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

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

By

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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

\[ \frac{\tilde{\omega}}{\hat{\beta} L_R} \] as a function of \( kL_R \) and \( lL_R \).

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 $N_0/f_0$.  

Nielsen-Gammon et al, MWR, 2008
Potential vorticity on the 320K isentrope

Fig. 3

Values above 1 PVU = 10^{-6}m^2s^{-1}Kkg^{-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)
When I find myself in times of trouble, Father Hoskins comes to me,

Speaking words of wisdom, P V _____ _ _ _

And in my hour of darkness, Baroclinic instability:

There will be an answer, P V _____ _ _ _

And when the broken contours tell us There's cascading enstrophy,

There will be a closure, P V _____ _ _ _

But it integrates to zero, P V _____ _ _ _

And when the night is cloudy, There's a diabatic theta-E

That modifies ___ the parcel's P V _____ _ _ _

Swirling round the isentropes, Around the world and back to me,

But it integrates to zero, P V _____ _ _ _

Yes it all adds up to nothing, P V _____ _ _ _

The PV Song (C) 1992- Nick Hall & John Thuburn
with contributions from Michael McIntyre
and the international atmospheric-science community

Figure courtesy of Juckes and McIntyre 1987, personal communication
Jet streak in westerly wind at $z=5\text{km}$

westerly wind increases linearly with $z$ (not shown)

Arrows: wind
Thin lines: pressure
Thick lines: isotachs
Jet streak is a result of dipole of anomalous PV

Fig. 5

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

Positive PV anomaly
Induced geostrophic wind adds to background westerlies
Negative PV anomaly

Holton and Hakim Fig 6.12
Dynamic evolution: jet streak moves downstream
Arrows show wind induced by the positive PV anomaly

Fig. 5

Holton and Hakim Fig 6.12
Dynamic evolution: jet streak moves downstream
Arrows show wind induced by the negative PV anomaly

Slowly advects positive PV anomaly downstream
Negative PV anomaly
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)

Fig. 7
But symmetric geopotential height at levels with easterlies

Fig. 8
Figure 9: Zonal mean wind climatology for January 25

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

Westerlies allow for propagation of planetary scale waves
Only planetary scale waves in winter (1/10/2006) at 30hPa

Fig. 10
Largely symmetric in summer (7/1/2006) at 30hPa
Contrast with presence of synoptic waves in troposphere

1/1/2006 at 500hPa

NOAA/ESRL Physical Sciences Division

500mb Geopotential Height (m) Composite Mean 01/1/06
NCEP/NCAR Reanalysis

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
Fig. 4. Streamfunction response to orography in a QG model on a $\beta$ 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 $0^\circ$ lon.
Climatological stationary wave pattern for January: no phase tilt with height
Fig. 17. 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.
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.”
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
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