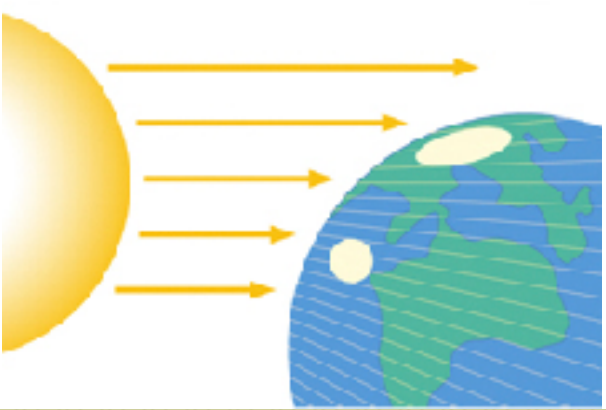
第二章:

大气环流的外部强迫(II)



授课教师: 张洋

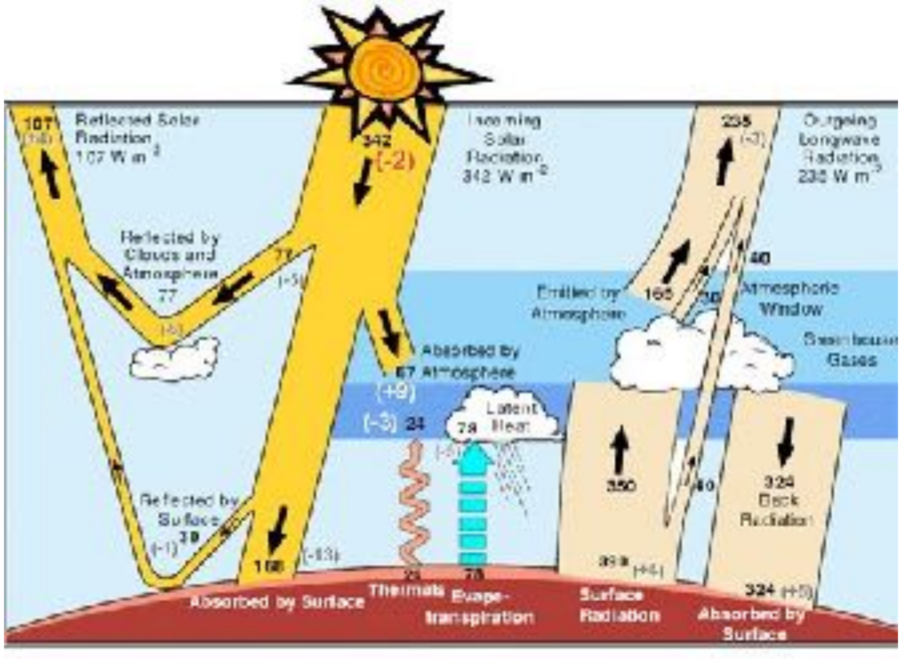
2019.9.25

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



SW ~ LW

$S(1-\alpha)$

← TOA

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

energy budget

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

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 ~ 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}
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Net longwave (LW)	-73 W m^{-2}
Net radiation (SW + LW)	103 W m^{-2}
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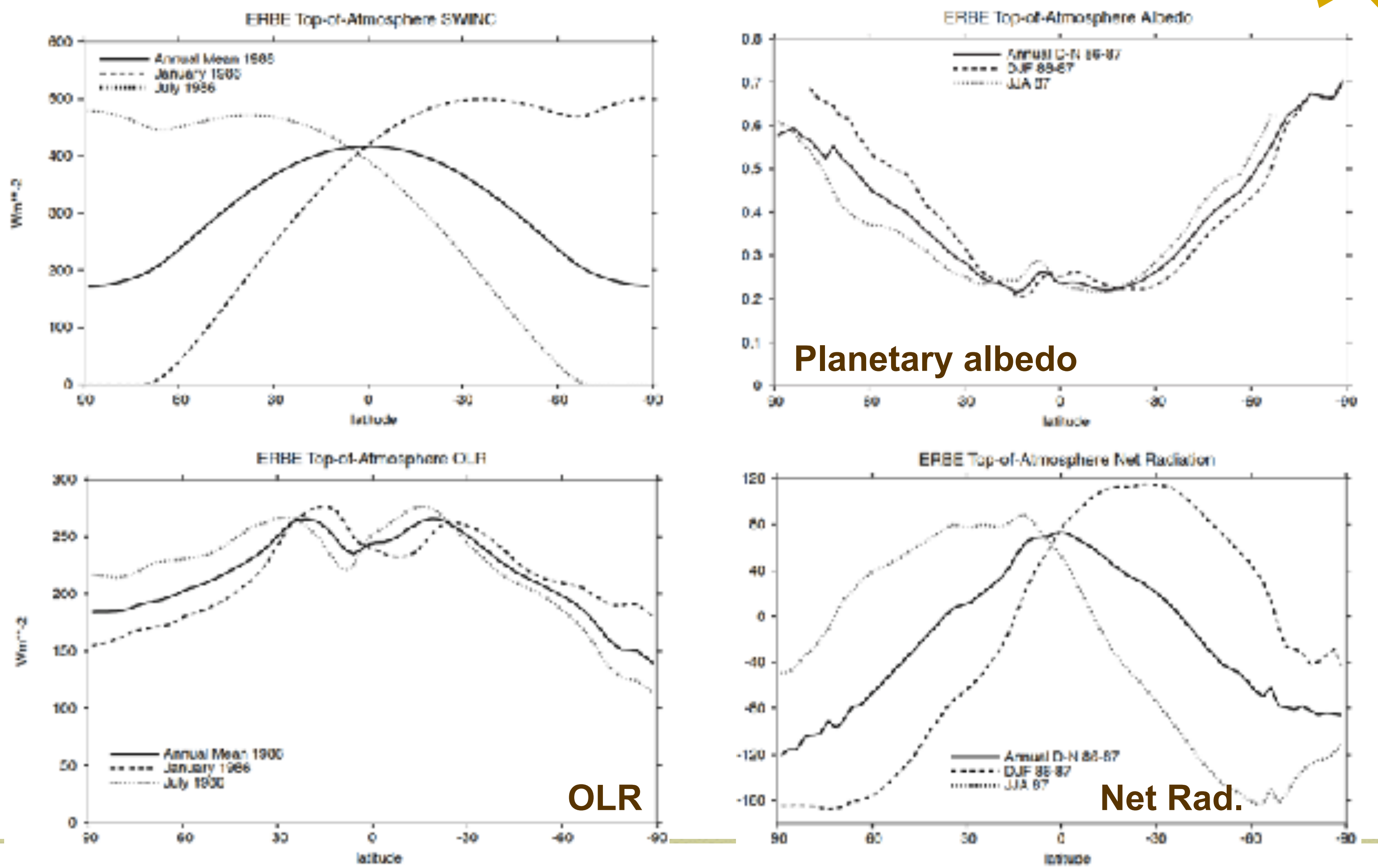
…e: SW(net) + LW(net) + LH +SH ~0 ← surface

Table: globally and annually averaged surface energy budget

Radiation budget at TOA

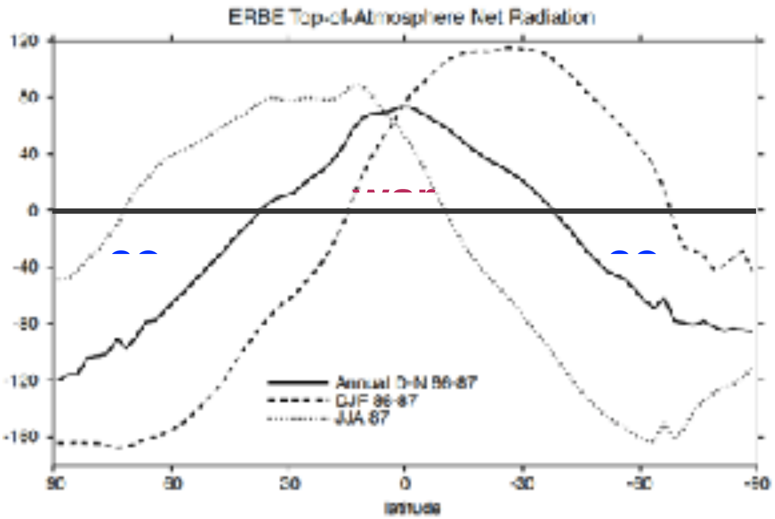
Review

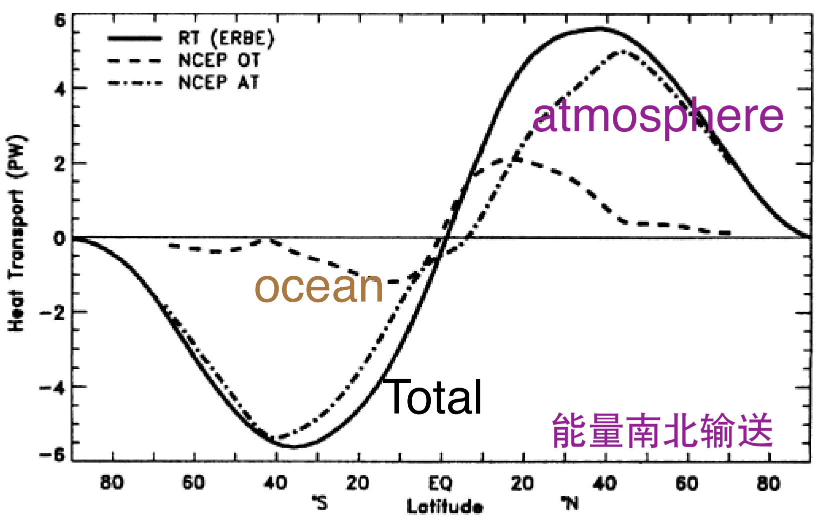


From Randall, 2009

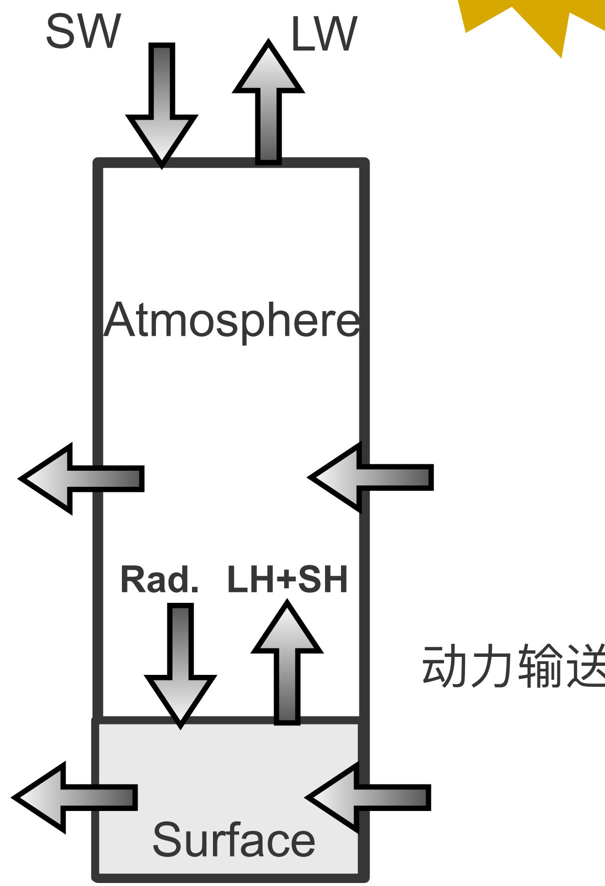
Radiation budget at TOA

Review





Wunsch (2005), J. Climate



Energy budget at SURFACE

Review

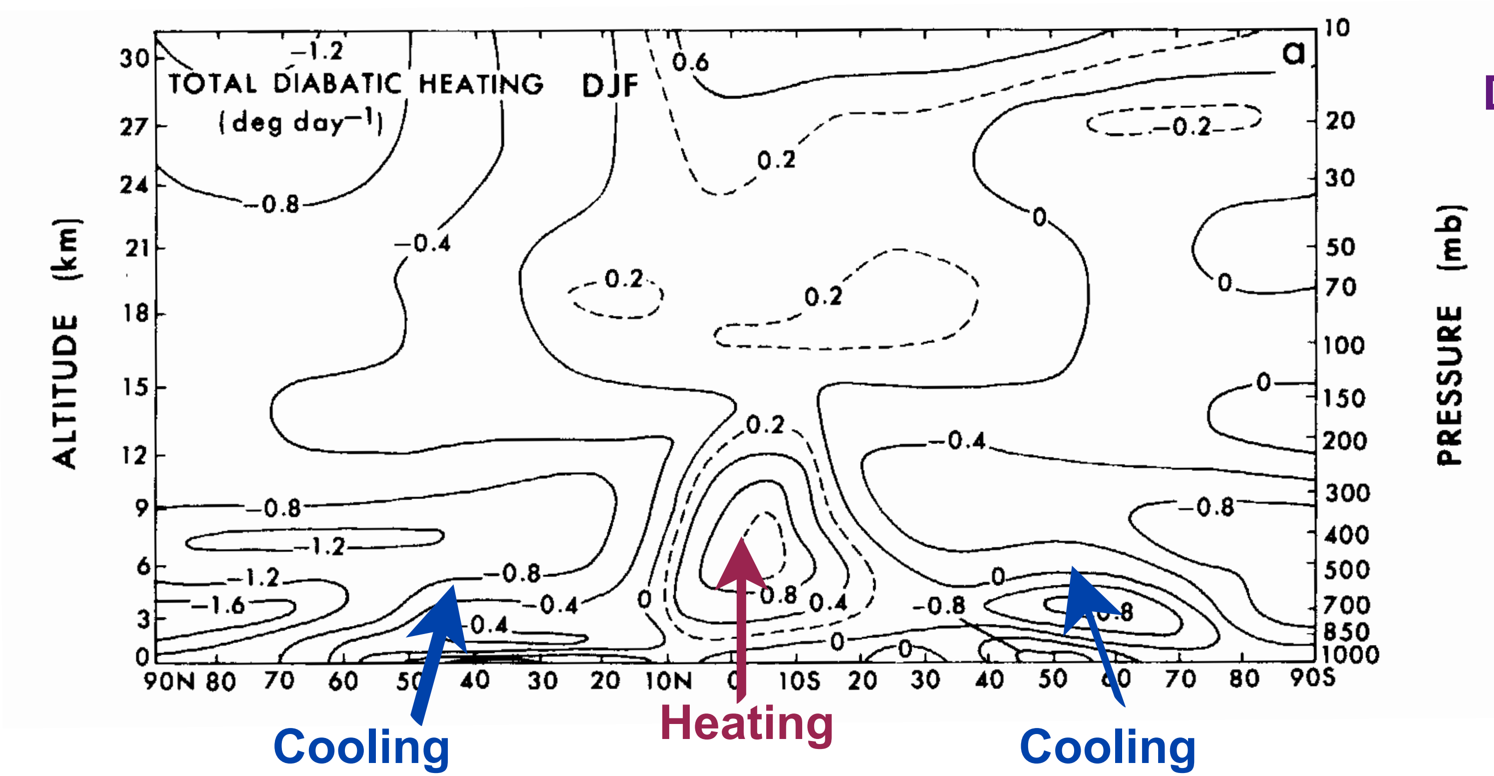
- Strong meridional variation in SW, LH and surface temperature
  - temperature: 250 - 310 K, strong seasonal variation in N.H.
  - absorbed solar radiation: 0 - 280 W/m^2, strong seasonal variation
  - latent heat: 0 - 150 W/m^2

Diabatic heating in atmosphere

estimated as residual

Review

DJF



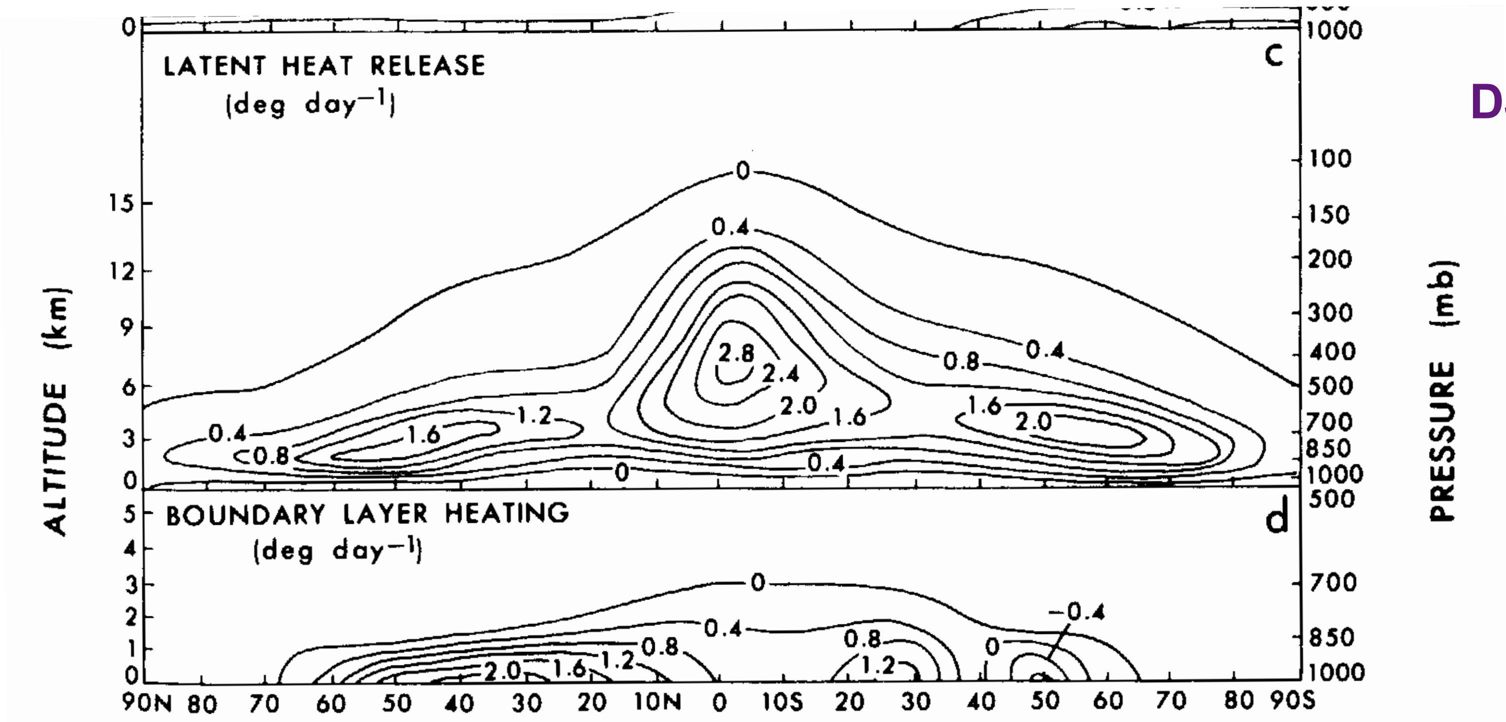
from Peixoto and Oort, 1992

Diabatic heating in atmosphere

estimated as residual

Review

DJF



Latent heating: strongest in the tropics, penetrating over the who troposphere; in the extratropics, confined in the lower levels;

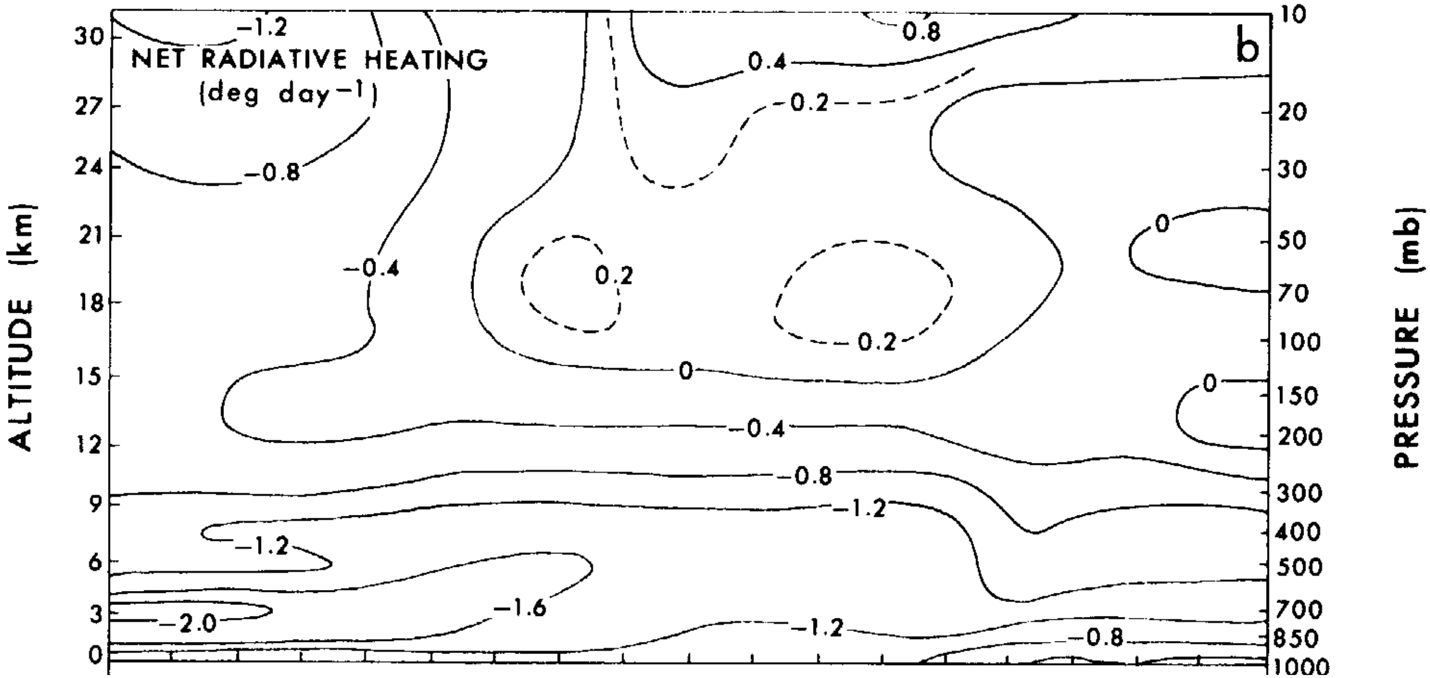
Sensible heating: in the boundary layer and strongest in the extratropics.

from Peixoto and Oort, 1992

Diabatic heating in atmosphere
estimated as residual

Review

DJF



Cooling over the troposphere
Small latitudinal variation

from Peixoto and Oort, 1992

Outline

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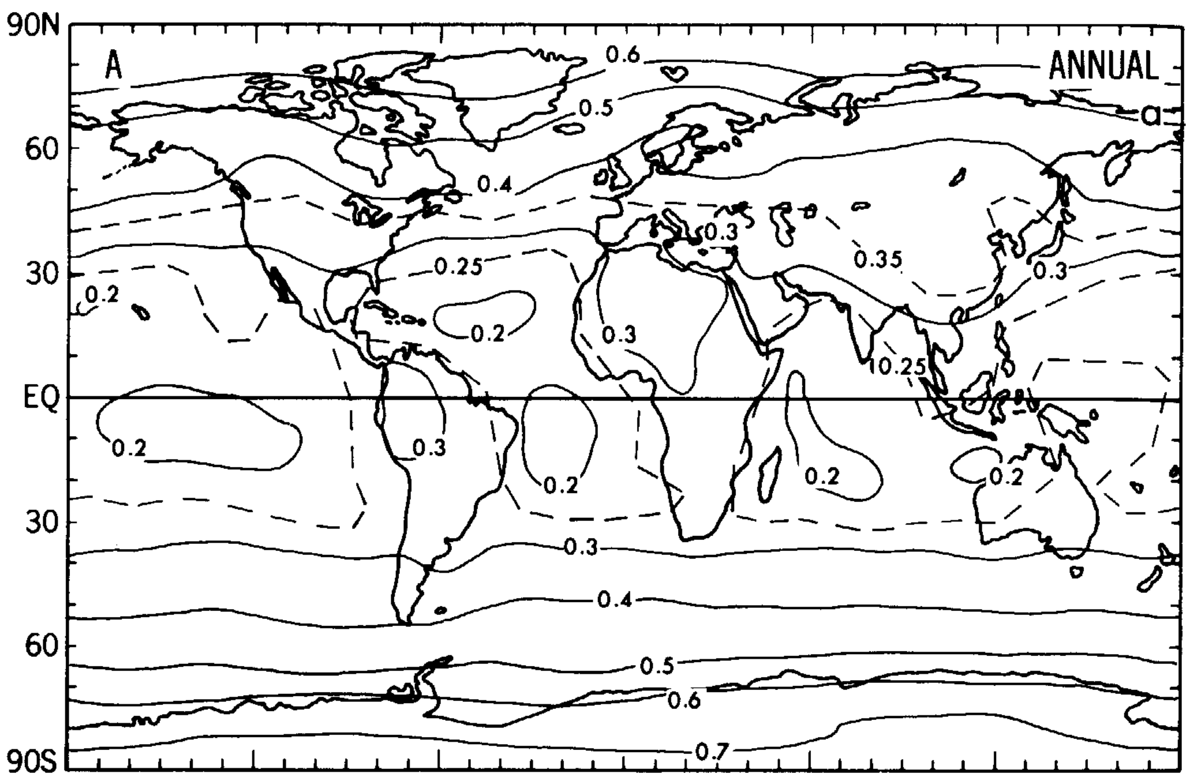
  - TOA
  - Surface
- Zonal distribution
  - TOA
  - Surface

Zonal variation of TOA energy flux

- Planetary albedo



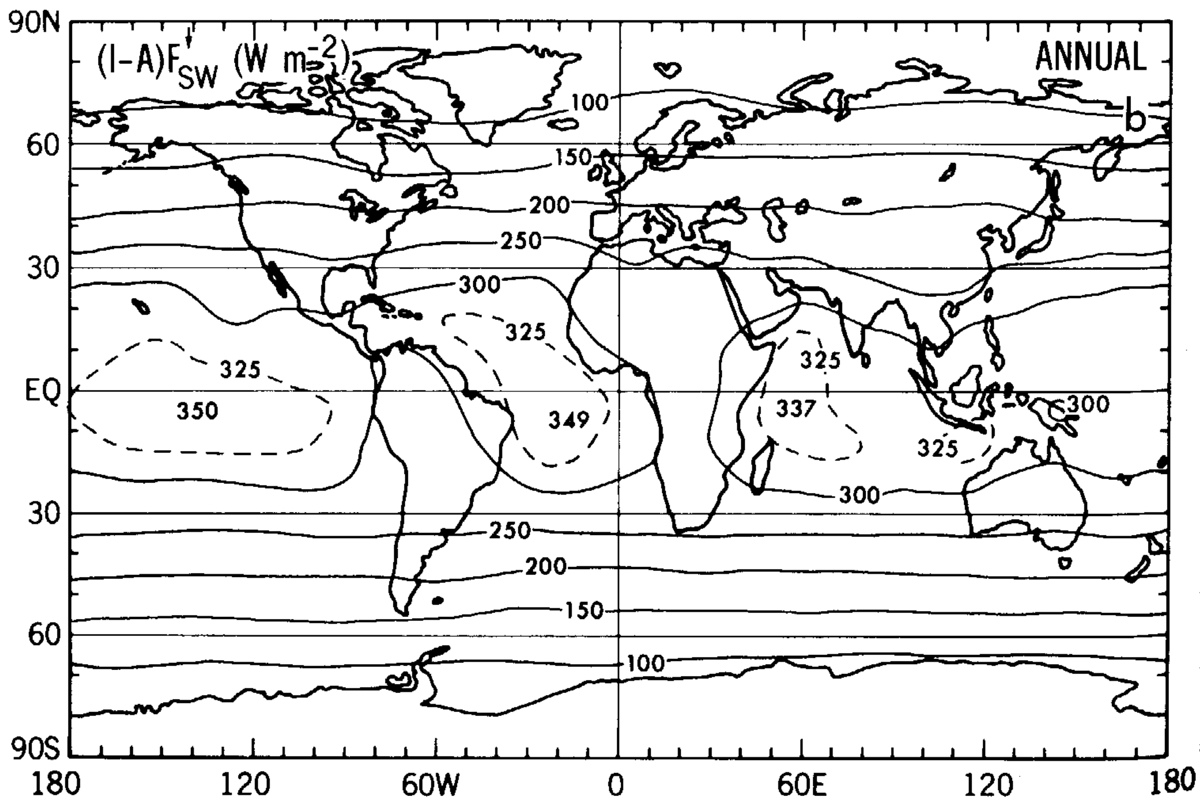
From Peixoto and Oort, 1992

Sample albedos

Surface	Typical albedo
Fresh asphalt	0.04[4]
Open ocean	0.06[5]
Worn asphalt	0.12[4]
Conifer forest (Summer)	0.08,[6] 0.09 to 0.15[7]
Deciduous trees	0.15 to 0.18[7]
Bare soil	0.17[8]
Green grass	0.25[8]
Desert sand	0.40[9]
New concrete	0.55[8]
Ocean ice	0.5–0.7[8]
Fresh snow	0.80–0.90[8]

Zonal variation of TOA energy flux

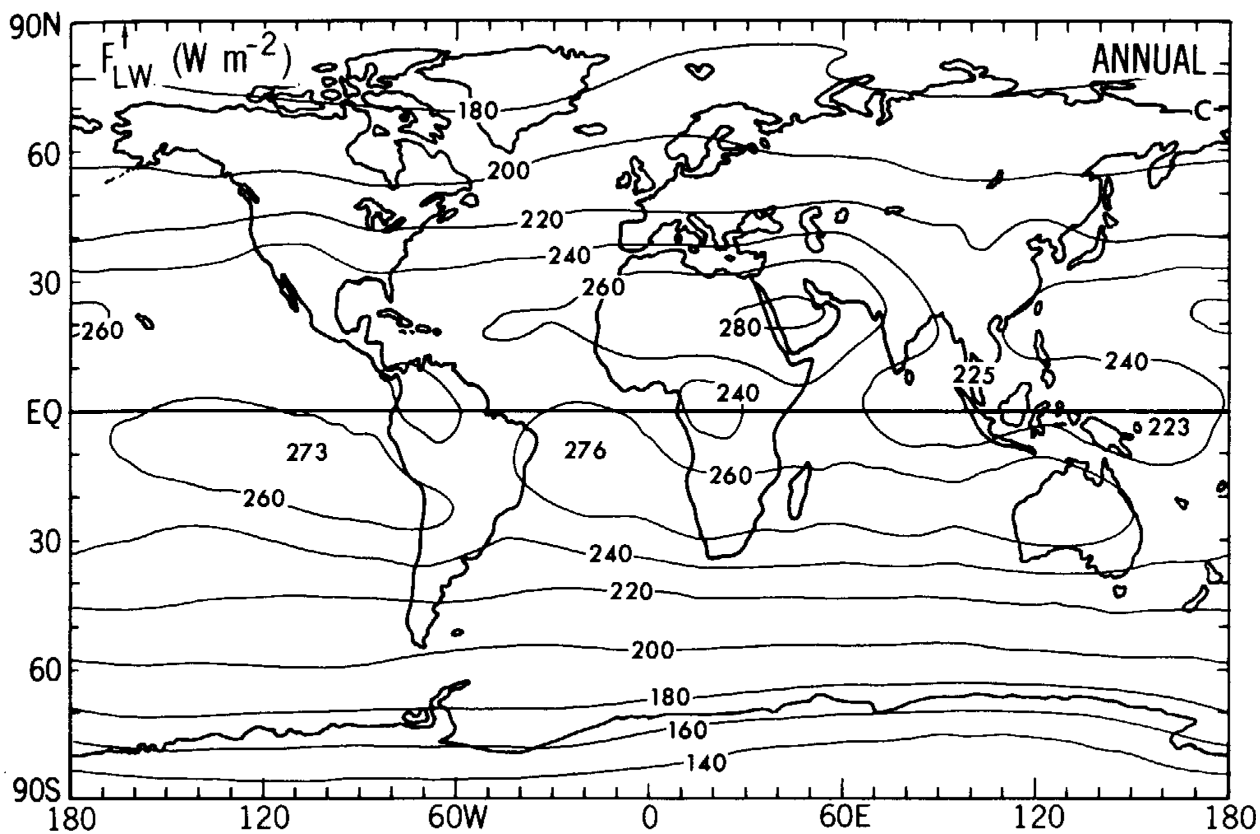
- Net short wave radiation



From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

- Net longwave radiation

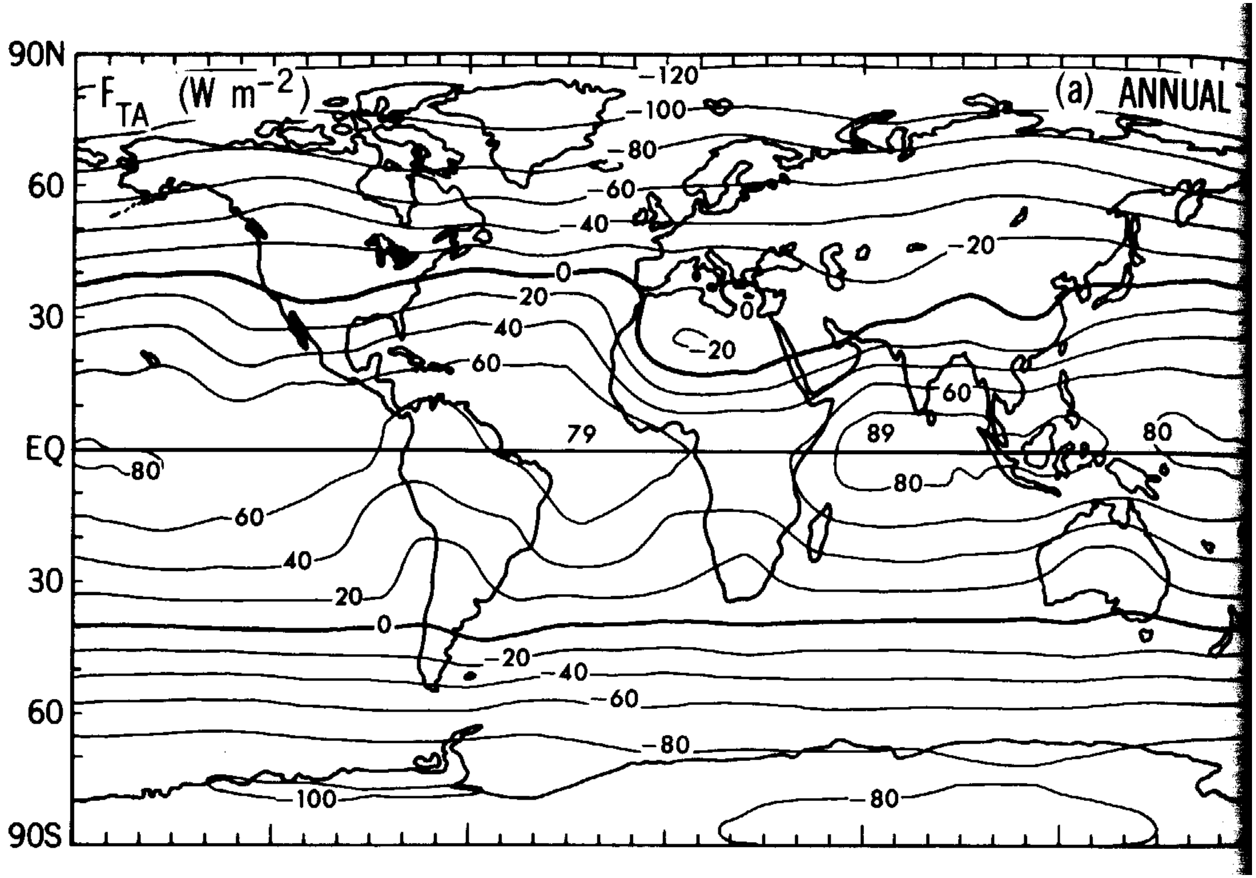


From Peixoto and Oort, 1992

Zonal variation of TOA energy flux

Review

- Net radiation at TOA



From Peixoto and Oort, 1992

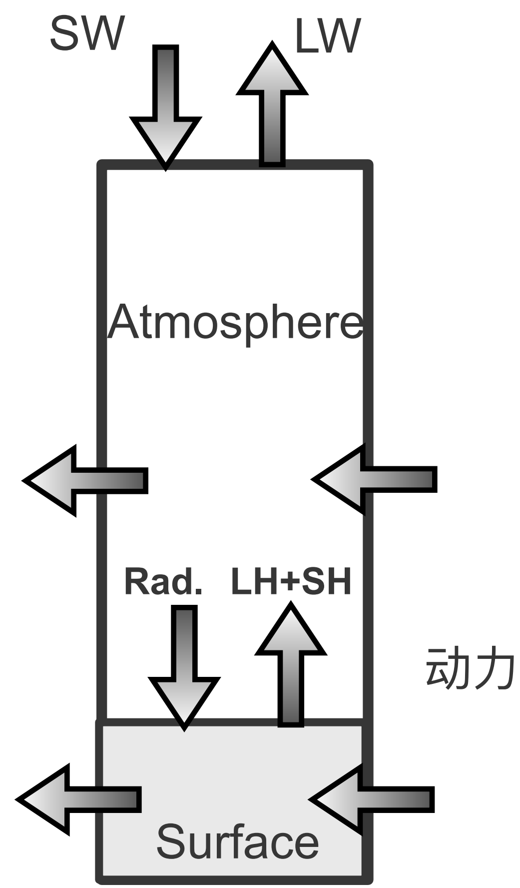
Zonal variation of TOA energy flux

- 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

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

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



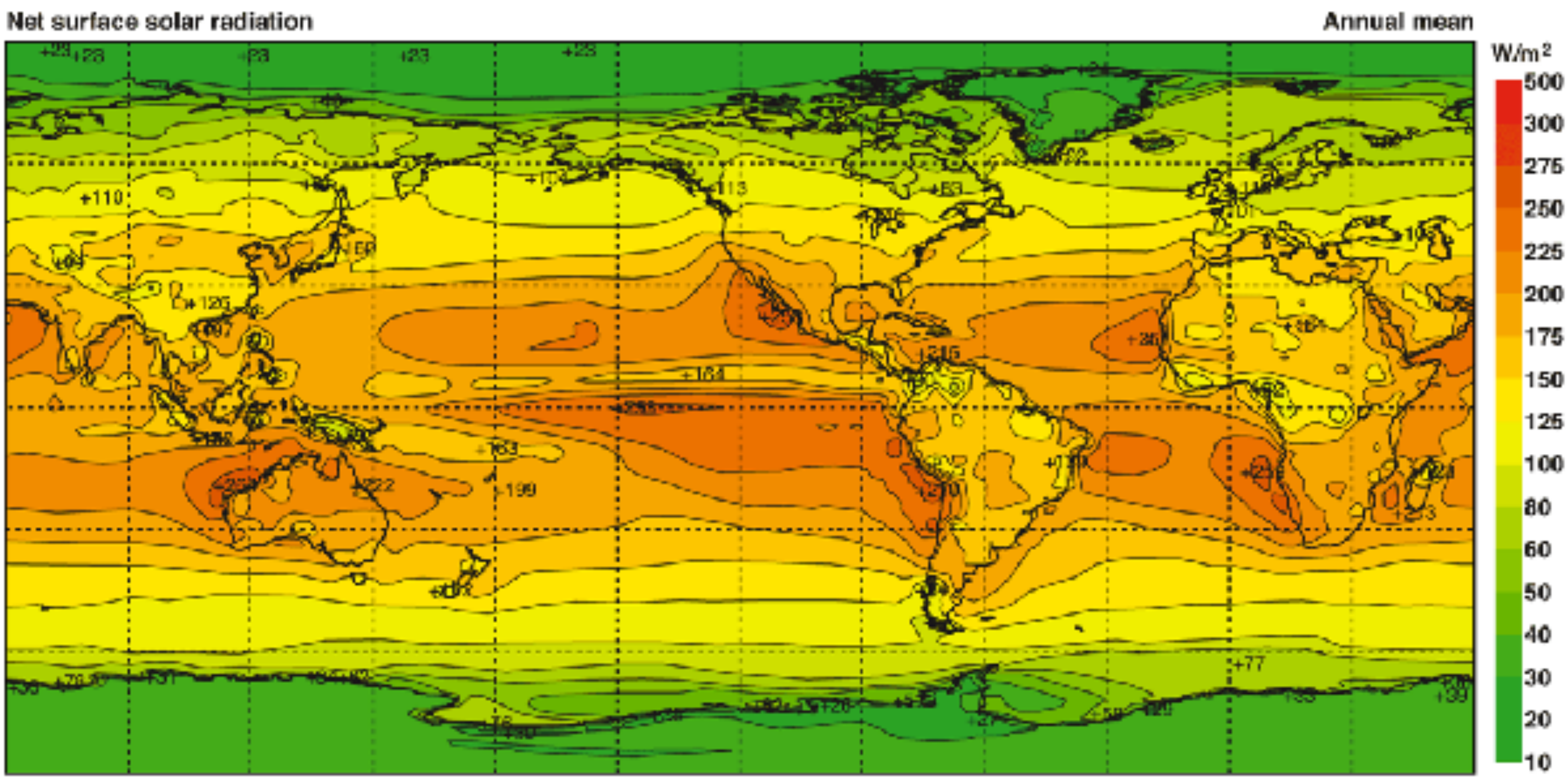
specific heat of ocean water: 4187 J/(kg* K)

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

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

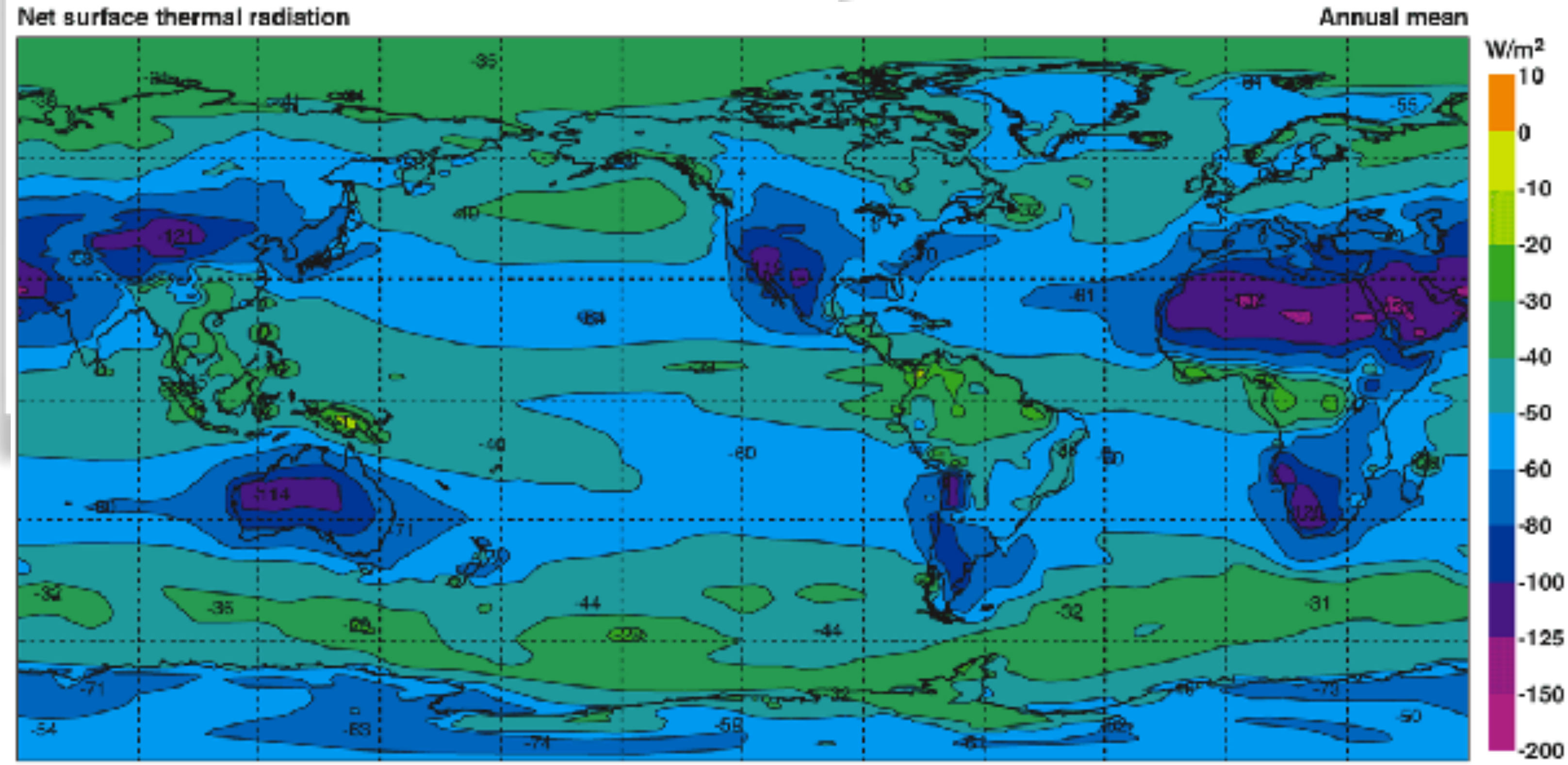
specific heat of atmosphere at constant pressure: 1004 J/(kg* K)

Zonal variation of surface energy flux – SW radiation



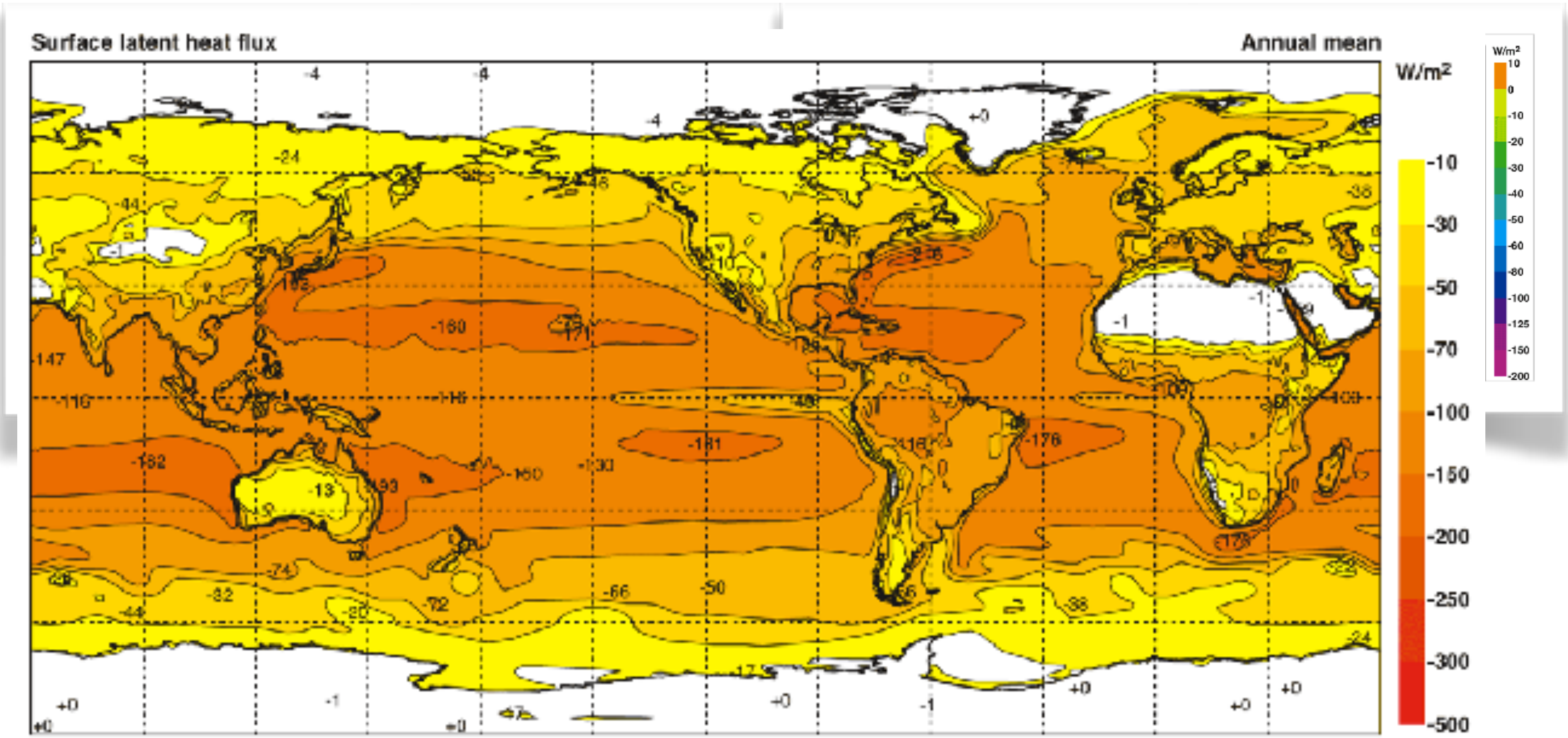
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux – LW radiation



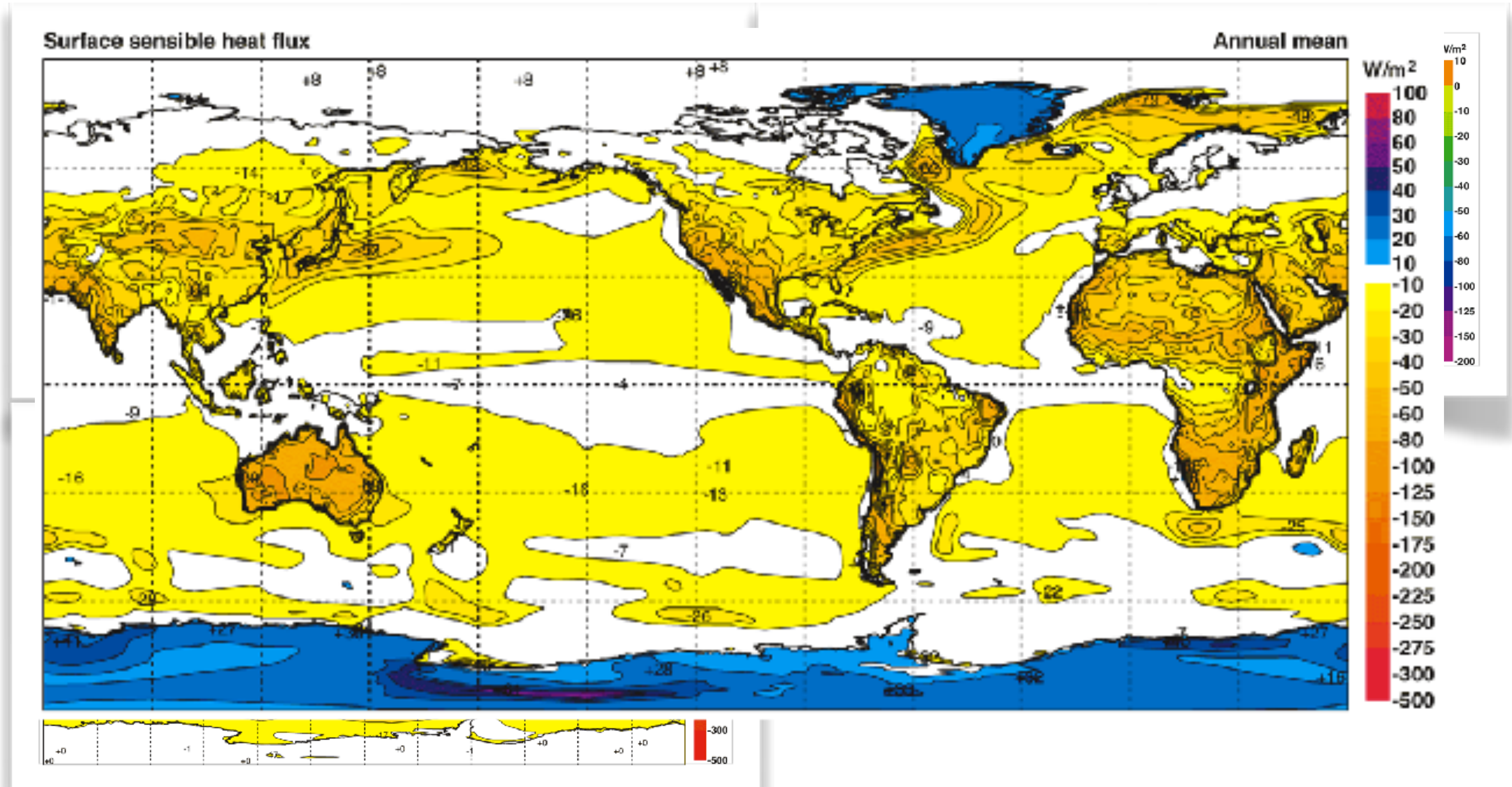
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux – latent heat



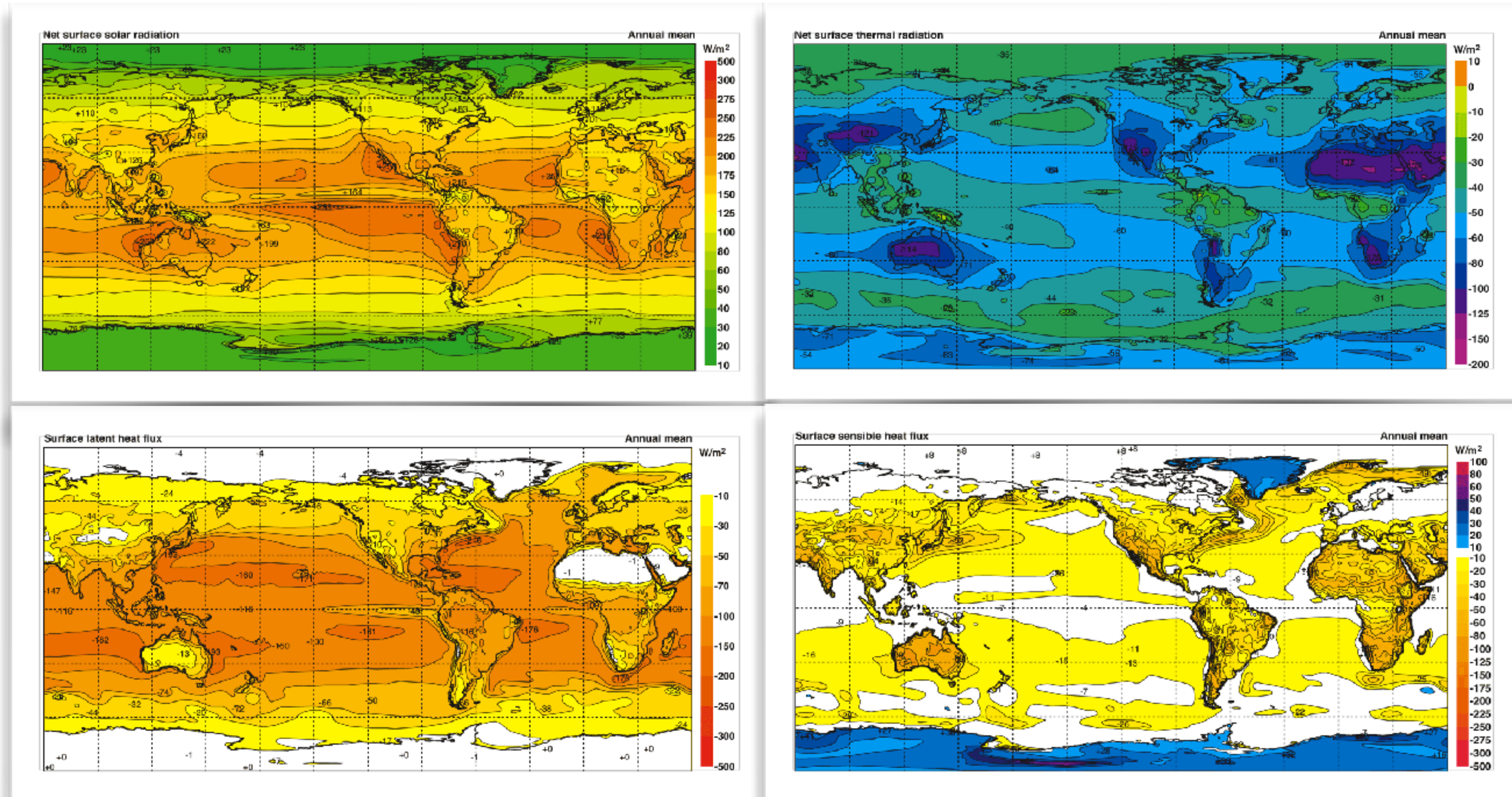
From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux - Sensible heat



From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux



From Stewart, 2005
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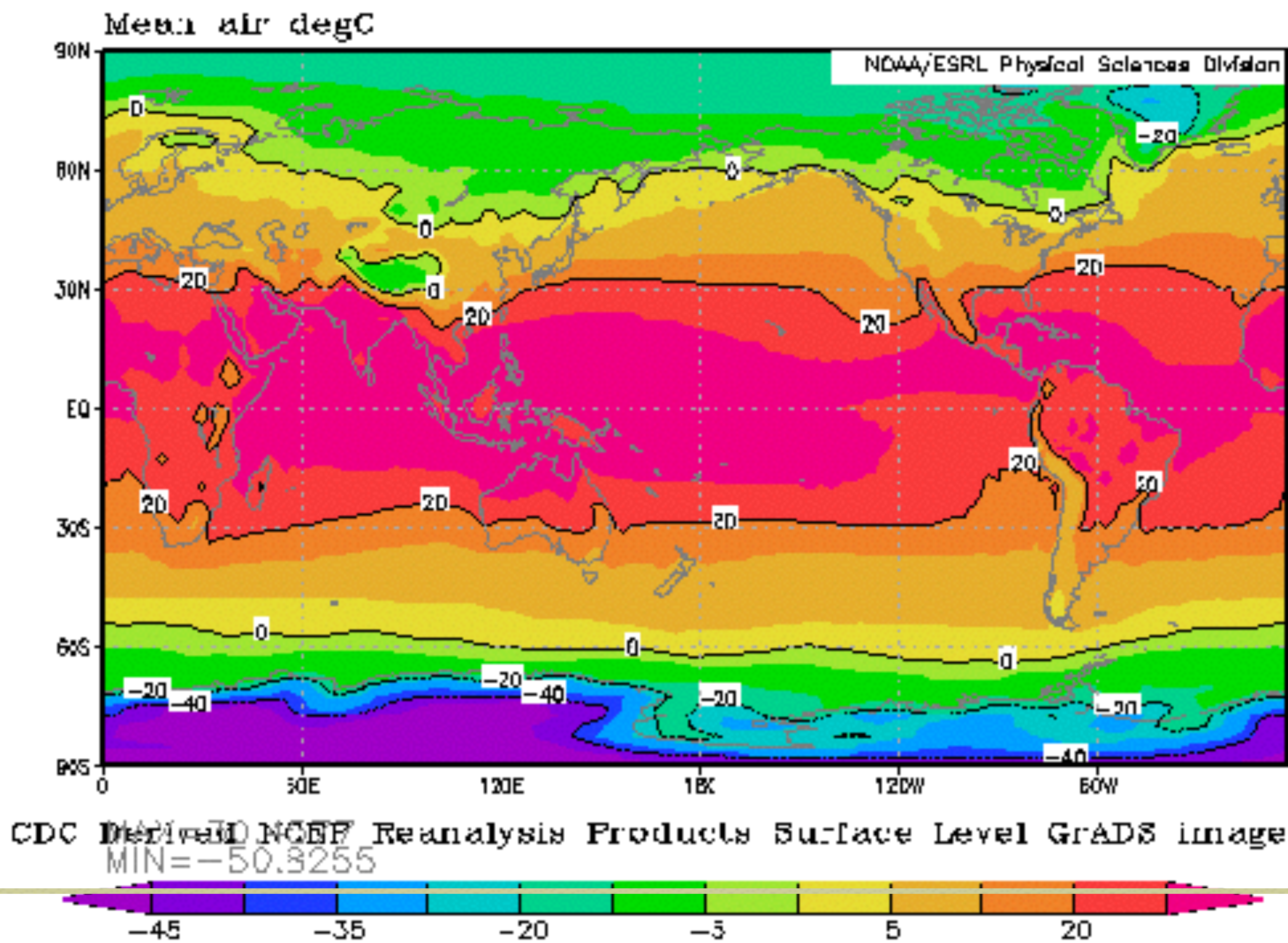
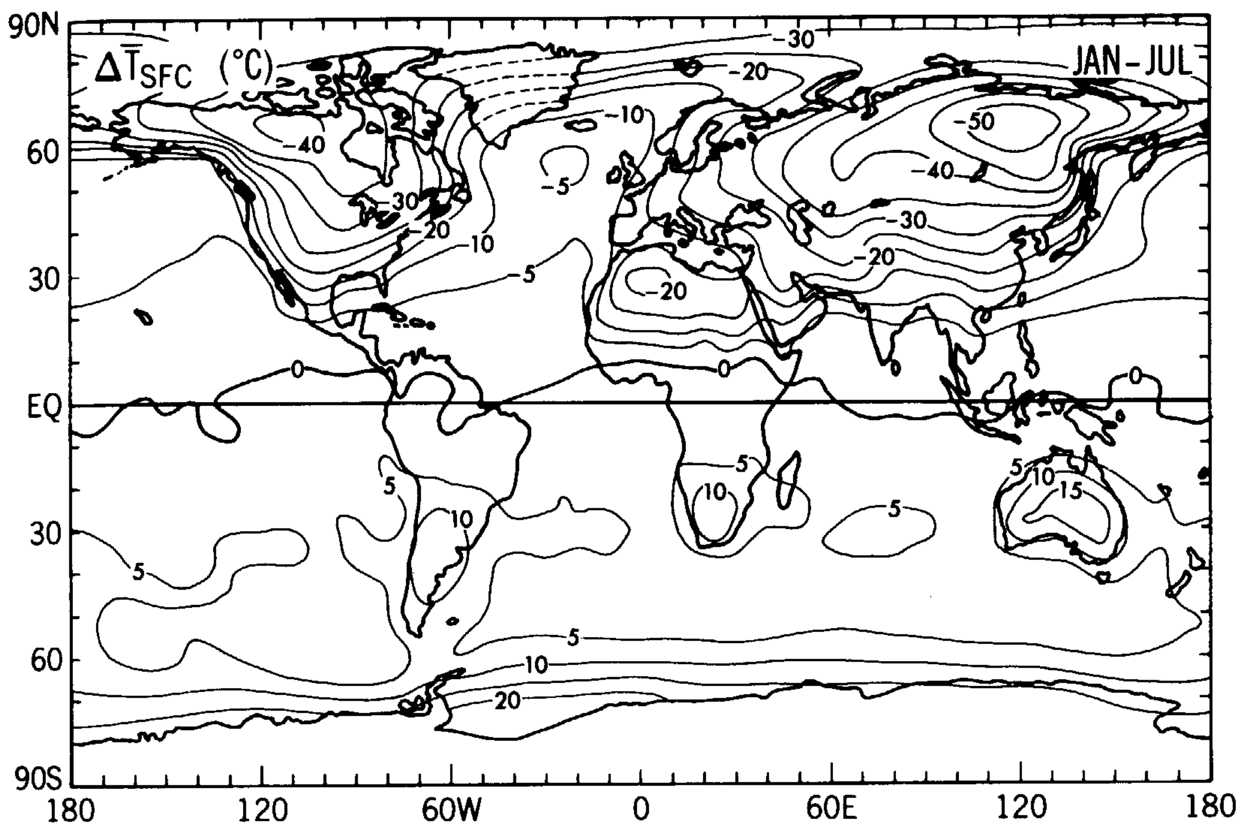
Zonal variation of surface energy flux

- Surface air



Zonal variation of surface energy flux

- Seasonal variation of surface temperature



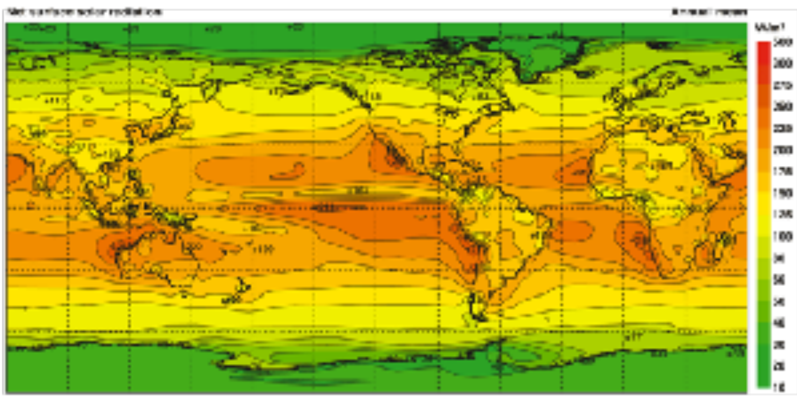
From Peixoto and Oort, 1992

Zonal variation of surface energy flux

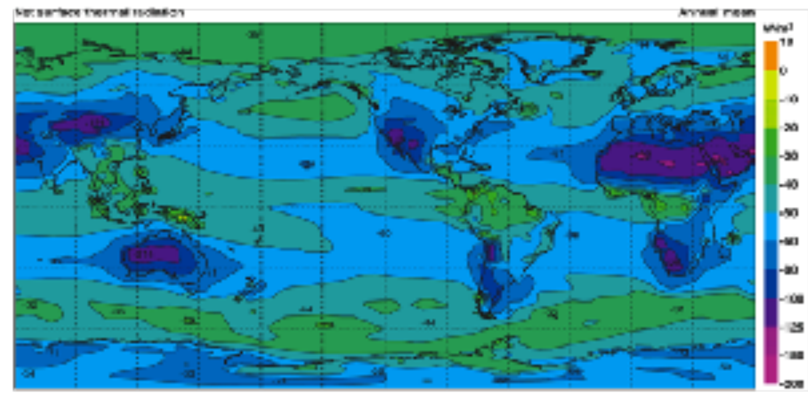
- Stronger zonal variation in surface LW, LH, SH and surface temperature
  - LW: stronger infrared cooling over land.
  - LH: stronger over ocean surface but weak over land
  - SH: stronger over land surface but weak over ocean
  - surface air temperature: stronger meridional temperature gradient and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

Zonal variation of surface energy flux

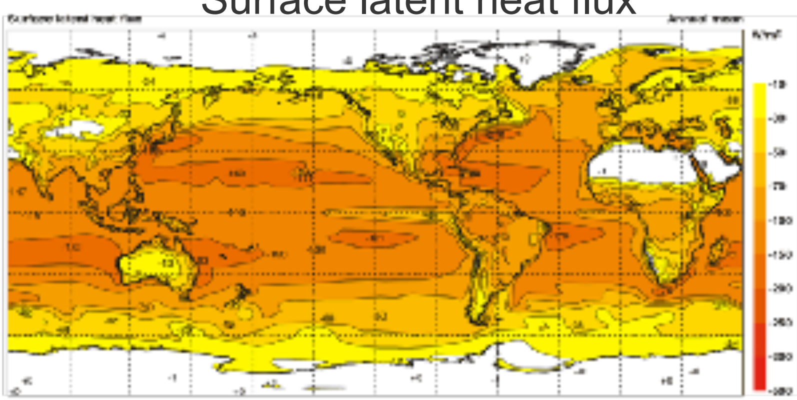
Net surface solar radiation



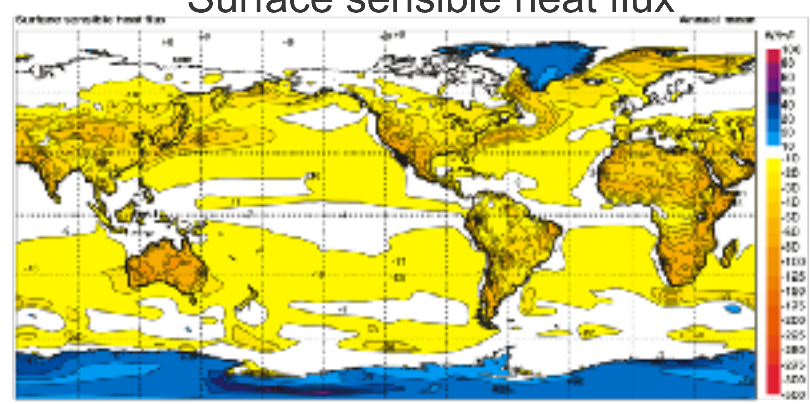
Net surface infrared radiation



Surface latent heat flux



Surface sensible heat flux



From Stewart, 2005
Introduction to Physical Oceanography

Zonal variation of surface energy flux

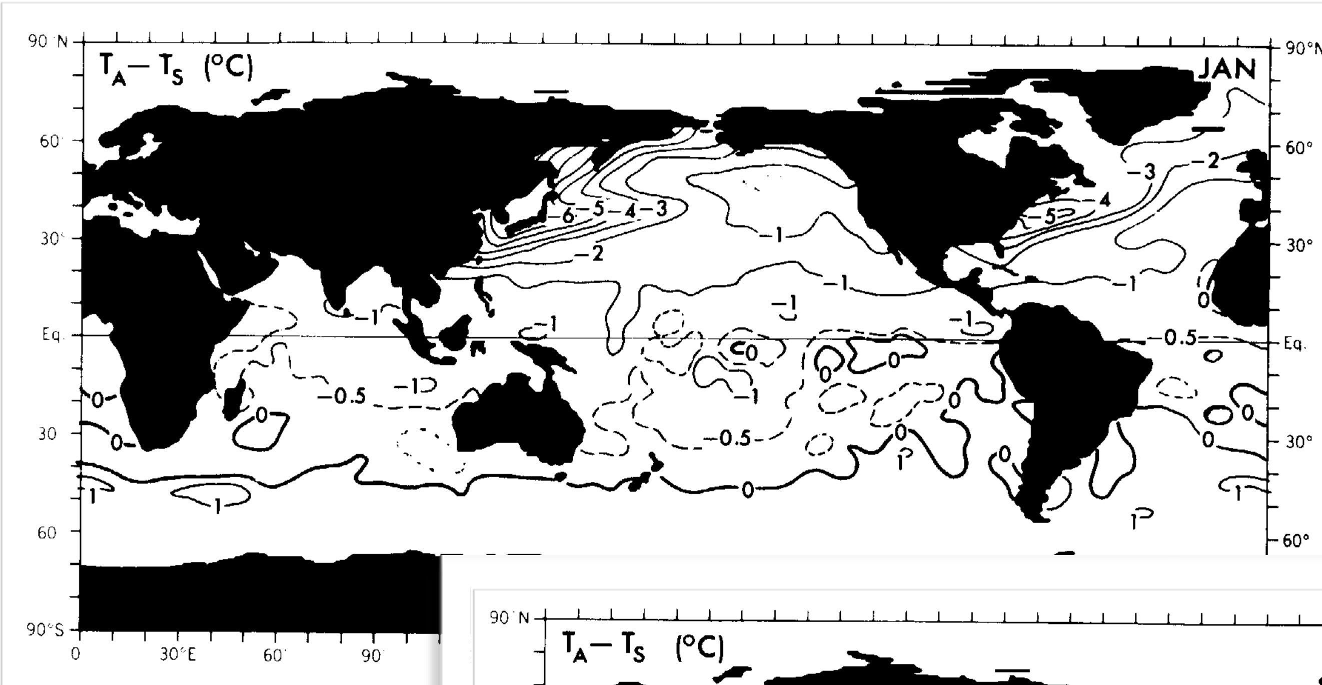
Surface sensible heat flux:

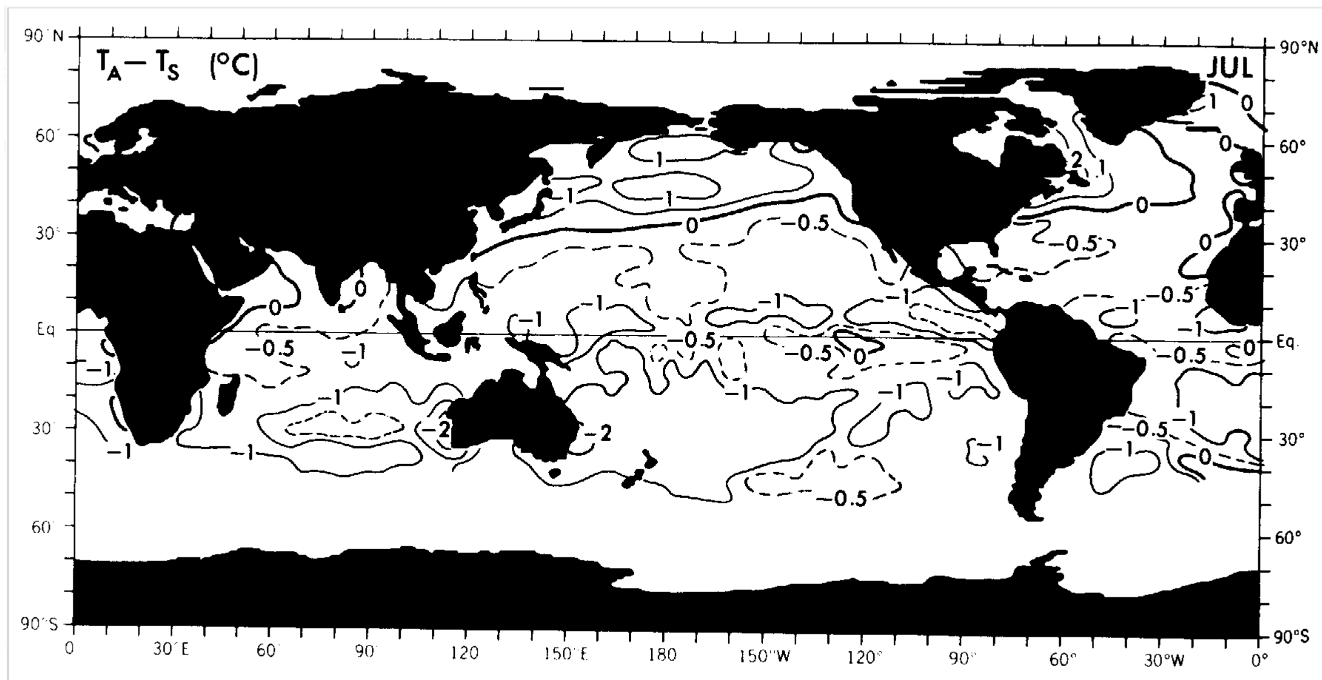
$$SH = c_p \rho \, \overline{\omega T} \approx c_p \rho \, C_d |\mathbf{v}| (T_s - T_a)$$

T_s - surface temperature

T_a - surface air temperature

Surface latent heat flux:


T_A − T_S (°C)
JAN


T_A − T_S (°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

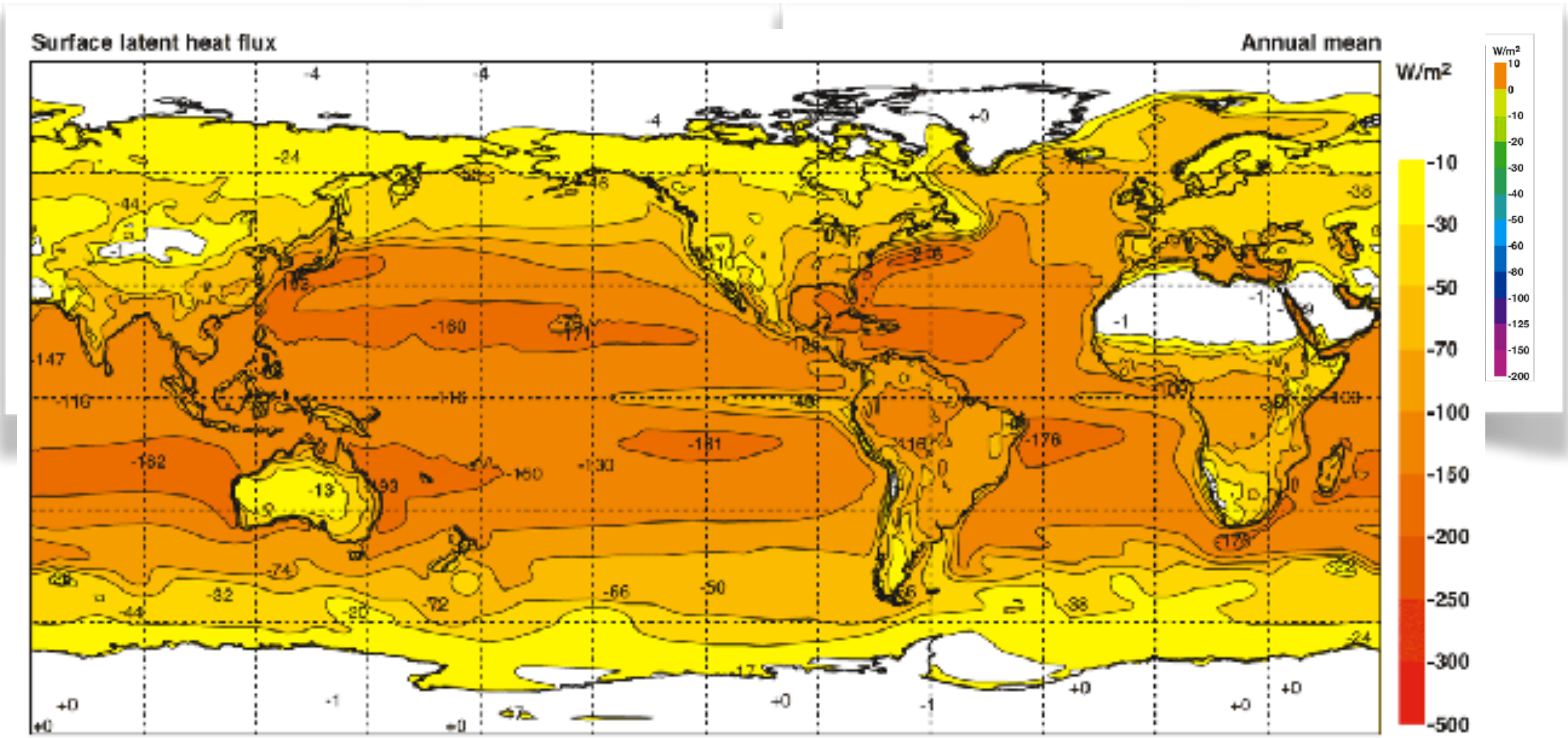
For ocean surface,

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

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

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

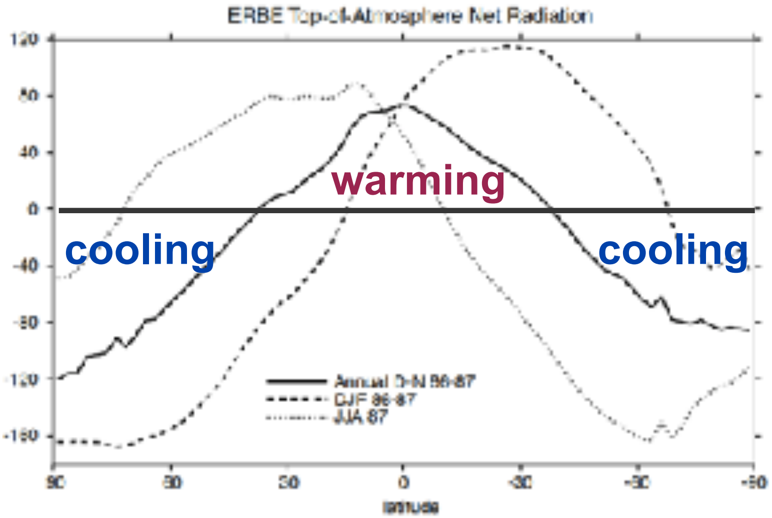
Zonal variation of surface energy flux – latent heat

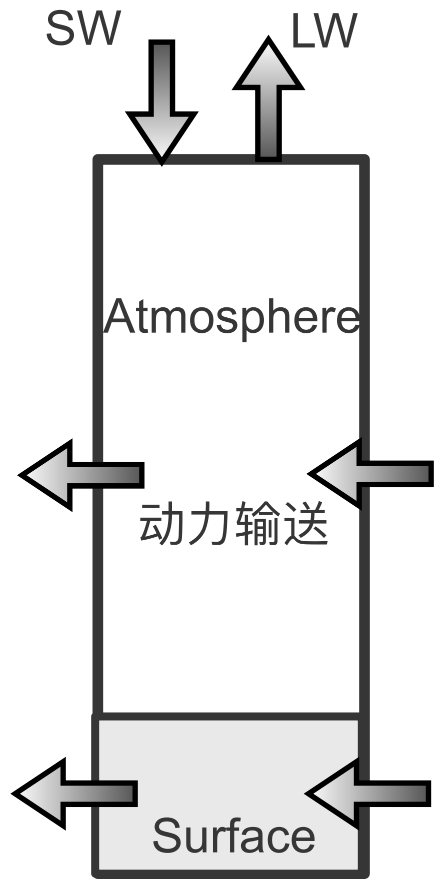


From Stewart, 2005
Introduction to Physical Oceanography

大气环流的外部强迫(III)

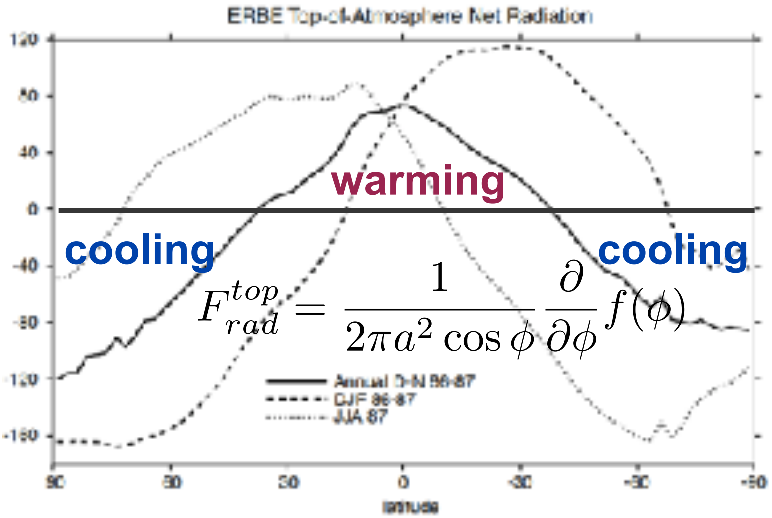
–Simple energy balance climate model





$$F_{rad}^{top} = \frac{1}{2\pi a^2 \cos\phi} \frac{\partial}{\partial \phi} f(\phi)$$

$f(\phi)$ – meridional energy transport by atmosphere and oceans



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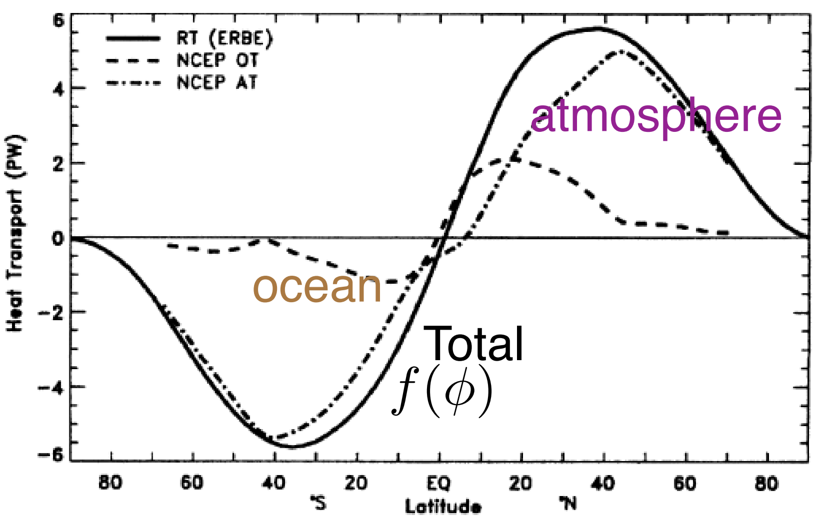
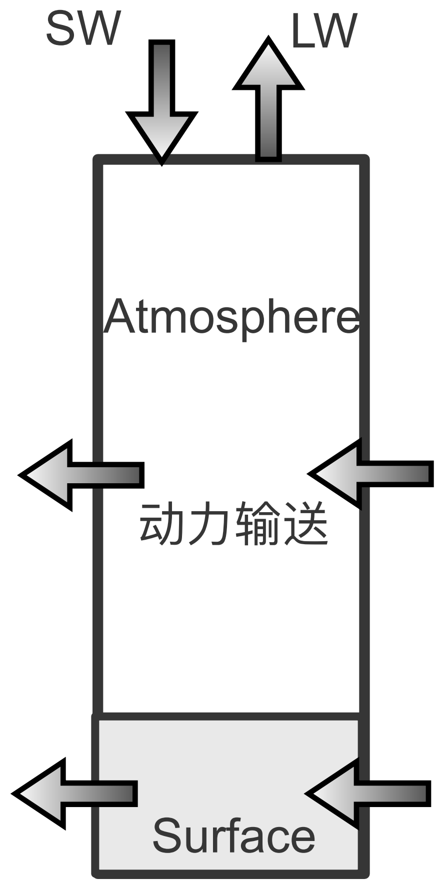


Wunsch (2005), J. Climate



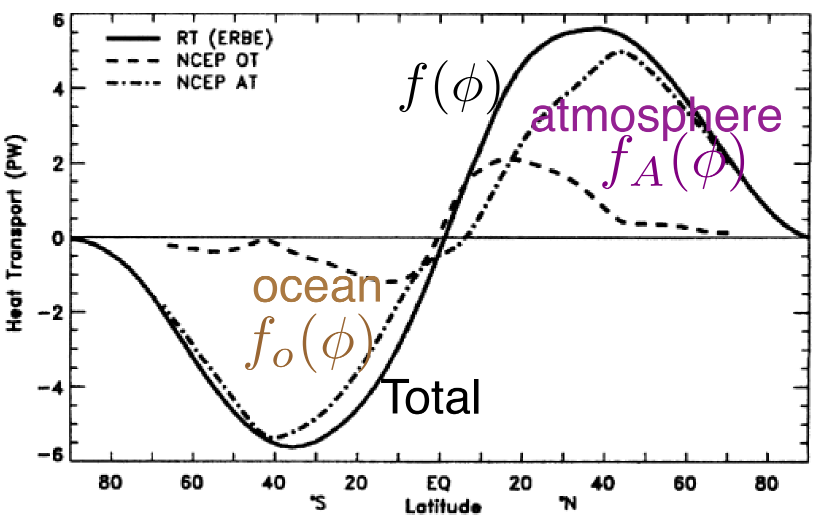
$$F_{rad}^{top} = \frac{1}{2\pi a^2 \cos\phi} \frac{\partial}{\partial\phi} f(\phi)$$

Atmosphere:

$$F_{rad}^{top} - F_{rad}^{sfc} + F_{LH} + F_{SH} = \frac{1}{2\pi a^2 \cos\phi} \frac{\partial}{\partial\phi} f_A(\phi)$$

Ocean:

$$F_{rad}^{sfc} - F_{LH} - F_{SH} = \frac{1}{2\pi a^2 \cos\phi} \frac{\partial}{\partial\phi} f_o(\phi)$$



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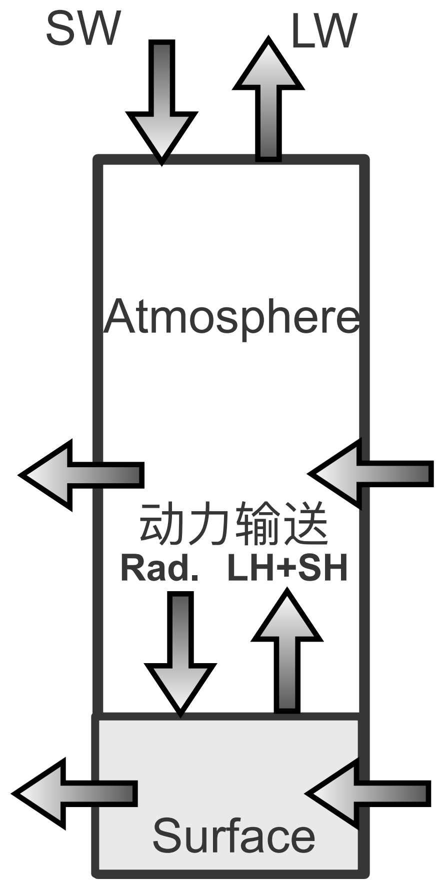
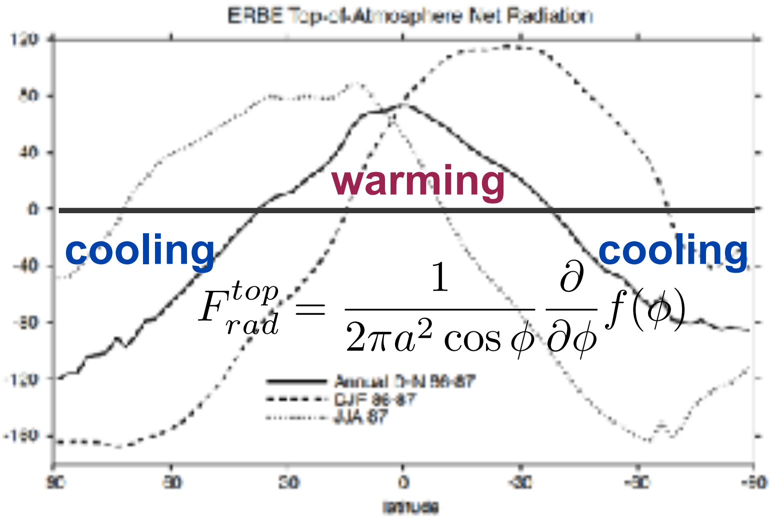


Simple energy balance climate models



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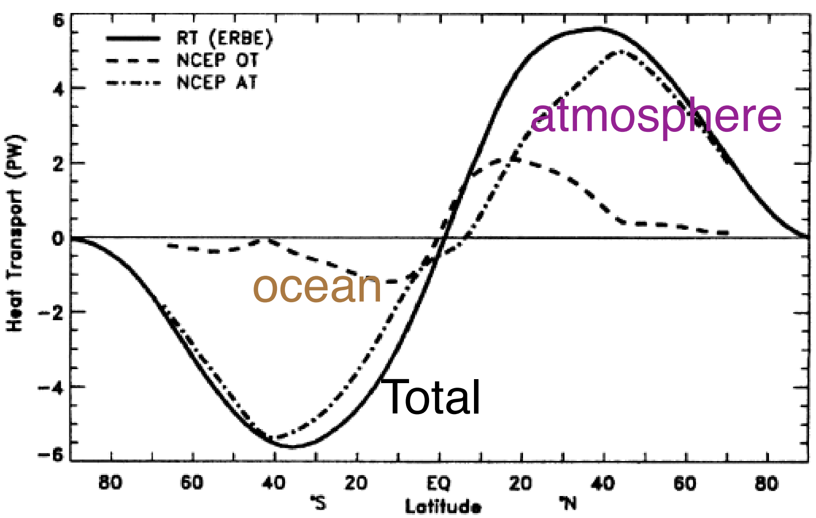

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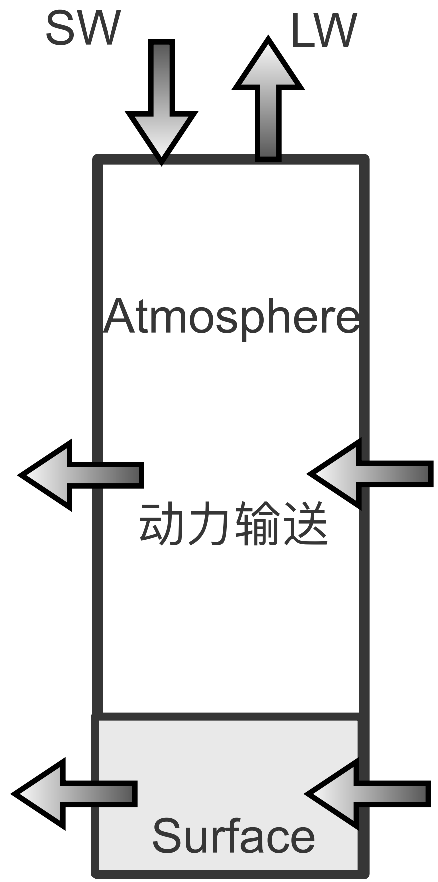
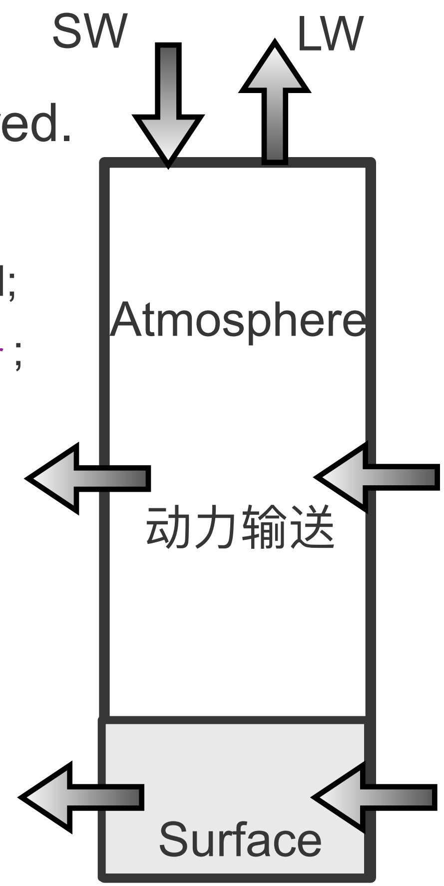


Simple energy balance climate models

- Simplest models in which the interactions between ***radiation*** and ***dynamic heat transport*** can be considered.
  - Assumptions are made below:
    - One-dimensional, only latitude dependences are considered;
    - Global energy budgets are assumed to be expressed in T_{sur} ;
    - Only annual mean conditions are considered;



$$\mathcal{C}\frac{\partial T(x,t)}{\partial t} = \text{solar radiation} - \text{infrared cooling}$$
$$-\text{divergence of heat flux}$$

$$x = \sin\phi, \text{ where } \phi \text{ is latitude.}$$

$$\mathcal{C}\frac{\partial T(x,t)}{\partial t} = F_{rad}^{top} - \frac{1}{2\pi a^2}\frac{\partial}{\partial x}f(x)$$

Simple energy balance climate models

$$\mathcal{C}\frac{\partial T(x,t)}{\partial t} = \text{solar radiation} - \text{infrared cooling}$$
$$-\text{divergence of heat flux}$$

$x = \sin\phi$, where ϕ is latitude.

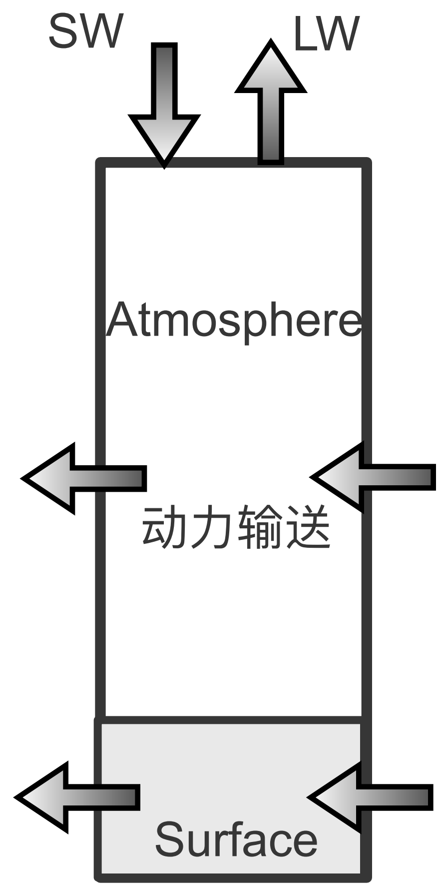
$$\text{solar radiation} = Qs(x)\mathcal{A}(T)$$

$s(x)$ – latitudinal distribution of SW, whose integral from the equator to pole is unity

$$\mathcal{C}\frac{\partial T(x,t)}{\partial t} = Qs(x)\mathcal{A}(T) - I(T) + F(T)$$

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$



Simple energy balance climate models

In equilibrium,

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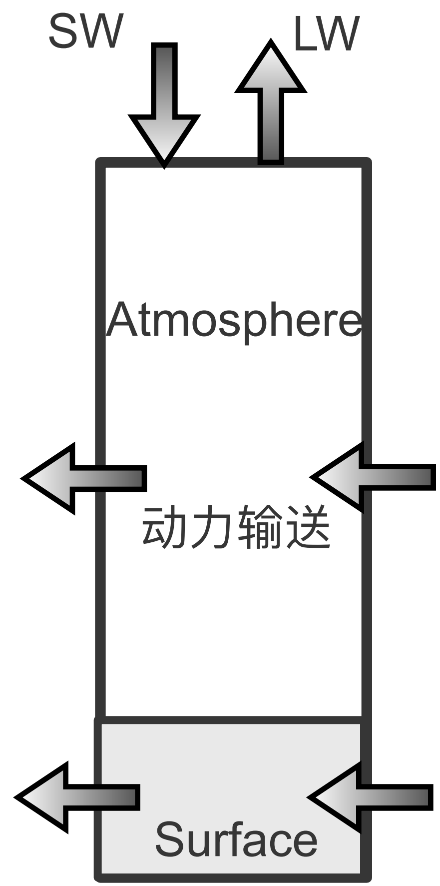


The snow line case:

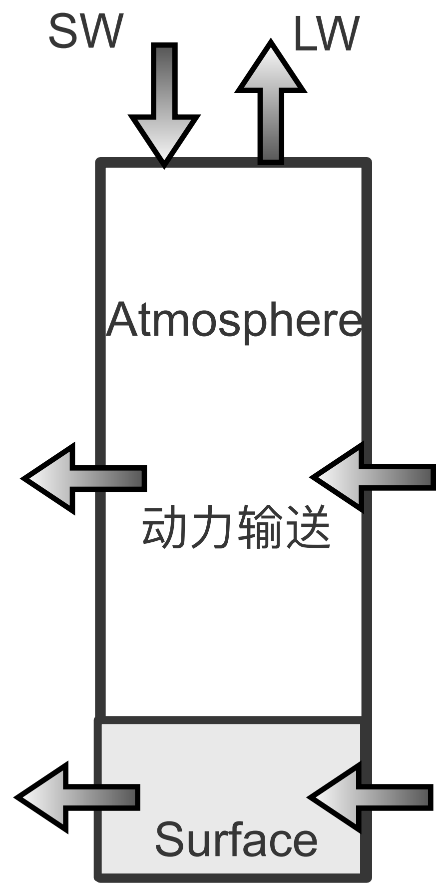
- Made assumptions below:
  - Planetary albedo is assumed to depend primarily on snow /ice cover;

$$\begin{aligned} \mathcal{A}(T) = \quad & \alpha, \quad \text{for } T < T_{snow} \\ \text{or} \quad = \quad & \beta, \quad \text{for } T > T_{snow} \end{aligned}$$

Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$



The snow line case:

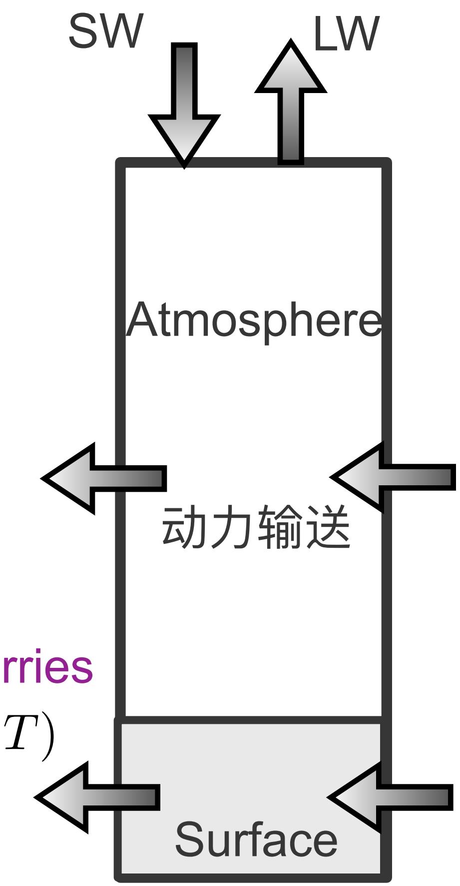
- Made assumptions below:
  - Planetary albedo is assumed to depend primarily on snow /ice cover;
  - The infrared cooling $I = A + BT$

$$\begin{aligned} \mathcal{A}(T) &= \alpha, \quad \text{for } T < T_{snow} \\ \text{or} &= \beta, \quad \text{for } T > T_{snow} \end{aligned}$$

Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$



The snow line case:

- Made assumptions below:
  - Planetary albedo is assumed to depend primarily on snow /ice cover;
  - The infrared cooling $I = A + BT$
  - The primary feature of the heat transport is that it carries heat from warmer to colder regions. $F(T) = C(\bar{T} - T)$

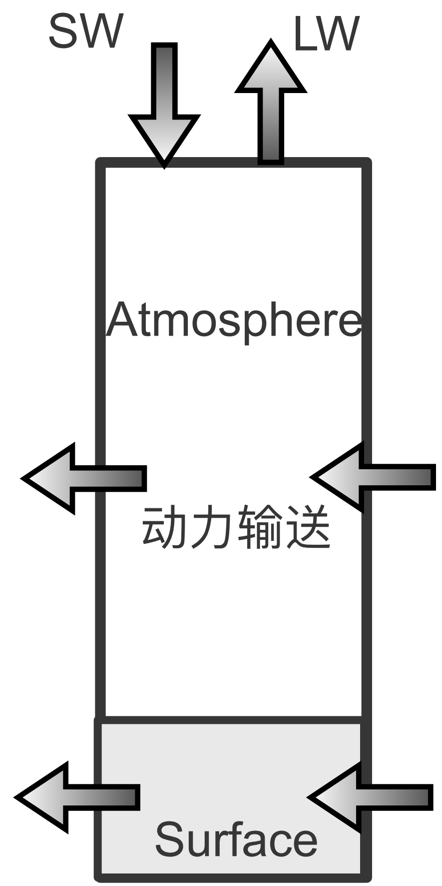
$$\begin{aligned} \mathcal{A}(T) &= \alpha, \quad \text{for } T < T_{snow} \\ \text{or} &= \beta, \quad \text{for } T > T_{snow} \end{aligned}$$

Note: *F(T)* is the **divergence** of heat flux

Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$



- One-dimensional, only latitude dependences are considered;
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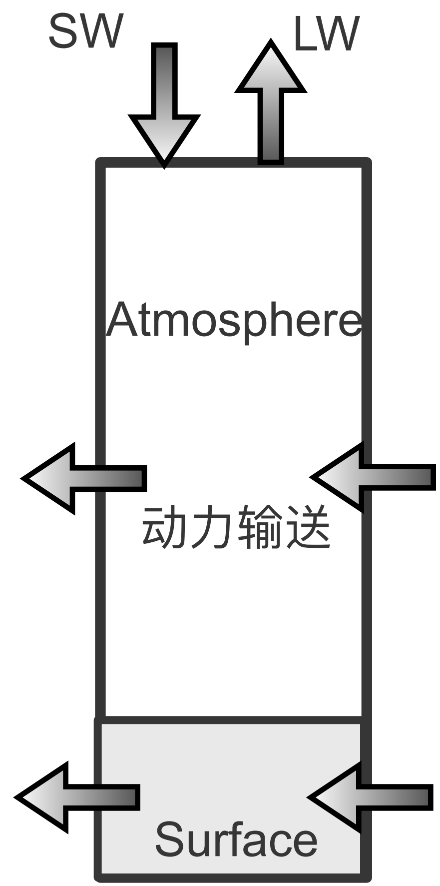
- Planetary albedo is assumed to depend primarily on snow /ice cover;
- Only annual mean conditions are considered;
- The primary feature of the heat transport is that it carries heat from warmer to colder regions.

Budyko, M.I. (1969). The effect of solar radiation variations on the climate of the earth. *Tellus* **21**, 611-619.

Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$



The snow line case: $\text{infrared cooling } I = A + BT$

$$F(T) = C(\bar{T} - T)$$

Assume:

$$\begin{aligned} \mathcal{A}(T) &= \quad \alpha = 0.4, \quad &\text{for } T < T_{snow} \\ &= \quad \beta = 0.7, \quad &\text{for } T > T_{snow} \\ &= \quad \tfrac{\alpha+\beta}{2}, \quad &\text{for } T = T_{snow} \end{aligned}$$

$$T_{snow} = -10^oC$$

$$s(x) = 1 - 0.241(3x^2 - 1)$$

$$A = 211.1\, Wm^{-2}, \text{ and } B = 1.55\, Wm^{-2}(^oC)^{-1}$$

Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$

The snow line case: infrared cooling $I = A + BT$

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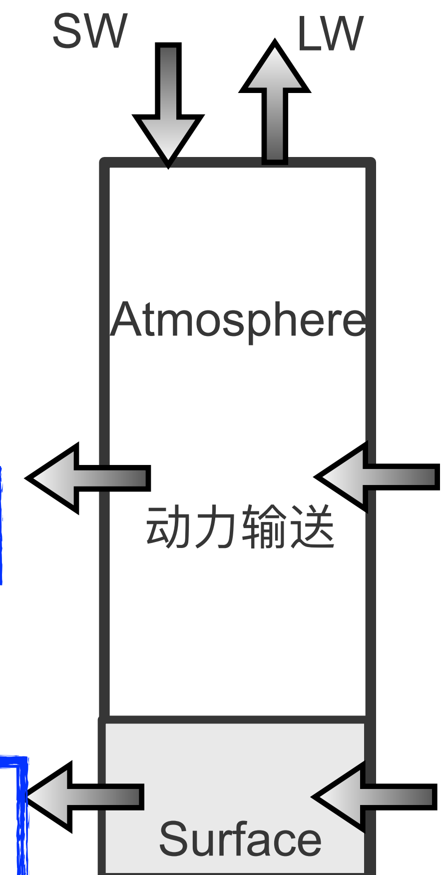
Hemisphere average:

$$\bar{T} = \int_0^1 T dx \qquad \bar{I} = \int_0^1 I dx \qquad F(I) = (C/B)(\bar{I} - I)$$

Radiation balance

$$\bar{I}/Q = \int_0^1 s(x)\mathcal{A}(x)dx = (\beta - \alpha)(1.241x_s - 0.241x_s^3) + \alpha$$



Simple energy balance climate models

In equilibrium,

$$Qs(x)\mathcal{A}(T) - I(T) + F(T) = 0$$

The snow line case:

$$I/Q = \frac{\frac{C}{B}\bar{I}/Q + s(x)\mathcal{A}(x, x_s)}{1 + \frac{C}{B}}$$

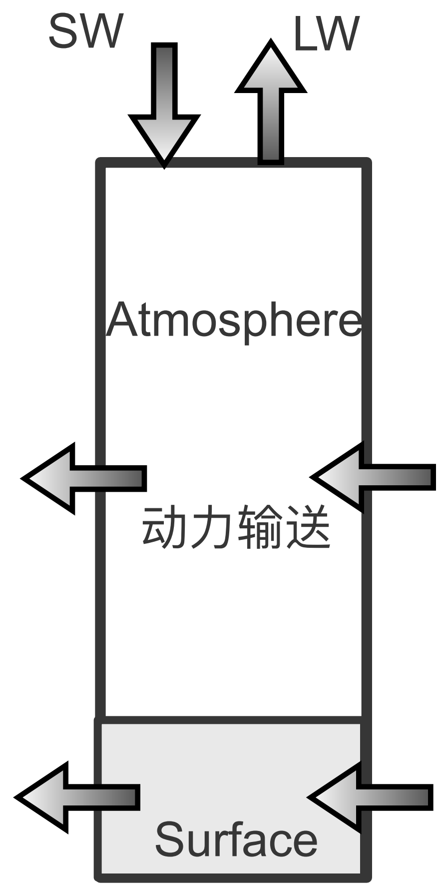
Determine C using current climate:

$$x_s = 0.95; Q = Q_o = 340\ W/m^2$$

$$I(x_s) = I(0.95) = I(T_{snow}), \text{ get the value of } \frac{C}{B}$$

Then

$$Q(x_s) = \frac{(1 + \frac{C}{B})(A + BT_{snow})}{\frac{C}{B}\bar{I}/Q + s(x_s)\frac{\alpha+\beta}{2}}$$



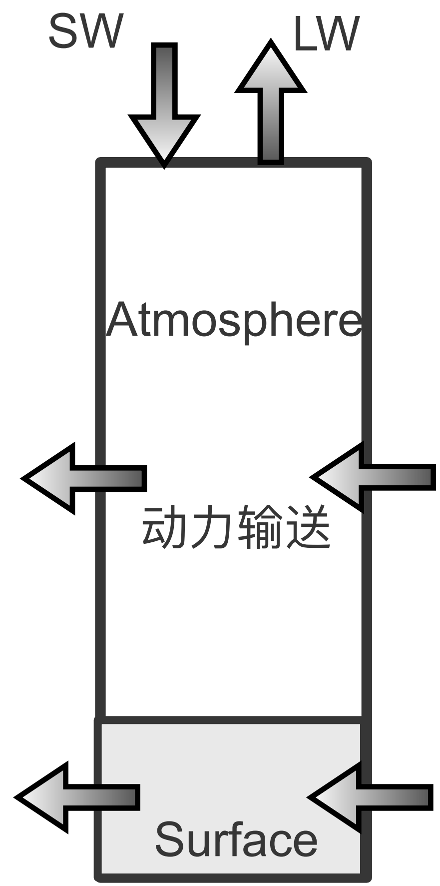
Simple energy balance climate models

The snow line case:

$$Q(x_s) = \frac{(1+\frac{C}{B})(A+BT_{snow})}{\frac{C}{B}\bar{I}/Q + s(x_s)\frac{\alpha+\beta}{2}}$$

The denominator:

$$\begin{aligned} den \quad = \quad & \frac{\alpha+\beta}{2}\times 1.241 + \alpha\frac{C}{B} \\ & +\frac{C}{B}(\beta-\alpha)\times 1.241x_s \\ & -\frac{\alpha+\beta}{2}\times 0.723x_s^2 \\ & -\frac{C}{B}(\beta-\alpha)\times 0.241x_s^3 \end{aligned}$$



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$$\begin{aligned} den \;&= \frac{\alpha+\beta}{2}\times 1.241 + \alpha\frac{C}{B} \\ &+\frac{C}{B}(\beta-\alpha)\times 1.241x_s \\ &-\frac{\alpha+\beta}{2}\times 0.723x_s^2 \\ &-\frac{C}{B}(\beta-\alpha)\times 0.241x_s^3 \end{aligned}$$

If C=0, no heat flux, radiative equilibrium, then as x_s increases, den. decreases, Q increases.

太阳辐射越强，冰雪线越向两极移动

If C is nonzero,

Simple energy balance climate models

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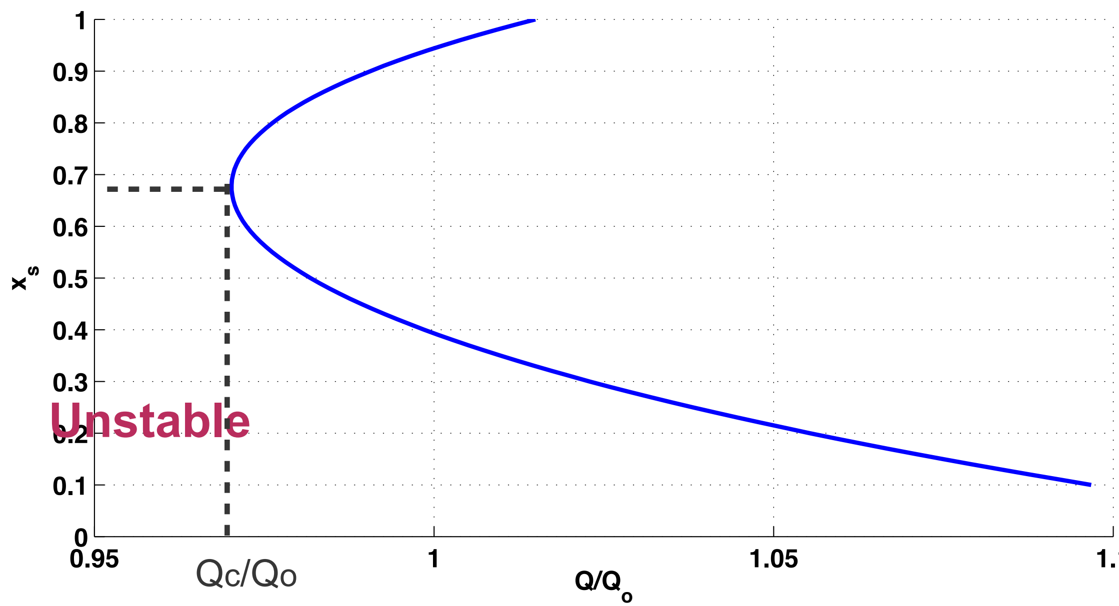
If C is nonzero,

The destabilizing effect of heat transport

There is a minimum value of Q, below which the climate will unstably proceed to a snow/ice covered earth.



Simple energy balance climate models

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