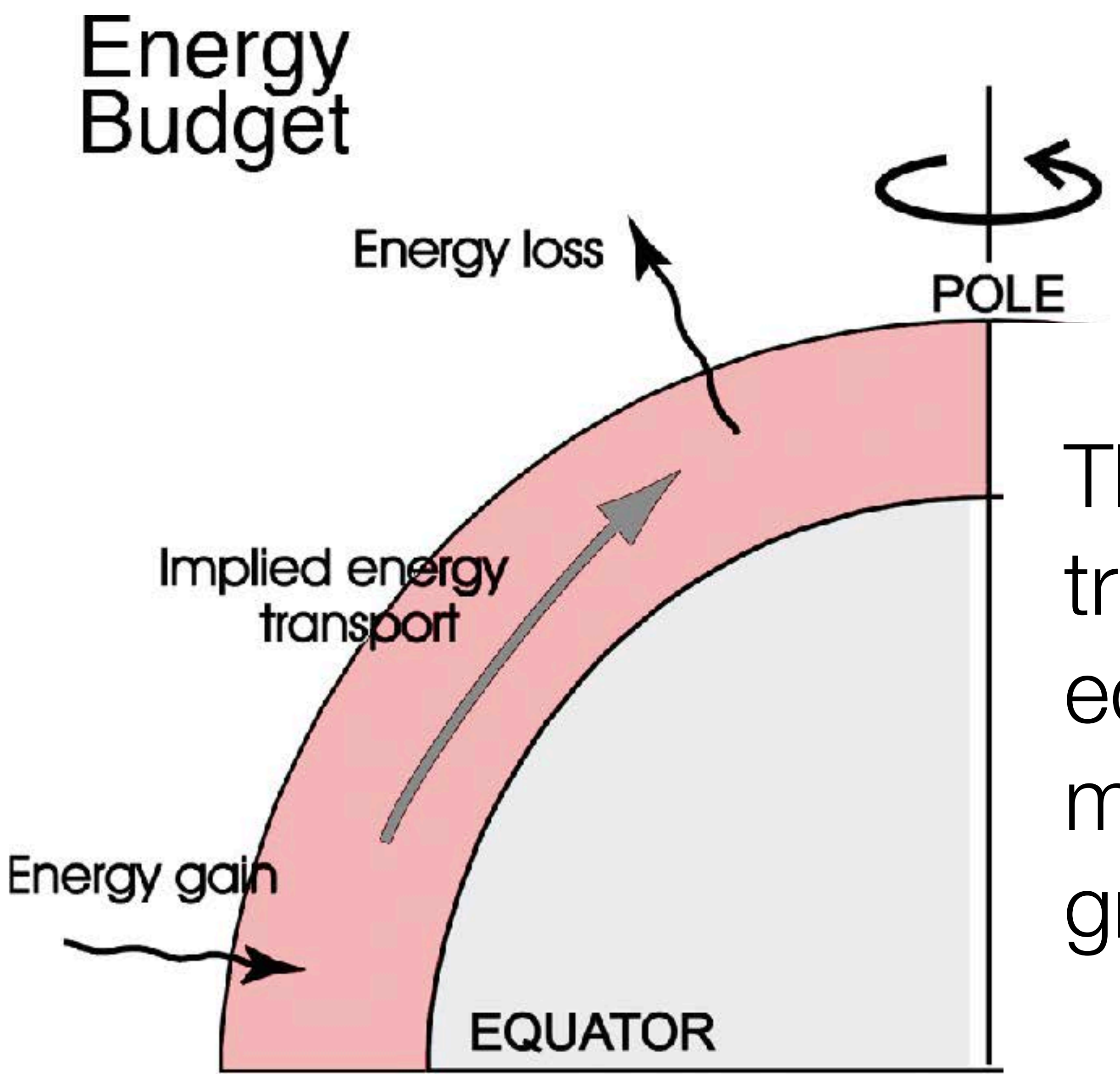
Atmosphere: #5
General circulation

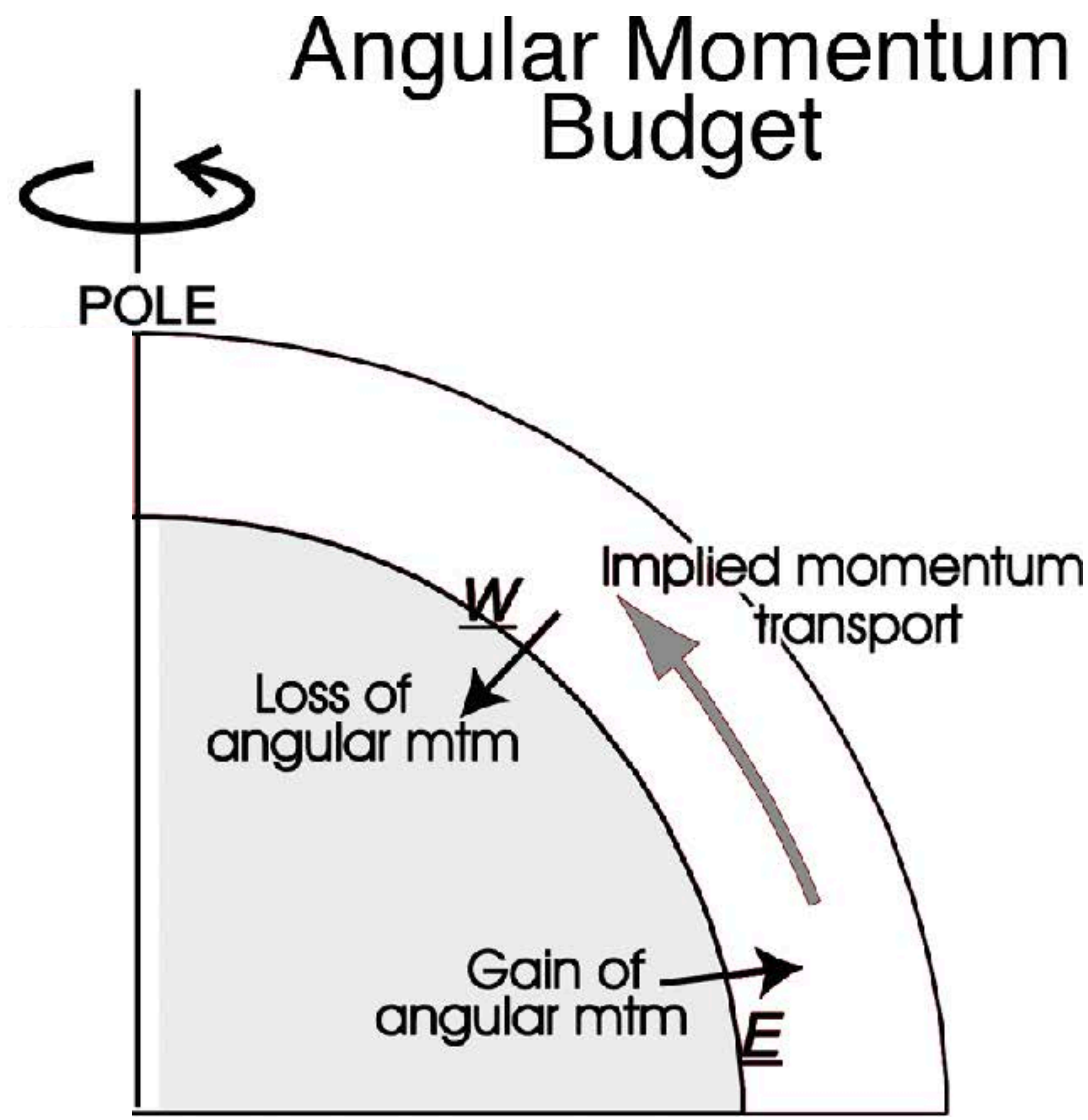
General circulation of the atmosphere



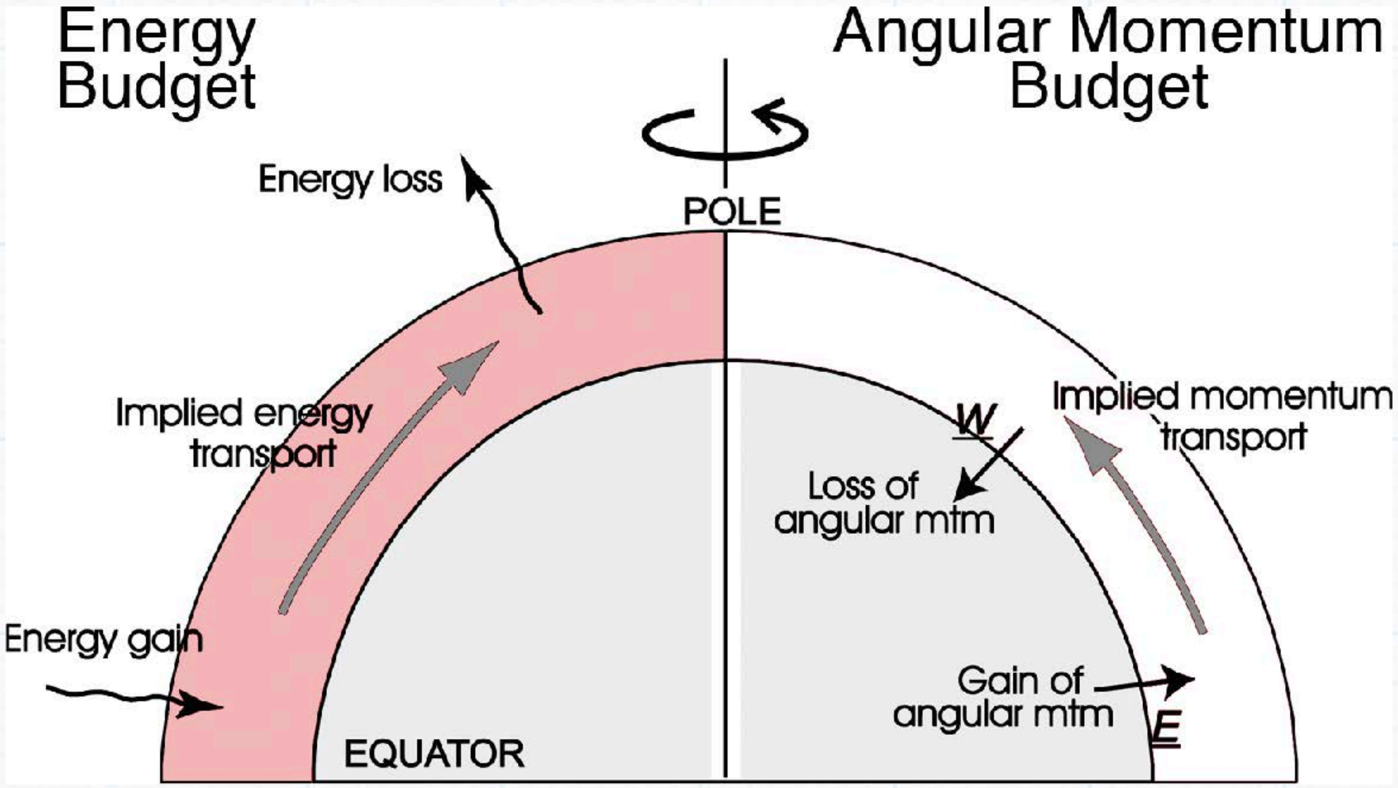
The atmosphere has to transport energy from equator to pole to maintain the temperature gradient

General circulation of the atmosphere

The atmosphere has to transport westerly angular momentum from low to middle latitude.



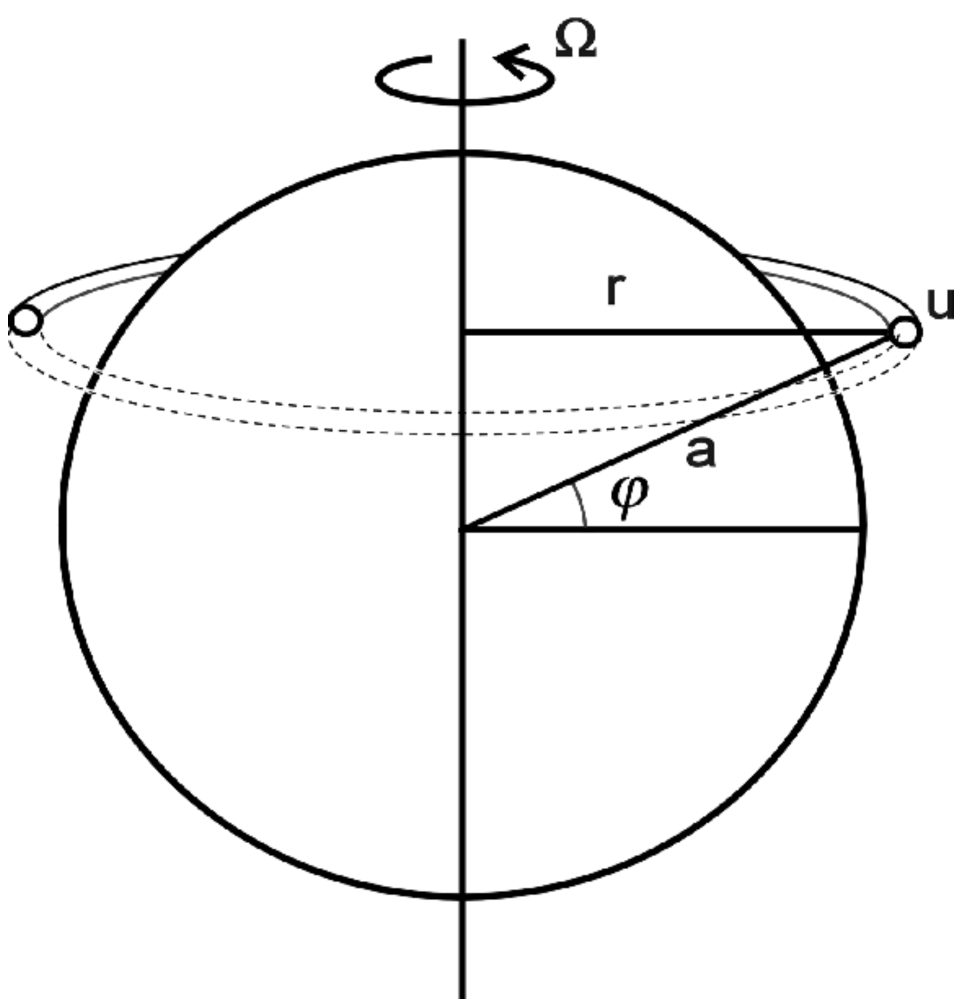
General circulation of the atmosphere



- In the upper troposphere, we know that the dominant flow is the west-to-east, which cannot explain the equator-to-pole transport of heat and angular momentum.
- This is why the overturning circulation becomes important.
- But the meridional overturning circulation does not extend all the way to the pole as in the figure. Why?

Mechanistic view of the circulation: tropics

- For simplicity, let's assume homogeneous surface with no seasonality.
- So we focus on the temperature gradient in latitudinal direction.



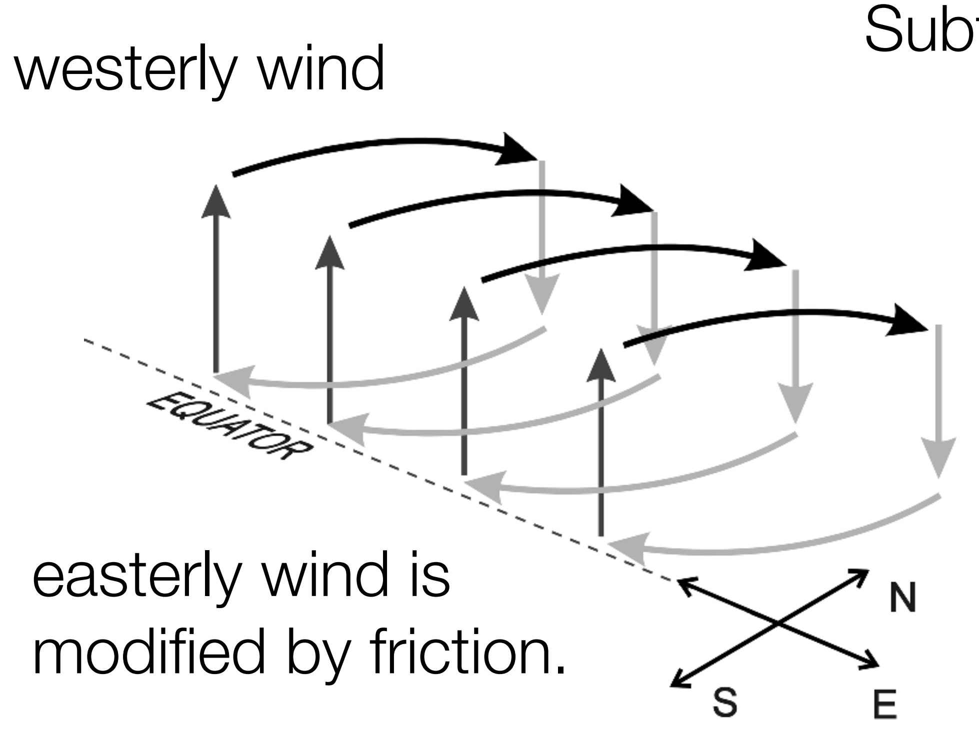
Absolute angular momentum

$$A = \Omega r^2 + ur$$

$$= \Omega a^2 \cos^2 \phi + ua \cos \phi$$

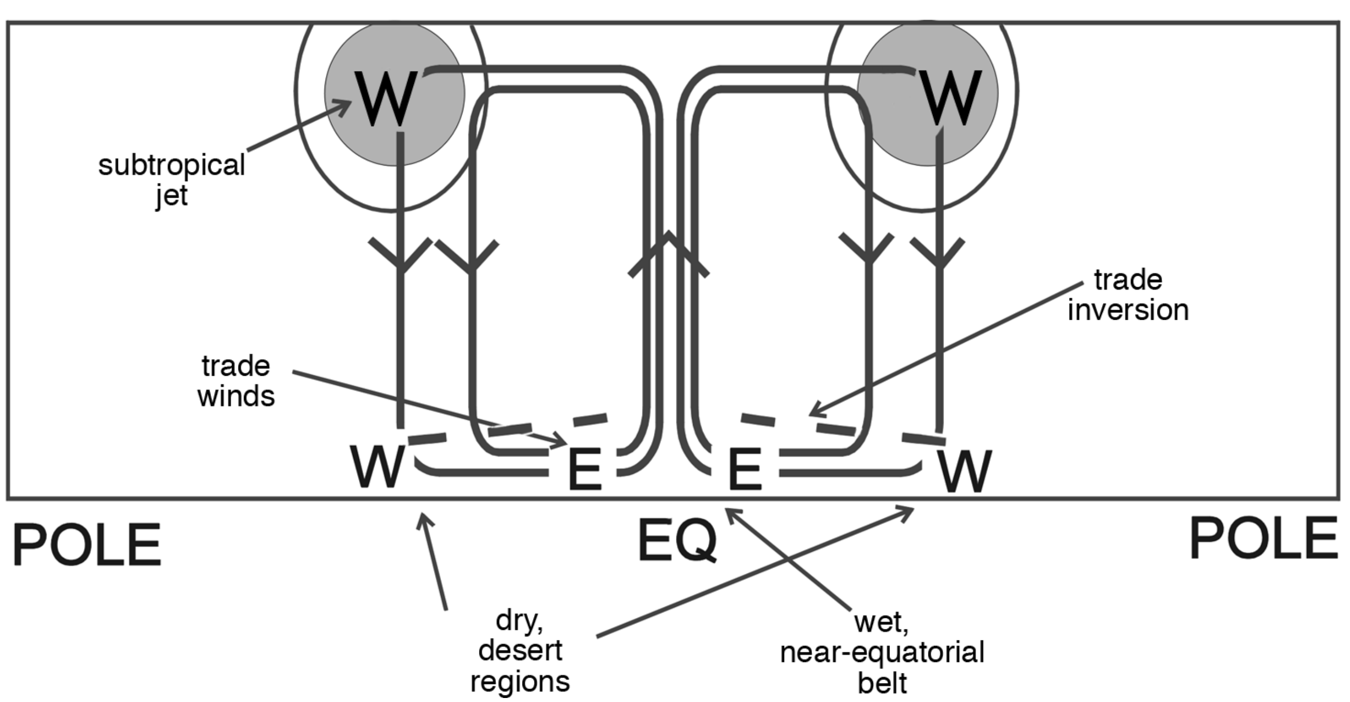
If we start $u=0$ at the equator, u grows as we go to the north.

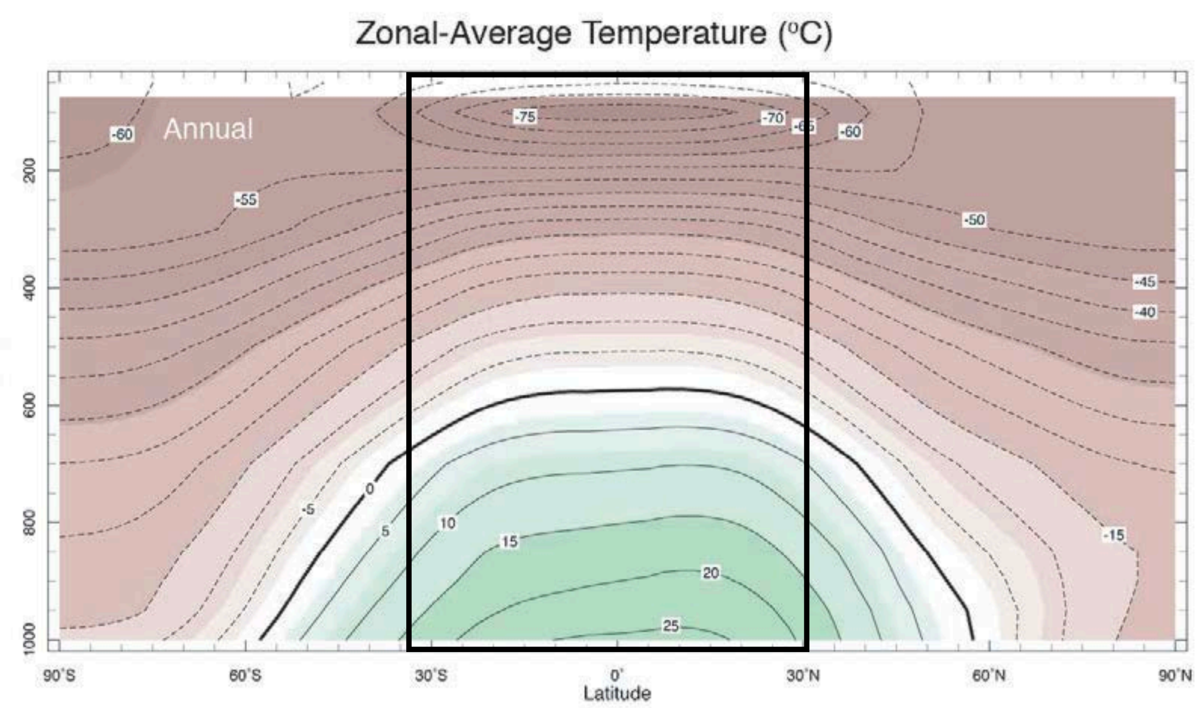
Mechanistic view of the circulation: tropics



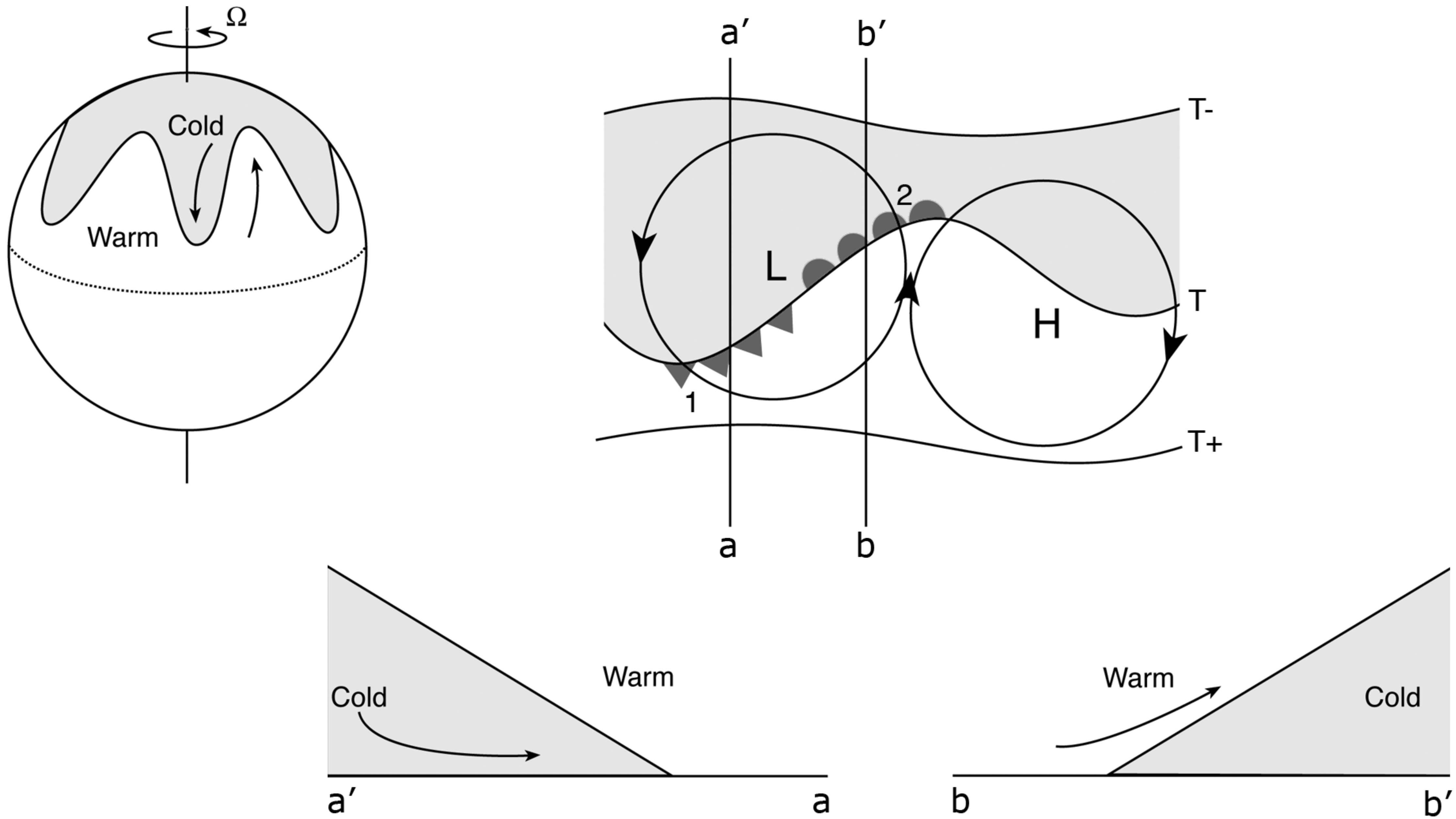
Subtropical jet is driven in large part by the advection of angular momentum by the Hadley cell.

Small T gradient reflects how effective Hadley cell is in transporting the heat.





Mechanistic view of the circulation: extratropics



Energetics of the thermal wind equation

Q: Why do we have this energetic flows?

A: Available potential energy that can be released by a redistribution of mass of the system

Energetics of the thermal wind equation

- Let's consider an incompressible fluid, like water, for simplicity.
- A potential energy (PE) of a fluid parcel of volume $dV = dx\, dy\, dz$ and density ρ would be $gz\rho dV$:
- The total potential energy is then

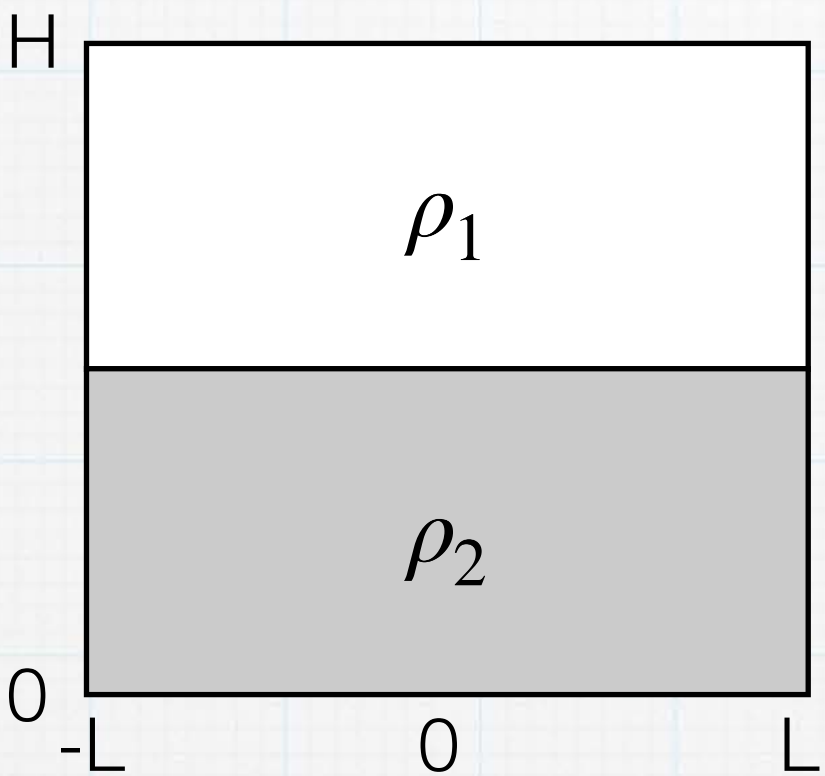
$$PE = g\int z\rho dV = g\int \rho dV \frac{\int z\rho dV}{\int \rho dV} = gM\langle z\rangle$$

The height of the center of mass

Energetics of the thermal wind equation

- Energy can be released and converted to kinetic energy only if some rearrangement of the fluid results in a lower total potential energy

Example:



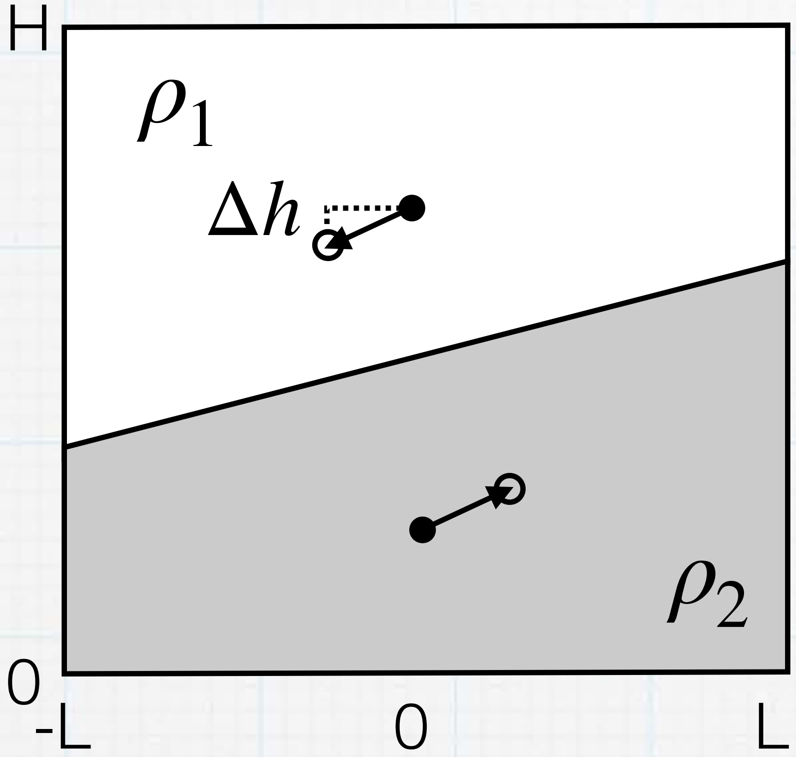
$$PE_1 = \rho_1 g \frac{3}{4} H$$

$$PE_2 = \rho_2 g \frac{1}{4} H$$

$$PE_A = gH\left(\frac{3\rho_1 + \rho_2}{4}\right)$$

Energetics of the thermal wind equation

$$PE_B = g\left[\rho_1\left(\frac{3}{4}H - \Delta h\right) + \rho_2\left(\frac{1}{4}H + \Delta h\right)\right]$$



$$PE_1 = \rho_1 g\left(\frac{3}{4}H - \Delta h\right)$$

$$PE_2 = \rho_2 g\left(\frac{1}{4}H + \Delta h\right)$$

Energetics of the thermal wind equation

- Which fluid has higher potential energy?

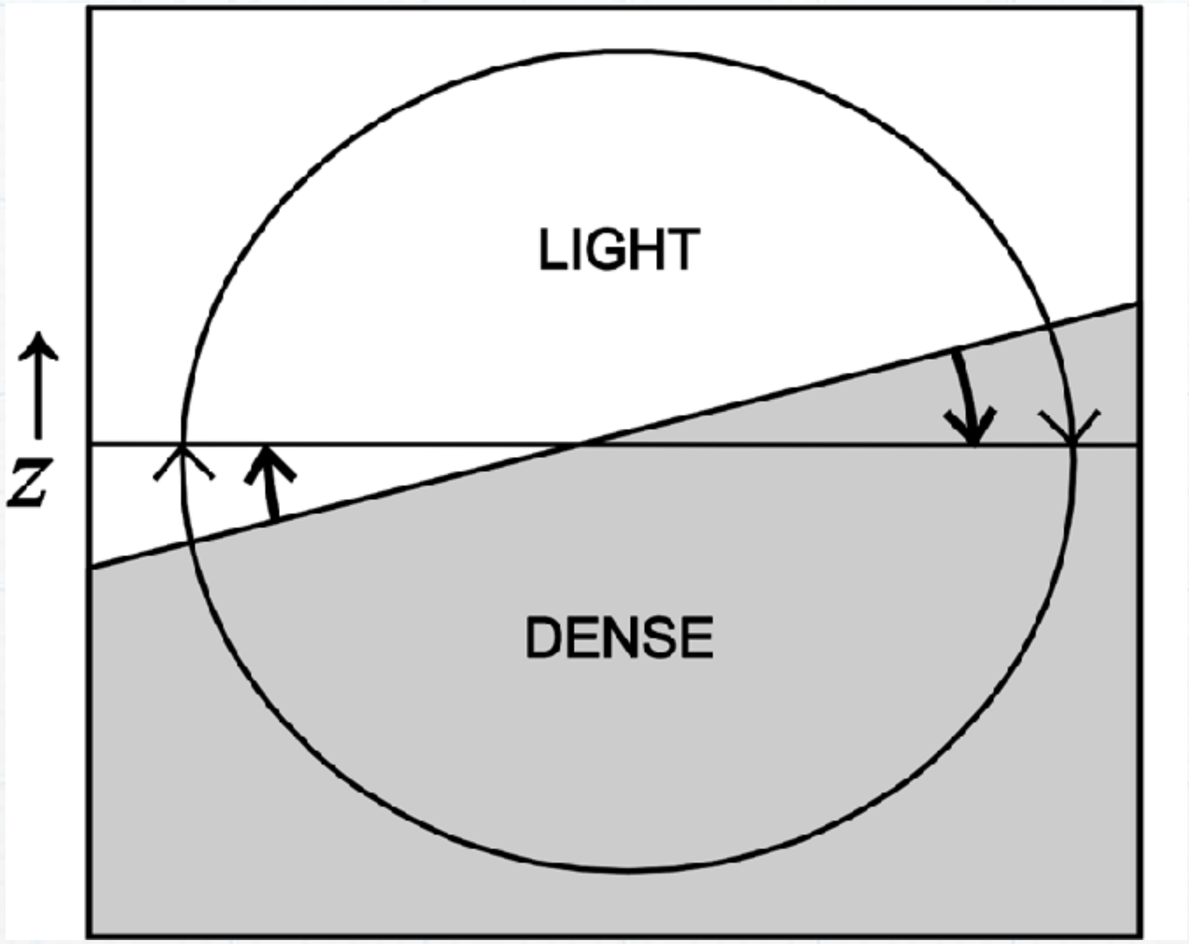
$$PE_A - PE_B = g\left(\rho_1 \frac{3}{4}H + \rho_2 \frac{1}{4}H - \rho_1 \frac{3}{4}H + \Delta h \rho_1 - \rho_2 \frac{1}{4}H - \Delta h \rho_2\right)$$

$$= g\Delta h\left(\rho_1 - \rho_2\right) < 0$$

- The case B has higher potential energy by $g\Delta h\left(\rho_1 - \rho_2\right)$
- This is available potential energy (APE).
- We can expect higher available potential energy when the interface has greater tilt.

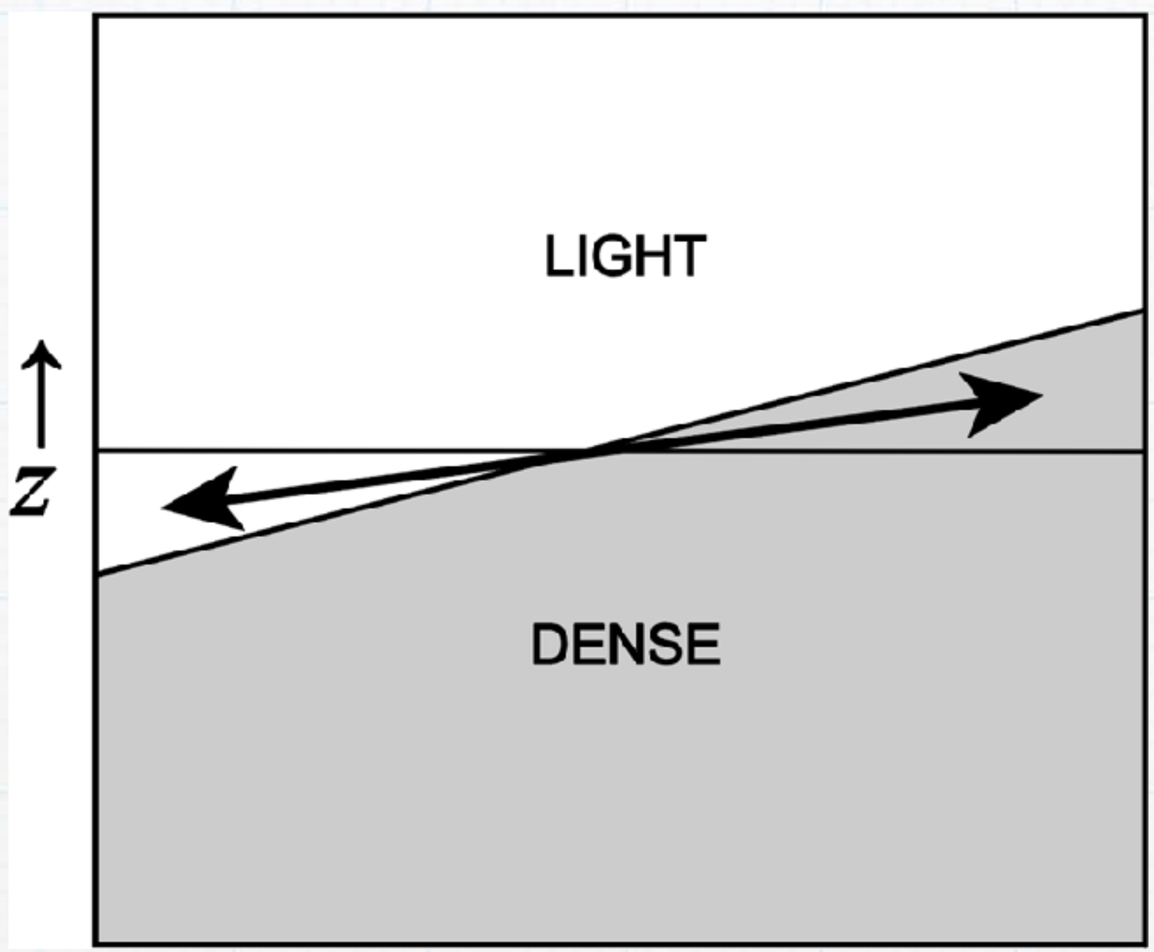
Energetics of the thermal wind equation

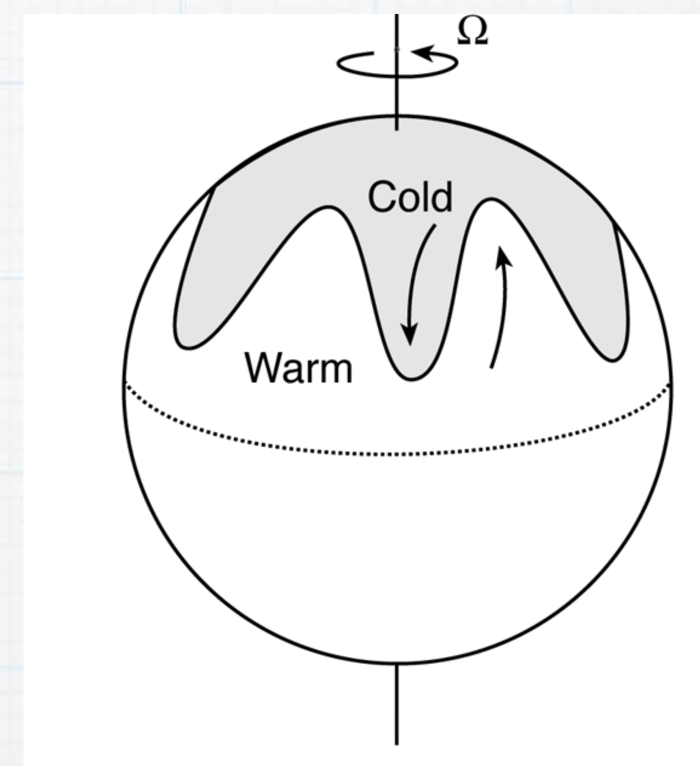
- Release of available potential energy
  - In a non-rotating fluid



Energetics of the thermal wind equation

- Release of available potential energy
  - In a rotating fluid, the tilted slope can be maintained in thermal wind balance



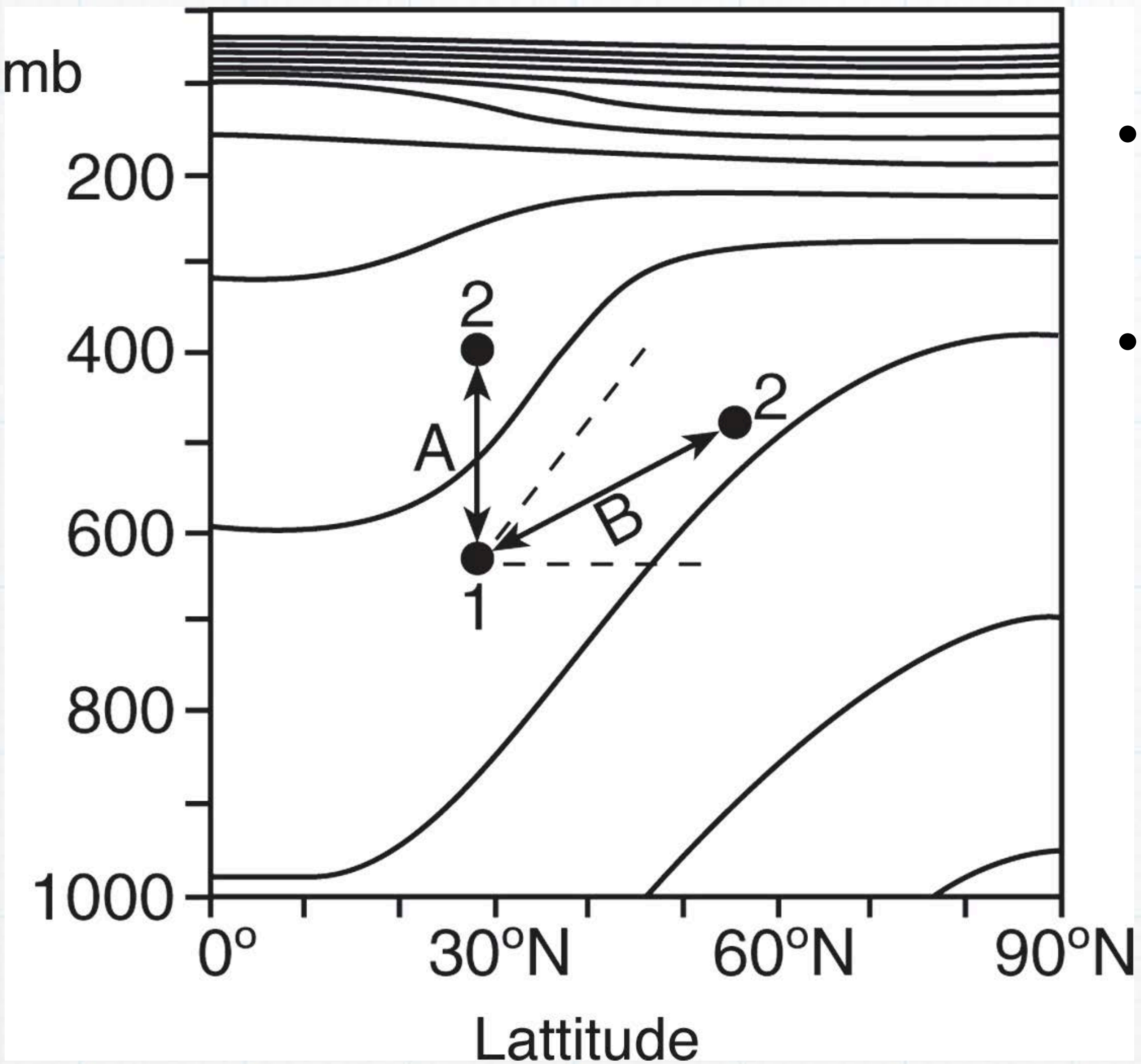


Energetics in a compressible atmosphere

- The air is compressible → we need to consider internal energy.
  - Internal energy goes up when compressed
  - Internal energy goes down when expanded
- The air can contain moisture → we need to consider latent heat when condensation occurs.
- Total energy of the atmosphere = potential energy + kinetic energy + internal energy + latent heat content

Energetics in a compressible atmosphere

Potential temperature (increasing with height)



- Moving from 1 to 2 along A : needs energy
- Moving from 1 to 2 along B : release energy → can excite eddies

1. Energy transport

- Total energy of the atmosphere = internal energy + potential energy + latent heat content + kinetic energy

$$E = c_p T + gz + Lq + \frac{1}{2}\mathbf{u} \cdot \mathbf{u}$$

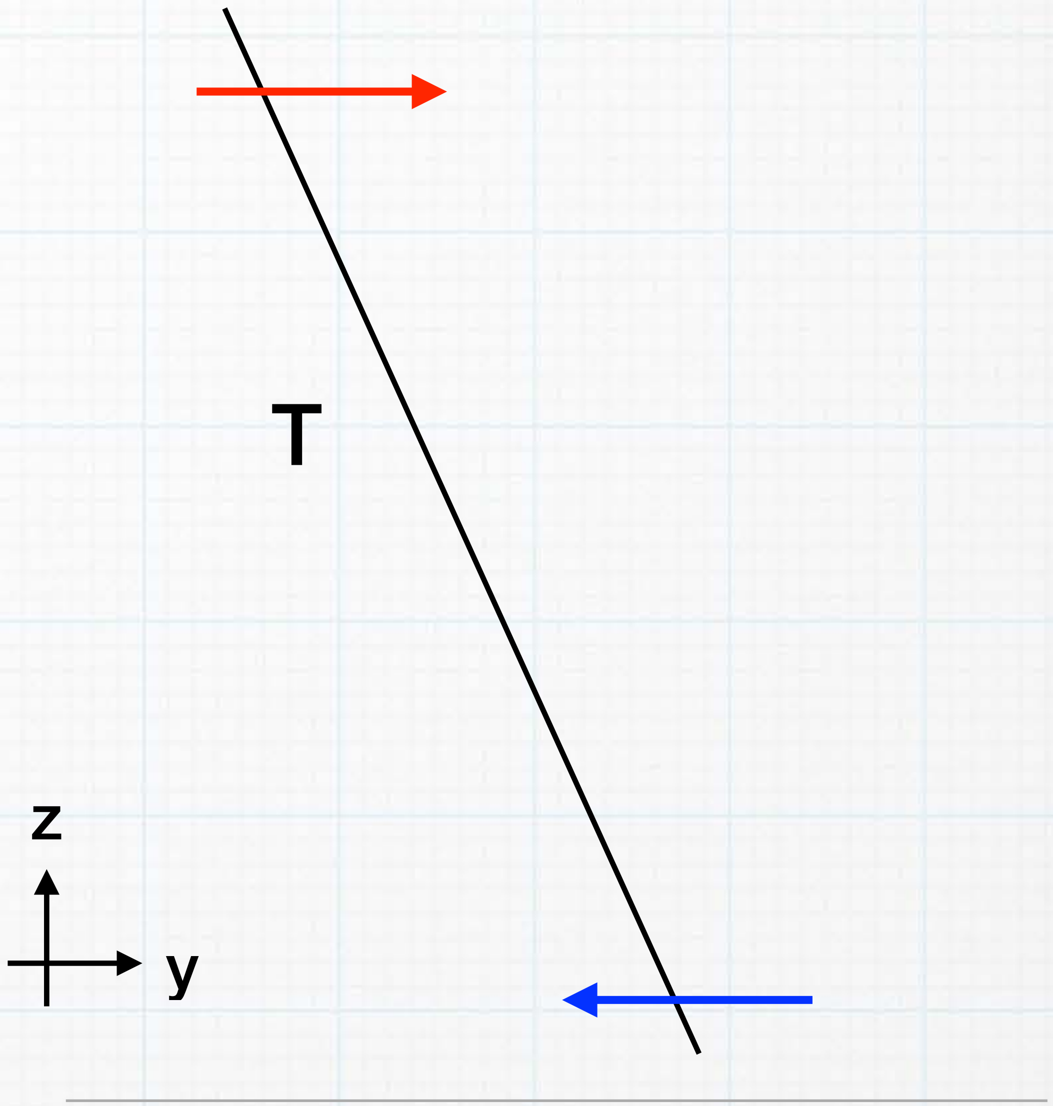
- Energy transport by the atmosphere across the unit area = $\rho v E \; dA$

- Total meridional energy transport = $\int\int \rho v E \; dxdz$

1. Energy transport, tropics

- The internal energy

$$\int_0^\infty \rho v c_p T \, dz < 0$$



Equatorward heat transport

The Hadley circulation carries heat toward the hot equator from the cooler subtropics!

1. Energy transport, tropics

- The internal energy + potential energy

$$\int_0^\infty \rho v(c_p T + gz)\ dz = c_p \int_0^\infty \rho v \left(T + \frac{g}{c_p} z \right)\ dz$$

$$= c_p \int_0^\infty \rho v \left(T - \left. \frac{dT}{dz} \right|_{dry} z \right)\ dz > 0$$

The atmosphere is stale in dry adiabatic process, which makes this term positive.

The Hadley circulation carries (heat+potential) energy poleward.

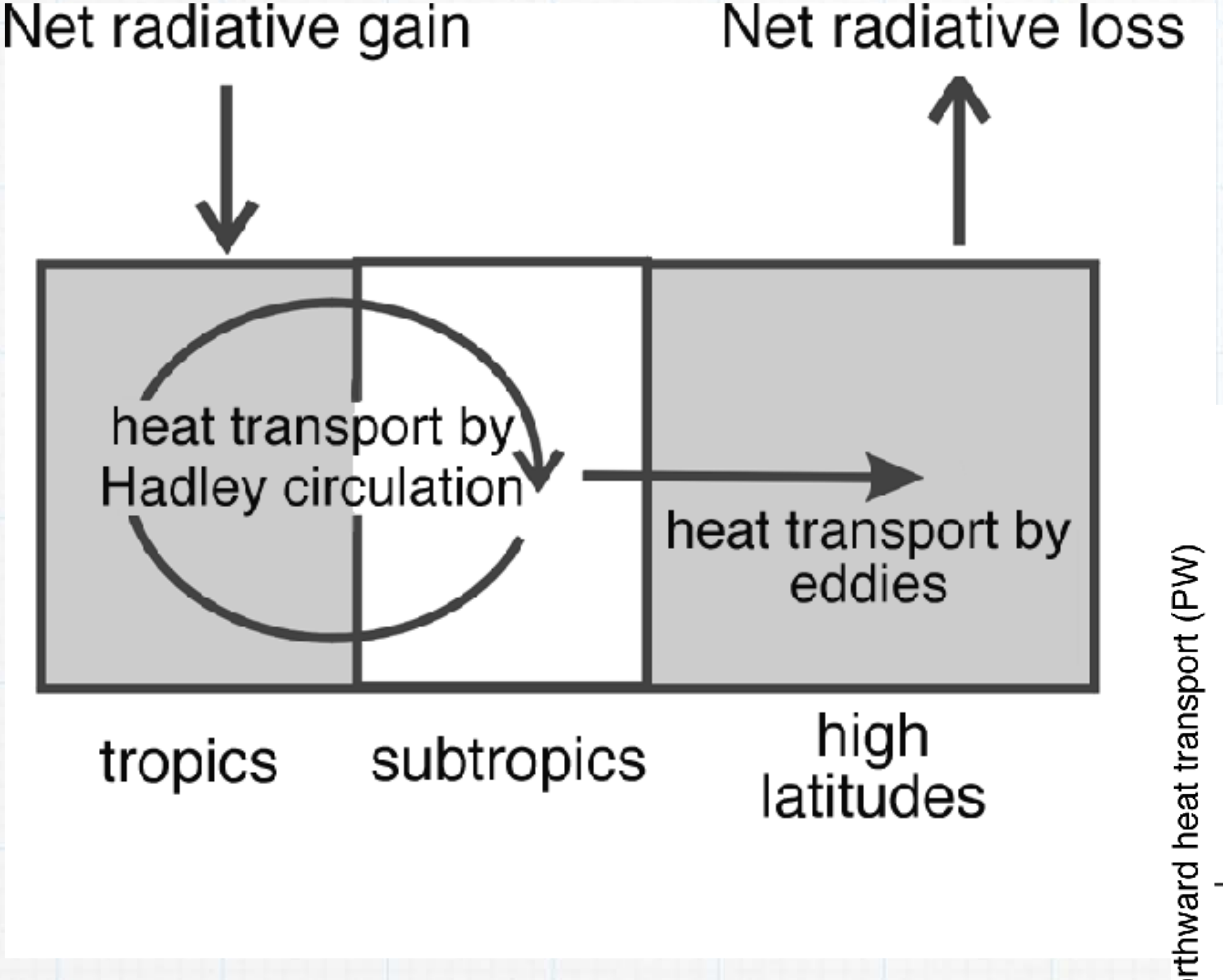
1. Energy transport, tropics

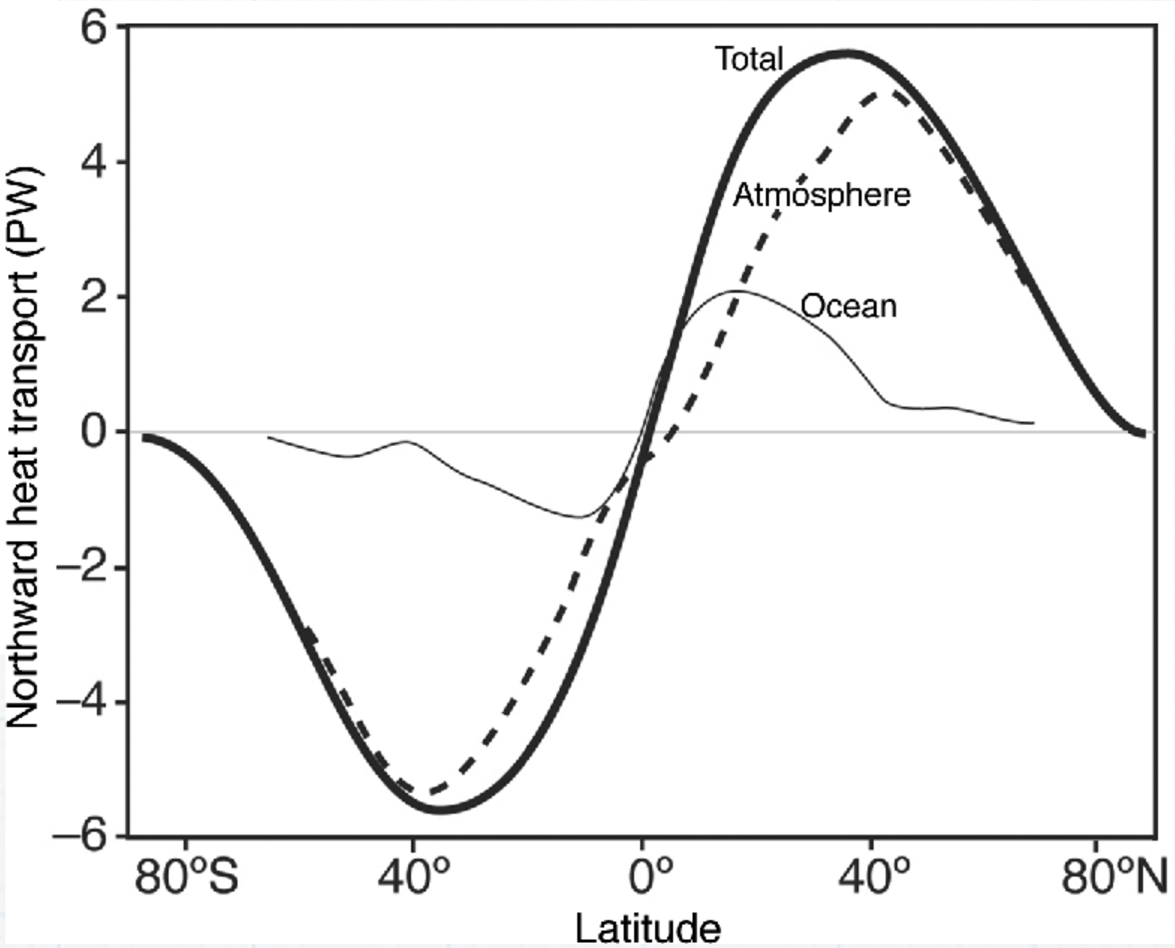
- Upper branch has far less moisture than lower branch of the Hadley cell.
- The net latent heat transport by the Hadley cell is equatorward.
- It turned out that poleward (heat+potential) energy transport and equatorward latent heat energy transport are in opposite sign with similar magnitude.
- The kinetic energy has negligible contribution to the total energy.
- In the net, then, the annually averaged energy flux by the Hadley cell is (weakly) poleward.

1. Energy transport, extratropics

- In the extratropics where the mean circulation is weak, the greater part of the transport is done by eddies.
- We saw that poleward/equatorward motions occur at almost the same altitude. → the vertical structure of the heat transport is not dominant.
- The heat transport, $\int_0^\infty \rho v c_p T \, dz$ is positive because the poleward winds are associated with higher temperature.
- The total energy transport in the midlatitude is poleward.

1. Energy transport



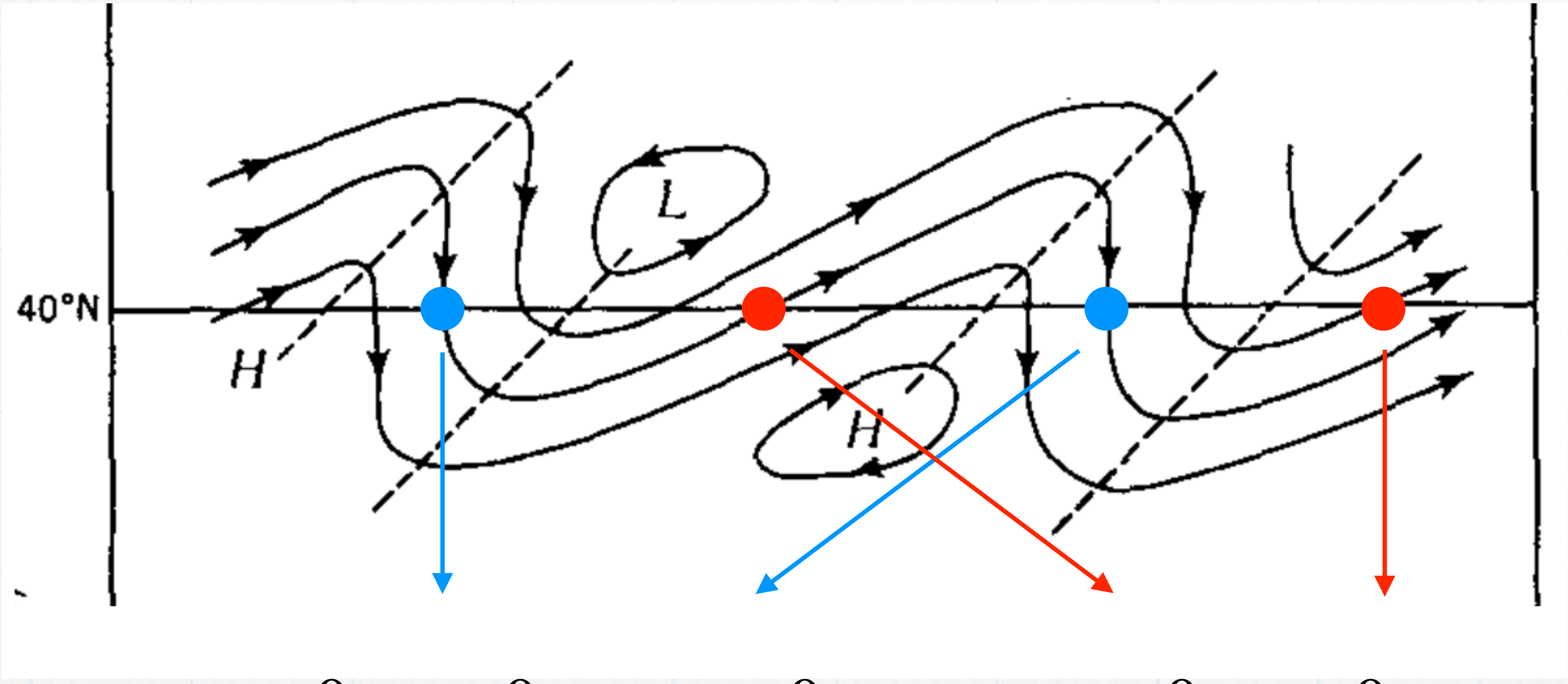


2. Momentum transport, tropics

- Upper branch transports westerly angular momentum poleward.
- Lower branch transport easterly angular momentum equatorward.
- Because of the friction, the momentum transport in the lower branch is weaker than the upper branch.
- The Hadley cell does a poleward transport of westerly angular momentum.

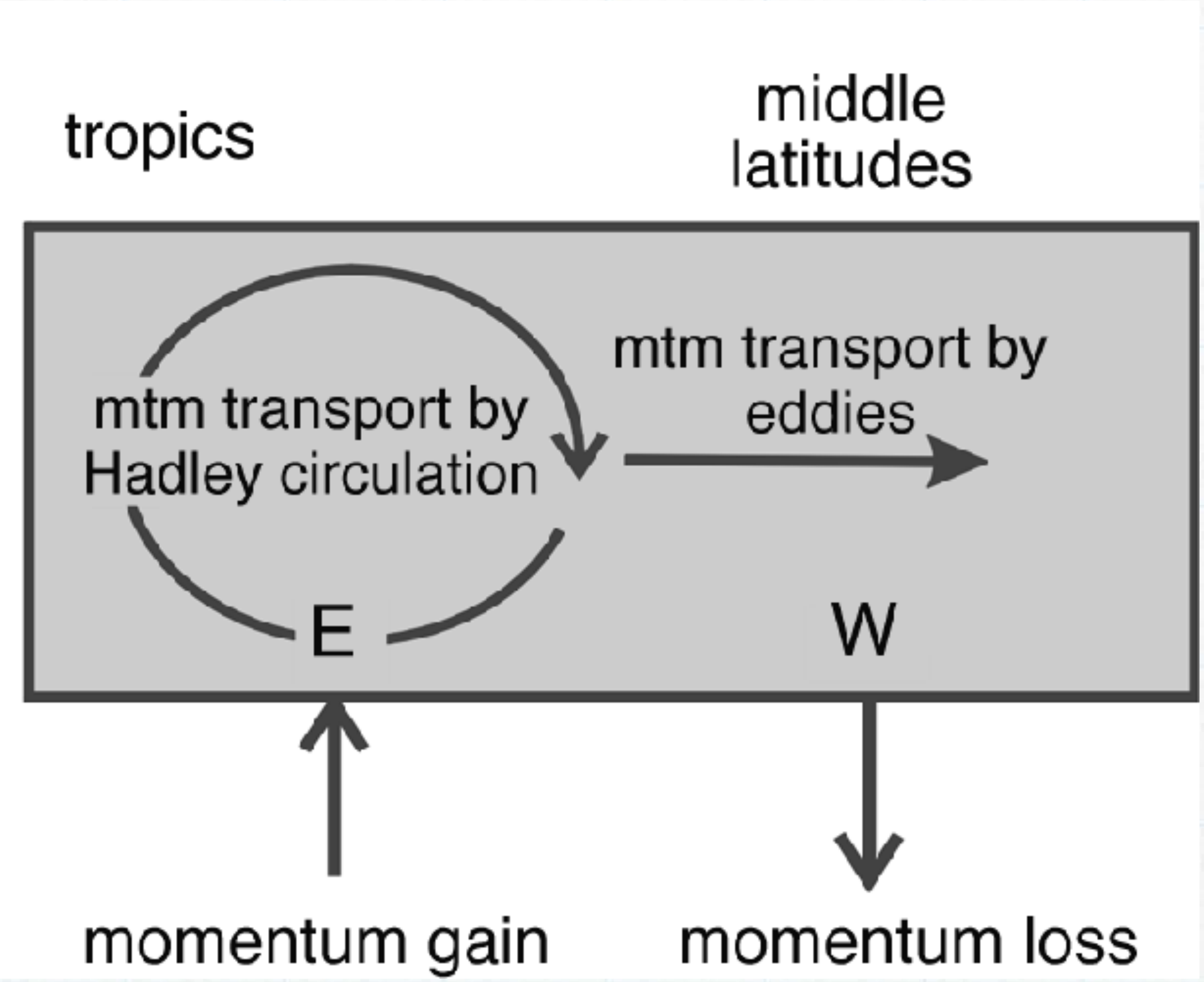
2. Momentum transport, extratropics

- Eddies in the extratropics also transport westerly momentum to poleward, but how?
- The meridional momentum transport
  $= v(\Omega r^2 + ur) = v\Omega r^2 + ruv$

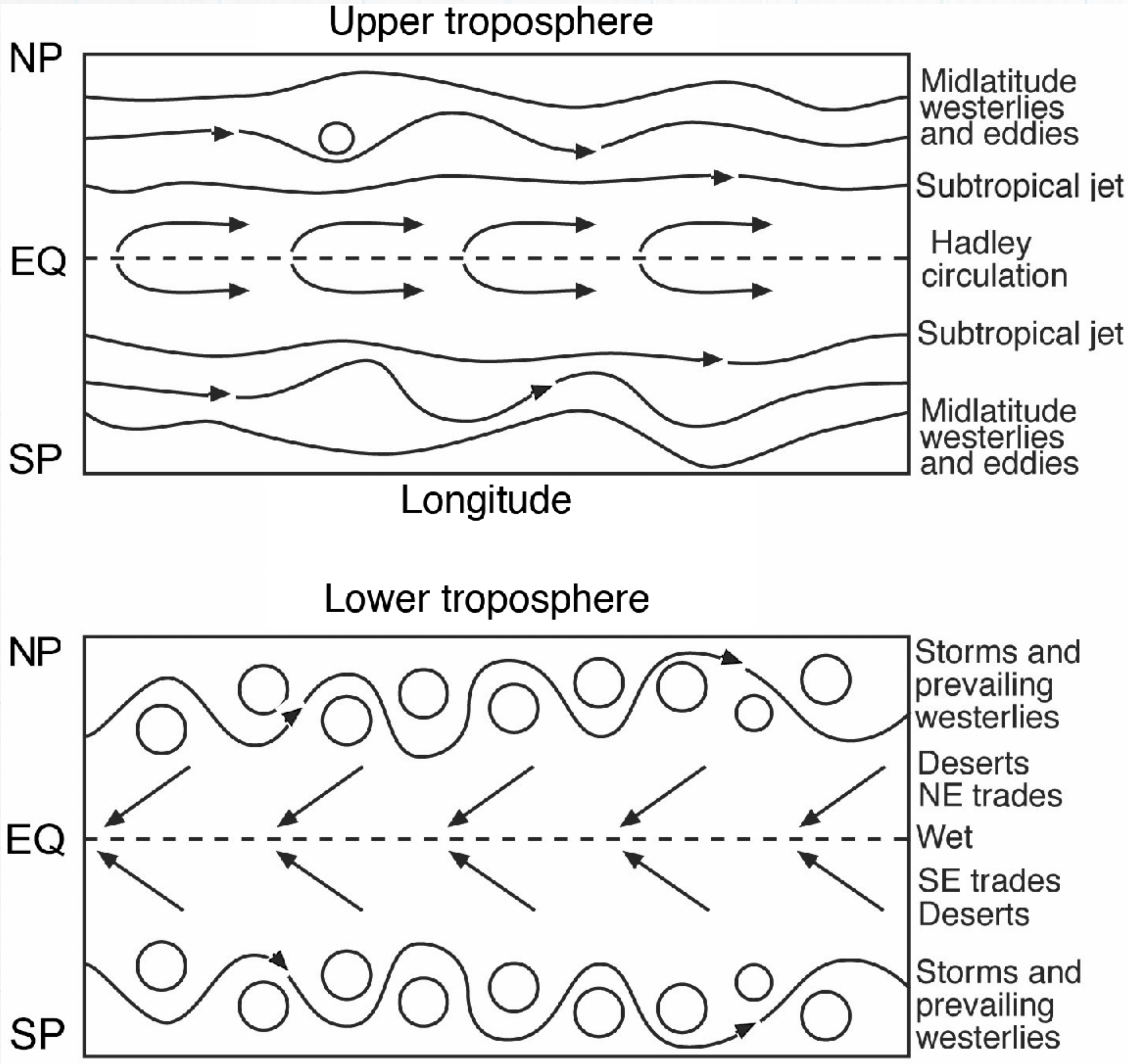


$u \sim 0,\ v < 0 \rightarrow uv \sim 0$ $\quad$ $u > 0,\ v < 0 \rightarrow uv > 0$

2. Momentum transport, extratropics



3. Latitudinal variations of climate



@ tropics : convergence and upward motion → intense rainfall

@ midlatitude : sinking and warming → desert belt

@ midlatitude : eddies that go around the globe → control the weather patterns