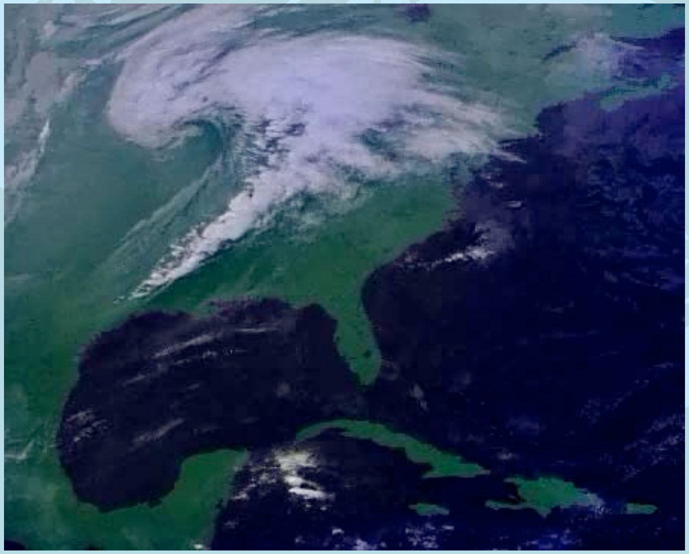
MFE 659 Lecture 1b Global Winds

Radiation Imbalance and Creation of the Jet Stream



Economic Considerations

- The location of jet streams determines seasonal climate variability in track of storms.
- Jet Streams provide energy used in winter storms to produce high impact weather.
- Jet streams provide steering for high impact winter storms tracks.
- Aviation Interests need to predict jet streams to improve fuel efficiency and avoid clear air turbulence.
- The influence of the Rocky Mountains on the location of the jet stream over the Atlantic is a large part of why Europe enjoys warmer air currents than their latitude would warrant.
- Others?

Review of Atmospheric Circulations

Outline

- Radiative Forcing
- Atmosphere and Ocean circulations
- Geostrophic Balance
- Development of the Jet Stream
- Thermal Wind
- Rossby Waves

Radiation Imbalance

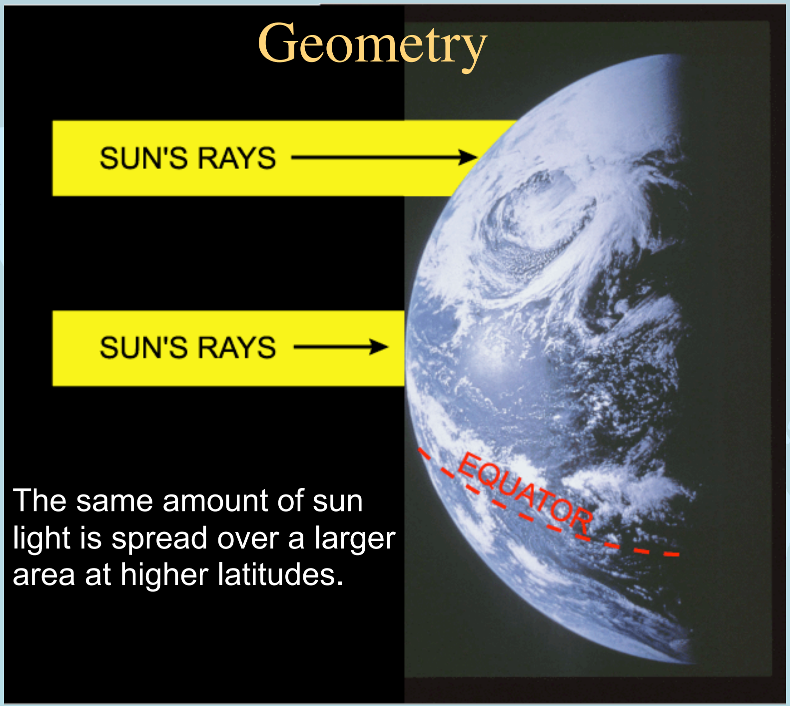
1. Geometry
2. Reflection/Albedo
3. Differing atmospheric path lengths

The factors that cause the seasons also lead to a local radiation imbalance whereby

- Incoming > outgoing at low latitudes
- Incoming < outgoing at high latitudes

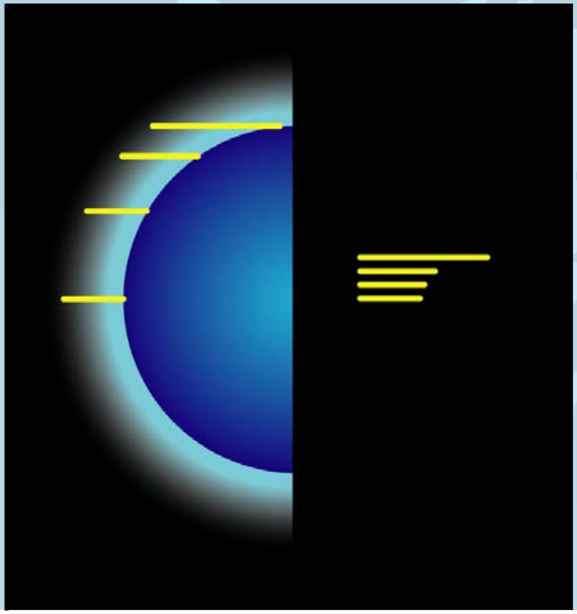
In turn the net radiation distribution drives the atmospheric circulation.

Geometry



The same amount of sun light is spread over a larger area at higher latitudes.

Path Length through Atmosphere



Path lengths for sun light through the atmosphere are longer at higher latitudes than at lower latitudes.

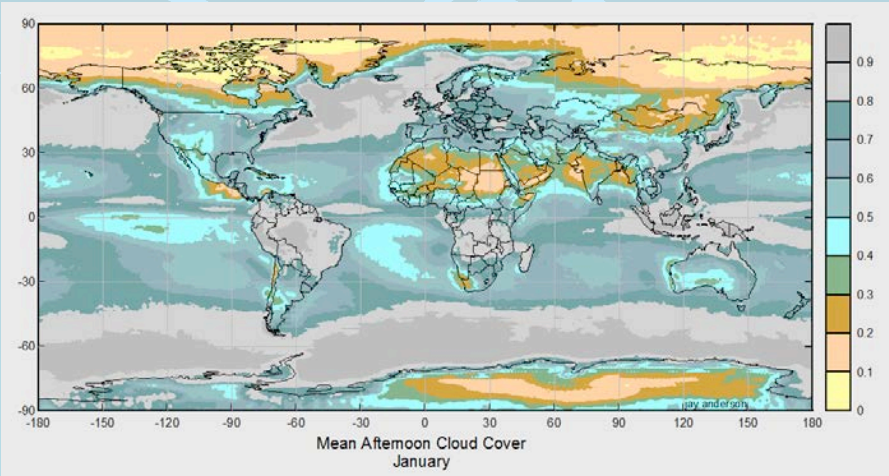
Therefore, more sunlight is absorbed and scattered away at higher latitudes.

Impact of Reflection (Albedo)

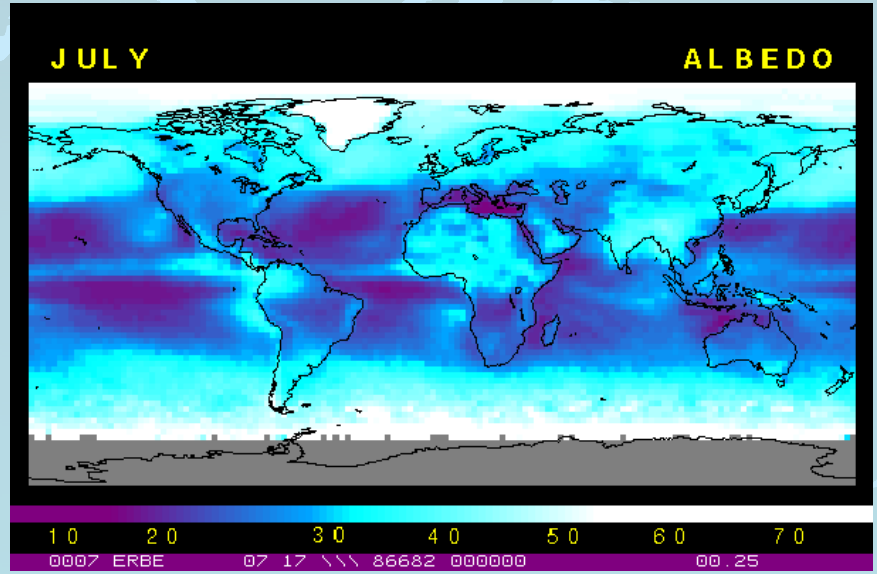
There are more clouds and ice at higher latitudes to reflect more sunlight (i.e., higher albedo).

Reflected sunlight is not available to heat the earth.

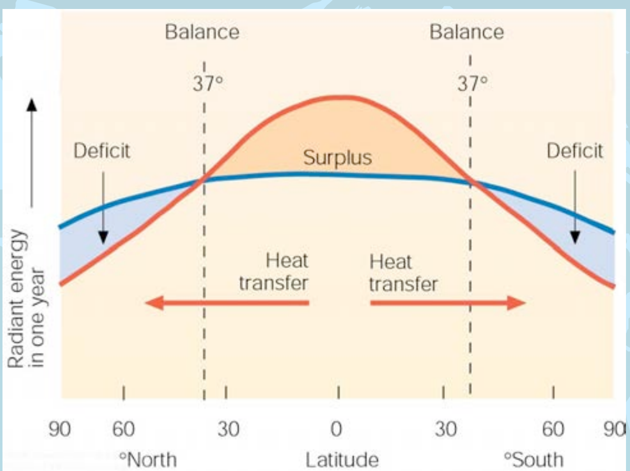
Global Cloud Cover



Impact of Reflection (Albedo)

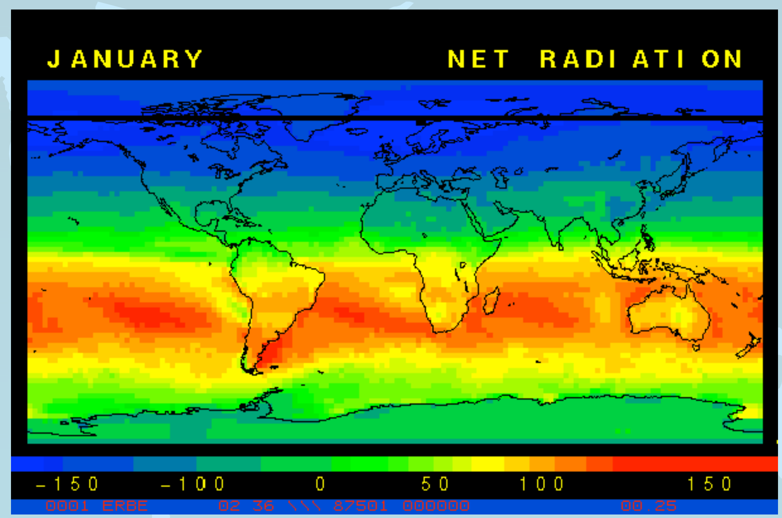


A Balancing Act



Global-scale circulations in the atmosphere and currents in the oceans redistribute the excess energy, moving the energy from the lower latitudes to the poles to compensate for the radiation imbalance.

Radiation Imbalance



The difference between the absorbed sun light and the emitted outgoing long wave radiation of the Earth is referred to as the net radiation budget.

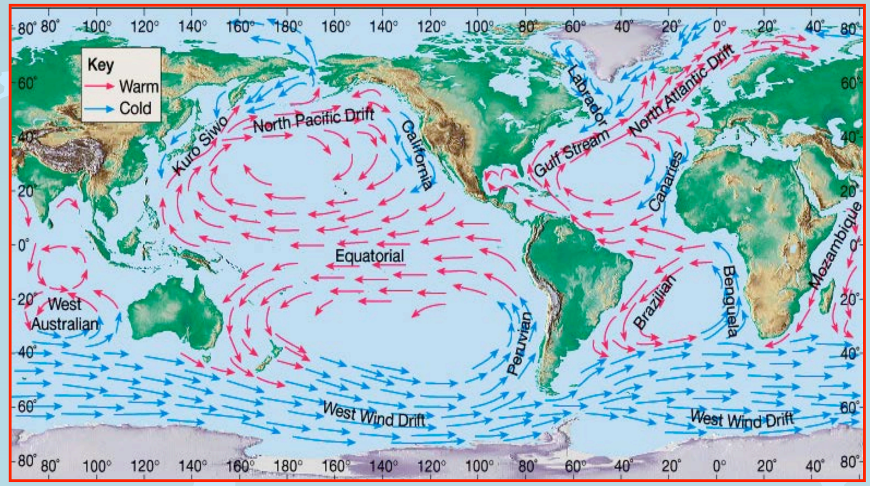
Global/Hemispheric Scale

The net radiation distribution drives the global atmospheric circulation. The hemispheric or global scale spans a distance of ~ 10,000 km or more.

Global Circulations

- Westerlies
  - Jet Stream
  - Planetary Waves or Rossby Waves
- Hadley Cell
  - ITCZ
  - Northeast Trade Winds
- Monsoon Circulation
- El Niño-Southern Oscillation (ENSO) and Ocean Circulations

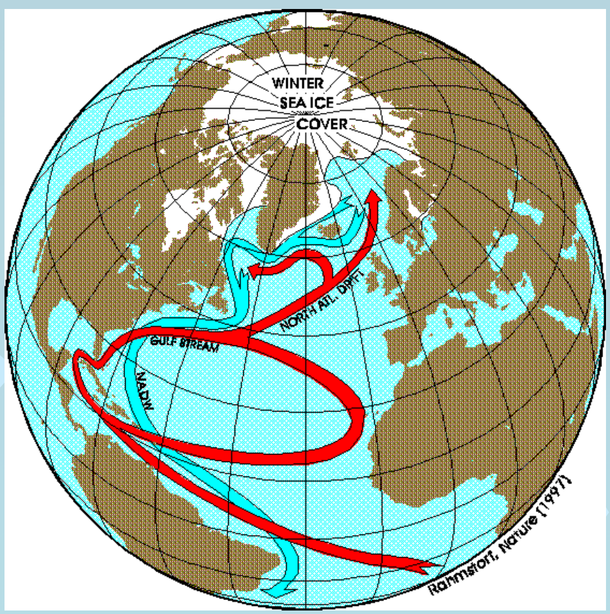
Ocean Currents



Ocean currents account for roughly 20% of the thermal advection needed to balance the radiation forcing.

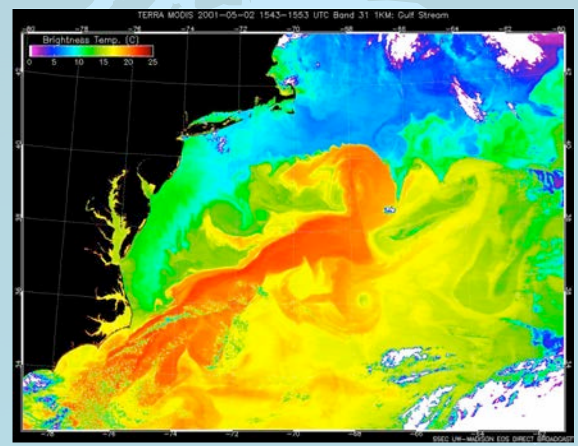
A Balancing Act

Europe's heating system. This highly simplified cartoon of Atlantic currents shows warmer surface currents (red) and cold north Atlantic Deep Water (blue).



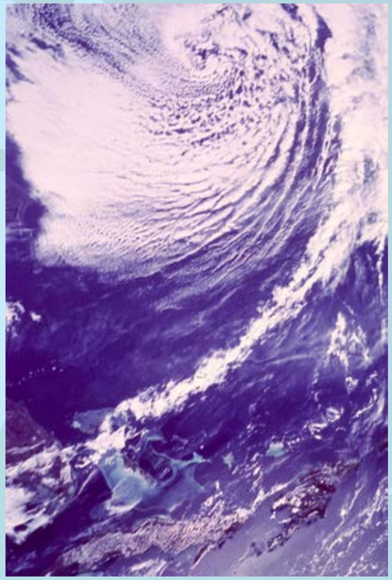
A Balancing Act

Gulf stream made visible just of the East Coast in this satellite image of sea surface temperature.



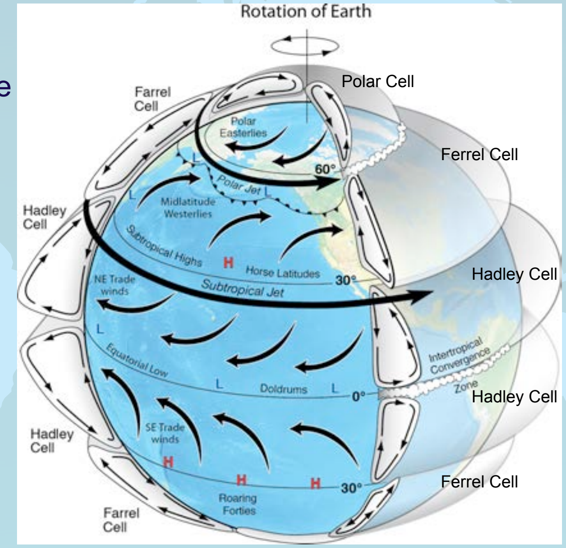
Atmospheric Circulation

The general circulation of the atmosphere accounts for the rest of the heat transport needed to balance the radiational forcing.

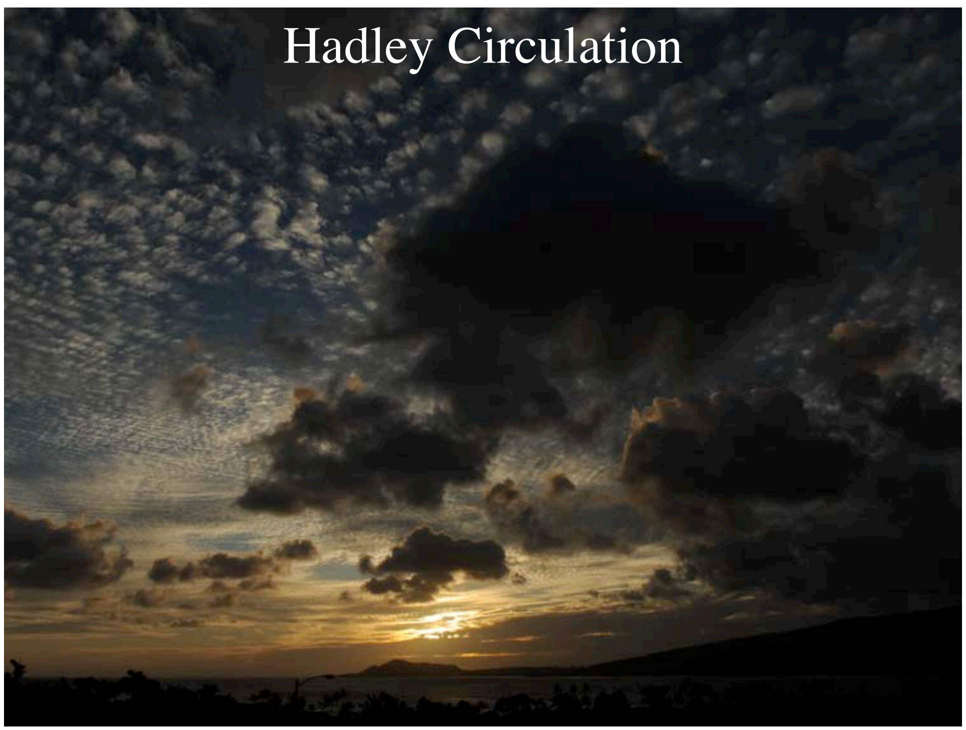


Idealized 3-Cell Model of Wind Patterns on a Rotating Earth

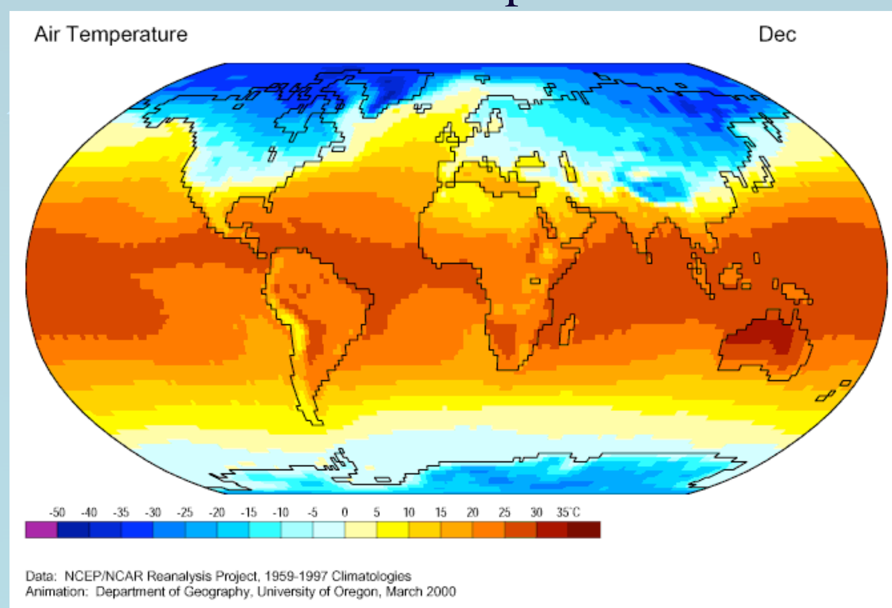
A schematic of the Earth's weather machine bringing warm moist air northward and cold dry air southward (latent and sensible heat).



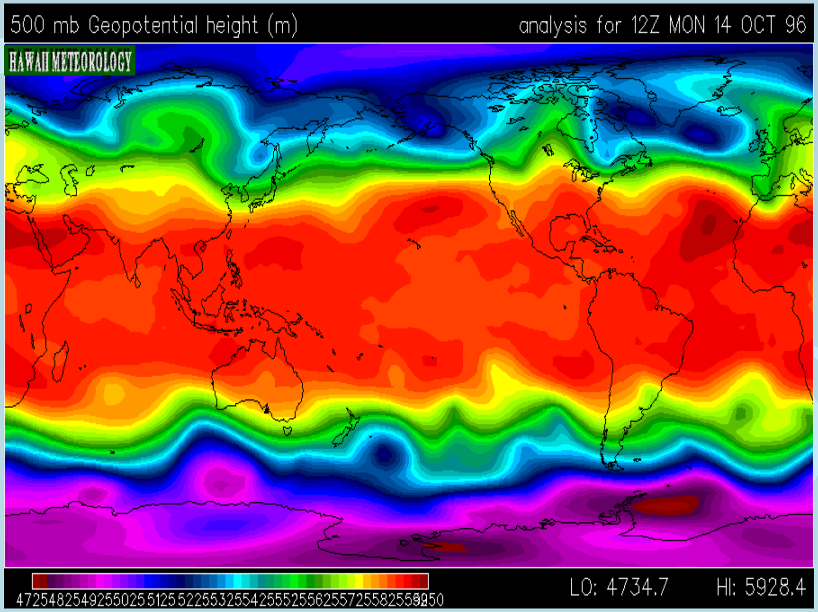
Hadley Circulation



Seasonal Surface Temperature Variation



500-mb Geopotential Height Analysis



Jet Streams

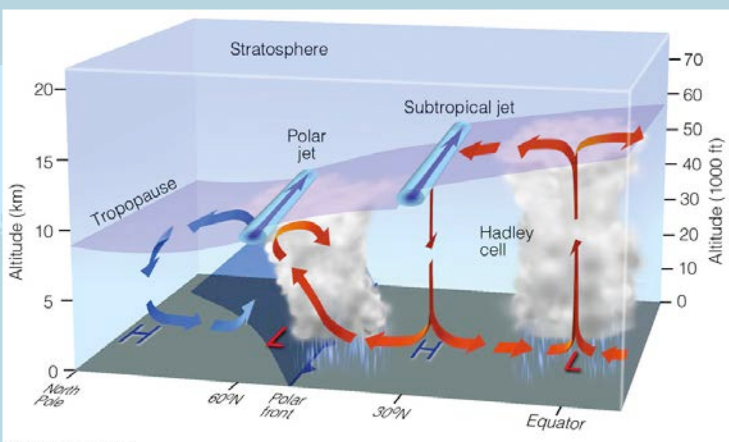
Definition of Jet stream: An “intense”, “narrow”, quasi-horizontal current of wind that is associated with “strong” vertical wind shear; found at or near the tropopause.

intense: at least 30 m/s for upper troposphere, at least 15 m/s for lower troposphere.

narrow: current whose width is ~ 1/2 to 1 order of magnitude less than its length.

strong vertical wind shear: at least 5-10 m/s per km; at least 1/2 to 1 order of magnitude greater than synoptic scale shear.

Jet Streams

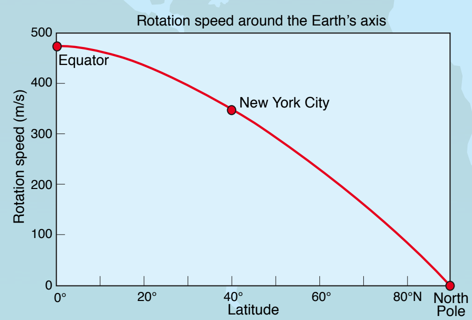


Fast air currents, 1000’s of km’s long, a few hundred km wide, a few km thick

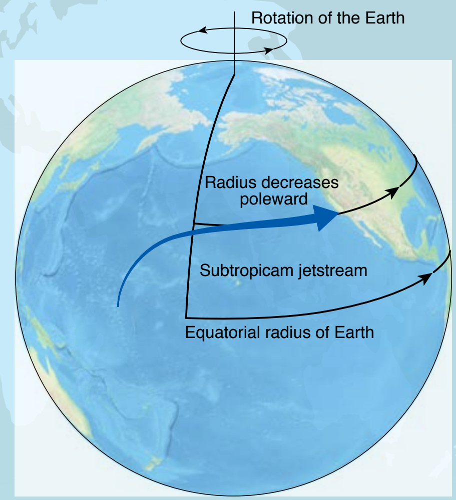
Typically find two jet streams (subtropical and polar front) at tropopause in NH

Subtropical Jet Stream

The subtropical jet stream results from the Coriolis acceleration of the poleward branch of the convection (Hadley) cell.



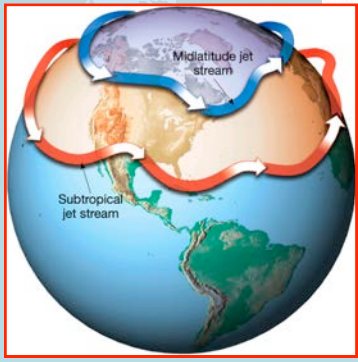
Rotation speed due to rotation of the earth

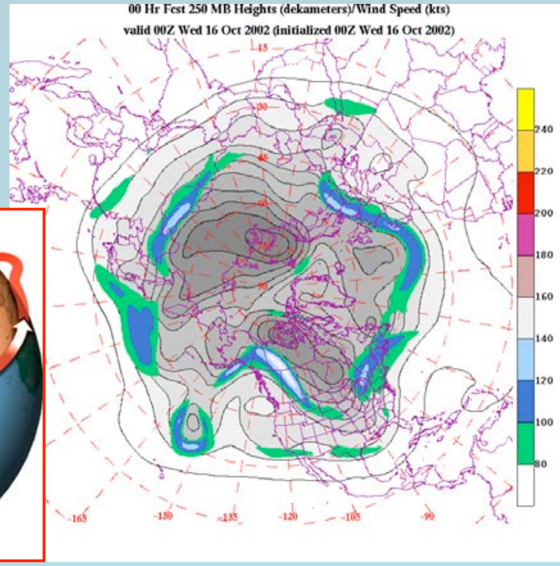


Jet Stream Visible in 250 mb Isotachs

Find the subtropical jet stream.

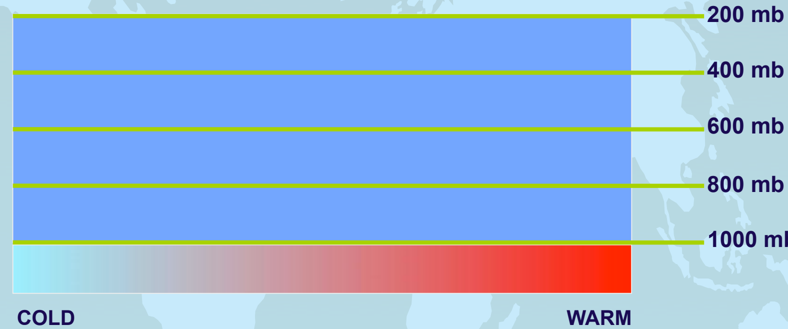
What is the origin of the polar jet stream?





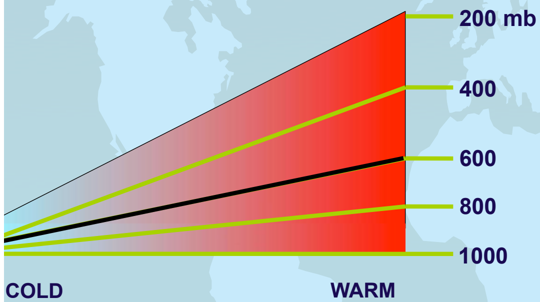
http://www.atmos.washington.edu/~ovens/loops/

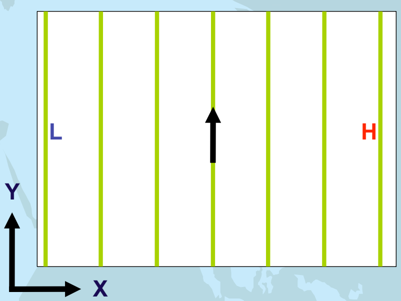
Origin of the Polar Jet Stream



- **Imagine the atmosphere is a ‘block’ of fluid that pushes down with 1000 mb of pressure at the bottom.**
- **The block starts out at a uniform temperature – the thickness of the atmosphere is the same everywhere.**
- **Now we make the block cold on the west side and warm on the east side.**

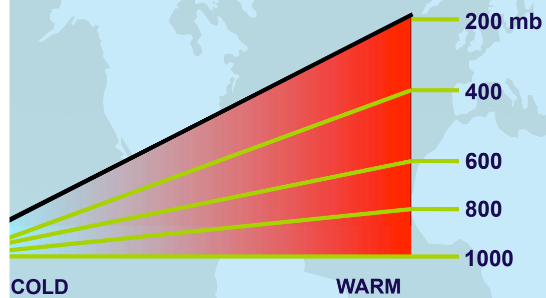
Origin of the Polar Jet Stream

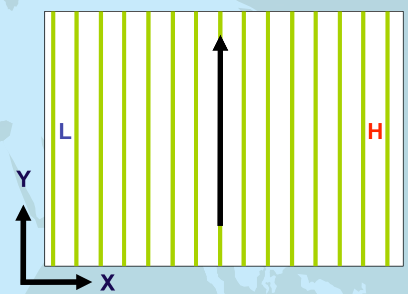




- **The 1000 mb pressure surface is still flat – there is the same amount of fluid above the surface whether you are on the cold side or the warm side.**
- **But above the surface, a pressure gradient appears that gets stronger as you go up.**

Origin of the Polar Jet Stream





- **The 1000 mb pressure surface is still flat – there is the same amount of fluid above the surface whether you are on the cold side or the warm side**
- **The pressure gradient is strongest at the top of the troposphere, ~200 mb in the tropics.**

Momentum Equation

$$\frac{D\mathbf{V}}{Dt} = -2\Omega \times \mathbf{V} - \frac{1}{\rho}\nabla p + g + F_r$$

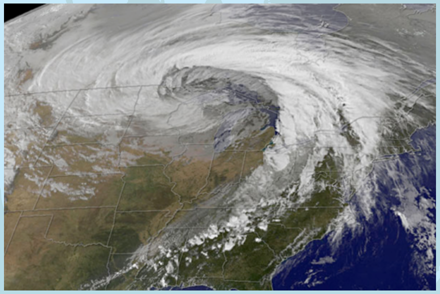
1   2   3   4

1. Coriolis — C_o
2. Pressure Gradient — PG
3. Gravity — g
4. Friction — F_r

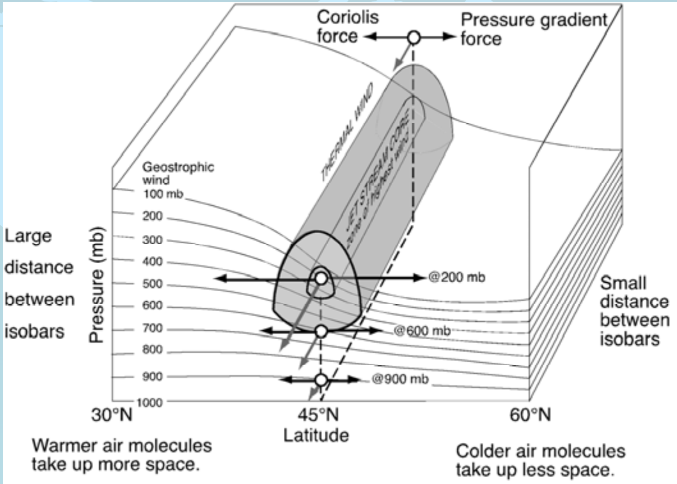
*Where is Centrifugal force?

Geostrophic Wind

- Geostrophic motion occurs when there is an exact balance between the PGF and the C_o, and the air is moving under the the action of these two forces only.
- It implies
  - No acceleration
    - e.g., Straight, parallel isobars
  - No other forces
    - e.g., no friction
  - No vertical motion
    - e.g., no pressure changes



Polar Jet Stream and the Thermal Wind



The jet stream associated with the polar front owes it existence to the differential solar heating from equator to pole. Thus, the jet is stronger in winter than in summer and moves north and south with the sun.

Thermal Wind

The geostrophic wind is proportional to the slope of a surface of constant pressure (aka height gradient).

Horizontal temperature gradients cause the thickness of gas layers between isobaric surfaces to increase towards higher temperatures. When multiple atmospheric layers are stacked upon each other, the slope of isobaric surfaces increases with height. This also causes the magnitude of the geostrophic wind to increase with height, e.g., wind shear.

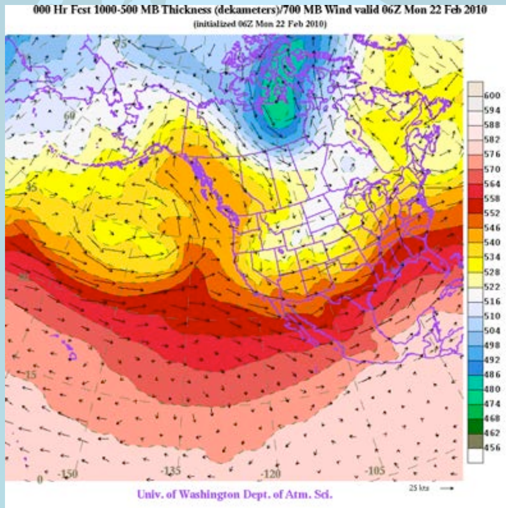
This shear of the geostrophic wind with height is called the thermal wind.

1000-500 mb Thickness with 700 mb Winds

Most of the gradient in thickness is concentrated in a narrow band in the middle latitudes in winter.

$$V_T = \frac{1}{f} k \times \nabla_p \left(\Phi_{500} - \Phi_{1000} \right)$$

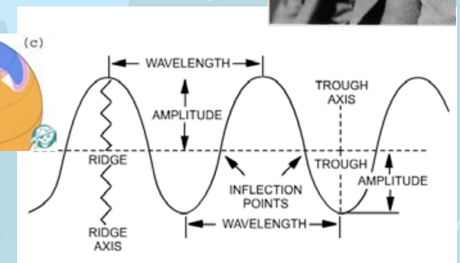
$\Phi_{500} - \Phi_{1000}$ = Thickness in meters between the heights of the 1000 and 500 mb levels.



Rossby Wave Definition

Rossby (or Planetary) waves are giant meanders in high-altitude winds that are a major influence on weather. Their emergence is due to shear in rotating fluids, so that the Coriolis force changes along the sheared coordinate. In planetary atmospheres, they are due to the variation in the Coriolis effect with latitude. The waves were first identified in the Earth's atmosphere in 1939 by Carl-Gustaf Rossby who went on to explain their motion. Rossby waves are a subset of inertial waves.

Meanders of the northern hemisphere's jet stream developing (a, b) and finally detaching a "drop" of cold air (c). Orange: warmer masses of air; pink: jet stream.

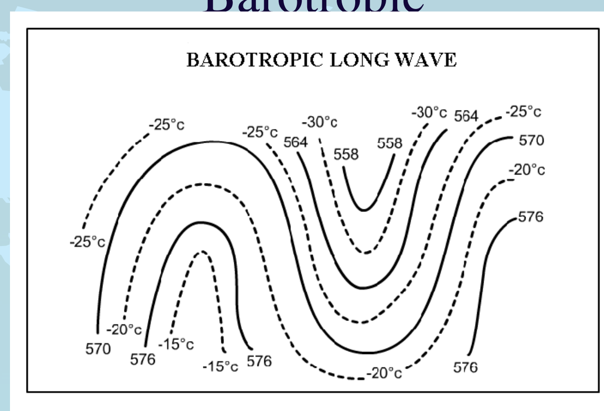


Significance of Planetary Waves

Planetary Waves

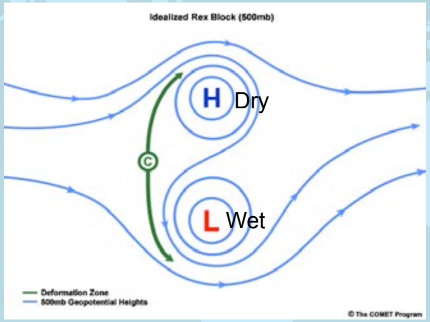
- They define the average jet stream location and storm track along the polar front
- They determine the weather regime a location will experience over several days or possibly weeks.
- They help move cold air equatorward and warm air poleward helping to offset the Earth's radiation imbalance.

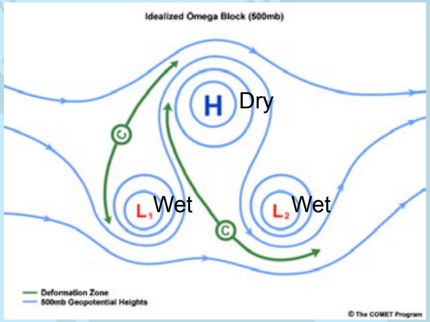
Rossby Waves are Equivalent Barotropic



- Thermal/contour trough axes in phase.
- Thermal/contour ridge axes in phase.

Blocking Patterns





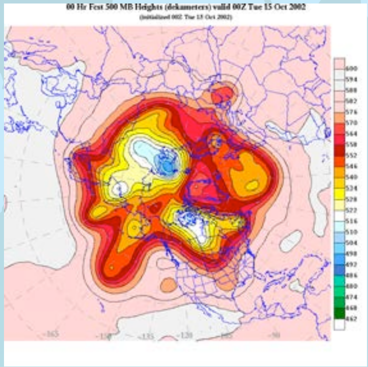
Rex block - high over low pattern - blocking generally lasts ~one week.

Omega block - blocking ridge with a characteristic "Ω" signature - blocking generally lasts ~ten days.

Diagnosing Rossby Waves

Blocking Patterns

- Rex block - high over low pattern - blocking generally lasts ~one week.
- Omega block - blocking ridge with a characteristic "Ω" signature - blocking generally lasts ~ten days.

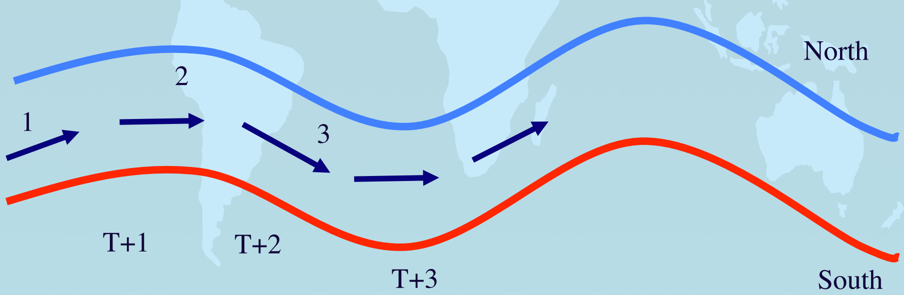


Absolute Vorticity is Conserved

at the level of non-divergence

$$\frac{d}{dt}(\zeta + f) \cong 0 \Rightarrow \zeta + f \cong \textit{Constant}$$

Point 2 to 3, f decreases so so ζ increases, curvature becomes cyclonic and the flow is forced northward.



Earth's Vorticity

Spin is maximum at poles

Spin is zero at equator

Vorticity is twice spin

The contribution of the Earth's vorticity locally in the atmosphere, depends on the component of the Earth's vorticity that maps onto the local vertical.

Vorticity = 2Ω at poles and 0 at the equator

Vorticity = 2Ωsinθ at latitude θ

Earth's vorticity = Coriolis parameter

$f = 2\Omega\sin\theta$

What Influences Rossby Wave Patterns?

Climatological positions and amplitudes are influenced by:

- Oceans
- Land masses
- Terrain features (such as mountain ranges)

Potential Vorticity is conserved.

$$P \equiv (\zeta + f)\left(-g\frac{\partial\theta}{\partial p}\right)$$

Accordingly, a decrease in the stability will result in an increase in the relative vorticity.

Rossby Waves Summary

- Jet-stream dynamics are governed by Rossby Waves.
- Rossby waves are the result of instability of the jet stream flow with waves forming as a result of the variation of the Coriolis force with latitude.
- Rossby waves are a subset of inertial waves. In an equivalent barotropic atmosphere Rossby waves are a vorticity conserving motion.
- Their thermal structure is characterized by warm ridges and cold troughs.
- The lengths of individual long waves vary from about 50˚ to 180˚ longitude; their wave numbers correspondingly vary from 6 to 2, with strong preference for wave numbers 4 or 5.
- Effective forecast period associated with Rossby waves is a week to 10 days.