

Lecture 3:

The Quasi-stationary Circulation

- Stationary Rossby waves
- The forcing of the Annular Mode.
- Preferential quasi-stationary modes.

Stationary planetary waves in a beta plane $f=f_0+\beta(y-y_0)$

The quasi-geostrophic (QG) potential vorticity

$$\frac{\partial Q}{\partial t} + \vec{v} \bullet \nabla Q = 0$$

$$Q = \nabla^2 \psi + \beta(y - y_0) + \frac{f_0^2}{\rho_r} \left(\frac{\rho_r \psi_z}{N^2} \right)_z$$

Relative vorticity \nearrow Planetary vorticity \uparrow Baroclinic vorticity \downarrow

In an homogeneous atmosphere Q could express only as:

$$Q = \beta(y - y_0)$$

The perturbation QG potential vorticity q can be determine by the first eq.

$$Q_T = Q + q$$

The linear eq. of (1) assuming $q \ll Q$ and a constant westerly flow U

$$\frac{\partial q}{\partial t} + U \frac{\partial q}{\partial x} + v \frac{\partial Q}{\partial y} = \frac{\partial q}{\partial t} + U \frac{\partial q}{\partial x} + v\beta = 0$$

We try to see how a small perturbation to Q will behave, we assume the form of the perturbation to be:

$$q = q_0 \exp(i(kx + ly - \omega t))$$

Where k and l are the wavenumbers in x and y respectively and ω is the frequency. Remembering that:

$$q = \nabla^2 \phi = \phi_{xx} + \phi_{yy} = -(k^2 + l^2)\phi \quad \text{Is proportional to the stream function}$$

$$v = \phi_x = ik\phi \quad \text{Where the geostrophic wind components are also proportional to the stream function.}$$

$$u = -\phi_y = -l\phi$$

Using the perturbation q eq.

$$\frac{\partial q}{\partial t} + U \frac{\partial q}{\partial x} + v\beta = 0$$

we can derive the dispersion relation; a relation between the wavenumbers and the frequency:

$$\omega = kU - \frac{\beta k}{(k^2 + l^2)}$$

Observed frequency Intrinsic frequency

$$\omega = kU - \frac{\beta k}{(k^2 + l^2)}$$

Doppler shifted

The phase velocity is not a vector, its components are not the speed of the wave in each direction. Still we can define the speed of the wave in the x and y directions as follow.

$$C_x = \frac{\omega}{k} = U - \frac{\beta}{(k^2 + l^2)}$$

$$C_y = \frac{\omega}{l} = \frac{kU}{l} - \frac{k\beta}{l(k^2 + l^2)}$$

The group velocity is a vector

$$C_{gx} = \frac{\partial \omega}{\partial k} = U + \frac{(k^2 - l^2)}{(k^2 + l^2)^2} \beta$$

$$C_{gy} = \frac{\partial \omega}{\partial l} = + \frac{2kl\beta}{(k^2 + l^2)^2}$$

For stationary waves the condition that $\omega = 0$ gives a condition for the wavenumbers.

$$(k^2 + l^2) = \frac{\beta}{U}$$

Only is possible for westerly flow $U > 0$

$$\beta \sim 1.5 \times 10^{-11} (\text{ms})^{-1}$$

$$U \sim 60 \text{ m/s}$$

$$|K| \sim 0.5 \times 10^{-6} (\text{m})^{-1}$$

$$\lambda = \frac{2\pi}{|K|} = 12566 \text{ km}$$

λ would be $\sim 6280 \text{ km}$ if the wind speed was 15 m/s instead of 60 m/s . If you replace the above condition of the stationary wave numbers into the Cg

$$C_{gx} = \frac{\partial \omega}{\partial k} = U + \frac{(k^2 - l^2)}{(k^2 + l^2)^2} \beta = \frac{2k^2 U}{(k^2 + l^2)}$$

$$C_{gy} = \frac{\partial \omega}{\partial l} = + \frac{2kl\beta}{(k^2 + l^2)^2} = \frac{2klU}{(k^2 + l^2)}$$

Energy only flows downstream always positive
In the zonal direction. In the meridional direction
could be to the north and/or south depending on
the sign of l .



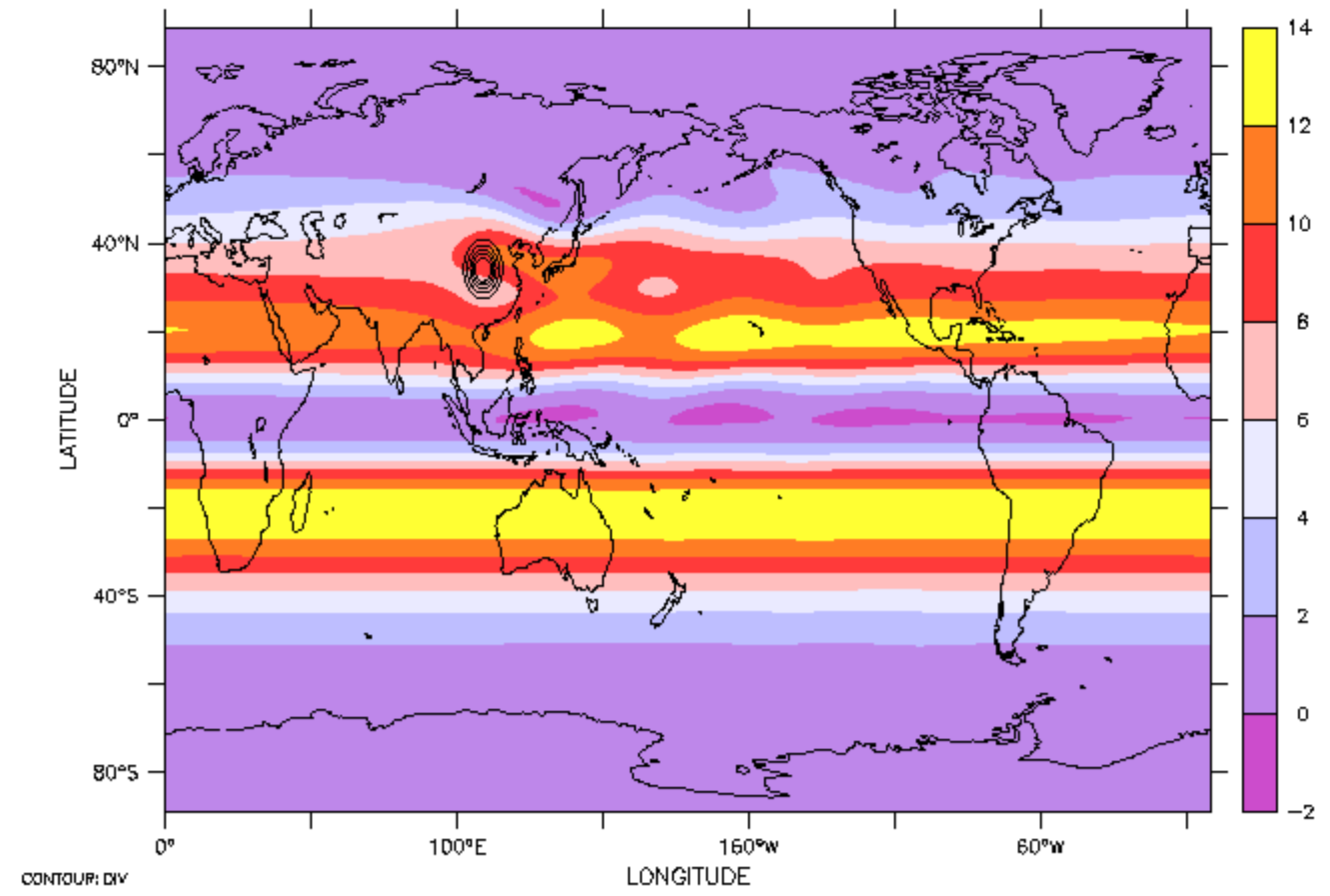
Fig. 10.15 The vorticity pattern generated on a sphere when a constant angular velocity westerly flow impinges on a circular forcing centered at 30°N and 45°W of the central point. Left to right, the response at 2, 4, and 6 days after switch on of the forcing. Five contour intervals correspond to the maximum vorticity response that would occur in 1 day if there were no wave propagation. Heavy lines correspond to zero contours. The pattern is drawn on a projection in which the sphere is viewed from infinity. (After Hoskins, 1983.)

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NOAA/PMEL TMAP
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T : 0.5 to 100.5 (averaged)

DATA SET: shallow

Diagnostics from spectral shallow water model



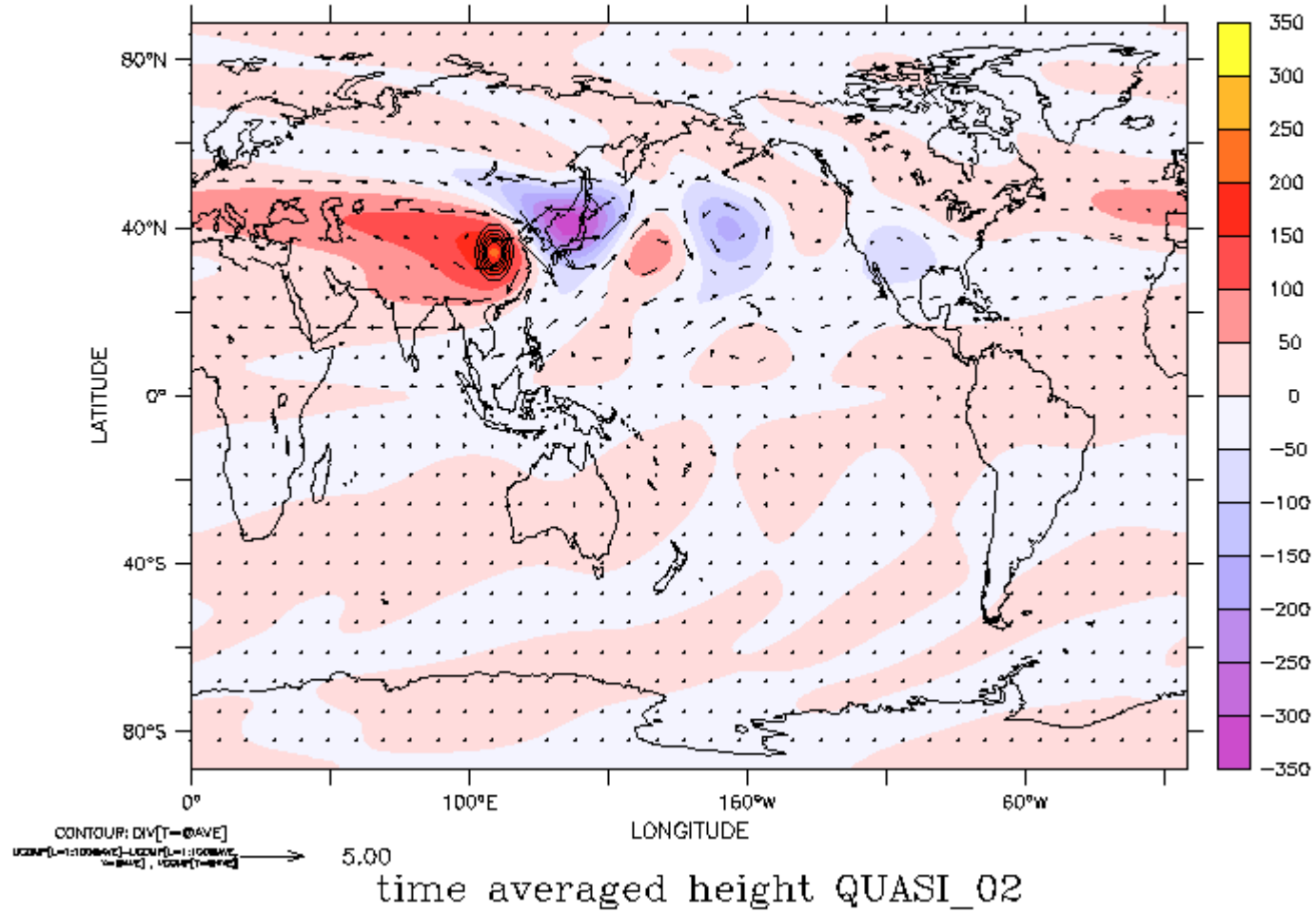
time averaged zonal wind

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DATA SET: shallow

Diagnostics from spectral shallow water model

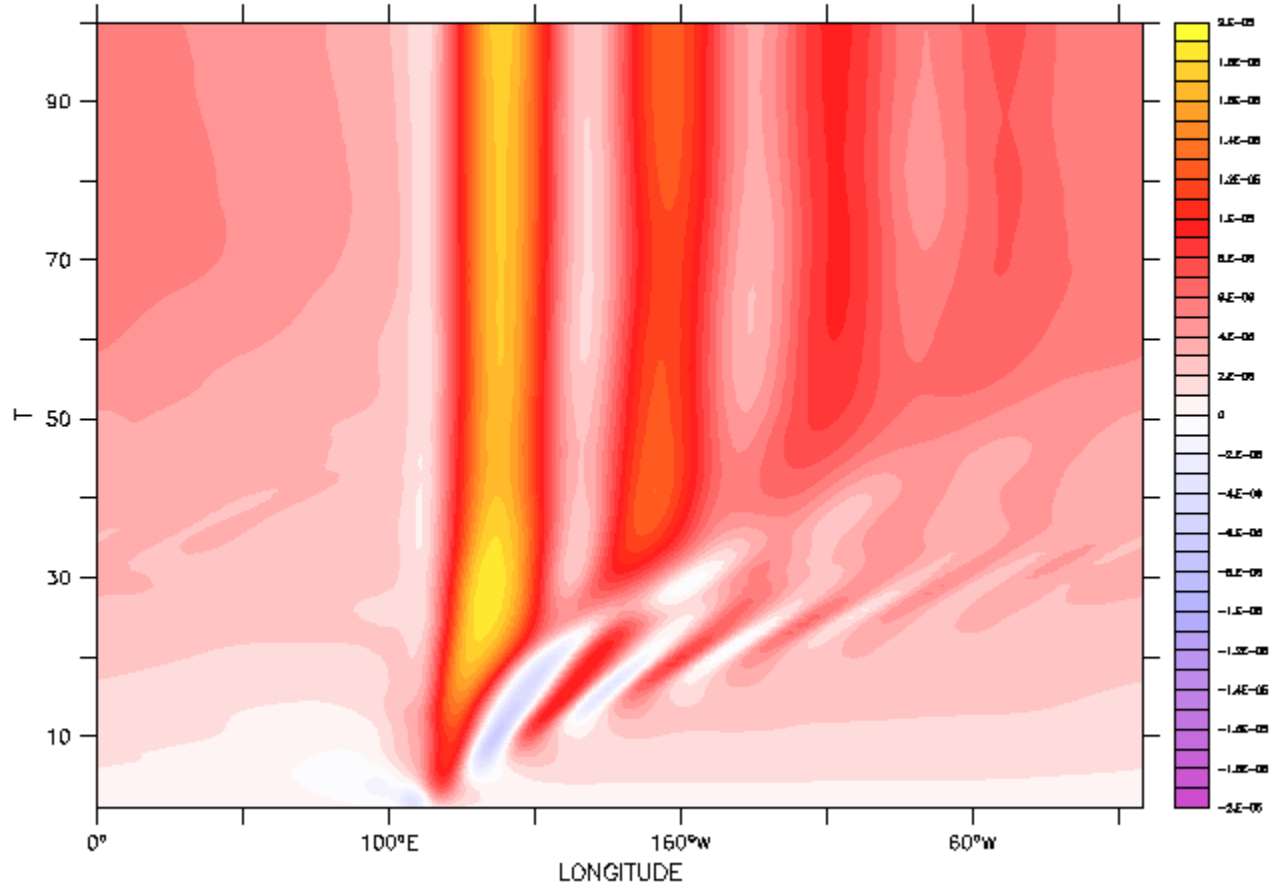


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LATITUDE : 39.9N

DATA SET: shallow

Diagnostics from spectral shallow water model

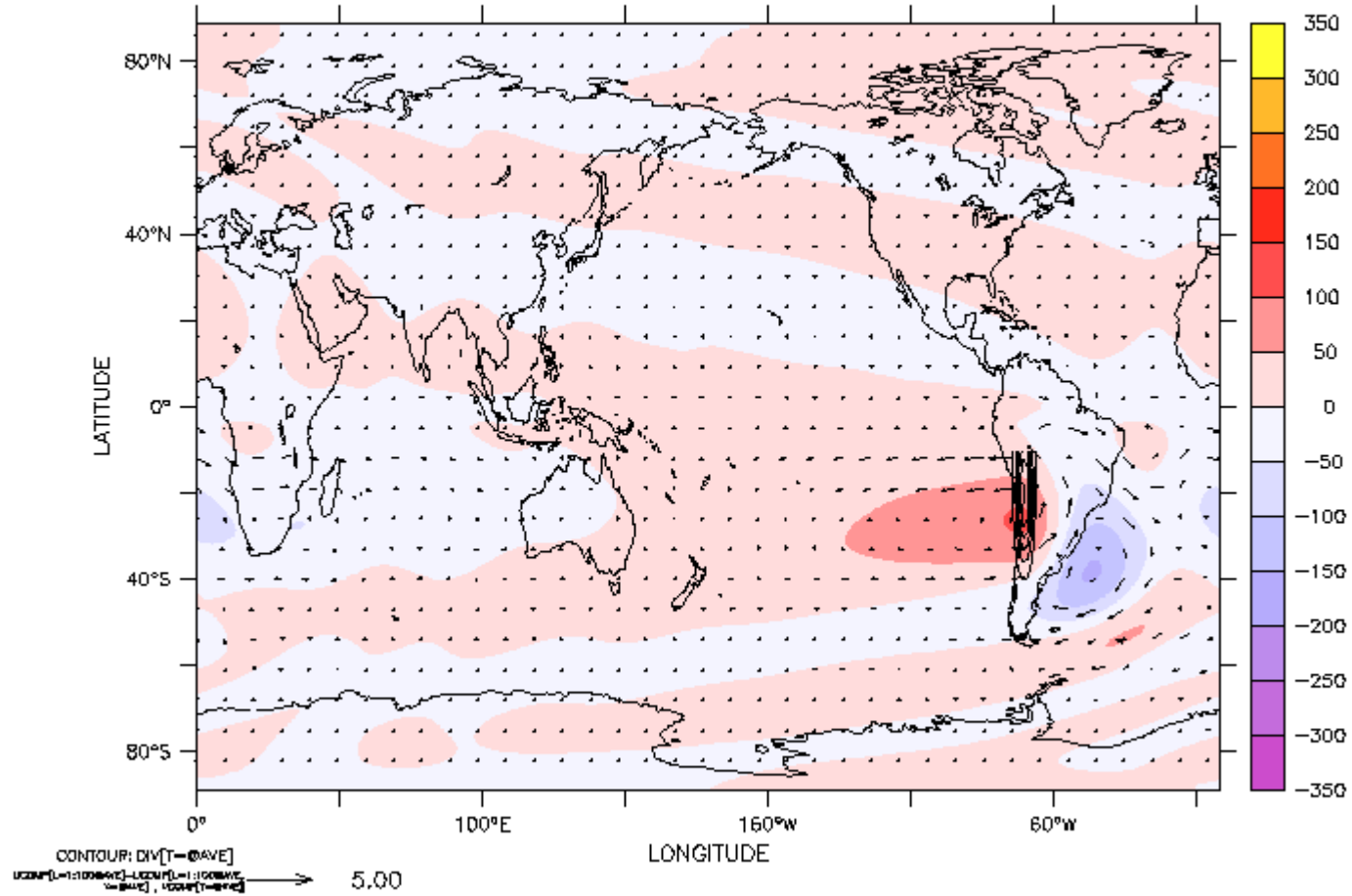


Vorticity as a function of longitud and time QUASI_02

T : 0.5 to 100.5

DATA SET: shallow

Diagnostics from spectral shallow water model



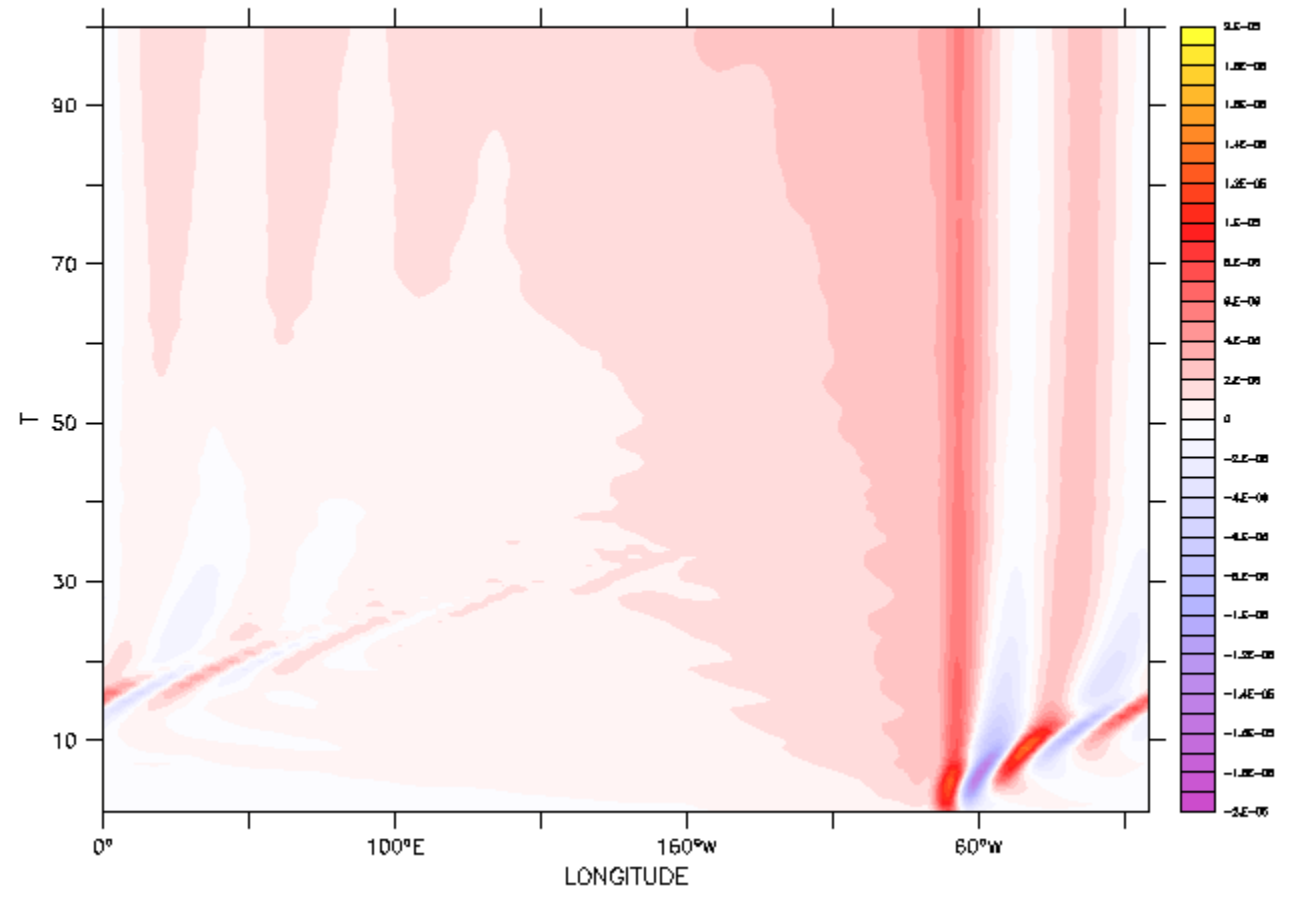
time averaged height QUASI_02

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LATITUDE : 20.3S

DATA SET: shallow

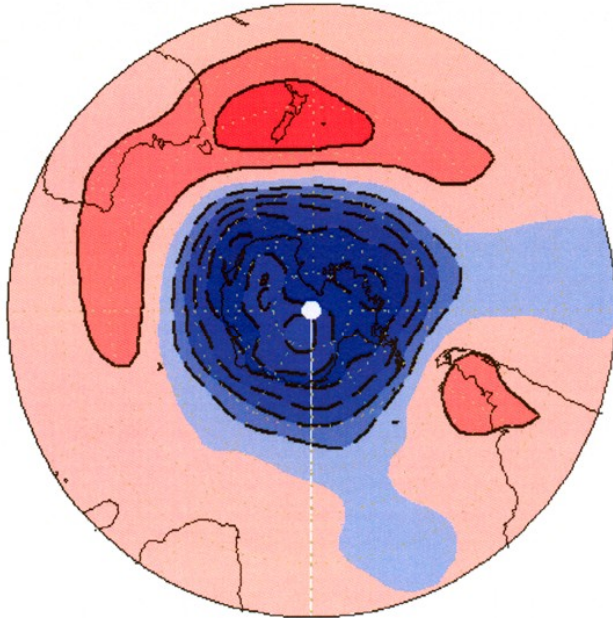
Diagnostics from spectral shallow water model



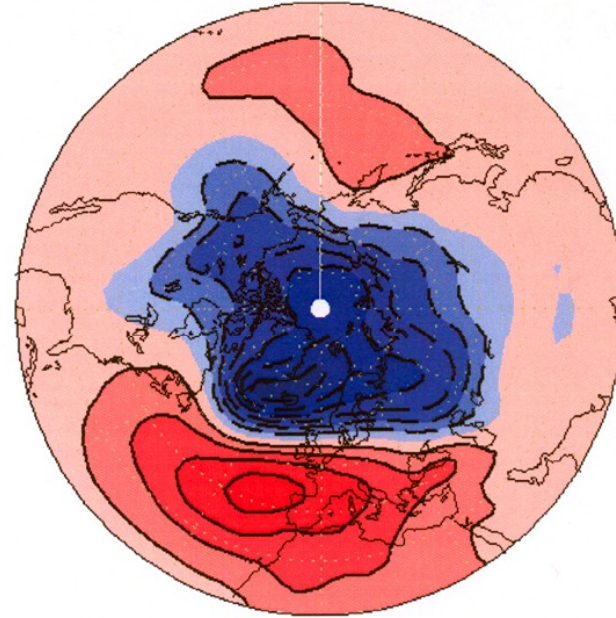
Vorticity as a function of longitud and time QUASI_02

Annular Modes of the troposphere

SH, July, 31.4%



NH, January, 28.9%



First empirical orthogonal functions of geopotential height at 1000 hPa, based on NCEP/NCAR-Reanalysis (following Thompson und Wallace, 2000). Contour interval 10 gpm. Positive values are red, negative blue.

EGU General Assembly 2005, EGU05-A-07295

**The importance of stationary waves
for the maintenance of
the Northern Annular Mode
as deduced from model experiments**

Heiner Körnich, Gerhard Schmitz and
Erich Becker

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Kühlungsborn, Germany

Overview

- § Introduction
- § Model simulations (SGCM)
- § Analysis of the wave-mean flow interaction
- § Summary

Model KMCM

Kühlungsborn Mechanistic general Circulation Model

- § Based on primitive equations
- § Resolution: T29, 24 hybrid-levels up to 0.3 hPa (60 km)
- § Length of model integration: 3600 days
- § Perpetual January conditions
- § Stationary wave forcing: Land-sea heating contrasts
Orography

Circulation experiments with stationary wave forcing

Aqua

None

Land-sea

Land-sea heating contrasts

Oro

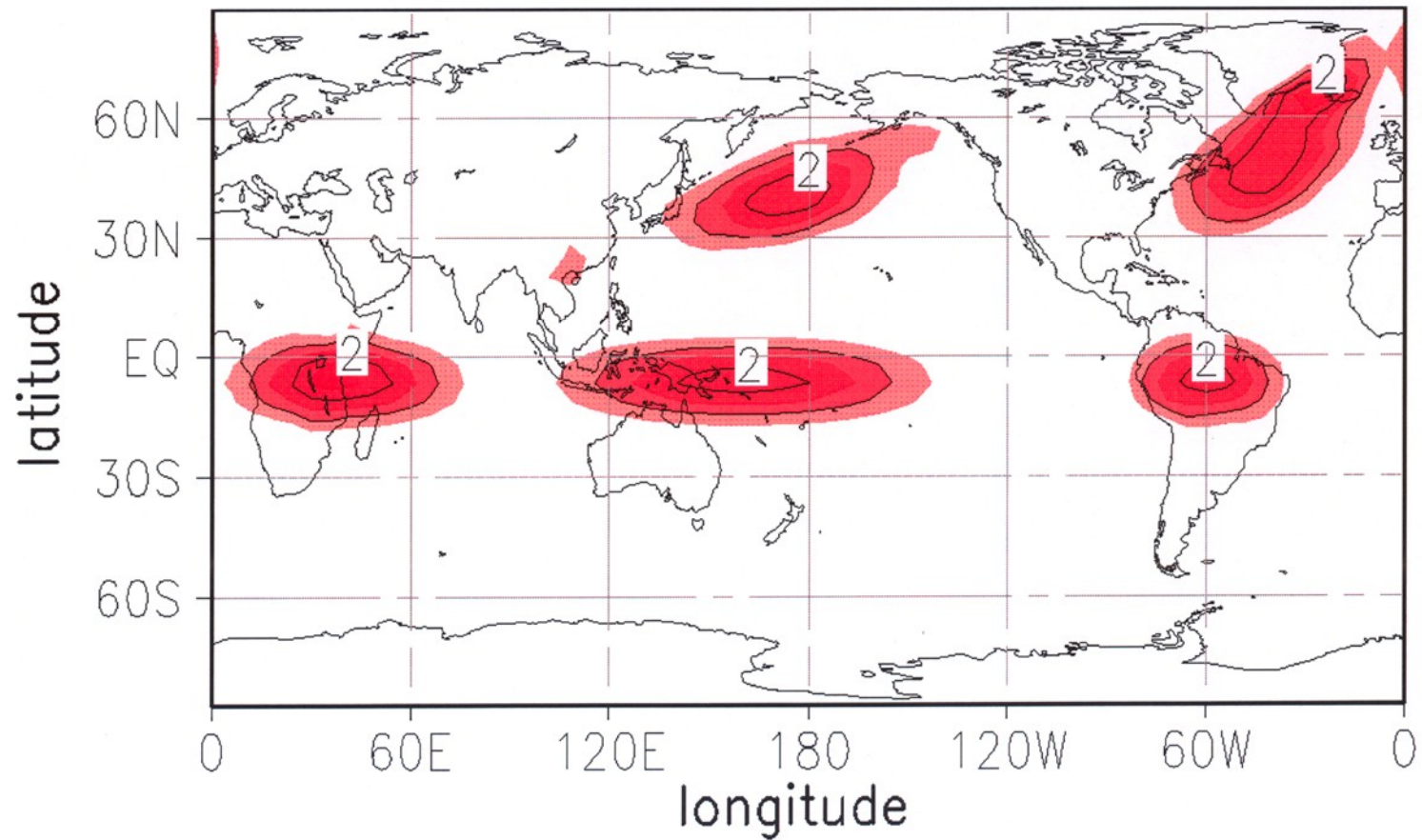
Orography

Full

Both

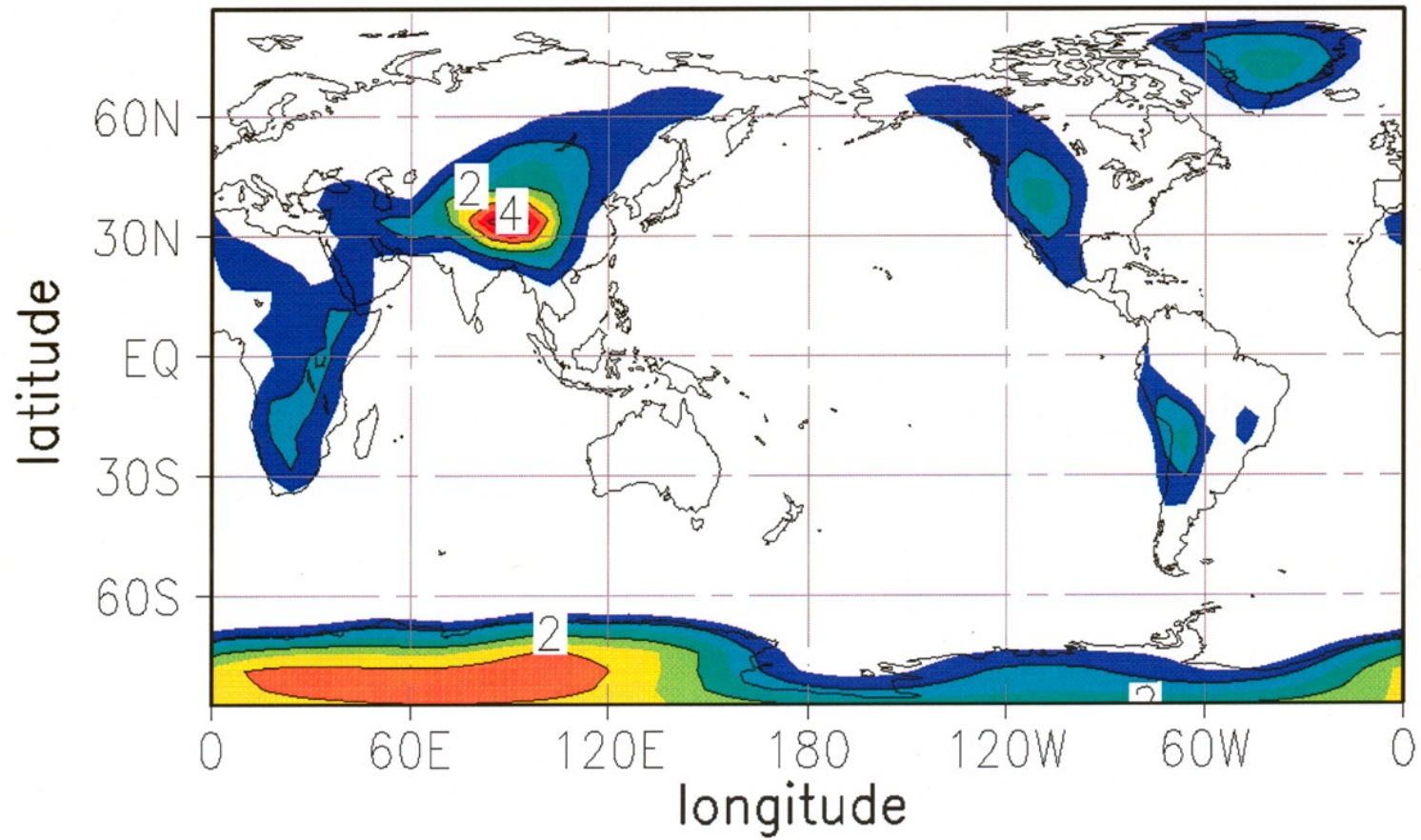
Land-sea heating contrasts

Heating rates [K/day]

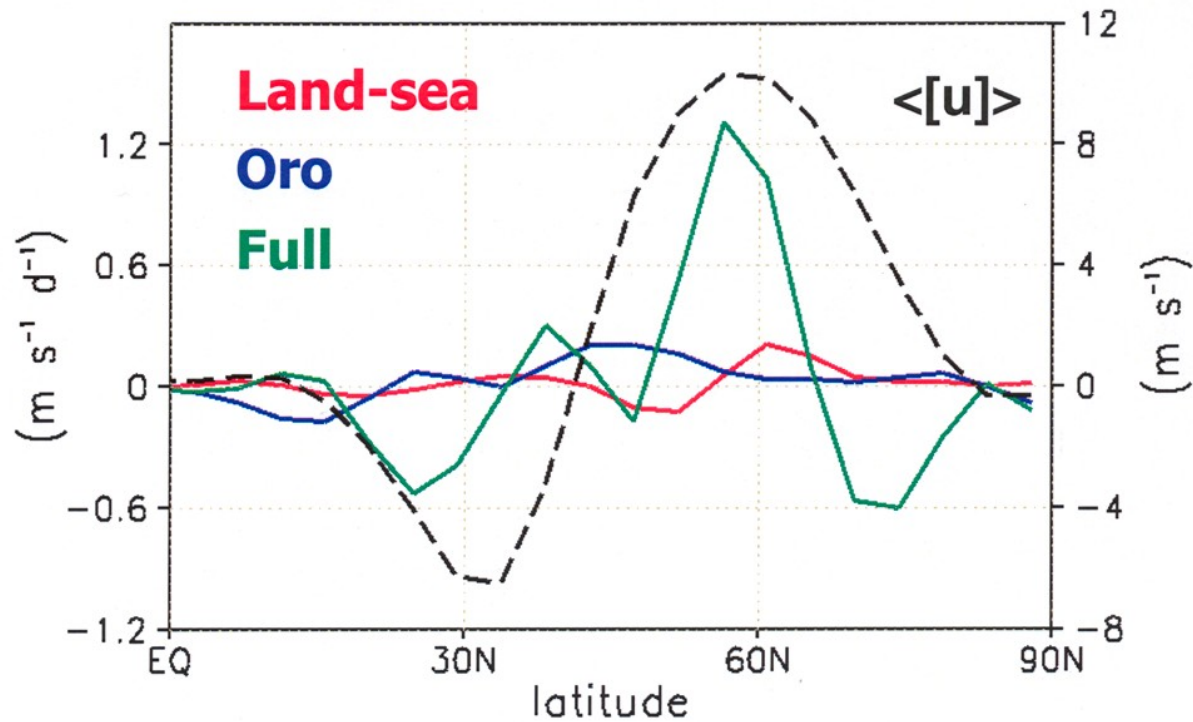


Orography

Φ_s/g in [gpkm]



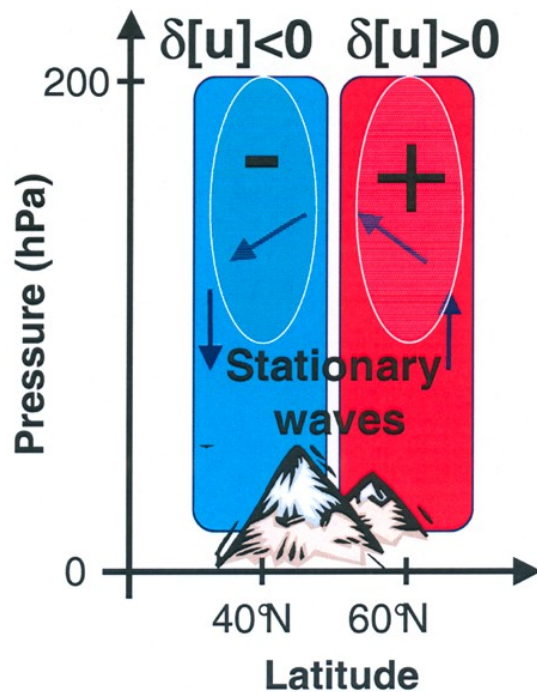
Feedback of the anomalous stationary waves in the experiments



Wave drag owing to linear anomalous stationary waves and zonal mean zonal wind anomaly, vertically integrated (1000–200 hPa)

Feedback between stationary waves and zonal mean wind

(DeWeaver and Nigam, 2000)



1. Zonal-eddy coupling from linear model
⇒ **anomalous stationary waves**
2. Interaction of anomalous stationary waves
⇒ **wave drag**

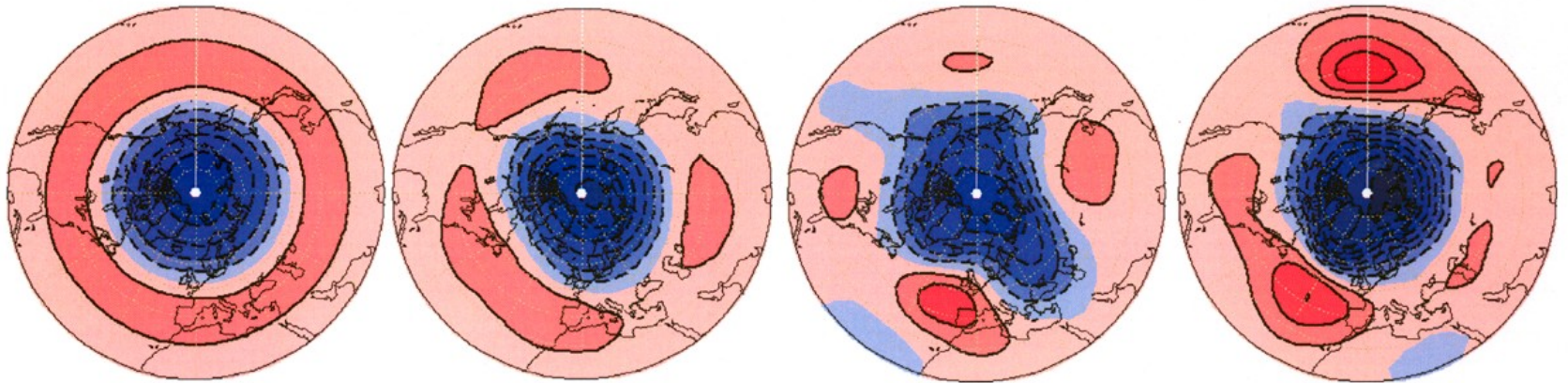
Leading variability patterns (Annular Mode = AM)

Aqua, 31.1%

Land-Sea, 24.9%

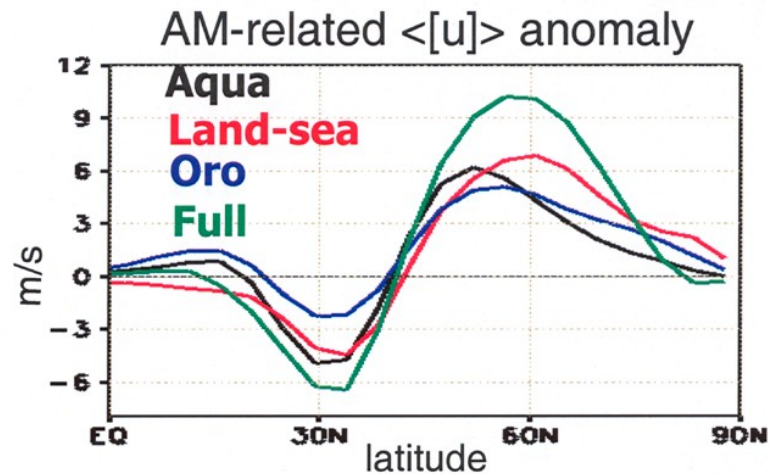
Oro, 22.3%

Full, 31.5%



First empirical orthogonal function of geopotential height at 1000 hPa.
Contour interval: 10 gpm. Positive values are red, negative blue.

The maintenance of the Annular Modes



$\langle [u] \rangle$ - zonally and vertically averaged zonal wind

Projection of daily budget terms on the AM-related $\langle [u] \rangle$ anomaly
 \Rightarrow Time series for each budget term (Lorenz and Hartmann, 2000)

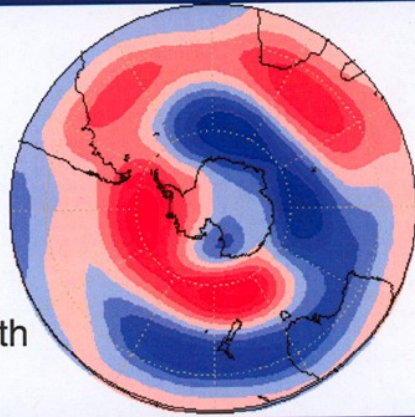
$$\left\langle \frac{\partial [u]}{\partial t} \right\rangle \approx \left\langle -\frac{\partial [u^* v^*]}{\partial y} \right\rangle - \frac{1}{p_0} \left[p_s \frac{\partial \Phi_s}{\partial x} \right]$$

Wave drag Mountain torque

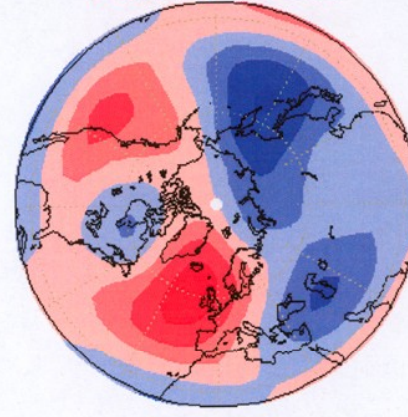
Mean stationary waves

(Geopotential height at 300 hPa)

Southern hemisphere, July

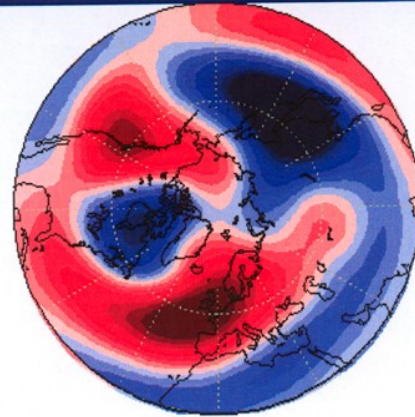


Land-sea

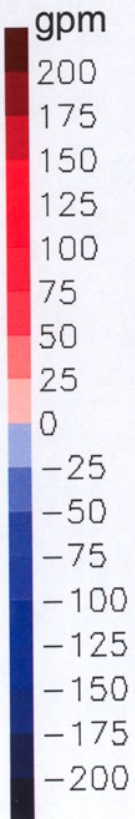
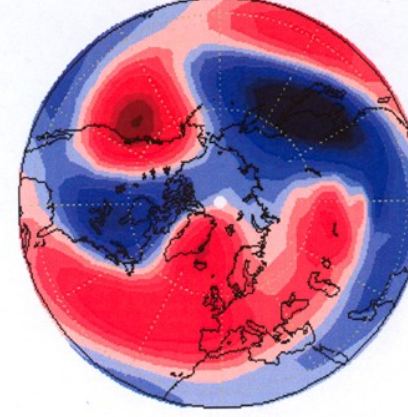


Comparison with
NCEP/NCAR-
Reanalysis

Northern hemisphere, January



Full



Wave-mean flow interaction

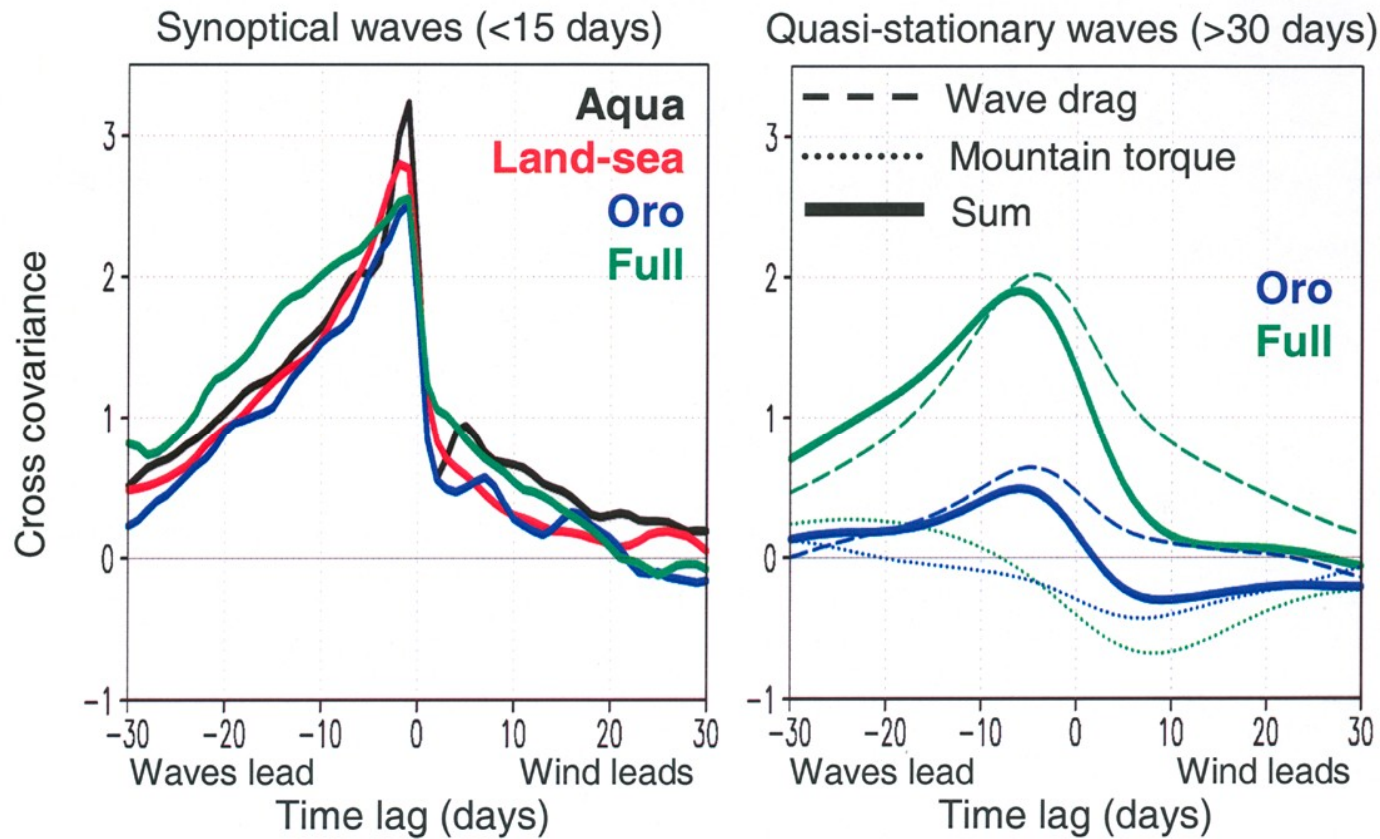
Zonally and vertically averaged tendency equation of the zonal wind:

$$\left\langle \frac{\partial [u]}{\partial t} \right\rangle = \left\langle -\frac{\partial [u^* v^*]}{\partial y} \right\rangle + \langle [X] \rangle - \frac{1}{p_0} \left[p_s \frac{\partial \Phi_s}{\partial x} \right]$$

Wave drag Friction Mountain torque

Owing to baroclinic and planetary waves

Wave-mean flow feedback of the Annular Modes



Correlation between zonal wind and wave drag / mountain torque

Summary

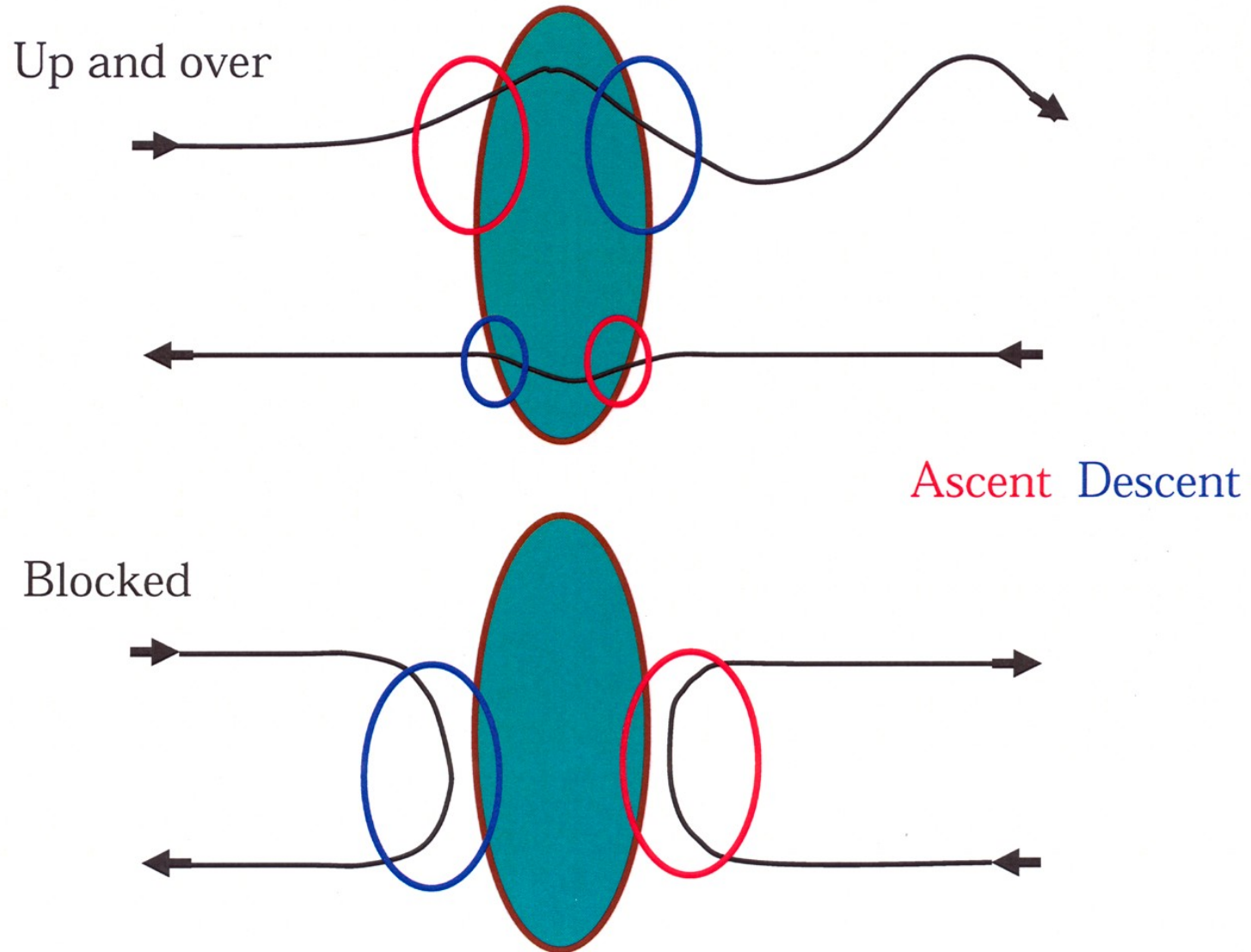
- The feedback between baroclinic waves and the zonal mean wind determines the Annular Mode.
- A realistic northern AM is simulated only with both orography and land-sea heating contrasts.
- This is due to the positive feedback between stationary waves and Annular Mode.

Körnich, Schmitz, and Becker, 2003, GRL

Körnich, Schmitz, and Becker, 2005, JAS, submitted

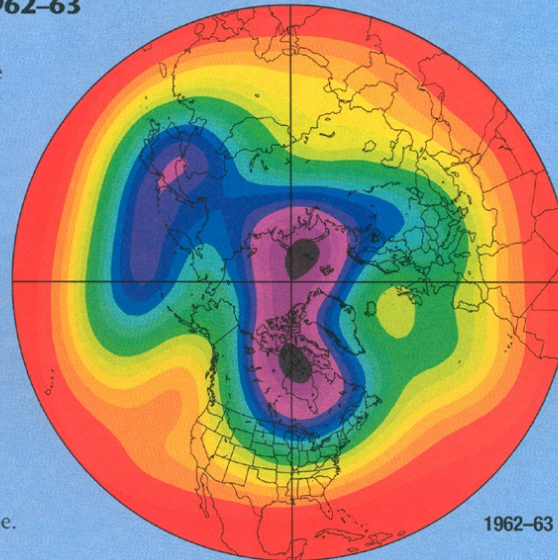
Quasi-stationary Modes in the Atmosphere and Ocean

- **Blocking: 1~2 weeks**
- **Asian Monsoon 2~3 months**
- **Madden-Julian Oscillation MJO: 30~40 days**
- **ENSO: El Nino La Nina: 3~4 year cycle**
- **Pacific North America PNA: months**
- **North Atlantic Oscillation NAO: weeks to months**
- **Pacific South America PSA months**
- **Arctic Oscillation AO**
- **Antarctic Oscillation AAO:**
- **Seasonal and annual cycles. Months**
- **Decadal Oscillation: few years**

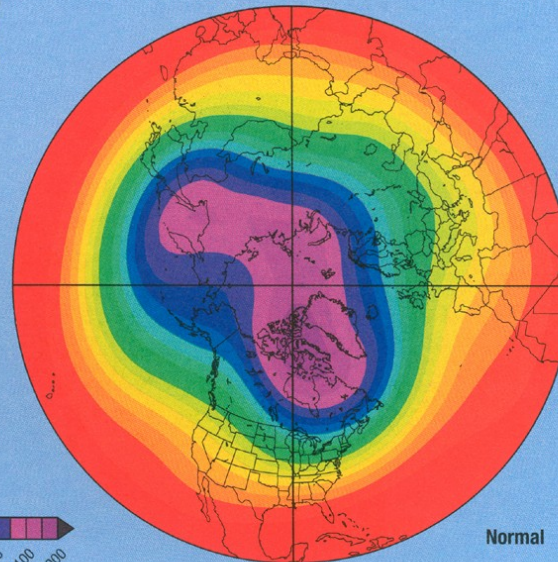


The winter of 1962-63

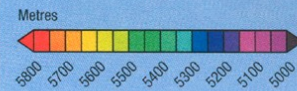
The winter of 1962-3 was a 'classic' example of blocking. In the upper atmosphere the circulation at 500 hPa (upper right) meandered much more than normal (lower right). At low levels during mid-December through January an intense, high pressure system persisted over the northeastern Atlantic and channelled cold Arctic air across Europe. Over Asia, the cold Siberian high was also stronger than normal while persistent highs over North America brought icy blasts down across the northeast. In contrast, Alaska, western Greenland and parts of central Asia experienced unusually warm conditions.



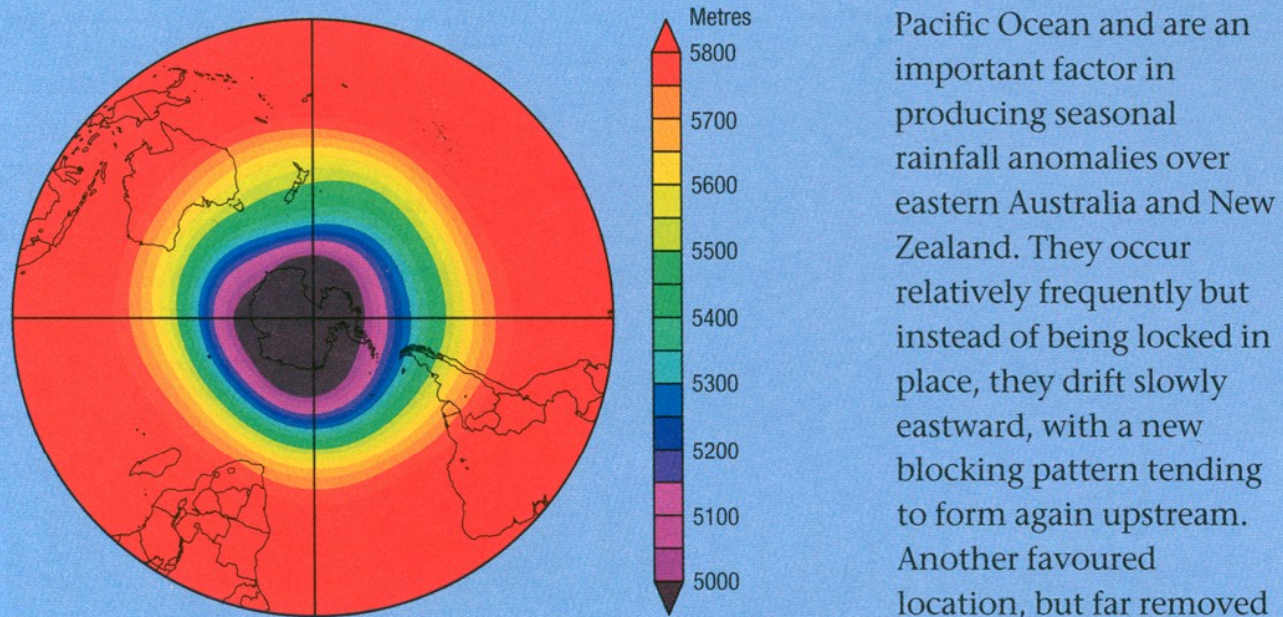
1962-63



Normal



Southern Hemisphere blocking – a gentler but still important cousin



In the Southern Hemisphere the westerlies are far more symmetric because of the weaker land-sea contrast and just one substantial middle latitude mountain range, the Andes.

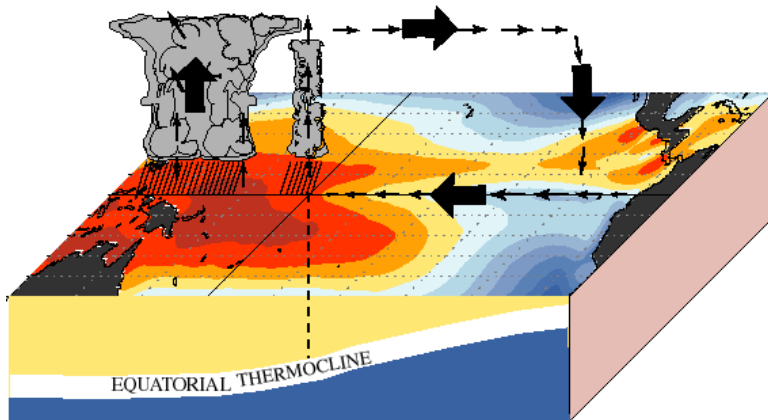
Blocking episodes are, at first glance, insipid by contrast with their Northern Hemisphere counterparts. Moderate strength blocking episodes occur over the southern parts of the

Pacific Ocean and are an important factor in producing seasonal rainfall anomalies over eastern Australia and New Zealand. They occur relatively frequently but instead of being locked in place, they drift slowly eastward, with a new blocking pattern tending to form again upstream. Another favoured location, but far removed from people, is a high pressure ridge bulging out from Antarctica that produces almost as frequent blocking as the Northern Hemisphere counterparts.

variability

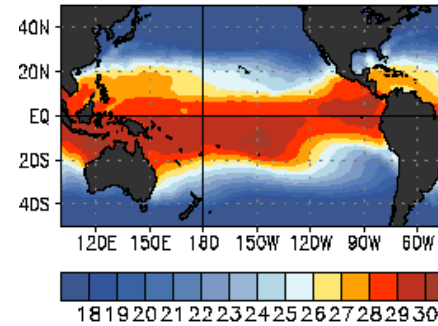
ENSO: El Niño – Southern Oscillation

December - February Normal Conditions

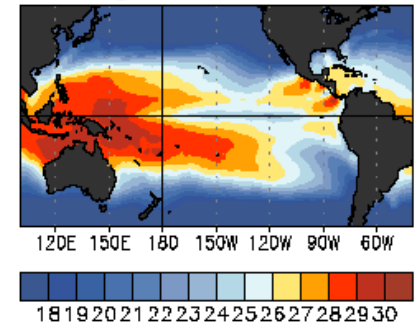


OCEAN TEMPERATURES (°C)

EL NIÑO
Jan-Mar 1998

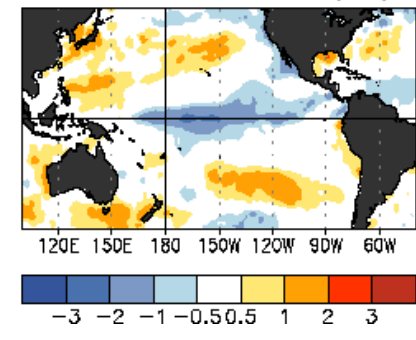
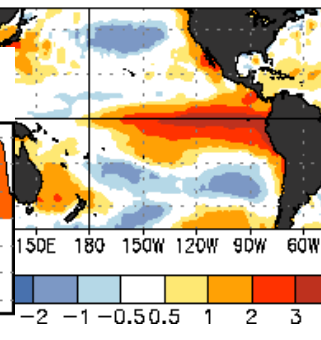
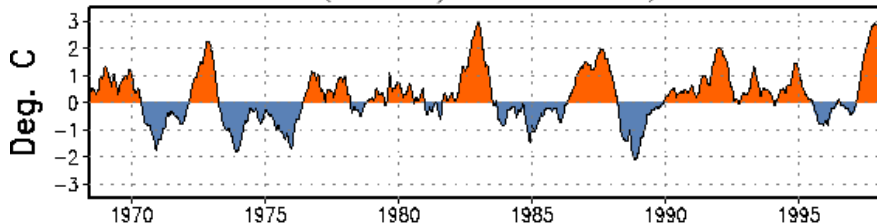


LA NIÑA
Jan-Mar 1989

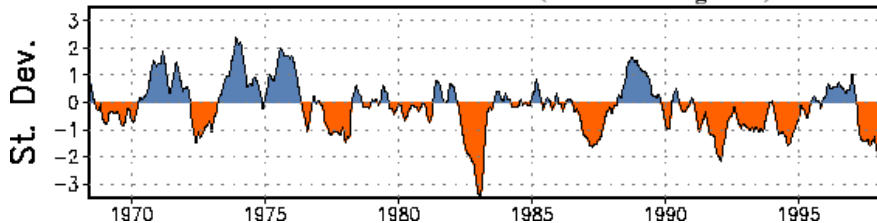


OCEAN TEMPERATURE DEPARTURES (°C)

Ocean Temperature Departures (°C) for Niño 3.4
(5°N-5°S, 170°W-120°W)



Tahiti - Darwin SOI (3 month-running mean)

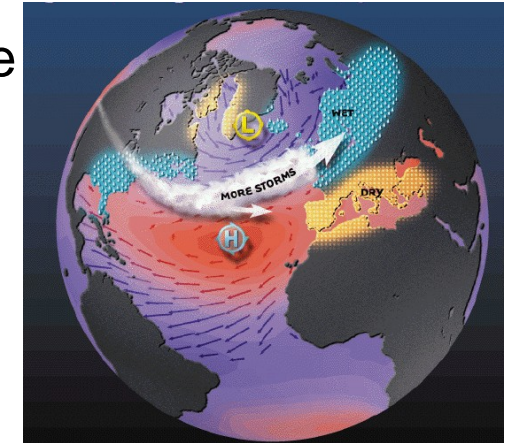


From the Climate Prediction Center website

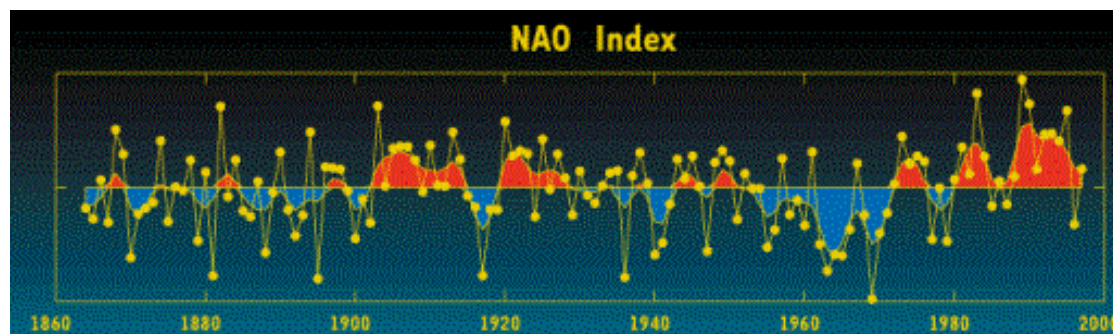
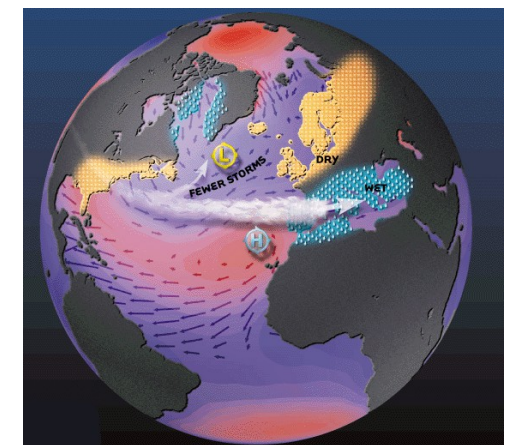
Other Natural Modes of Variability – North Atlantic Oscillation (NAO)

- Determined by anomalies in SLP between the Icelandic Low and the Azores High pressure systems (2-10 yrs)
- Affects weather and climate in the region of the Atlantic Ocean

Positive phase



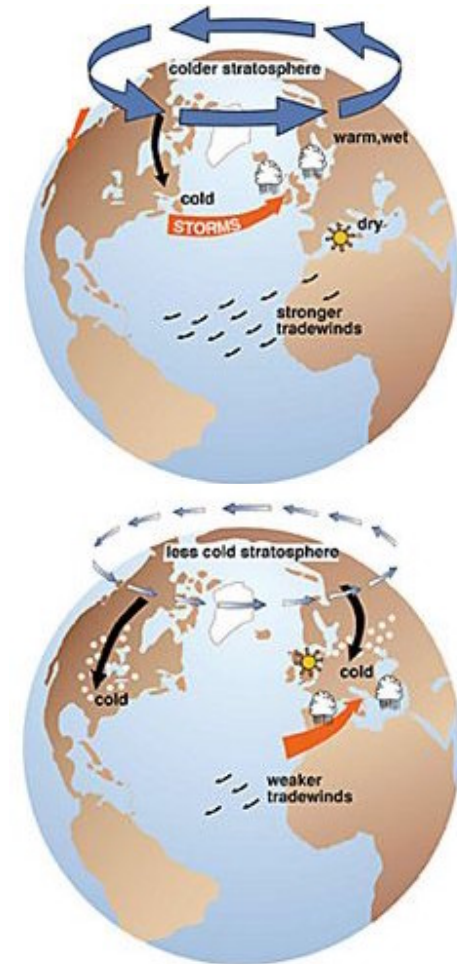
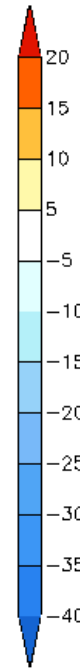
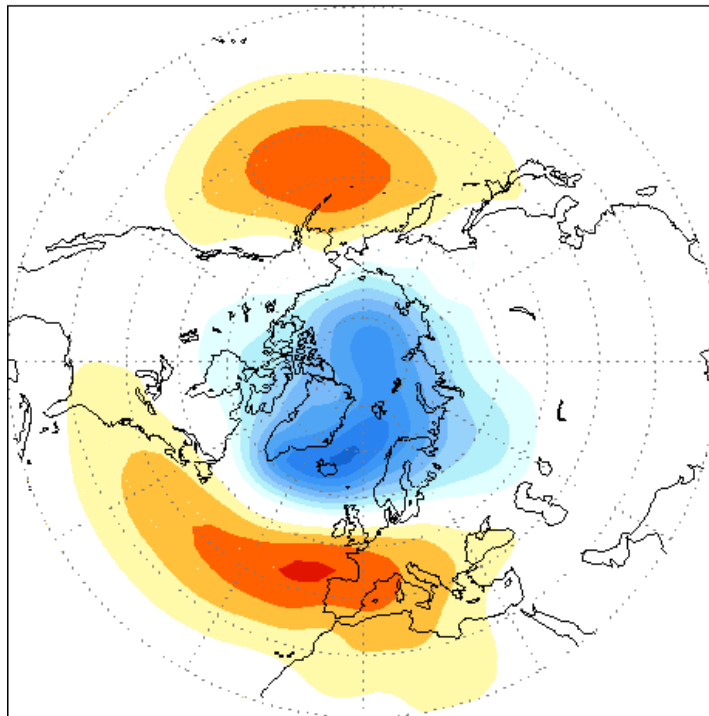
Negative phase



Other Natural Modes of Variability – Arctic Oscillation (AO)

- “Seesaw” of atmospheric mass between the polar cap and mid-latitudes (10-40 yrs)
- Affects climate and storm tracks in the northern hemisphere

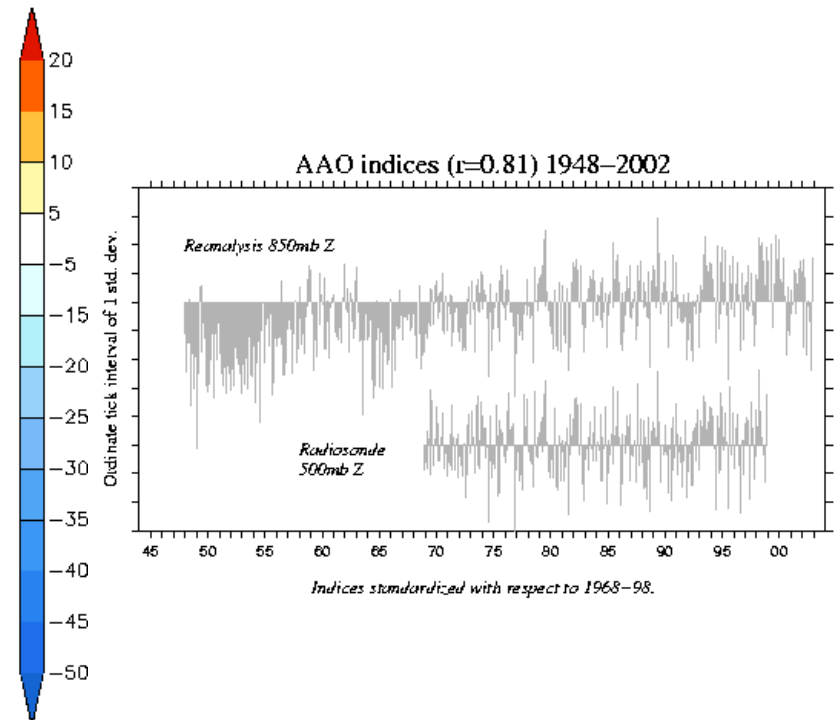
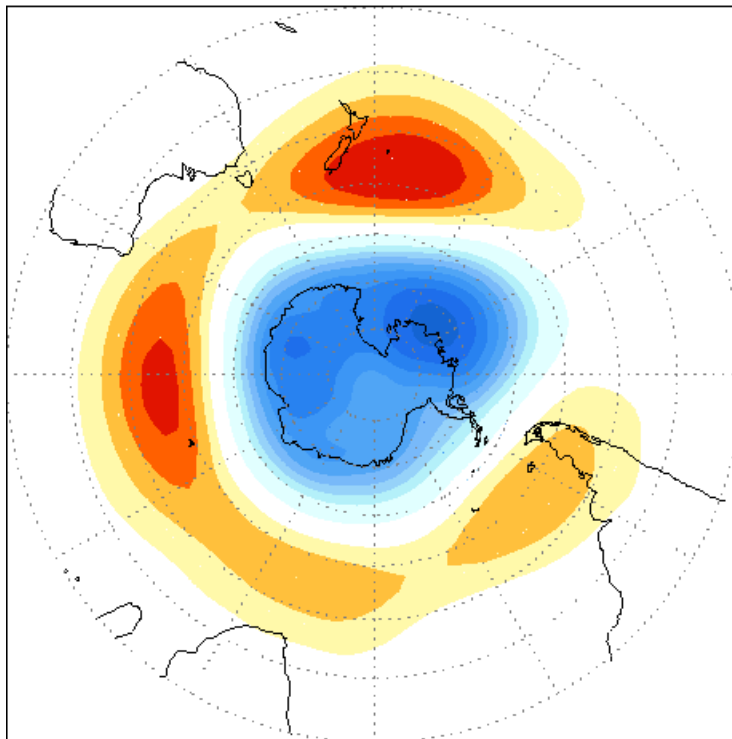
Leading EOF (19%) shown as regression map of 1000mb height (m)



Variability – Antarctic Oscillation (AAO)

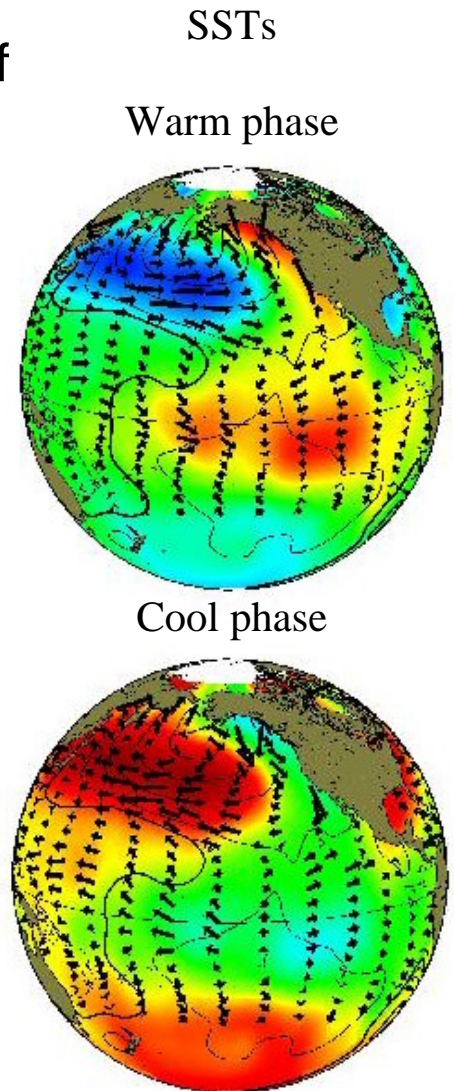
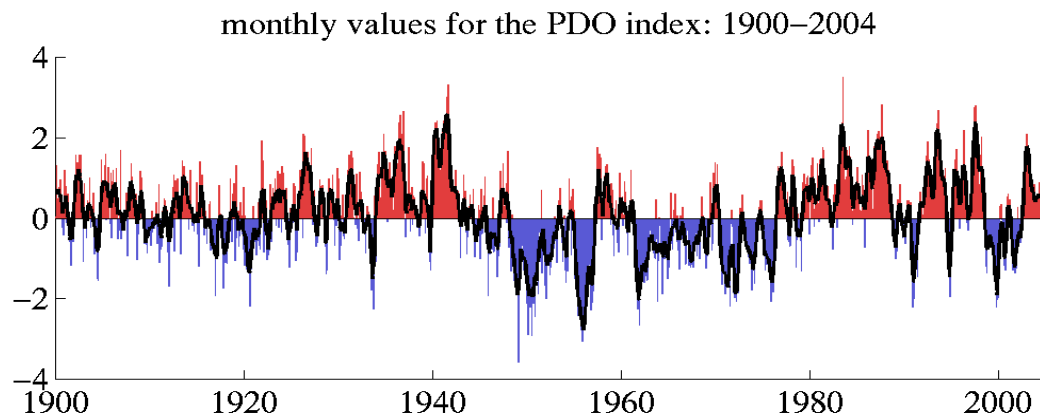
- Zonal pressure fluctuations between Mid- and high latitudes of the Southern Hemisphere (~5 yrs)
- Mainly affects the southern hemisphere but may have teleconnections to northern hemisphere climate

Leading EOF (27%) shown as regression map of 700mb height (m)



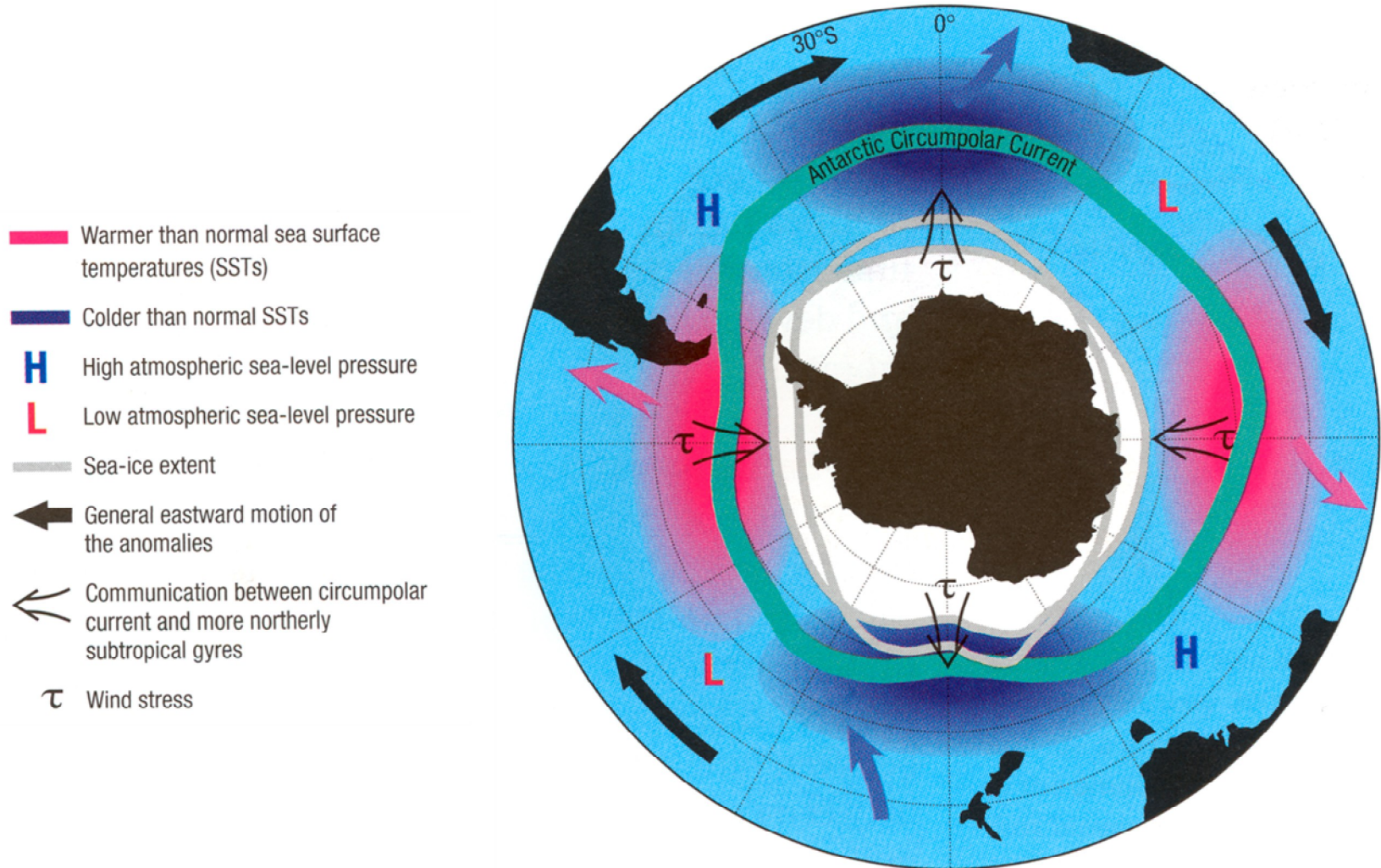
Variability – Pacific Decadal Oscillation (PDO)

- Characterized by SST anomalies in different parts of the Pacific (20-30 yrs)
- Mainly affects the north Pacific regions
- Related to ENSO



Antarctic Circumpolar Wave

The stretching and compression of the sea ice by the wind produce a very slow propagating wave (~3 years)

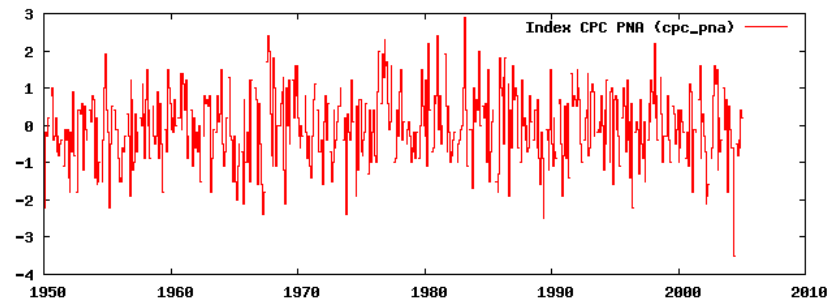
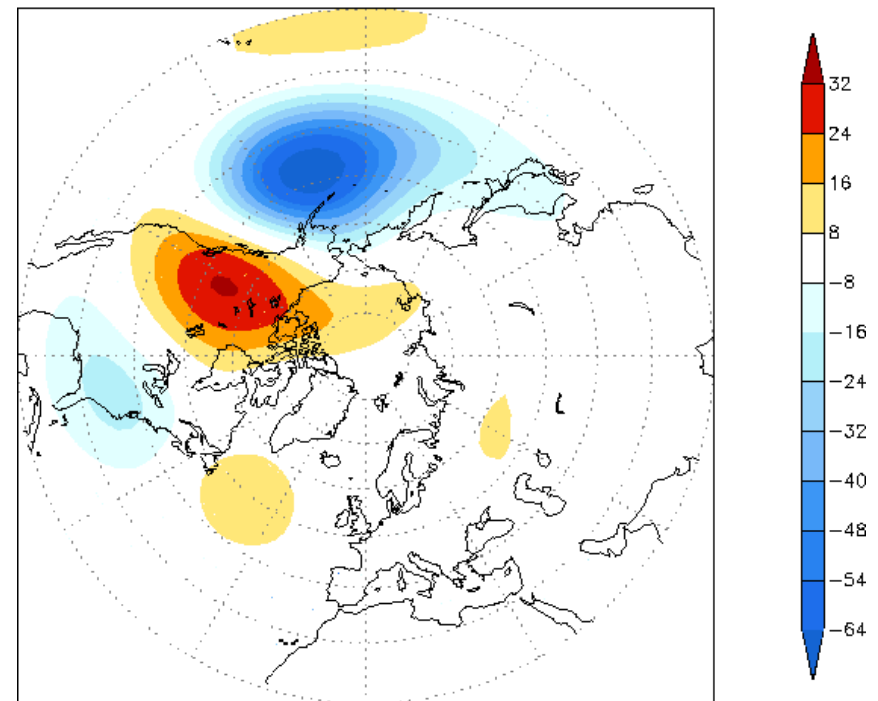


Climate into the 21st Century, WMO

Variability – Pacific/North American Pattern (PNA)

- Determined by pressure/height anomalies at several different points across the Pacific into North America (<1yr-4yrs)
- Atmospheric flow near the west coast of North America is out of phase with the flow of the Eastern Pacific and Southeast United States

REOF (8.5%) shown as regression map of 500mb height (m)



Things to remember from Lecture 3.

- Planetary waves could be stationary and radiate energy downstream. These waves are main component of the atmospheric quasi-stationary patterns.
- Land-sea contrast, topographic features etc can force quasi-stationary wave patterns. Also a major forcing are the high-frequency waves (periods less than 15 days (baroclinic and barotropic waves)).
- The variability of these waves year to year tend to produce the inter annual variability in climate.
- Even in the shorter time-scale they can produce blocking events that modifies the regional weather patterns.
- Whether SST anomalies or/and the high frequency wave activity tend to force quasi-stationary modes that produce climate variability NAO, ENSO, PNA, PSA etc.