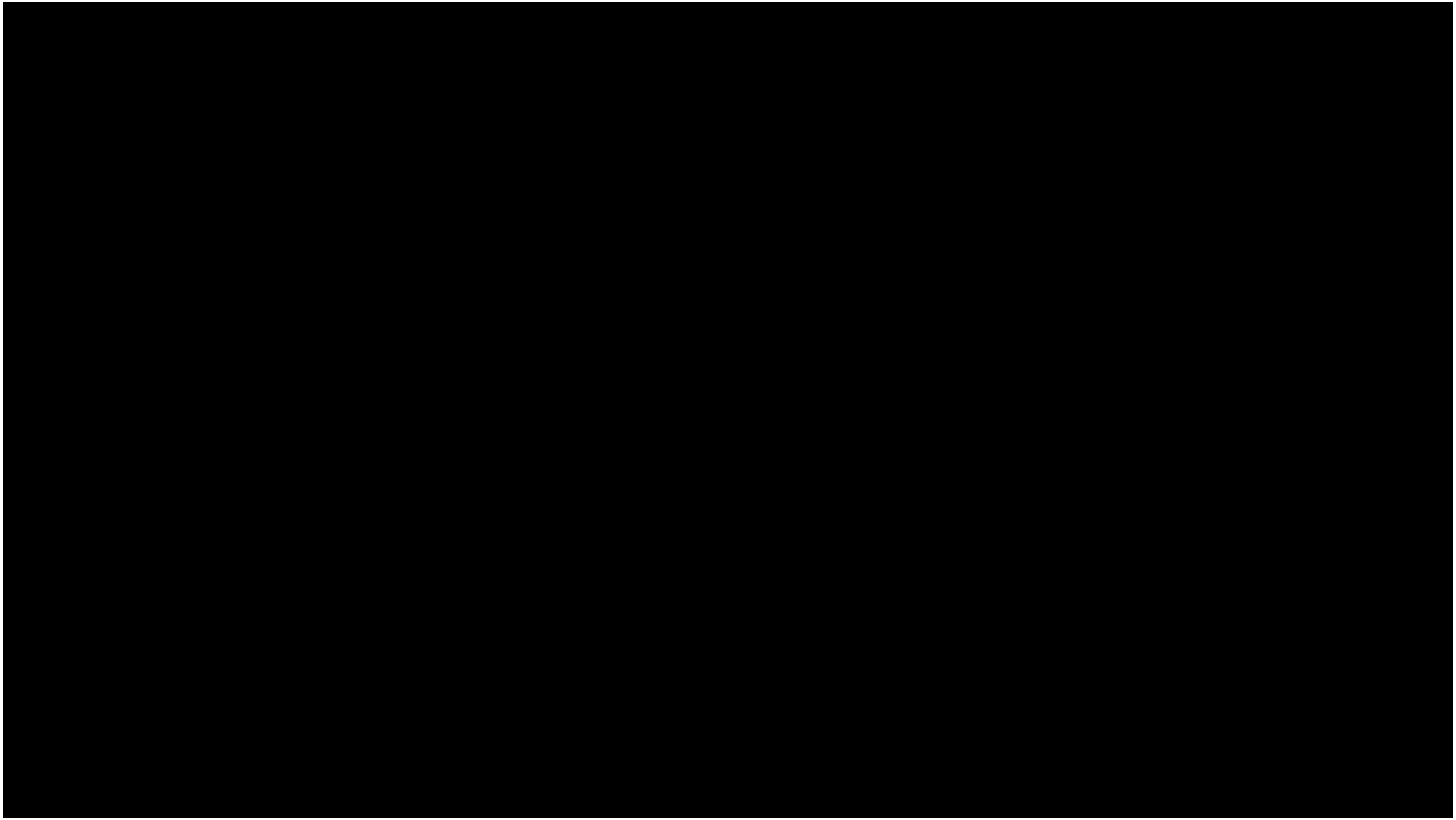
12.810 Dynamics of the Atmosphere

Large-scale flow with rotation and stratification

Visualization of meandering jet stream



Upper level winds from June 10th to July 8th 1988 from MERRA
Red shows faster winds (animation credit NASA)

Teleconnections: Propagation of quasi-stationary Rossby waves from imposed heating in tropical West Pacific

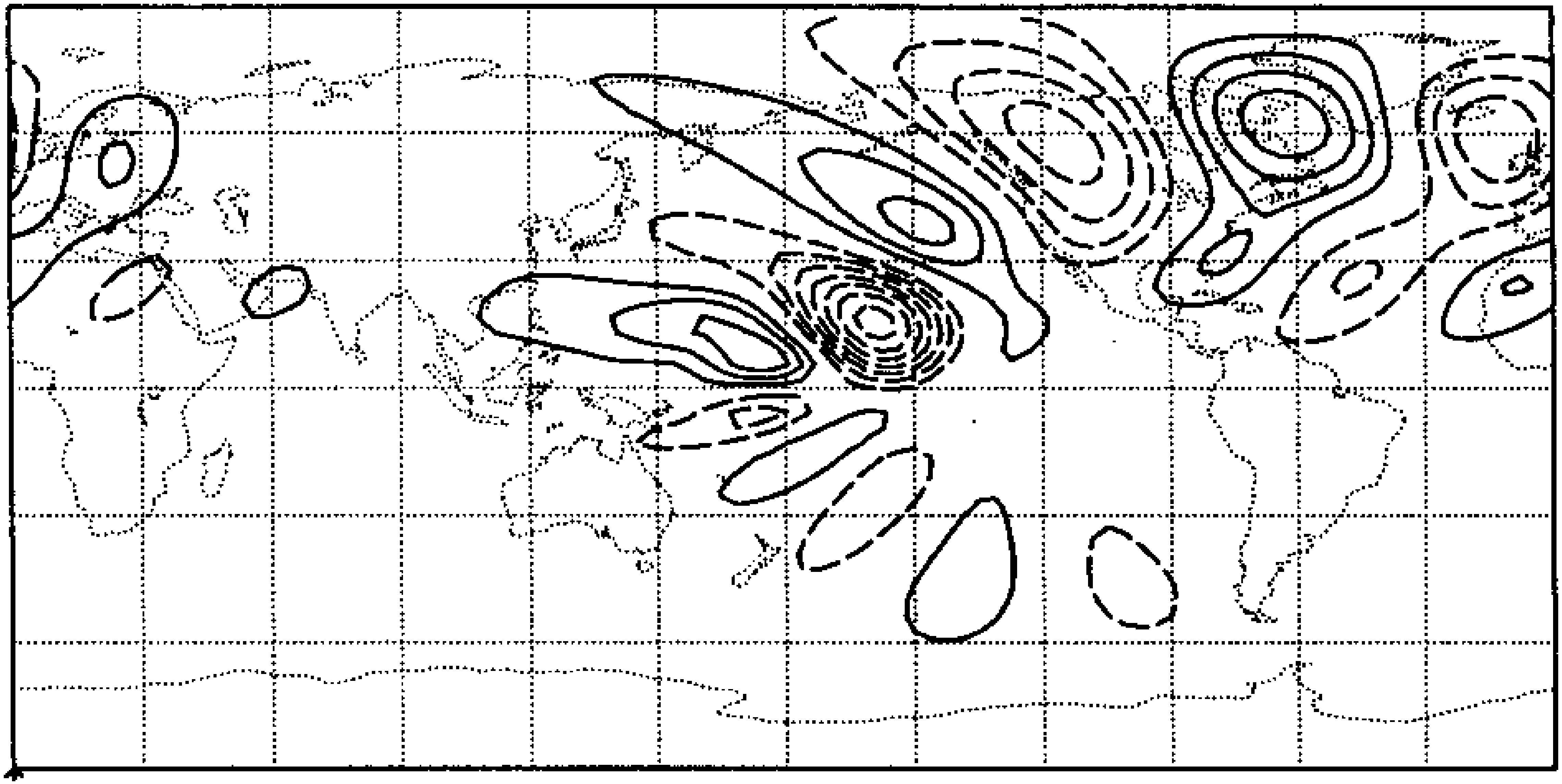
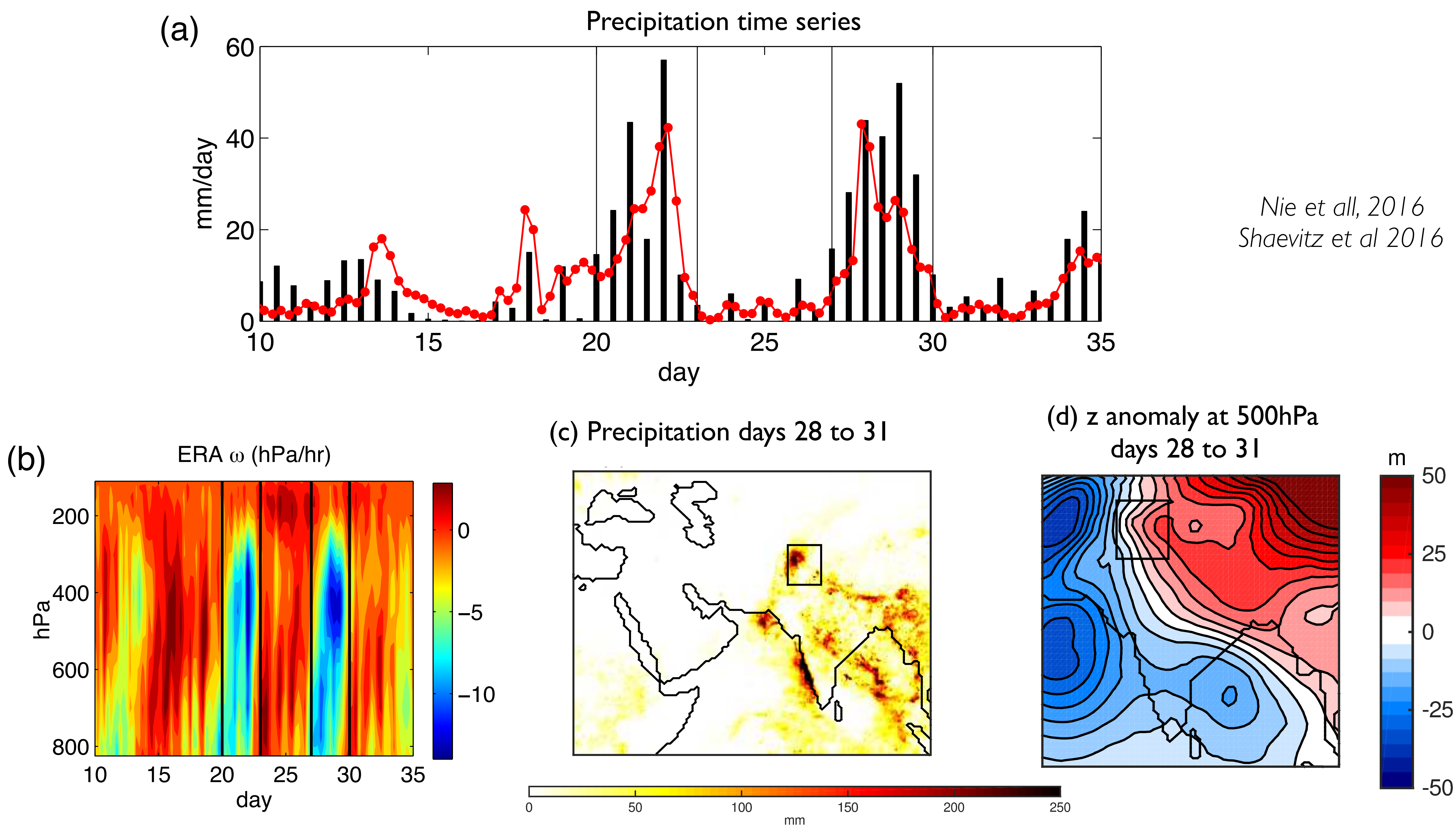


FIG. 8. Longitude–latitude picture of the day 15 $\sigma \approx 0.24$, meridional wind perturbation for the heating on a Dec–Feb zonal flow. The contour interval is 0.5 m s^{-1}. The zero contour is not shown, and the negative contours are dashed.

Jin and Hoskins, JAS 1995

Large-scale dynamics: Important for events like the 2010 Pakistan flooding event



Nie et all, 2016
Shaevitz et al 2016

(a) Twelve hourly precipitation from the ERA-Interim reanalysis (black bars) averaged over northern Pakistan regional box. (b) The time series of large-scale vertical velocity in the ERA data as functions of time and pressure. Day 0 indicates 1 July 2010. The black vertical lines mark days 20, 23, 27, and 30, indicating the time windows of the two extreme precipitation events. (c) Rainfall from TRMM accumulated from days 28 to 31. (d) Geopotential height anomaly at 500hPa days 28 to 31

Large-scale flow with rotation and stratification: Lecture plan

1. Potential vorticity and Rossby waves in the shallow water system

2. Quasigeostrophic dynamics in a continuously stratified atmosphere

3. Vertical and horizontal propagation of Rossby waves on the sphere

Rossby waves

RELATION BETWEEN VARIATIONS IN THE INTENSITY OF THE ZONAL CIRCULATION OF THE ATMOSPHERE AND THE DISPLACEMENTS OF THE SEMI-PERMANENT CENTERS OF ACTION*

BY

C.-G. ROSSBY AND COLLABORATORS

Massachusetts Institute of Technology

This paper attempts to interpret, from a single point of view, several at first sight independent phenomena brought into focus through the synoptic investigations carried on at the Massachusetts Institute of Technology during the last few years. Since this interpretation is very largely based on a consideration of the changes in vorticity which must occur in vertical air columns which are displaced from one latitude to another and since such vorticity changes play a fundamental role also in Ekman's general ocean current theory (1932), the results would appear to be of enough interest to physical oceanographers to warrant their publication in this journal. The

$$c = U - \frac{\beta L^2}{4\pi^2}$$

Rossby, J. Marine Res., 1939

Rossby-wave dispersion relation

$\tilde{\omega}/\hat{\beta}L_R$ as a function of kL_R and lL_R

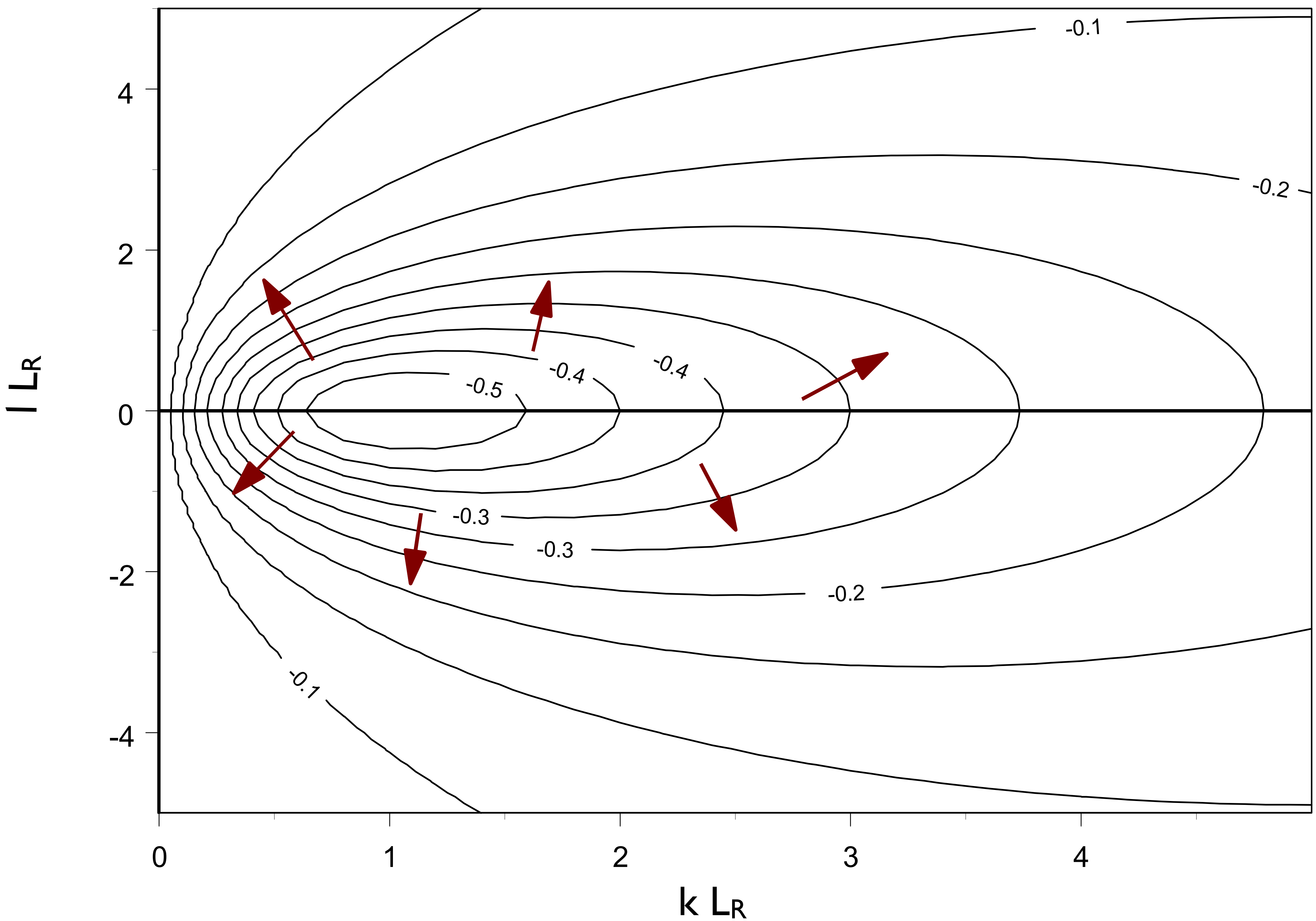


Fig. 1 Arrows show direction of group velocity

PV inversion for a ball of cyclonic PV in NH

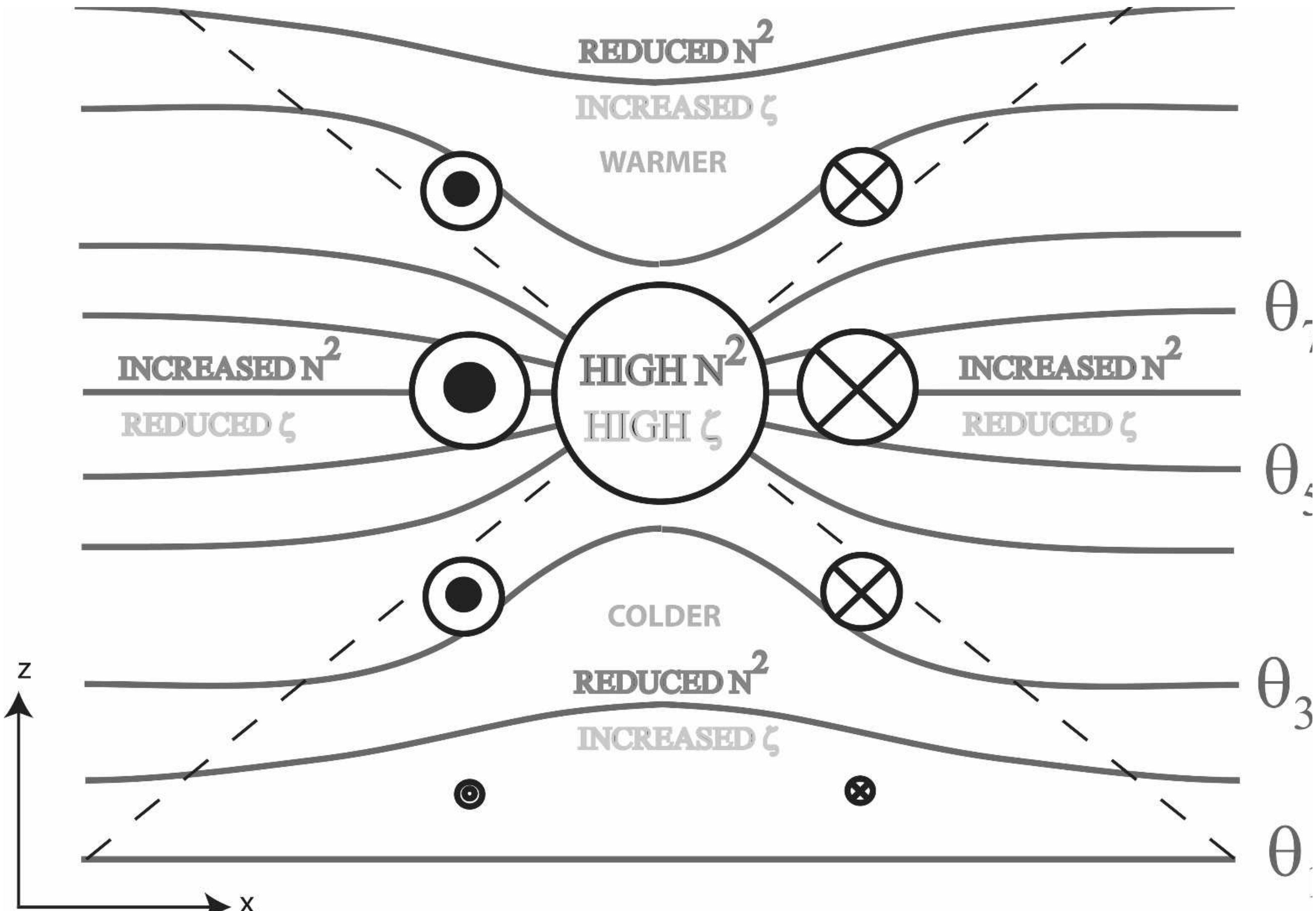


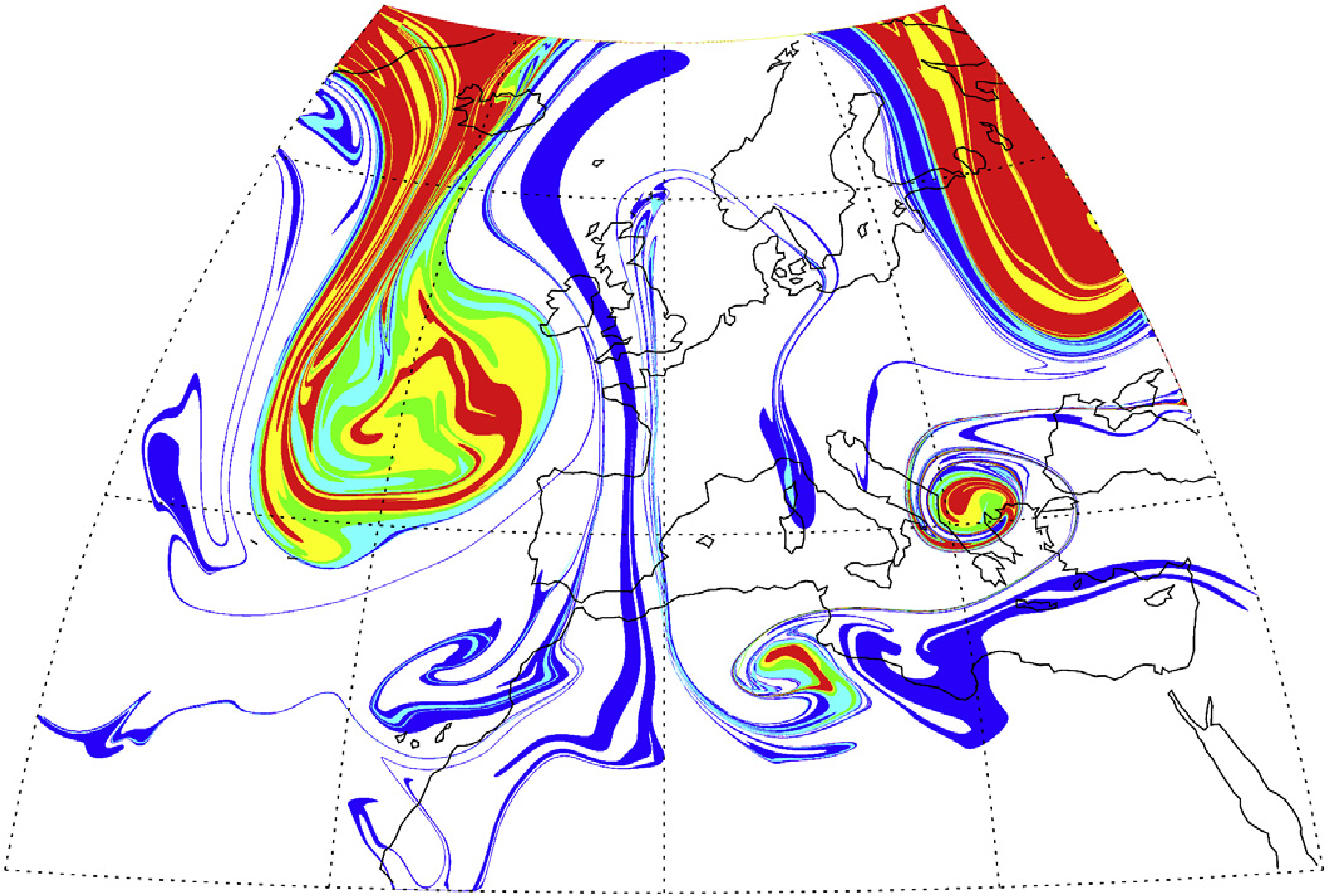
FIG. 1. Idealized schematic of an isolated cyclonic spherical PV anomaly in a uniform background state. The vertical axis is scaled by N_0/f_0.

Fig. 2

Nielsen-Gammon et al, MWR, 2008

Potential vorticity on the 320K isentrope

Fig. 3



Values above 1 PVU = $10^{-6} m^2 s^{-1} K\ kg^{-1}$ are colored; date 5/14/92 12GMT; McIntyre, PV, 2015

Zonal and time-mean potential temperature (K)

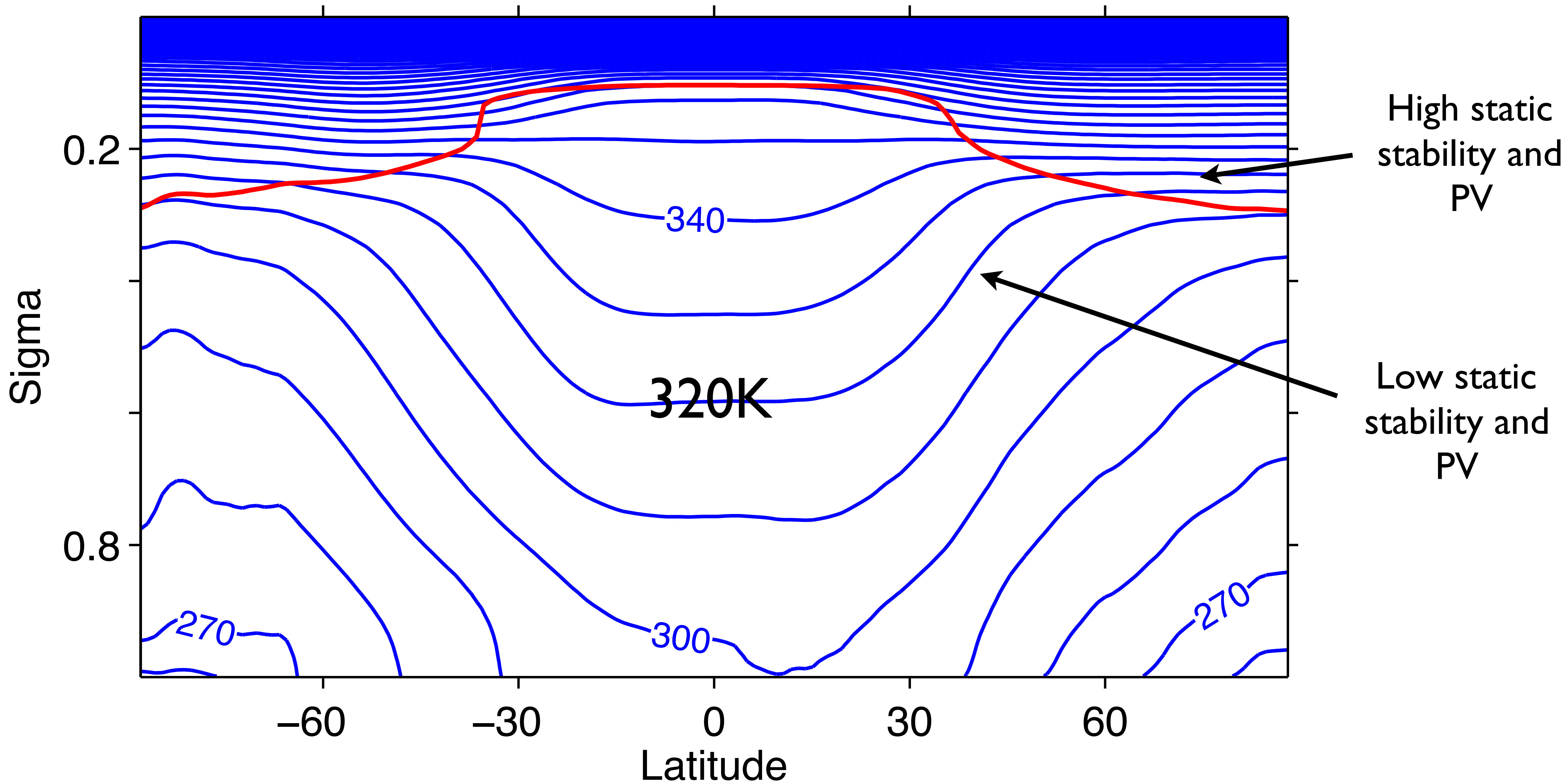


Fig. 4

(ERA40 reanalysis data 1980-2001)

PV song

G D Em C C6
When I find myself in times of trouble, Father Hoskins comes to me,

G D C d/b c/a b/g = G
Speaking words of wisdom, P V_____ _ _ _

G D Em C C6
And in my hour of darkness, Baroclinic instability:

G D C d/b c/a b/g = G
There will be an answer, P V_____ _ _ _

Em Bm C G
P V, P V, P V, P V,

G D C d/b c/a b/g = G
There will be an answer, P V_____ _ _ _

G D Em C C6
And when the broken contours tell us There's cascading enstrophy,

G D C d/b c/a b/g = G
There will be a closure, P V_____ _ _ _

G D Em C C6
And when it's less than zero and it's Lost its ellipticity,

G D C d/b c/a b/g = G
You just can't invert it, P V_____ _ _ _

Em Bm C G
P V, P V, P V, P V,

G D C d/b c/a b/g = G
You just can't invert it, P V_____ _ _ _

(funky instrumental interlude ad lib,
with performers gyrating cyclonically
and anticyclonically, pairing off etc.)

G D Em C C6
And when the night is cloudy, There's a diabatic theta-E

G D C d/b c/a b/g = G
That modifies___ the parcel's P V_____ _ _ _

G D Em C C6
Swirling round the isentropes, Around the world and back to me,

G D C d/b c/a b/g = G
But it integrates to zero, P V_____ _ _ _

Em Bm C G
P V, P V, P V, P V,

G D C d/b c/a b/g = G
Yes it all adds up to nothing, P V_____ _ _ _

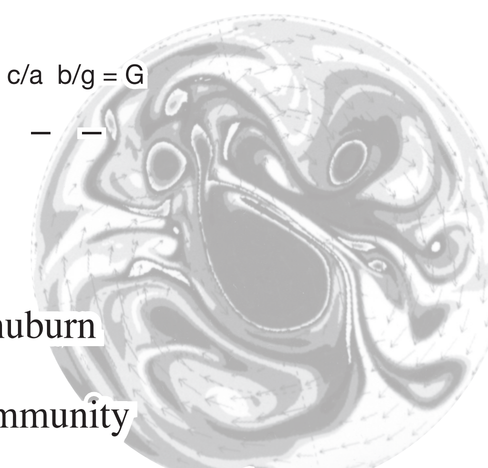
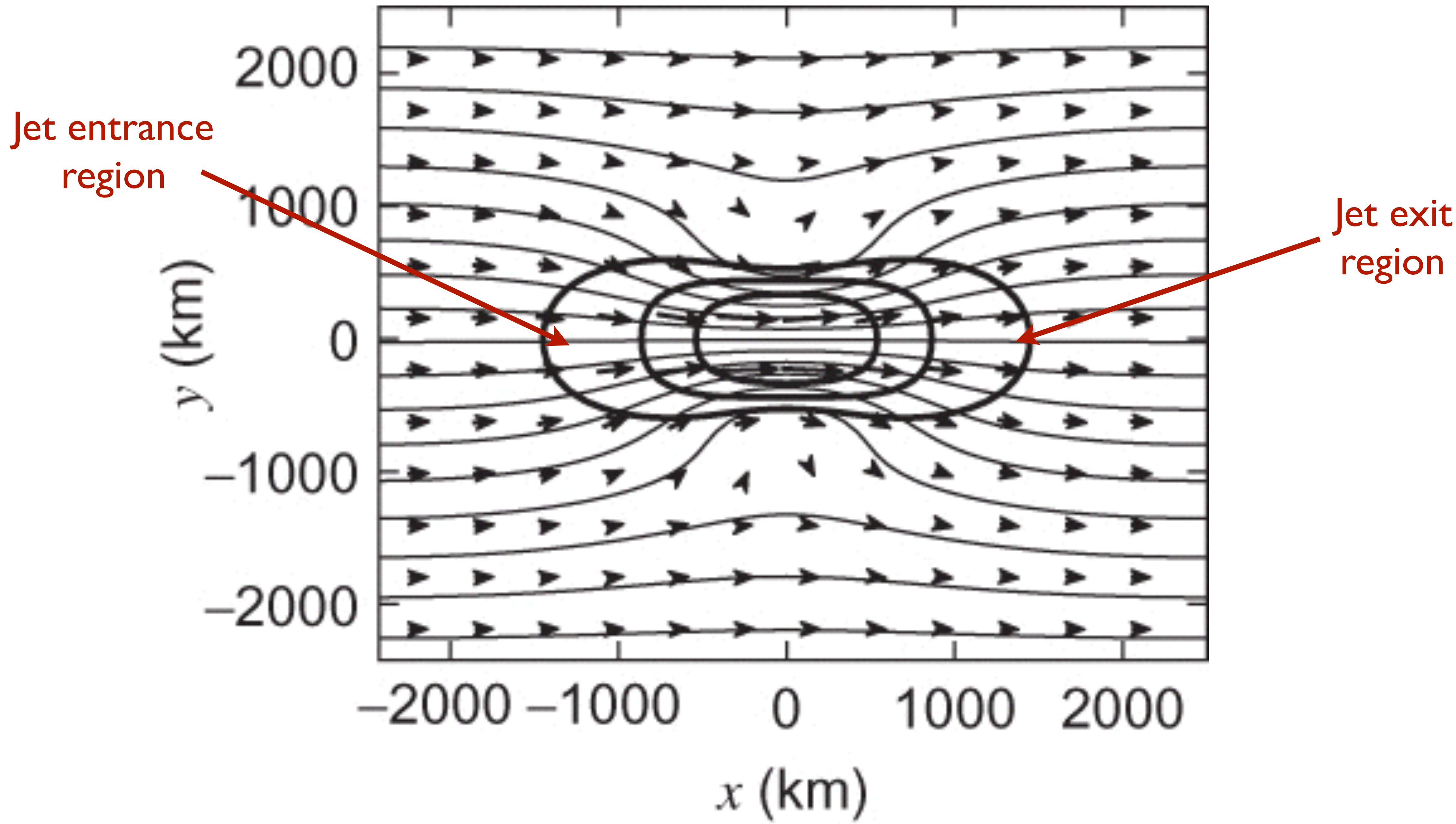


Figure courtesy of Juckes and McIntyre 1987, personal communication

Jet streak in westerly wind at z=5km

westerly wind increases linearly with z (not shown)

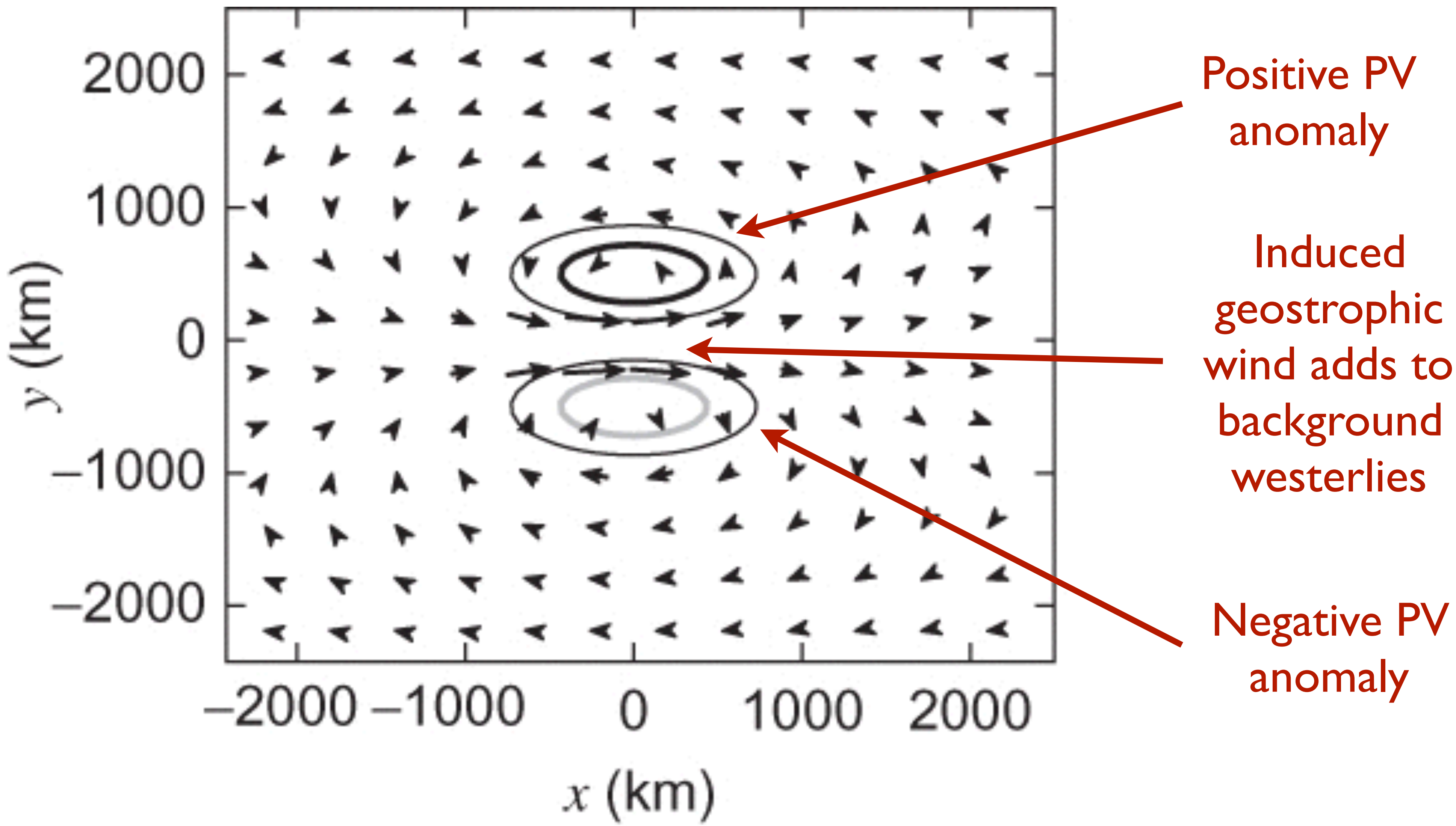


Arrows: wind
Thin lines: pressure
Thick lines: isotachs

Fig. 5

Holton and Hakim Fig 6.12

Jet streak is a result of dipole of anomalous PV



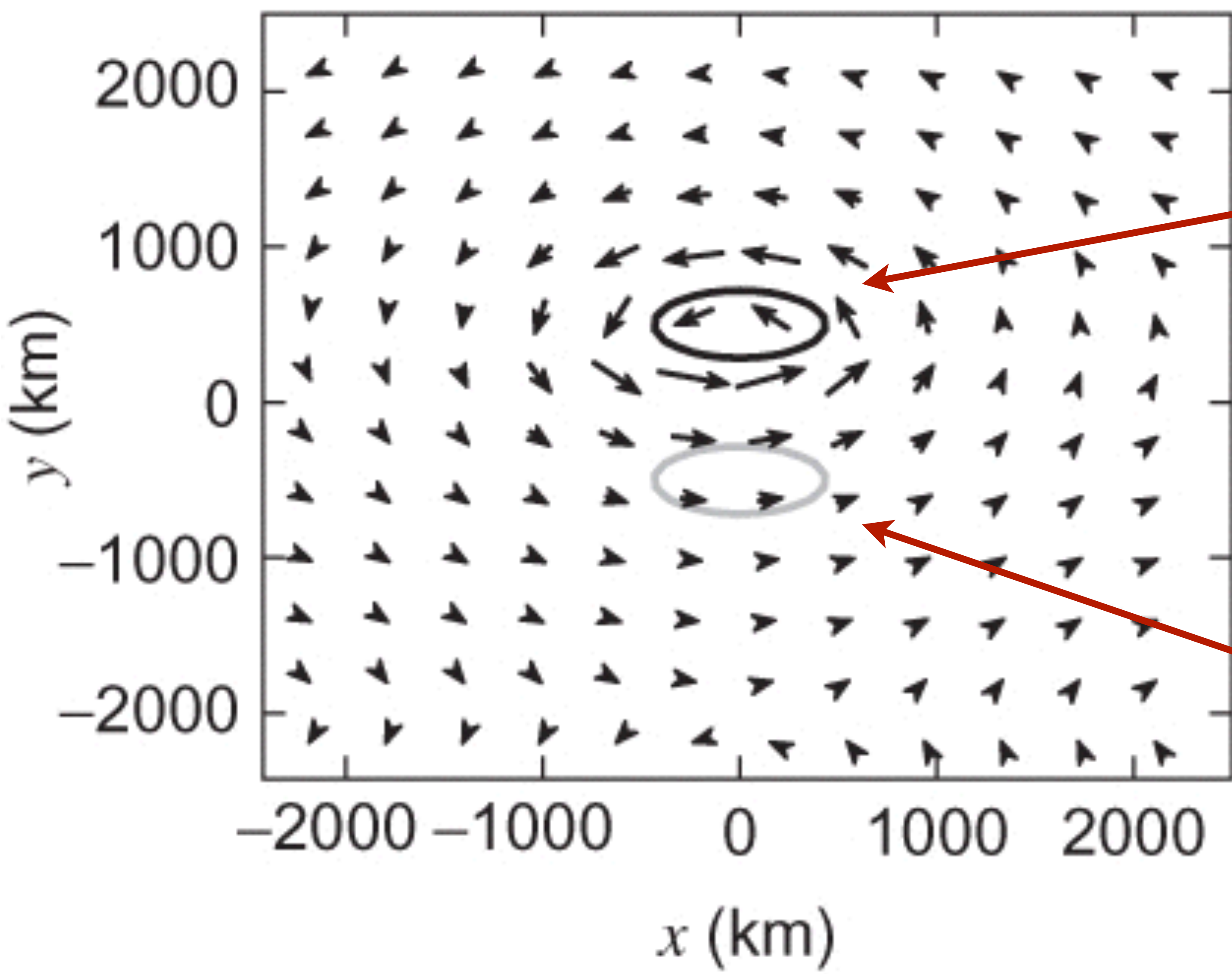
Arrows: wind induced by the PV anomalies
Lines: contours of PV

Fig. 5

Holton and Hakim Fig 6.12

Dynamic evolution: jet streak moves downstream

Arrows show wind induced by the *positive* PV anomaly



Positive PV anomaly

Slowly advects negative PV anomaly downstream

Fig. 5

Holton and Hakim Fig 6.12

Dynamic evolution: jet streak moves downstream

Arrows show wind induced by the *negative* PV anomaly

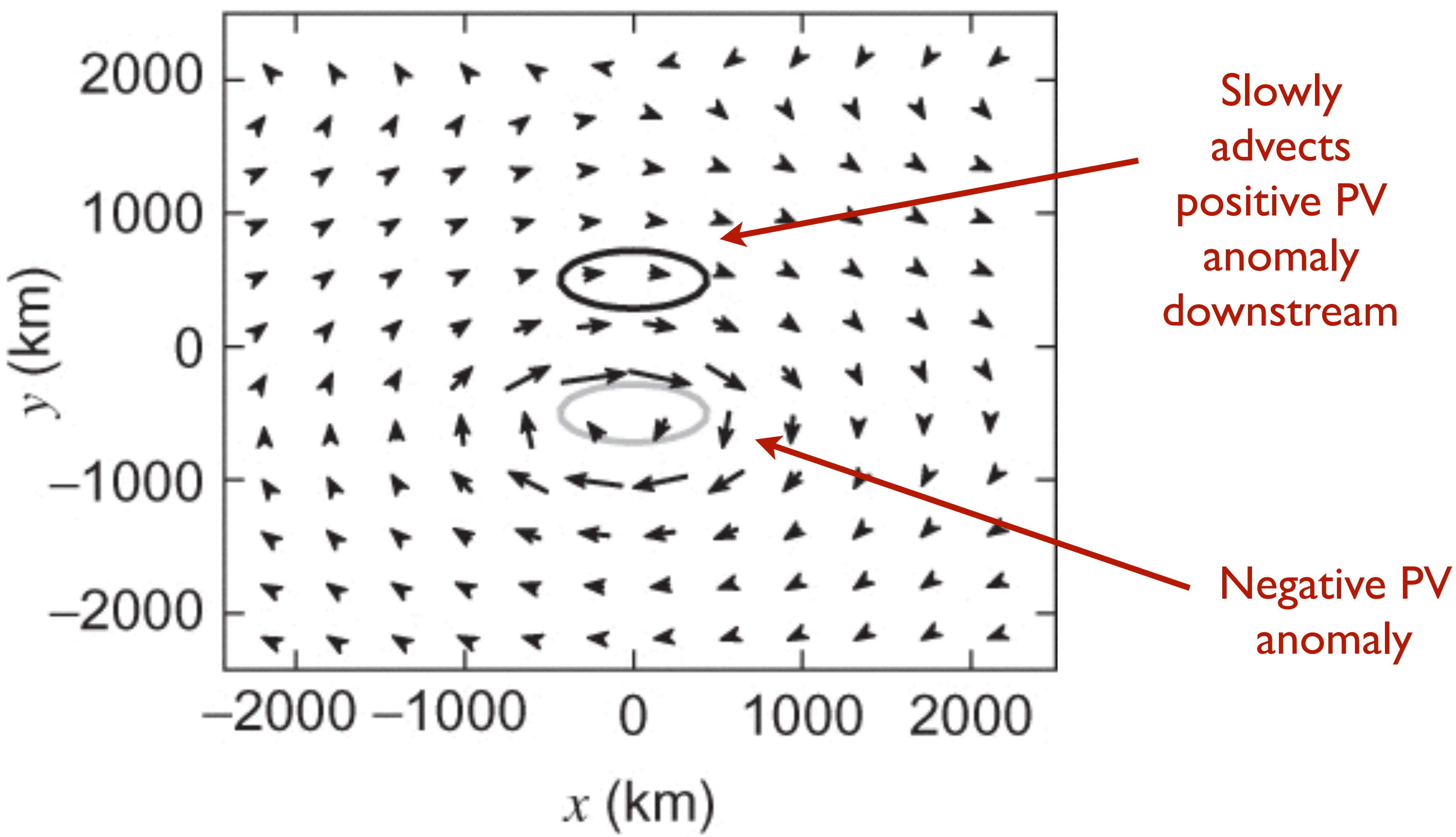
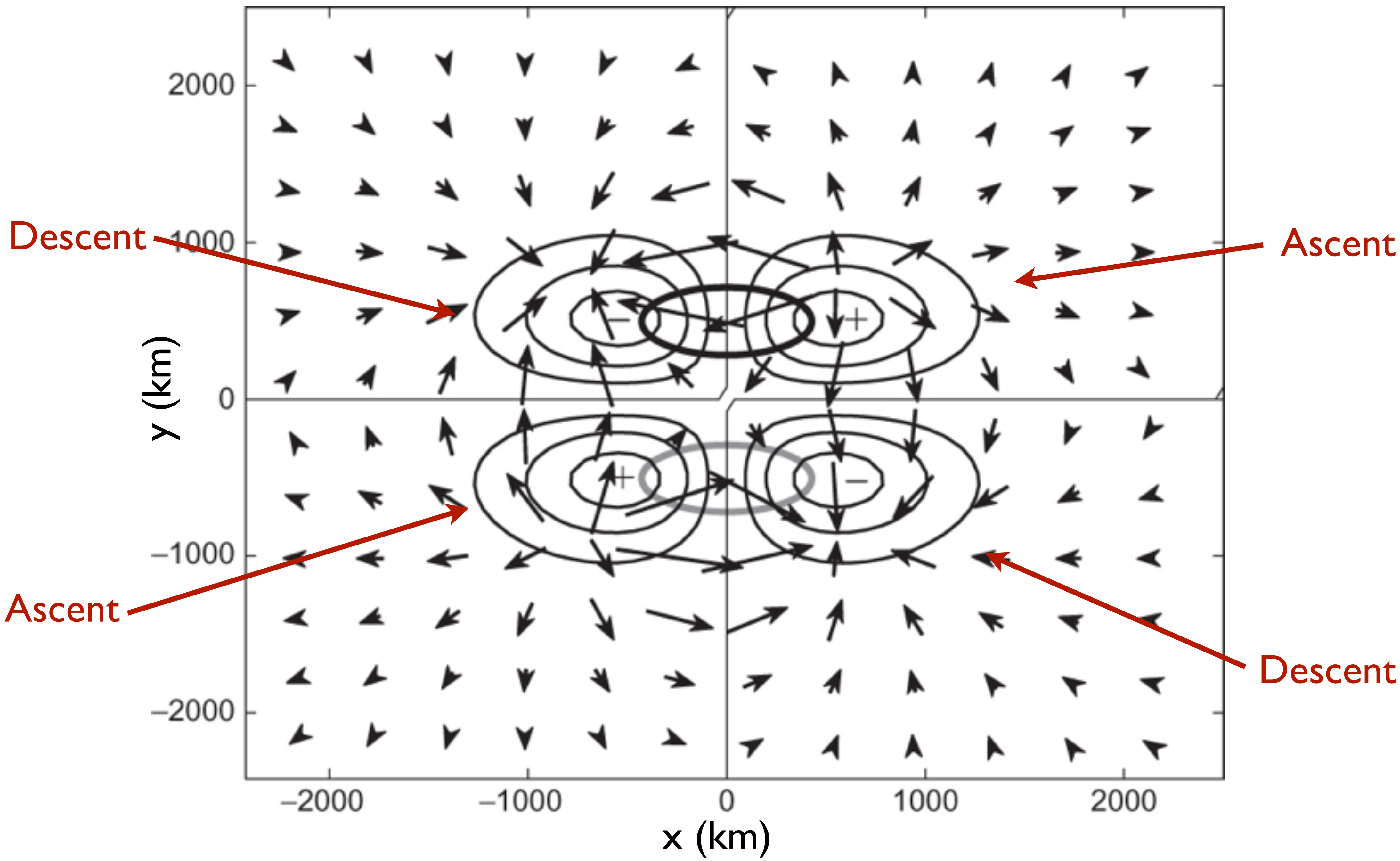


Fig. 5

Holton and Hakim Fig 6.12

Ageostrophic circulation (u_a, v_a) and w associated with jet streak



Arrows: ageostrophic wind
Lines: contours of w
Thick lines: contours of anomalous PV
Assumes background du/dz>0

Fig. 5

Holton and Hakim Fig 6.16

Zonal wind affects whether Rossby waves can propagate (Charney-Drazin filtering)

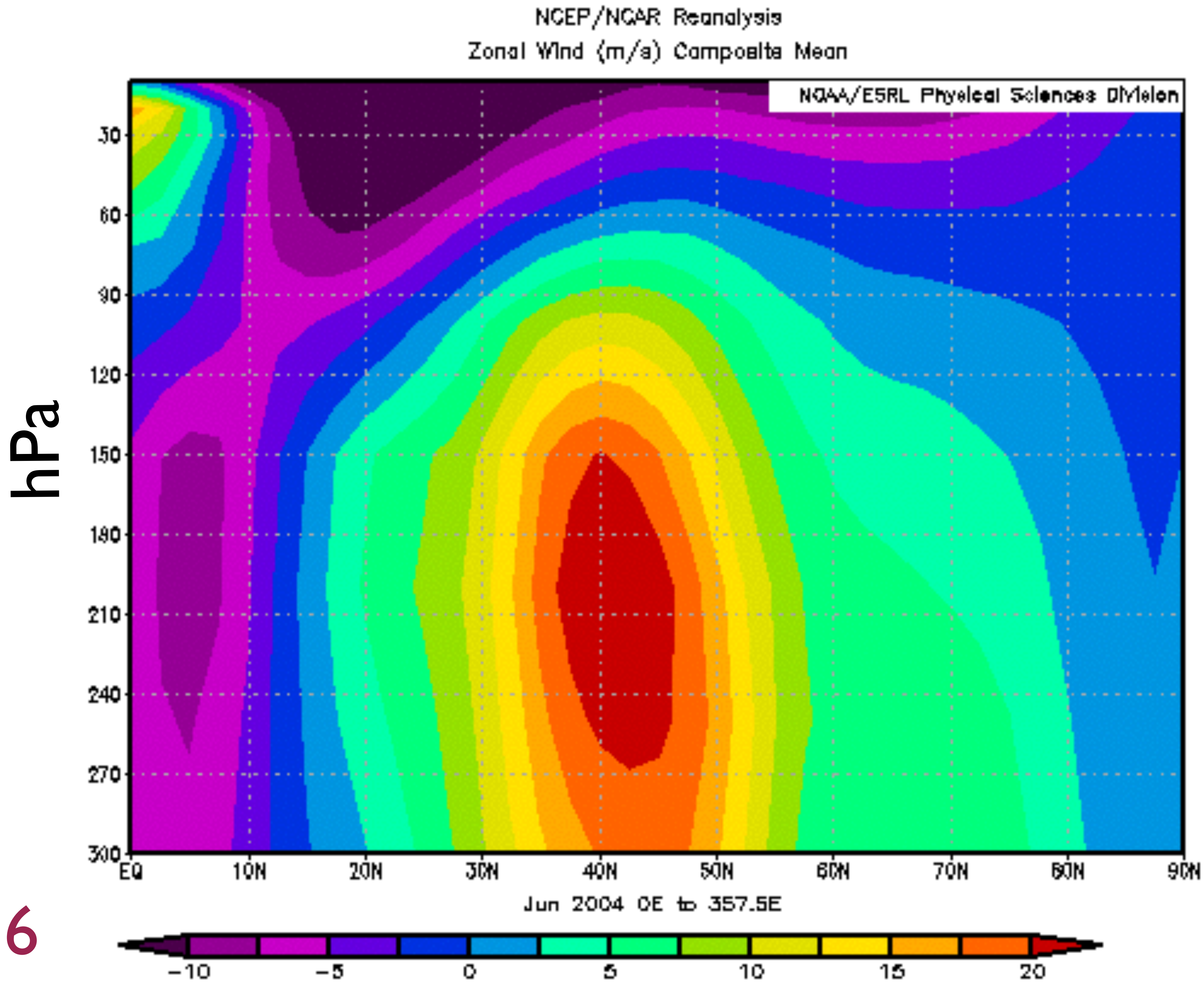
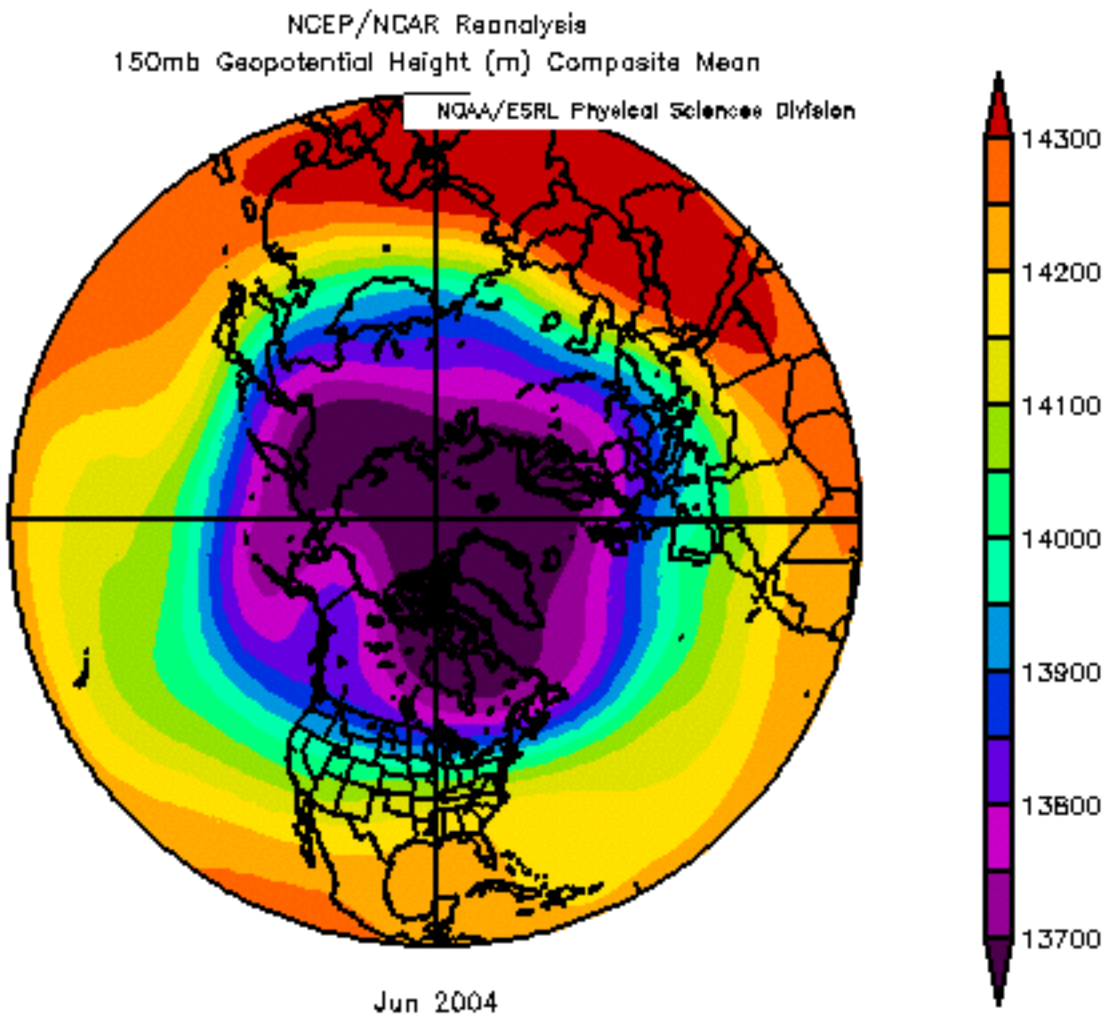
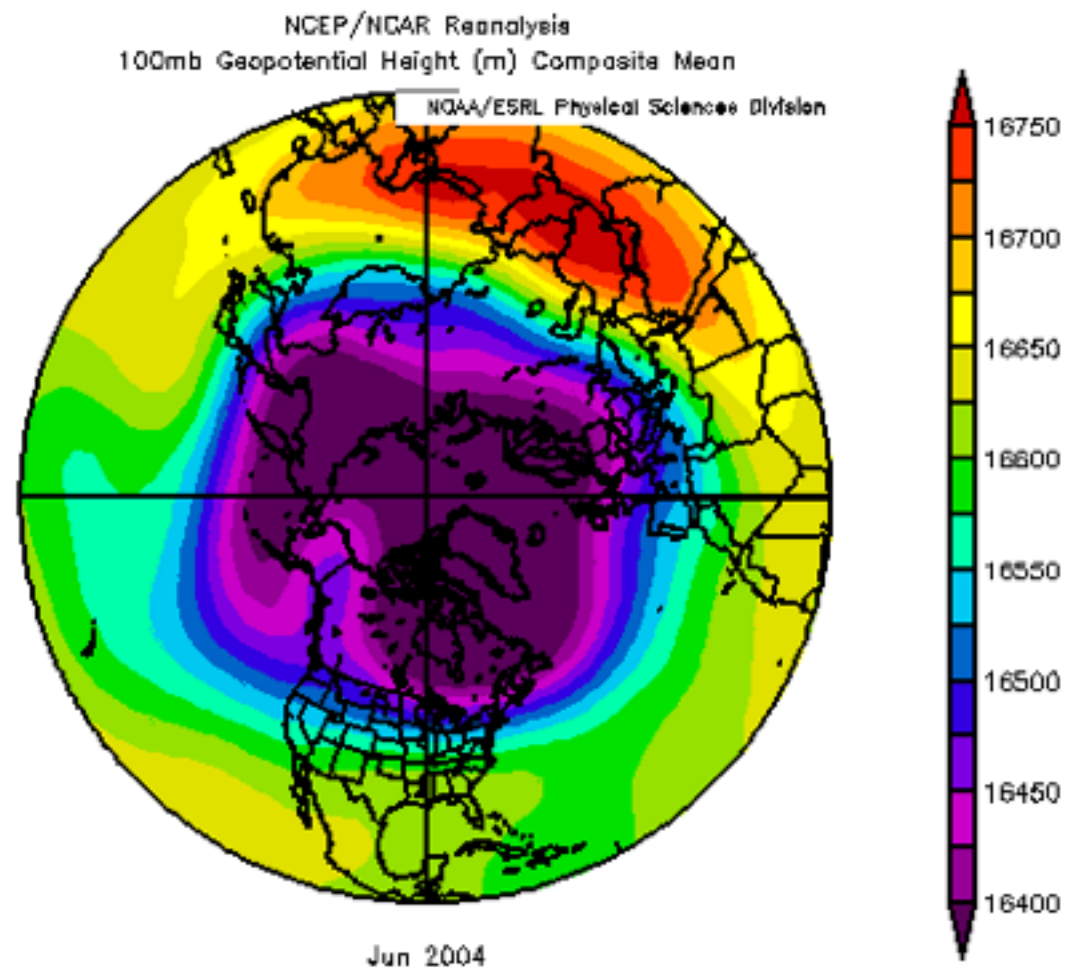


Fig. 6

Stationary waves in the geopotential height at different pressure levels (June 2004)



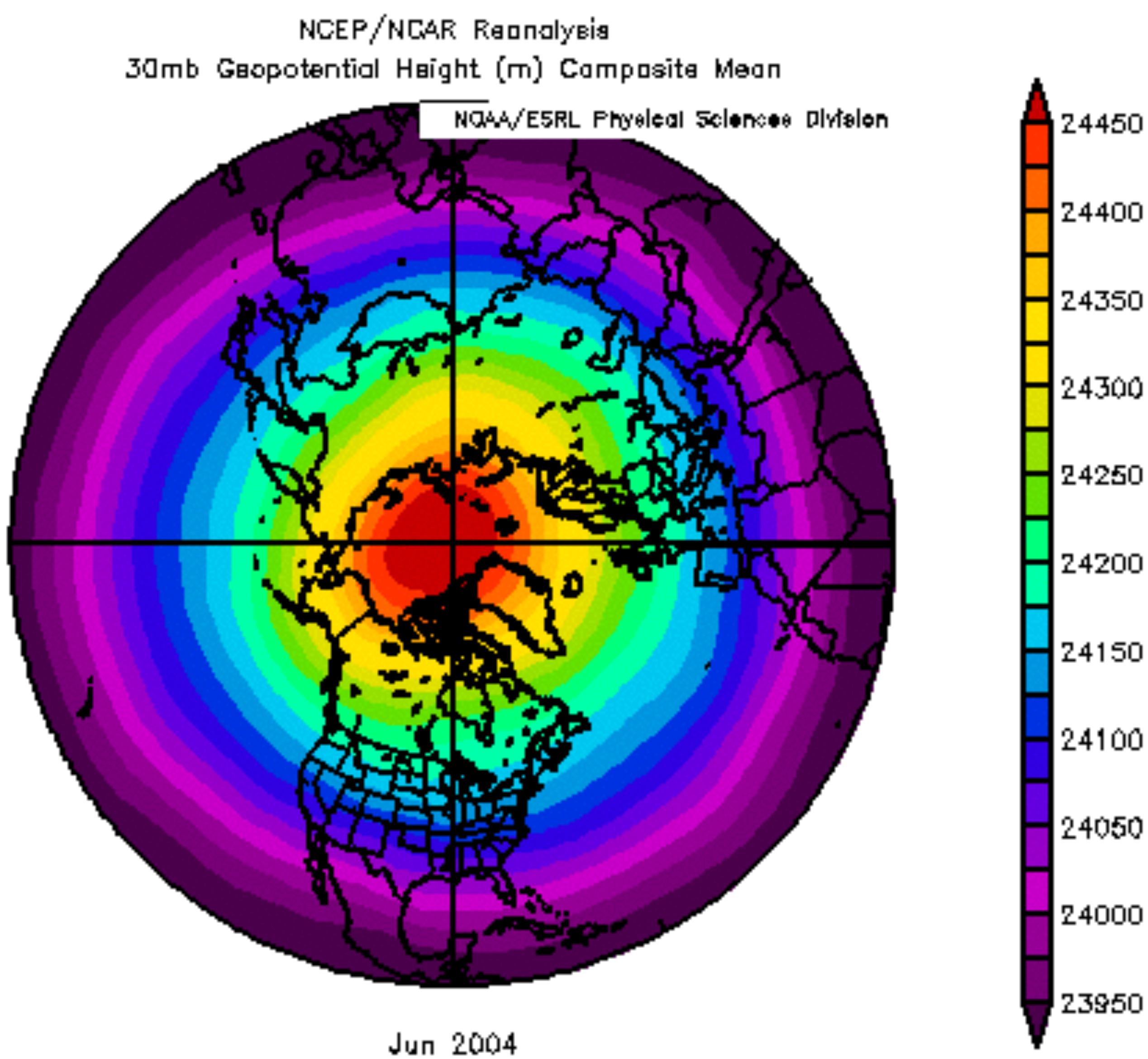


150hPa

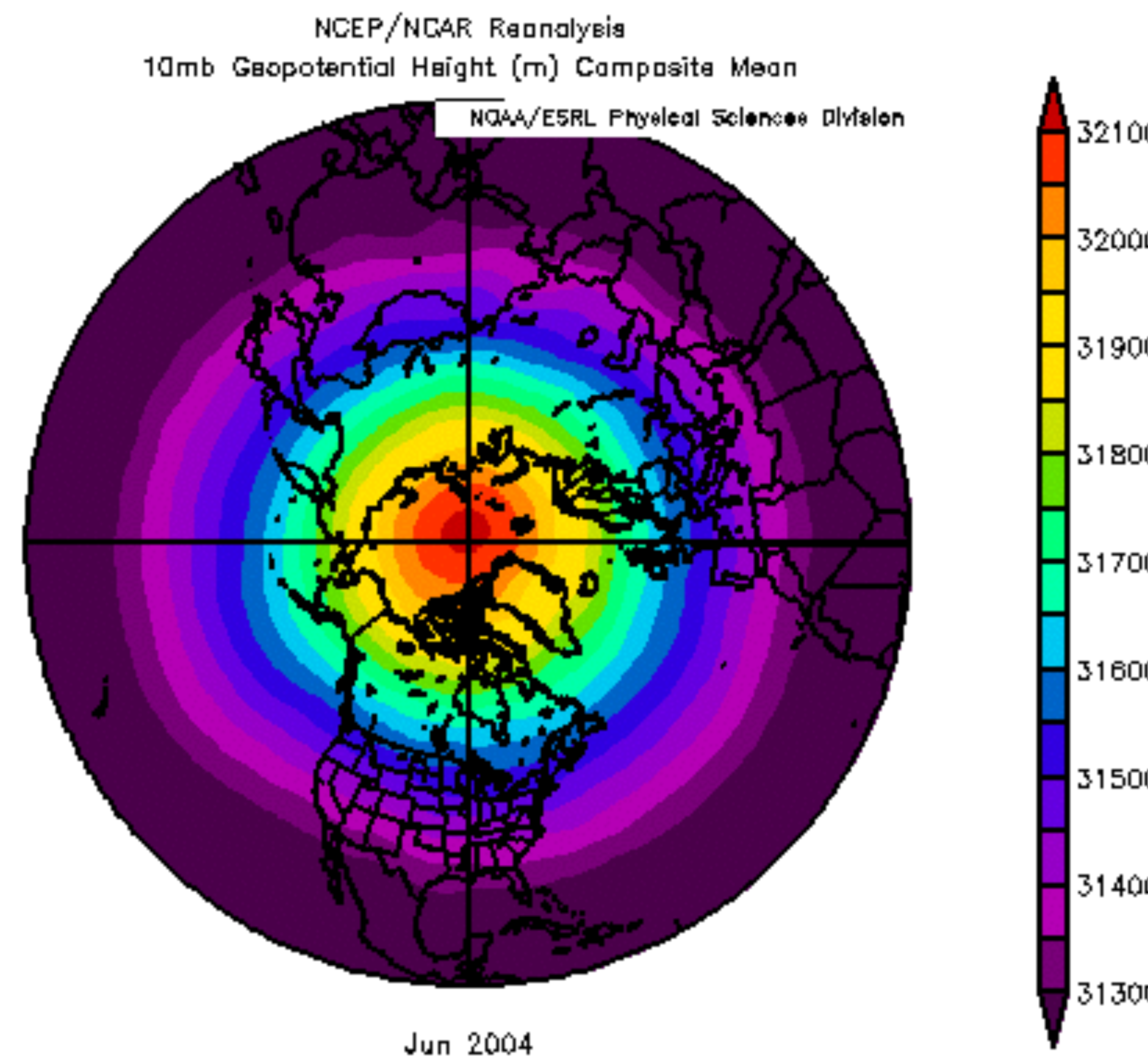
100hPa

Fig. 7

But symmetric geopotential height at levels with easterlies



30hPa



10hPa

Fig. 8

Effect of filtering for stratosphere: only planetary scale waves in winter, largely symmetric in summer

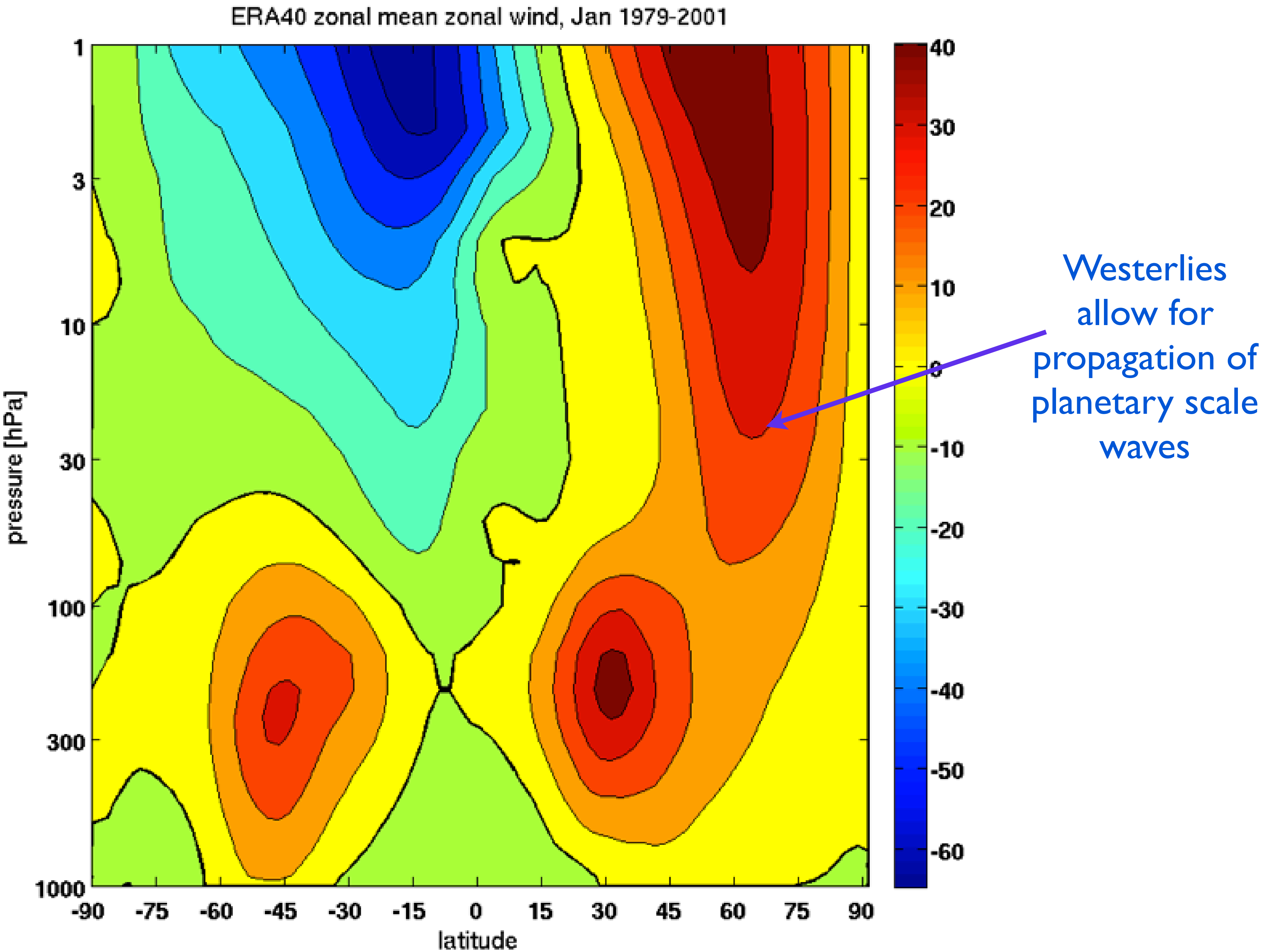


Fig. 9

Only planetary scale waves in winter (1/10/2006) at 30hPa

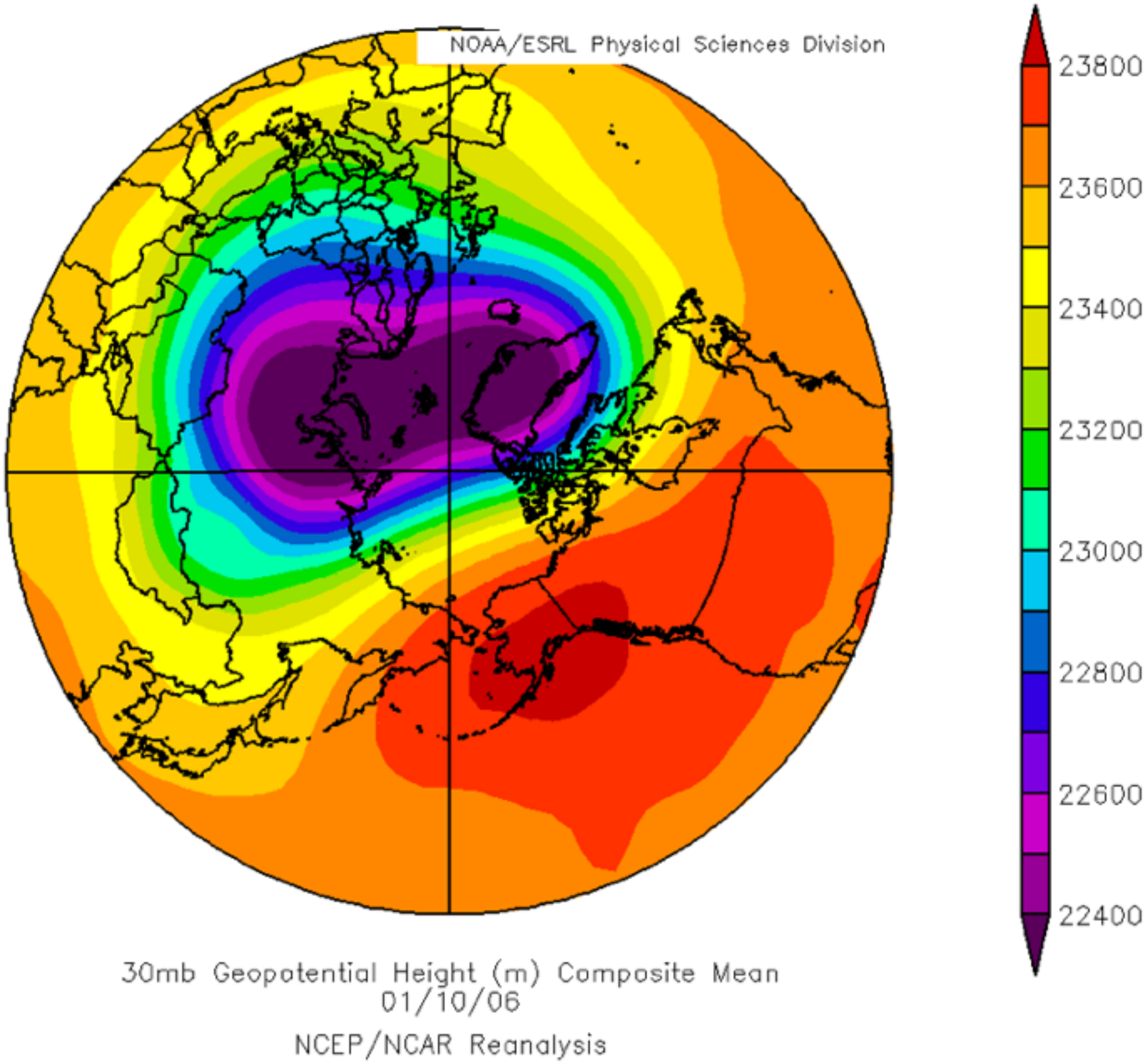


Fig. 10

Largely symmetric in summer (7/1/2006) at 30hPa

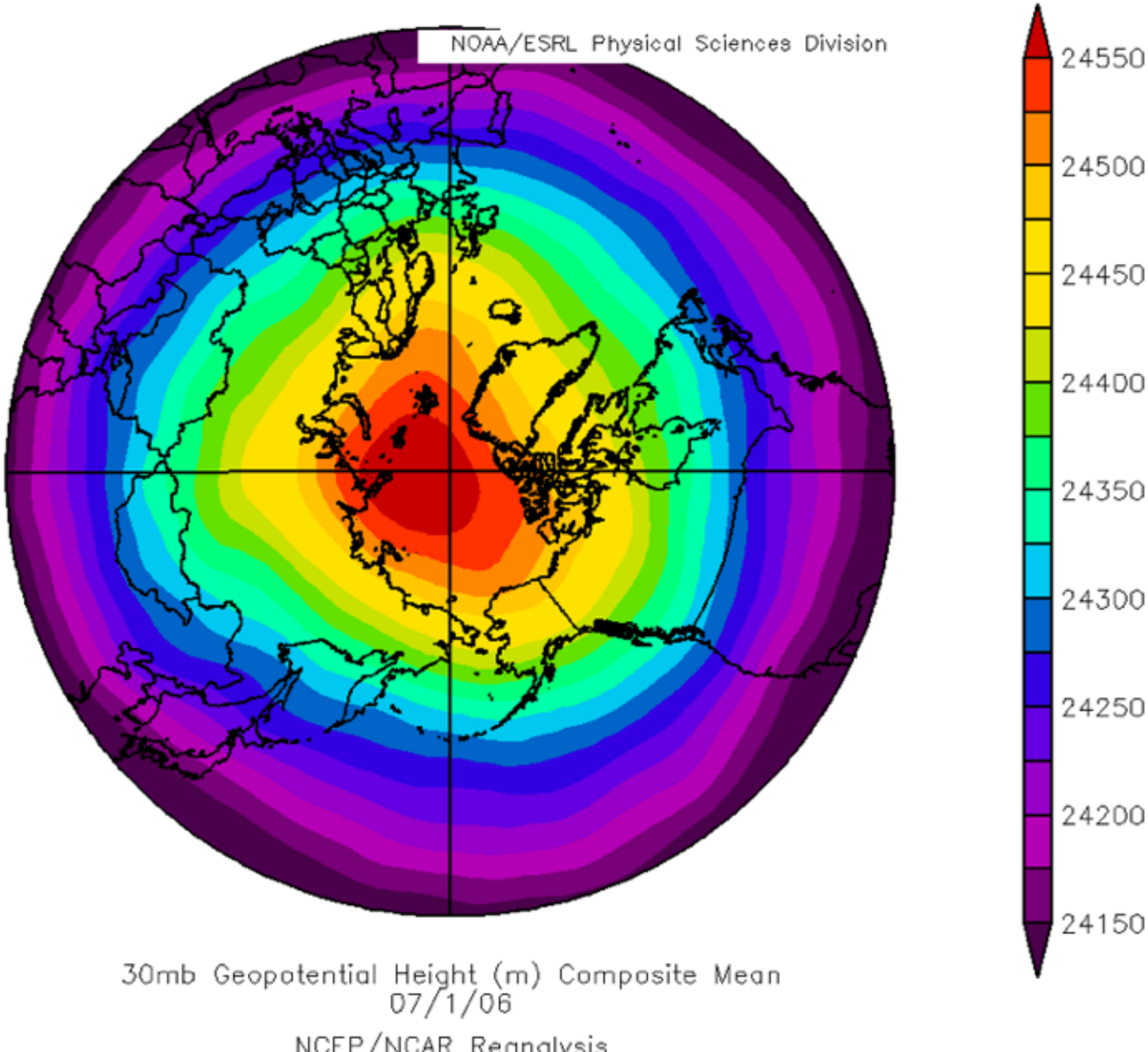


Fig. 11

Contrast with presence of synoptic waves in troposphere

1/1/2006 at 500hPa

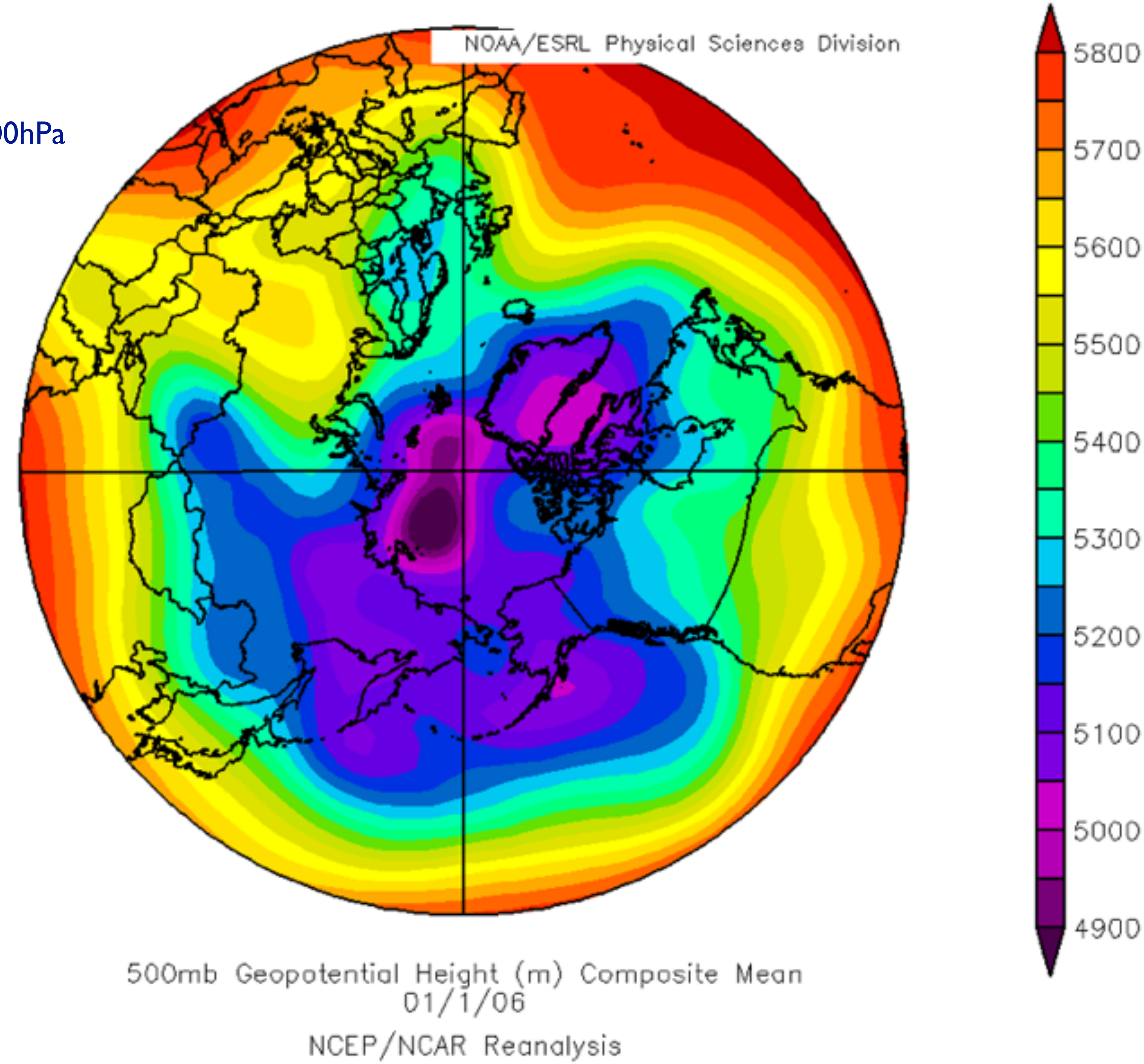


Fig. 12

Observed stationary waves in January climatology: Geopotential height at 300hPa

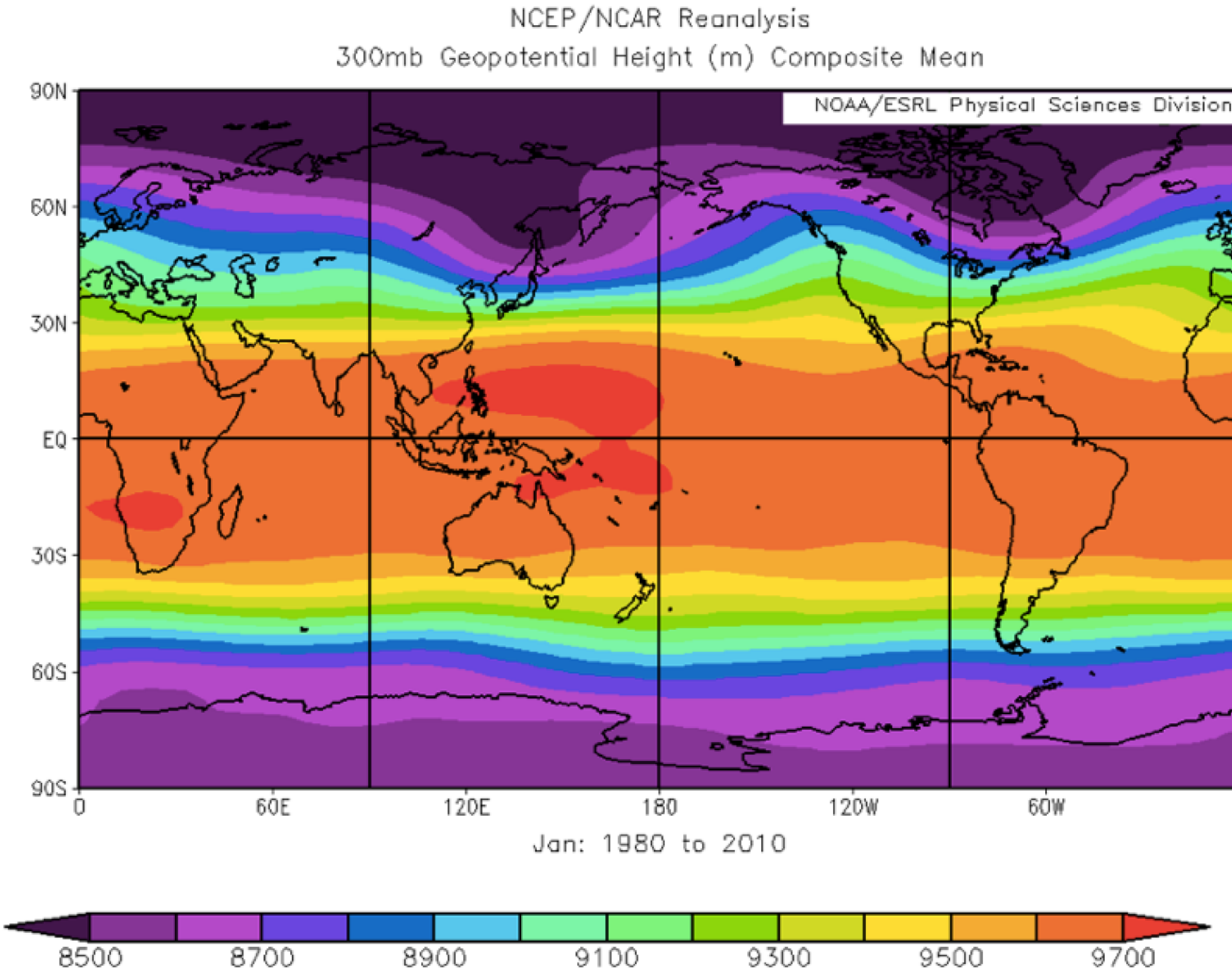


Fig. 13

Observed stationary waves in January climatology: Meridional wind at 300hPa

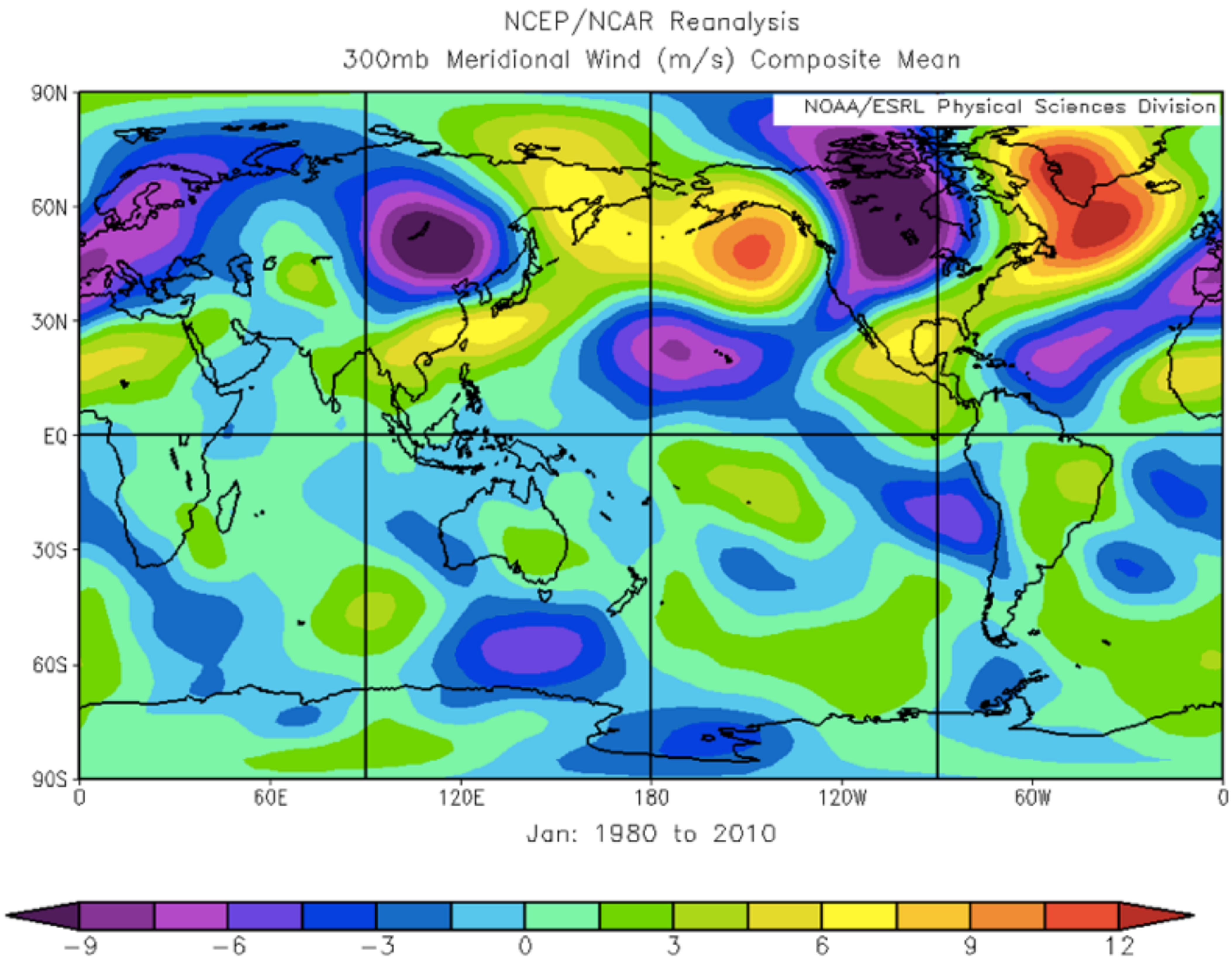


Fig. 13

Flow past a barrier: understanding the response using conservation of potential vorticity

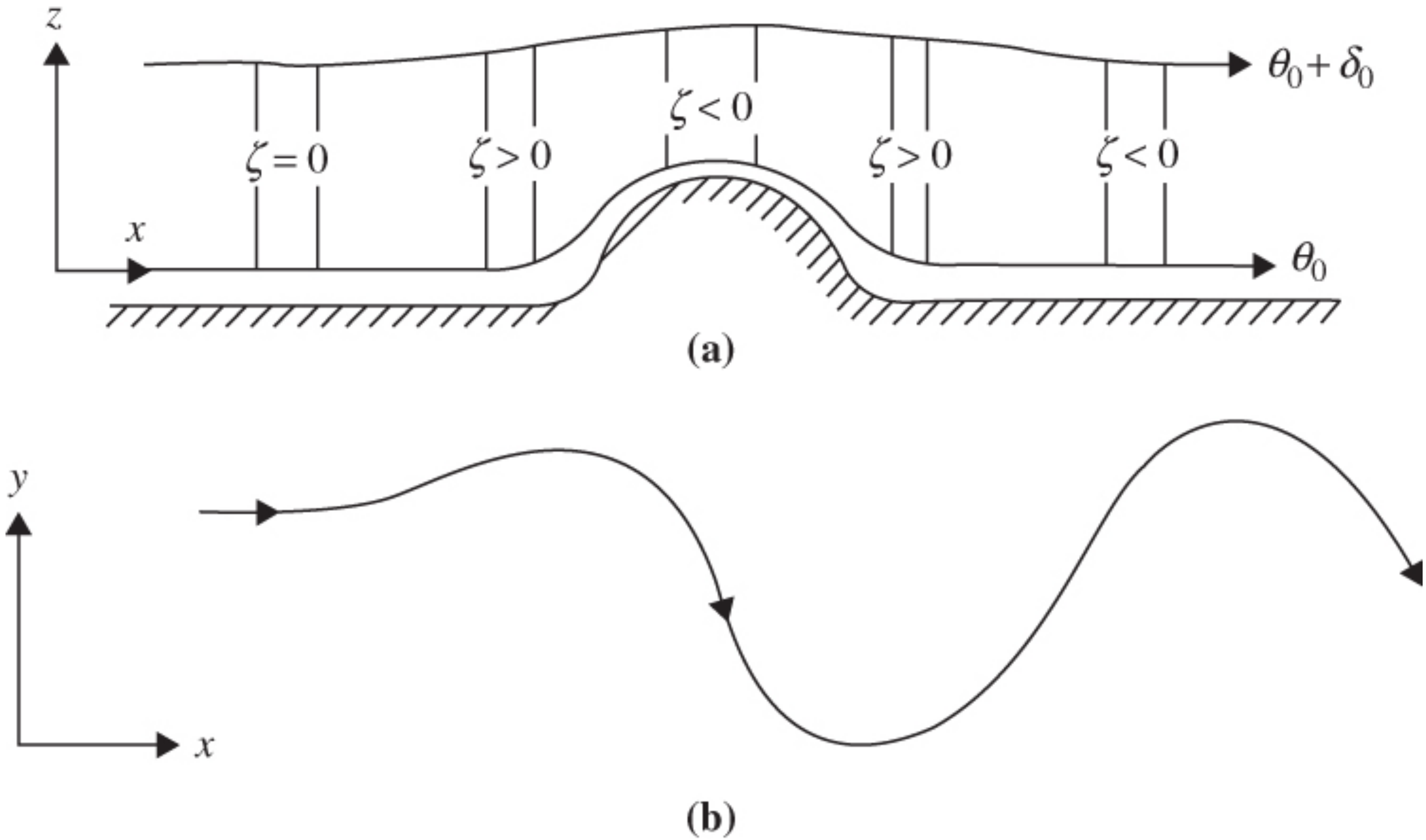


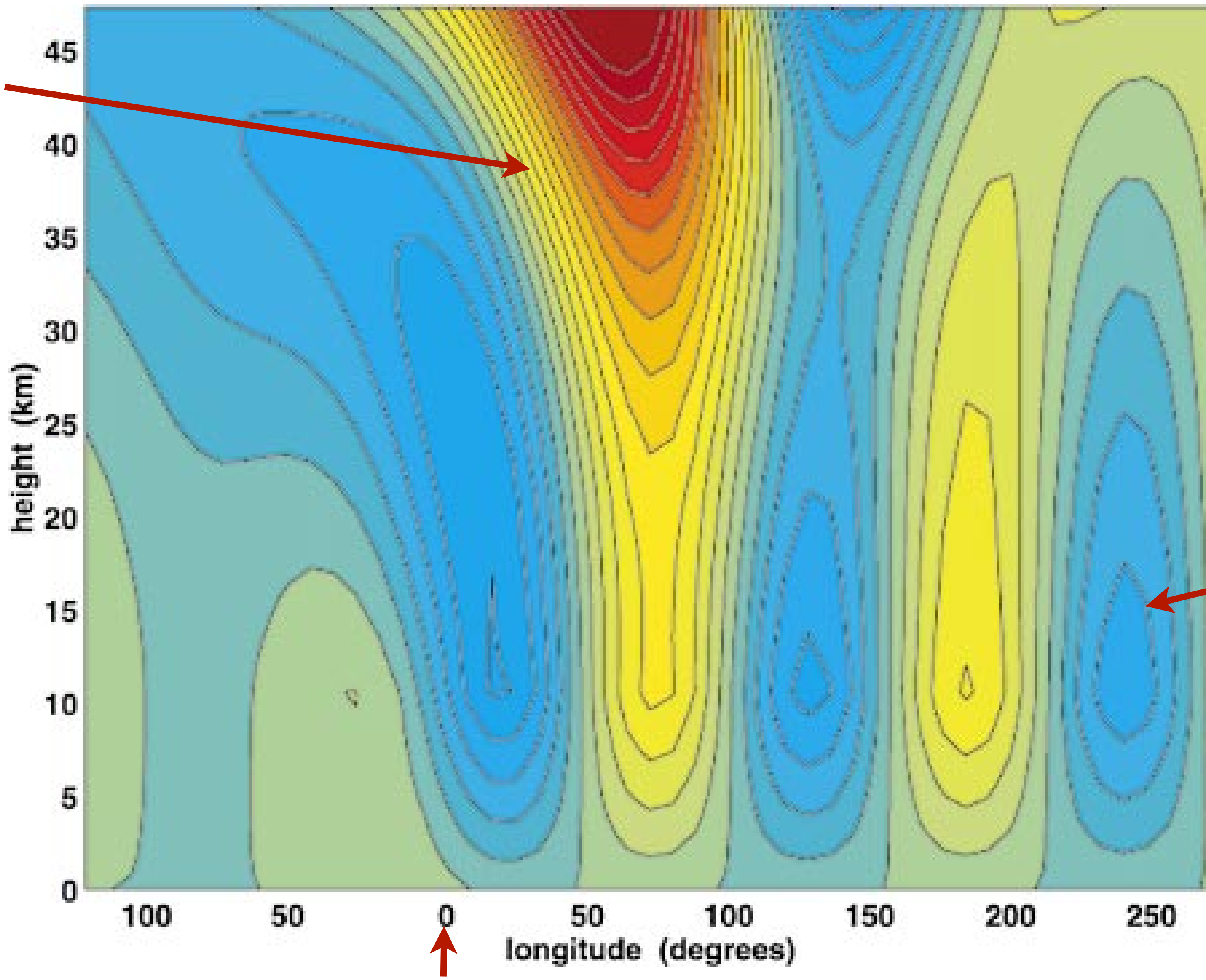
Fig. 14

Schematic view of westerly flow over a topographic barrier: (a) the depth of a fluid column as a function of x and (b) the trajectory of a parcel in the (x, y) plane.

Holton and Hakim

Vertical structure of response to flow over an isolated mountain

Vertically propagating wave



Wave with fixed structure in z (external mode)

FIG. 4. Streamfunction response to orography in a QG model on a β plane with uniform Brunt–Väisälä frequency, in which the mean zonal flow is linear in height below the tropopause (at 10 km) and uniform above the tropopause. The orography and the solution are assumed to be independent of latitude. The orography is centered at 0° lon.

Fig. 15

Held et al J. Climate 2002

Climatological stationary wave pattern for January: no phase tilt with height

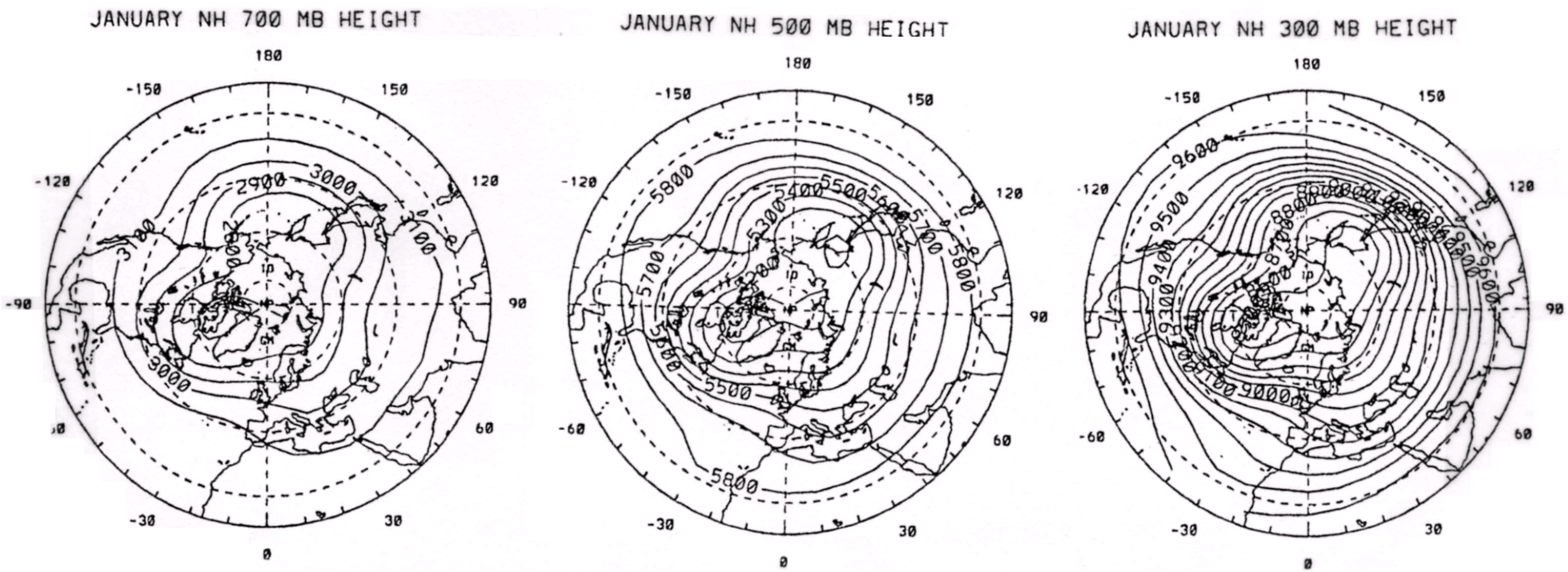


Fig. 16

Alan Plumb notes

Vertical structure of external mode

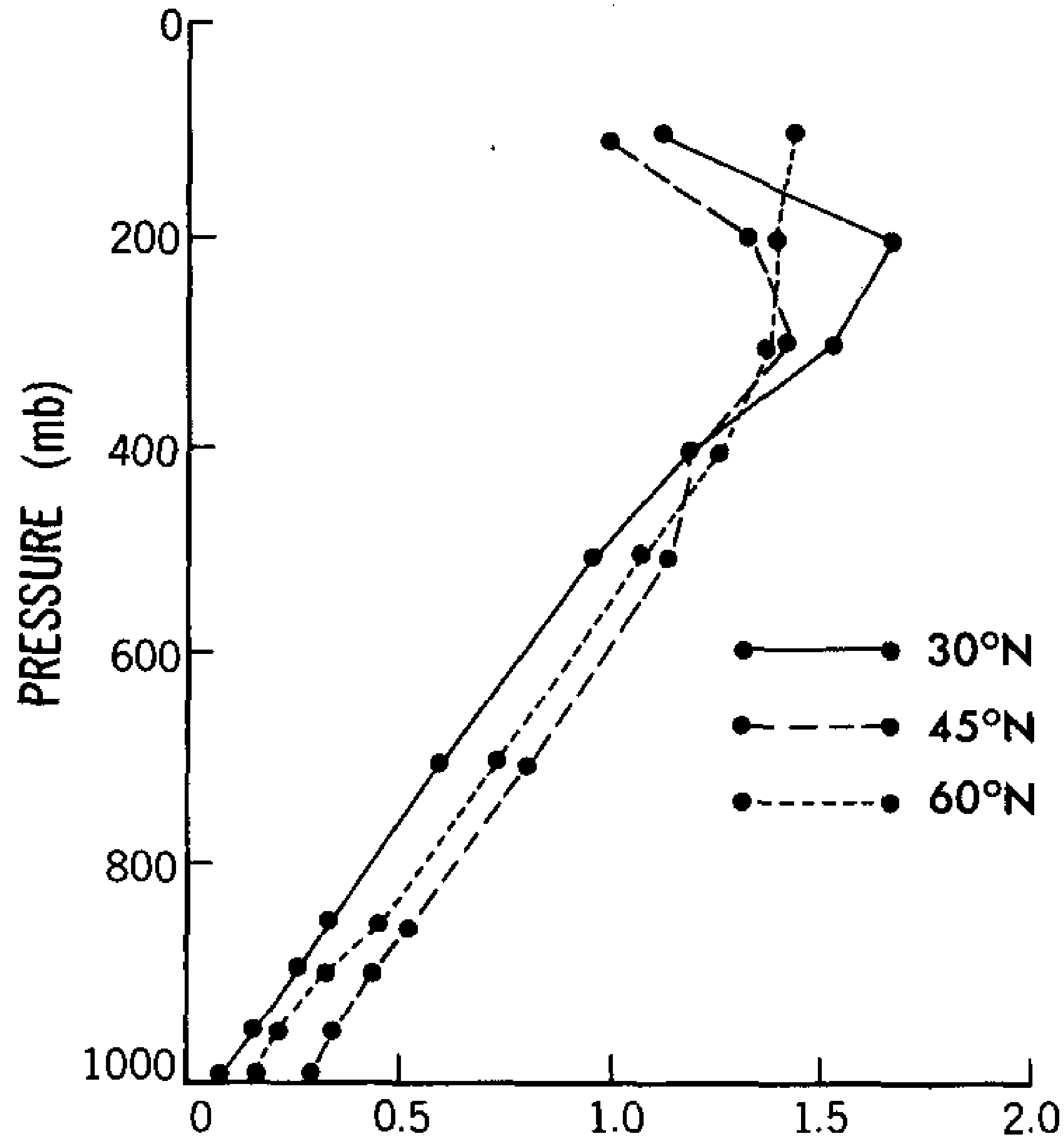


FIG. 12. Vertical structure of the stationary external mode geopotential in the finite-differenced model described in the text, using observed Northern Hemisphere zonal winds and static stabilities, at three different latitudes.

Fig. 17

Held et al, JAS, 1985

Animations of stationary waves

"This animation is the response of a two-dimensional flow on the surface of a rotating sphere to a source that mimics stationary localized heating centered on the equator. The loop covers about 40 days, but the pattern is fully set up in less than half that time. The continental outlines are just meant to help orient the viewer; the surface in this model is featureless. At the start of the animation the flow is purely zonal and the forcing is turned on instantaneously and then maintained."

Fig. 18

Isaac Held Blog post 57

Animations of stationary waves

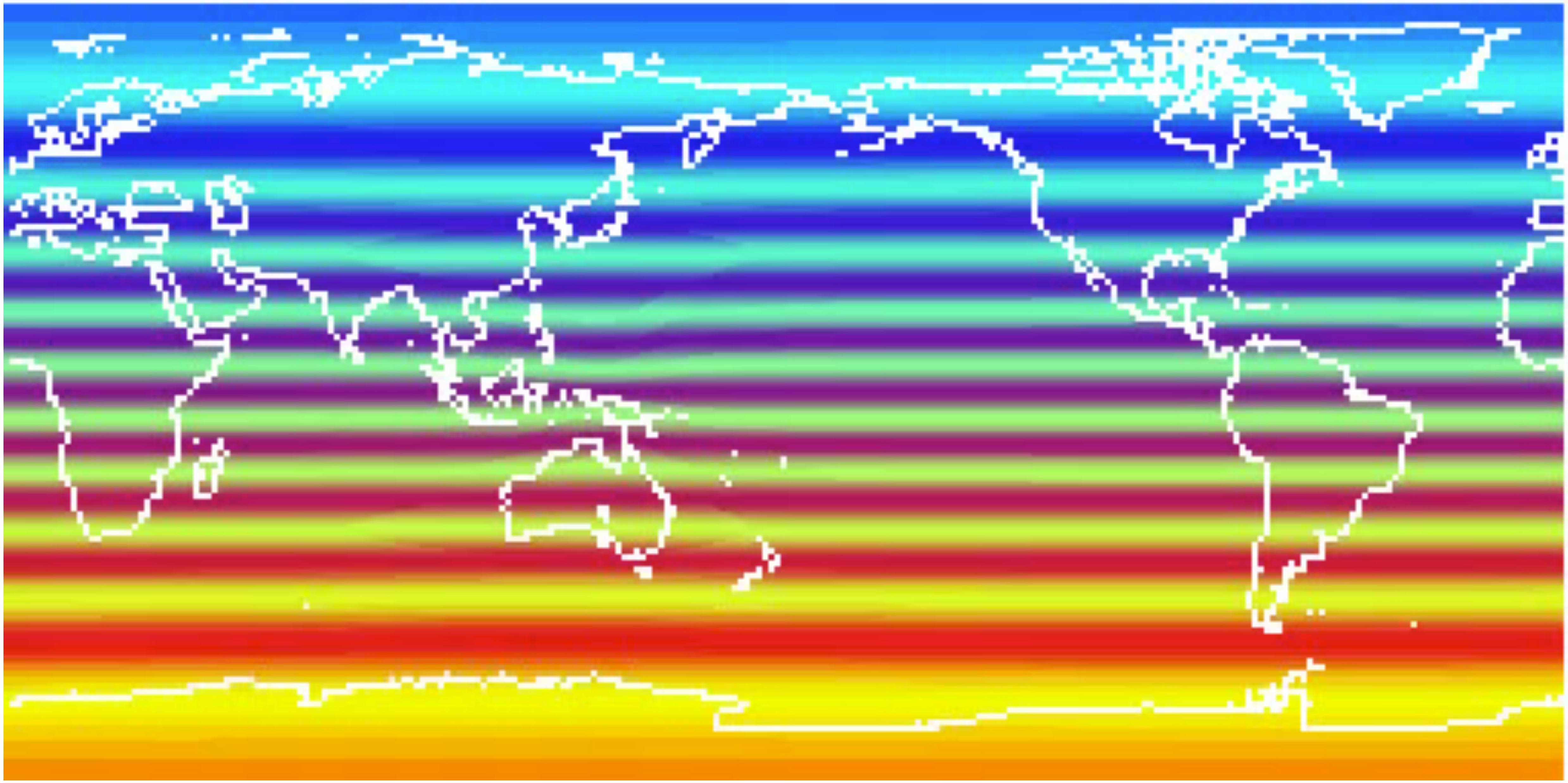


Fig. 18

Streamfunction of the total horizontal flow

Isaac Held blog

Animations of stationary waves

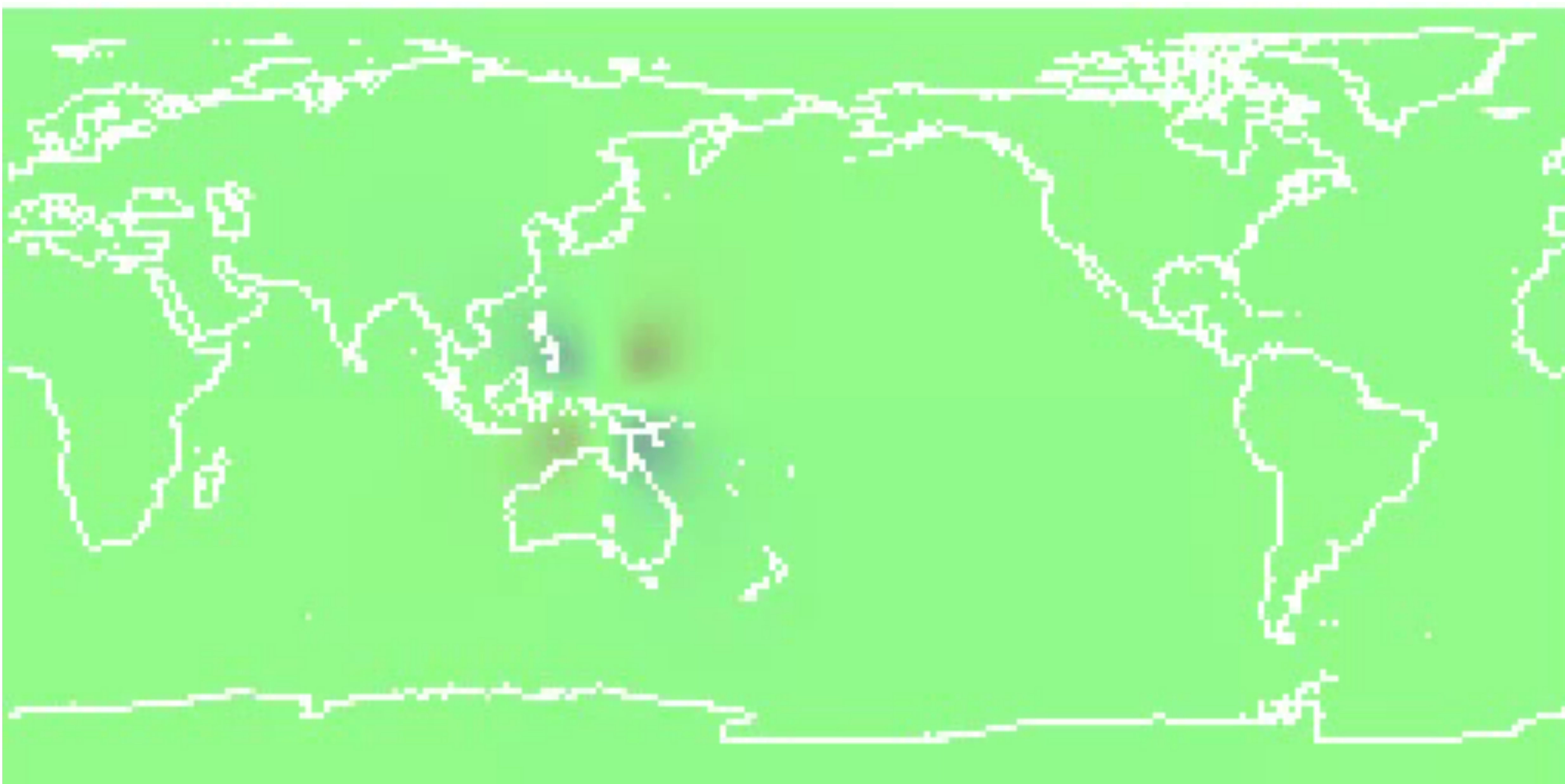


Fig. 18 Meridional wind. Red is northward. Blue is southward

Isaac Held blog

Wavetrains from topography in Eastern and Western hemispheres

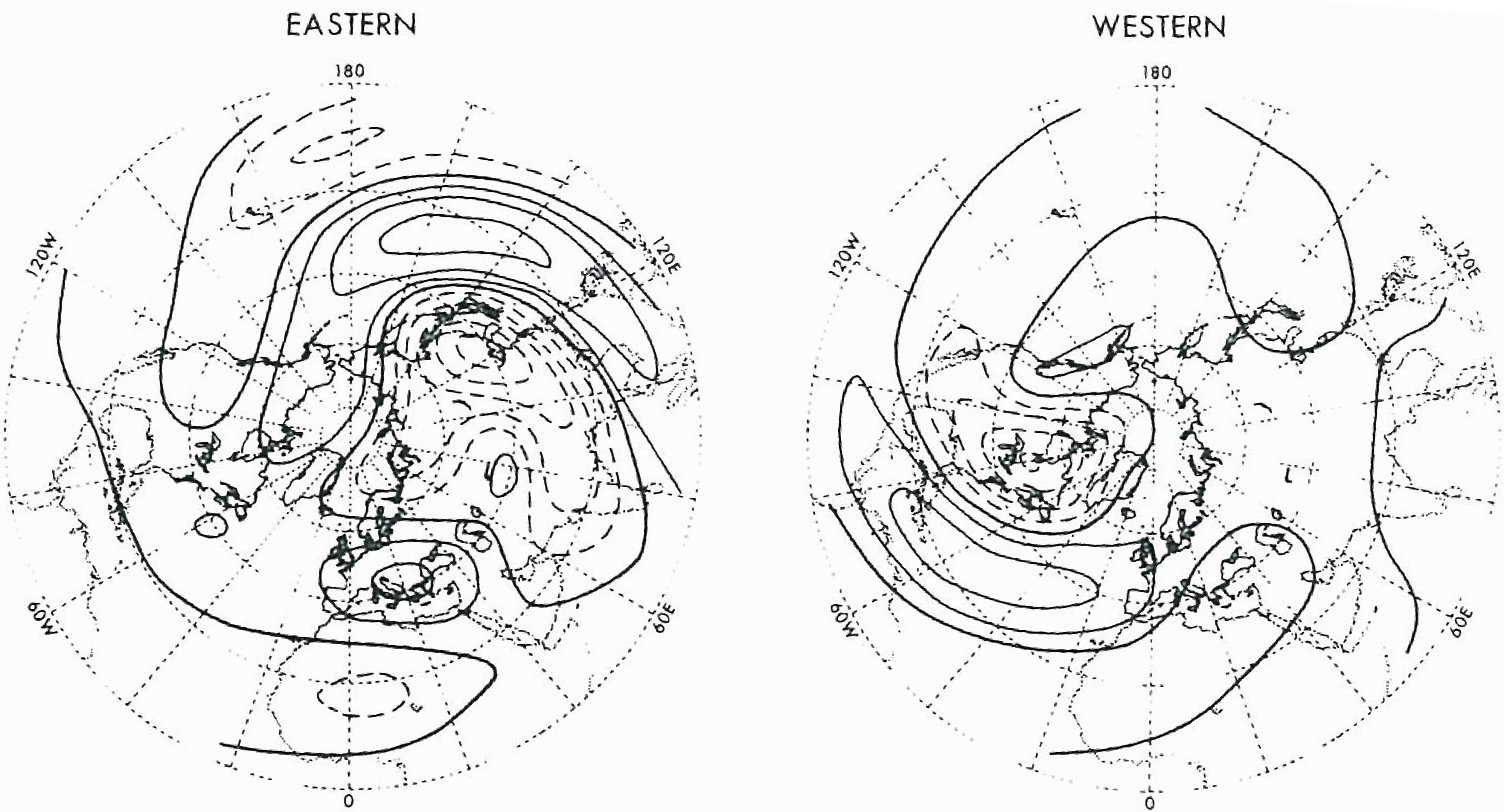


Fig. 19 Streamfunction response in a numerical model split into response to topography in the Eastern (Tibet, Alps) and Western (Rockies) hemispheres. Eastward propagating wavetrains are damped out on a timescale of 20 days. *Held, 1983*

Two wavetrains emanating from mountain at 30N

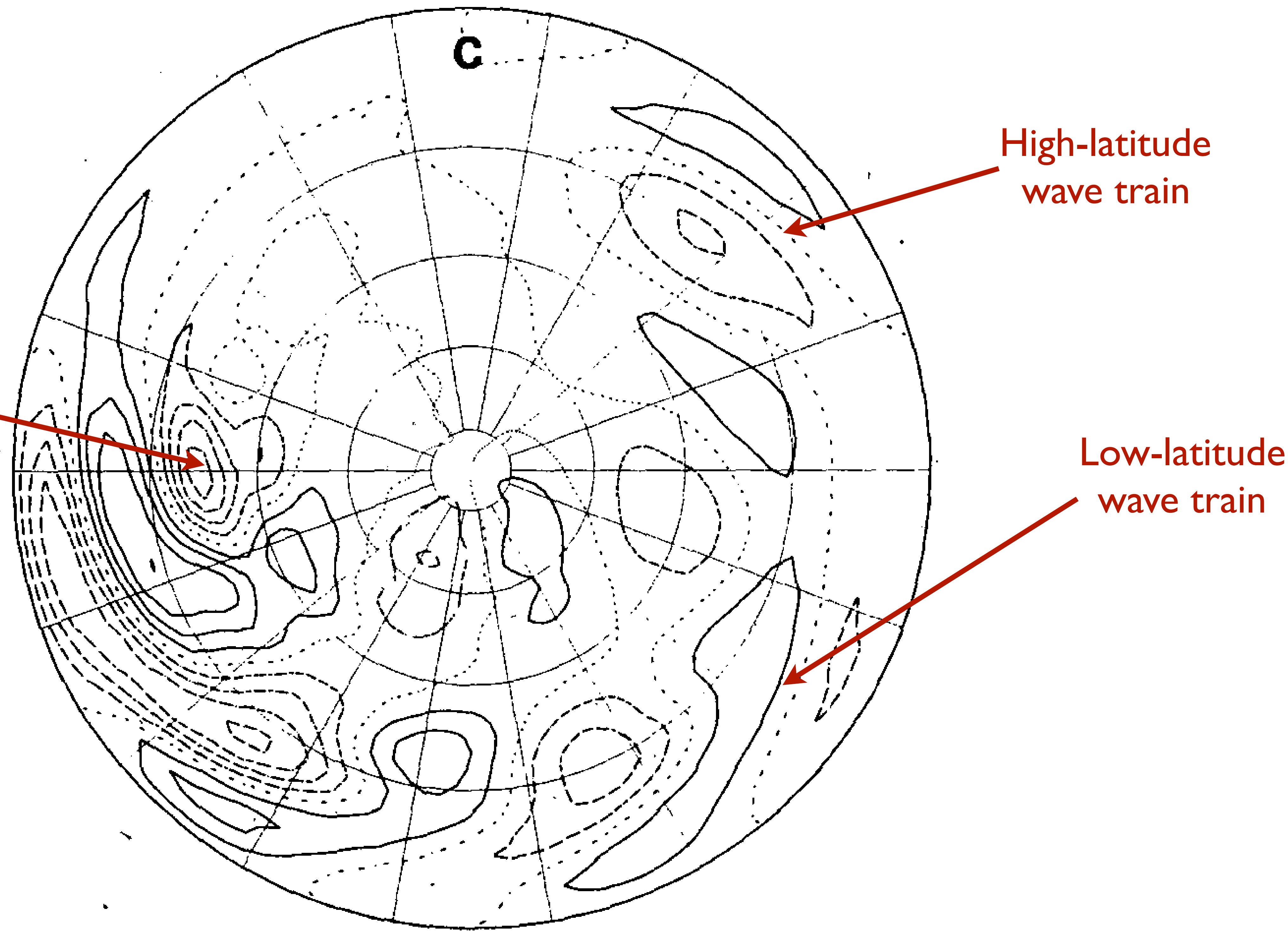


Fig. 20

Linear stationary wave response to circular mountain at 30N
Shown is the vorticity perturbation at 300hPa
Base flow is NH winter

Hoskins and Karoly 1981