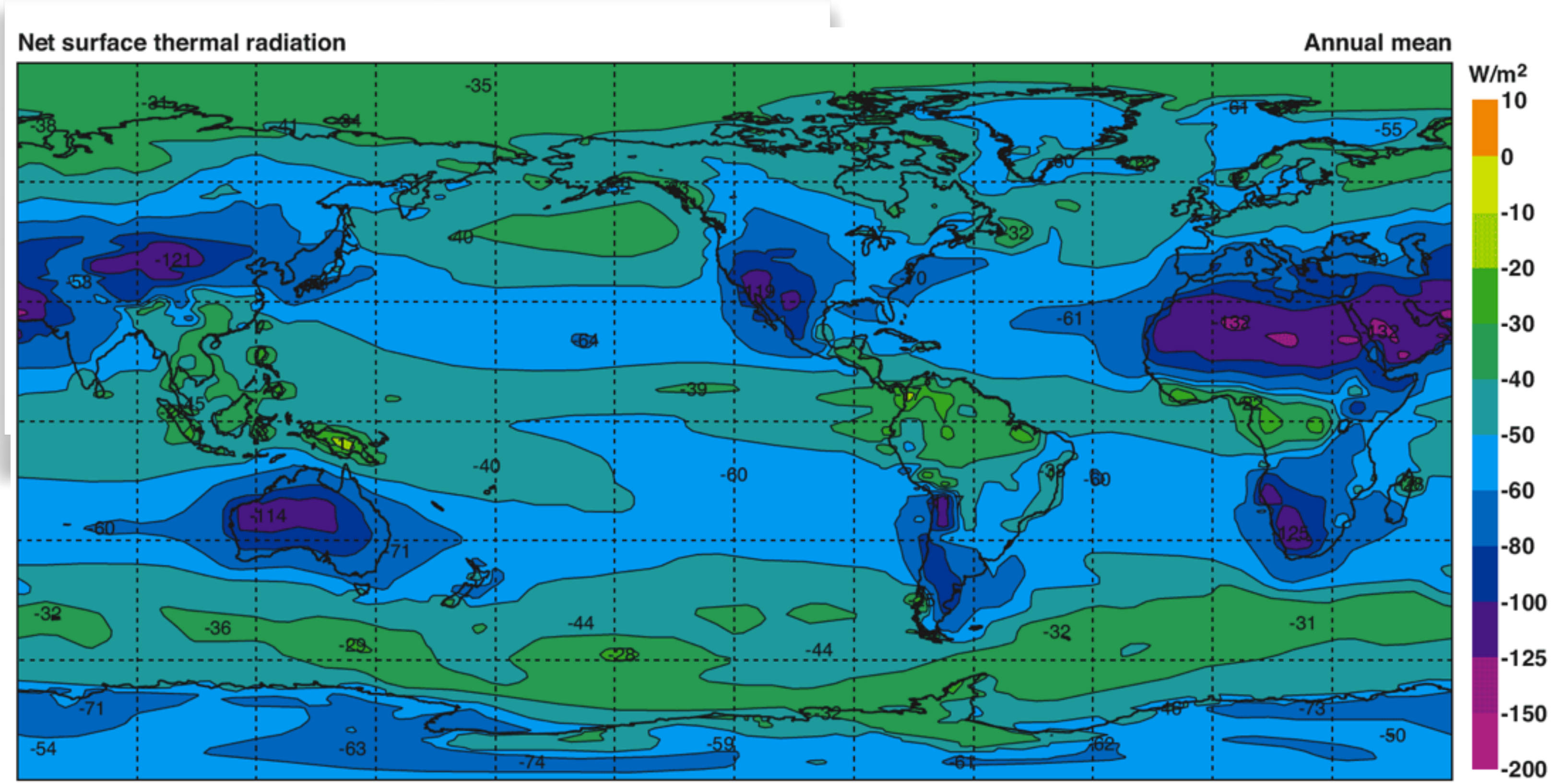
specific heat of atmosphere at constant pressure: 1004 J/(kg* K)

Zonal variation of surface energy flux – SW radiation



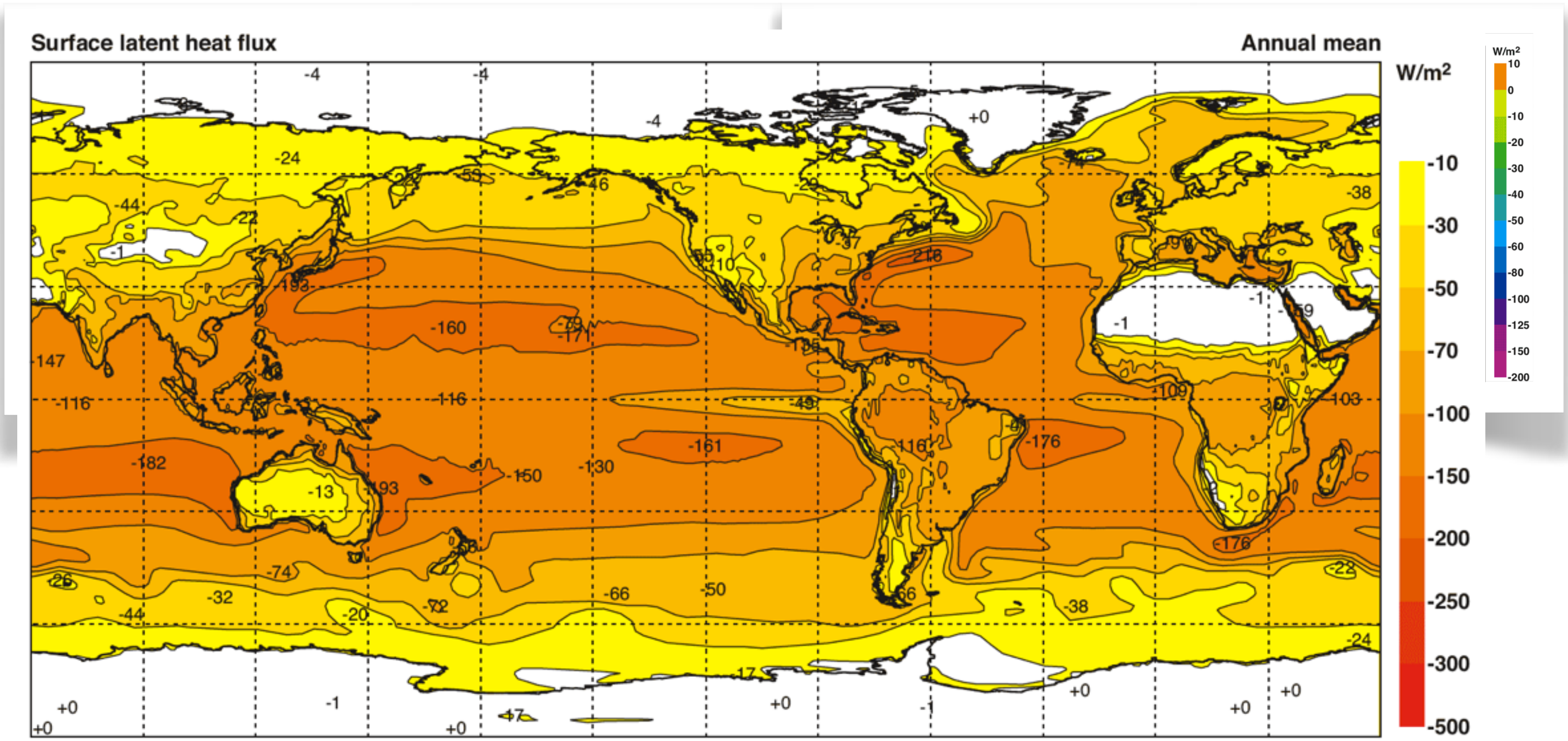
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux – LW radiation



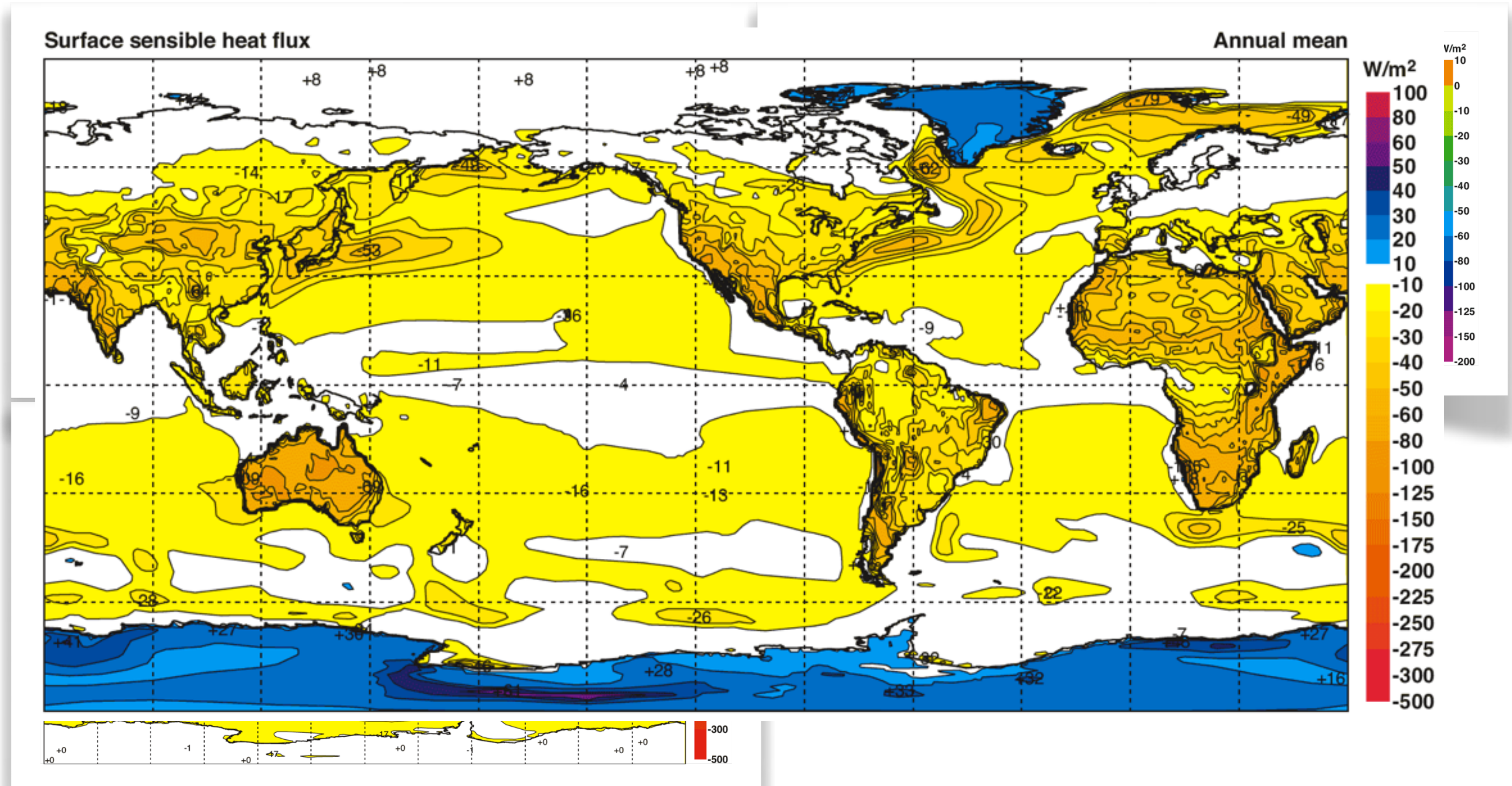
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux - latent heat



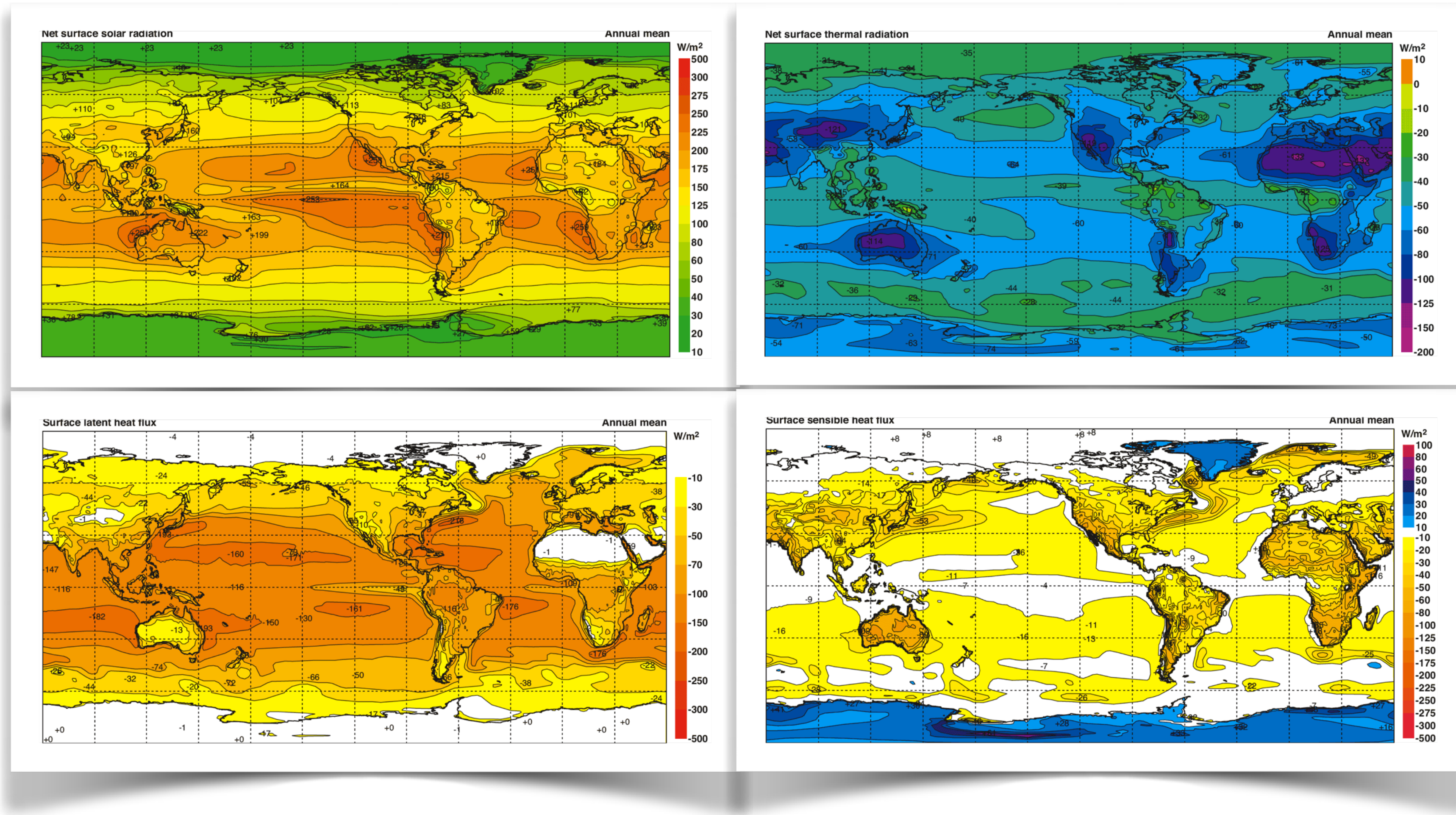
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux - Sensible heat



From Stewart, 2005
Introduction to Physical Oceanography

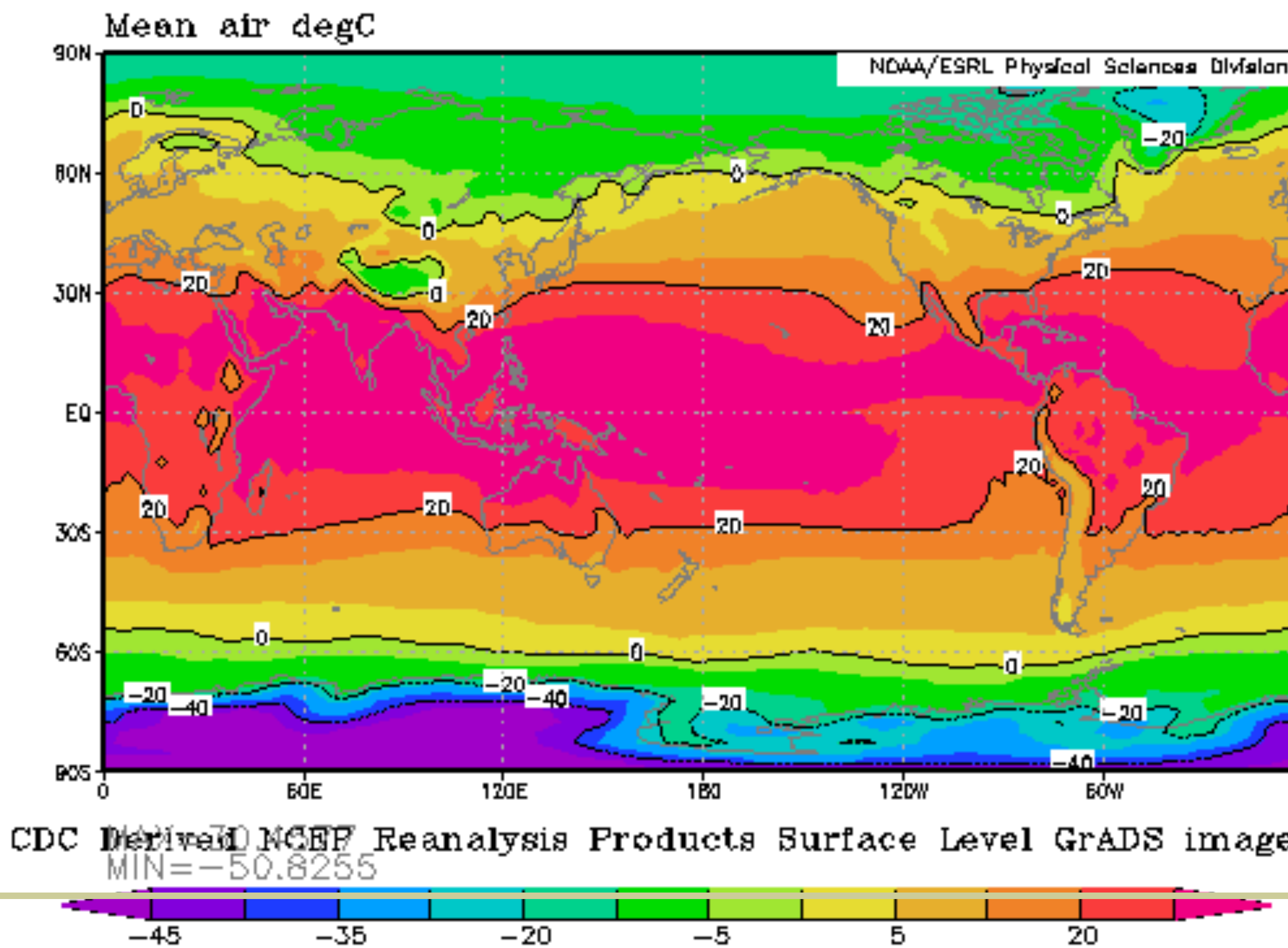
Zonal variation of surface energy flux



From Stewart, 2005
Introduction to Physical Oceanography

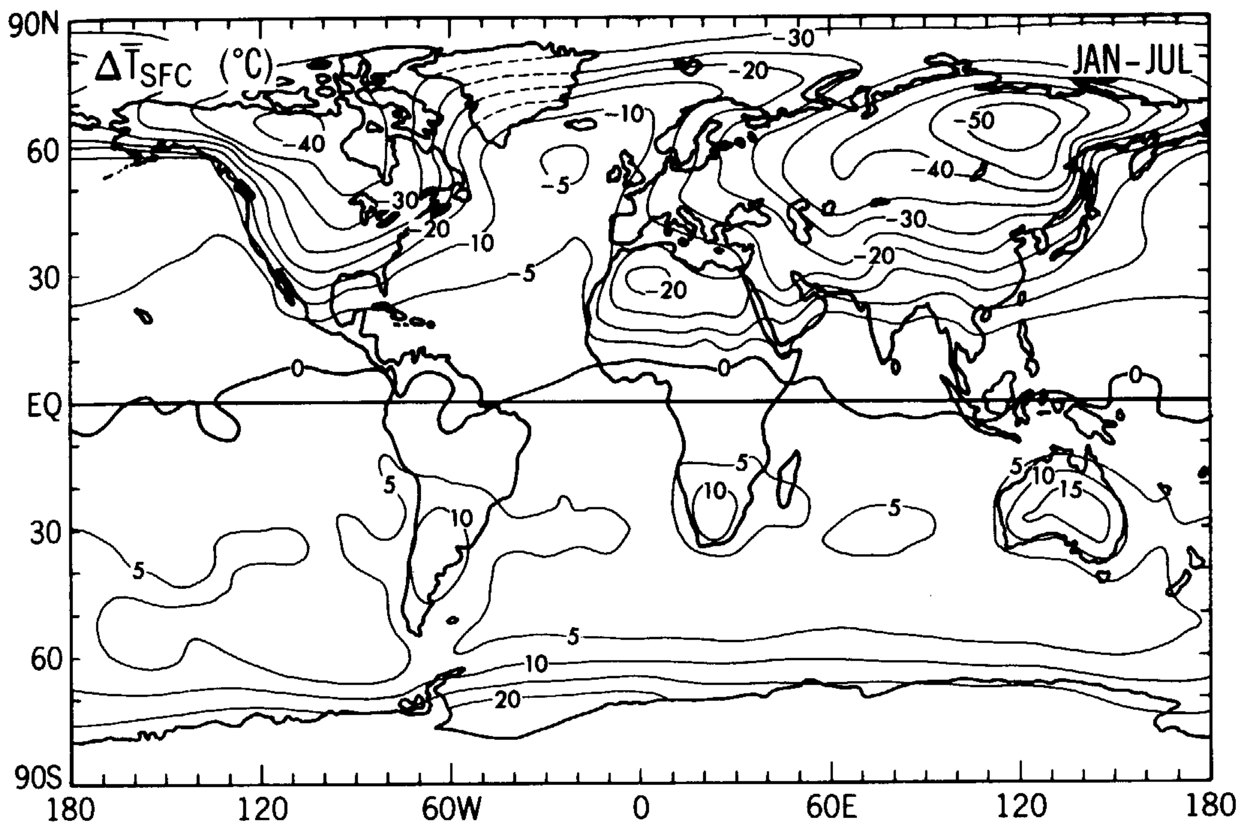
Zonal variation of surface energy flux

- Surface air



Zonal variation of surface energy flux

- Seasonal variation of surface temperature



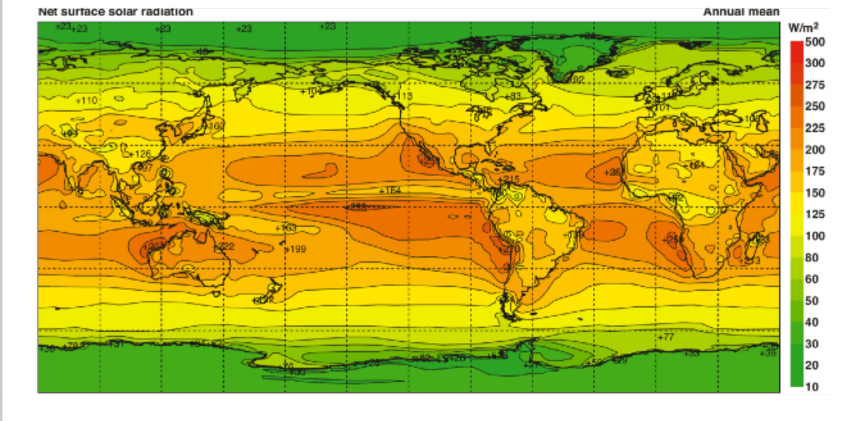
From Peixoto and Oort, 1992

Zonal variation of surface energy flux

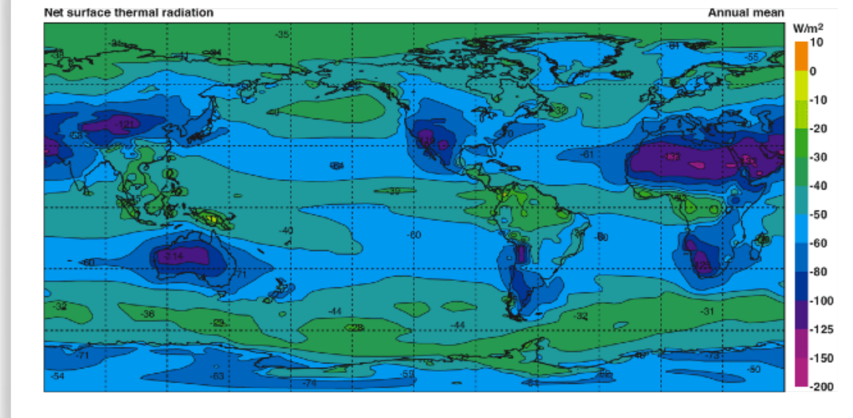
- Stronger zonal variation in surface LW, LH, SH and surface temperature
  - LW: stronger infrared cooling over land.
  - LH: stronger over ocean surface but weak over land
  - SH: stronger over land surface but weak over ocean
  - surface air temperature: stronger meridional temperature gradient and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

Zonal variation of surface energy flux

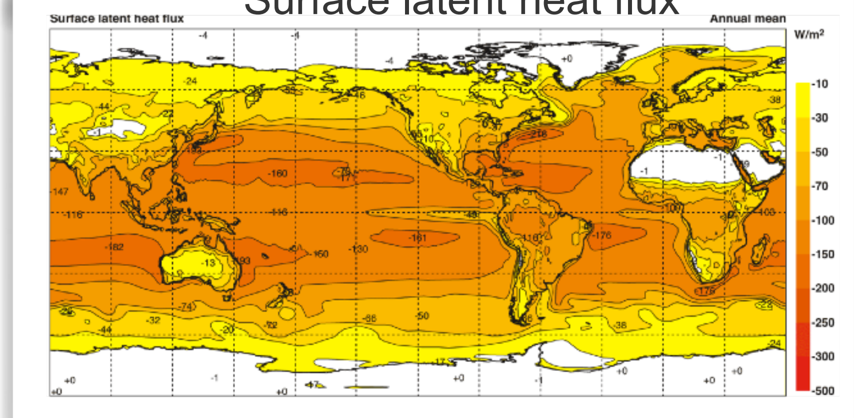
Net surface solar radiation



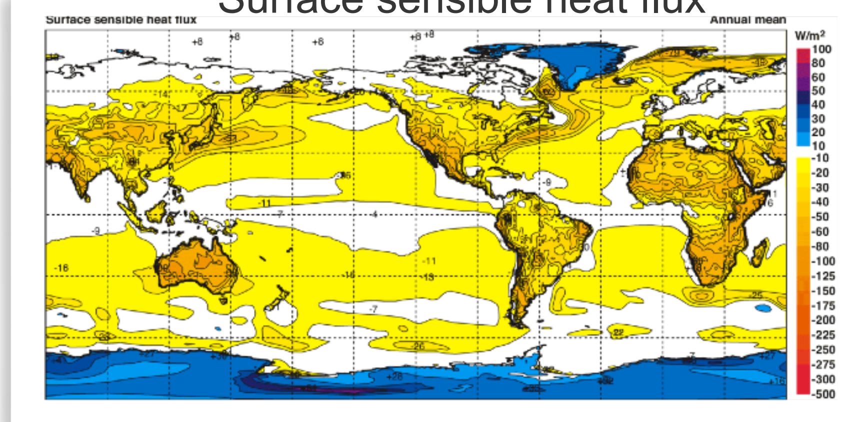
Net surface infrared radiation



Surface latent heat flux



Surface sensible heat flux



From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux

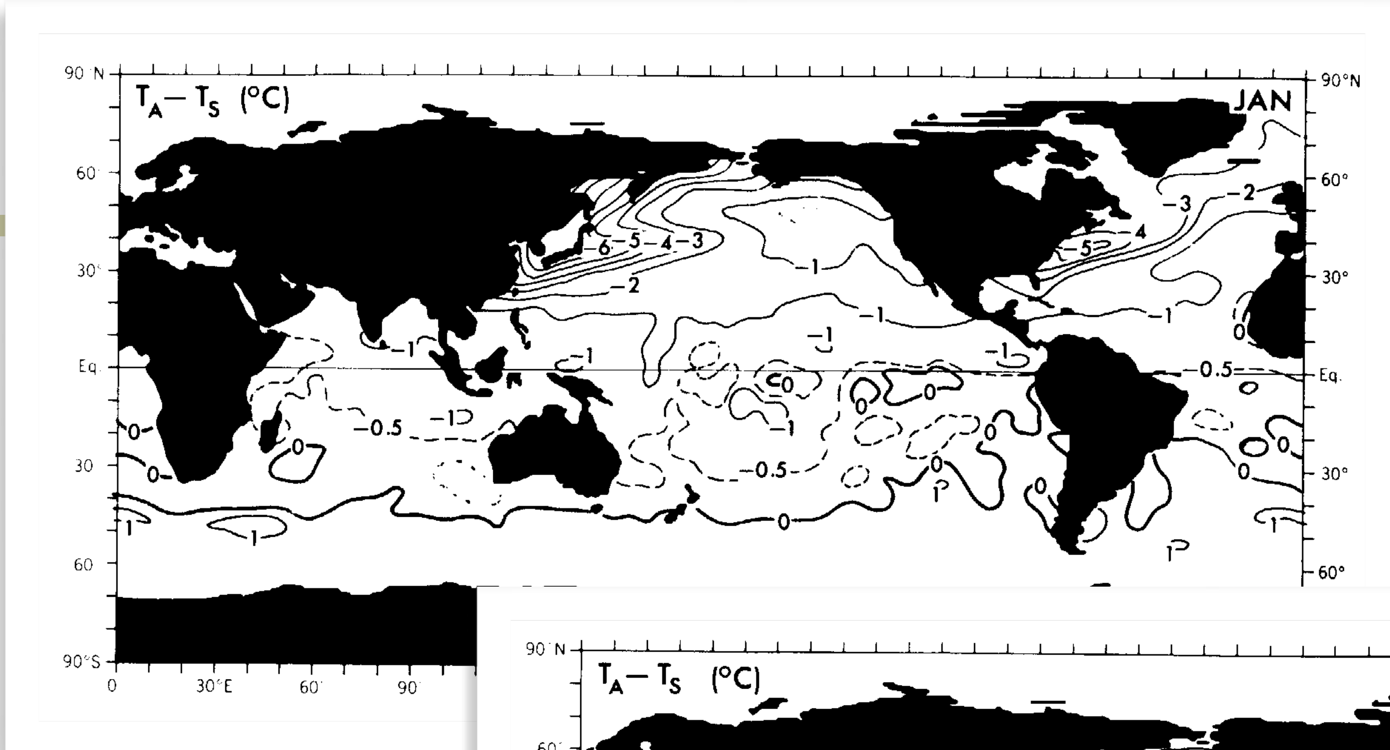
Surface sensible heat flux:

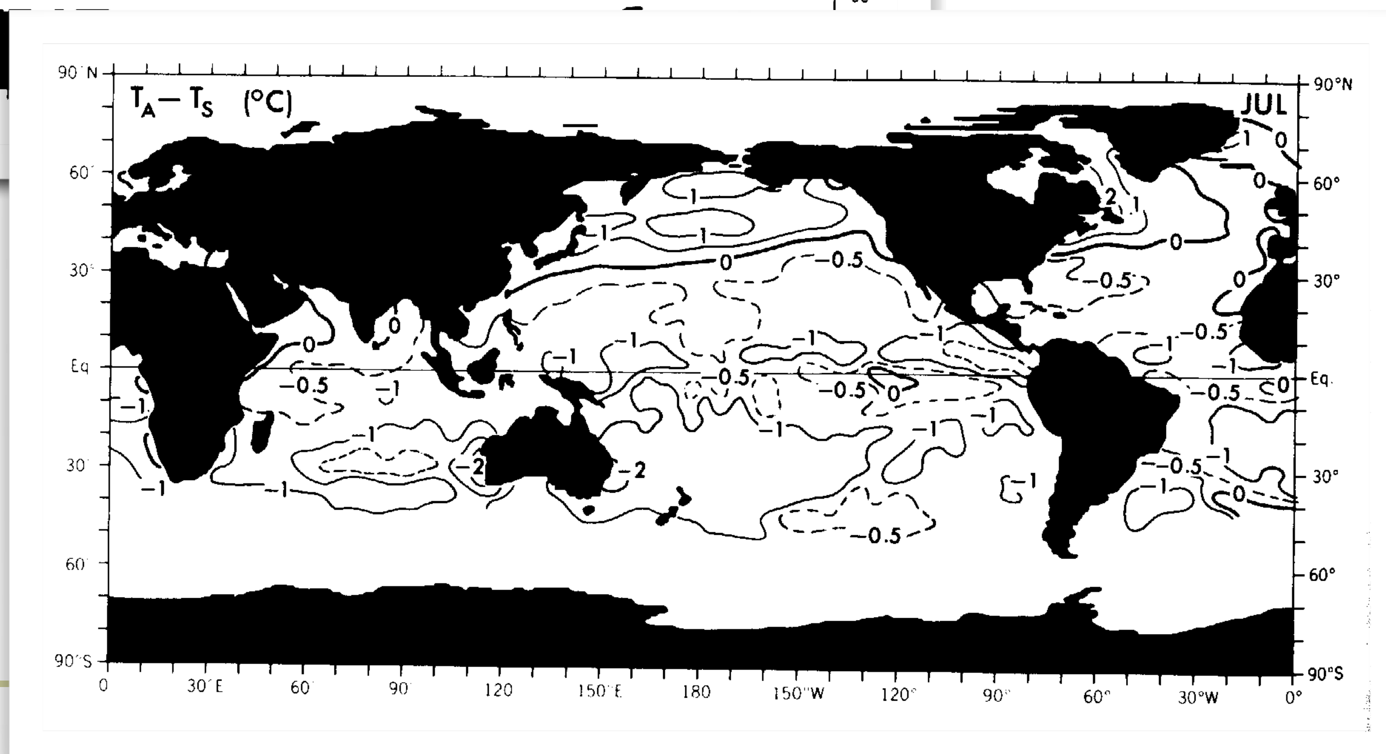
$$SH = c_p \rho \, \overline{\omega T} \approx c_p \rho \, C_d |\mathbf{v}| (T_s - T_a)$$

T_s - surface temperature

T_a - surface air temperature

Surface latent heat flux:


TA — TS (°C)
JAN


TA — TS (°C)
JUL

Zonal variation of surface energy flux

Surface sensible heat flux:

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

T_s - surface temperature

T_a - surface air temperature

Surface latent heat flux:

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

q_s - specific humidity at surface

q_a - specific humidity of surface air

For ocean surface,

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

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

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