中緯度動力核心:斜壓盛衰週期
Baroclinic Life Cycle

林和
台大大氣系

中央氣象局 11/29/2017

Theme

- Even Earth atmosphere is chaotic (nonlinear) by natural, it is neither a fully-developed turbulence nor a periodic system. You can define mean flow whichever you like, eddies are always as big as, if no bigger than, mean flow.
- Yet observations show clear signs of linear dynamics (gravity wave, Rossby wave, baroclinic instability). Most likely, the Earth atmosphere stays in a weakly non-linear manifold.

This talk will focus on midlatitude dynamics/climate

- (1) Rossby wave propagation in an inhomogeneous medium

- (2) Baroclinic life cycle

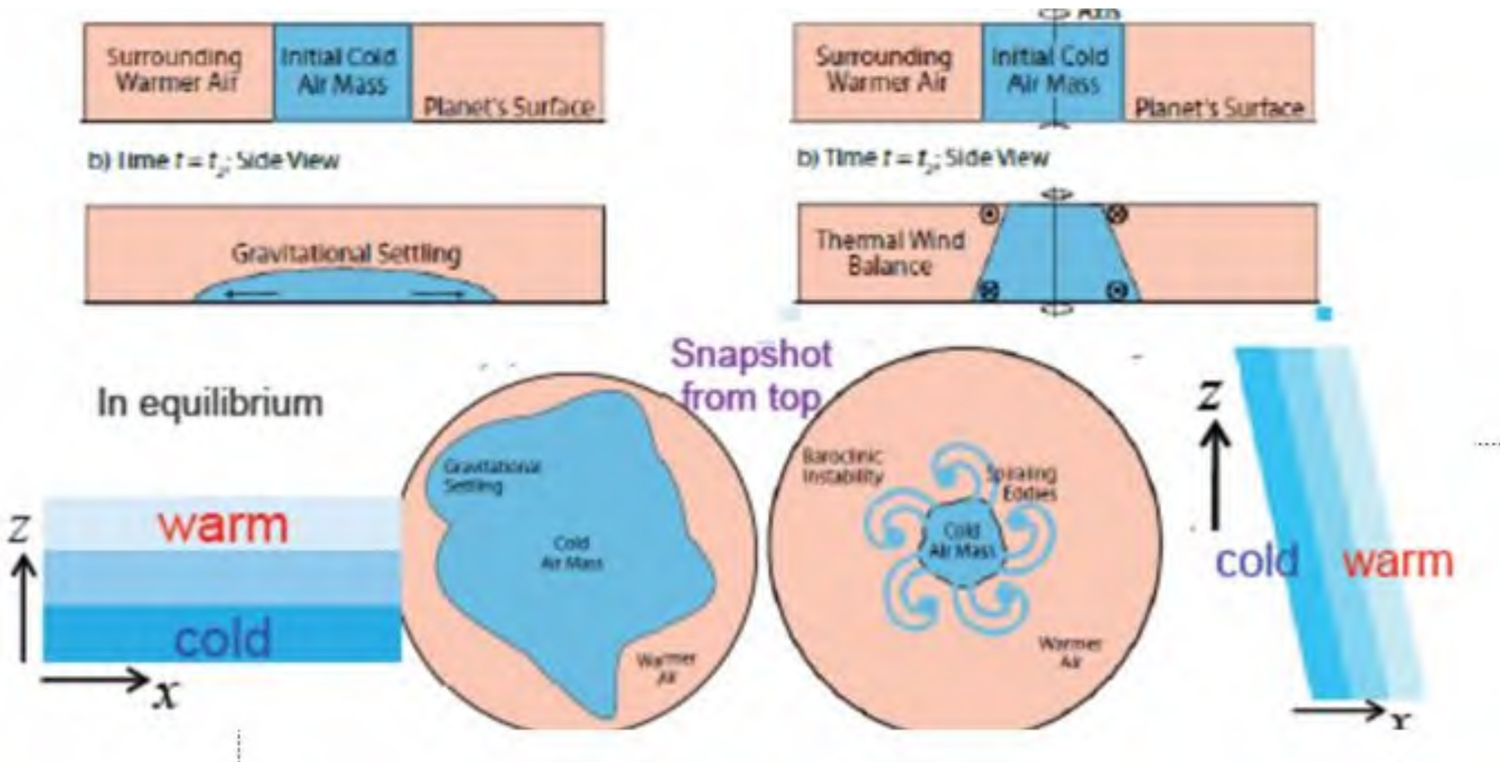
- Basic ideas are wave packet, quasi-geostrophic potential vorticity, Eliassen-Palm flux, refraction index.

Part 1

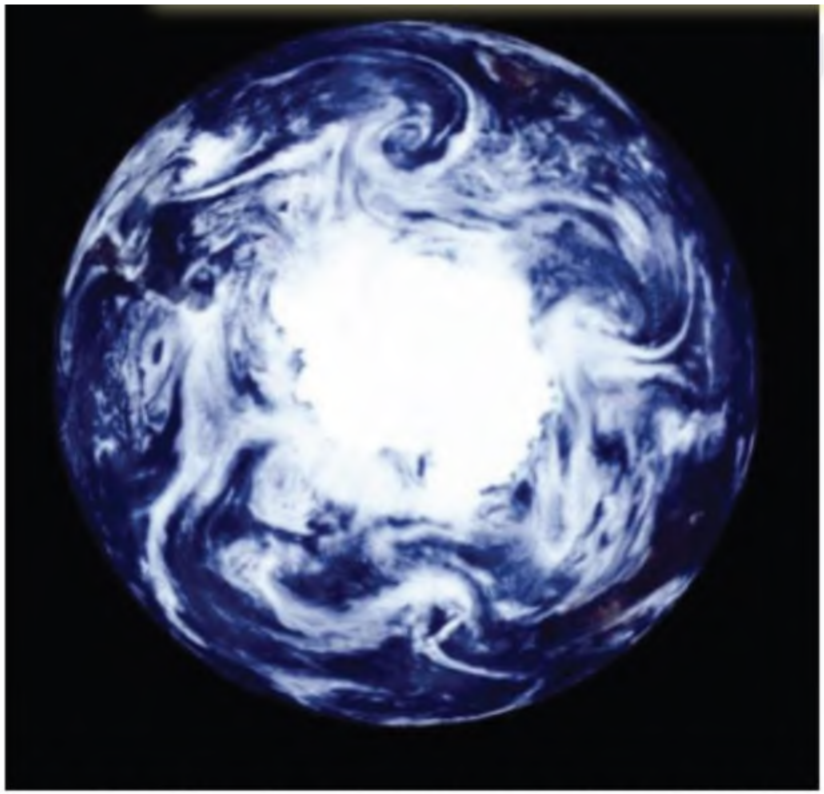
The very basic

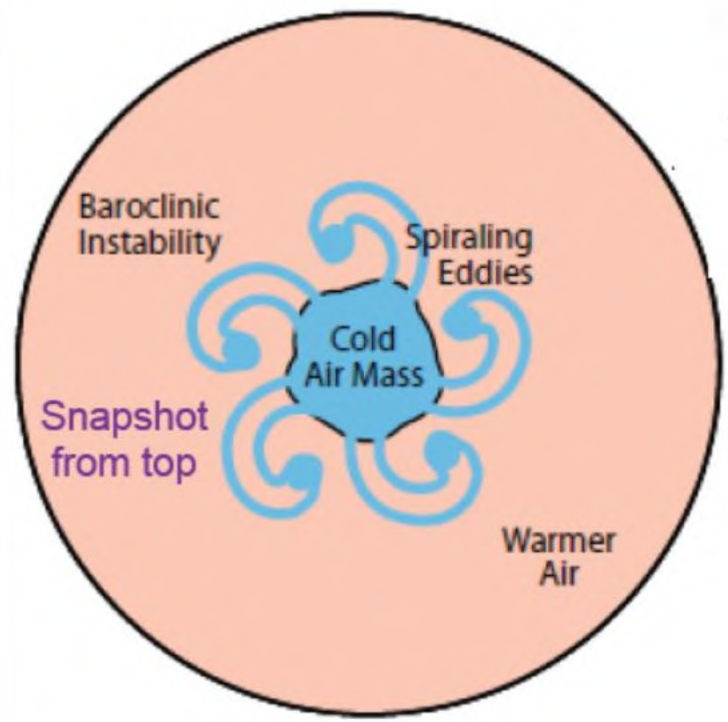
Theory of midlatitude dynamics, after 70 years, has been connecting with observations very well now!

Rossby's famous geostrophic adjustment problem



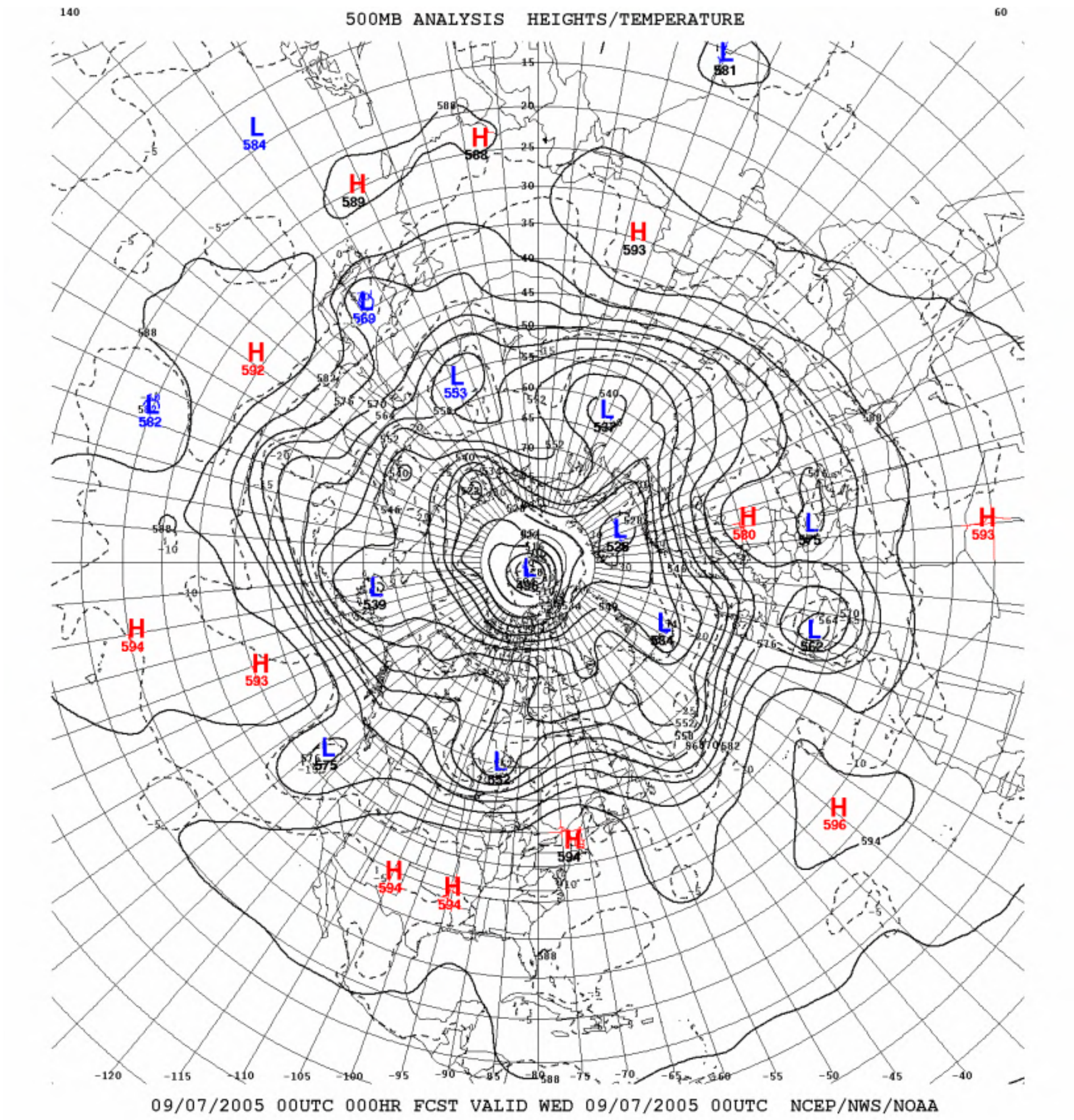
It might look chaotic, but the detailed structure of eddies is well-organized following linear dynamics.





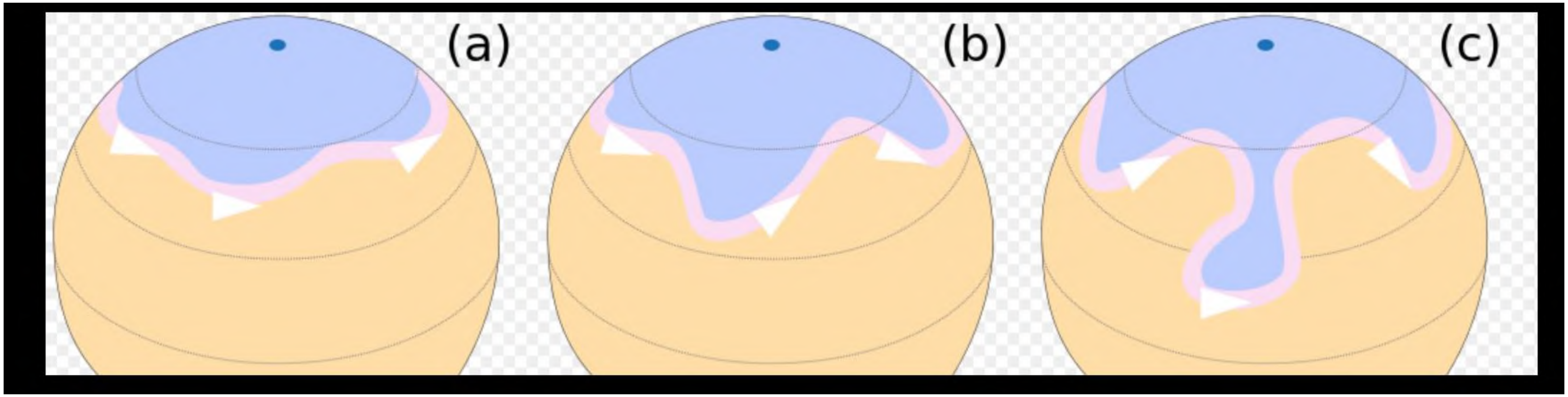
Satellite view at south pole from NASA

Look closely…



500hPa height snapshot

Evolution of NAO (cold surge)—a horizontal picture



Stage 1: Baroclinic instability

Stage 2: Rossby wave propagation

Stage 3: Wave break near critical layer

Three key papers

(1) Eady 1949

(2) Charney and Drazin 1961

(3) Thorncroft, Hoskins and McIntyre 1993

They are all formulated within a quasi-geostrophic framework. The governing equation is surprisingly simple. It is QG PV law, Dq/Dt=o, with boundary conditions where Dq/Dt=0

Rossby wave dynamics

For those who enjoy a bit mathematical gymnastics…. following Vallis book.

$$\left(\frac{\partial}{\partial t} + \boldsymbol{u}\cdot\nabla\right)q = 0, \qquad q = \beta y + \nabla^2\psi' + \frac{f_0^2}{\rho_R}\frac{\partial}{\partial z}\left(\frac{\rho_R}{N^2}\frac{\partial\psi'}{\partial z}\right)$$

$$\left(\frac{\partial}{\partial t} + \overline{u}(y,z)\frac{\partial}{\partial x}\right)q' + v'\frac{\partial\overline{q}}{\partial y} = -\left(\frac{\partial u'q'}{\partial x} + \frac{\partial v'q'}{\partial y}\right)$$

$$(\overline{u} - c)\frac{\partial q'}{\partial x} + v'\frac{\partial\overline{q}}{\partial y} = 0$$

Linearized equation starts to insert wave dynamics

$$\psi' = \mathrm{Re}\,\widetilde{\psi}\mathrm{e}^{\mathrm{i}(kx+ly+mz-\omega t)}$$

From top: Vallis
Eq 5.1, 5.2, 5.3, 5.5

Normal mode solution

$$\left(\frac{\partial}{\partial t} + \overline{u}(y,z)\frac{\partial}{\partial x}\right)q' + v'\frac{\partial \overline{q}}{\partial y} = 0$$

$$\psi' = \widetilde{\psi}(y,z)\mathrm{e}^{\mathrm{i}k(x-ct)}$$

$$\frac{\partial^2 \widetilde{\psi}}{\partial y^2} + \frac{f_0^2}{N^2}\frac{\partial^2 \widetilde{\psi}}{\partial z^2} + n^2(y,z)\widetilde{\psi} = 0 \qquad \text{where} \qquad n^2(y,z) = \frac{\partial \overline{q}/\partial y}{\overline{u} - c} - k^2$$

Refraction index

$$0 < \overline{u} - c < \frac{\partial \overline{q}/\partial y}{k^2 + \gamma^2}$$

$$\omega \equiv ck = \overline{u}k - \frac{\partial \overline{q}/\partial y}{k^2 + l^2}$$

$$\frac{\partial^2 \widetilde{\psi}}{\partial y^2} + l^2(y)\widetilde{\psi} = 0, \quad \text{where} \quad l^2(y) = \frac{\partial \overline{q}/\partial y}{\overline{u} - c} - k^2$$

$$\widetilde{\psi}(y) = A_0 l^{-1/2}\exp\left(\mathrm{i}\int l\,\mathrm{d}y\right)$$

WKB approximation

$$c_g^x = \overline{u} + \frac{(k^2 - l^2)\partial \overline{q}/\partial y}{(k^2 + l^2)^2}, \qquad c_g^y = \frac{2kl\,\partial \overline{q}/\partial y}{(k^2 + l^2)^2}$$

From top: Vallis
Eq 5.8, 5.9, 5.10, 5.12, 5.14, 5.15, 5.16, 5.17

From top:Vallis
Eq 5.18, 5.19

$$\frac{\partial \mathcal{A}}{\partial t} + \nabla \cdot \boldsymbol{\mathcal{F}} = 0$$

Eliassen-Palm Flux

$$\mathcal{A} = \frac{\overline{q'^2}}{2\partial\overline{q}/\partial y}, \qquad \boldsymbol{\mathcal{F}} = -\overline{u'v'}\,\mathbf{j} + \frac{f_0}{N^2}\overline{v'b'}\,\mathbf{k}$$

Wave action

As emphasized by Edmon et al (1980), EP flux should be considered a fundamental diagnostics because it relates the wave-action and group velocity concept. McIntire (1976) pointed out that whenenver the eddy dynamics is wavelike, F may be regarded as a measure of the net rate of transfer of wave activity from one latitude and height to another. Considering this interpretation of F, the conservation equation related

We can use the same formalism with almost absurd simplicity to formulate Eady's model, this time the mean flow is even simpler.

- Eady's model (1949)

This result fits Sutcliff's development theory (Omega equation) and hints EP flux

a) The basic zonal flow has uniform vertical shear,

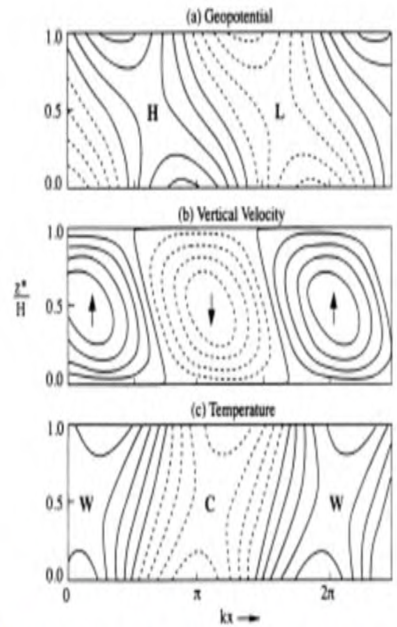
$$U_o(Z) = \Lambda Z, \quad \Lambda \text{ is a constant}$$

b) The fluid is uniformly stratified, N^2 is a constant.

c) Two rigid lids at the top and bottom, flat horizontal surface, that is $\omega = 0$ at $Z = 0$ and H.

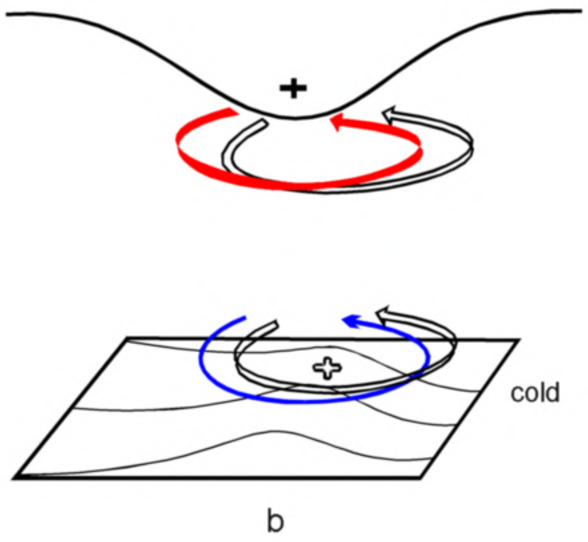
d) The motion is on the f -plane, that is

$$\beta = 0$$



8.10 Properties of the most unstable Eady wave. (a) Contours of perturbation geopotential height; H and L designate ridge and trough axes, respectively. (b) Contours of vertical velocity; up and down arrows designate axes of maximum upward and downward motion, respectively. (c) Contours of perturbation temperature; W and C designate axes of warmest and coldest temperatures, respectively. In all panels 1 and 1/4 wavelengths are shown for clarity.

It took a while for us to realize that the key of Eady model's success lays on its *boundary condition* which induces **mutual intensification of PV anomalies**



Since Eady's great discovery, we knew a lot more about what happens for local baroclinic wave...

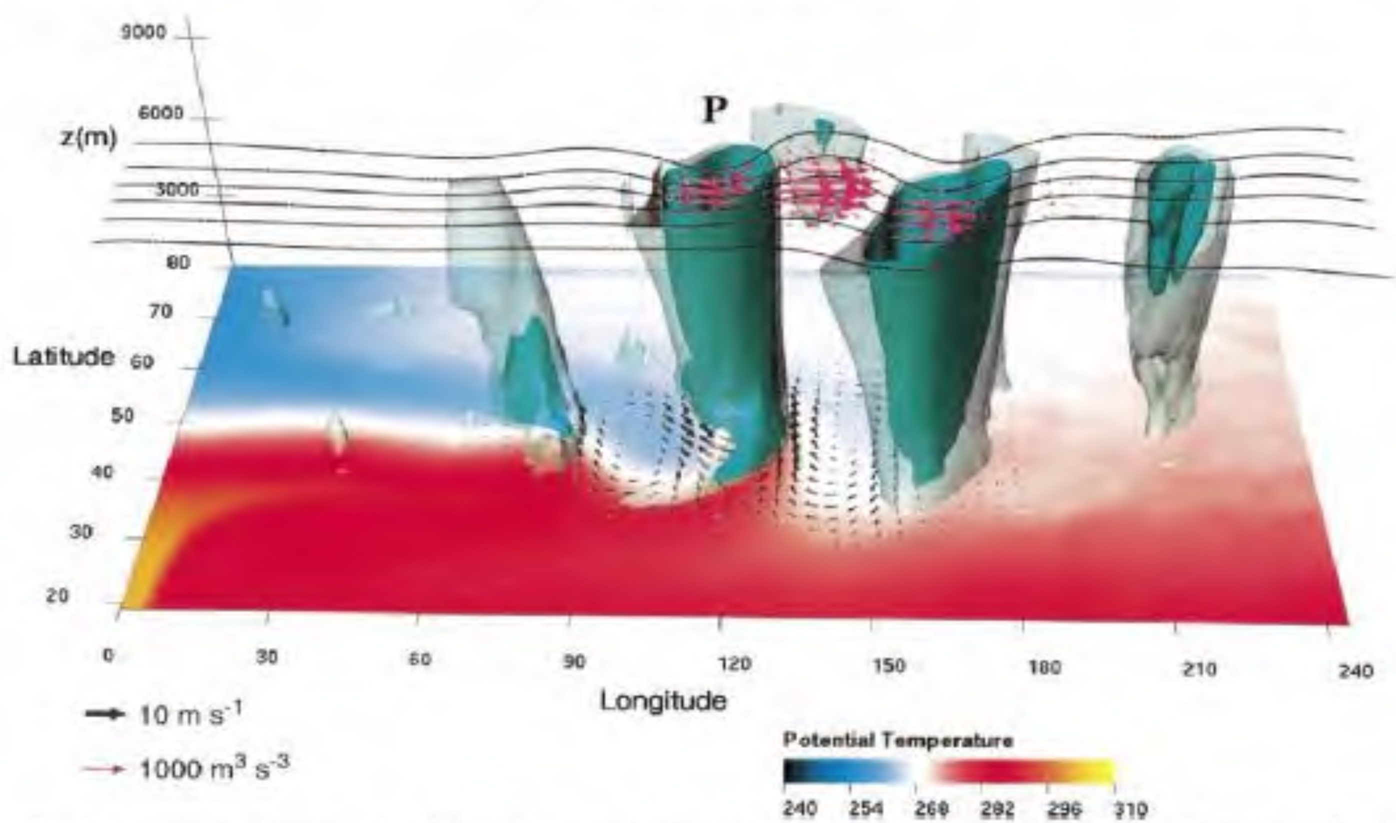


Fig. 3. Regression with zero time lag of the cyclonic relative vorticity (light blue 3×10^{-6} s^{-1} and dark blue 7×10^{-6} s^{-1} isosurfaces), surface potential temperature (color shading in K), surface wind (black vectors), ageostrophic geopotential fluxes at 10 km (magenta vectors), and geopotential at 10 km (contours every 2190 m^2 s^{-2}). The largest surface wind vector corresponds to about 8 m s^{-1}, and the largest geopotential flux vector corresponds to about 1500 m^3 s^{-3}. "P" denotes the principal eddy.

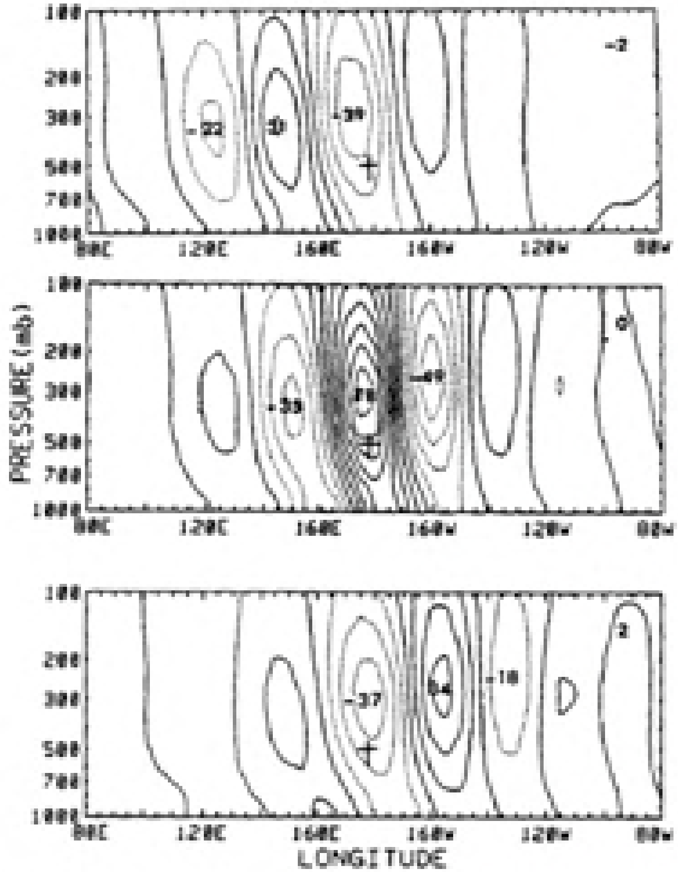


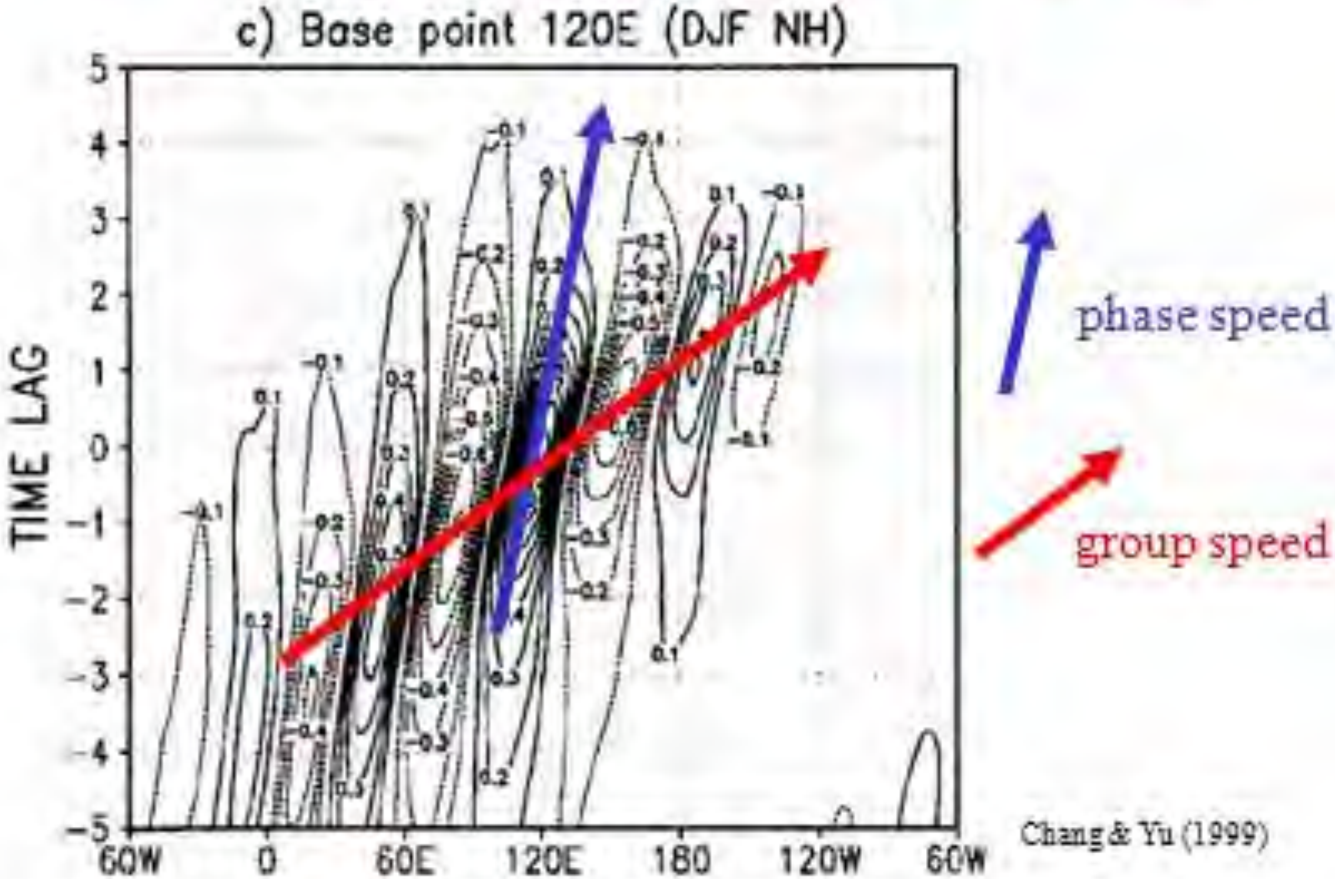
FIG. 4. Lag-regression cross sections of geopotential height along 40°N for the same reference time series as in Fig. 1. Lag in days relative to the reference time series is marked in the upper right corner of each panel. Negative contours are dashed. Contour interval: 10 m.

Baroclinic Waves

Wavelength ~4000 km
Phase speed ~ 15 m/s.
Period ~ 3 d.
Due to baroclinic instability.
Organize into packets.

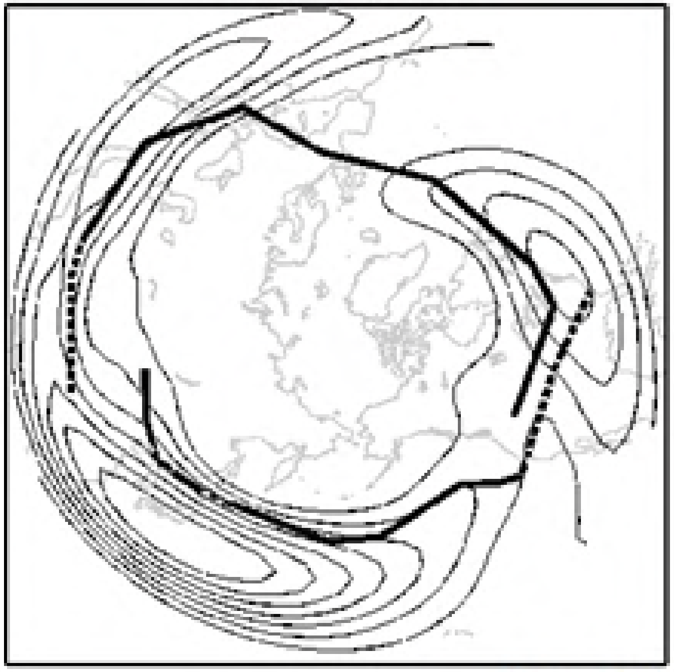
Lim & Wallace (1991)

Wave Packet Phase & Group Speed



Chang & Yu (1999)

Wave Packet Tracks



Hakim (2003)

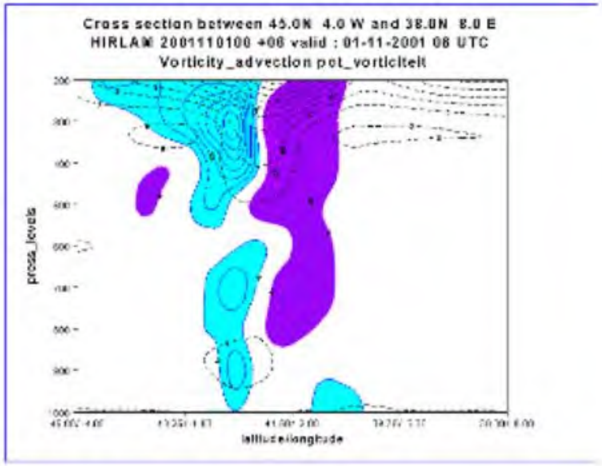
Jet-stream wave guides.

Storm-track recycling.

PV diagnosis is intuitive and mathematically can be inverted to other variables

Schematic of PV anomalies in the upper troposphere and the connected vorticity advection and omega patterns

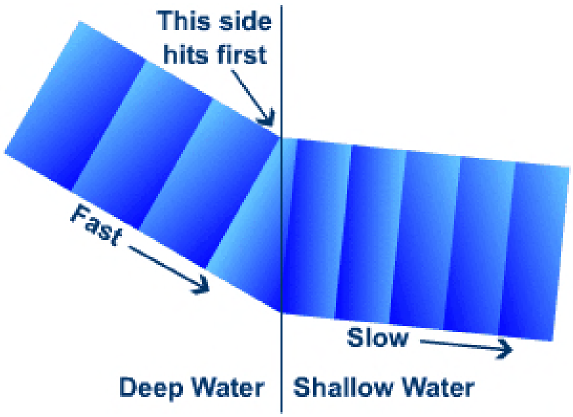
01 November 2001/06.00 UTC - Vertical cross section; black: potential vorticity, magenta: vorticity advection - PVA, cyan: vorticity advection - NVA



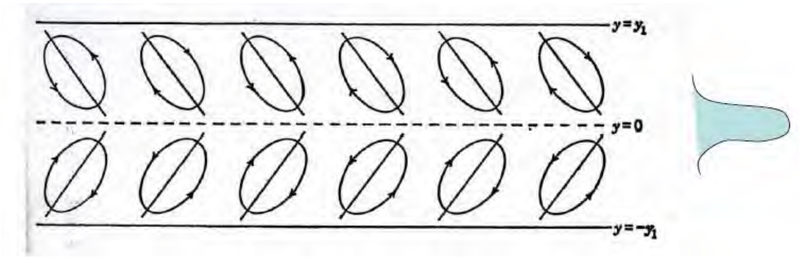
Part 2

Rossby wave everywhere

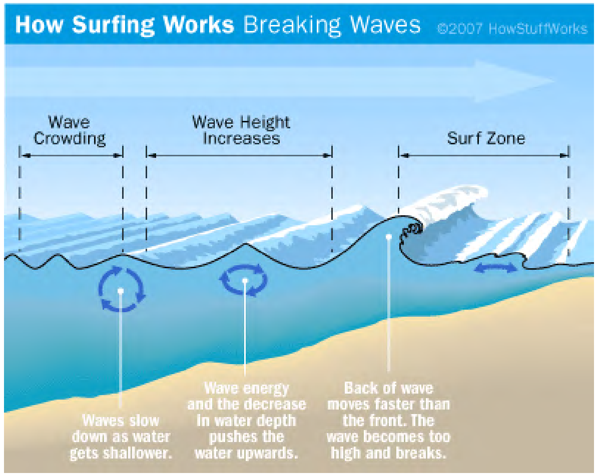
Basic wave features



Wave can veer

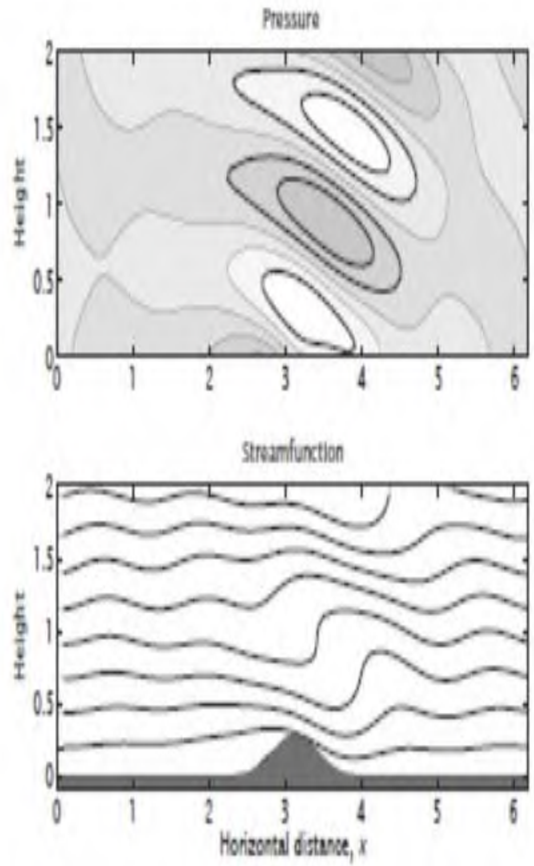


Wave can create its own mean flow

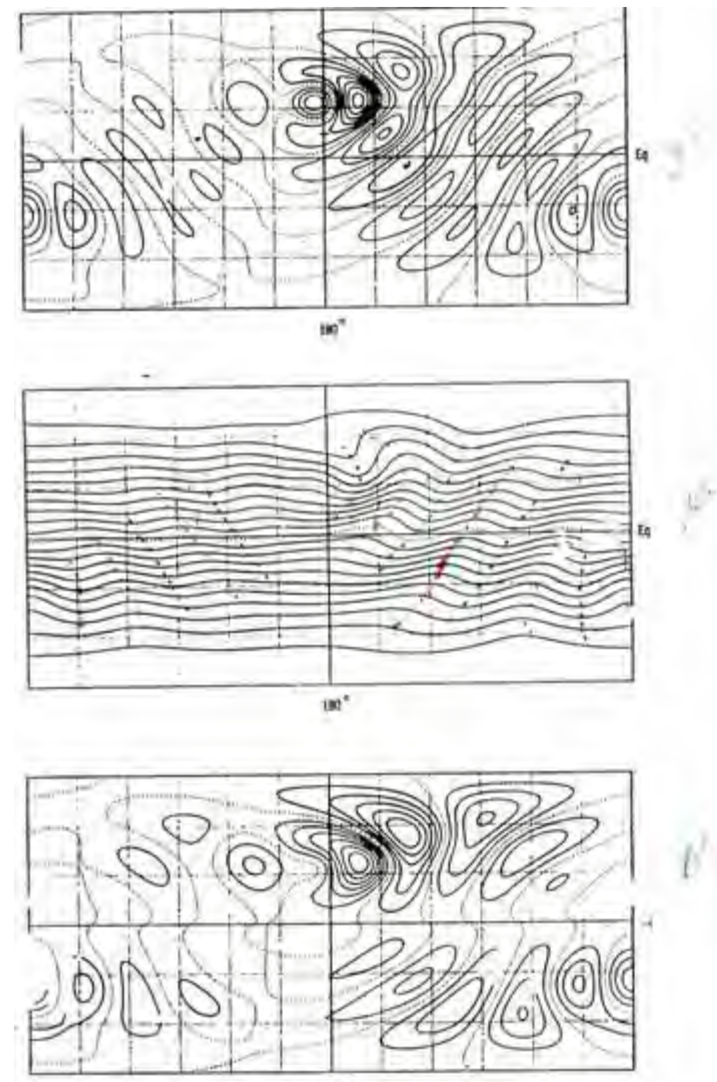


Wave can amplify!

How to see air in a 5D space (x,y,z,t,variable)?



Which one is gravity wave ? Rossby wave? Can you figure out group line? Phase line?



Wave propagates in an inhomogeneous (mean q grad) media

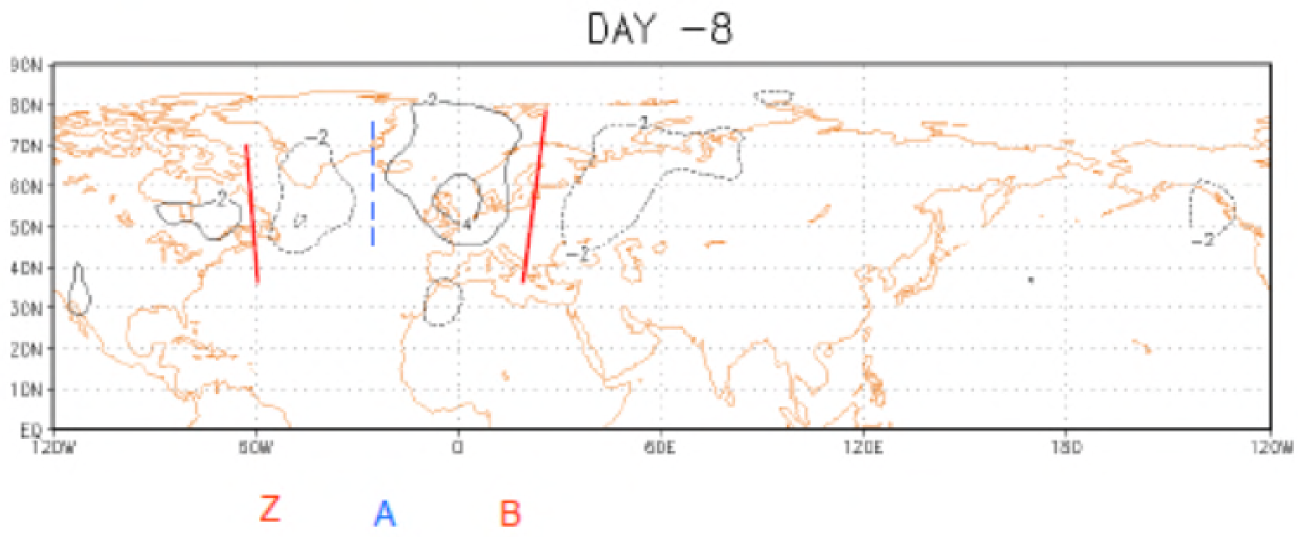
- Among all wave behaviors, the most important is refraction.
- Wave tends to propagate toward high refractive index area. Under extreme conditions which lead to reflection or wave breaking near the critical layer.

- We are talking dispersive waves excited by a localized source, hence the basic element of wave is wave train (wave packet).

Now a more vivid (x,y,t) loop

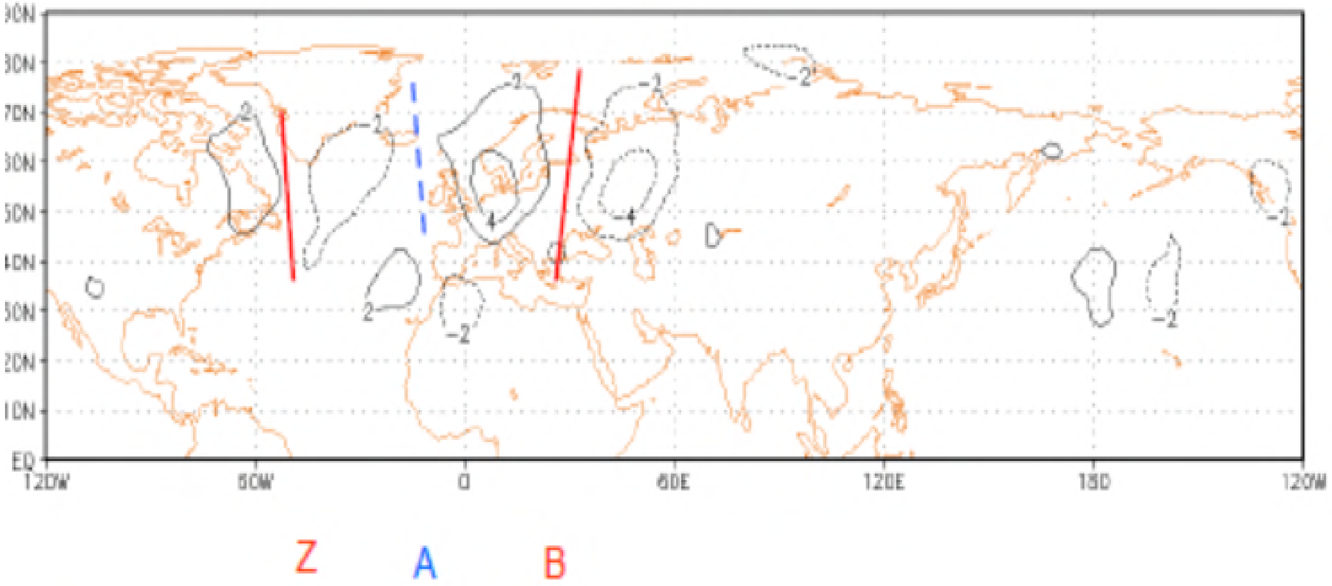
Contours: 300 hPa v

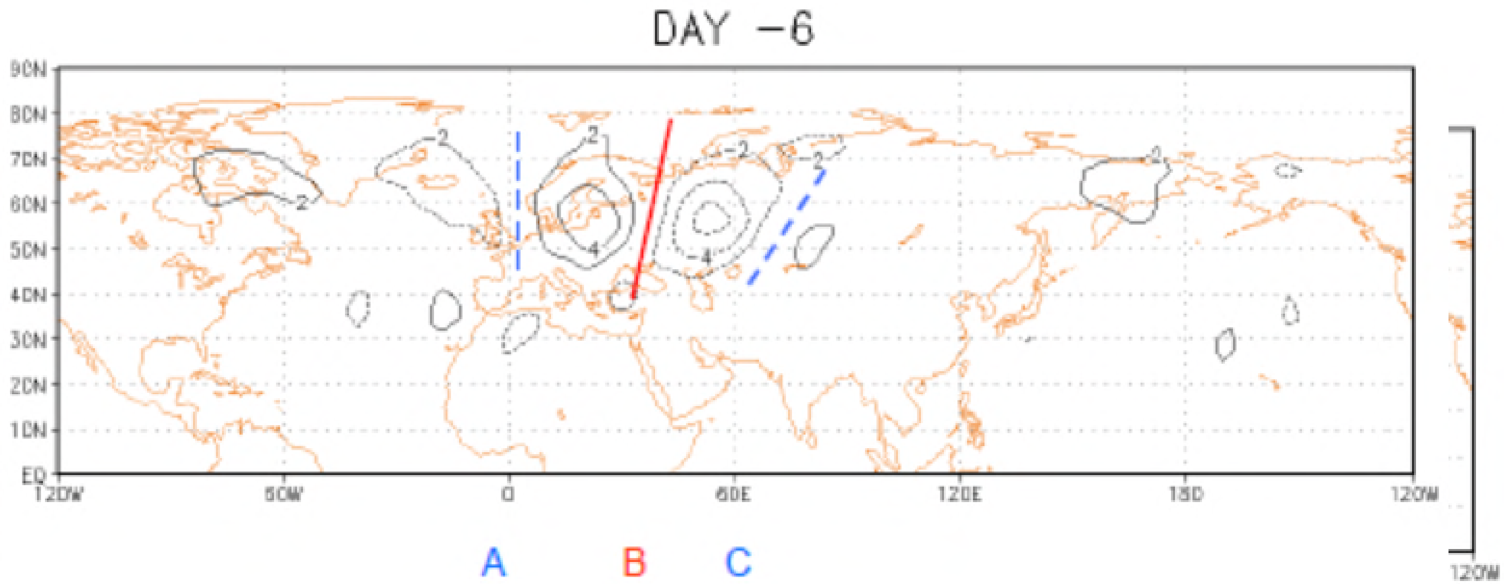
Red solid line: ridge axis
Blue dashed line: trough axis



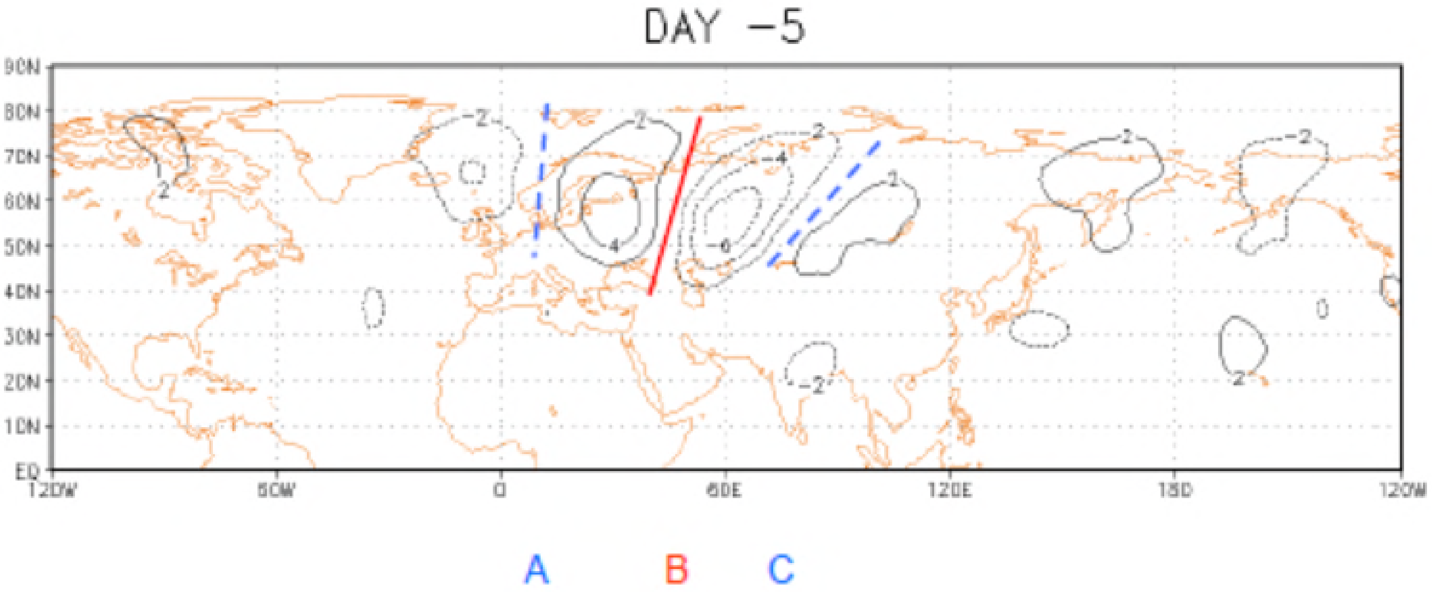
Edmund Chang's talk

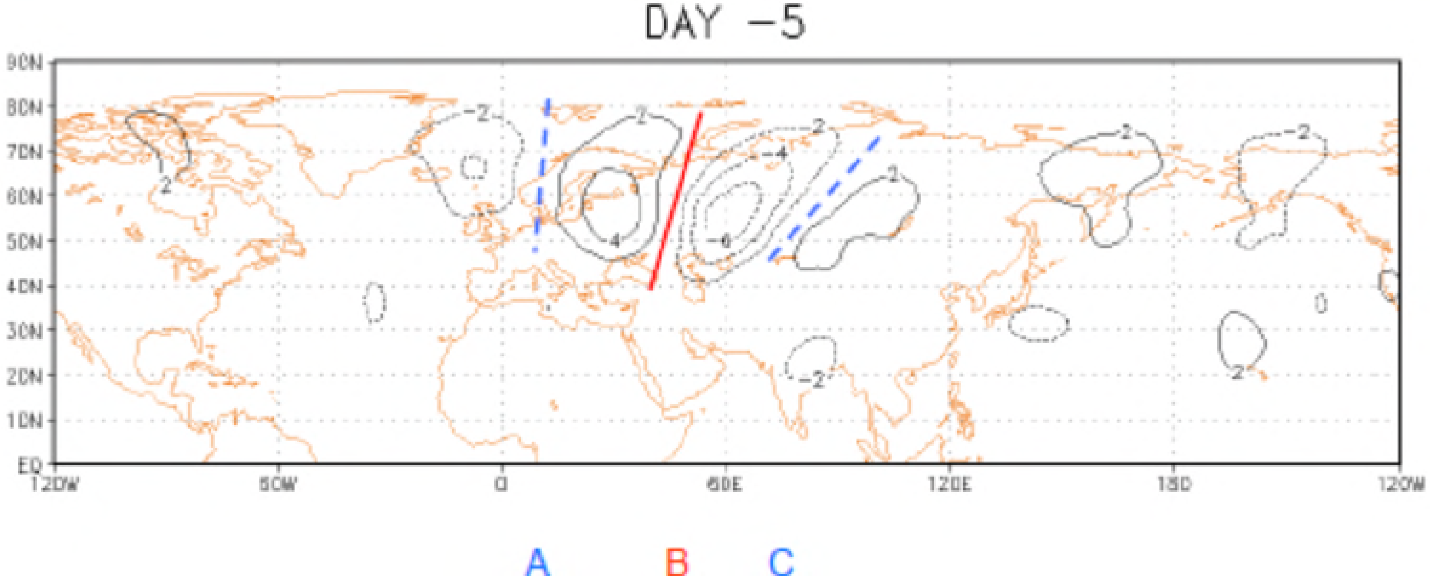
DAY −7

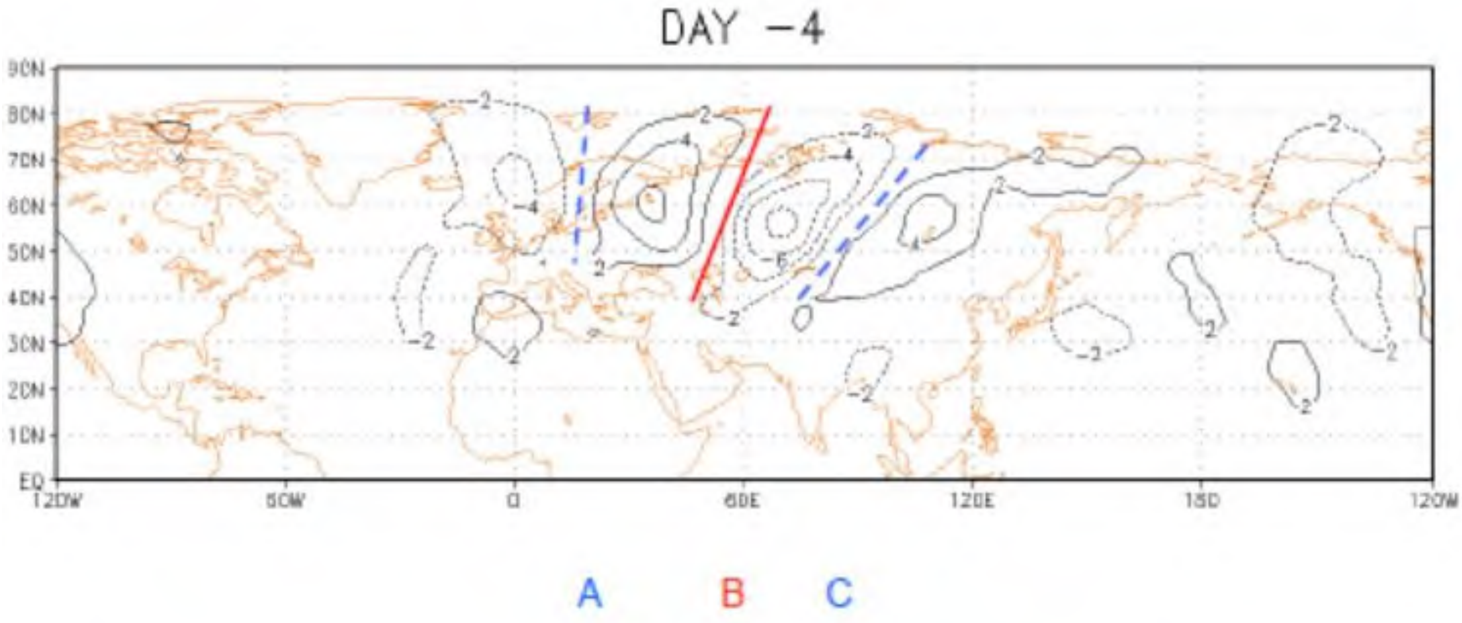


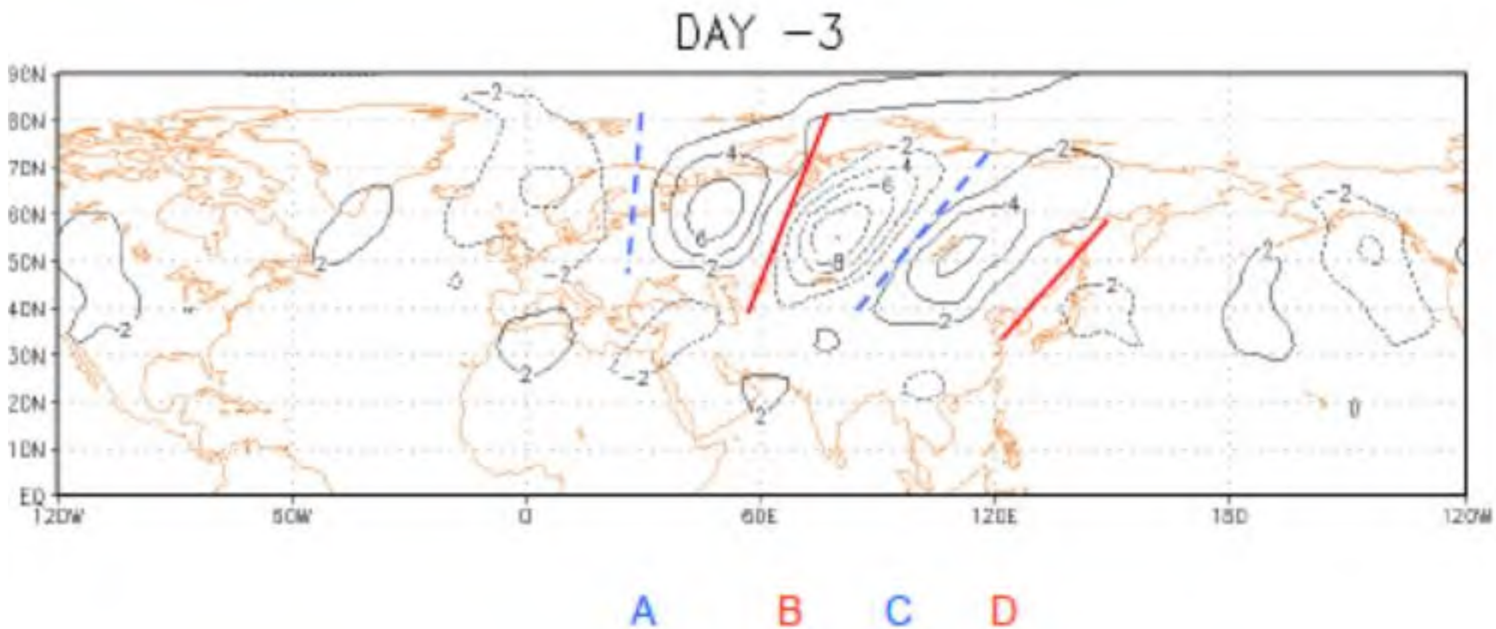


DAY -6
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
A
B
C

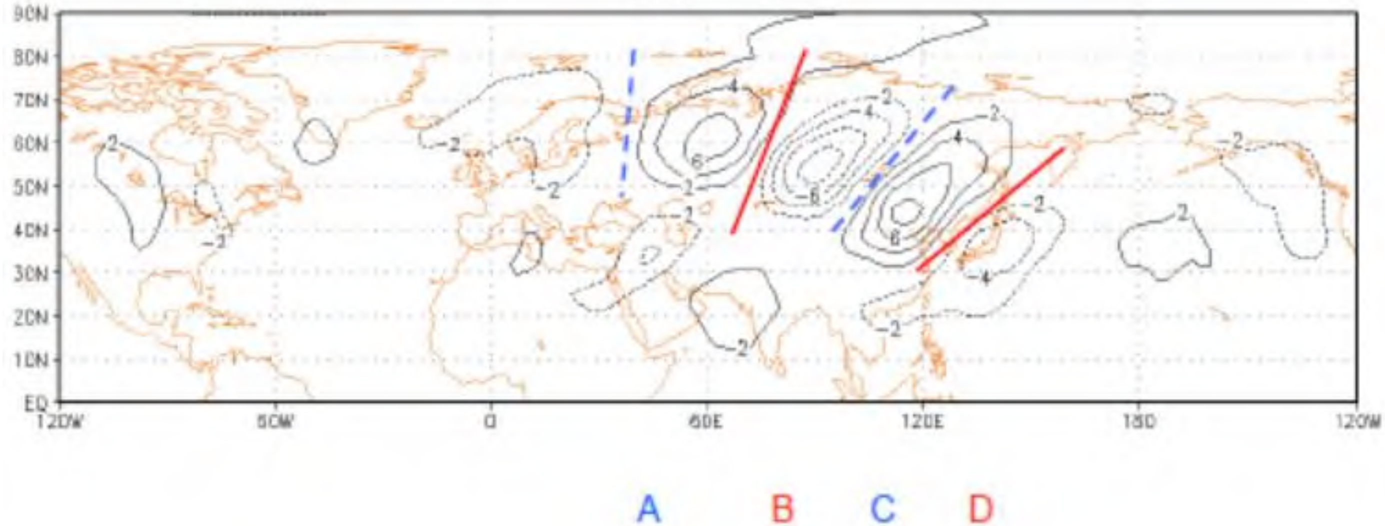

DAY -5
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
A
B
C


DAY -5
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
A
B
C

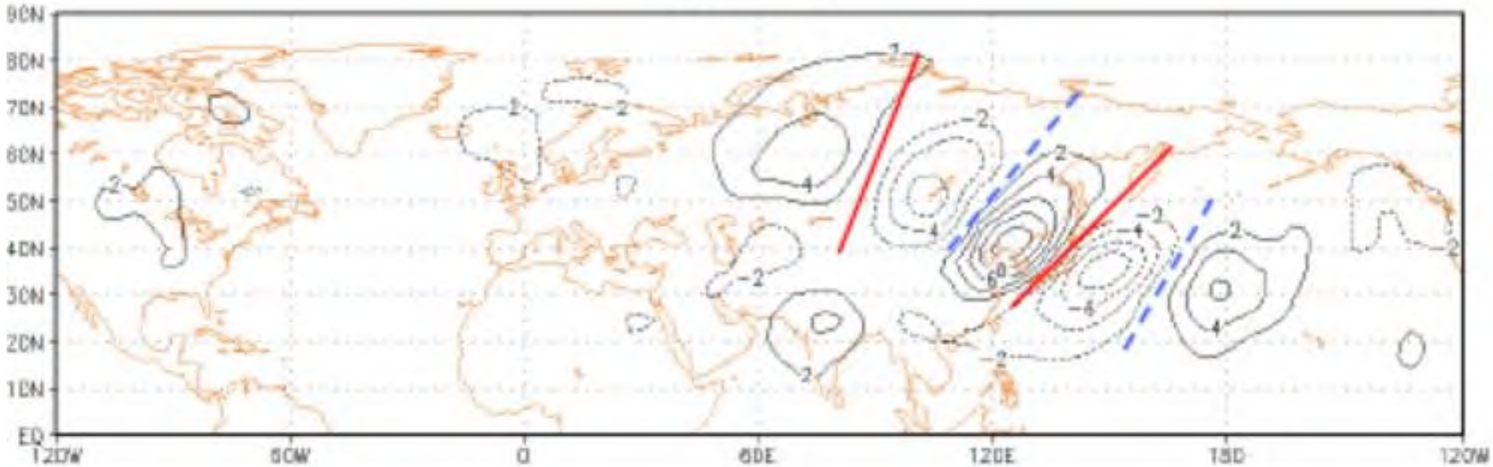

DAY -4
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
A
B
C


DAY −3
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
A
B
C
D

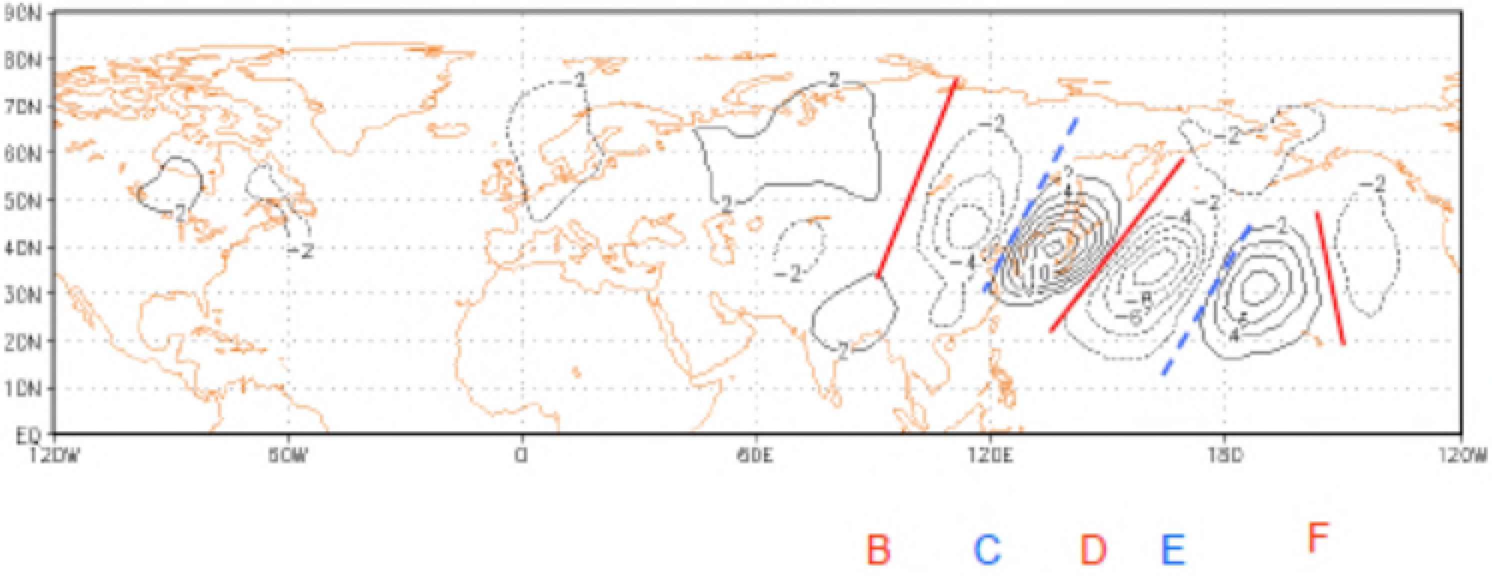
DAY −2


90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
A
B
C
D

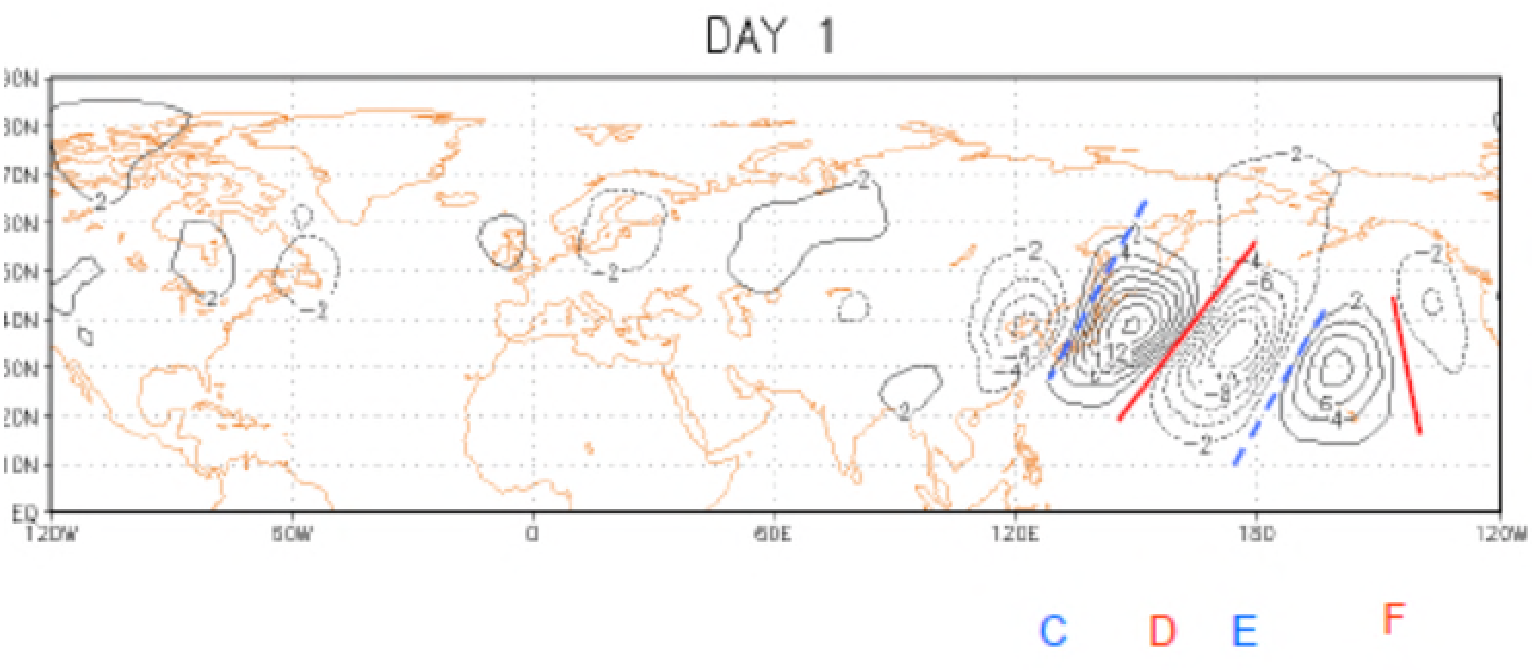
DAY -1


90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
B
C
D
E

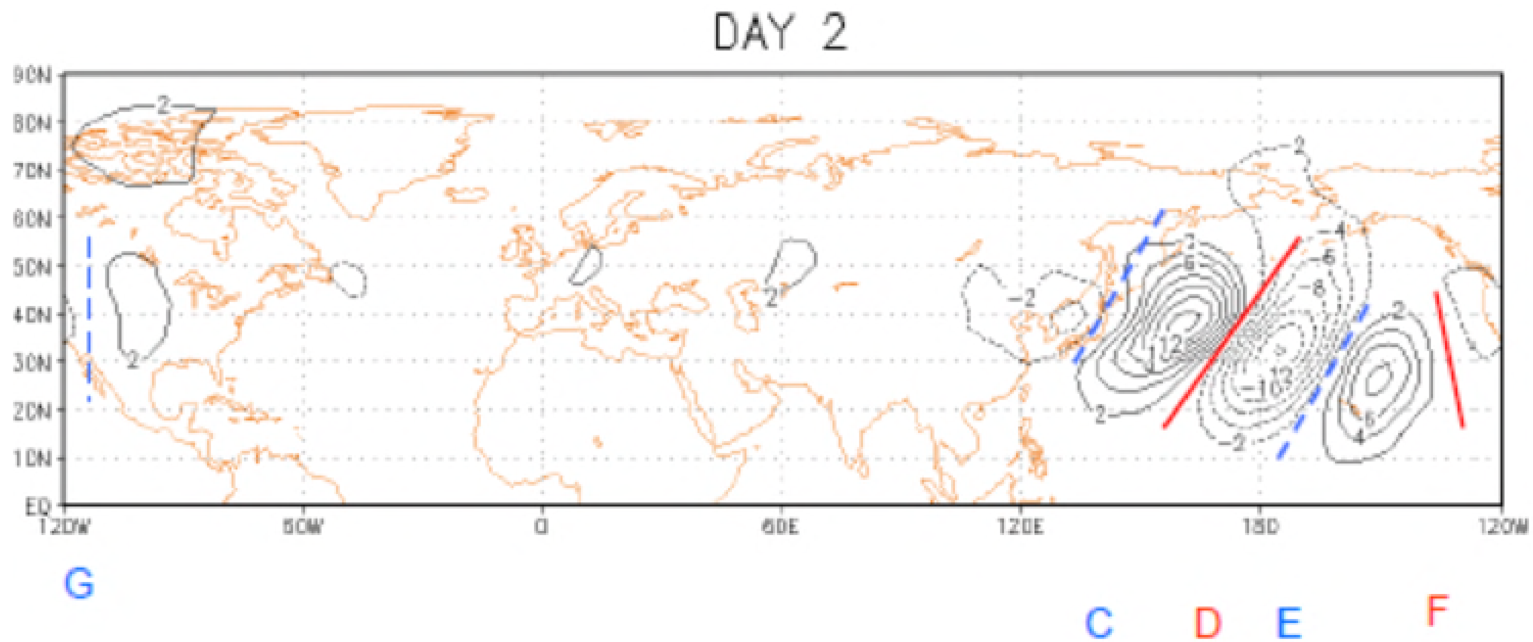
DAY 0



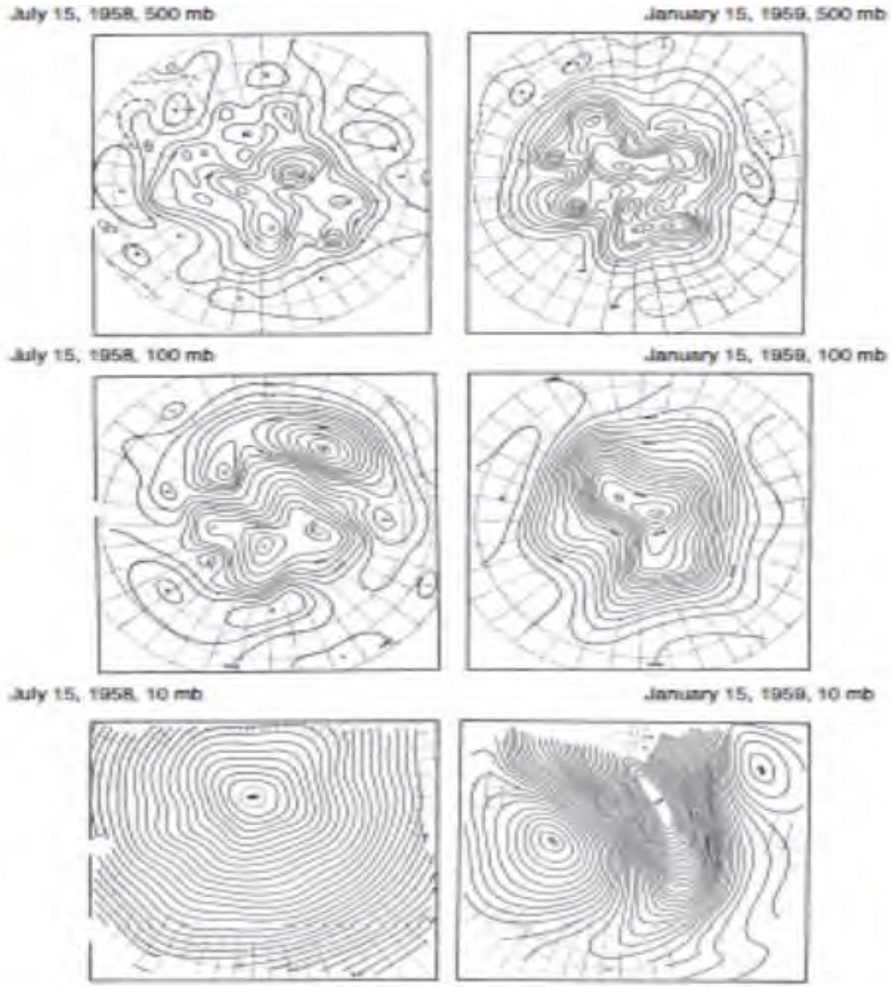
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
B
C
D
E
F



DAY 1
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
C
D
E
F


DAY 2
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
120W
60W
0
60E
120E
180
120W
G
C
D
E
F

Vertical propagation of stationary Rossby wave— after the celebrated Charney-Drazin theory



ure 9.5: These Northern Hemisphere data were collected during the International Geophysical Year. opotential heights for July 15, 1958 are shown on the left, and those for January 15, 1959 are shown the right. The levels plotted are 500 mb, 100 mb, and 10 mb. From Charney (1973).

Refraction index in summer and winter

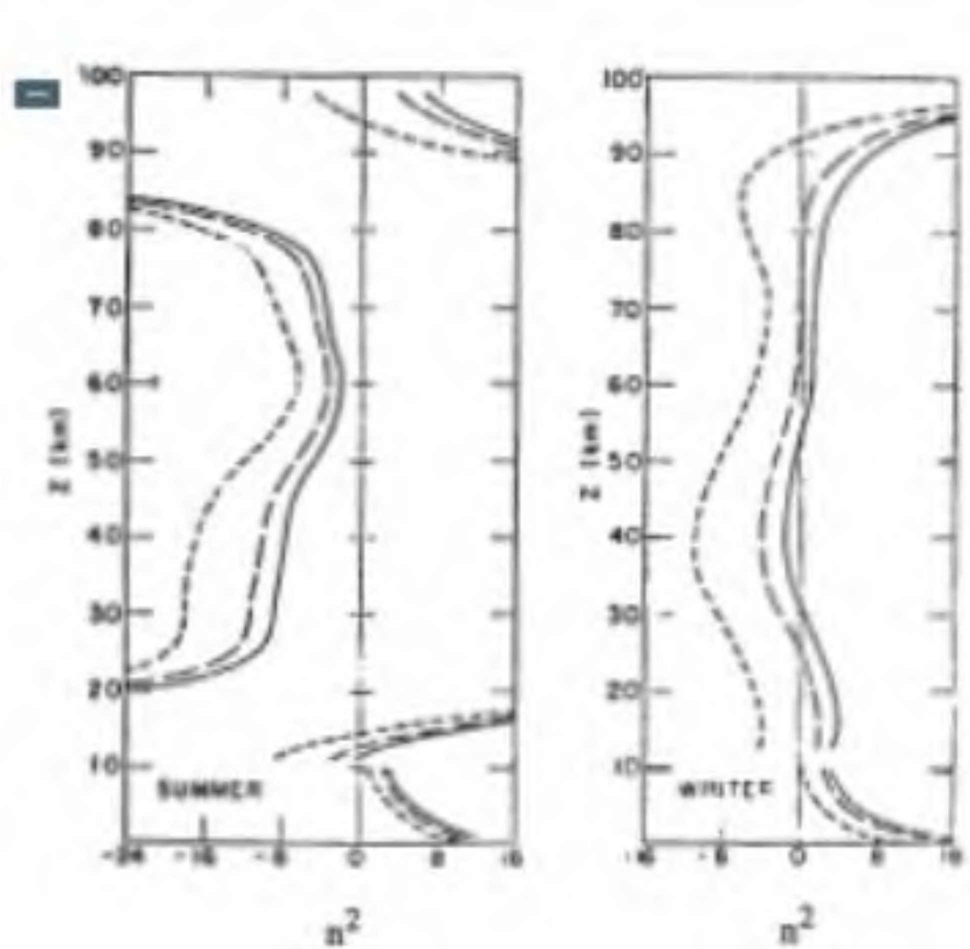


Figure 9.4: The square the index of refraction (summer and winte averaged between 30° a 60°N, for waves of differe wavelengths, L. The sho dashed lines correspond L = 6,000 km, the lon dashed lines correspond L = 10,000 km, and the so lines correspond to L 14,000 km. From Charn and Drazin (1961).

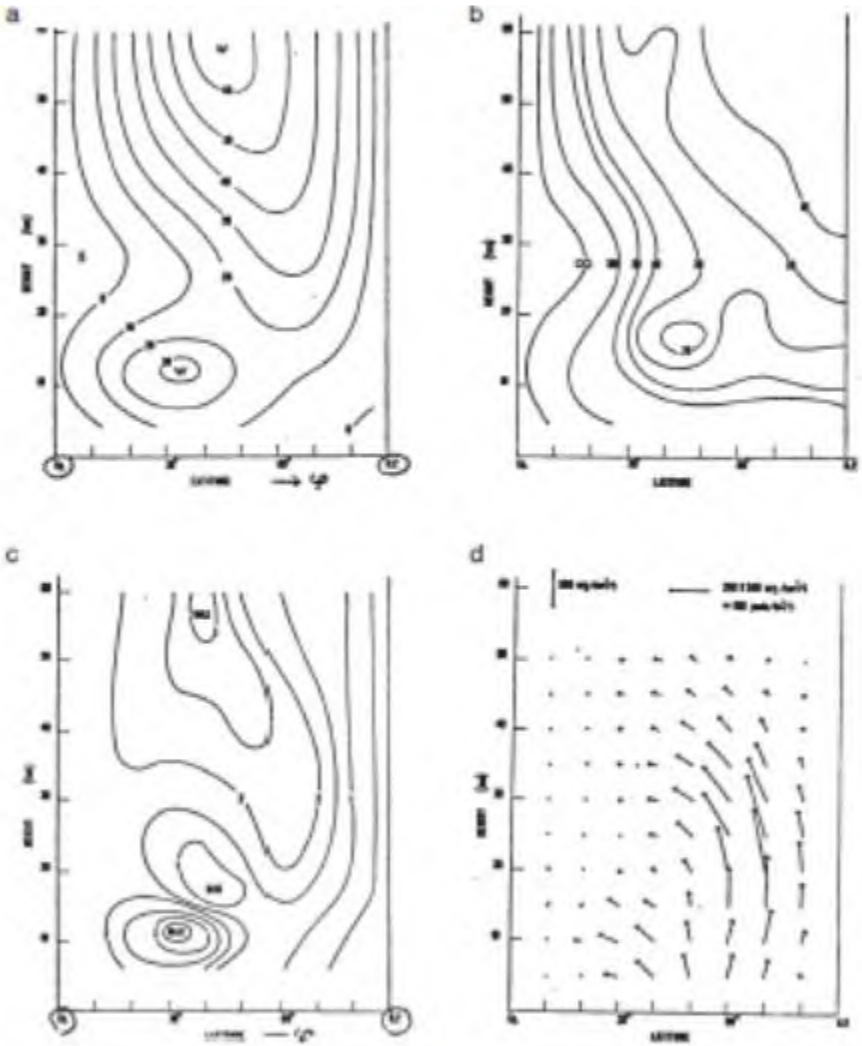
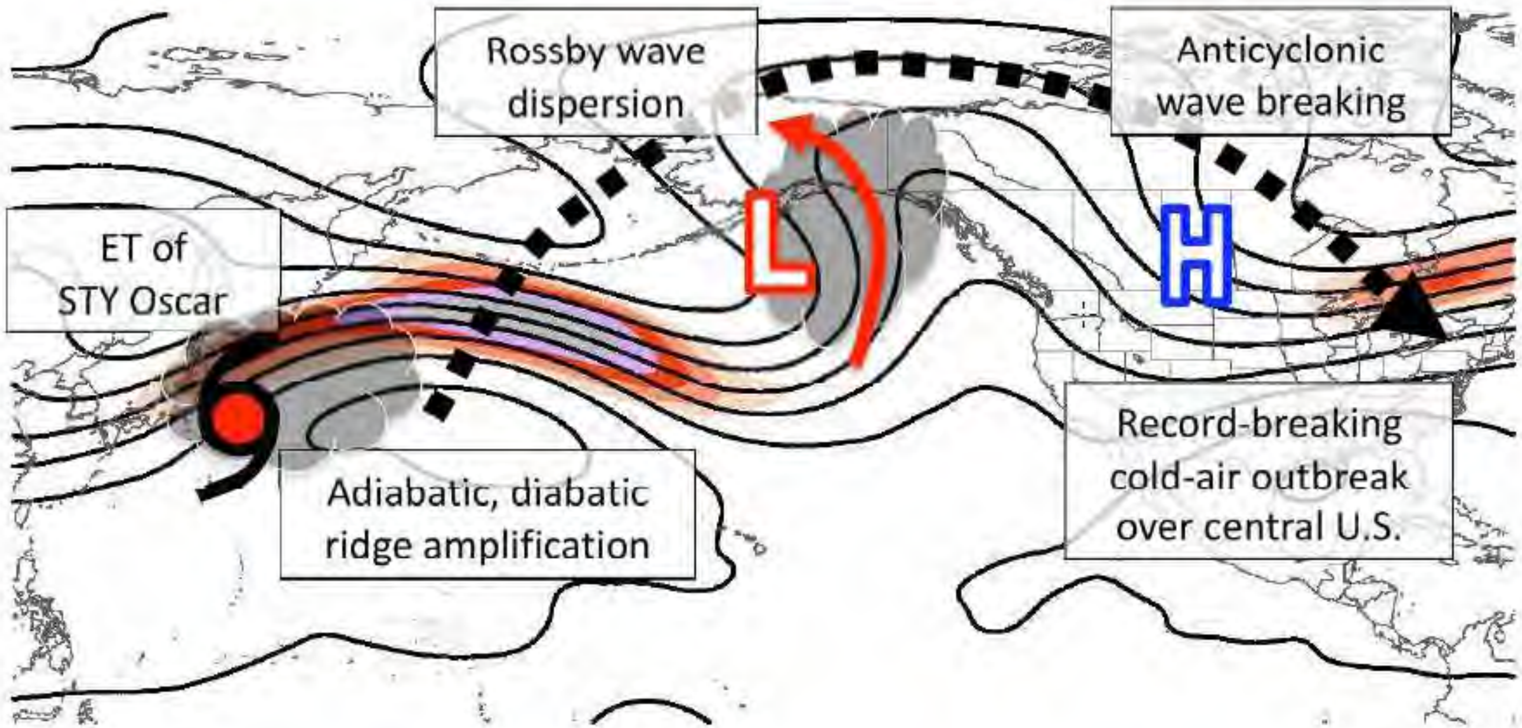


Figure 9.6: a) An idealized basic state zonal wind distribution (in m s⁻¹) for the Northern Hemisphere winter. b) The latitudinal gradient of the potential vorticity, $\partial[q]/\partial\varphi$, expressed as a multiple of the Earth's rotation rate. c) The refractive index square n^2, for the $k=0$ wave. d) Computed distribution of energy flow in the meridional plane associated with zonal wave number 1. From Matsuno (1970).

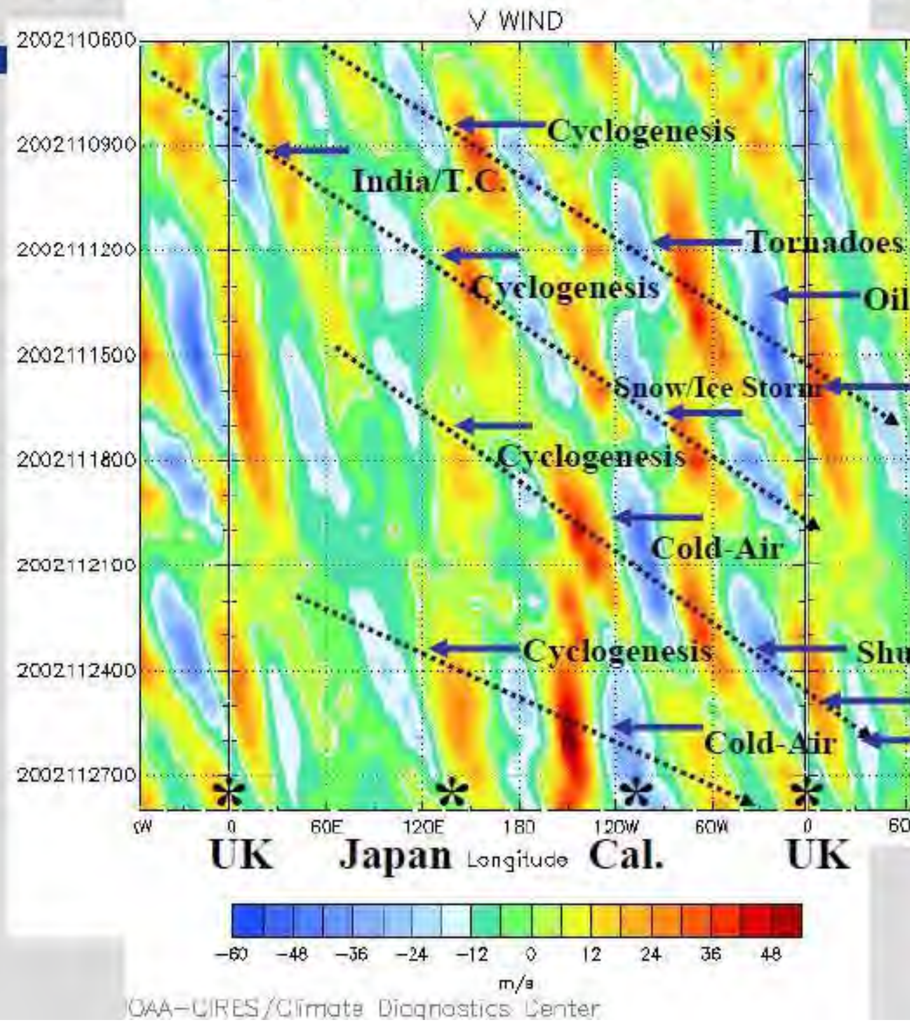
1. Q
2. dq/dy
3. refraction index
4. eddy flux of wave number 1

Rossby Wave Train Leading to a High-Impact Weather Event over the U.S.



Example Case Study: 16–23 Sep 1995

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



Courtesy of Mel Shapiro

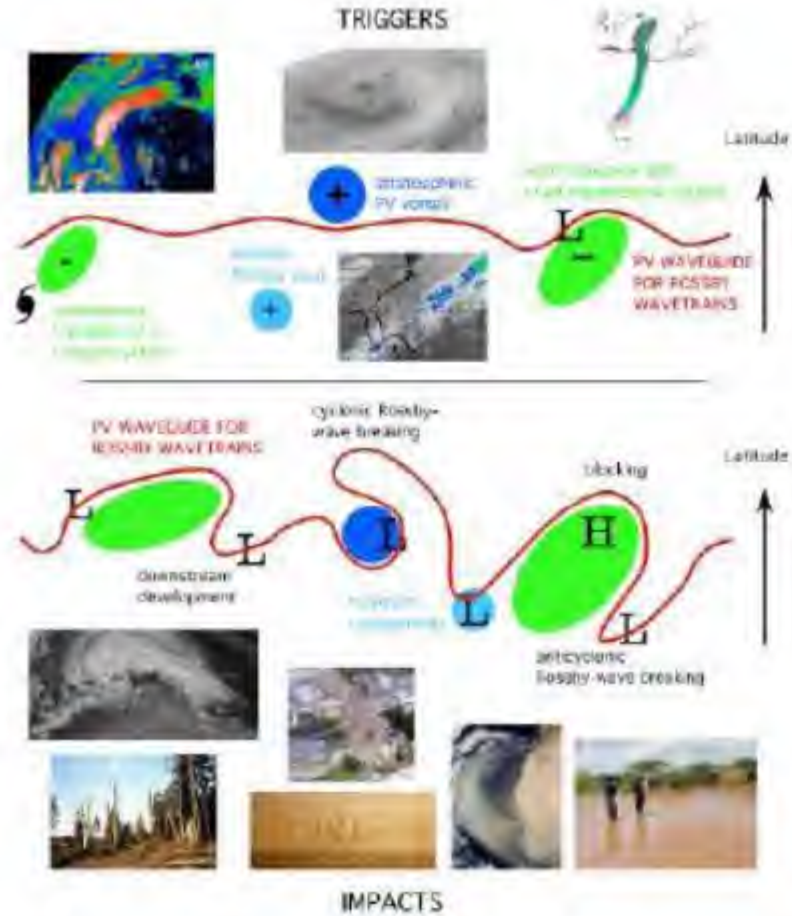
1. Triggering of wave guide disturbances by different dynamic processes

- extra-tropical transition of tropical cyclones
- intense extra-tropical cyclones in the western North Atlantic
- polar stratospheric PV anomalies
- large-scale orographic forcing

2. Subsequent downstream evolution of the disturbances along the wave guide

3. Downstream impacts of the wave guide disturbances over Europe, the Mediterranean and Northern Africa

- breaking of Rossby waves (i.e. the formation of PV streamers and upper-level cut-offs),
- heavy precipitation (in particular to the south of the Alps),
- blocking over the eastern North Atlantic,
- Mediterranean cyclones,
- long-range transport of Saharan dust towards Europe



From: Szunyogh *et al.* (2008): Recent Developments in Predictability and Dynamical Processes (PDP) Research: A Report by the THORPEX PDP Working Group. Submitted to BAMS.

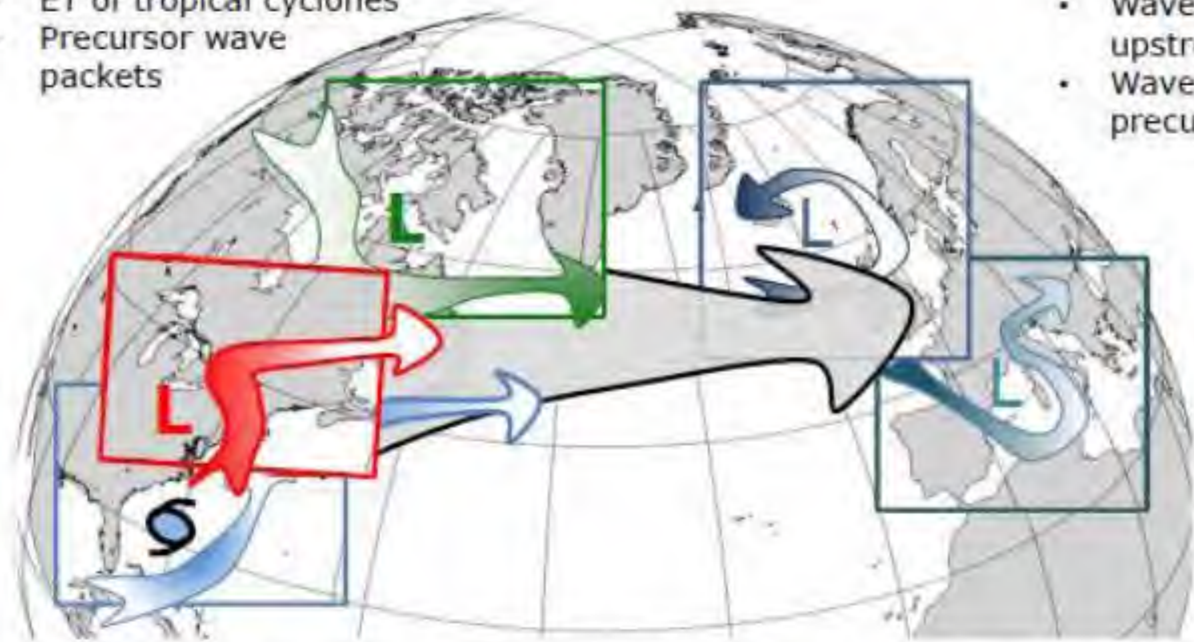
Scientific scope

Factors modifying wave-guide disturbances

- Tropopause polar vortices (pos. PV anomalies)
- WCB outflow (neg. PV anomalies)
- ET of tropical cyclones
- Precursor wave packets

Downstream impact diabatically modifie anomalies

- Wave breaking sensiti upstream disturbances
- Wave breaking can be precursor for HIW



Evolution of Rossby waves along the waveguide

- Dispersion of Rossby waves and sensitivity to PV gradient
- Downstream evolution of PV anomalies
- Modification from Greenland
- *Local* modification of Rossby waves by pos. and neg. PV anomalies

Part 3

From baroclinic instability to baroclinic life cycle

Linear dynamics stretches to a full climate model

- From baroclinic instability to baroclinic life cycle.

- As good as Eady's model, instability is, after all, just, instability: perturbation growing, growing.. exponentially!!! It *cannot* last forever.
- In Eady's model, PV is zero in interior. Who will stop the growth after zonal available potential energy is exhausted?
- Answer: barotropic governor (the meridional variation of dq/dy).

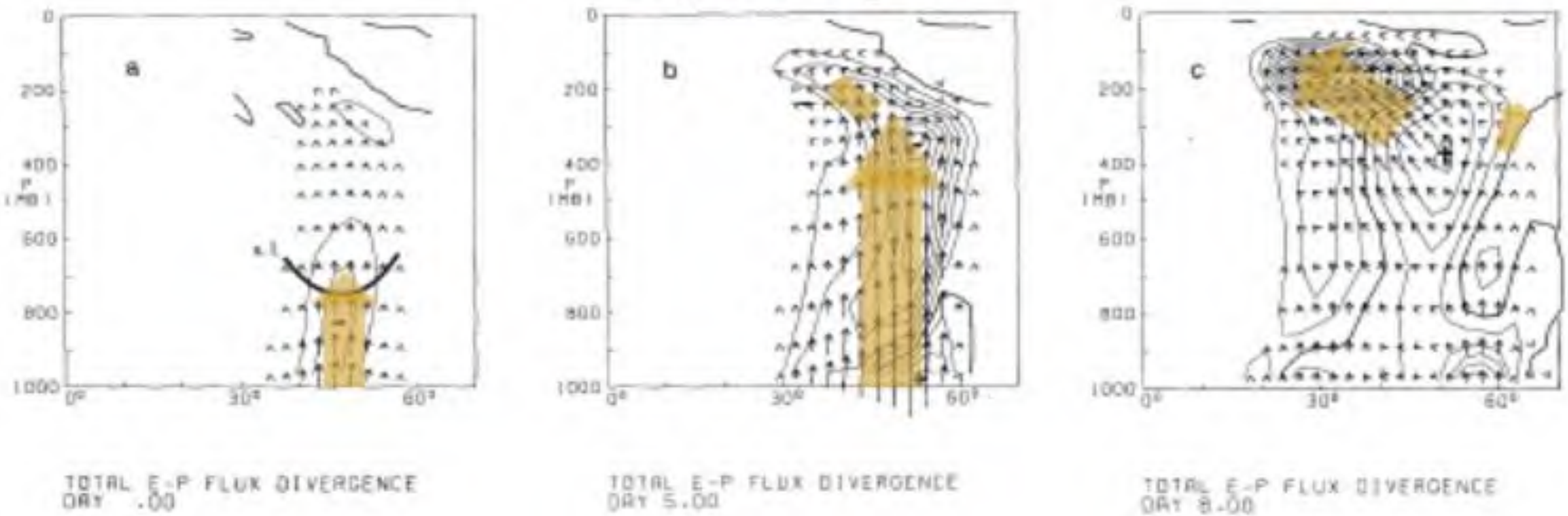
EP flux connects baroclinic instabily, Rossby wave propagation

$$\mathcal{F} \equiv -[u^* v^*]\,\mathbf{j} + f\frac{[v^*\theta^*]}{\partial\theta_s/\partial p}\,\mathbf{k}$$

$$\vec{\mathcal{F}} = \vec{c_g}\mathcal{A}$$

Numerical results from
Simmons and Hoskins, 1978, JAS

Eddies: generate at lower level, propagate upwards and away from the eddy source region



Left turn? Right turn?

$$\mathcal{F} \equiv -[u^*v^*]\,\mathbf{j} + f\frac{[v^*\theta^*]}{\partial\theta_s/\partial p}\,\mathbf{k}$$

$$\vec{\mathcal{F}} = \vec{c_g}\mathcal{A}$$

$$\frac{\partial[u]}{\partial t} = f[\tilde{v}] + \nabla\cdot\mathcal{F} + [F_x]$$

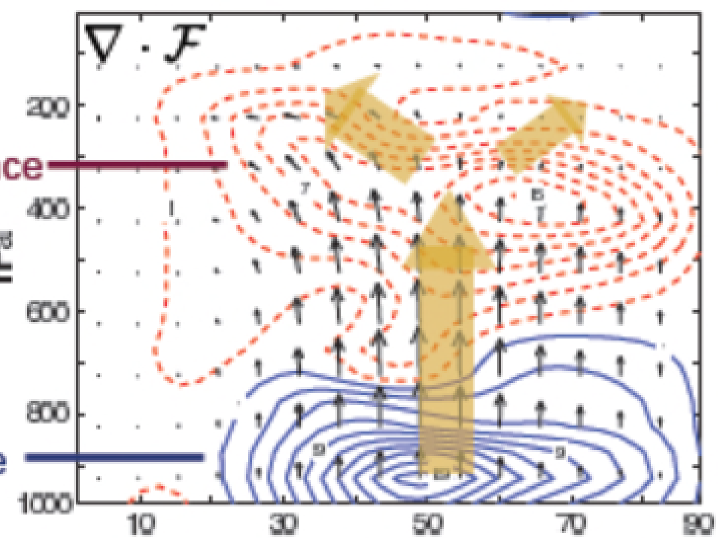
In the vertical direction:

Accelerating the lower jet
decelerating the upper jet
reduce the vertical shear of U

Wave energies:
propagate **upwards** and **away** from the center of the jet

Convergence

Divergence



Two different baroclinic life cycles in Thorncroft, Hoskins, McIntyre

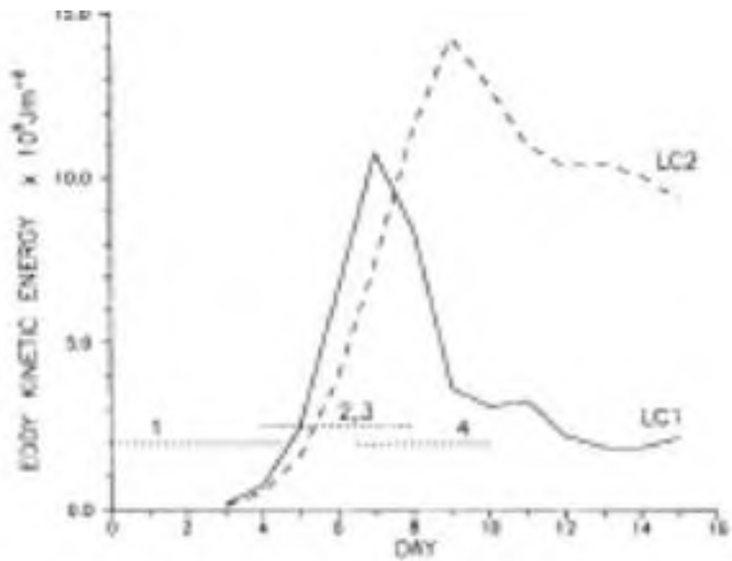


Figure 4. Eddy-kinetic-energy evolution for LC1 (solid) and LC2 (dashed). Also indicated on the graph as horizontal dashed lines are the different overlapping stages of LC1 with numbers corresponding to the discussion in section 7.

These are all simulation based on
Simmon's model allows only k-6 mode

Potential temperature on PV2 surface

LC1

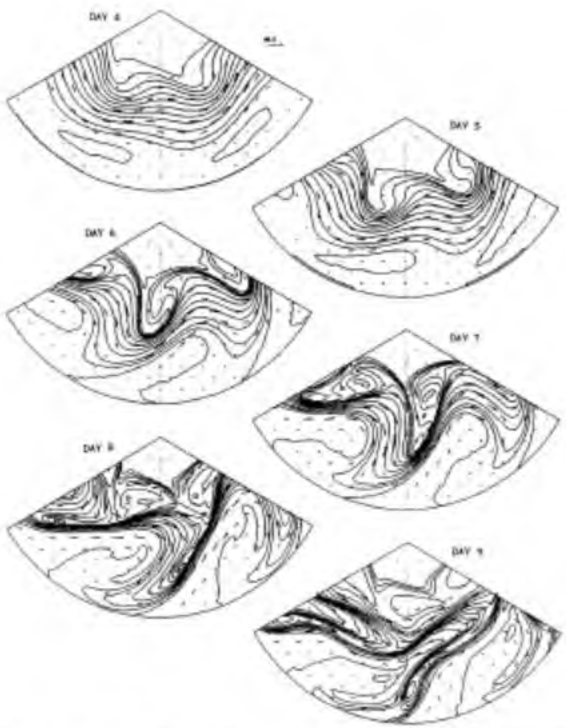


Figure 7. Potential temperature on the PV = 2 PVU surface in LC1 between days 4 and 9. Contours are drawn every 5 K from 290 K to 350 K going equatorward. Wind vectors are included; for days 4 to 7 these have had the phase speed of the normal mode removed to give the relative flow. The arrow scale is as in Fig. 11 (with allowance for the different figure dimensions). Sections are shown for two wavelengths between latitude 20°N and the pole. Lines of constant latitude and longitude are drawn every 20 and 30 degrees, respectively.

LC2

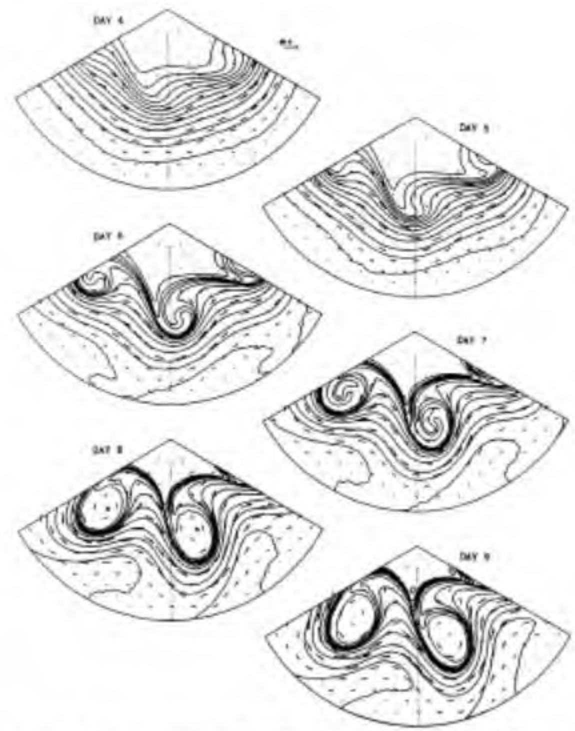
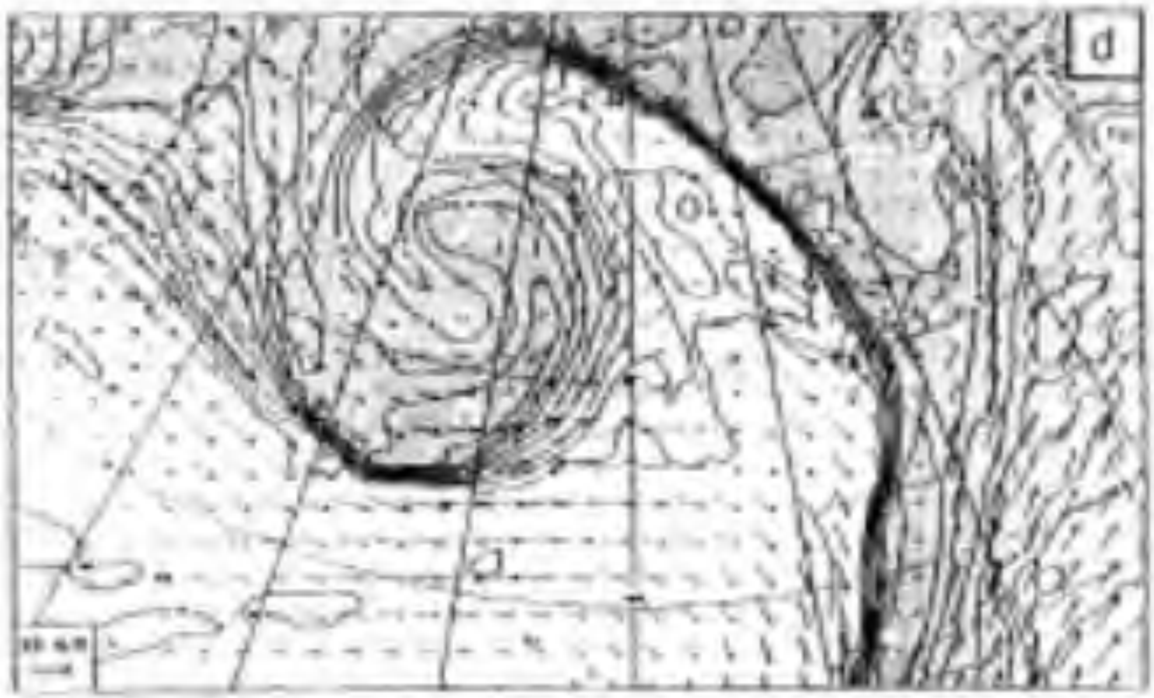


Figure 10. Potential temperature on the PV = 2 PVU surface in LC2 between days 4 and 9. Contours are drawn every 5 K from 290 K to 350 K going equatorward, except that on day 9 model hyperdiffusion has produced additional small closed 285 K contours near 70°N. Wind vectors are included; for days 4 to 7 these have had the phase speed of the normal mode removed to give the relative flow. The arrow scale is as in Fig. 11 (with allowance for the different figure dimensions). Sections are shown for two wavelengths between latitude

One would imagine what the yz cross section looks like?

A real LC1 and LC2 weather



EP flux is the best tool to analyze eddy-mean flow interaction

LC1 LC2

Day 0

Day 5

Day 8

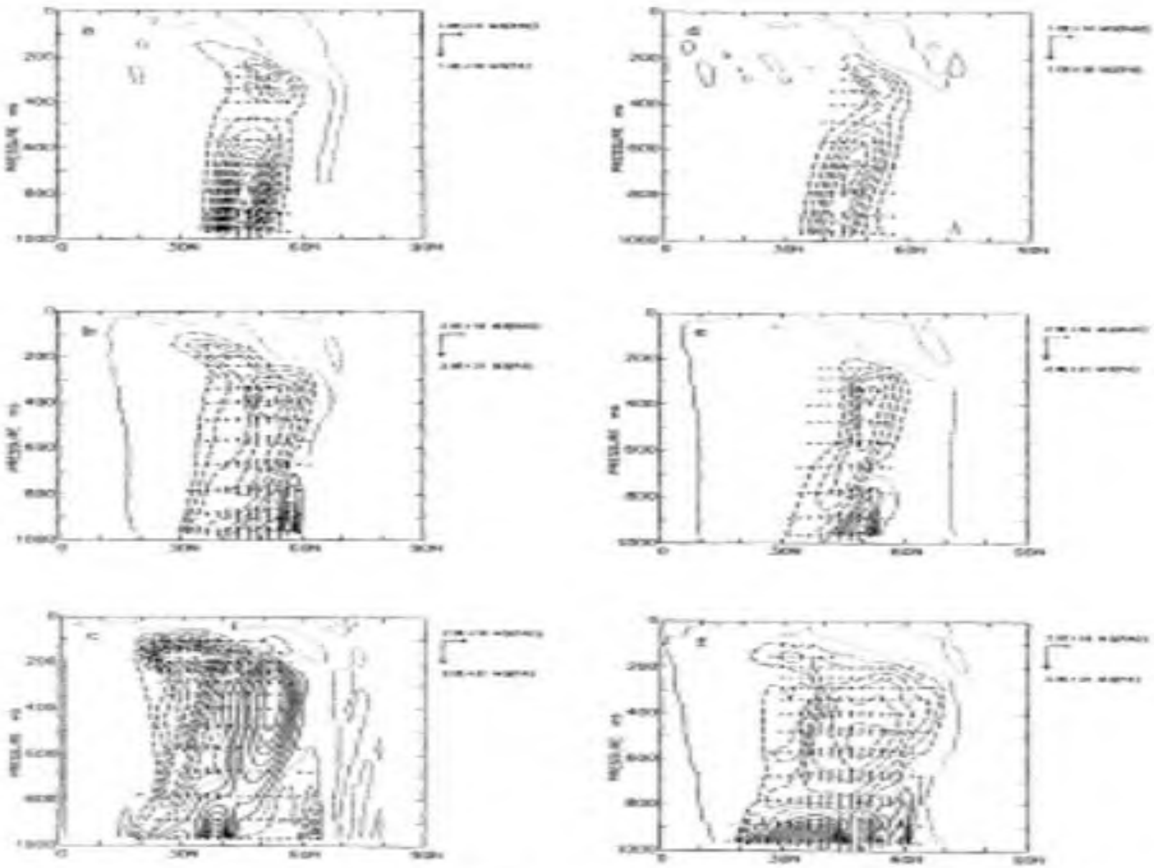


Figure 15. EP flux and its divergence during the two life cycles. (a), (b) and (c) are for days 0, 5 and 8 in LC1 and (d), (e) and (f) are for the same days in LC2. Dashed contours are negative and the contour interval is 4 × 10[illegible] m[illegible]. The divergence in (a) and (d) has been multiplied by 400; note also the different arrow scalings (different by a factor 200), and recall that the surface pressure amplitude is 1 mb at day 0 and that the EP flux and divergence both scale with the amplitude squared. Units are as in Edmon *et al.* It should also be noted that these and subsequent sections overemphasize the vertical contribution to the EP vector because of the stretched ratio of vertical to horizontal scales.

It can be explained by refraction analysis

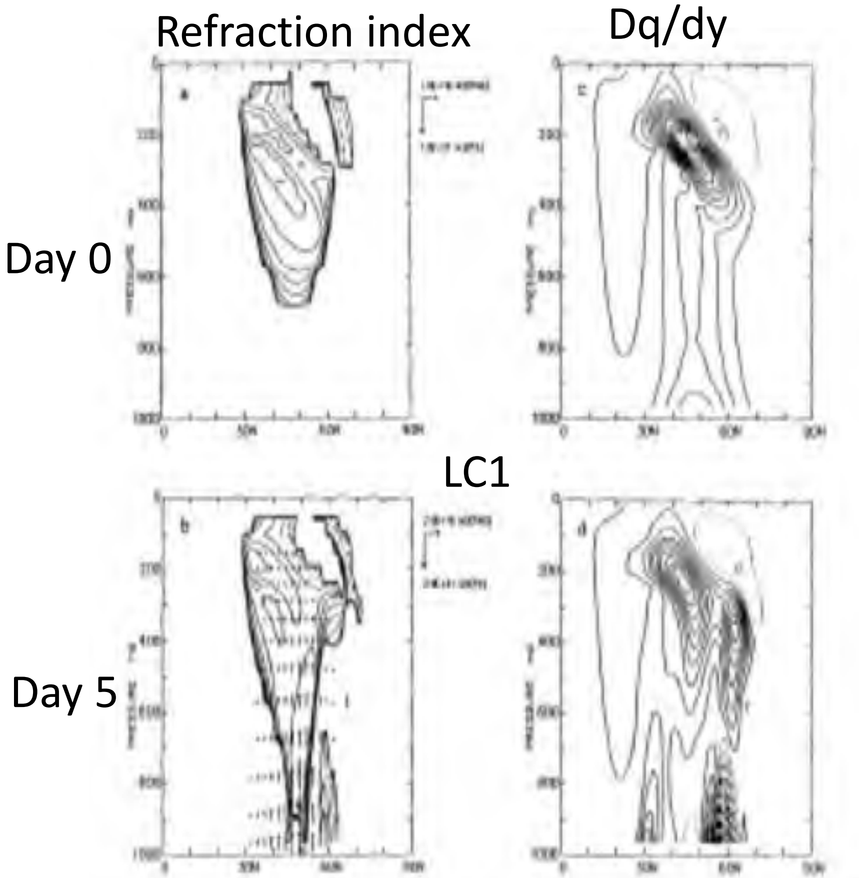


Figure 16. The modified refractive index K, or dimensionless 'total wavenumber', with EP flux vectors and $\bar{q}_y$ in LC1. Only positive values of K are plotted. (a) and (b) show K for days 0, 5 and (c) and (d) show $\bar{q}_y$ for the same days. The contour interval for K is 2, the dotted line represents $K = 6$ and dashed lines K values less than this. K takes the value 6.2 in the upper central minimum discussed in the text and marked by a minus sign, the largest contour value in the tropopause ridge, just above, is 12. The contour interval for $\bar{q}_y$ is $2 \times 10^{-11}\,s^{-1}\,m^{-1}$; the dotted contour is 0 and dashed contours are negative.

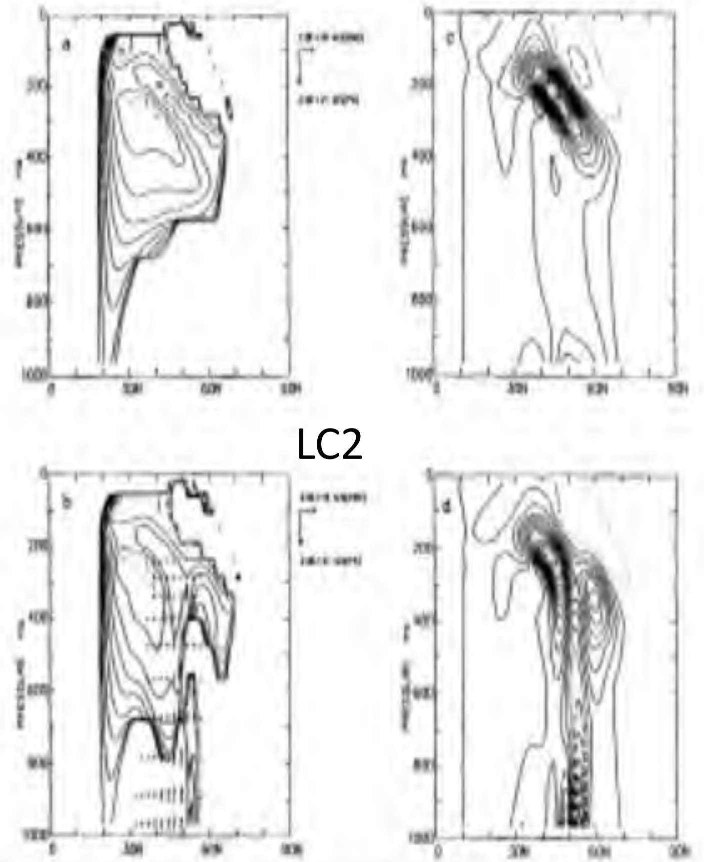
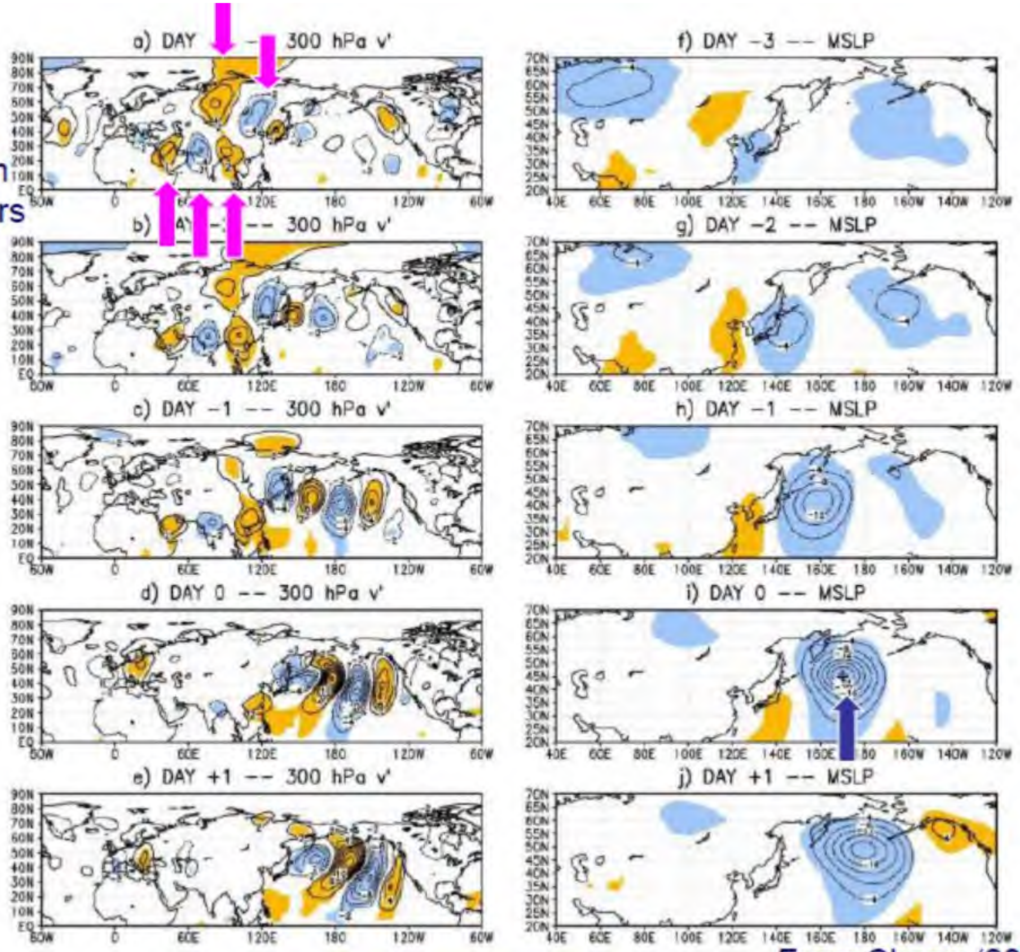


Figure 17. The modified refractive index K, or dimensionless 'total wavenumber', with EP flux vectors and $\bar{q}_y$ in LC2. Only positive values of K are plotted. (a) and (b) show K for days 0, 5 and (c) and (d) show $\bar{q}_y$ for the same days. The contour interval for K is 2, the dotted line represents $K = 6$ and dashed lines K values less than this. K takes the value 5.1 in the upper central minimum discussed in the text and the largest contour value in the tropopause ridge, just above, is 12. The contour interval for $\bar{q}_y$ is $2 \times 10^{-11}\,s^{-1}\,m^{-1}$; the dotted contour is 0 and dashed contours are negative.

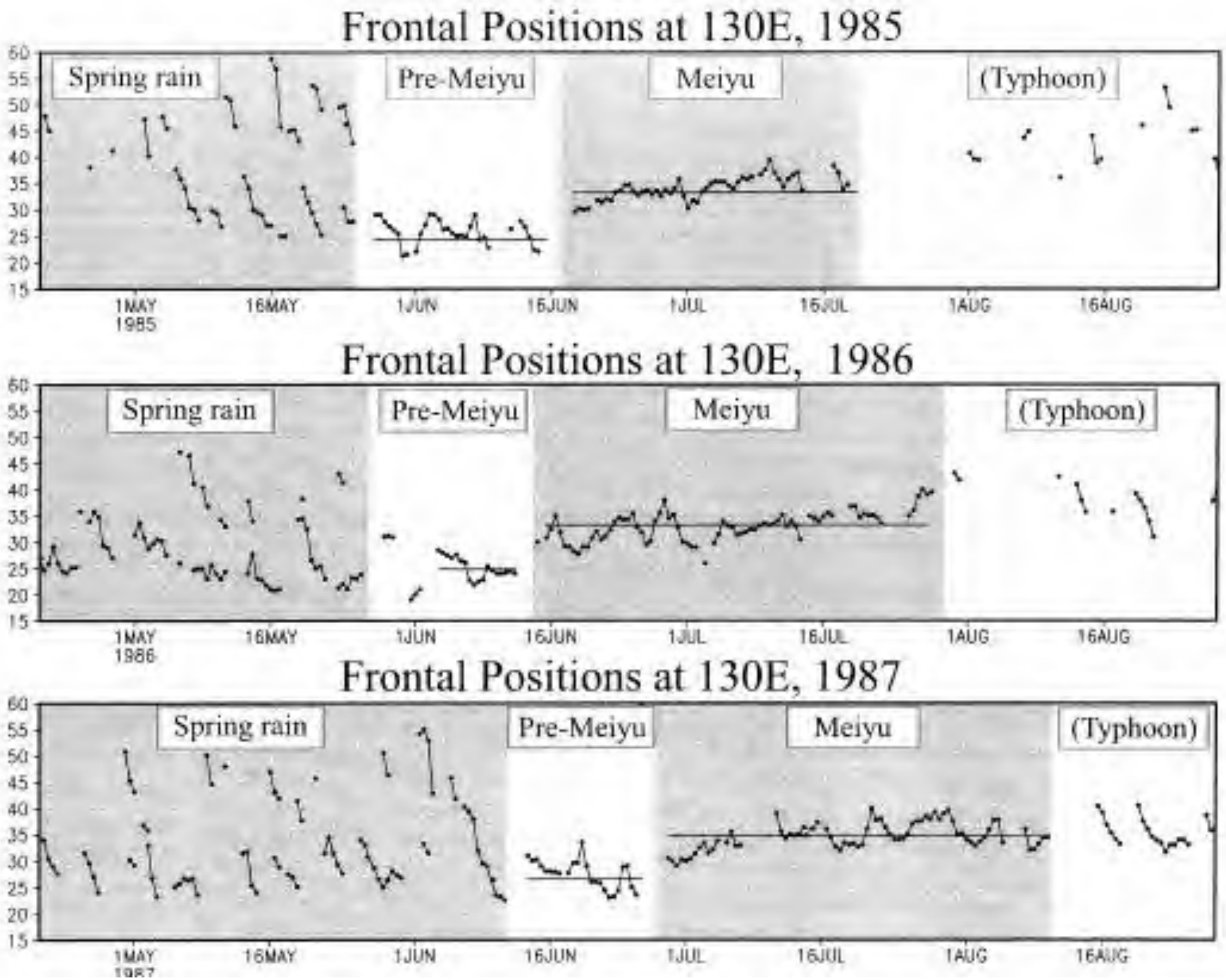
jet moves north in LC1, opposite for LC2

Figure 12. Schematic of a PV-theta contour in an Atlantic storm track sharing its main characteristics with (a) an LC1-type life cycle and (b) an LC2-type life cycle. The dashed line marks the approximate position of the mean jet at each stage.

Upstream Precursors



From Chang (2005)


Frontal Positions at 130E, 1985
Spring rain
Pre-Meiyu
Meiyu
(Typhoon)
60
55
50
45
40
35
30
25
20
15
1MAY
1985
16MAY
1JUN
16JUN
1JUL
16JUL
1AUG
16AUG
Frontal Positions at 130E, 1986
Spring rain
Pre-Meiyu
Meiyu
(Typhoon)
1MAY
1986
16MAY
1JUN
16JUN
1JUL
16JUL
1AUG
16AUG
Frontal Positions at 130E, 1987
Spring rain
Pre-Meiyu
Meiyu
(Typhoon)
1MAY
16MAY
1JUN
16JUN
1JUL
16JUL
1AUG
16AUG

Based on baroclinic life cycle, one can build various climate models

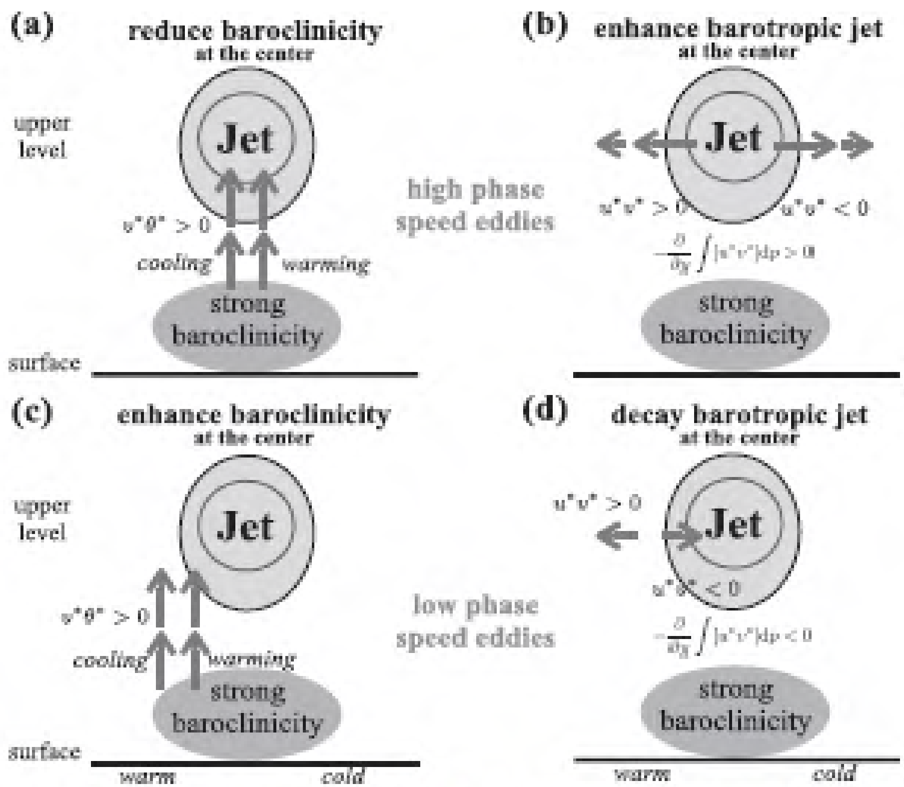


FIG. 9. Diagrams showing the impacts of eddy heat and momentum fluxes on the zonal flow baroclinicity and zonal winds at the center of the jet for zonal wavenumbers (a),(b) 6 and (c),(d) 4 in the standard run. Arrows denote the propagation of baroclinic wave activity. In (c) and (d), because of space limits, only the eddies generated at one flank of the jet are illustrated. High-phase-speed eddies at zonal wavenumber 6 generated at the center of jet act to reduce the baroclinicity and enhance the barotropic jet. Low-phase-speed eddies at zonal wavenumber 4 generated at the flanks of the jet act to enhance the baroclinicity at the jet center and decay the barotropic jet.

Zhang Yang, XQY, Gang Chen 2012

Meteorology and Physical Oceanography are the last heir apparent of classical physics in the College of Science

- The beauty of our field is nothing in core dynamics against our intuition (gathered by human sensory).
- The aim of our education is to build up trust of equations which intimately link to outside world.

End