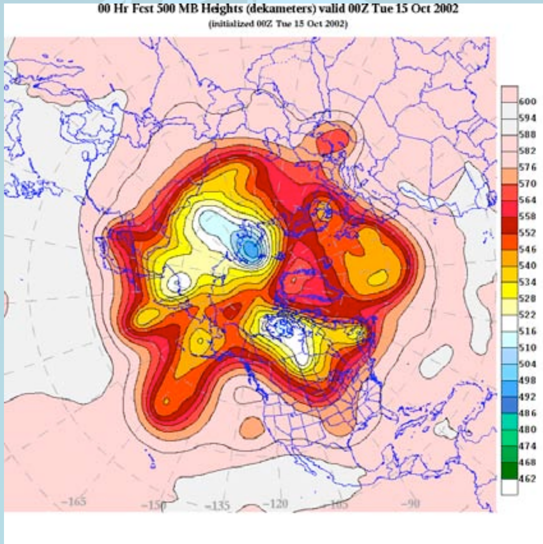
Lecture 1b Planetary (Rossby) Waves

Outline

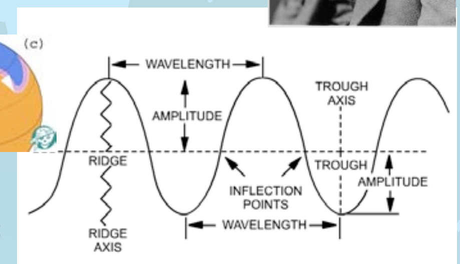
- Definition
- Significance to Forecasting
- Characteristics
- Formation
- Propagation
- Forcing



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.



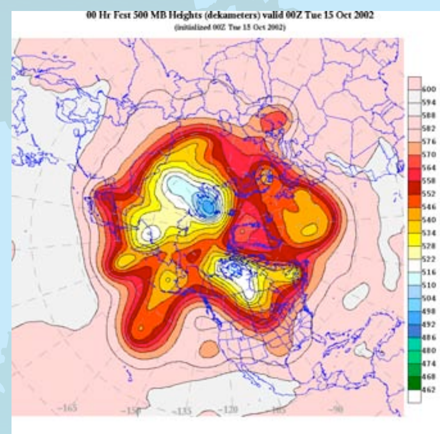
Significance of Planetary Waves

Planetary Waves

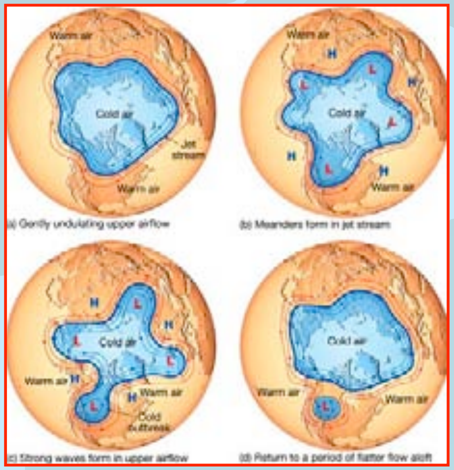
- Define the average jet stream location and storm track along the polar front
- Determine the weather regime a location will experience over several days or possibly weeks.
- Help move cold air equatorward and warm air poleward helping to offset the Earth's radiation imbalance.

Rossby Waves

- Wavelength: 50° to 180° of longitude.
- Wave number: Varies with the season (typically 4 to 5)
- The number of waves per hemisphere ranges from 6 to 2.



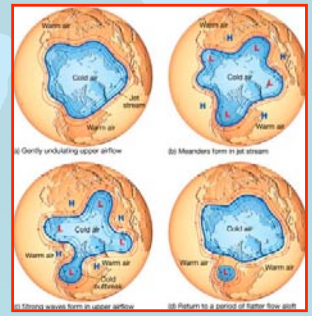
Rossby Waves



Axis of polar front jetstream outlines the Rossby wave pattern.

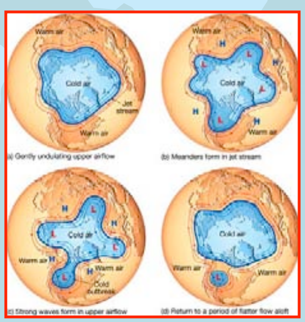
a) Zonal Flow

- Basic flow - west to east
- Little north to south energy (heat and moisture) transfer occurs.
- Large north to south temperature variations quickly develop.
- Small west to east temperature variations.
- Minimal phasing of waves.
- Weather systems tend to be weak and move rapidly from west to east



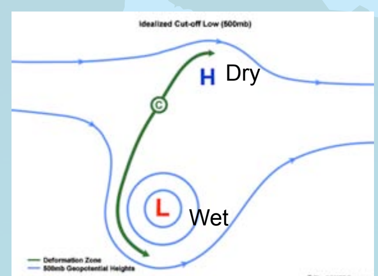
c) Meridional Flow

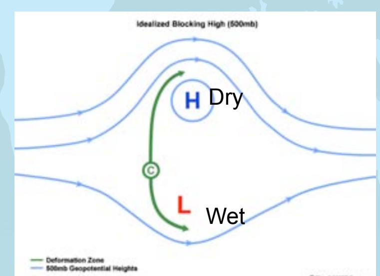
- Large north to south component to the flow
- Large-scale north–south energy transfer occurs.
- North to south temperature variations quickly weaken.
- Large west to east temperature variations.
- Weather systems are often strong and slower moving, with cyclones, producing large cloud and precipitation shields.



Blocking Patterns in Highly Meridional Flow

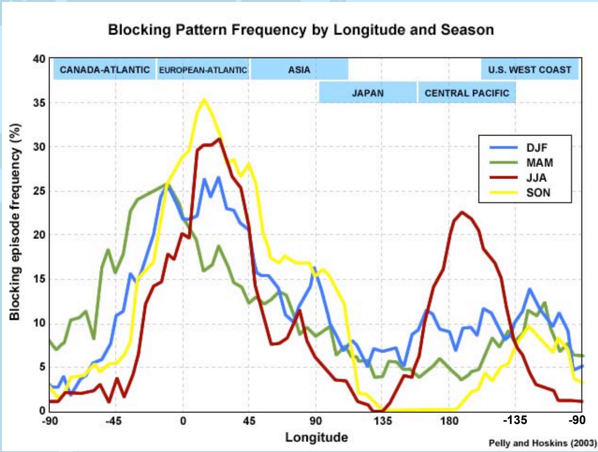
Identifying blocking patterns helps forecasters decide where to focus their attention over the forecast period. When blocking patterns develop, surrounding weather becomes more predictable, and understanding when the block will break down gives forecasters a better picture of the future progressive atmosphere.





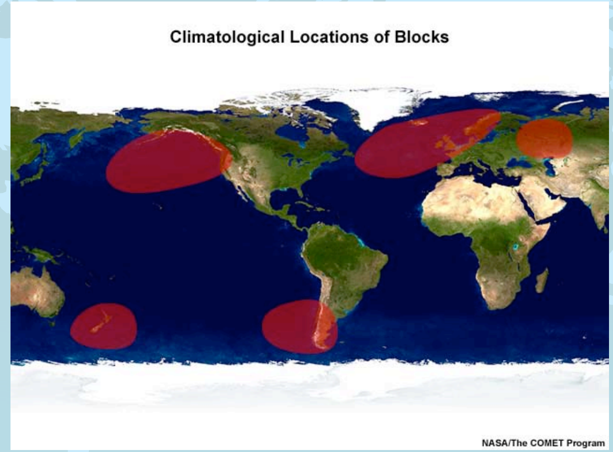
Green lines denote deformation zones.

Blocking Patterns



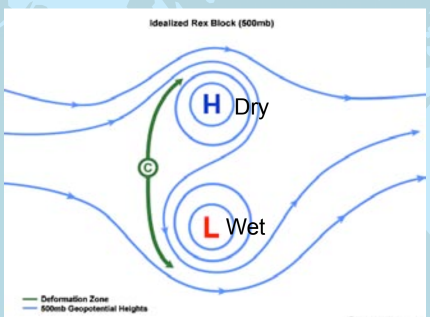
Blocking pattern frequency by longitude and season

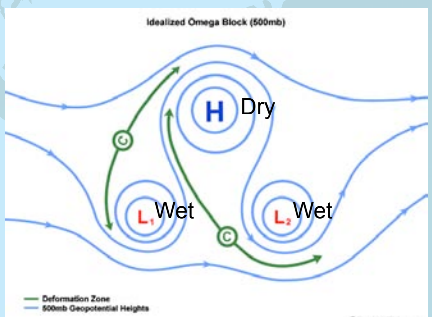
Blocking Patterns



Climatological locations of blocks.

Blocking Patterns



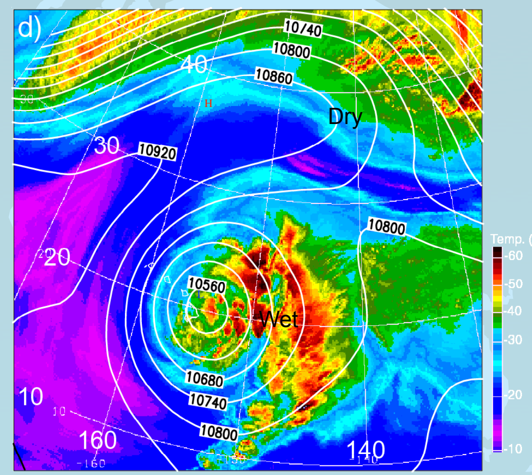


Rex block - high over low pattern - blocking generally lasts ~one week.

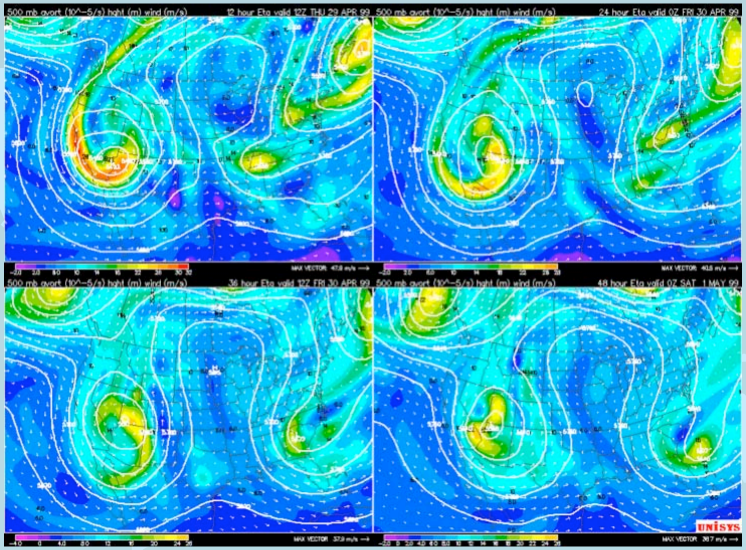
Omega block - blocking ridge with a characteristic "Ω" signature - blocking generally lasts ~ten days.

Rex Block

A Rex block is a high over low pattern, with the low to the south cut off from the westerlies. Kona lows occur with a Rex block low near or over Hawaii. The westerlies are split upstream of the block. A Rex blocking pattern has a life expectancy of 6-8 days.

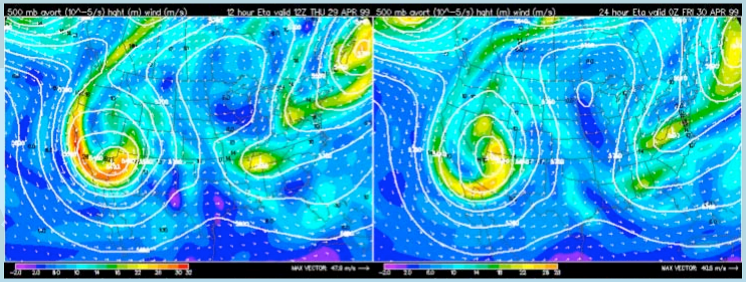


Omega Block



An omega blocking pattern has a life expectancy of 10-14 days. Chart shows 500-mb heights and absolute vorticity.

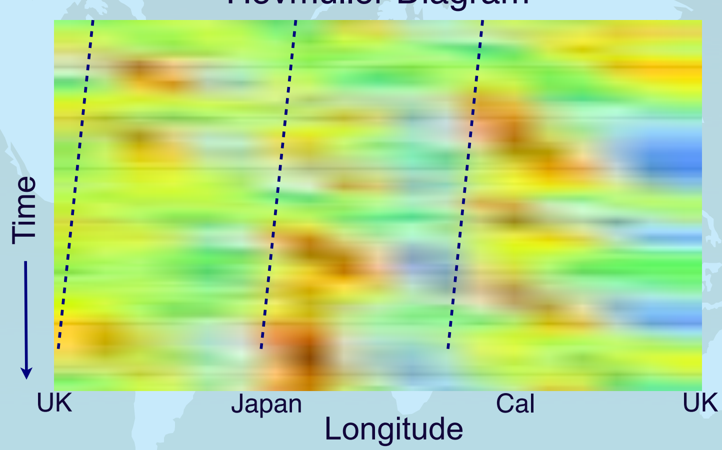
Omega Block



- The region under the omega block experiences dry weather and light wind for an extended period of time while rain and clouds are common in association with the two troughs on either side of the omega block.
- Omega blocks make forecasting easier since you can pinpoint areas that will be dominated by dry or rainy weather for several days.
- The right side of the omega block will have below normal temperatures (due to CAA) while the region to the left will have above normal temperatures (due to WAA) in this case.

Diagnosing Rossby Waves

Hovmuller Diagram



250-mb Meridional Wind (m s^{-1}); 35-60 N
Red: S, Blue: N 6-28 November 2002

Why do Rossby Waves form?

First let's review vorticity

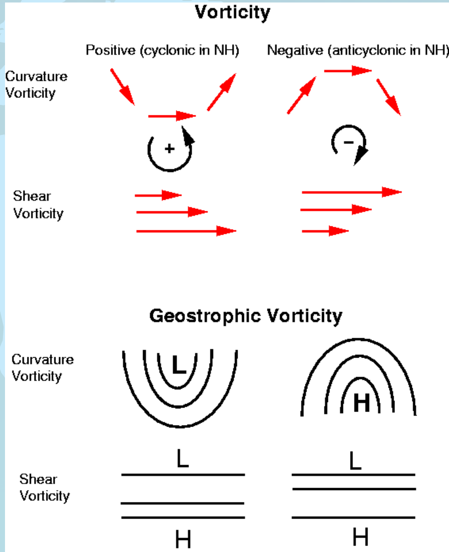
1. A measure of the intensity of a vortex
2. Related to the spin in 3 dimensions. only vertical is considered in evaluating the dynamics of Rossby Waves.
3. Twice the rate of angular rotation for solid body rotation. $\zeta r = 2V/r$
4. + for cyclonic, - for anticyclonic (Northern Hemisphere)

Planetary and Relative Vorticity

Relative Vorticity: $\zeta = \nabla \times \mathbf{V}$
Planetary Vorticity: $f = 2\Omega \sin\theta$

There are two parts or components of relative vorticity.

1. Shear vorticity
2. Curvature vorticity



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 = $2\Omega\sin\theta$ at latitude θ
- Earth's vorticity = Coriolis parameter

  $f = 2\Omega\sin\theta$

Vorticity Equation

Vertical component of vorticity equation in isobaric coordinates is obtained by taking the the x-derivative of the v-momentum equation and subtracting the y-derivative of the u-momentum equation and can be written

$$\zeta \equiv \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

$$\frac{d\zeta}{dt} + v\frac{\partial f}{\partial y} + (\zeta + f)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \frac{\partial v}{\partial p}\frac{\partial \omega}{\partial x} - \frac{\partial u}{\partial p}\frac{\partial \omega}{\partial y} \cong 0$$

$$v\frac{\partial f}{\partial y} = \frac{df}{dt}$$

$$\frac{d}{dt}(\zeta + f) + (\zeta + f)\nabla_p \cdot \mathbf{V} = \frac{\partial u}{\partial p}\frac{\partial \omega}{\partial y} - \frac{\partial v}{\partial p}\frac{\partial \omega}{\partial x} \cong 0$$

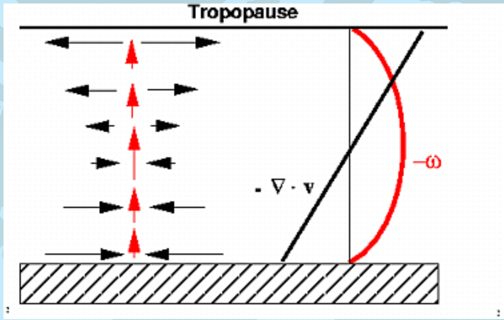
Simplified Vorticity Equation

Thus the vorticity equation can be simplified to

$$\frac{d}{dt}(\zeta + f) \cong -(\zeta + f)\nabla_p \cdot V$$

The rate of change of absolute vorticity of particular portions of fluid is equal to minus the absolute vorticity multiplied by the divergence.

Absolute Vorticity is Conserved



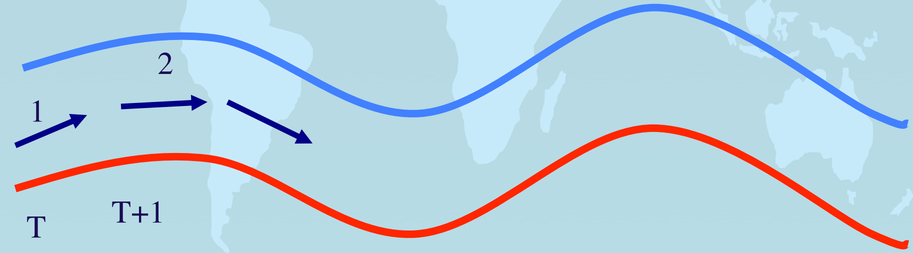
If we look back to our simplified model of upper-level and lower-level divergence, at mid levels the divergence must approach zero. At that level, absolute vorticity is conserved.

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

Absolute Vorticity Conservation

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

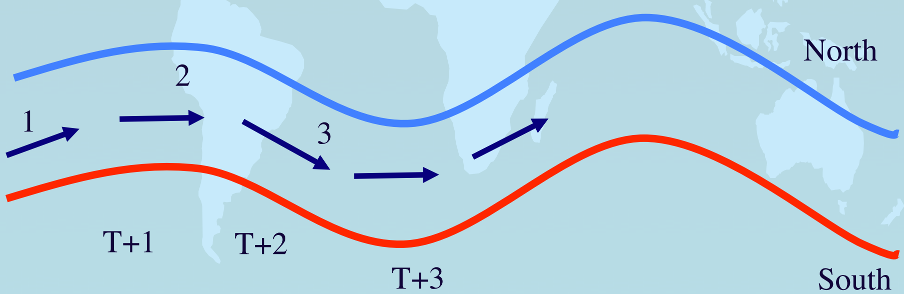
Point 1 to 2, *f* increases so ζ decreases, curvature becomes anticyclonic and the flow turns southward.



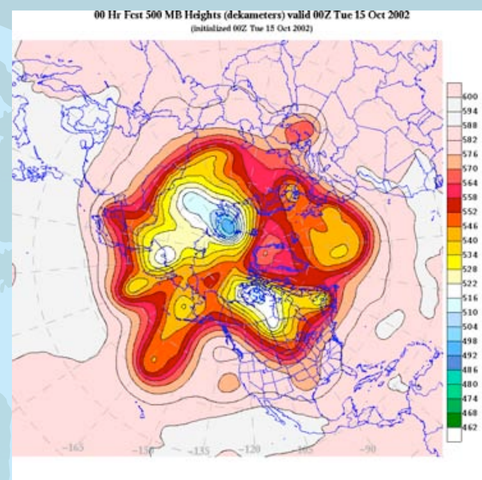
Absolute Vorticity is Conserved

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

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

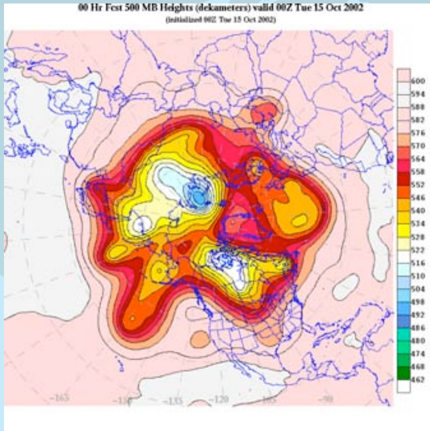


Planetary Waves Conserve Absolute Vorticity



This cyclonic (anticyclonic) oscillation of air parcels as they move equatorward (poleward) describes the alternating trough/ridge pattern seen in the mid-latitude westerlies.

Planetary Wave Propagation



For Planetary waves, which generally span more than 10,000 km, f -advection is much greater than ζ advection. Therefore, the sign of the f advection determines whether η (≡ ζ+f) advection will be + (PVA→ falling heights) or - (NVA → rising heights)

Rossby Wave Propagation

- In northwesterly flow upstream of the trough axis, *f* advection is positive (wind is blowing from higher toward lower values of *f*). Thus PVA produces height falls upstream (west) of the trough.
- In southwesterly flow downstream of the trough axis, *f* advection is negative (the wind is blowing from lower toward higher values of *f*). Thus NVA produces height rises downstream (east) of the trough
- Height falls west of the trough axis and height rises east of the trough axis force the trough to move westward (retrograde) against the flow.

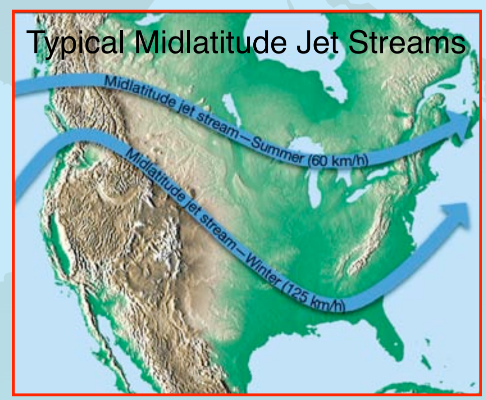
What Influences Rossby Wave Patterns?

Climatological positions and amplitudes are influenced by:

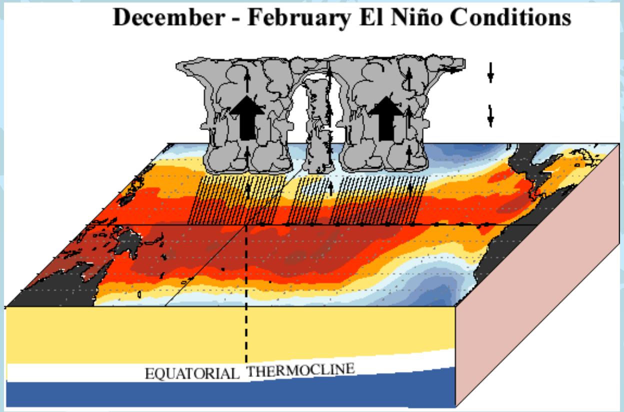
- Oceans
- Land masses
- Terrain features (such as mountain ranges)

Rossby Wave Forcing

- Mountains set up waves in westerlies (Rockies, Andes)
- Regions of strong thermal heating also set up waves. (e.g., ENSO and MJO)
- Regions of strong thermal contrast: cold land to warm sea

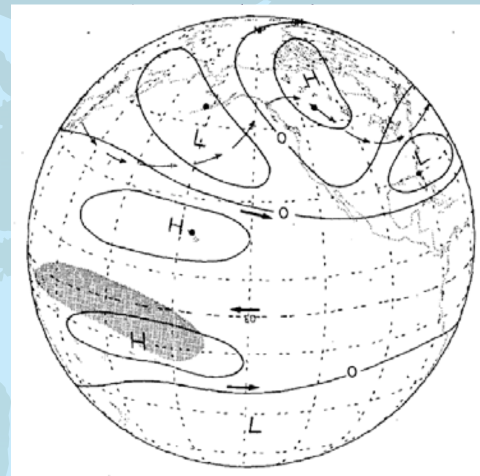


Rossby Wave Forcing by El Niño



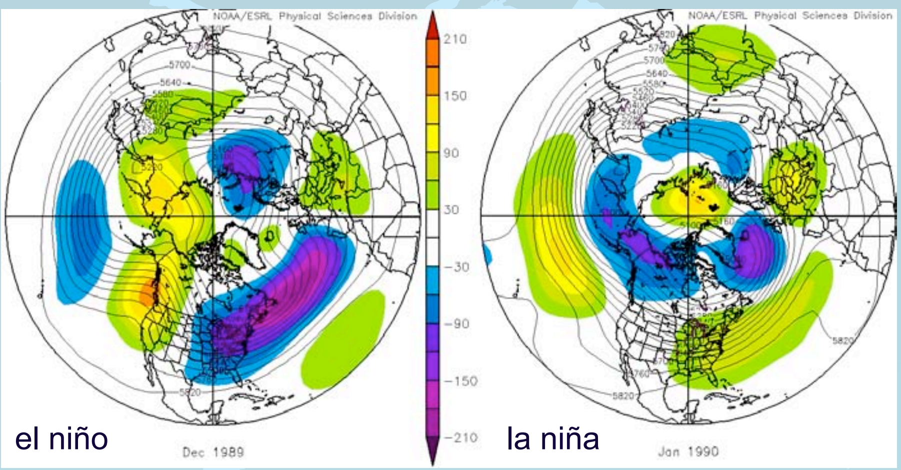
Enhanced convection over the central equatorial Pacific results in a ridge aloft and a Rossby wave train called the Pacific North America (PNA) pattern.

Rossby Wave Forcing



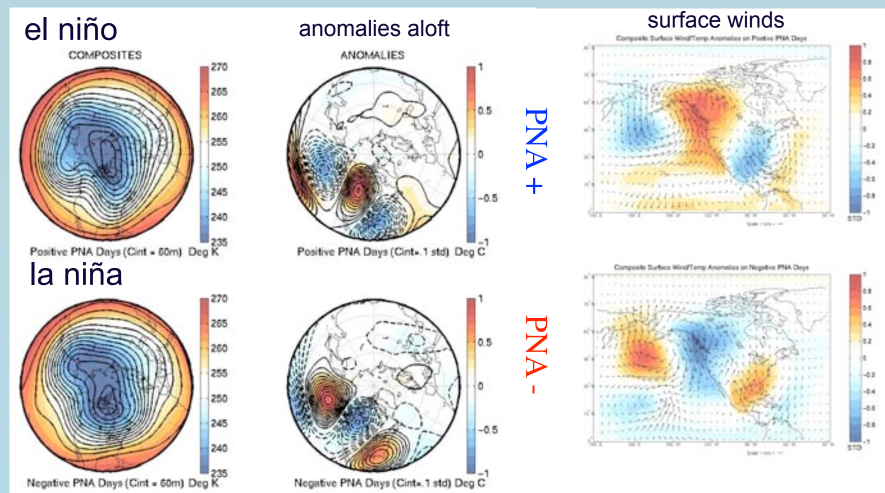
Enhanced convection over the central equatorial Pacific during el niño results in a ridge aloft and a Rossby wave train called the Pacific North America (PNA) pattern (Horel and Wallace 1981).

Rossby Wave Forcing by ENSO



Enhanced convection over the central equitorial Pacific results in a ridge aloft and a Rossby wave train called the Pacific North America (PNA) pattern.

Rossby Wave Forcing



Enhanced convection over the central equatorial Pacific results in a ridge aloft and a Rossby wave train called the Pacific North America (PNA) pattern. La Niña results in a -PNA pattern.

Planetary Wave Forcing

PNA+ leads to

drought over Hawaii with large surf.

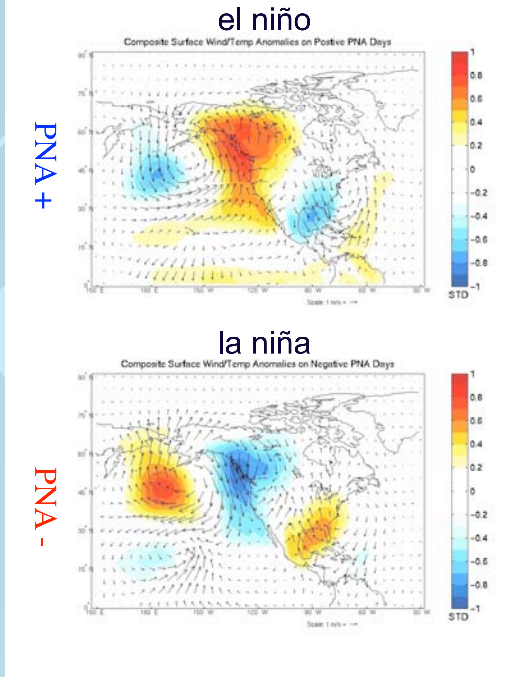
Warm and dry in the Pacific NW.

Wet over CA and wet and cold over the SE US.

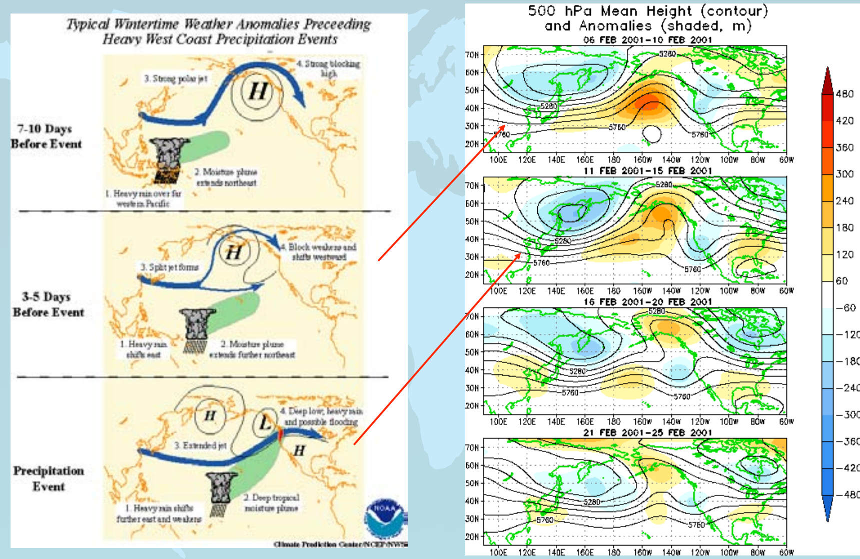
PNA- leads to

Wet for Hawaii

Cold and snowy over the Pacific NW and dry over the SE US

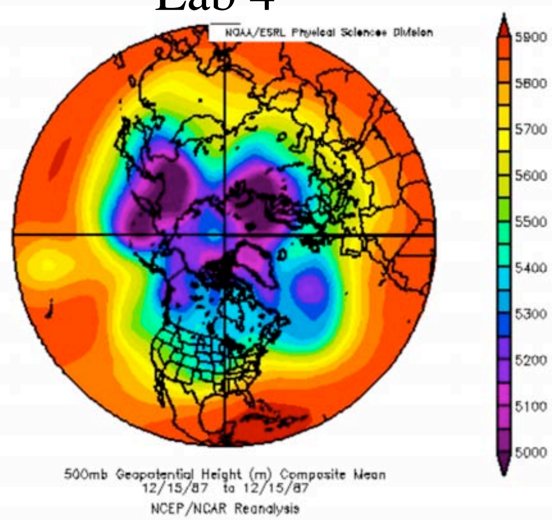


Madden-Julian Oscillation



MJO Influence on US Temperature and Precipitation

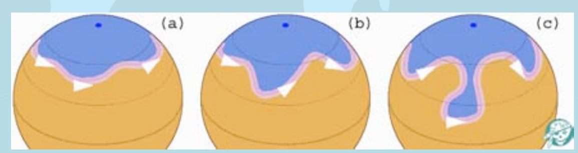
Lab 4



Where are the Rossby Wave Trough Axes?

Rossby Waves Summary

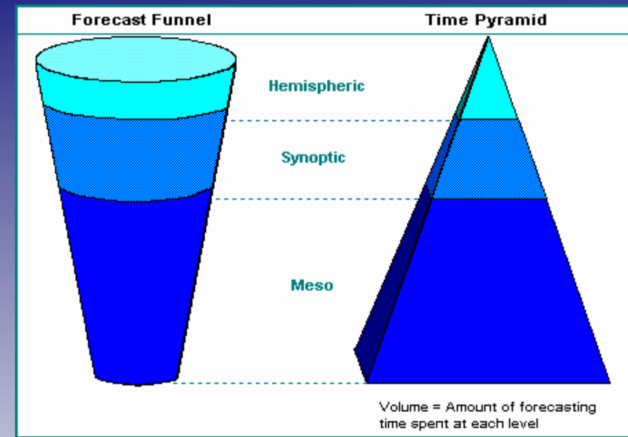
- Jet-stream dynamics are governed by Rossby Waves.
- Rossby waves are the result of instability of the jet stream flow with waves forming as a result of the variation of the Coriolis force with latitude.
- Rossby waves are a subset of inertial waves. In an equivalent barotropic atmosphere Rossby waves 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.



Synoptic-Planetary Scale Interaction

The Global and Synoptic context of High Impact Weather Systems

The Forecast Context



- Forecast Funnel – focus attention from the global scale on down to the local scale.
- Time Pyramid – gauge the amount of time that may be needed to assimilate the different scales of interest.

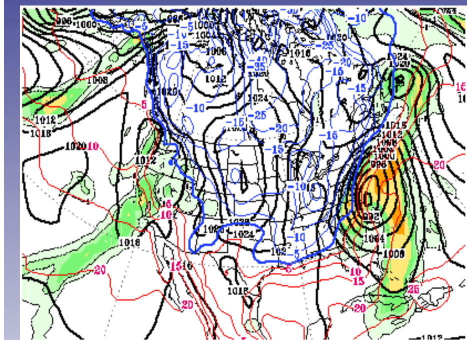
High-impact forecasts with limited skill

The Great Snowstorm: 25-27 January 2000

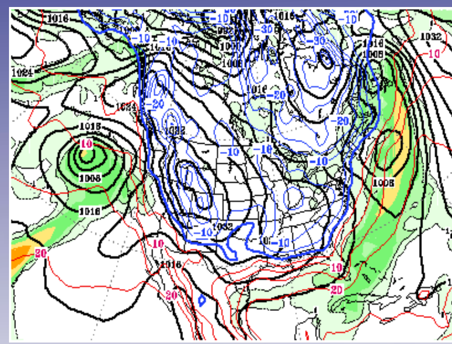
SeaWiFS Project NASA/ Goddard: 31 January 2000

Washington D.C., 27 January 2000

=NCEP 96-h Forecast versus Verification



MRF Analysis



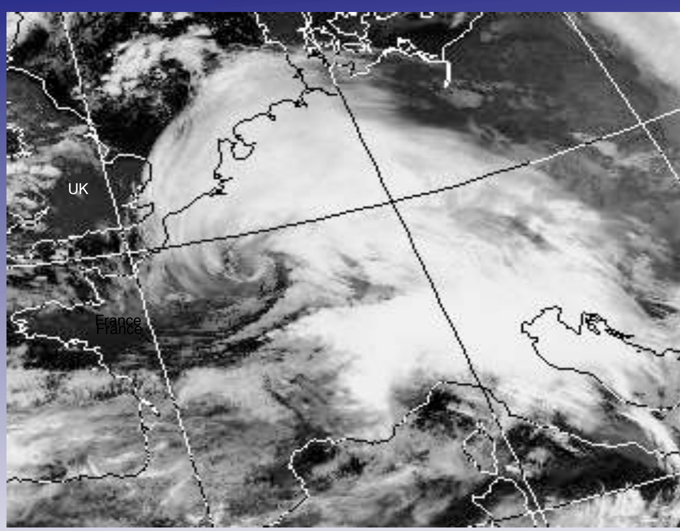
MRF 96-h Forecast

Medium-range 96-h sea-level pressure forecast valid at 1200 UTC 25 Jan. 2000

European Wind Storm: December 1999

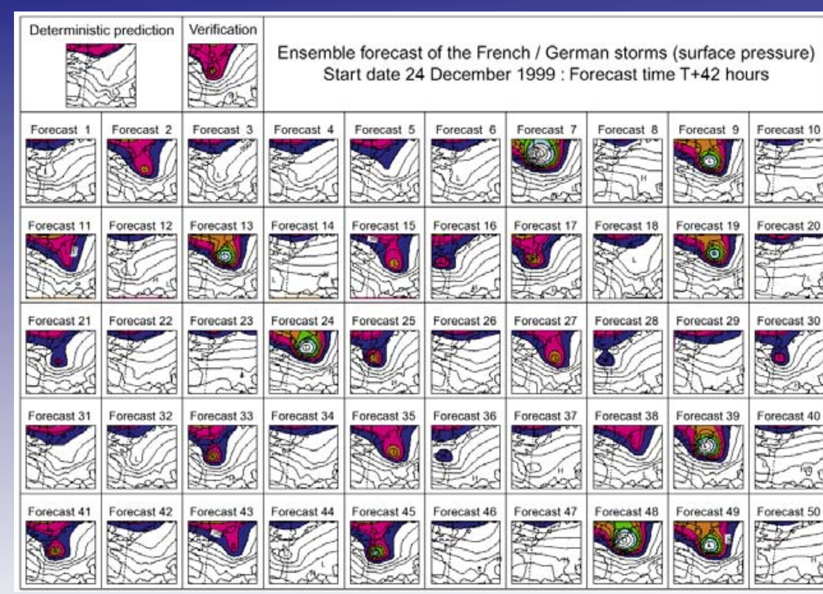
Destruction of the church in Balliveirs (left) and the devastation of the ancient forest at Versailes (below).

Lothar

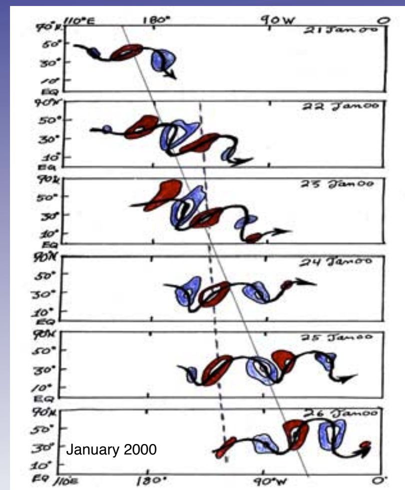


Dundee Satellite Station: 0754 UTC 26 December 1999

Lothar (T+42 hour TL255 rerun of operational EPS)

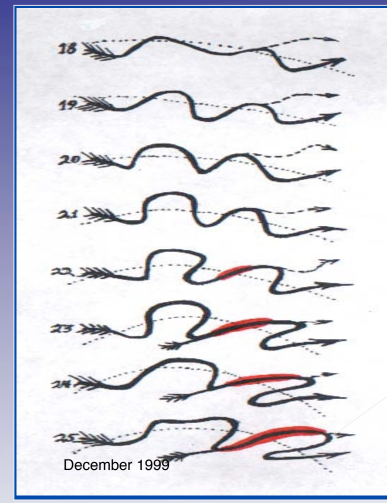


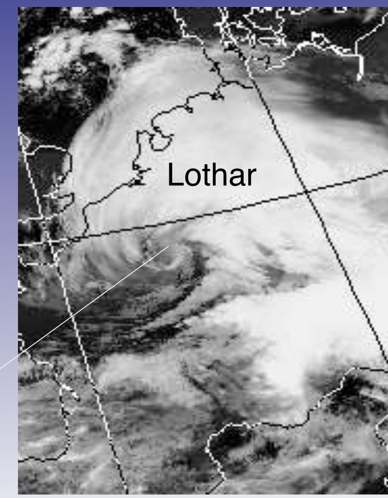
Rossby Wave Trains



Rossby Wave Trains

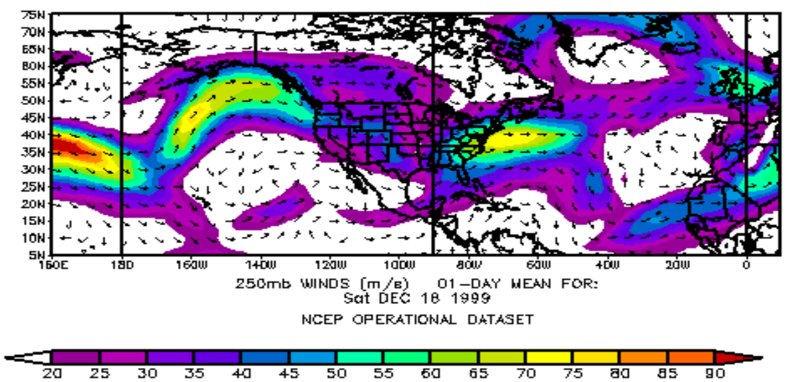
European Wind Storm



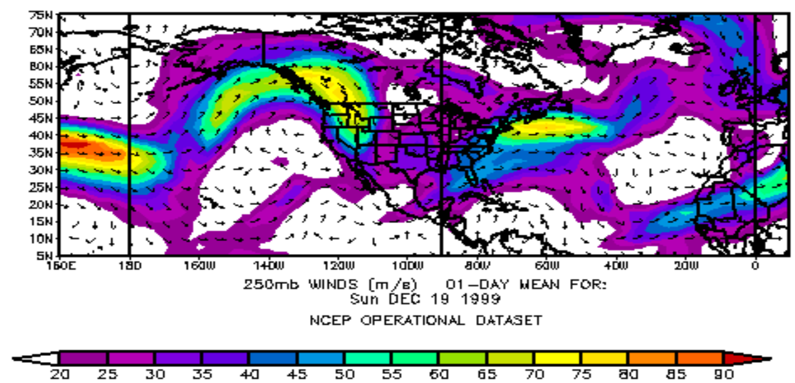


0754 UTC 26 December 1999

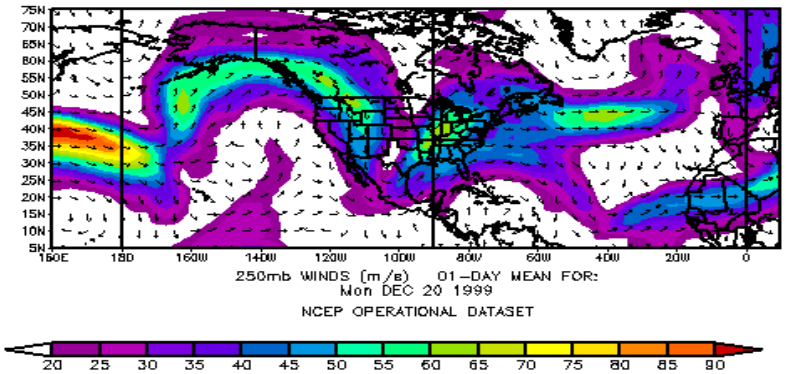
Rossby Wave Trains



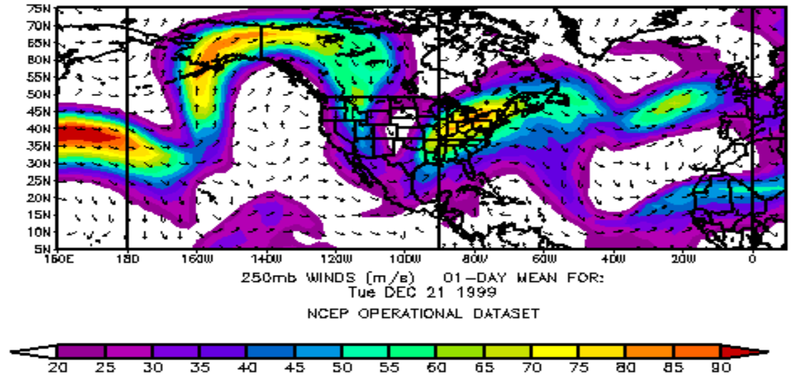
Rossby Wave Trains



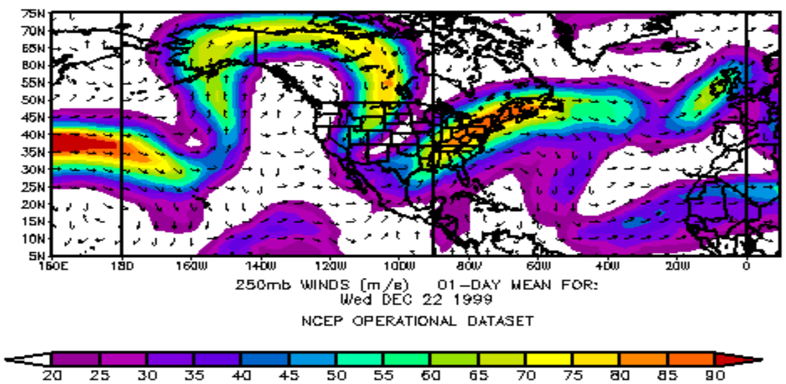
Rossby Wave Trains



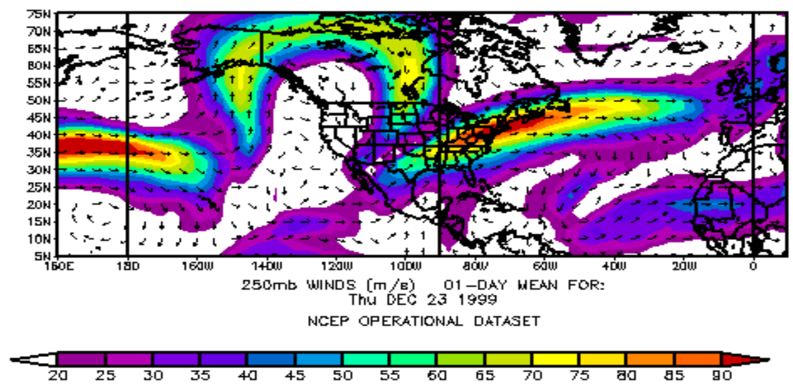
Rossby Wave Trains



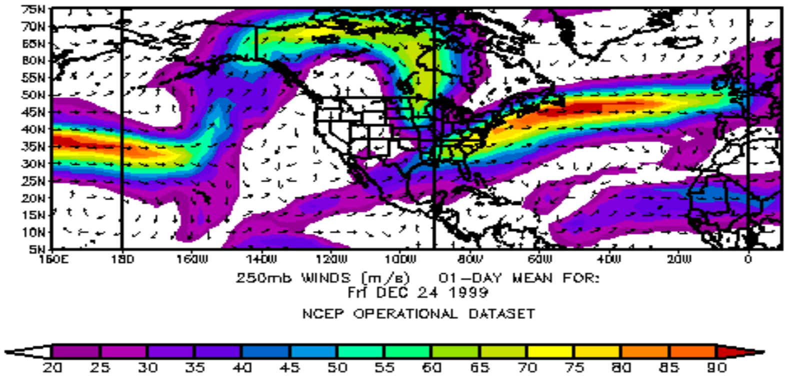
Rossby Wave Trains



Rossby Wave Trains



Rossby Wave Trains



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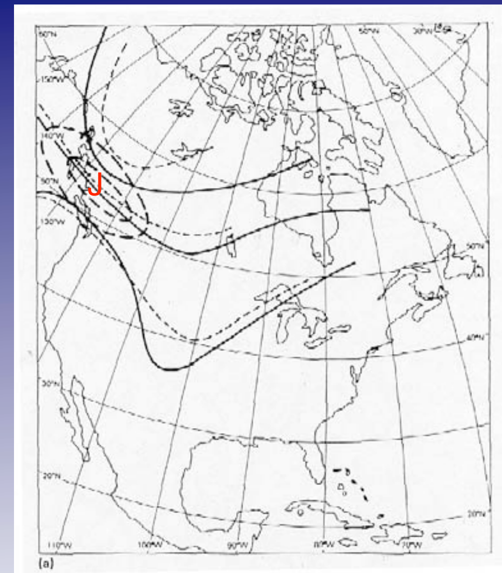
Conceptual Model of Shortwave/Jet Streak



Time = t_0

Schematic depiction of the propagation of a mid-tropospheric jet streak through a Rossby wave over 72 h.

Solid lines: height lines

Thick dashed lines: isotachs

Thin dashed lines: isentropes

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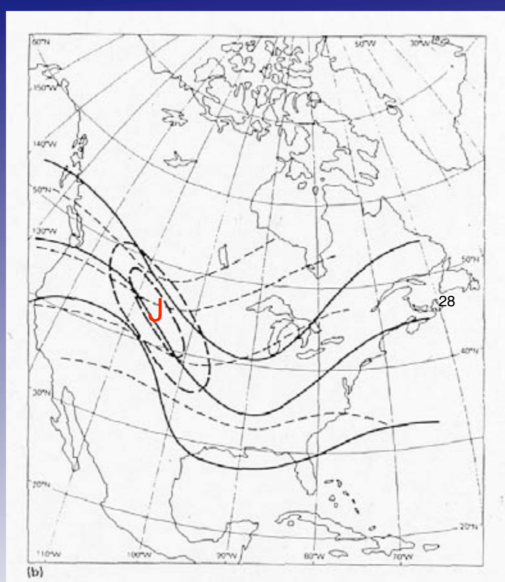
Conceptual Model of Shortwave/Jet Streak

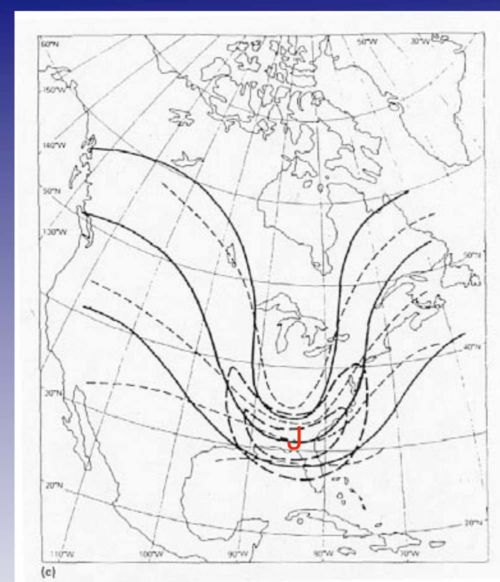


Time = t_0 + 24 h

Jet streak on northwestern side of diffluent trough at mid-tropospheric levels; note cold advection into amplifying trough.

55

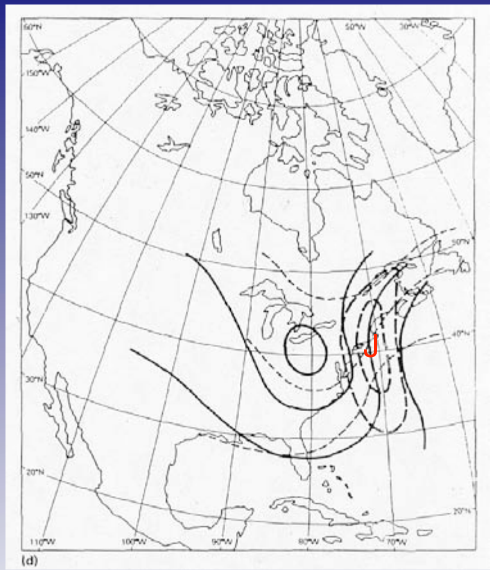
Conceptual Model of Shortwave/Jet Streak



Time = t_0 + 48 h

Jet streak at the trough axis of a nearly fully developed wave. Note: banana-shaped jet streak is not often seen due to strong upstream ageostrophic flow in base of trough. Often a new jet streak develops on eastern side of trough.

56

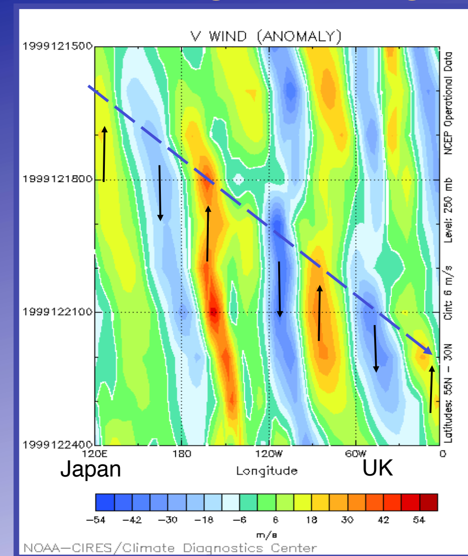


Conceptual Model of Shortwave/Jet Streak

Jet streak situated in the southwesterly flow of the short wave trough (i.e., lifting wave) that is deamplifying. Note: surface system is typically still deepening during this stage.

Time = t_0 + 72 h

Time-Longitude Diagram

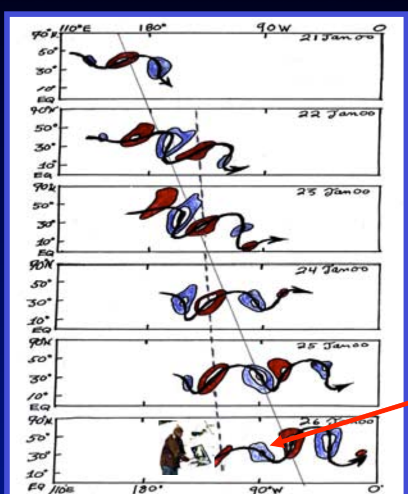


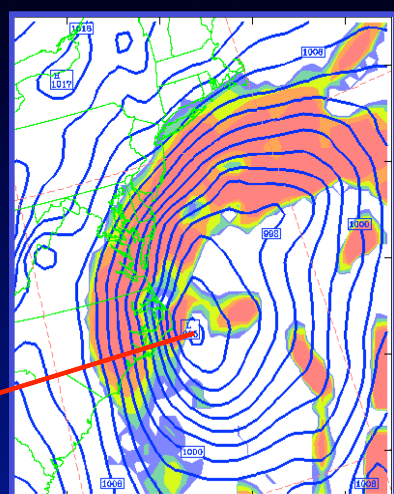
6 Days

250-mb meridional wind (m s^{-1})

15-24 Dec. 1999, Lat. 30-55 N, Long. 120 E-360

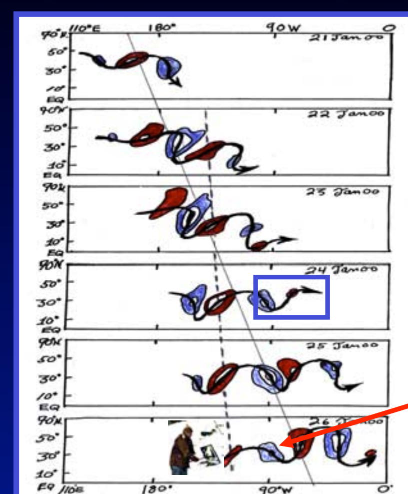
Rossby Wave Trains

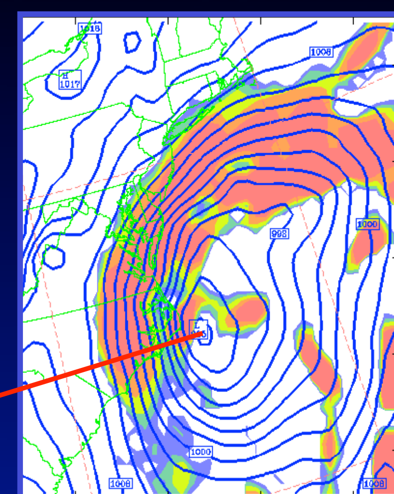




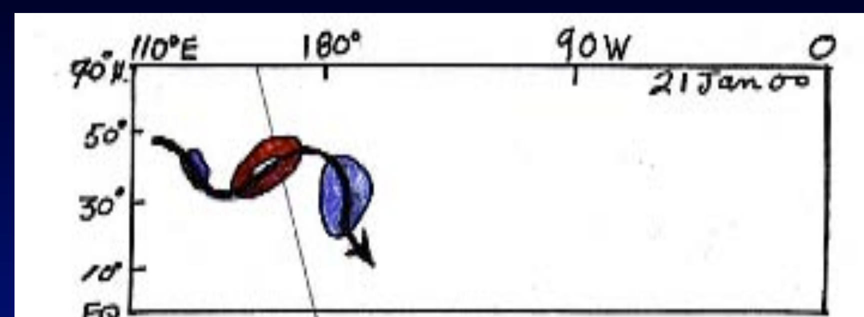
January 2000 Blizzard

Rossby Wave Trains



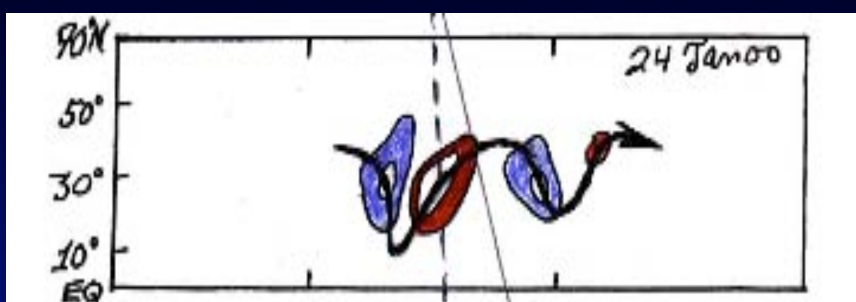


January 2000 Blizzard

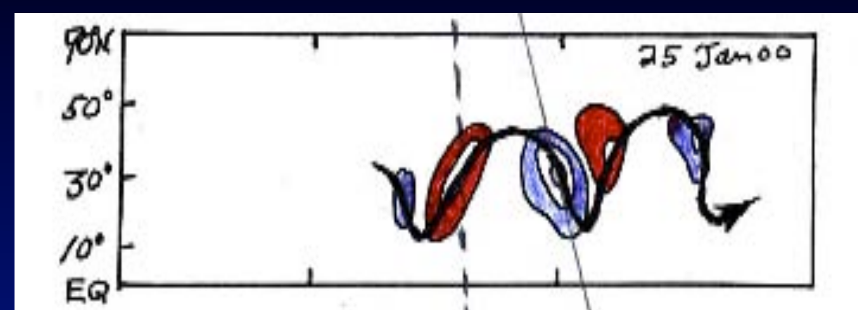

110°E
180°
90W
0
90°N
21 Jan 00
50°
30°
10°
EQ

22 Jan00
90°N
50°
30°
10°
EQ

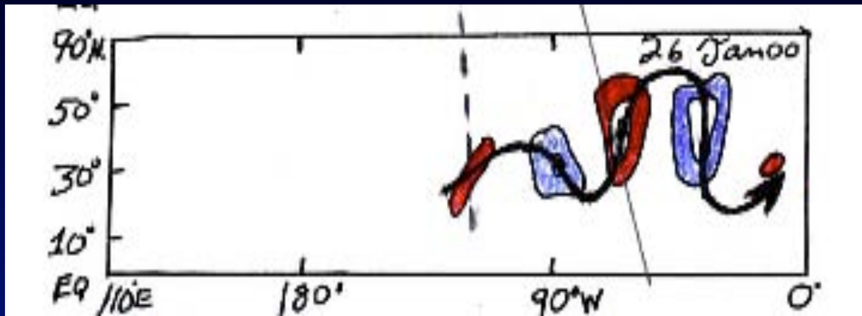
23 Jan00
90°N
50°
30°
10°
EQ



24 Jan00
90°N
50°
30°
10°
EQ



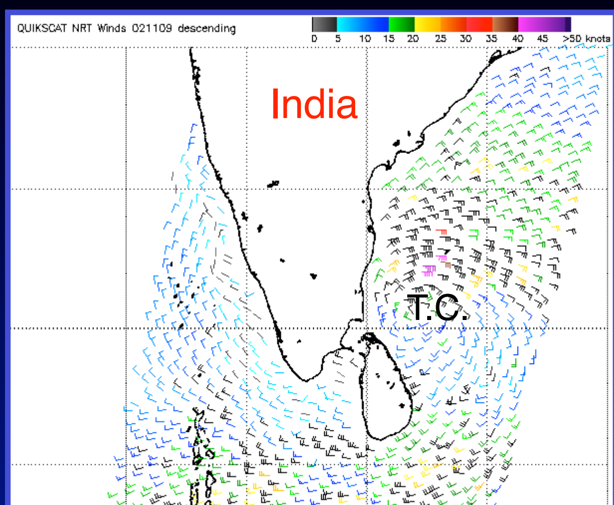
25 Jan00
90°N
50°
30°
10°
EQ



Societal Economic Impacts of Extreme Weather

A Global-to-Regional Perspective of The events of November 2002

Tropical Cyclone: 9 November 2002



QUIKSCAT Surface Winds (knots)

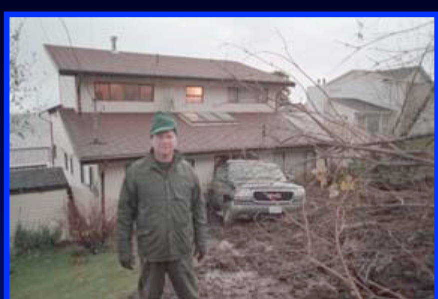
Bay of Bengal Tropical Cyclone: 10 November 2002

~200 fisherman lost at sea

US Tornado Outbreak: 11 November 2002

US Tornado Outbreak: 11 November 2002

12 November 2002

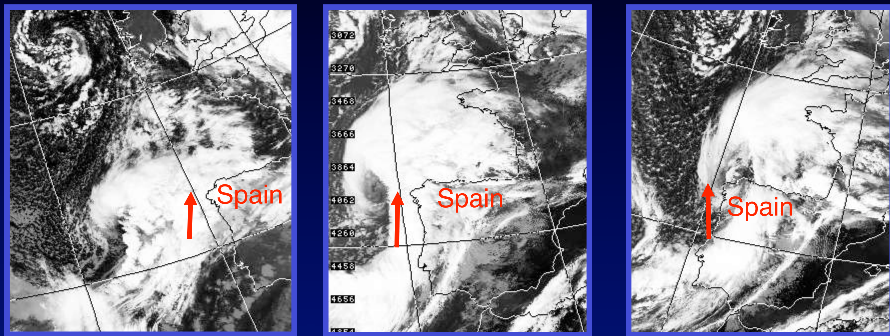


Poorly forecast rainfall event over Eastern Vancouver Island
40-50 mm in 24 h. Impacts: Mudslides, power outages

Oil Tanker “Prestige”Disaster

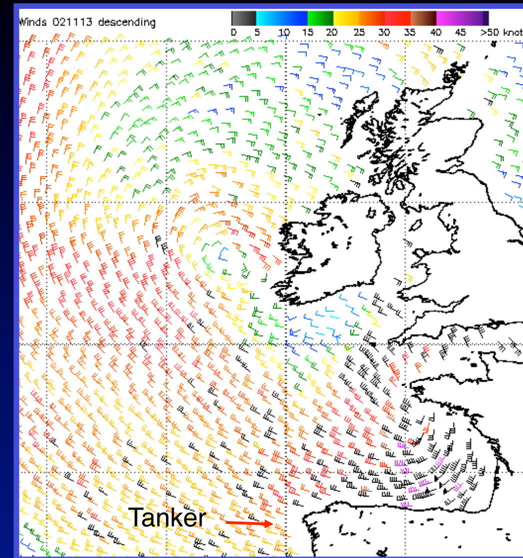
13-19 November 2002

13 November 2002
Oil Tanker



Dundee Satellite Station

QUIKSCAT Surface Winds



13 November 2002

Oil Tanker "Prestige"Disaster

Alpine Floods: 16-17 November 2002

Swiss -Italian Flooding: 0000 UTC 16 November

Eastern Switzerland: 17 November 2002

Austrian-German Alpine Wind Storm

17 November 2002

Austrian-German Alpine Wind Storm

Eastern US-Canadian Snow and Ice Storm

16 November 2002

November 18/19 2002

School Gymnasium in Vancouver collapses under heavy rains.

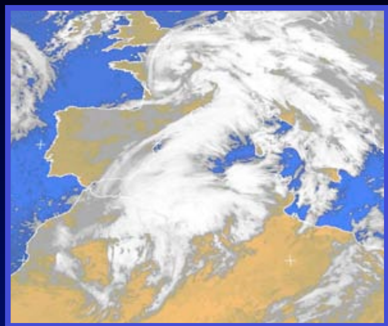
NASA space shuttle Endeavor and crew prepare for liftoff
23 November 2002

Spanish-born, U.S. astronaut Michael Lopez-Alegria, right, waves as he leaves the Operations and Checkout Building at Kennedy Space Center in Cape Canaveral, Fla., Saturday afternoon with fellow crew members, John Herrington, left, the first tribal registered American-Indian astronaut, and Don Pettit, center, for a trip to launch pad 39-A for a planned liftoff onboard the space shuttle Endeavour. (AP Photo)

“Rain in Spain creates liftoff pain”

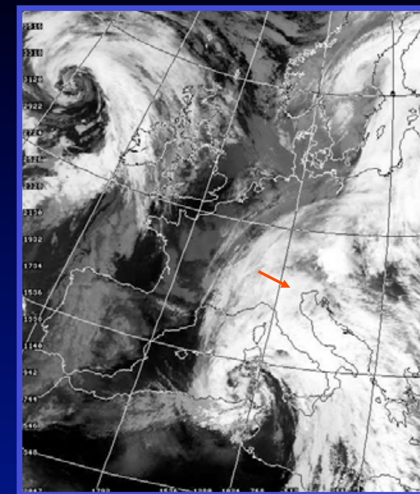
“ NASA fueled space shuttle Endeavor for liftoff Saturday,
but storms in Spain loomed as a possible show stopper – again”.

Moroccan Flood: 0600 UTC 25 November 2002



Italian Alps: 26 Nov 2002

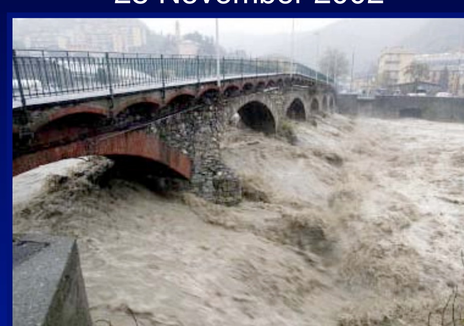
Dundee Satellite Image



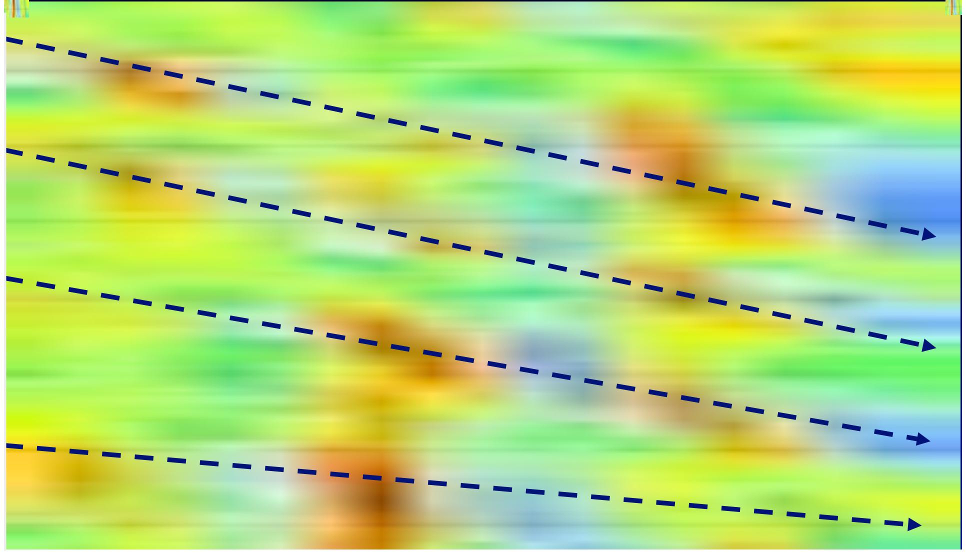
Flooding in Italian Alps

Lago Maggiore:
26 November 2002

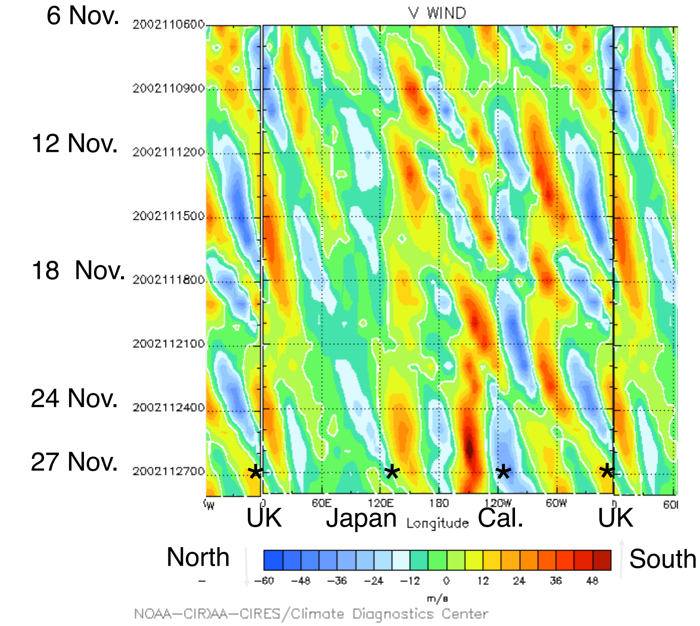
Northern Italy
28 November 2002



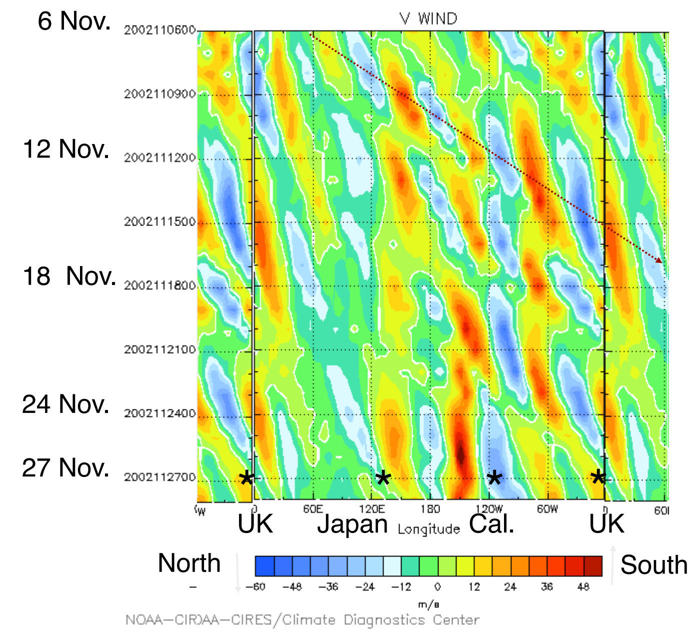
A Rossby-Wave Perspective of High-Impact Weather: November 2002



Time/Long. Diagram: 250-mb Meridional Wind (m s^{-1}); 35-60 N
6-28 November 2002



Time/Long. Diagram: 250-mb Meridional Wind (m s^{-1}); 35-60 N
6-28 November 2002



Time/Long. Diagram: 250-mb Meridional Wind (m s^{-1}); 35-60 N
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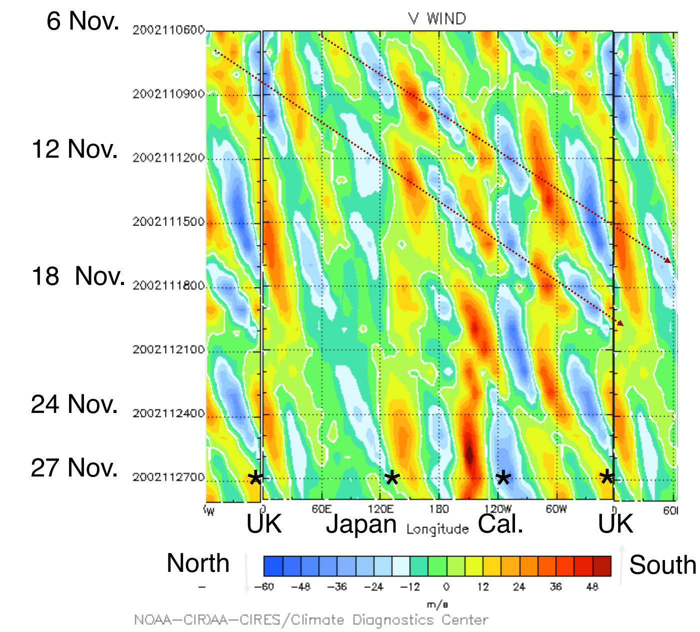
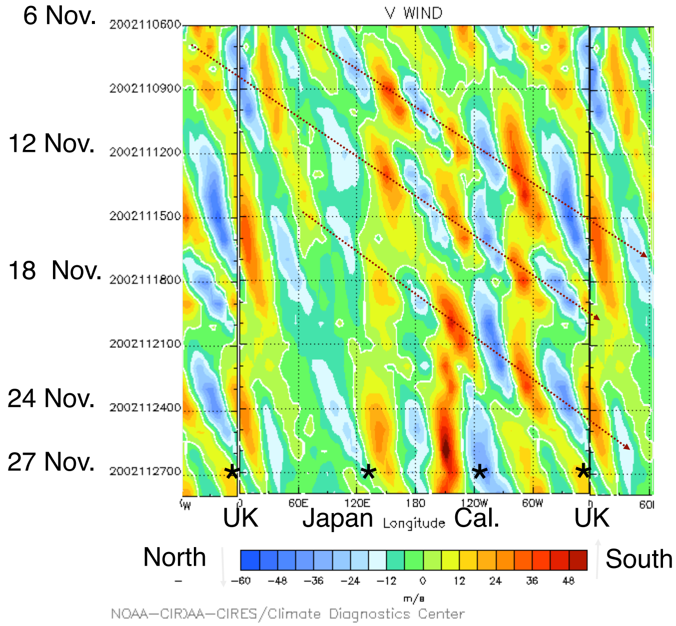
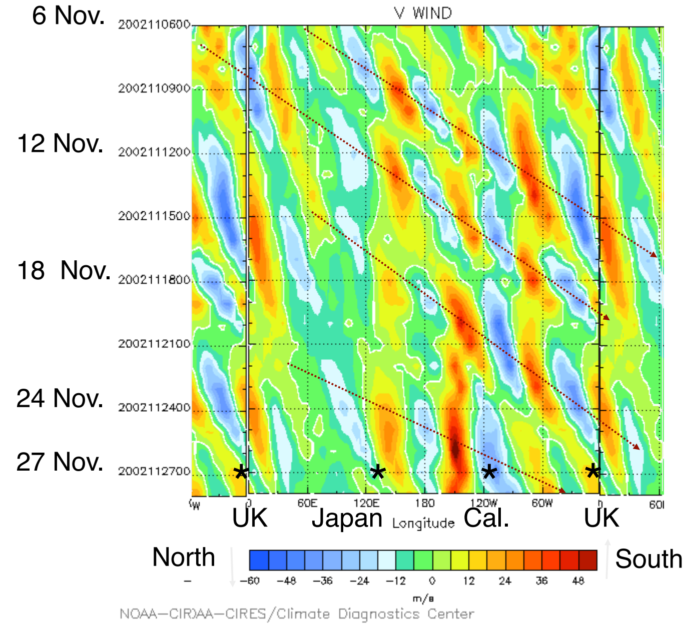


Time/Long. Diagram: 250-mb Meridional Wind ($m\ s^{-1}$); 35-60 N
6-28 November 2002



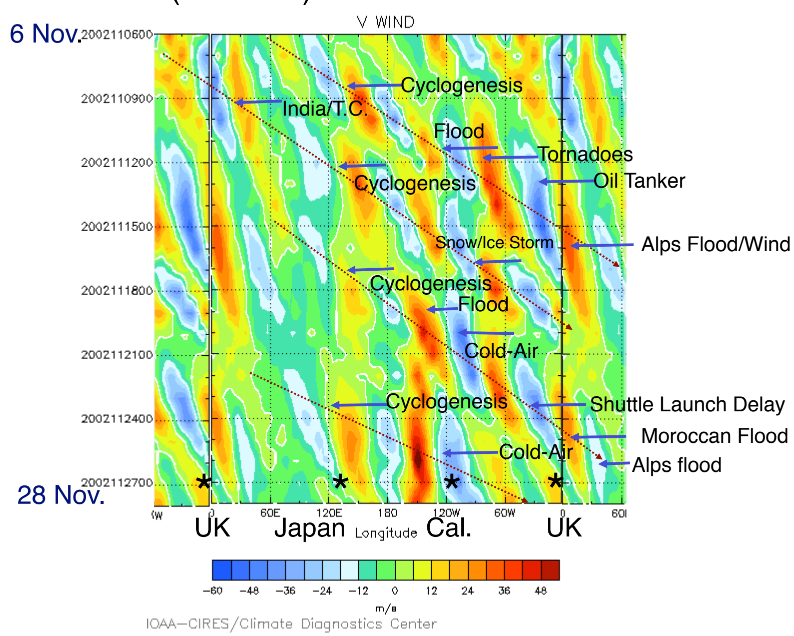
97

Time/Long. Diagram: 250-mb Meridional Wind ($m\ s^{-1}$); 35-60 N
6-28 November 2002



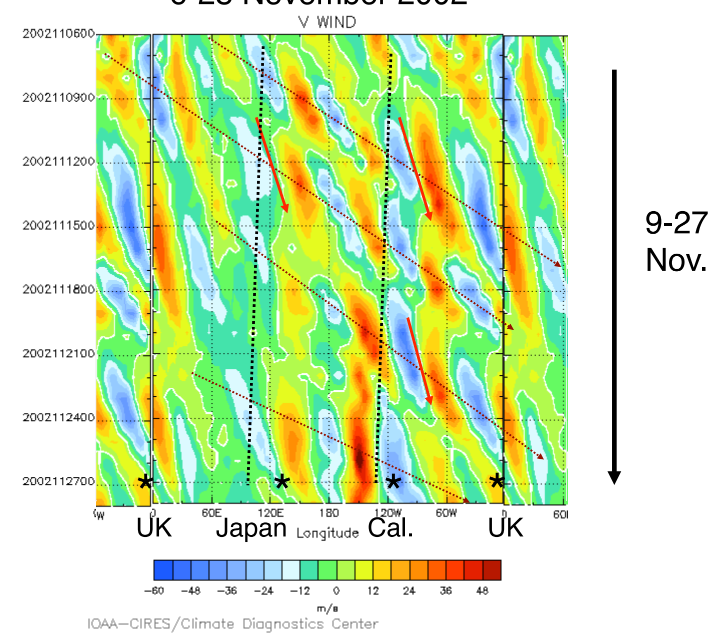
98

Time/Long. Diagram: 250-mb Meridional Wind ($m\ s^{-1}$)
Latitude Belt (35-60 N) 6-28 November 2002



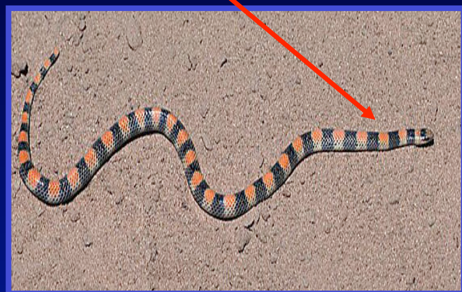
99

Time/Long. Diagram: 250-mb Meridional Wind ($m\ s^{-1}$); 35-60 N
6-28 November 2002



100

High-impact weather develops at the leading edge of expanding Rossby wave trains



Northwestern Floods

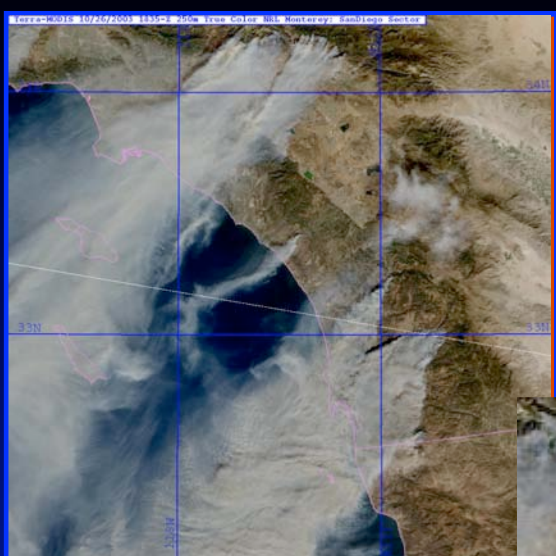
October 2003

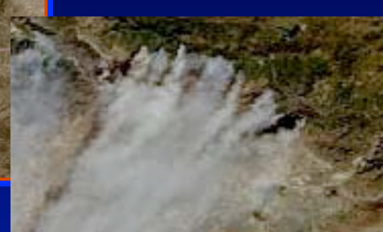
Two sub-tropical weather systems dropped 470 millimetres -- 18.5 inches -- of rain on some parts of coastal B.C. in a six-day period"

British Columbia - Record breaking heavy rain in Vancouver, Abbotsford and Victoria on October 16. Bridge washout cuts access to Pemberton, BC. "It is being called the worst flood of the past century" in British Columbia.

Washington - Snohomish, Nooksack and Skagit rivers overflowed October 17-18. Seattle broke a one-day rainfall record on October 20. Record levels on Skagit River at Concrete. Record levels on Snohomish River on October 21. Entire town of Hamilton under water. Flood damages have exceeded $160 million.

California Wild Fires





October 2003

California Wild Fires

October 2003

California Mud Slides

November 2003

October 2003

Synoptic-scale-waves

Wave-trains

Time-mean planetary-waves

3-5 billion dollar catastrophe

October 2003

Synoptic-scale waves

Wave trains

Time-mean planetary-waves

3-5 billion dollar catastrophe

October 2003

Synoptic-scale waves

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Time-mean planetary-waves

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October 2003

Synoptic-scale waves

Wave trains

Time-mean planetary-waves

3-5 billion dollar catastrophe

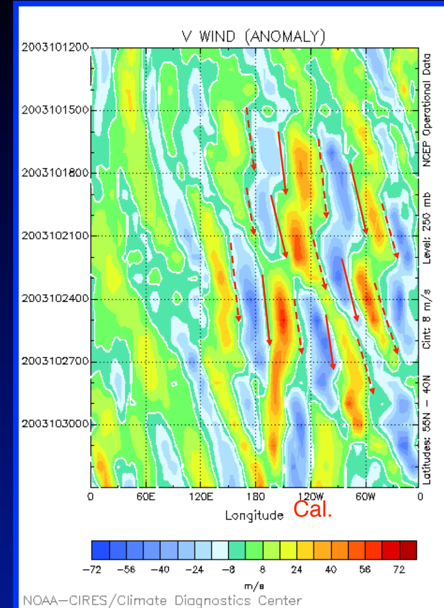
Time/Longitude: 250-mb Meridional Wind (m s^{-1}); 55-40N.

Oct. 12

Oct. 18

Oct. 24

Nov. 3



Synoptic Waves

Ridge Axes

Trough Axes

3-4 day life cycle

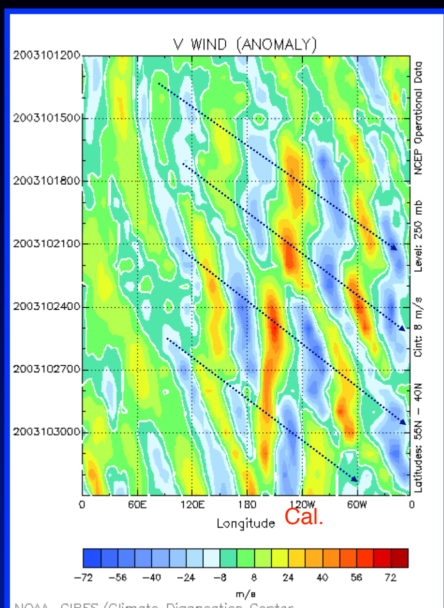
Time/Longitude: 250-mb Meridional Wind (m s^{-1}); 55-40N.

Oct. 12

Oct. 18

Oct. 24

Nov. 3



Rossby Wave Trains

6-14+day life cycle

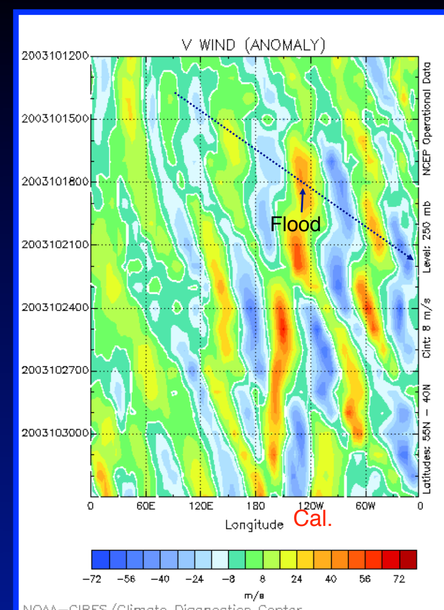
Time/Longitude: 250-mb Meridional Wind (m s^{-1}); 55-40N.

Oct. 12

Oct. 18

Oct. 24

Nov. 3



Time/Longitude: Meridional Wind (m s^{-1}); 55-40N.

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Oct. 24

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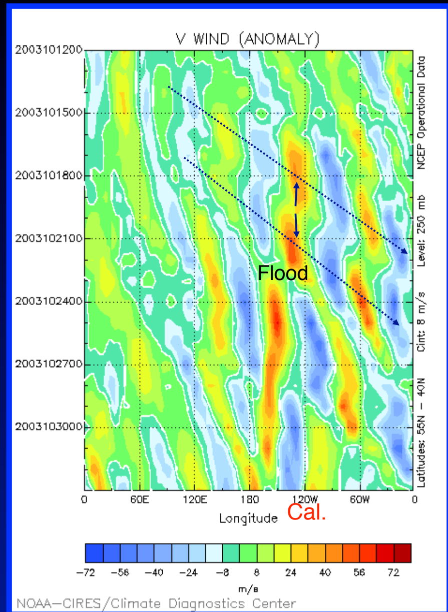

Time/Longitude: Meridional Wind (m s^{-1}); 55-40N.

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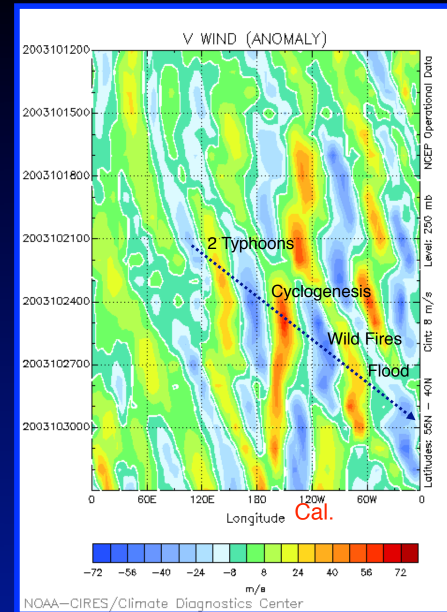
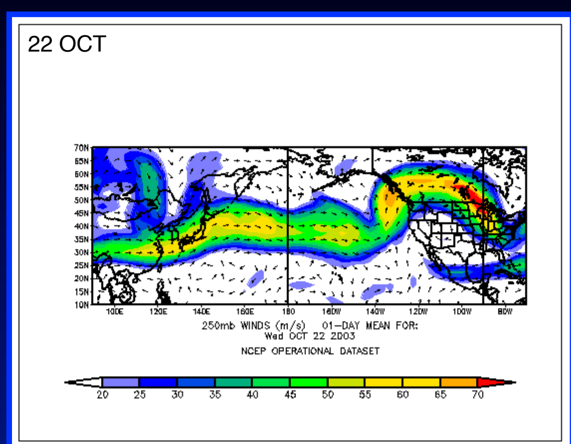
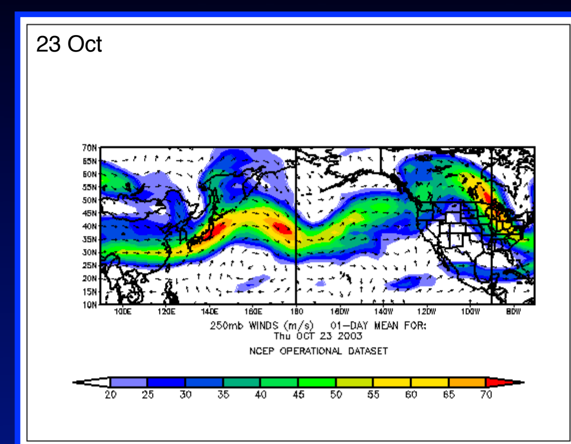


Rossby Wave Trains

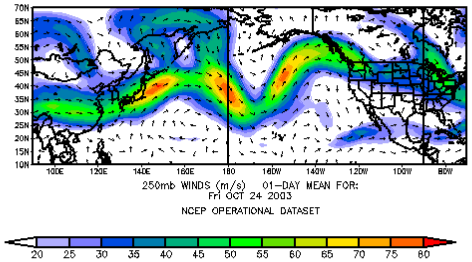


Rossby Wave Trains



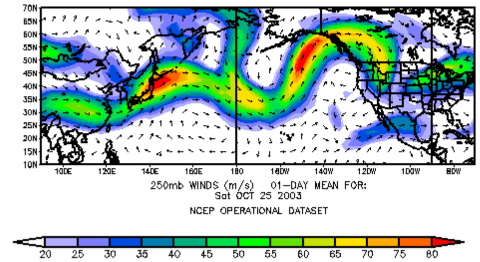
Rossby Wave Trains

24 Oct



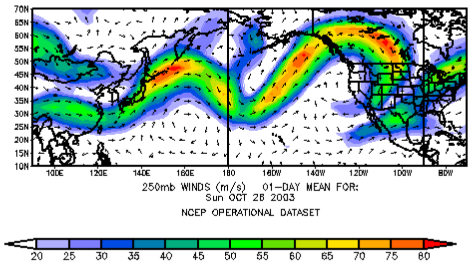
Rossby Wave Trains

25 Oct



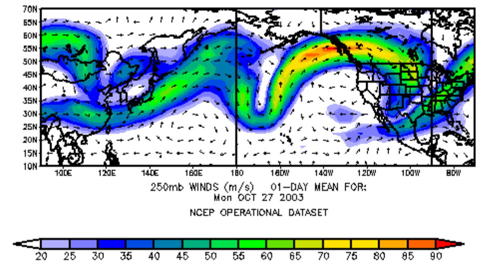
Rossby Wave Trains

26 Oct



Rossby Wave Trains

27 Oct



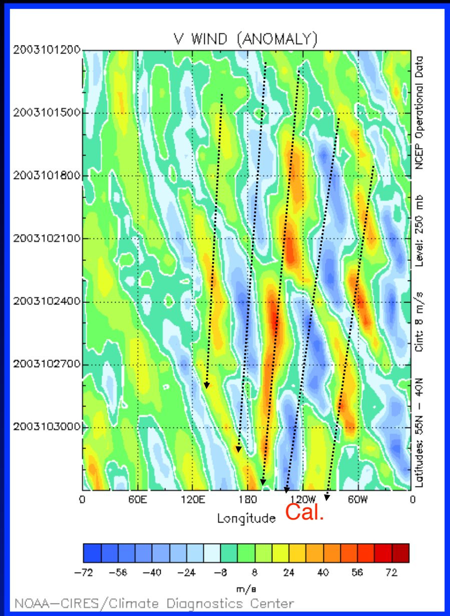
Time/Longitude: Meridional Wind (m s^{-1}); 55-40N.

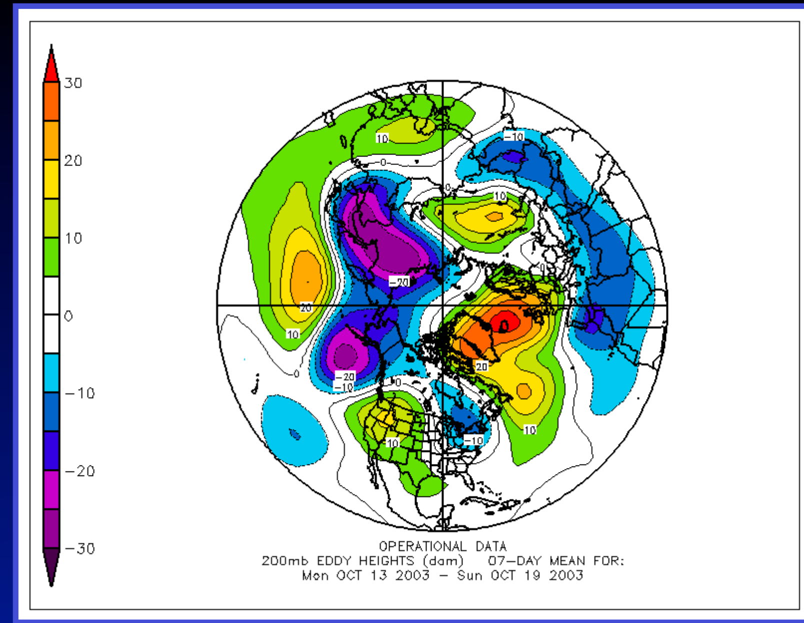
Oct. 12

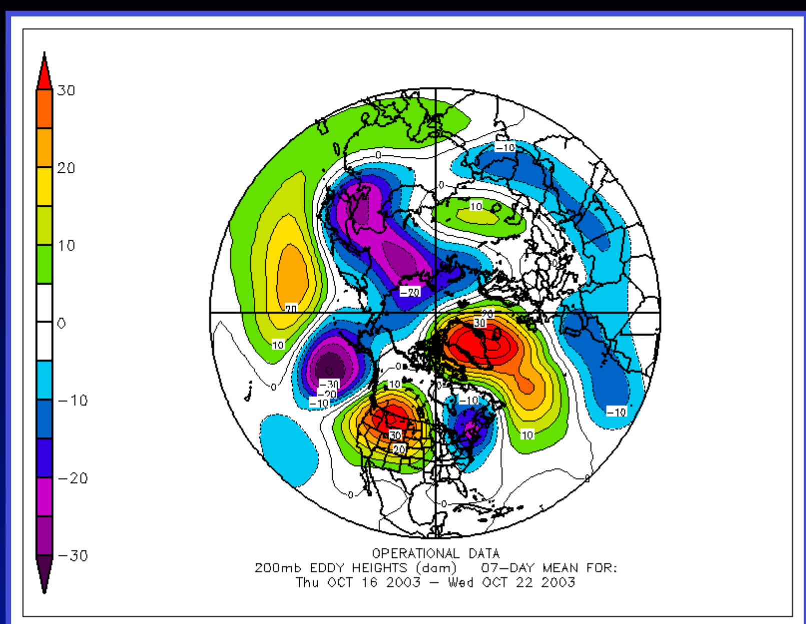
Oct. 18

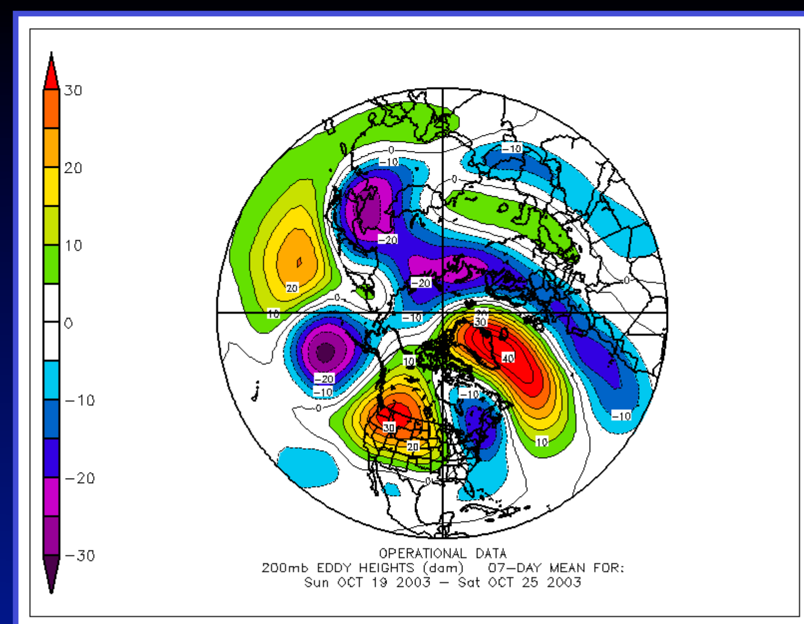
Oct. 24

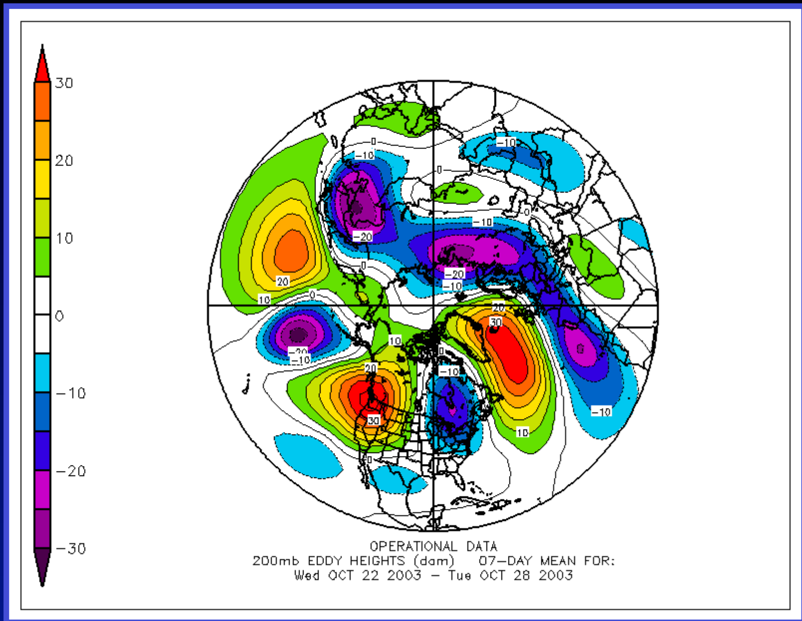
Nov. 3

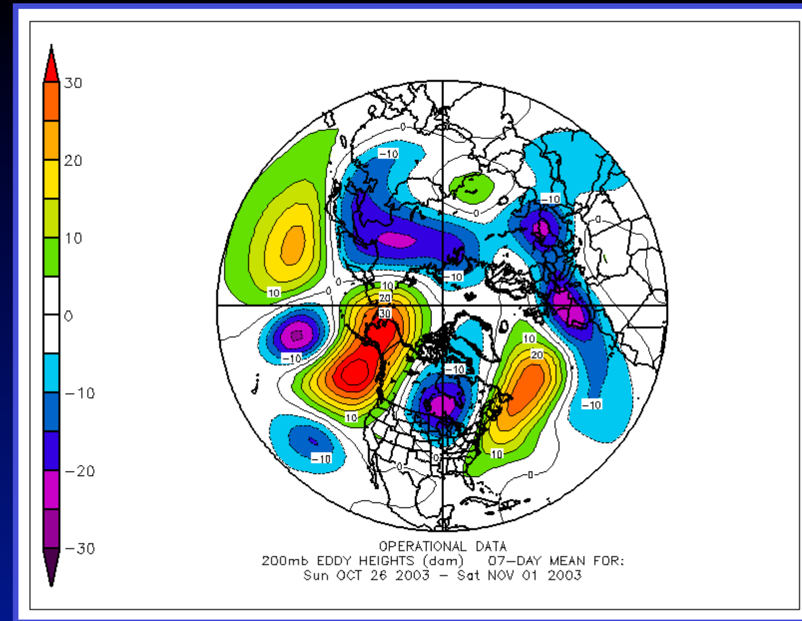












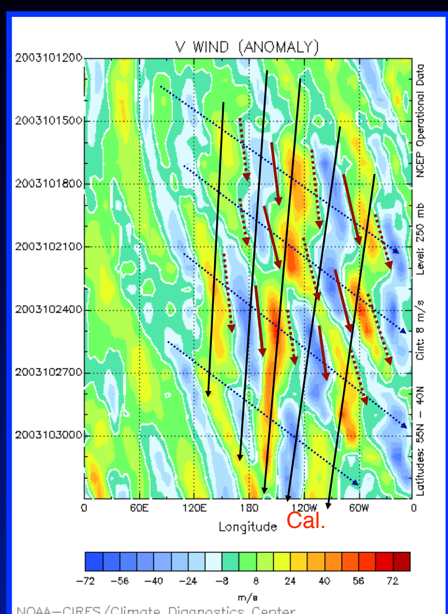
Time/Longitude: Meridional Wind (m s^{-1}); 55-40N.

Oct. 12

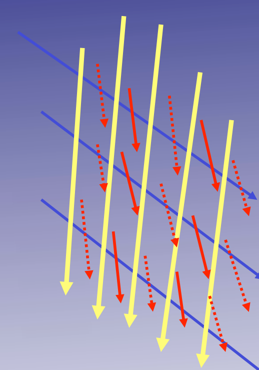
Oct. 18

Oct. 24

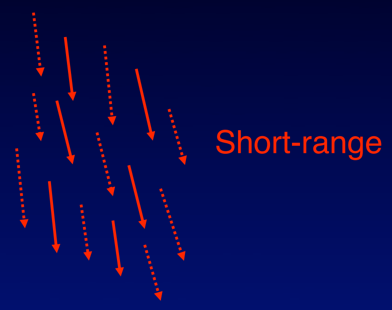
Nov. 3



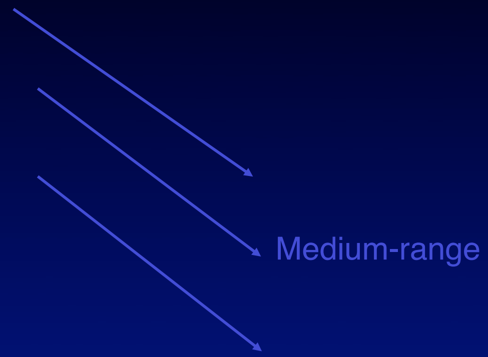
Three Time Scales



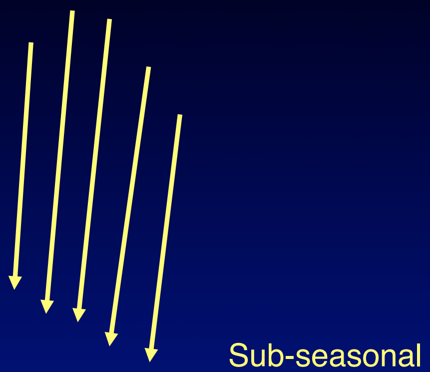
Synoptical-Scale



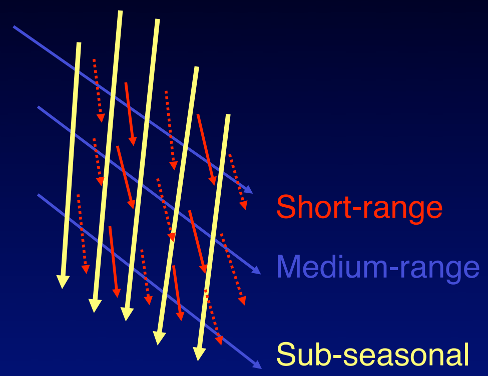
Rossby Wave Trains



Planetary Rossby Waves

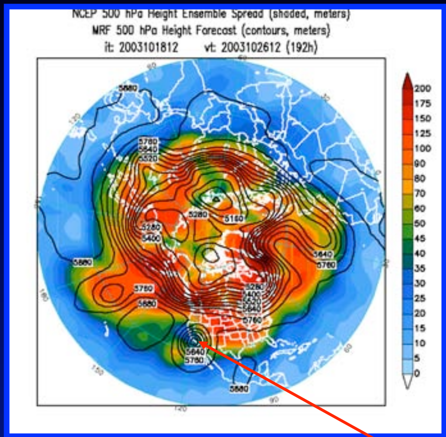


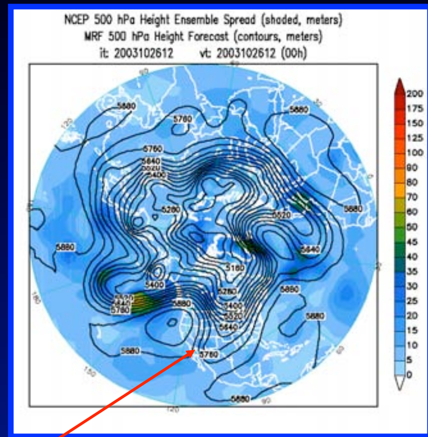
Three Interacting Time Scales



NOAA/NCEP Global Forecast System

196-h Forecast: 12:00 UTC 18 Nov. 2003 — Verifying Analysis

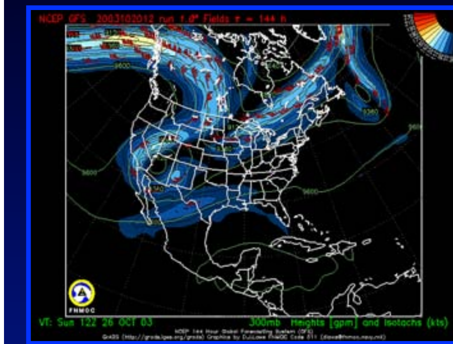


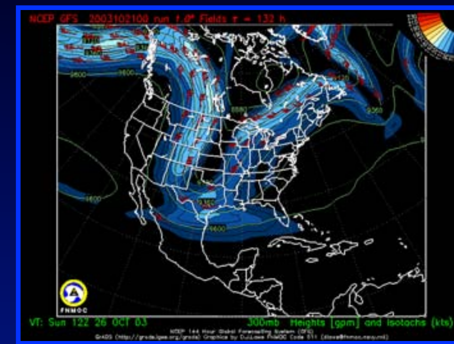


California wild fires: Forecast Bust?

Major changes in the deterministic forecast within 12 hours

NCEP 144-h Forecast — NCEP 132-h Forecast





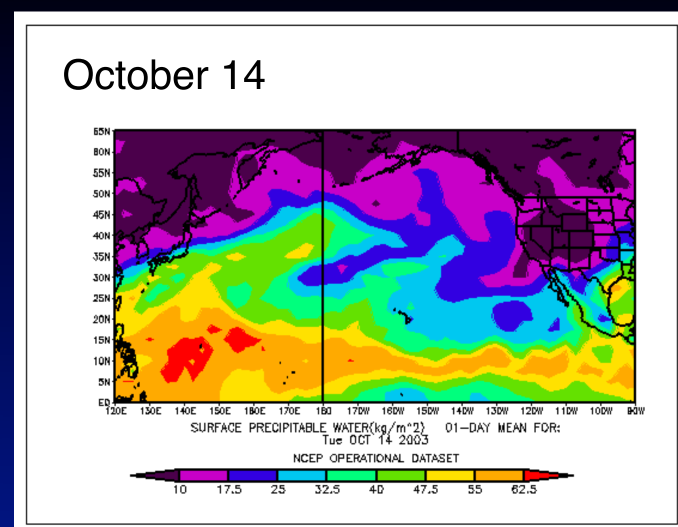
Verification: 1200 UTC 26 Oct 2003

Tropical to Extratropical Interactions

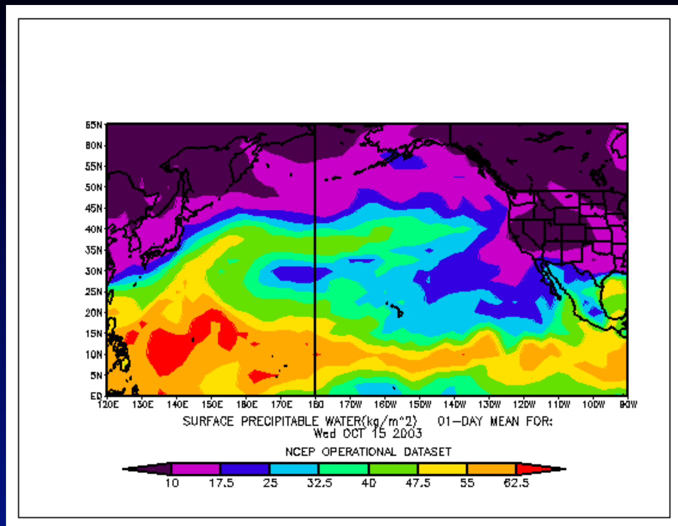
Energy from tropical convection can propagate into the extratropics to influence predictive skill.

- El Niño and La Niña regimes have significantly different extratropical sensitive regions.
- Lothar storm may have been influenced by a Madden-Julian Oscillation event over the eastern Pacific ocean 10 days earlier.

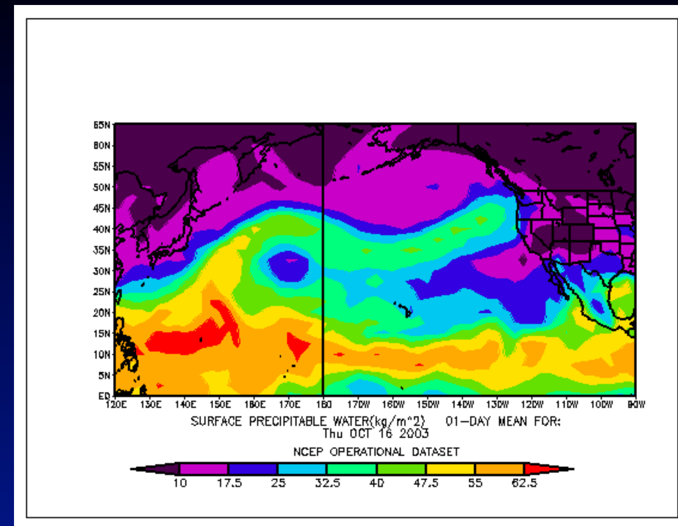
Tropical to Extratropical Interactions



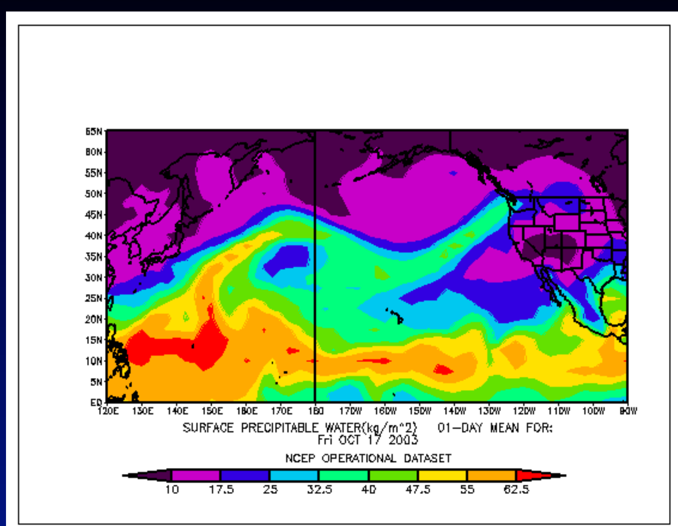
Tropical to Extratropical Interactions



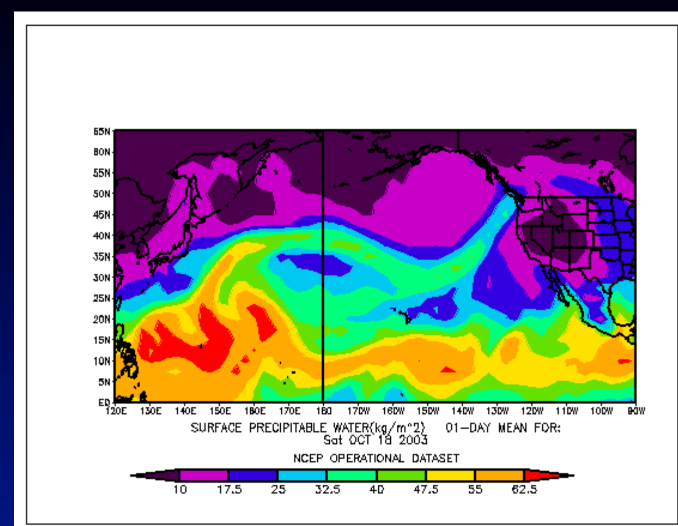
Tropical to Extratropical Interactions



Tropical to Extratropical Interactions



Tropical to Extratropical Interactions



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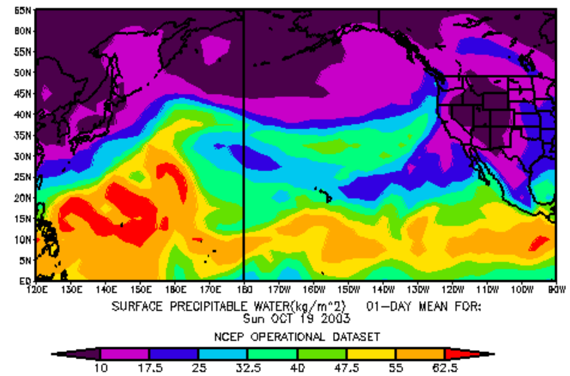

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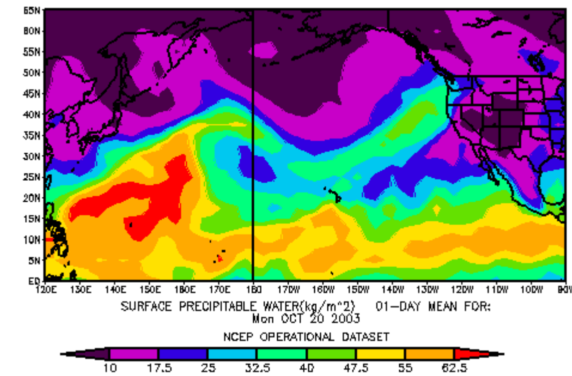

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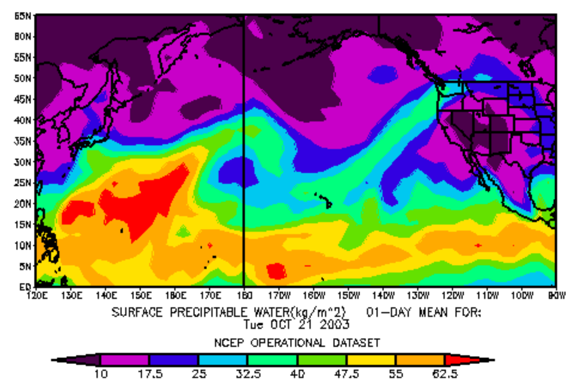

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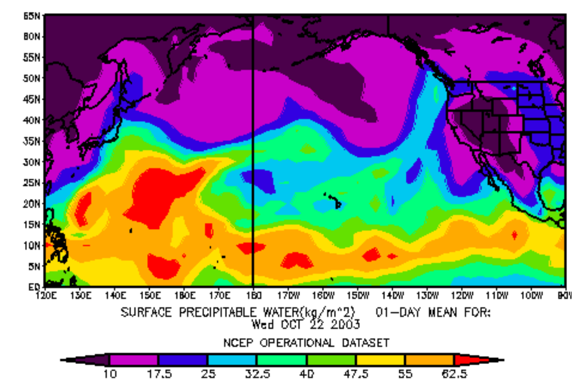

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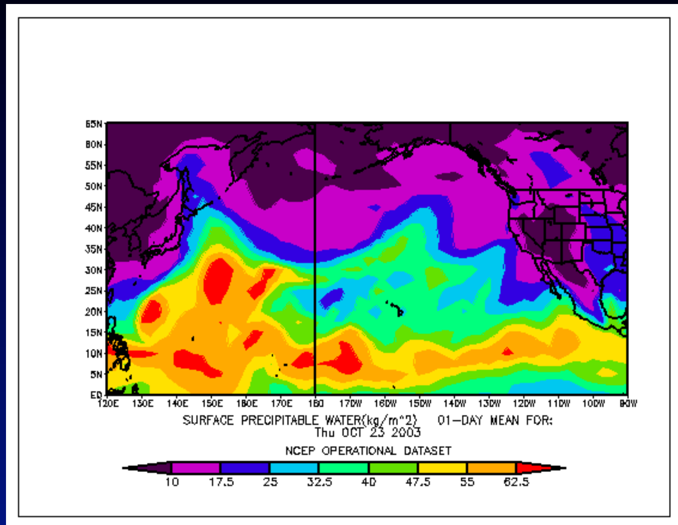

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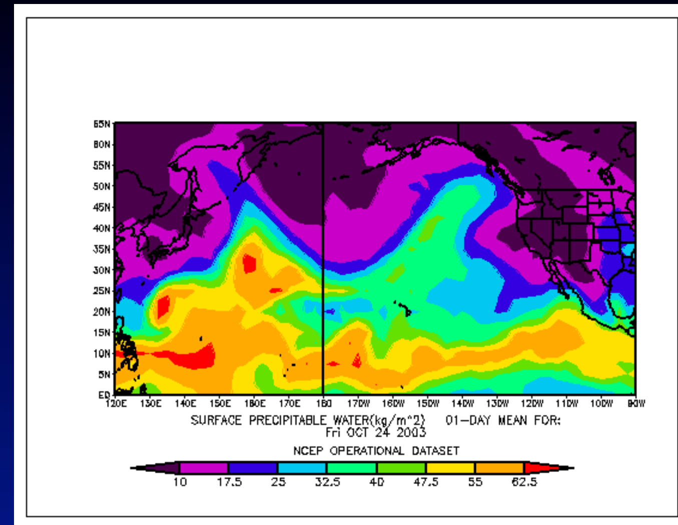
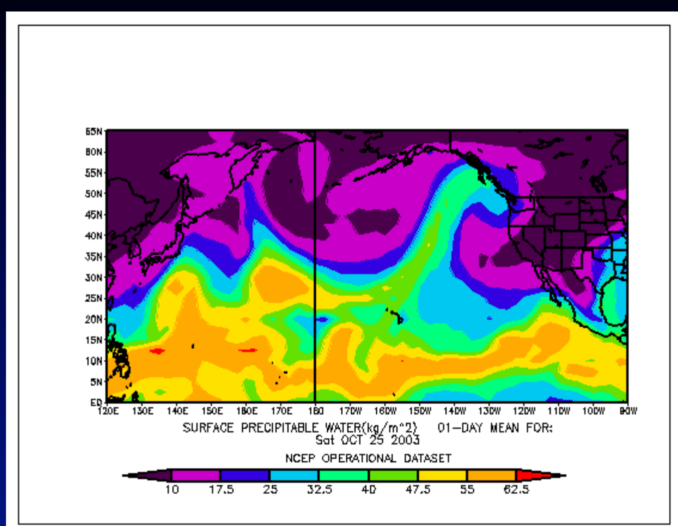
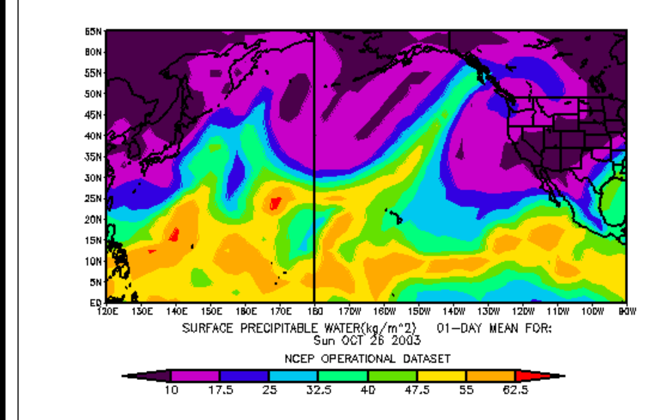


Tropical to Extratropical Interactions

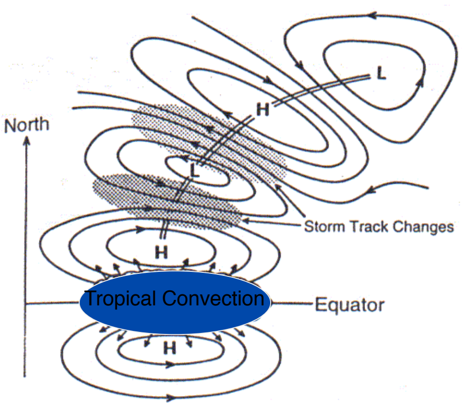


Tropical to Extratropical Interactions

October 26



Northward Propagating Rossby-Wave Train



(Trenberth, et al. 1998)

Figure 4. Schematic view of the dominant changes in the upper troposphere, mainly in the northern hemisphere, in response to increases in SSTs, enhanced convection, and anomalous upper tropospheric divergence in the vicinity of the equator (scalloped region). Anomalous outflow into each hemisphere results in subtropical convergence and an anomalous anticyclone pair straddling the equator, as indicated by the streamlines. A wave train of alternating high and low geopotential and streamfunction anomalies results from the quasi-stationary Rossby wave response (linked by the double line). In turn, this typically produces a southward shift in the storm track associated with the subtropical jet stream, leading to enhanced storm track activity to the south (dark stipple) and diminished activity to the north (light stipple) of the first cyclonic center. Corresponding changes may occur in the southern hemisphere.

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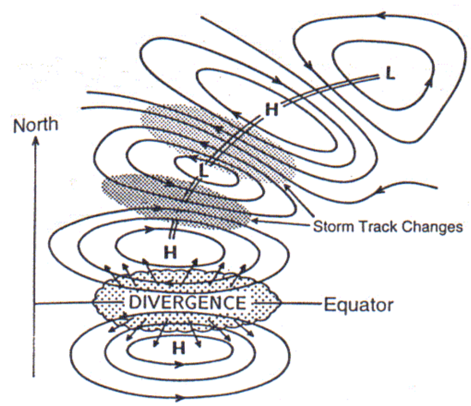

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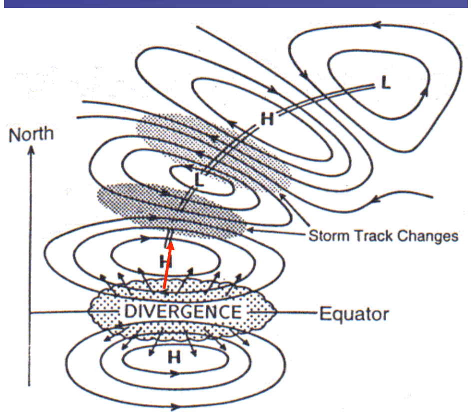

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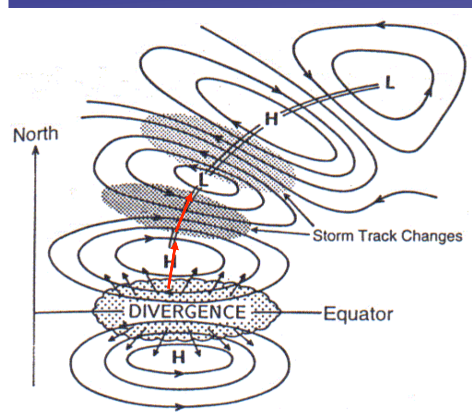

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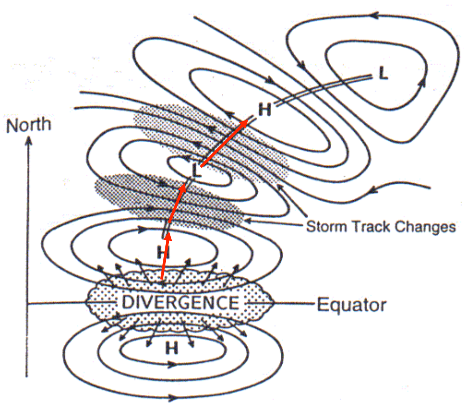

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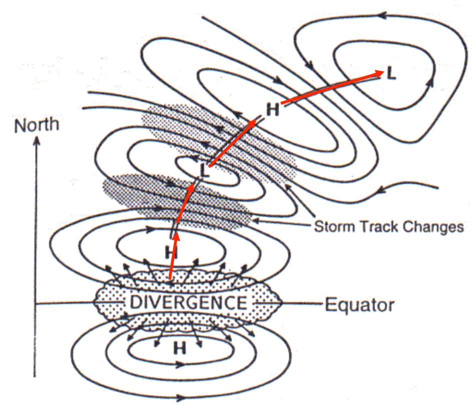

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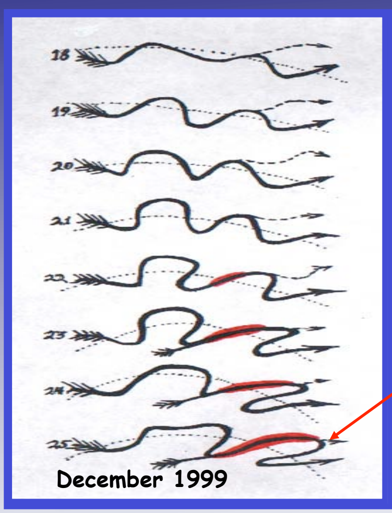
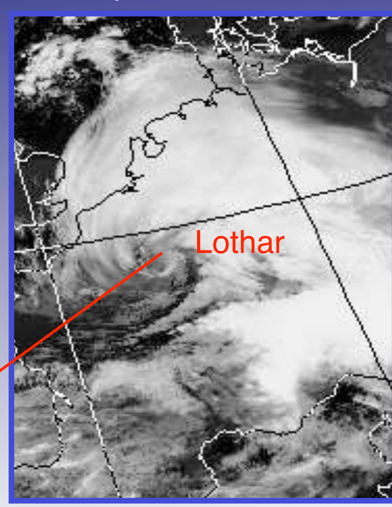
Questions?

European Wind Storm





0754 UTC 26 December 1999