Clouds

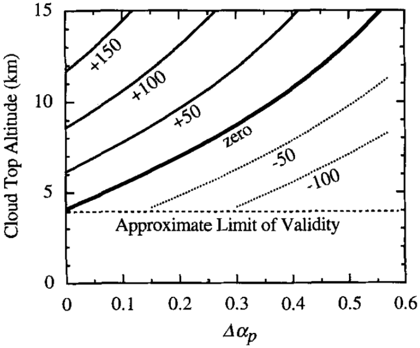


Figure: Hartmann 1994

Clouds have two effects:

- ≈ -50 W m^{-2} Increased reflection of shortwave ($\Delta\alpha$) $\rightarrow$ cooling
- $\approx +20$ W m^{-2} Colder longwave emission temperature $\rightarrow$ warming

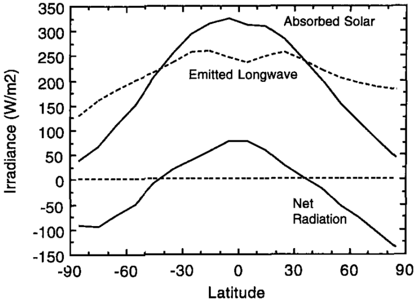
so that the sign of the cloud contribution to the radiative balance depends on cloud top temperature and cloud thickness

- SCu Thick, low clouds (like stratocumulus) have a large cooling effect
- Ci Thin, high clouds (like cirrus) have a large warming effect

Zonal-mean radiative balance at TOA

TOA radiative balance. . .

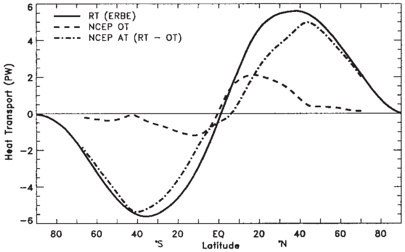
- The top-of-atmosphere (TOA) radiative balance measures how much energy enters or leaves the climate system
- In the tropics, the net energy flux is positive (into the climate system)
- In the extratropics, the net energy flux is negative (out of the climate system)



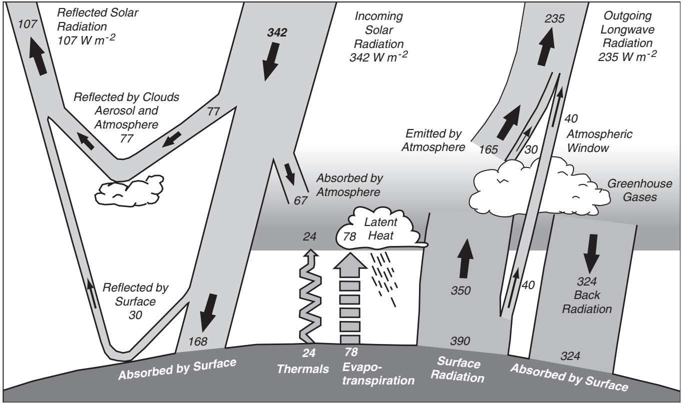
Figures: Hartmann (1994), Trenberth and Caron (2001)

. . . requires meridional energy transport

- To maintain a steady state (e.g., constant long-term zonal-mean temperature), energy transport from the tropics into the extratropics is required
- The *meridional divergence* of the energy transport balances the radiative energy flux
- Contributions to transport from ocean and atmosphere – subject of the next section



Energy fluxes into and out of the atmosphere



Radiative energy balance of the atmosphere (sign convention: downwelling positive) is

$$
\begin{aligned}
R_a = F_{\mathrm{TOA}} - F_s + R_{\mathrm{TOA}} - R_s &= (342 - 107) - 168 + (-235) - (324 - 390) \text{ W m}^{-2} \\
&= \mathcal{O}(-100 \text{ W m}^{-2}), \qquad (5.12)
\end{aligned}
$$

balanced by fluxes of sensible and latent heat into the atmosphere

Figure: Kiehl and Trenberth, 1996

Today's Lecture: General circulation of the atmosphere

Reference

Hartmann, *Global Physical Climatology* (1994), Ch. 2, 3, 6
Peixoto and Oort, Ch. 4, 6, 7, 14, 15

5.2 – General circulation of the atmosphere

- Atmospheric transport in response to radiative imbalance
- Mean meridional circulation and eddy circulation
- Energy cycle
- Entropy cycle

5.2 – General circulation of the atmosphere

- Atmospheric transport in response to radiative imbalance
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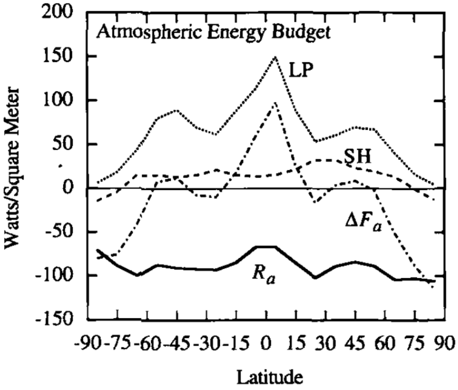
- Energy cycle
- Entropy cycle
- Cycles of momentum, angular momentum
- Hydrological cycle

Radiative balance requires atmospheric transport



- As we saw in the previous section, the net radiative energy balance of the atmosphere is $R_a = \mathcal{O}(-100 \text{ W m}^{-2})$; the balance is fairly constant in latitude
- The radiative energy loss is balanced by latent (LP) and sensible (SH) heat flux from land and ocean; but these are strong functions of latitude
- Meridional advective atmospheric energy flux is required to provide local energy balance:

$$\Delta F_a + R_a + F_{\text{LH}} + F_{\text{SH}} = 0 \tag{5.13}$$

- The advective energy flux is the meridional divergence of the meridional heat transport (sign convention: northward positive):

$$\frac{dN}{d\phi} = \int_0^{2\pi} d\lambda \, R_E^2 \, \Delta F_a(\phi) \cos\phi = 2\pi R_E^2 \, \Delta F_a(\phi) \cos\phi \tag{5.14}$$

Figures from Hartmann (1994) unless noted

Streamfunction

The zonal-mean continuity equation (zonal flow is integrated out) is

$$\frac{1}{R_E \cos\phi}\frac{\partial}{\partial\phi}([\bar{v}]\cos\phi) + \frac{\partial[\bar{\omega}]}{\partial p} = 0 \tag{5.15}$$

For a nondivergent flow, velocity components can be written with the aid of a streamfunction:

$$[\bar{v}] = \frac{g}{2\pi R_E \cos\phi}\frac{\partial\Psi_M}{\partial p} \tag{5.16}$$

$$[\bar{\omega}] = \frac{-g}{2\pi R_E^2 \cos\phi}\frac{\partial\Psi_M}{\partial\phi} \tag{5.17}$$

(5.16) and (5.17) satisfy (5.15); normalization, including the minus sign, is convention – but the relative minus sign is required. To calculate Ψ_M, first impose boundary condition $\Psi_M = 0$ at TOA, then integrate (5.16):

$$\Psi_M = \frac{2\pi R_E \cos\phi}{g}\int_0^p [\bar{v}]\, dp' \tag{5.18}$$

The normalization is chosen to give units of kg s^{-1} (*mass streamfunction*); the $\cos\phi$ factor is required to ensure constant Ψ_M for constant meridional flow. Mass transport is tangent to contours of the streamfunction. Mass flow between two contours is equal to $\Delta\Psi_M$.

Mean meridional circulation

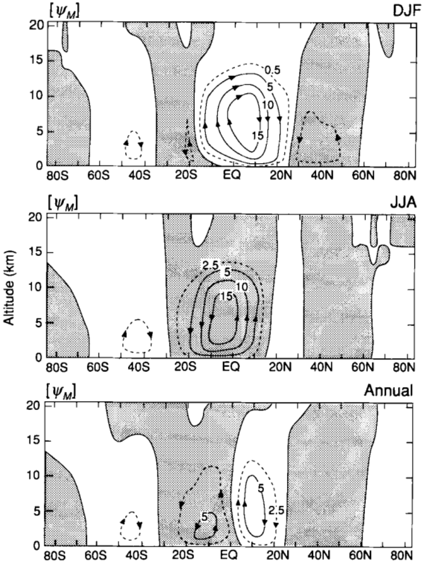


Figure: Hartmann (1994); shaded: $\Psi_M < 0$; units: 10^{10} kg s^{-1}

- Hadley cell with rising branch in the ITCZ and descending in the subtropics
- Transport is from winter hemisphere to summer hemisphere at the surface, summer hemisphere to winter hemisphere at altitude $\rightarrow$ transport of potential energy, latent heat, sensible heat
- Mass transport by mean circulation is small outside the Hadley cell
- This is where (temporal and zonal) fluctuations in the circulation are important – eddy transport

Averaging operators

Temporal mean

$$\overline{A} = \overline{A}(\lambda, \phi, p) = \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} A(\lambda, \phi, p, t)\, dt \qquad (5.19)$$

and the *zonal mean*

$$[A] = [A](\phi, p, t) = \frac{1}{2\pi} \int_{0}^{2\pi} A(\lambda, \phi, p, t)\, d\lambda \qquad (5.20)$$

The instantaneous value of A is given by

$$A = \overline{A} + A' \qquad (5.21)$$

where A' is called the *fluctuating* component of A. Likewise

$$A = [A] + A^* \qquad (5.22)$$

where A^* is the departure from the zonal mean.
Decomposition of a field into time-average and fluctuating, zonally symmetric and zonally asymmetric components:

$$A = [\bar{A}] + [A'] + \bar{A}^* + A'^* \qquad (5.23)$$

Decomposition of the flow

Products of fields contain covariance terms (where fluctuations do not average to zero)

$$\overline{AB} = \bar{A}\bar{B} + \overline{A'B'} \tag{5.24}$$

$$[AB] = [A][B] + [A^*B^*] \tag{5.25}$$

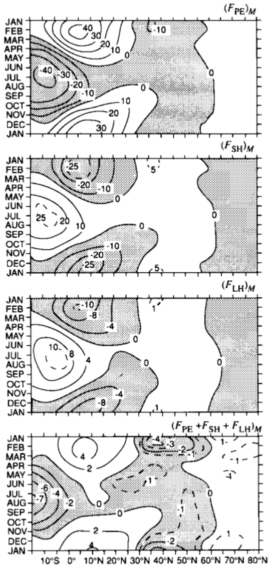
$$\left[\overline{AB}\right] = \left[\bar{A}\right]\left[\bar{B}\right] + \left[\bar{A}^*\bar{B}^*\right] + \left[\overline{A'B'}\right] \tag{5.26}$$

The terms in (5.26) are the mean circulation, stationary eddies, and transient eddies. To take a concrete example, the decomposition of northward flux of sensible heat is

$$c_p\left[\overline{vT}\right] = c_p\left[\bar{v}\right]\left[\bar{T}\right] + c_p\left[\bar{v}^*\bar{T}^*\right] + c_p\left[\overline{v'T'}\right] \tag{5.27}$$

This week's homework will analyze the relative importance of each contribution as a function of latitude.

Meridional energy transport



- Recall static energy (2.61): sum of potential energy (PE), sensible heat (SH) and latent heat (LH)

$$h = gz + c_p T + L_{lv} q \tag{5.28}$$

  The divergence of poleward transport of these energy terms balances the atmospheric energy budget.
- Mean transport dominates in the Hadley cell – but note large terms of opposite signs
- Eddy transport, especially in winter (large temperature gradient), dominates in midlatitudes