Topic 3: Atmospheric circulation

MATH3261/5285: Fluids, Oceans, and Climate

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2.1 A brief overview of atmospheric circulation

"The storm is up, and all is on the hazard."

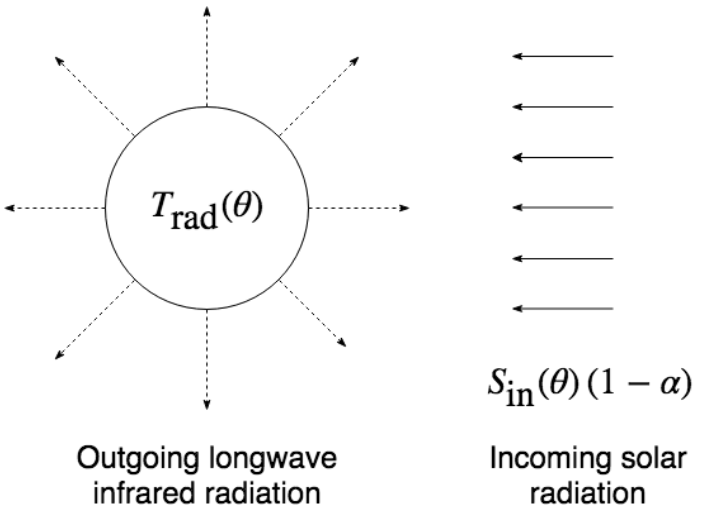
William Shakespeare, *Julius Caesar* Act V Scene 1.

General circulation = large-scale motion of the atmosphere

1000 km	$\longrightarrow$	10000 km
synoptic scale		planetary scale

Radiative equilibrium

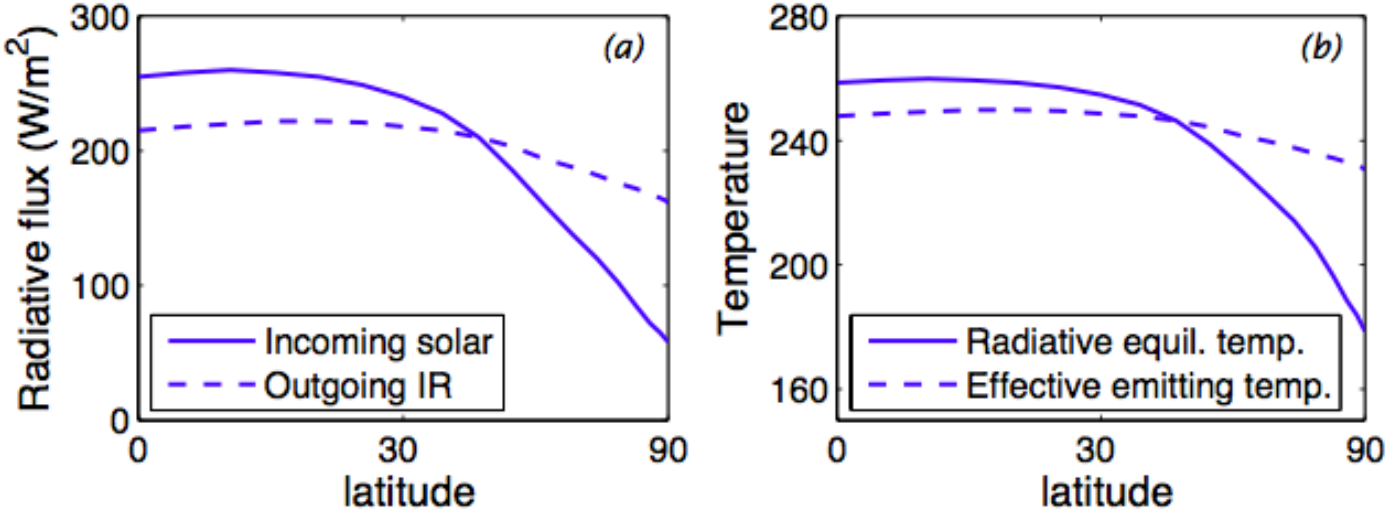
What would the temperature be if there was no atmosphere or ocean?



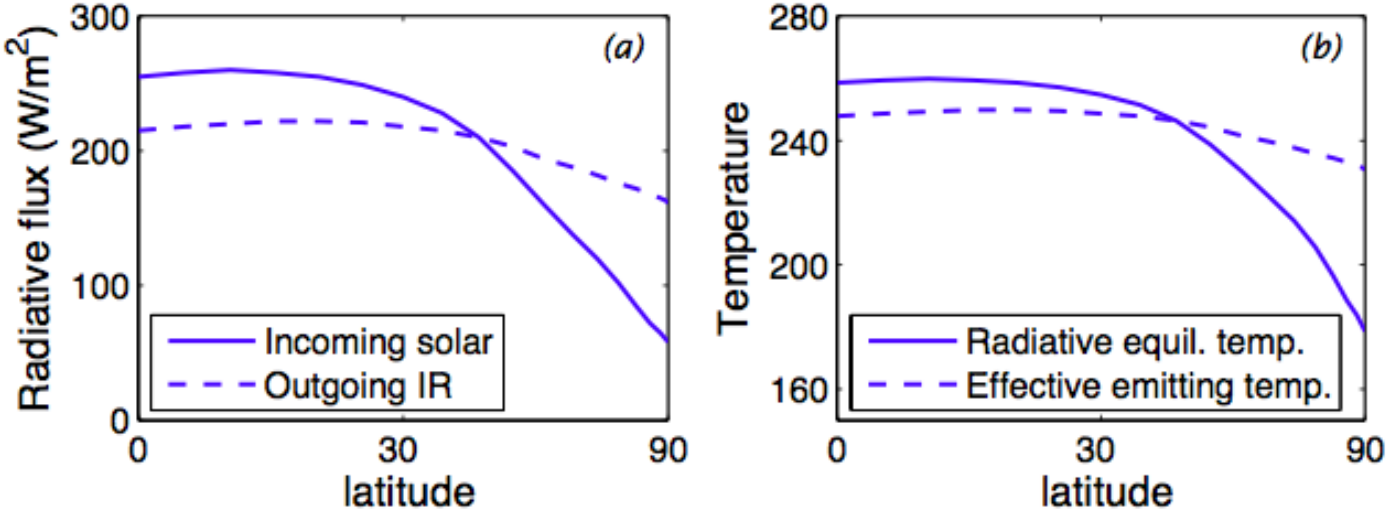
Assume that each point on Earth's surface absorbs incoming solar radiation and radiates as a "black body" with a temperature given by the **Stefan-Boltzmann law**

$$S_{\text{in}}(\theta)\,(1-\alpha) = \sigma\, T_{\text{rad}}^4\,(\theta)\,,$$

where α is the albedo and $\sigma = 5.67 \times 10^{-8}$ W m^{-2}K^{-4}.



(Credit: Vallis 2006)



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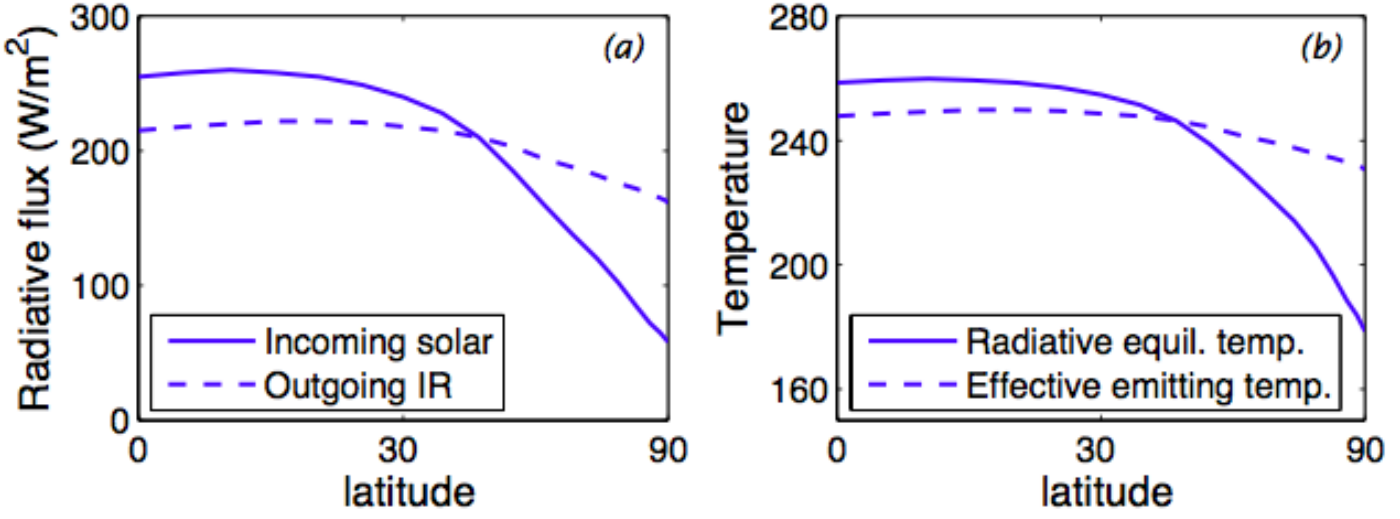
Emitting temperature (outgoing radiation) has weaker pole-to-pole gradients than **radiative equilibrium temperature** (incoming radiation)



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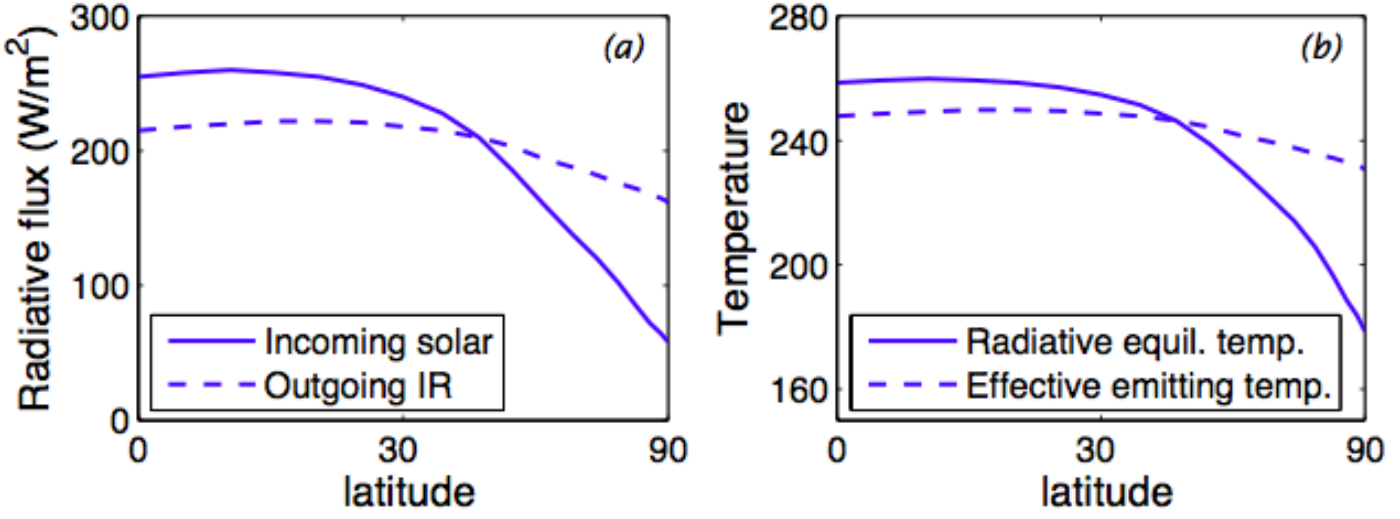
Heat is redistributed away from equator towards poles



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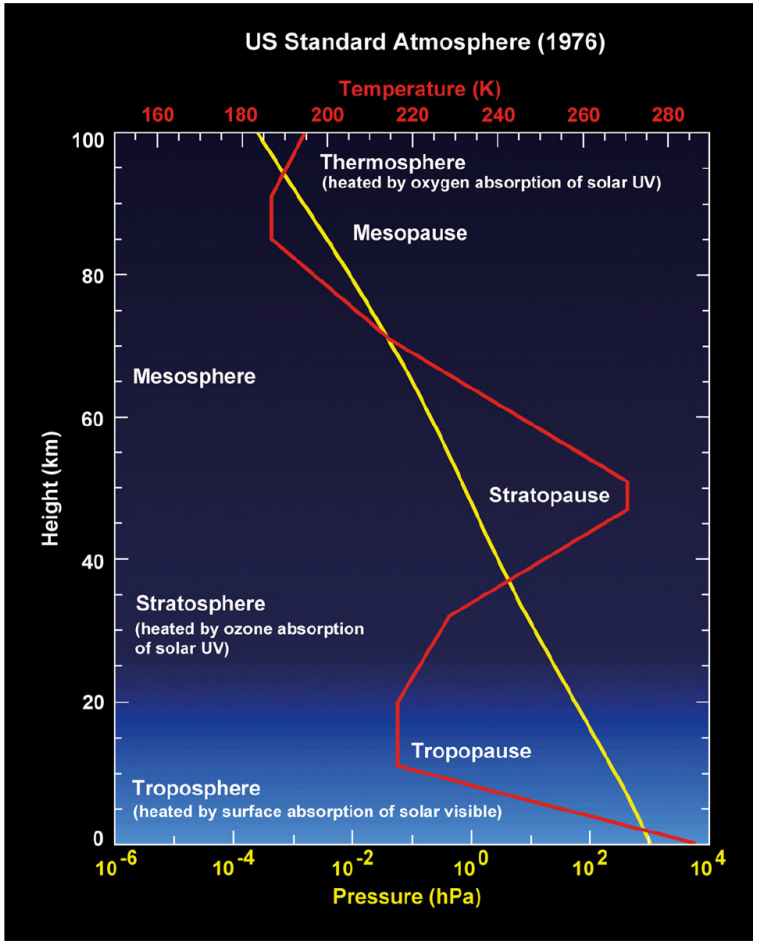
Large-scale circulation in the atmosphere and ocean moves warm air/water towards poles and cool air/water towards equator, eroding gradient imposed by radiative forcing.

Temperature and pressure vs height



(Credit: European Space Agency)

Troposphere (0 km to 8-18 km)

- monotonic *decrease* of temperature with height
- **tropopause** (top of troposphere) changes height with latitude and season
- contains about 80% of the mass of the atmosphere

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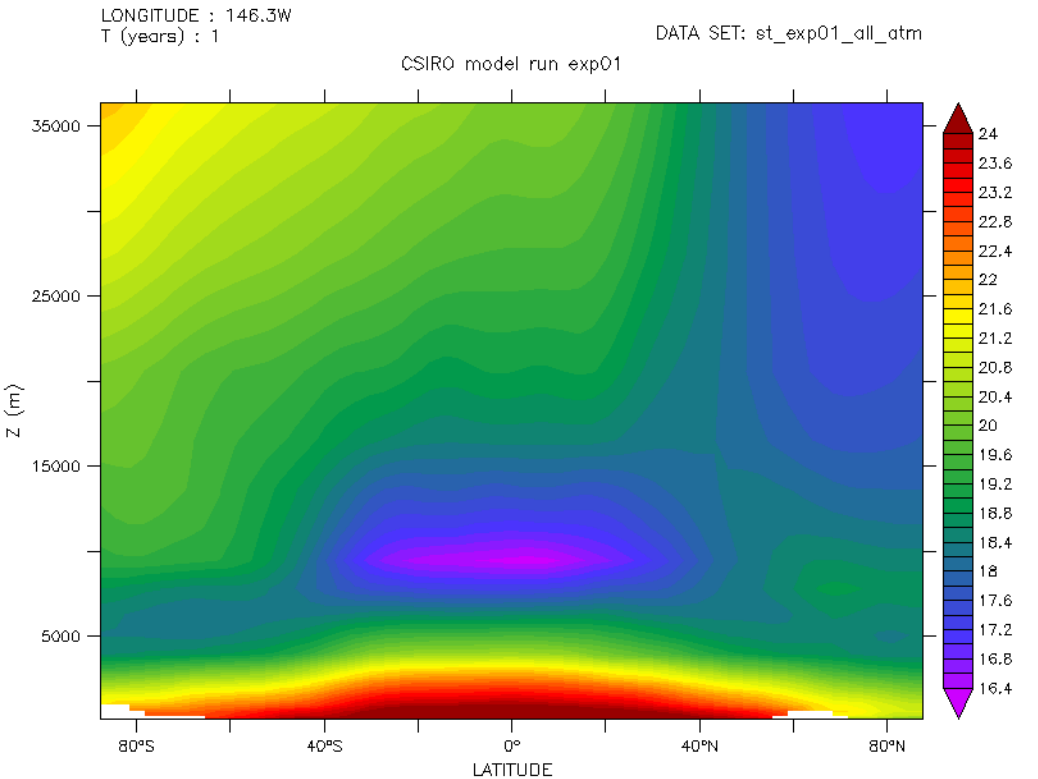
Mesosphere, Thermosphere, and Exosphere (>50 km)

- temperature decreases with height then increases again
- very tenuous / little mass

Temperature and wind fields

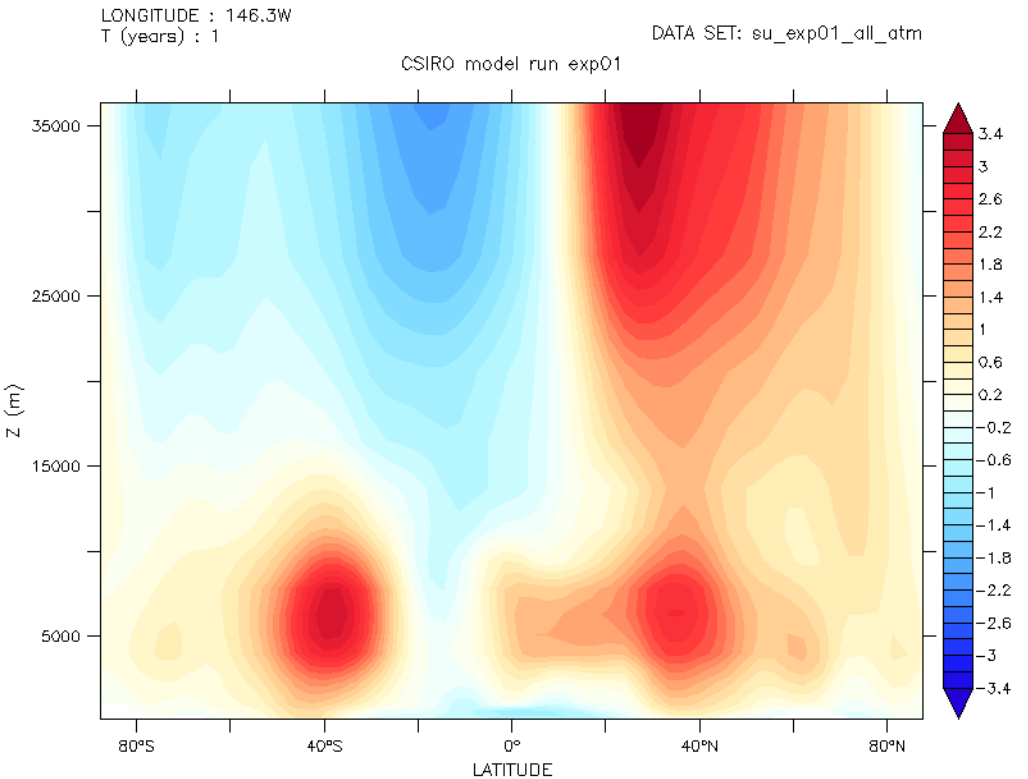
Temperature averaged in the zonal direction (east-west)



Zonally averaged air Temp (oC)

Temperature and wind fields

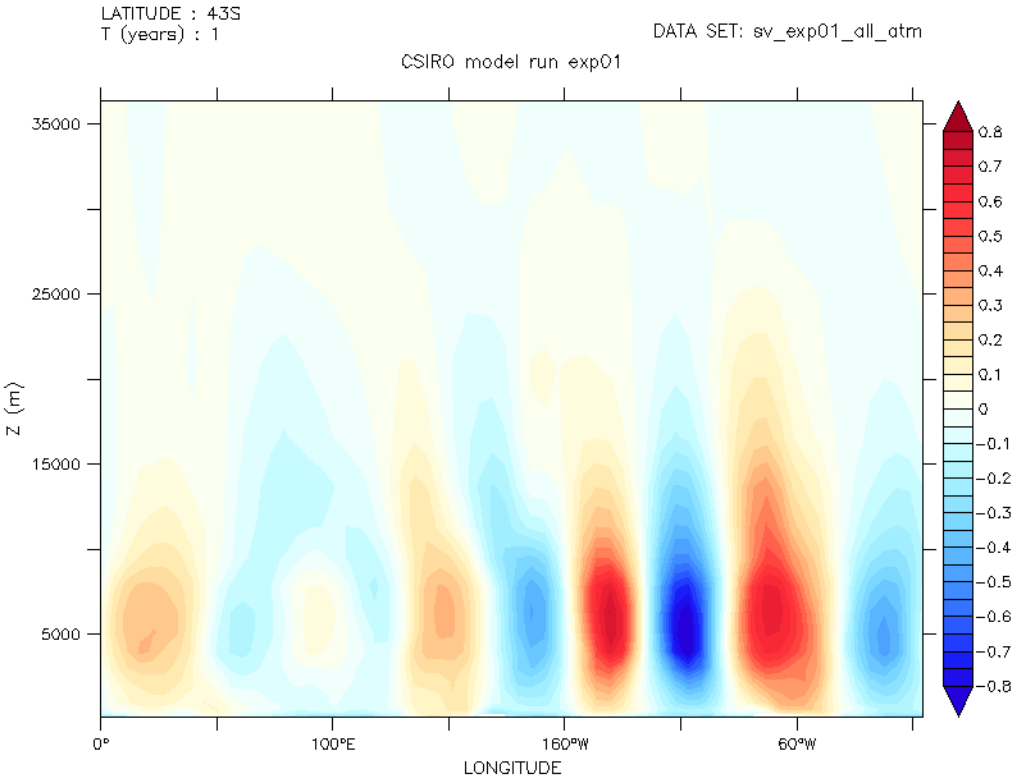
Zonal wind (east-west) averaged in the zonal direction



Zonal wind velocity at 146.3W (m/s)

Temperature and wind fields

Meridional (north-south) wind averaged in the zonal direction



Meridional wind velocity at 43S (m/s)

Tropopause bulges upward at equator

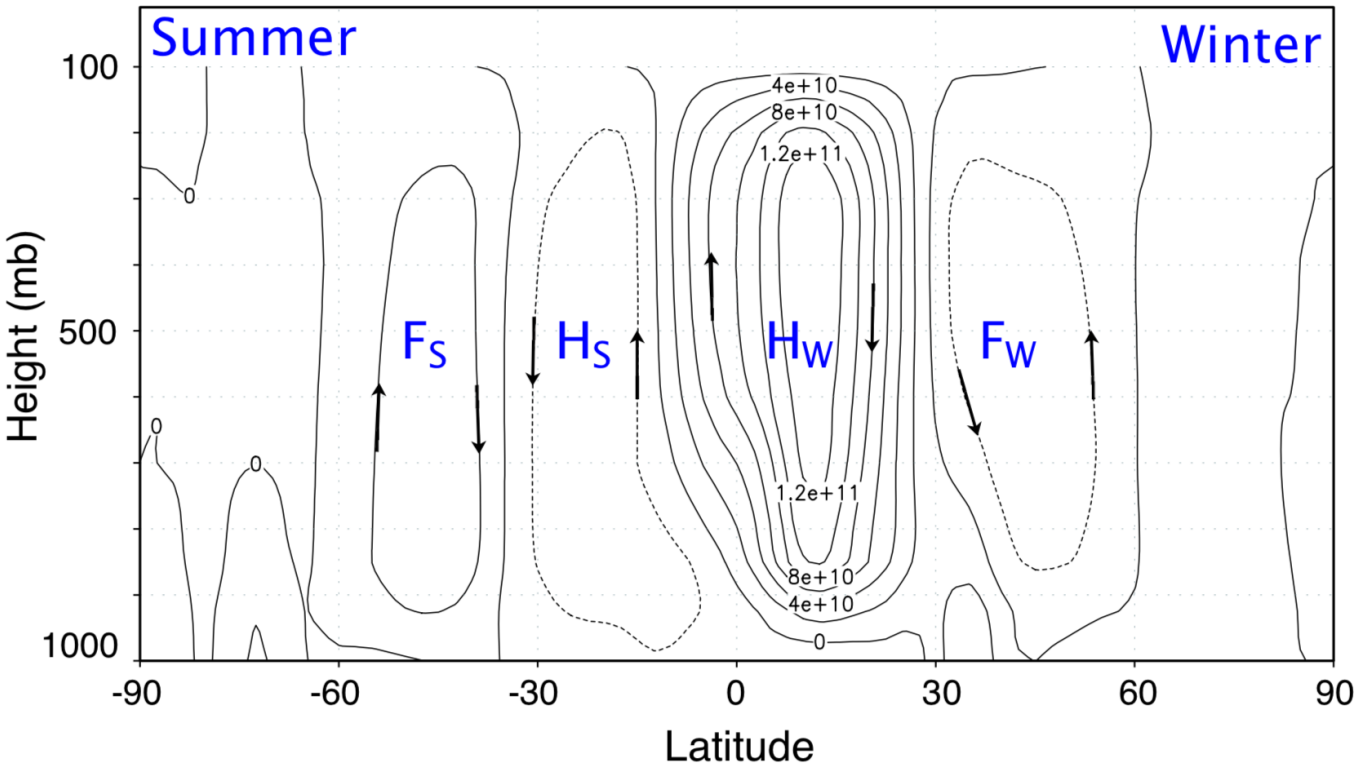
Strong meridional temperature gradients at subtropics

- drives an eastward **zonal jet** because of thermal wind balance

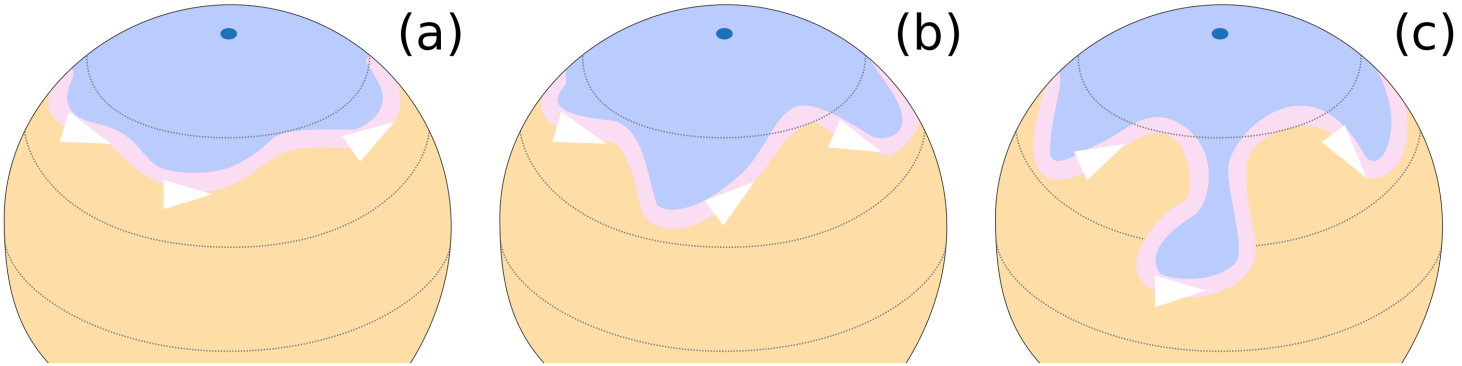
Convergence/divergence of meridional wind leads to upwelling and downwelling of air.

Surface winds are *not* due to thermal wind balance, but caused by alternating overturning cells

Overturning circulation



Zonally asymmetric winds



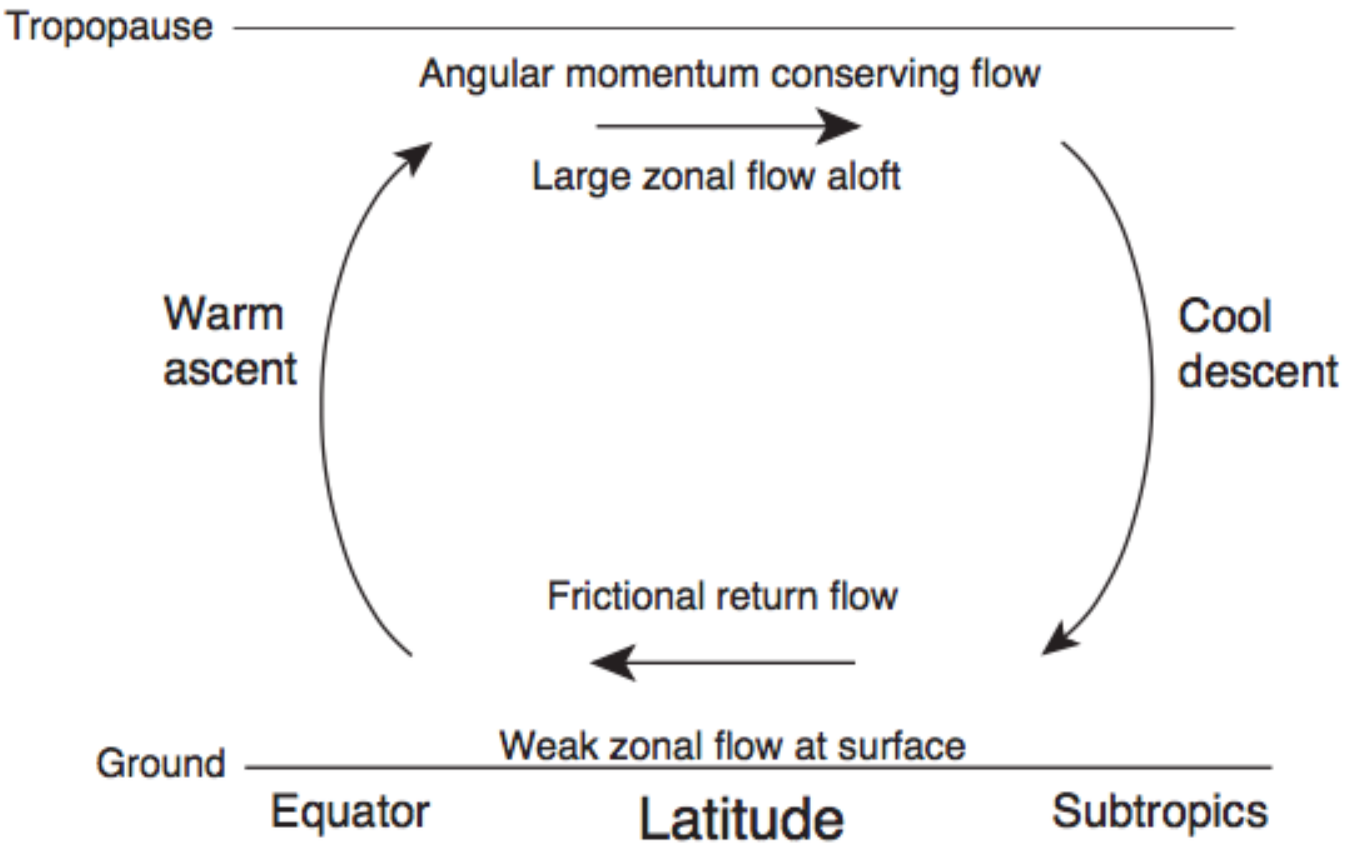
- Zonal average ignores zonal asymmetries (good in tropics, not so good in mid-latitudes)
- Midlatitude (polar) jet stream has strong meanders due to propagating **Rossby waves**
- If these meanders grow and detatch, they produce cyclones and anticyclones, aka **weather**

{Youtube movie of Rossby waves}

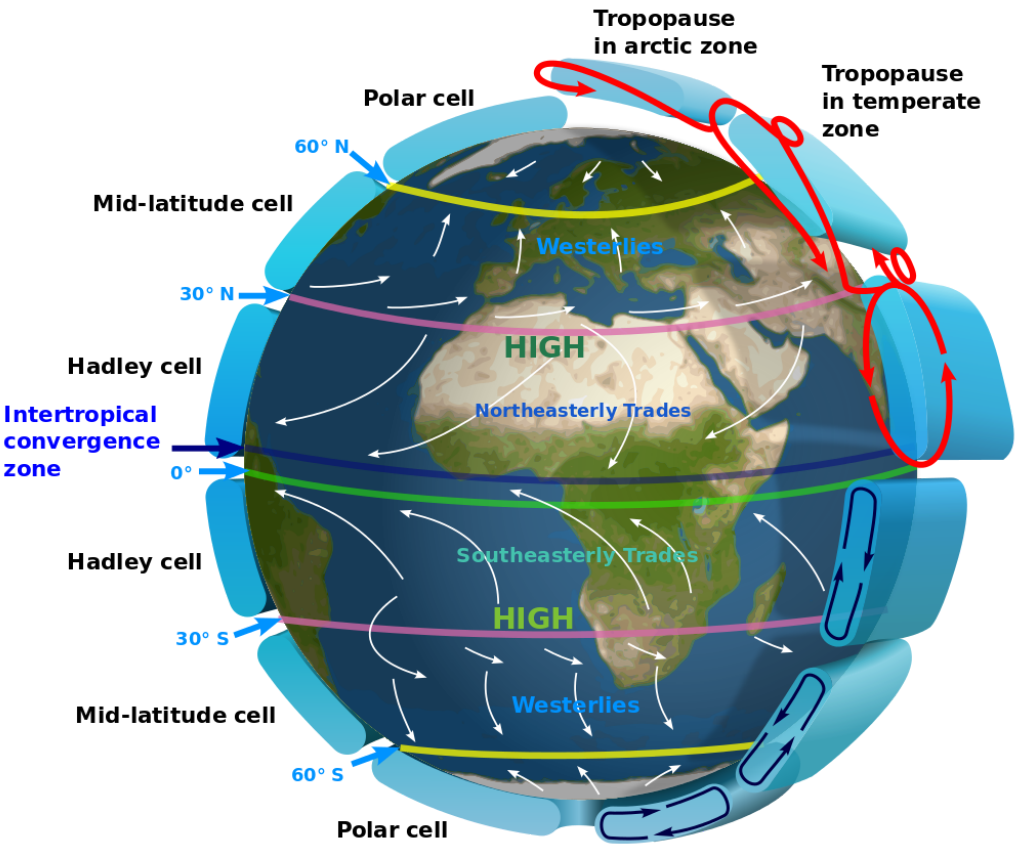
2.2 The Hadley Cell

"The answer, my friend, is blowin' in the wind."

Bob Dylan



(Credit: G. Vallis)

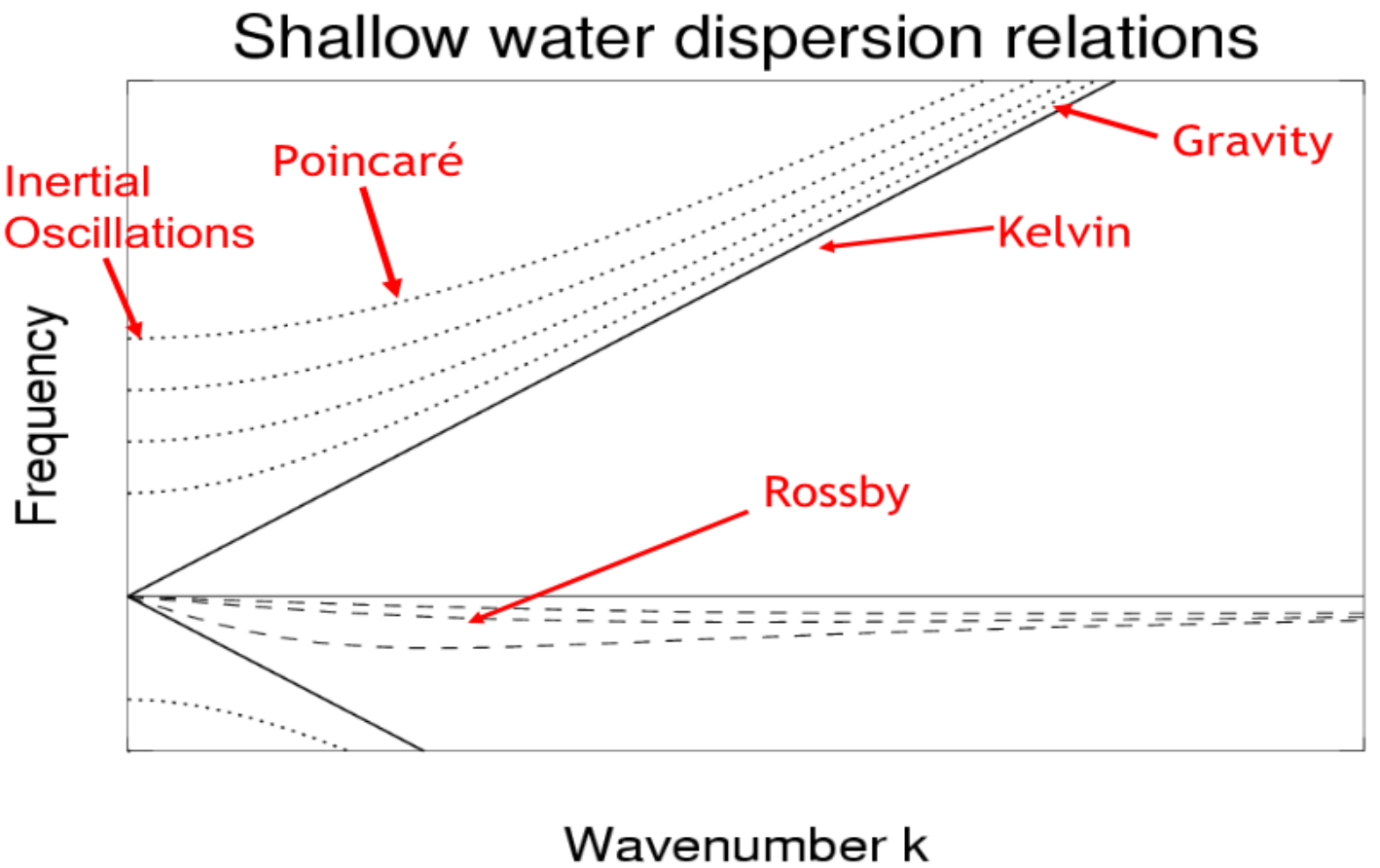

Tropopause
in arctic zone
Tropopause
in temperate
zone
Polar cell
60° N
Mid-latitude cell
Westerlies
30° N
HIGH
Hadley cell
Northeasterly Trades
Intertropical
convergence
zone
0°
Hadley cell
Southeasterly Trades
HIGH
30° S
Mid-latitude cell
Westerlies
60° S
Polar cell

2.3 Shallow water waves

"Is there any peace

In ever climbing up the climbing wave?"

Alfred, Lord Tennyson, *The Lotus-eaters*



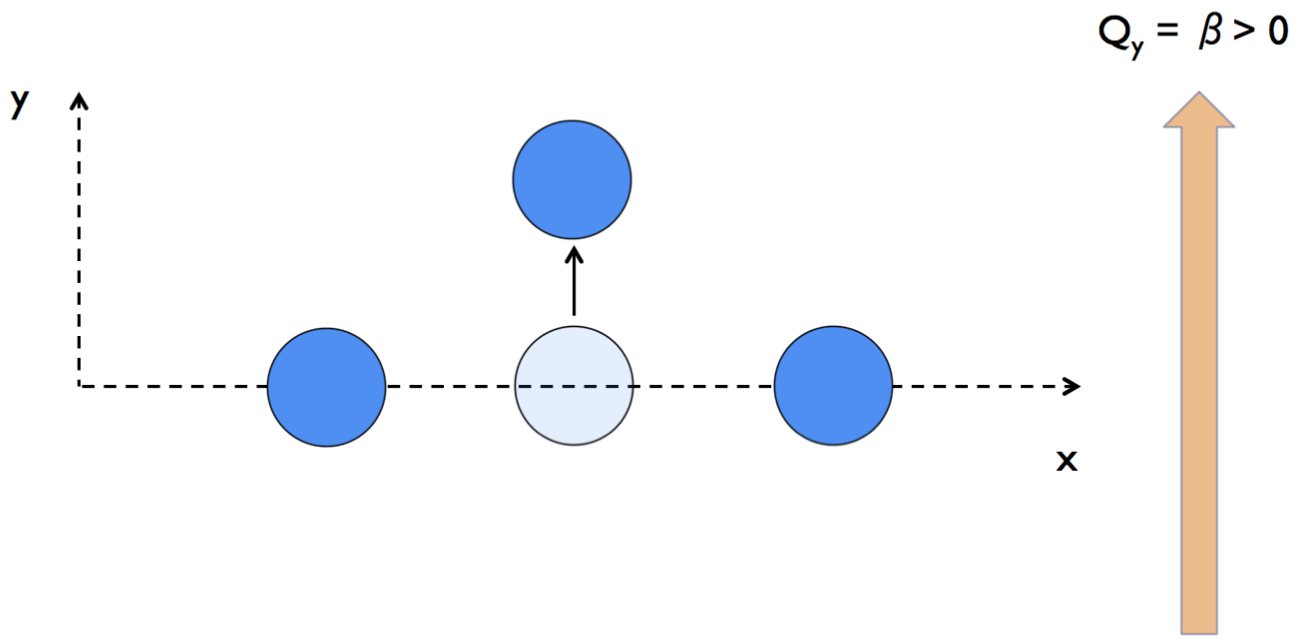
(Credit: I. Simpson)

2.4 Rossby waves

"Perhaps I occasionally sought to give, or inadvertently gave, to the student a sense of battle on the intellectual battlefield. If all you do is to give them a faultless and complete and uninhabited architectural masterpiece, then you do not help them to become builders of their own."

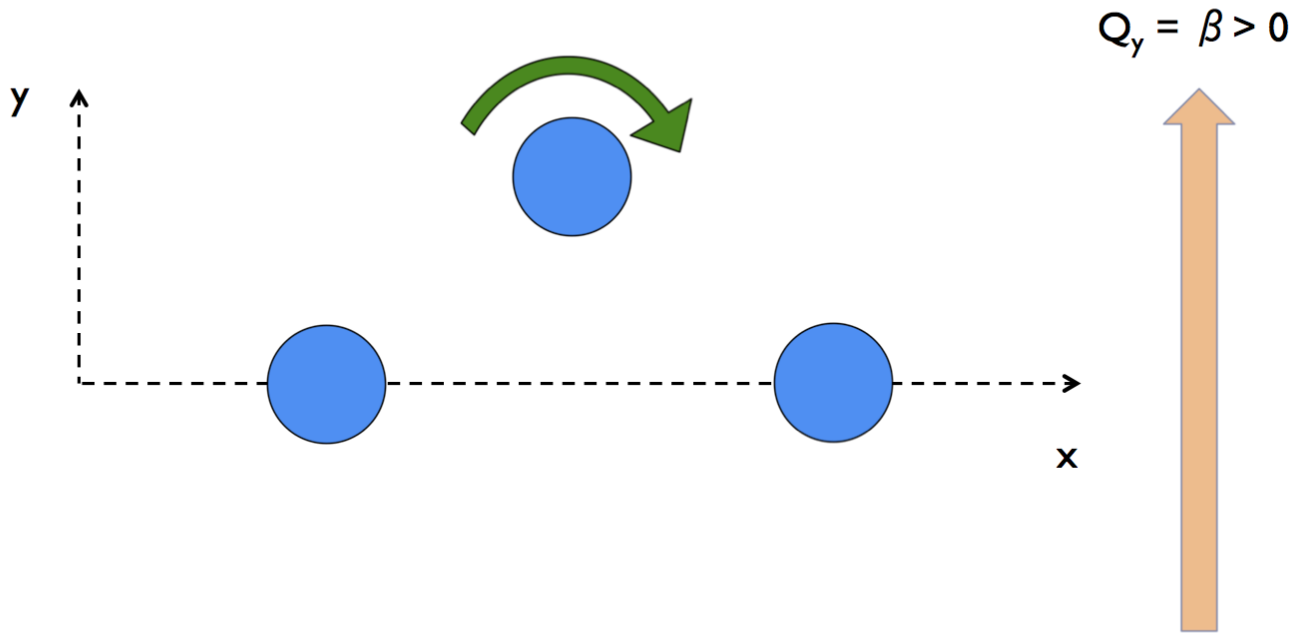
Carl-Gustaf Rossby

Mechanism: Barotropic Rossby wave



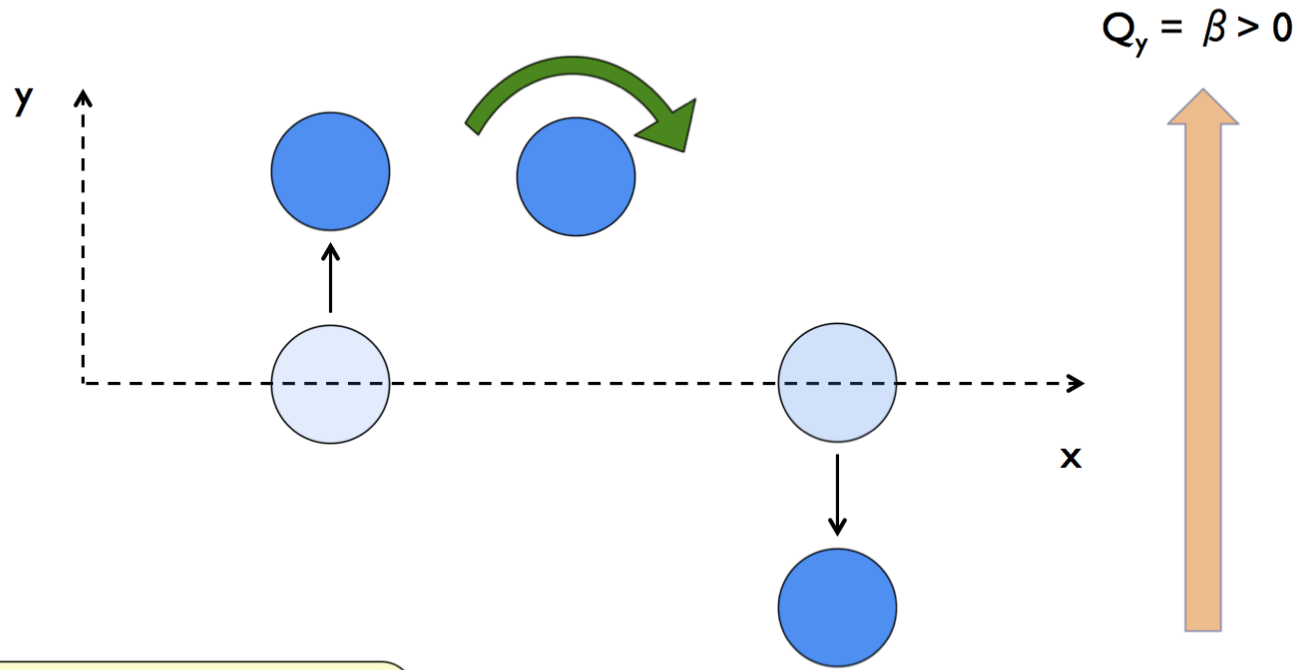
1. Perturb a fluid parcel northward into region of higher planetary vorticity

Mechanism: Barotropic Rossby wave



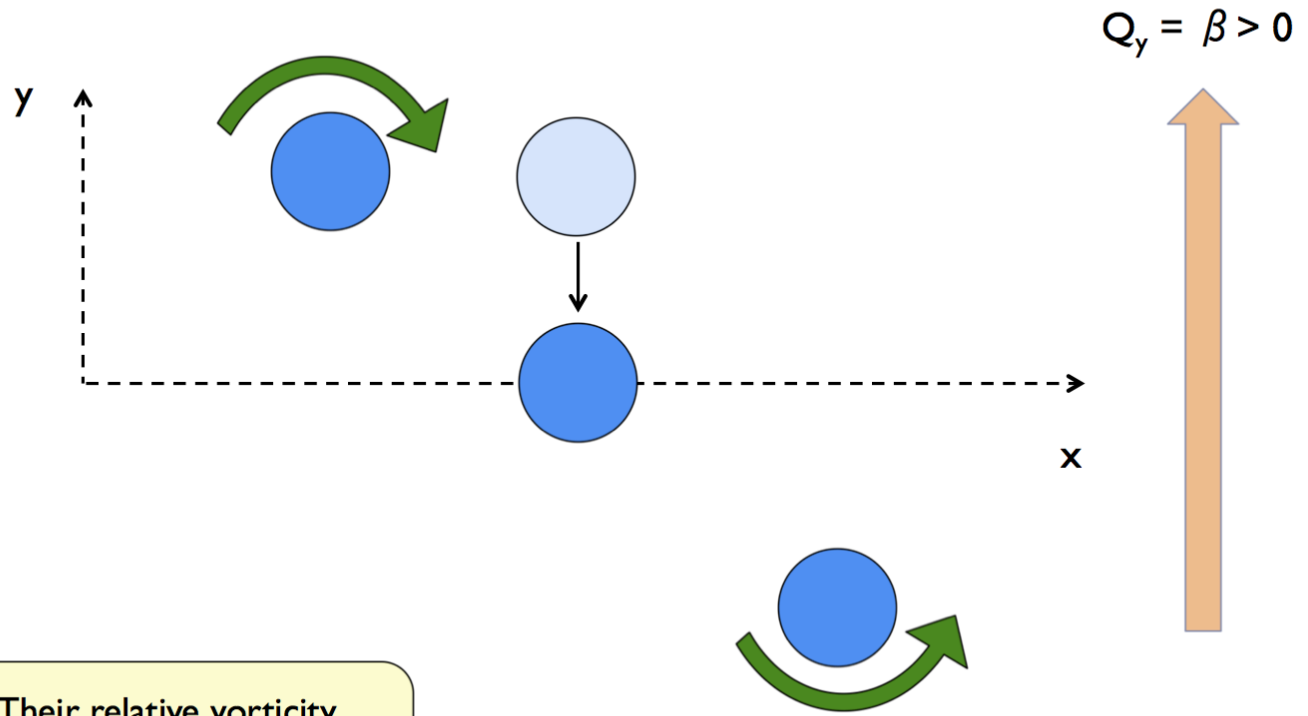
2. To conserve total PV, the parcel develops negative relative vorticity

Mechanism: Barotropic Rossby wave



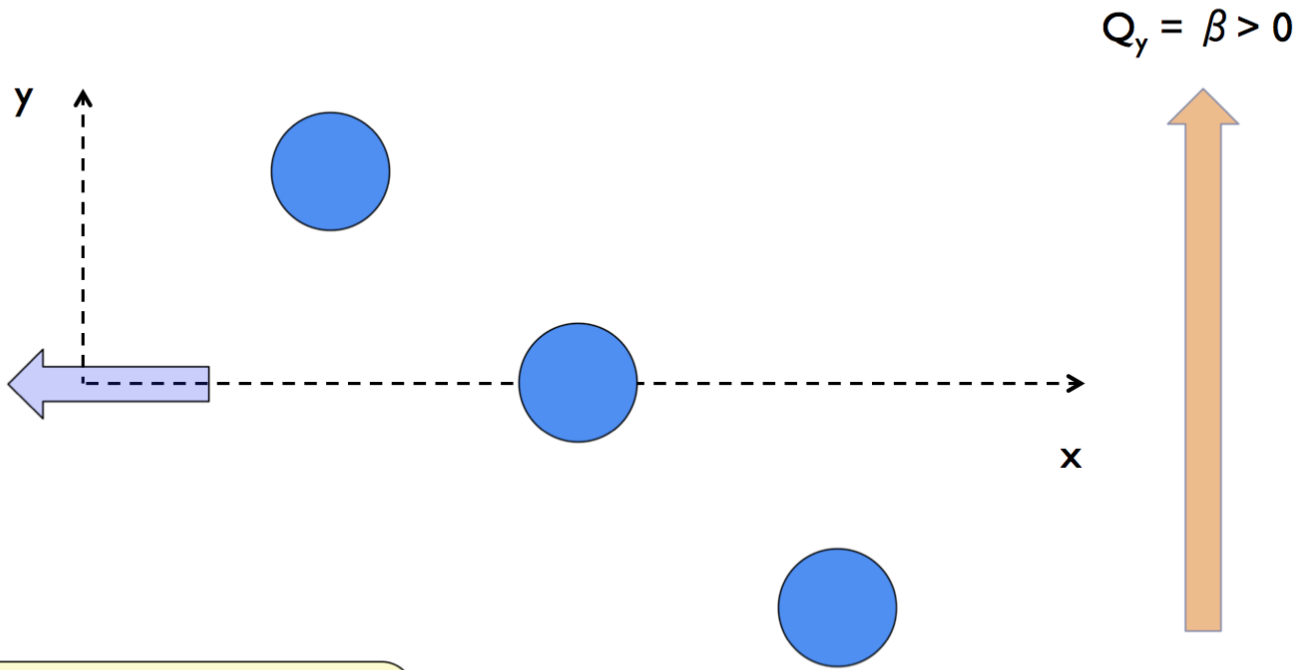
3. This relative vorticity perturbs neighboring fluid parcel north and south

Mechanism: Barotropic Rossby wave



4. Their relative vorticity restores the first parcel to its original position

Mechanism: Barotropic Rossby wave



5. The perturbation propagates westward as a Rossby wave