Fundamentals of synoptic meteorology

Lecture 18

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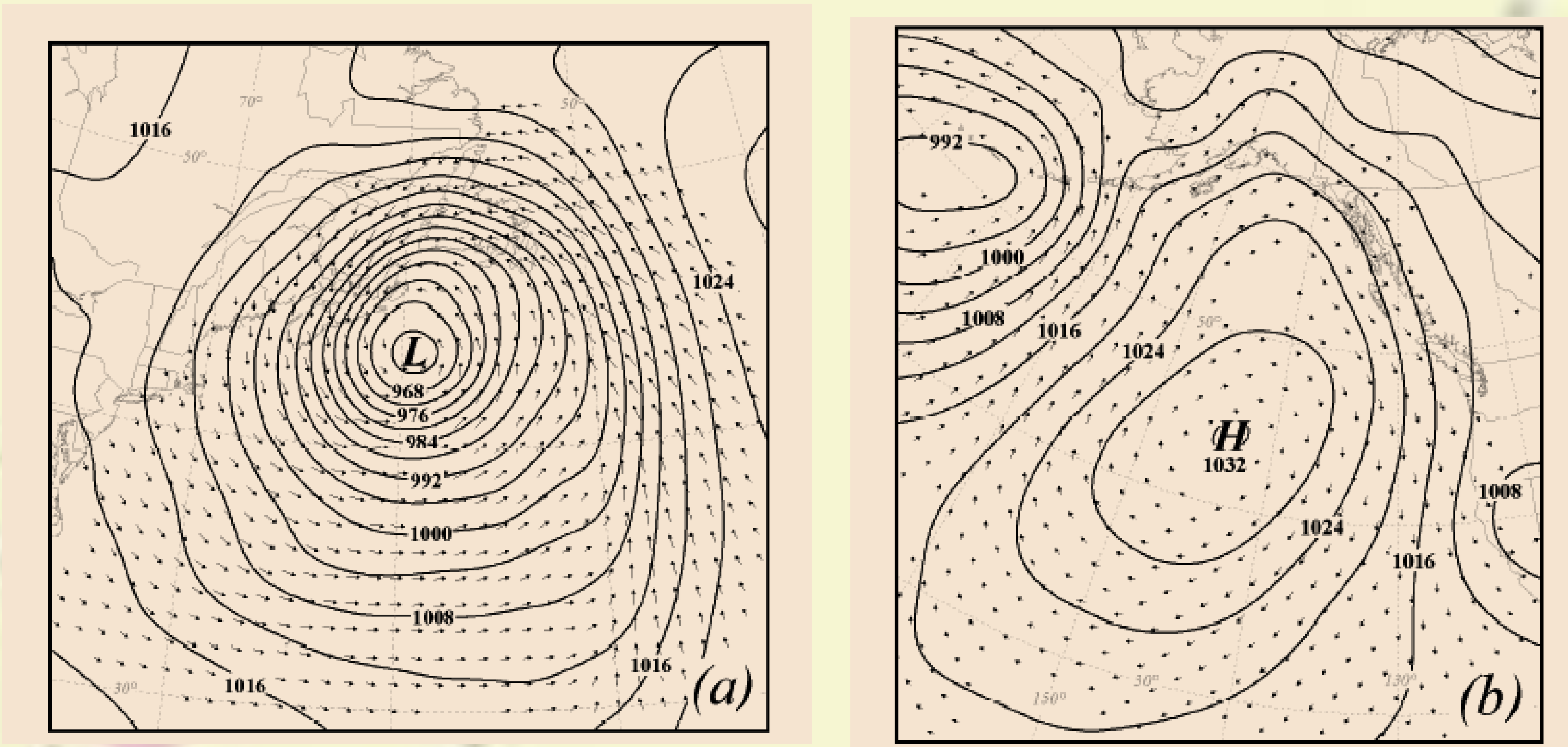
FLUID ROTATION

Circulation and Vorticity



Circulation and Vorticity

Two primary measures of rotation in a fluid

By convention, both circulation and vorticity are positive in the counterclockwise direction.

(cyclonic in the Northern Hemisphere)

Circulation: Macroscopic measure of rotation for a finite area of the fluid = integration of the tangential component of velocity around a closed path

Vorticity: The tendency to spin about an axis; Microscopic measure of rotation at any point in the fluid

Circulation: The tendency for a group of air parcels to rotate.
If an area of atmosphere is of interest, you compute the circulation.

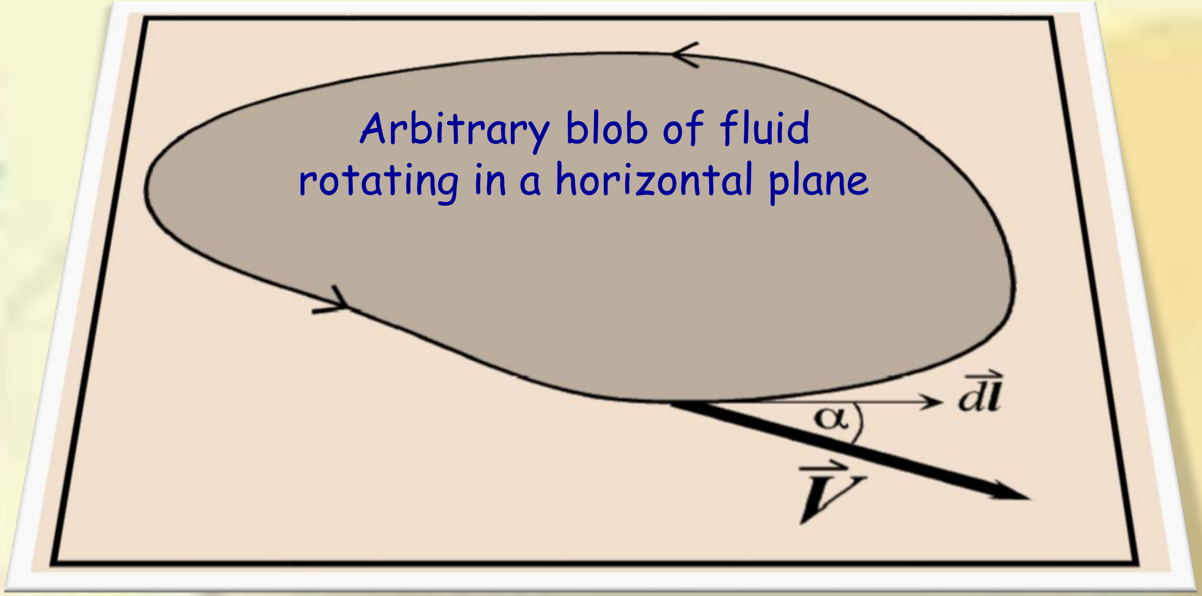
Vorticity: The tendency for the wind shear at a given point to induce rotation.

If a point in the atmosphere is of interest, you compute the vorticity

Circulation

A measure of the rotation within a finite element of a fluid

$$C = \oint \vec{V} \cdot \vec{dl} = \oint |V| \cos\alpha \cdot \vec{dl}$$



In meteorology, changes in circulation are associated with changes in the intensity of weather systems.

We can calculate changes in circulation by taking the time derivative of the circulation:

$$\frac{dC}{dt} = \frac{d}{dt}\left(\oint \vec{V}.d\vec{l}\right)$$

Calculate the circulation within a small fluid element with area $\partial x \delta y$

$$C = \oint udx + vdy$$

$$= u\delta x + \left(v + \frac{\partial v}{\partial x}\delta x\right)\delta y - \left(u + \frac{\partial u}{\partial y}\delta y\right)\delta x - (v)\delta y$$

$$C = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\delta x \delta y$$

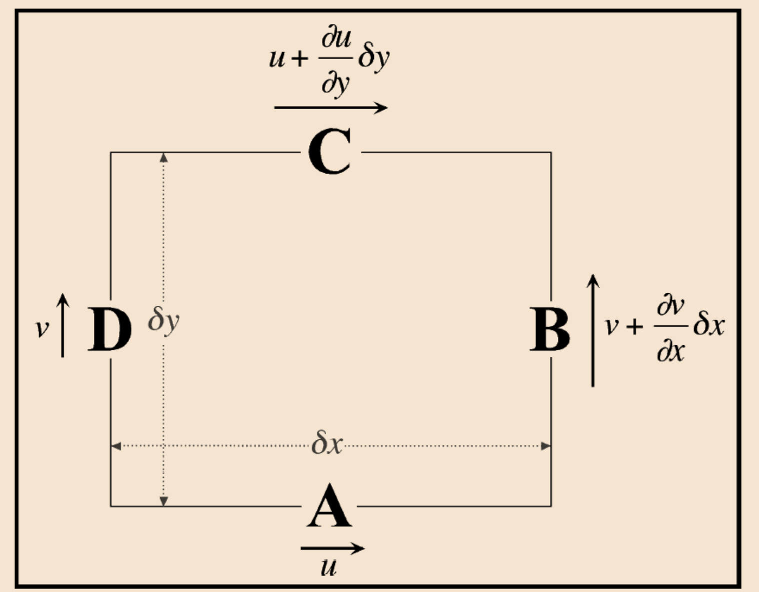


Fig. 5.5 Schematic illustrating the calculation of vorticity around an infinitesimal fluid element with Area=$\delta x \delta y$. See text for explanation.

$$\lim_{\delta x \delta y \to 0}\left(\frac{C}{\delta x \delta y}\right) = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \zeta = relative\ vorticity$$

The relative vorticity is the microscopic equivalent of macroscopic circulation

Consider an arbitrary large fluid element, and divide it into small squares.

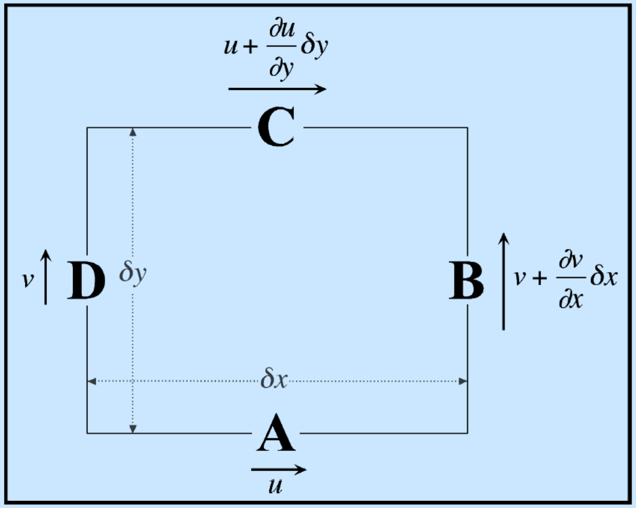


Fig. 5.5 Schematic illustrating the calculation of vorticity around an infinitesimal fluid element with Area=$\delta x \delta y$. See text for explanation.

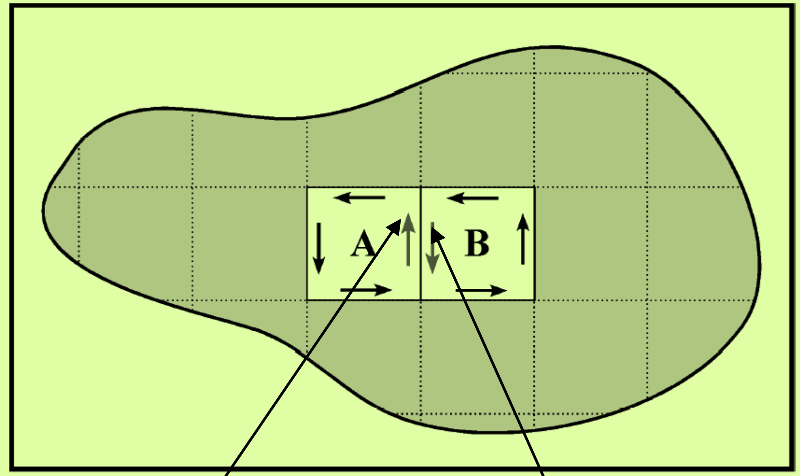


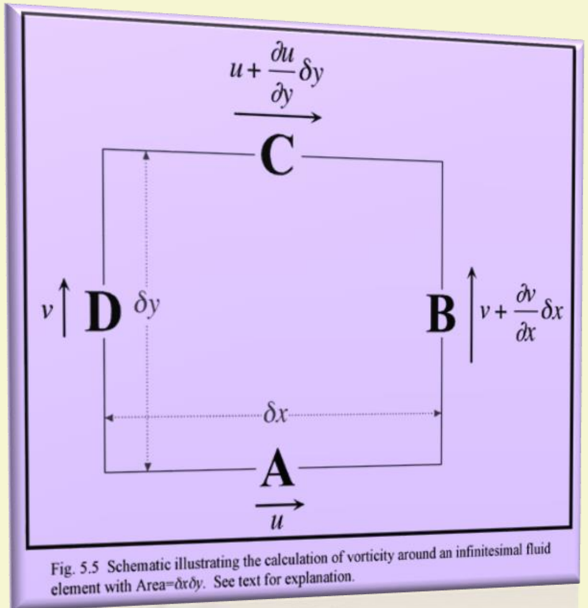
Fig. 5.6 Circulation around the shaded fluid element can be represented by summing the circulations around a series of squares such as A and B. Note that the circulation around the combined rectangle AB is comprised of only the contributions from the periphery of AB, the gray arrows, on the side common to both A and B, contribute oppositely to the circulation and therefore cancel.

$$C_A = \oint u\,dx + v\,dy = (u)\delta x + \left(v + \frac{\partial v}{\partial x}\delta x\right)\delta y - \left(u + \frac{\partial u}{\partial y}\delta y\right)\delta x - (v)\delta y$$

$$C_B = \oint u\,dx + v\,dy = (u)\delta x + \left(v + \frac{\partial v}{\partial x}\delta x\right)\delta y - \left(u + \frac{\partial u}{\partial y}\delta y\right)\delta x - (v)\delta y$$

Sum circulations: common side cancels

Make infinitesimal boxes: each is a point measure of vorticity and all common sides cancel



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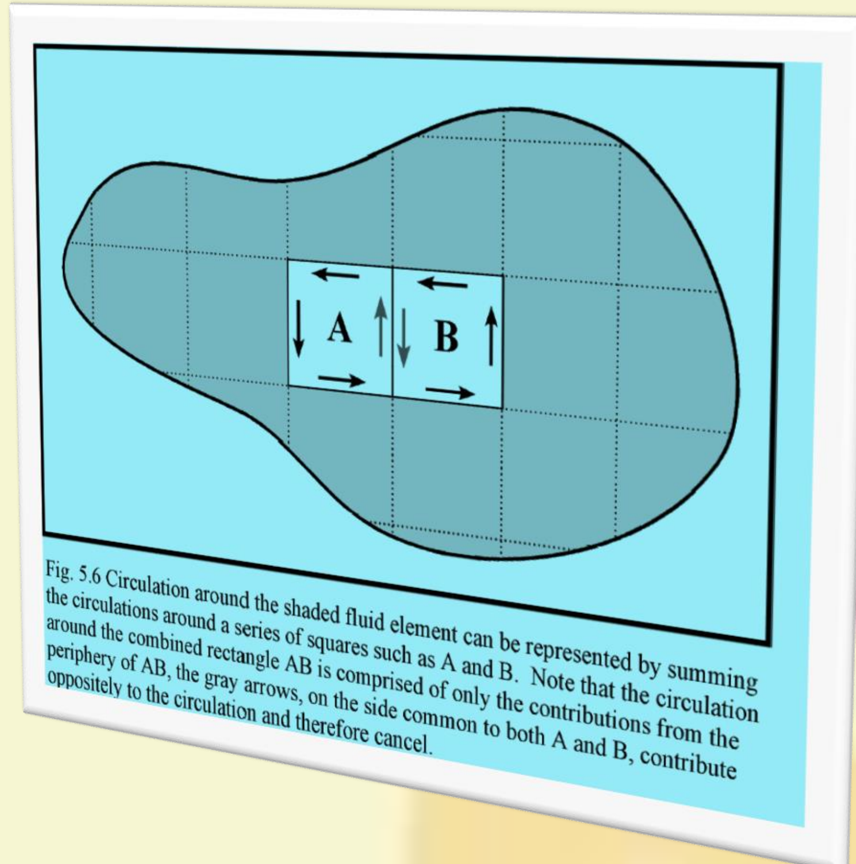


Fig. 5.6 Circulation around the shaded fluid element can be represented by summing the circulations around a series of squares such as A and B. Note that the circulation around the combined rectangle AB is comprised of only the contributions from the periphery of AB, the gray arrows, on the side common to both A and B, contribute oppositely to the circulation and therefore cancel.

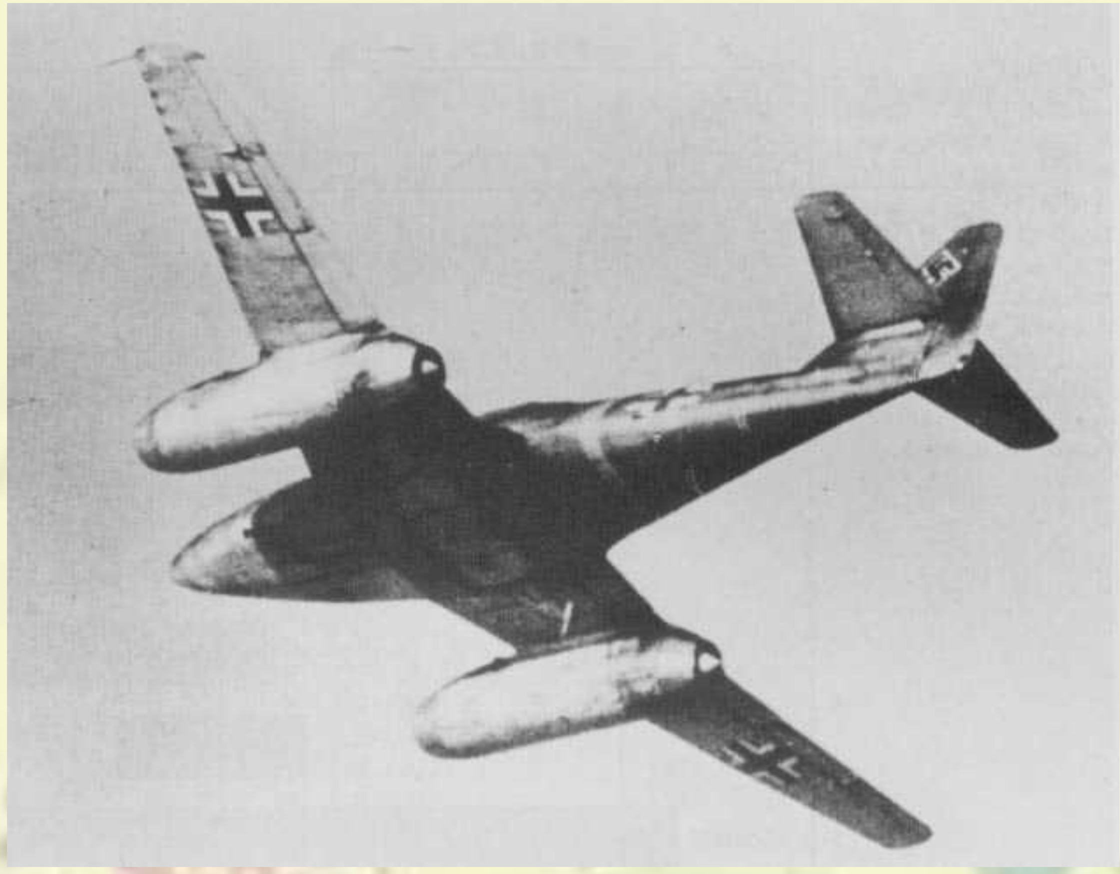
Fill area with infinitesimal boxes: each is a point measure of vorticity and all common sides cancel so that:

$$C=\oint (u\,dx+v\,dy)=\iint_{Area}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)\delta x\delta y$$

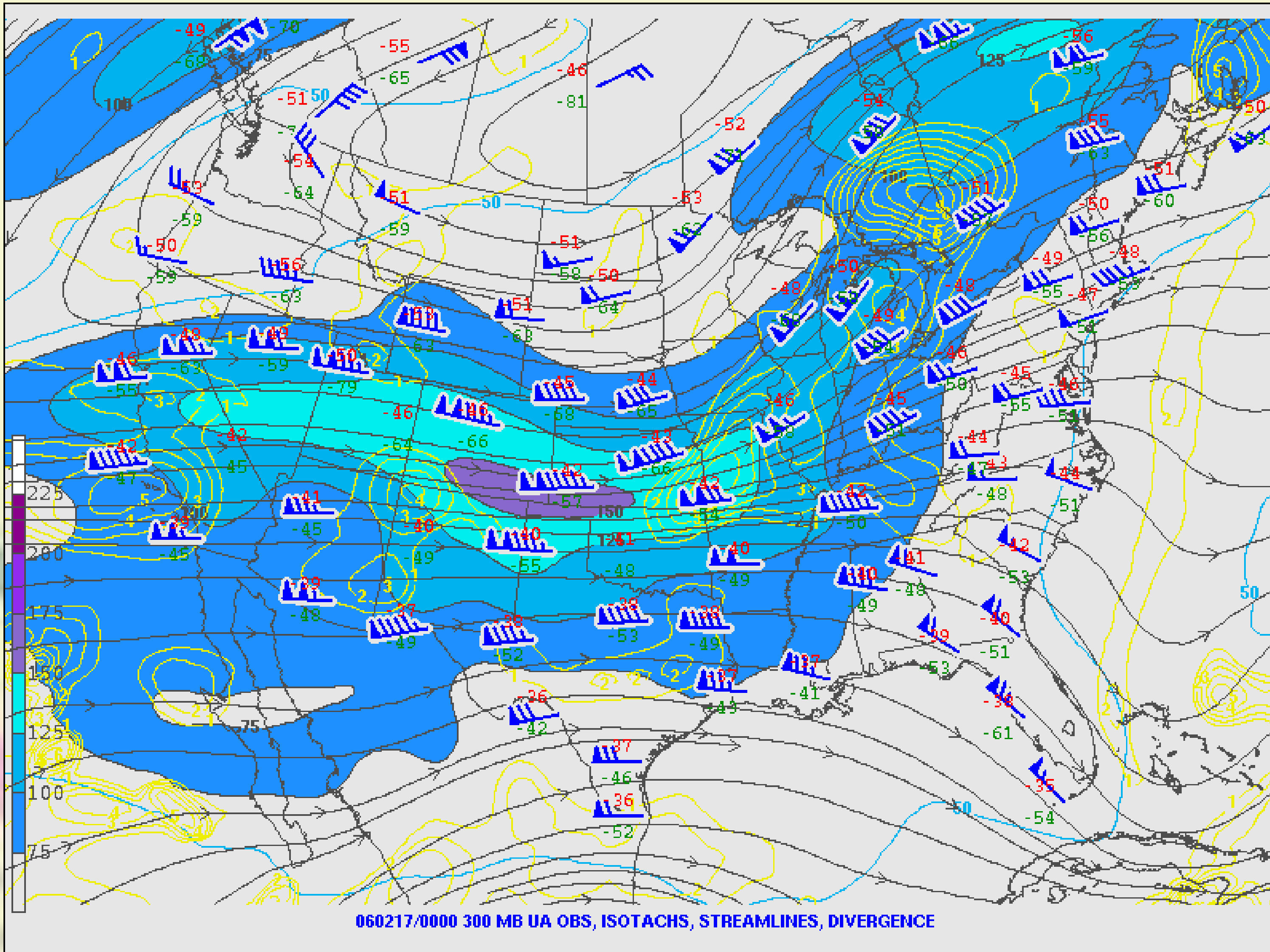
The circulation within the area is the area integral of the vorticity

During World War II, allied pilots encountered high speed winds in the upper air.

They named those winds after the fastest planes they came up against: fighters equipped with jet engines.



Jet Streams and Jet Streaks



Jet Streams

Basic Characteristics:

Long narrow band of strong winds

~500-6000 km in length

~100-400 km in width

Not a continuous band

Maximum winds ~50-250 knots

Can be located at any altitude

Common mid-latitude types include the polar, subtropical, and low-level jets

Migrate and evolve over times scales from a few hours to seasonally

Primarily influence the motion and evolution of **synoptic-scale** systems

Contribute to the initiation and evolution of mesoscale systems and deep convection

Air masses are steered by the jet stream

JET STREAMS

1. Polar jet stream

Follows the edge of Rossby waves.
Found at 10-12 km elevation (33,000-40,000 ft)
Wind speed: 75-125 m/s (170-280 mi/hr)

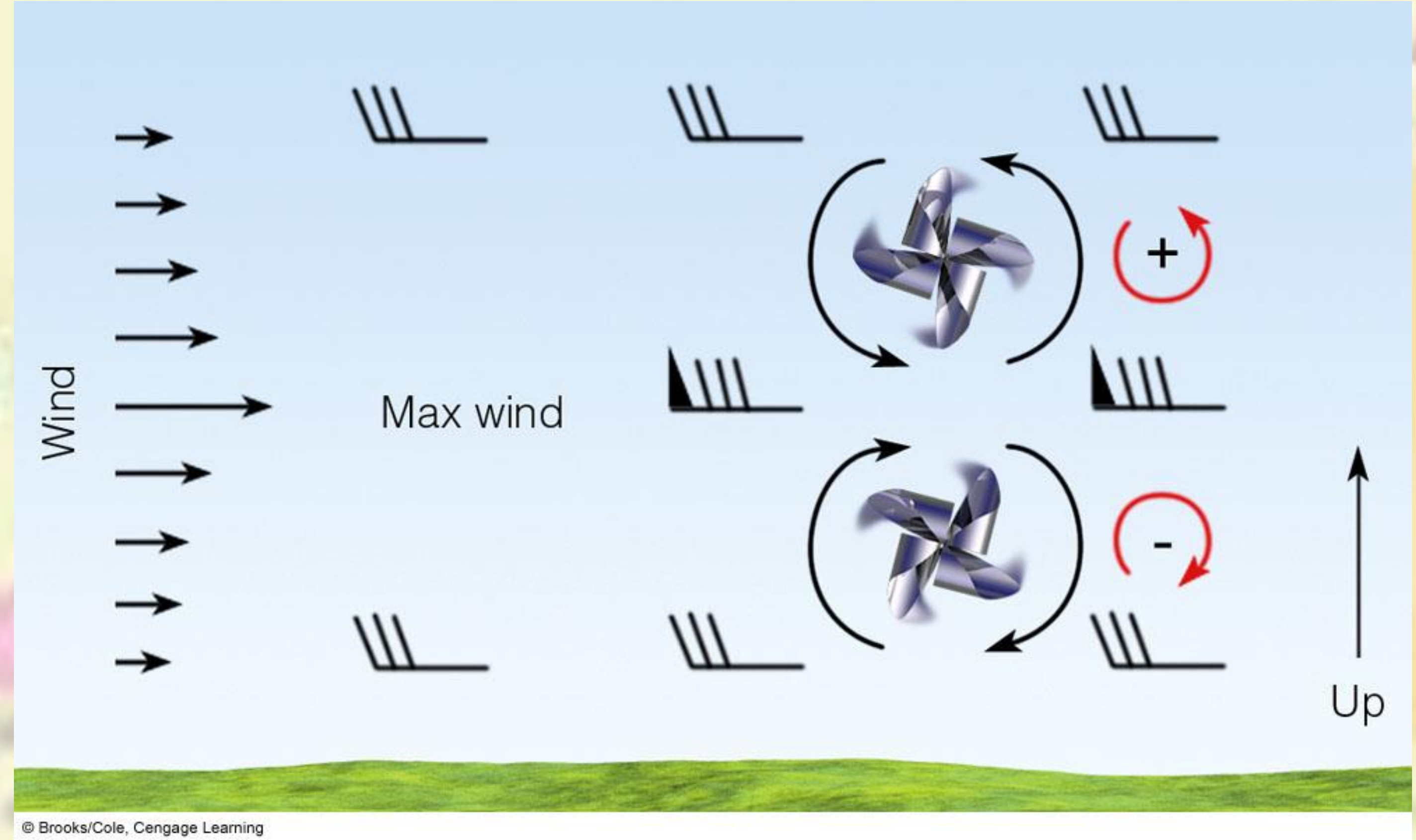
2. Subtropical jet stream

In the subtropical latitude zone
Speed 100-110 m/s

3. Tropical easterly jet stream
In summer season, over Asia, India, Africa, only in Northern Hemisphere

Areas of cyclonic (positive) relative vorticity and anticyclonic (negative) relative vorticity can form in a region of strong wind-speed shear.

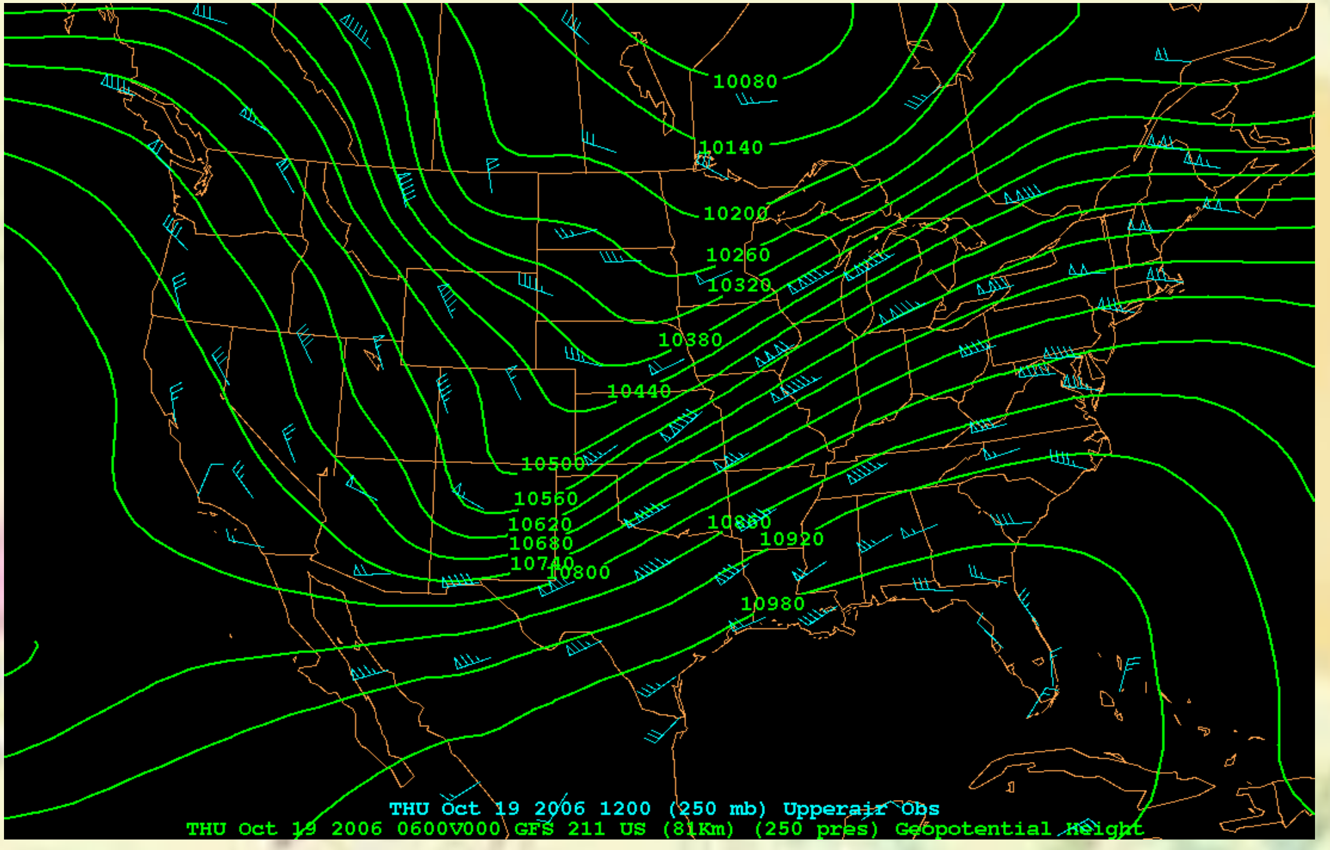
Notice that the pinwheel changes its direction of spin when placed above and below the region of maximum winds.



Jet Stream

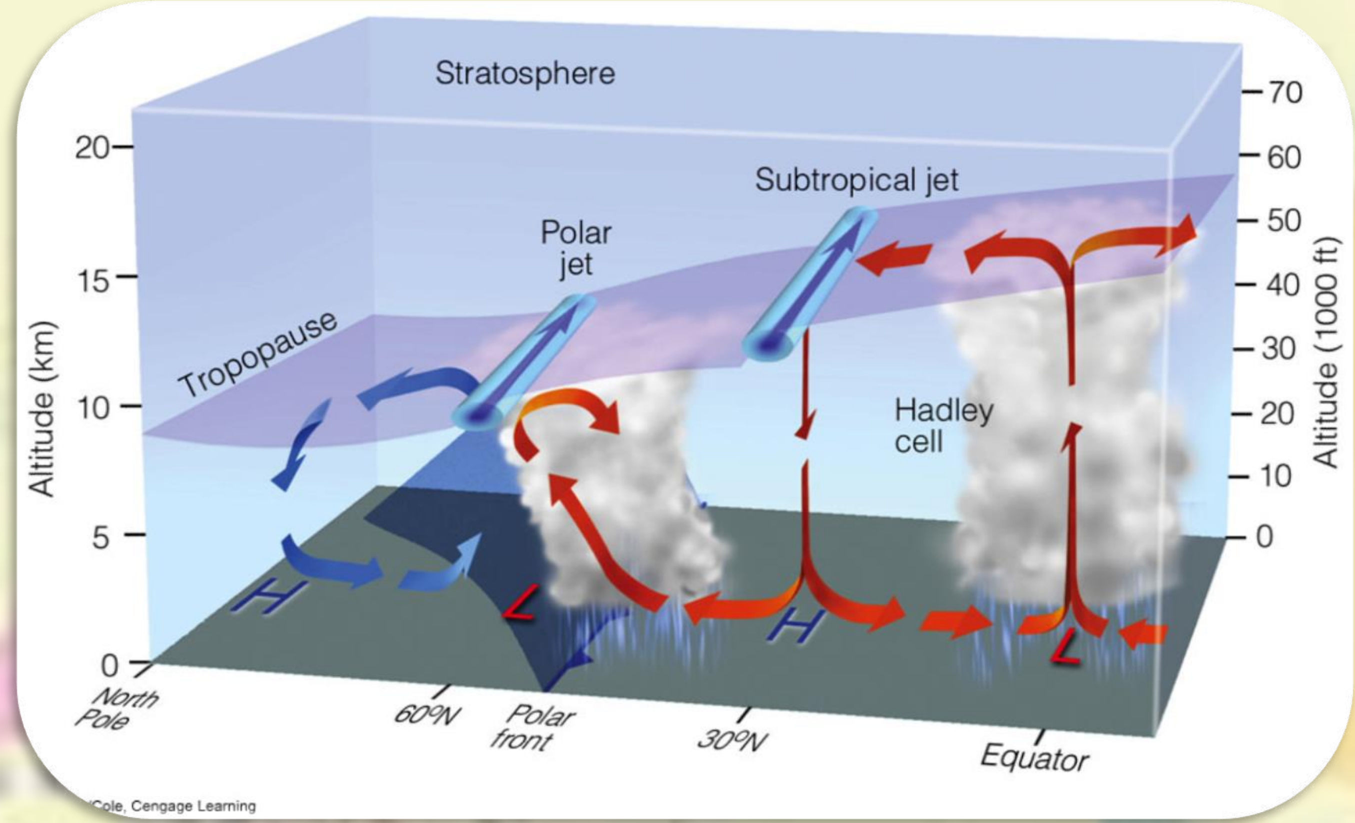
When warm and cold air masses collide, the strongest winds occur just below the tropopause (the top of the troposphere, about 250 mb)

This fast flowing river of air over mid-latitudes = mid-latitude jet stream



Jet Streams

100-200 kt winds at 10-15km, thousands of km long, several 100 km wide and a few km thick (polar and subtropical).



Scales of Atmospheric Circulations

Jet Stream – Very important upper-air features known as jet streams are often embedded in the zone of strong westerlies

A jet stream is a narrow band of high-speed winds that reaches its greatest speed near the tropoause (24, 000 to 50, 000 feet MSL)

Typical jet stream speeds range between 60 knots and about 240 knots

Jet streams are typically thousands of miles long, hundreds of miles wide, and a few miles thick.

Scales of Atmospheric Circulations

The polar front jet stream – On the average, two jet streams are found in the westerlies, the polar front jet stream is one of them

As the name implies, the polar front jet stream is found near the latitude of the polar front

Similar to the behavior of the polar front, it is stronger and farther south in the winter and weaker and further north in summer.

Jet Streams

A band of wind in the upper troposphere

150 – 500 km wide
0.9-2.2 km thick
Speeds may exceed 300 km/h

Polar Jet Stream:
Between Polar and Ferrel cells

Meanders from 30-70° N or S

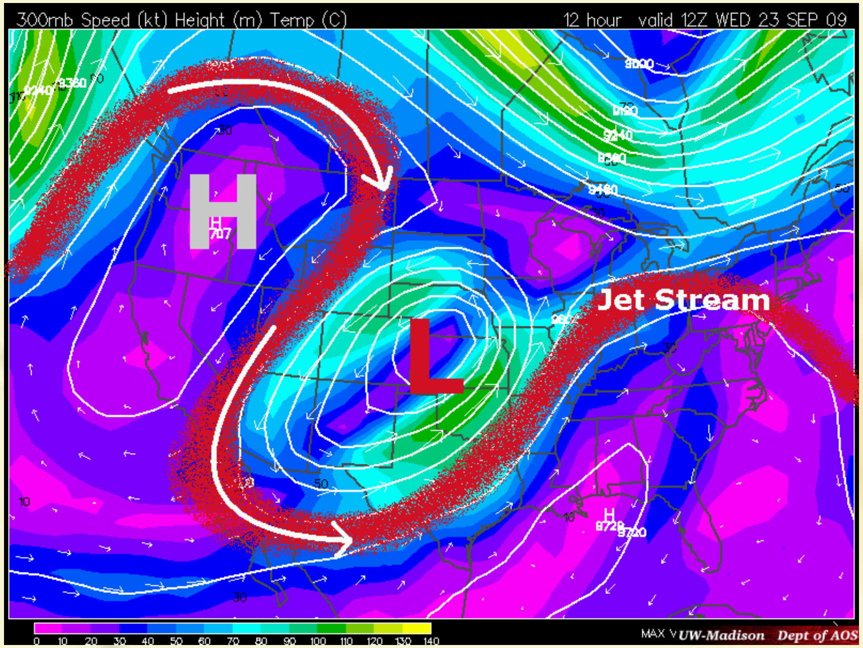
Moves more poleward in summer

Influences (and is influenced by) storm paths

Subtropical Jet Stream
Between Hadley and Ferrel Cells

Meanders from 20-50° N or S

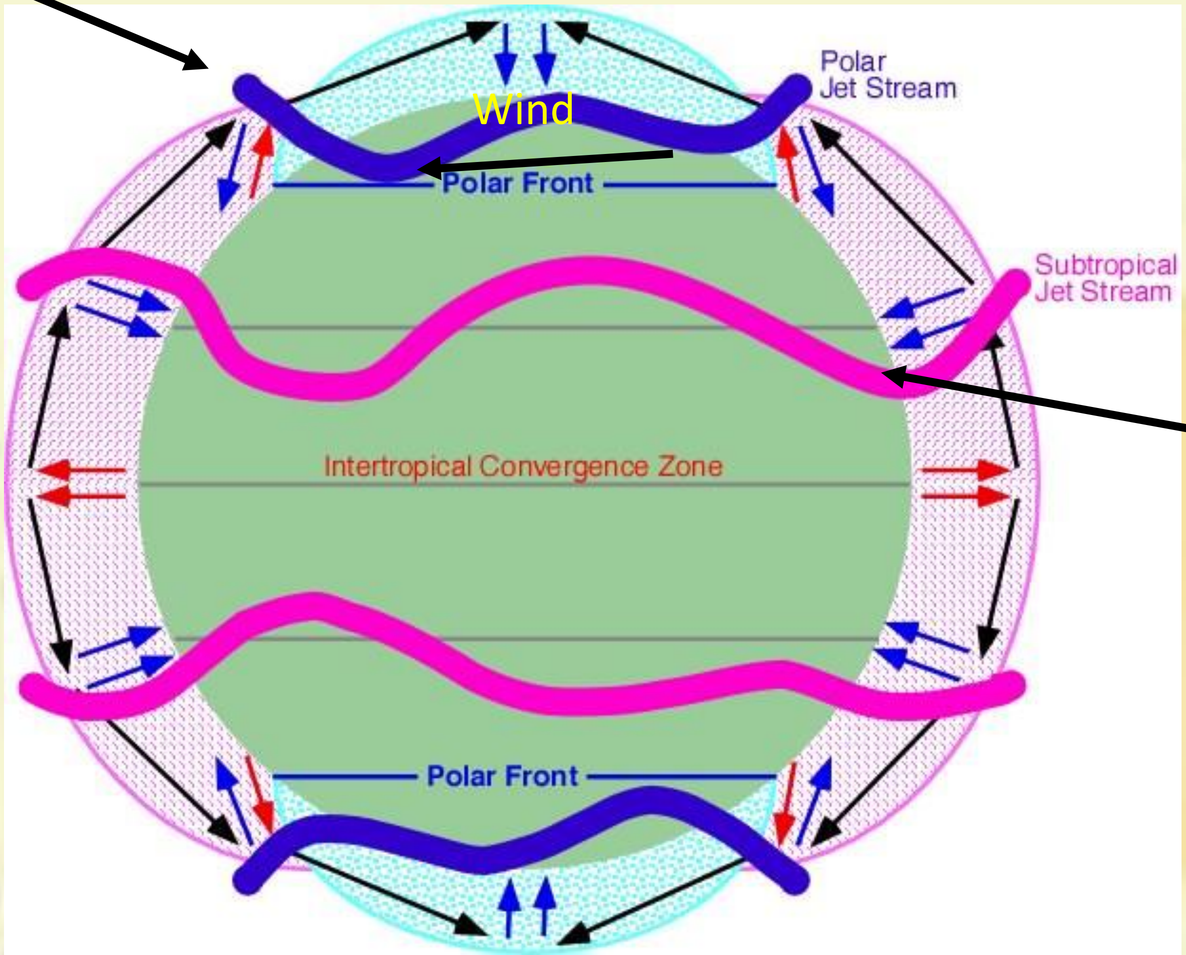
May occur simultaneously with Polar Jet in NA



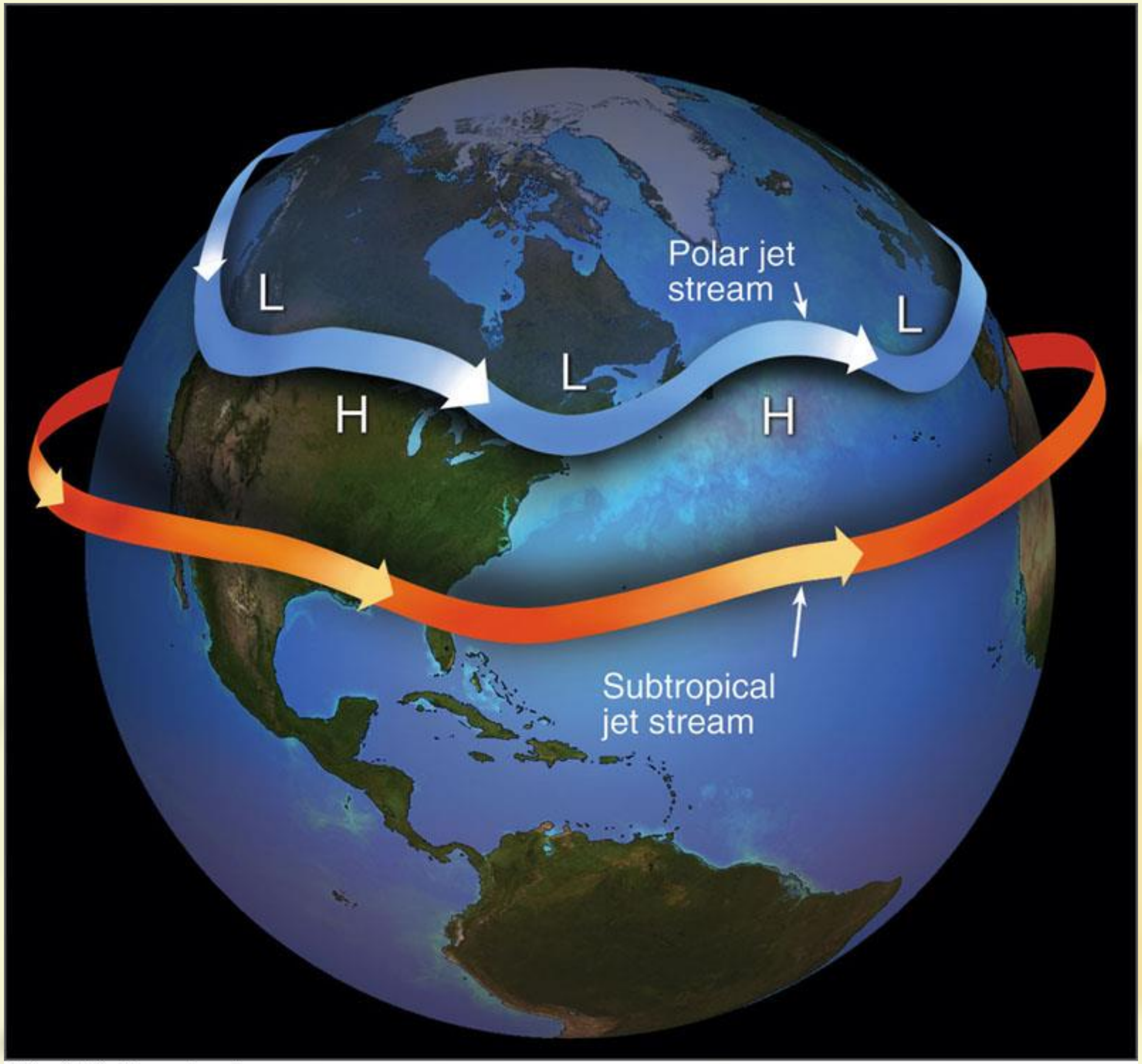
The subtropical jet stream tends to develop during the winter season.

The subtropical jet stream can also help develop and steer storms and disturbances.

Altitude:
10000m



Altitude:
13000m


Polar jet stream
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Subtropical jet stream

Scales of Atmospheric Circulations

The subtropical jet stream - On the average, two jet streams are found in the westerlies, the subtropical jet stream is one of them

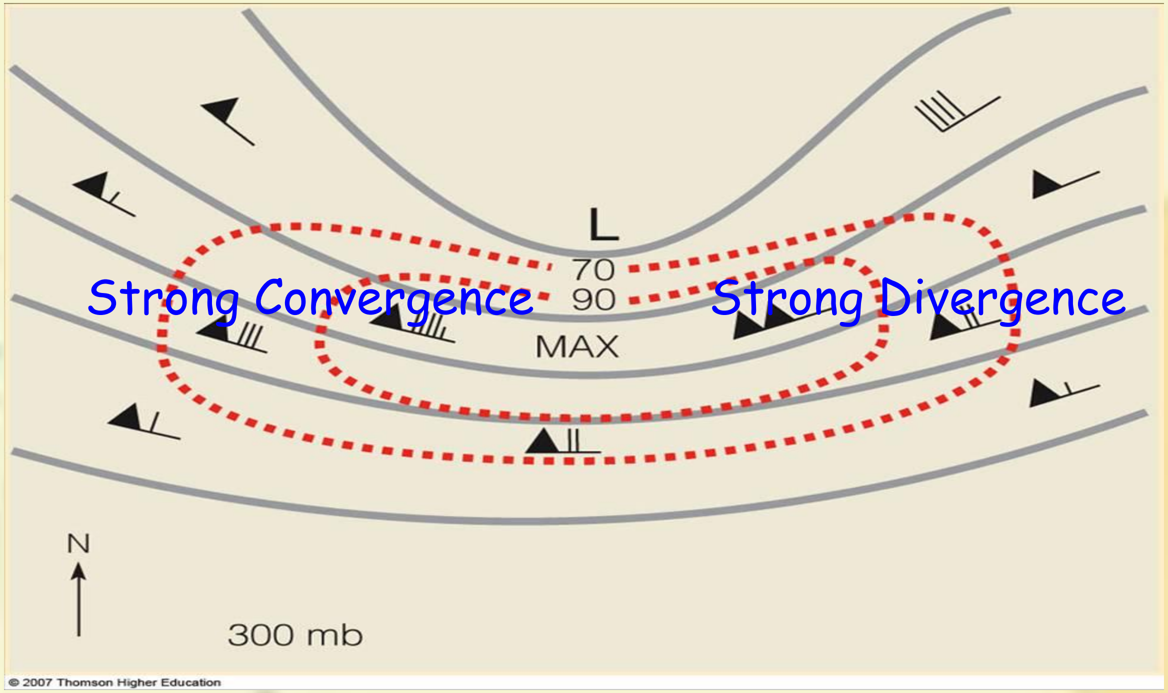
The subtropical jet stream has no related surface frontal structure and shows much less fluctuation in position

It is typically found near 25 degrees north to 30 degrees north latitude near North America

The subtropical jet stream reaches its greatest strength in the wintertime and generally disappears in summer.

The Jet Stream: Divergence and Convergence

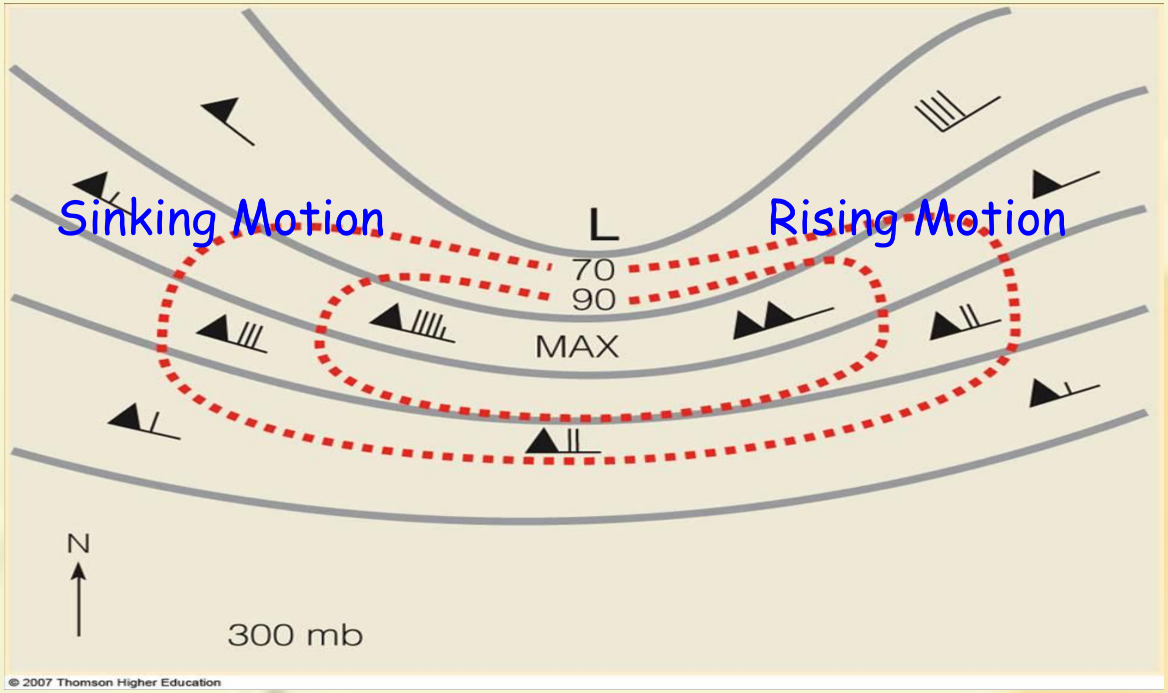
Strongest divergence and convergence occurs when both vorticity and jet streak effects occur simultaneously:



In the upper atmosphere:

Convergence -> sinking motion

Divergence -> rising motion



Sinking Motion
Rising Motion
L
70
90
MAX
N
300 mb
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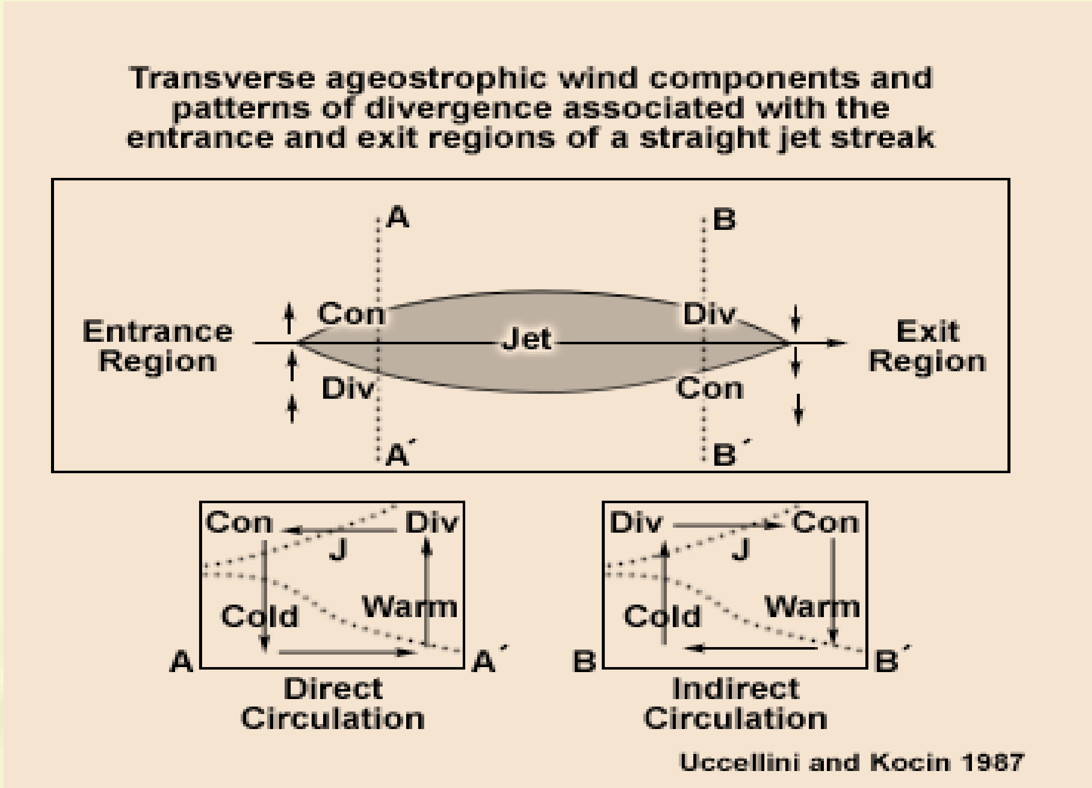
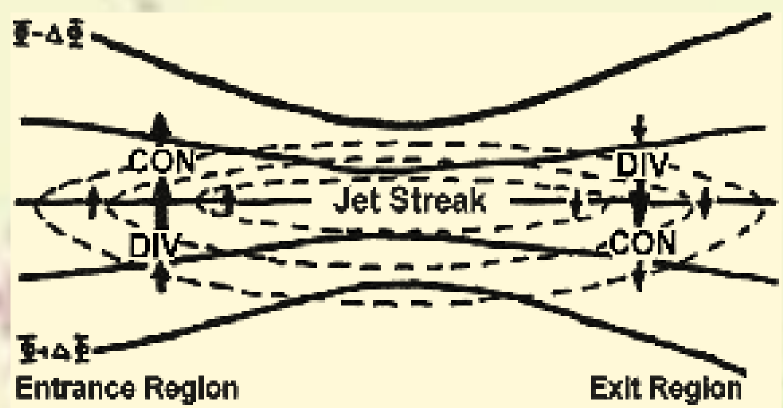
Jet streaks cause convergence and divergence due to:

Confluence/diffluence





Jet Streak Vertical Motions

Physical Interpretation of the Basic Pattern:

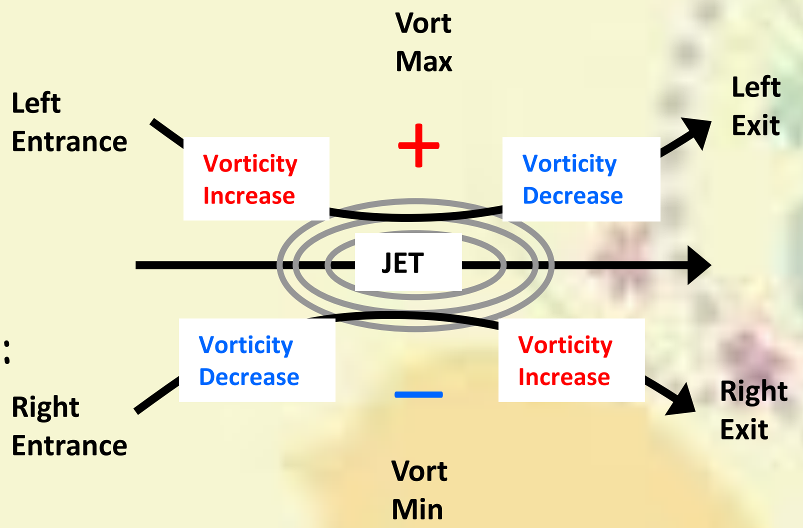
Using a simplified vorticity equation:

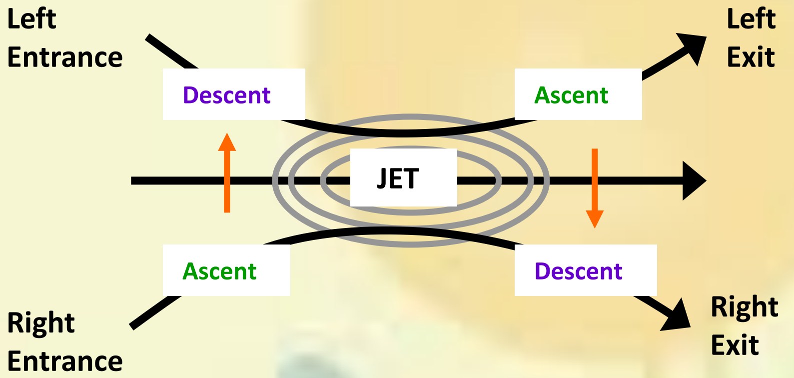
$$\underbrace{\frac{D\zeta}{Dt}}_{\text{Vorticity Change}} \propto \underbrace{-\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)}_{\text{Divergence}}$$

Thus, the vorticity change experienced by an air parcel moving through the jet streak:

Vorticity decrease → Divergence aloft → Upward motion

Vorticity increase → Convergence aloft → Downward motion

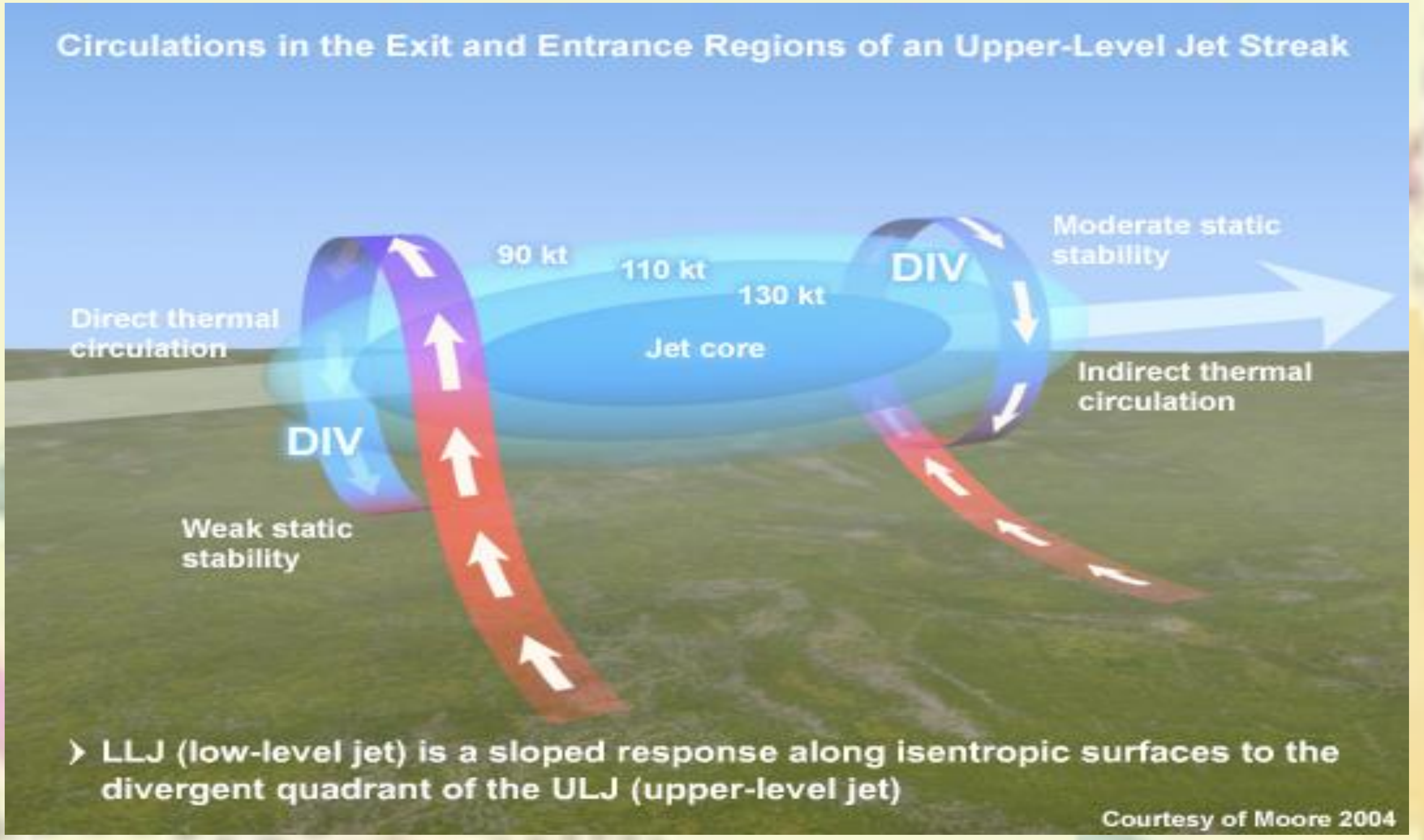




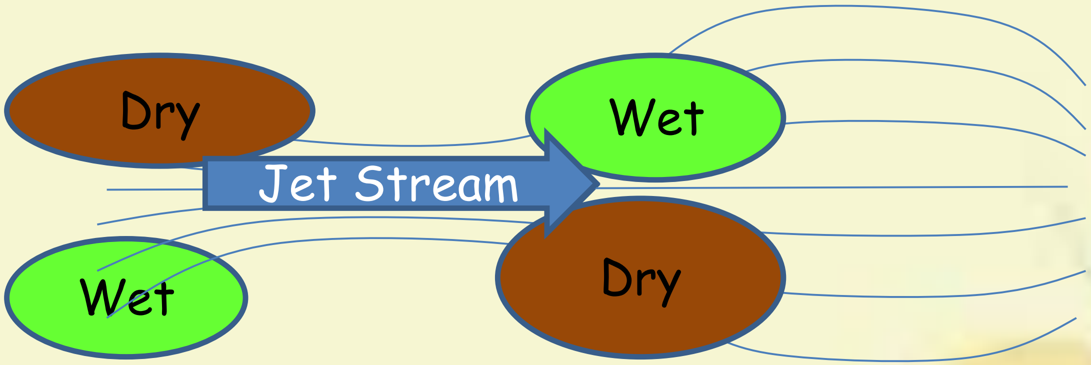
Recall: QG theory provides an alternative explanation (with the same result)

Divergence / convergence patterns result from **ageostrophic motions**

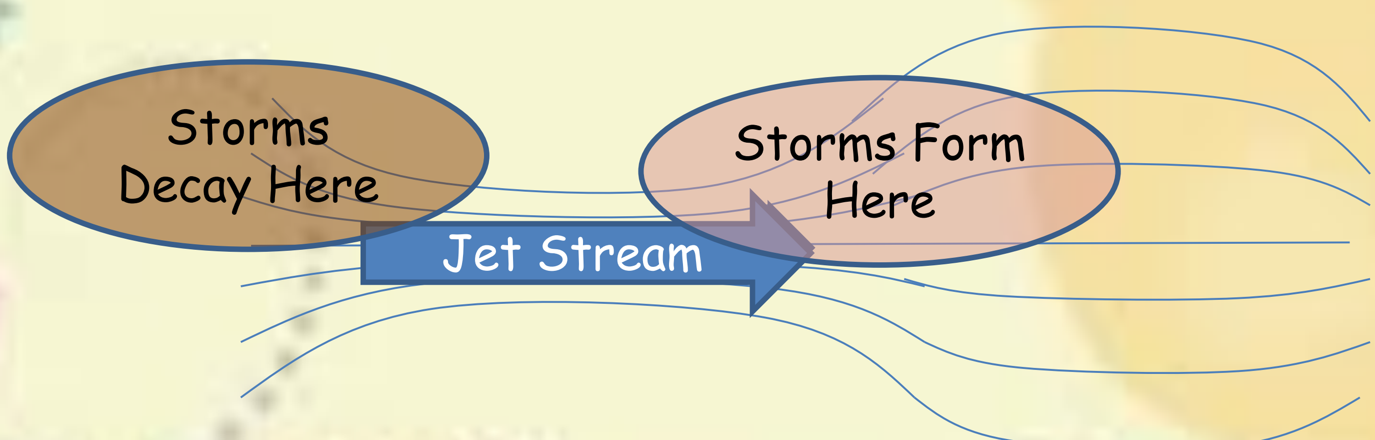
3 Dimensional View of the Vertical Circulations Associated to a Jet



Associated Wet and Dry Patterns



Jet Streams produce a 4-celled pattern of wet/dry



Jet streams strongly influence regions of storm formation

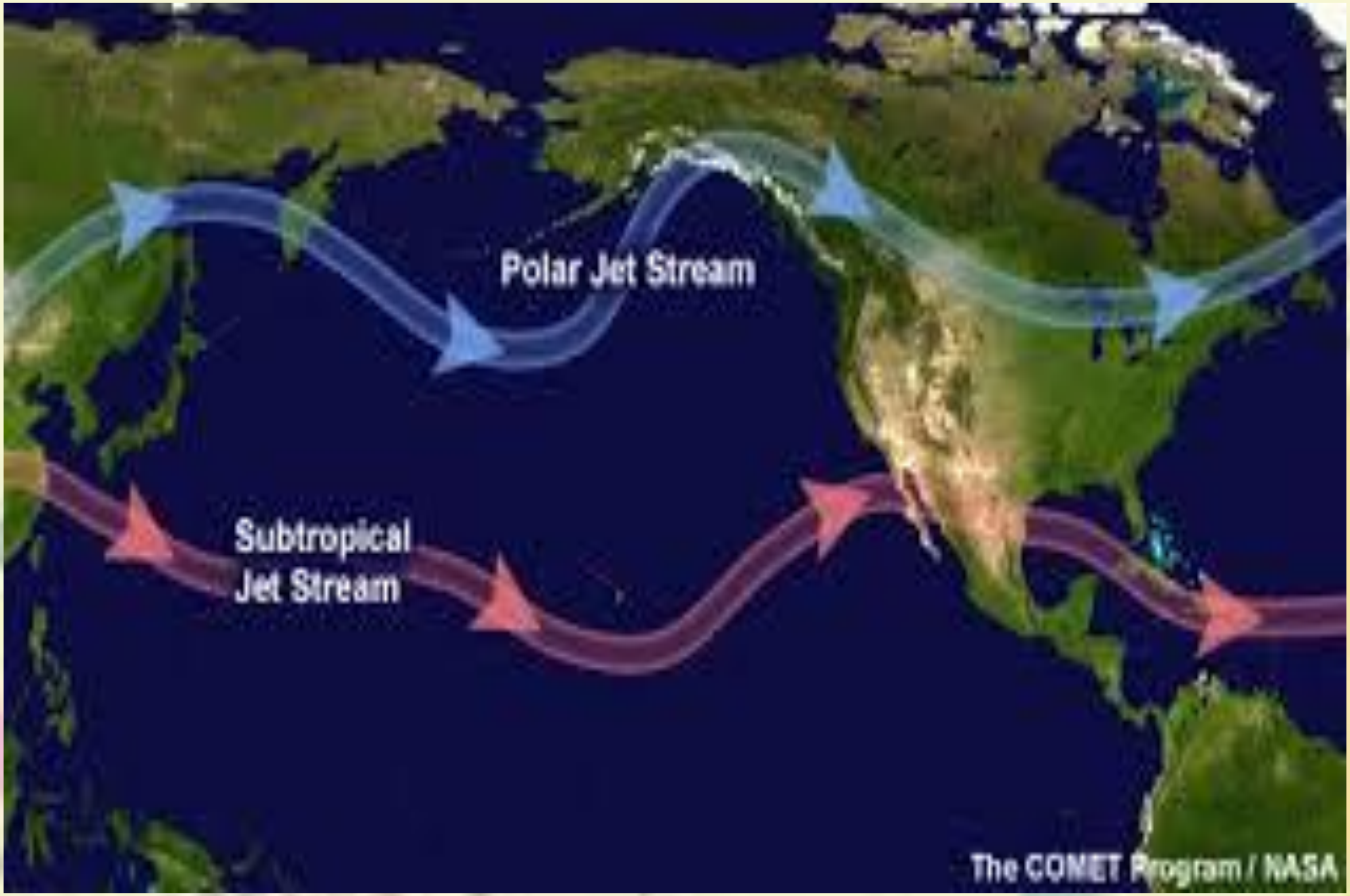
JET STREAMS

Jet streams tend to be weaker in summer than in winter

Jet streams are less intense in the Southern Hemisphere due to smaller land masses

Strongest jet stream have been recorded during winter over Southern Japan (speeds up to 310 mph)

Winds in the Upper Troposphere



Jet Streams

Polar and Subtropical Jet

Established by steep temperature and pressure gradients between circulation cells.

Between tropical-mid-latitude cell (subtropical) and mid-latitude-polar cell (polar)

Gradients greatest at polar jet

Topic: Momentum
Low-latitudes: atmosphere gains momentum
High-latitudes: atmosphere losses momentum
Conservation of Momentum

Why Do We Care About the Jet?

Knowing the location of jet streams can aid in weather forecasting.

The path of jet streams steers cyclonic storm systems at lower levels in the atmosphere.

The main commercial relevance of the jet streams is in air travel, as flight time can be dramatically affected by either flying with the flow or against the flow of a jet stream.

Clear-air turbulence is could be found in a jet stream's vicinity.

It can cause aircraft to plunge and is a potential hazard to aircraft passenger safety.

More on jet streams

Embedded in mid-latitude “westerlies”

Only several hundred kilometers wide, thousands of km long

Discontinuous

Sharp surface front underneath jet stream

Moves south in winter, north in summer

Stronger in winter than summer

Jet Streak: Pocket of faster winds embedded in the jet stream

Located in regions with enhanced height gradients at ~ 250 mb

Jet Streaks

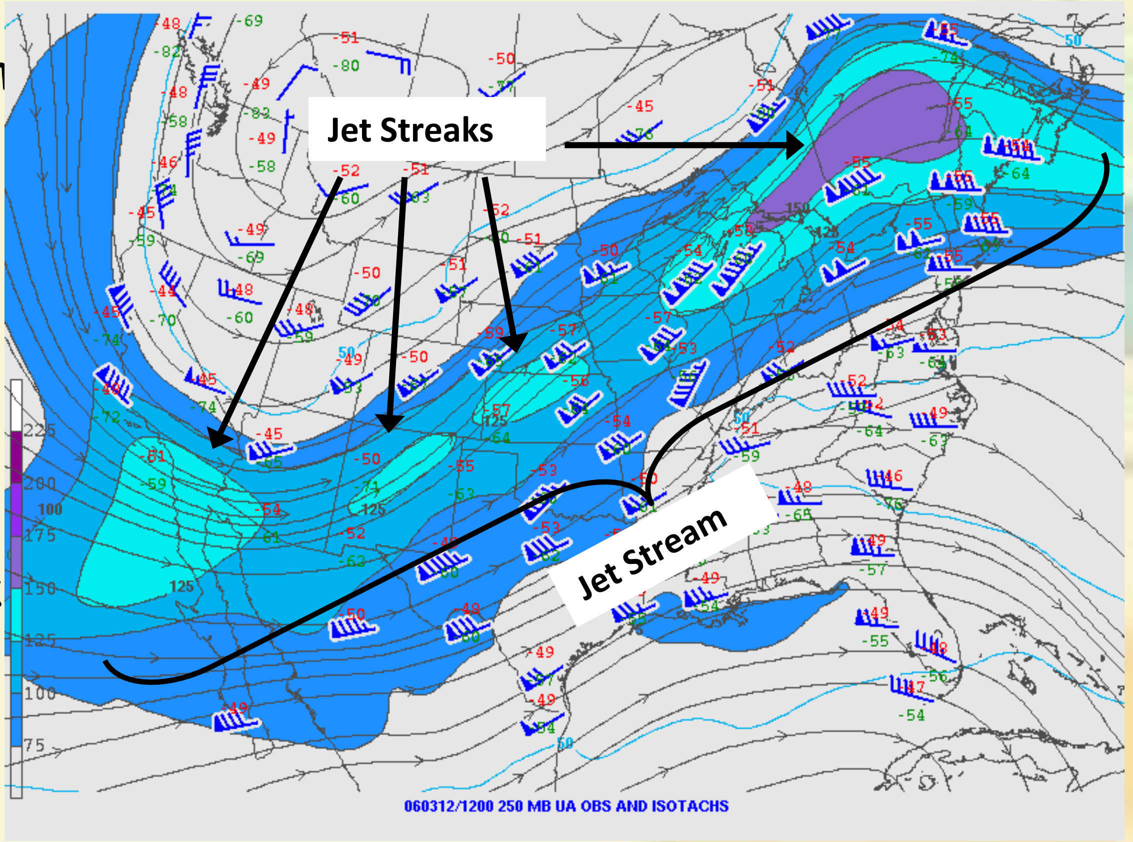
Basic Characteristics:

Faster moving “pockets” of air embedded within the jet stream
~250-1000 km in length
~50-200 km in width

Migrate and evolve over times scales from a few hours to a few days
Motion is often much slower than the speed of the wind within the jet stream or streak

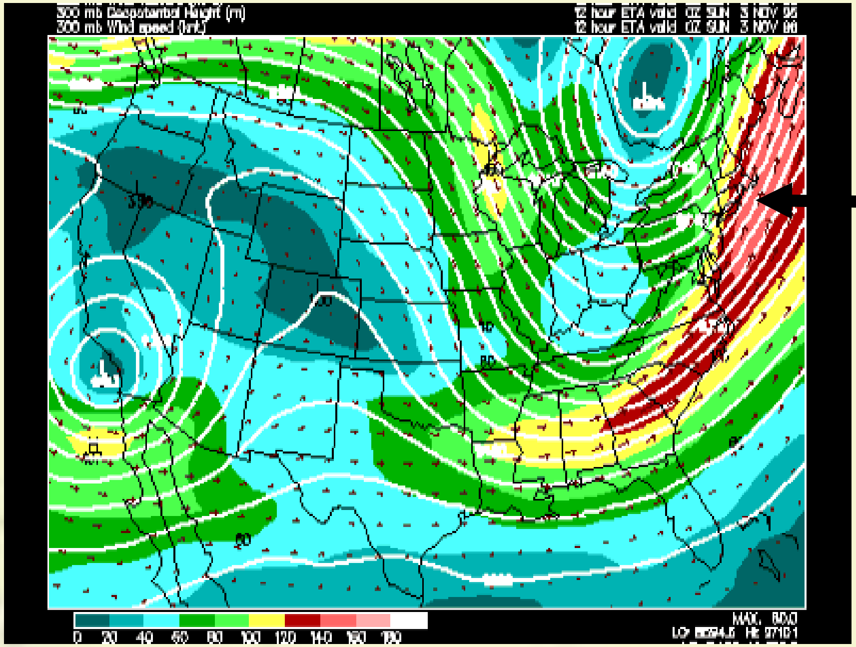
Primarily influence the initiation and evolution of **mesoscale** systems and deep convection

Contribute to the evolution of synoptic-scale systems since most contain strong PVA



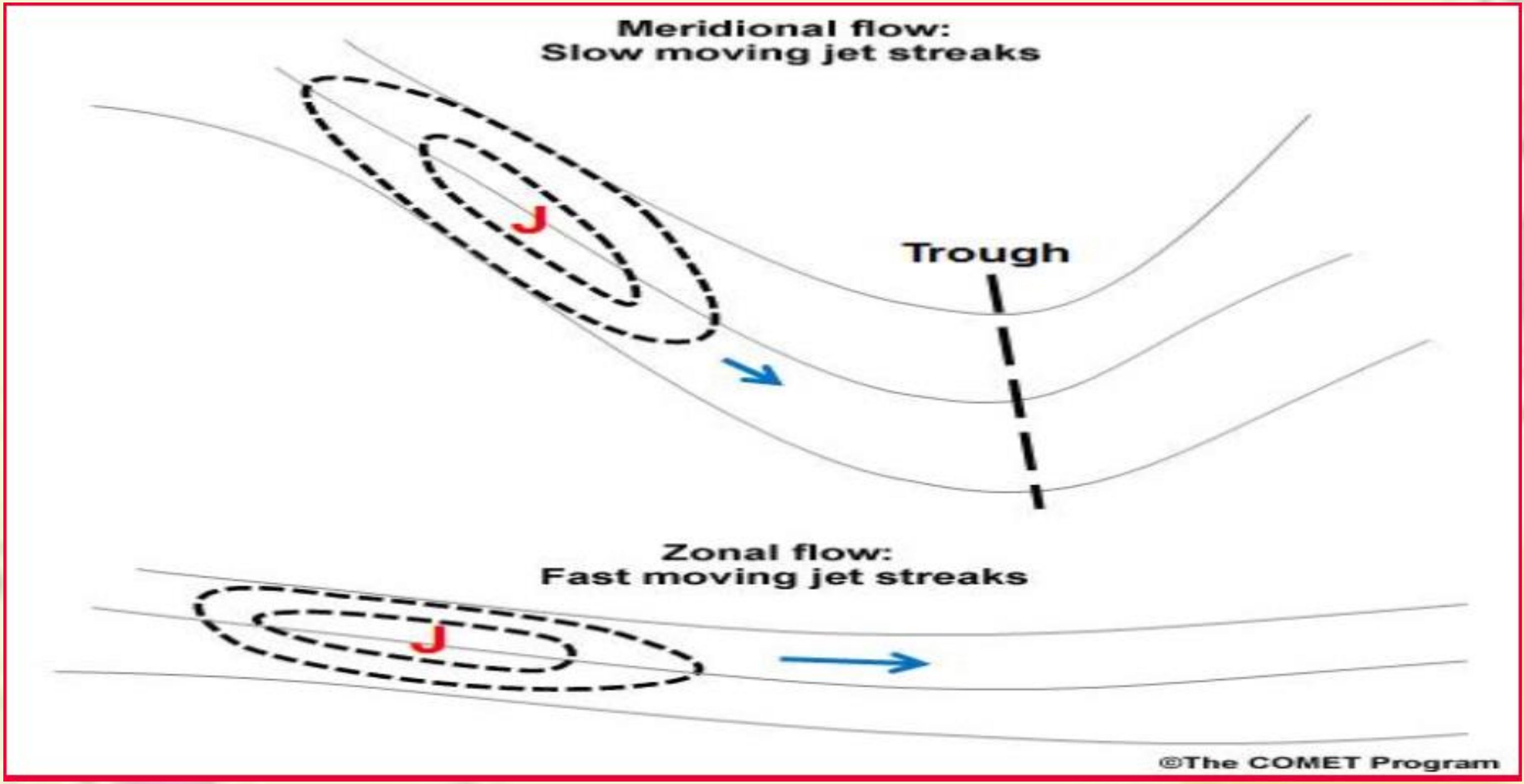
Jet Streak

300 km/h



Jet streaks are localized regions of very fast winds embedded within the jet stream.

Jet streaks – localized regions of maximum wind speeds along the jet stream



Meridional flow:
Slow moving jet streaks
J
Trough
Zonal flow:
Fast moving jet streaks
J
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The Jet Stream: Divergence and Convergence

Convergence and divergence is caused by the jet stream in 2 ways:

1) **Vorticity** – the "spin" of the atmosphere

2) Jet streaks – localized regions of maximum wind speeds along the jet stream