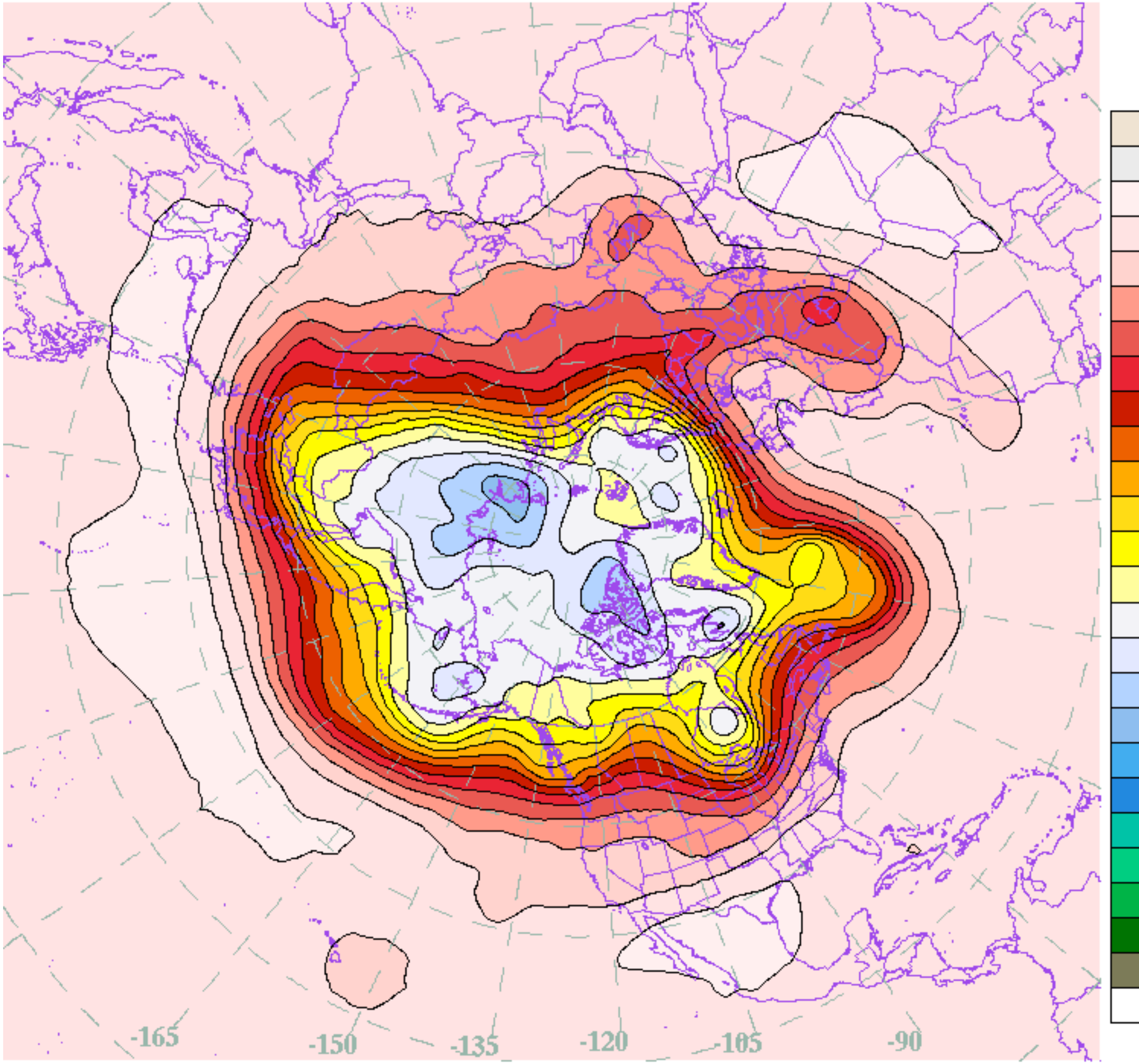
Time lapse animation
daily fields, unfiltered
500 hPa height field

courtesy of David Ovens

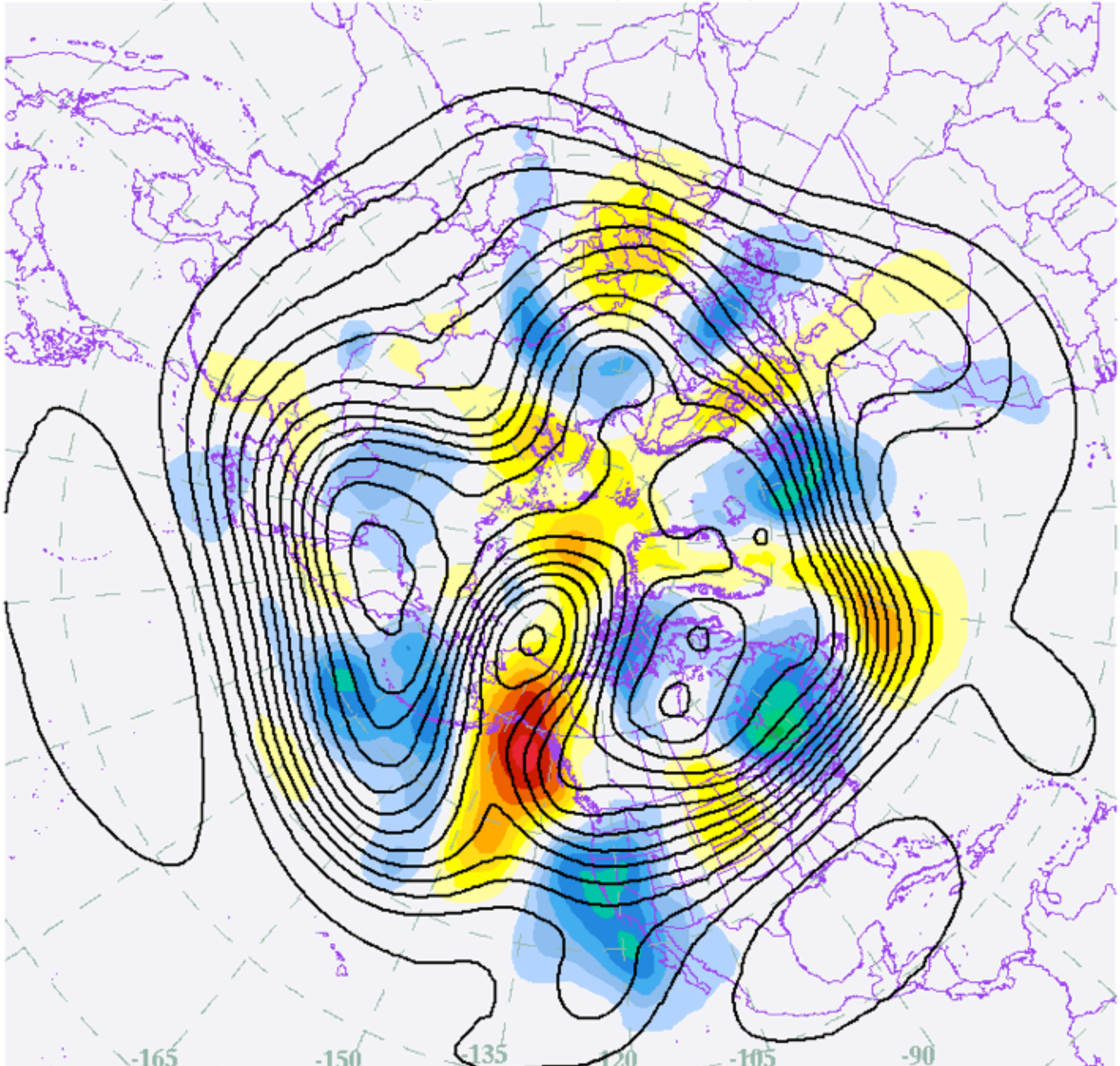


http://www.atmos.washington.edu/~bsmoliak/teleconnection.html

Lowpass filter: 5-day running mean

Highpass filter: departure from....

5-day centered 500 MB Heights/Anomalies (dekameters) valid 00Z 01 Dec 2007



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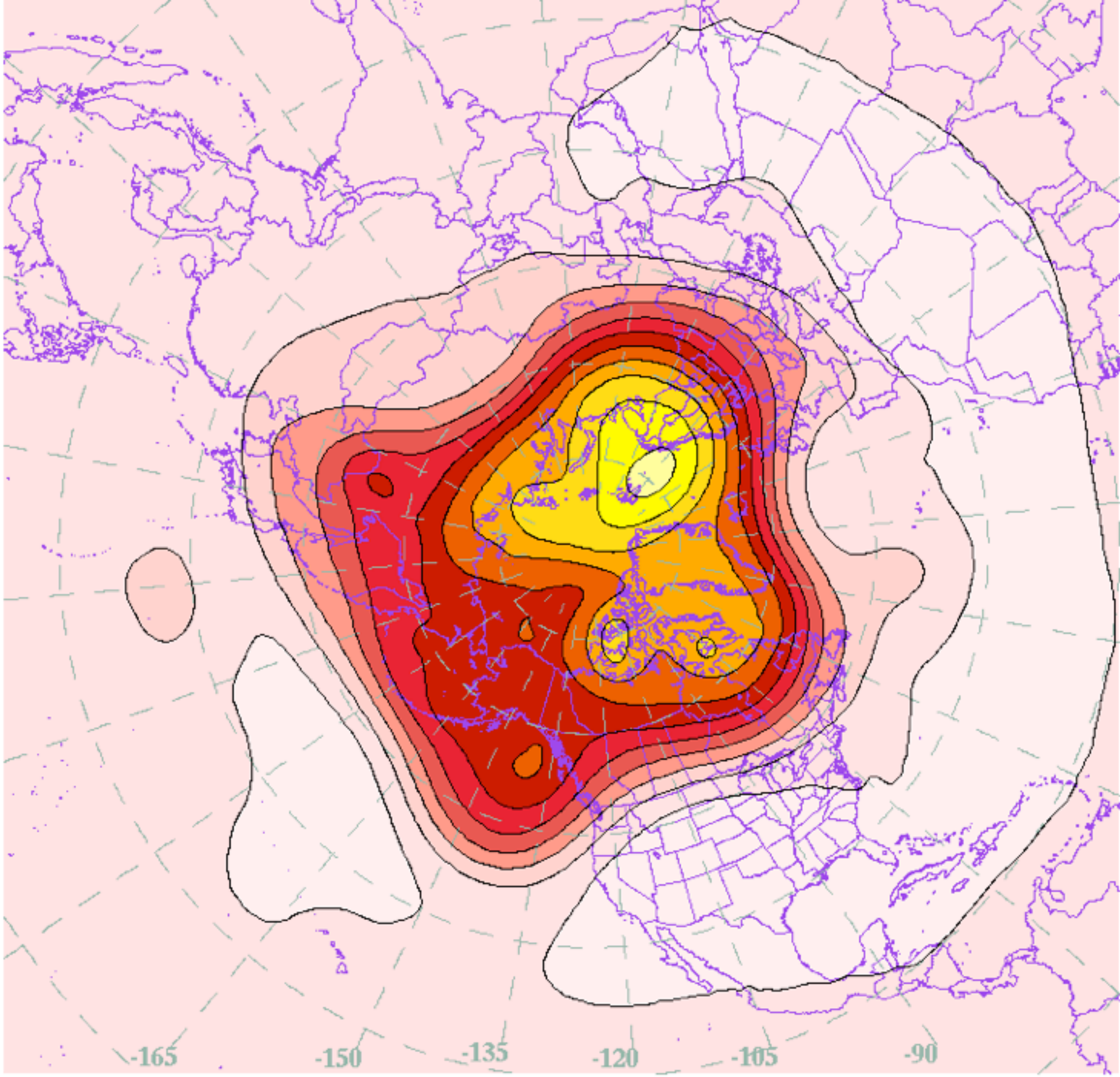
Time lapse animation
lowpass filtered
500 hPa height field

courtesy of David Ovens



http://www.atmos.washington.edu/~bsmoliak/teleconnection.html

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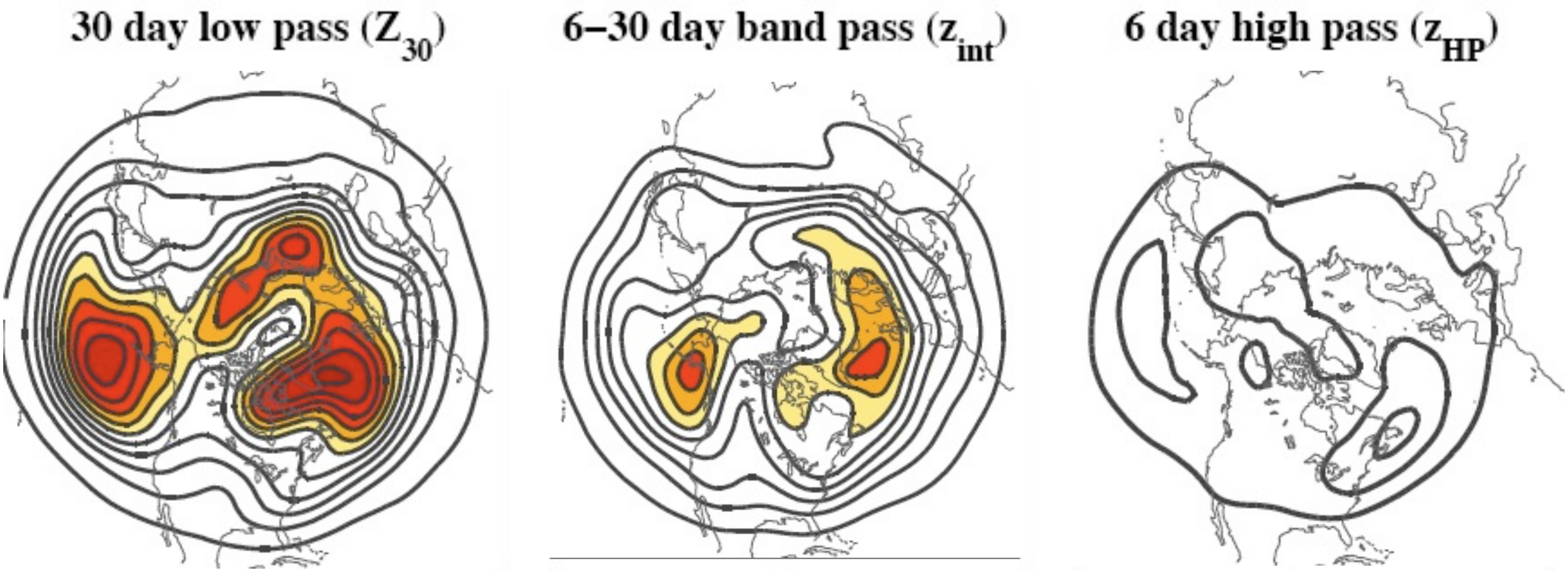
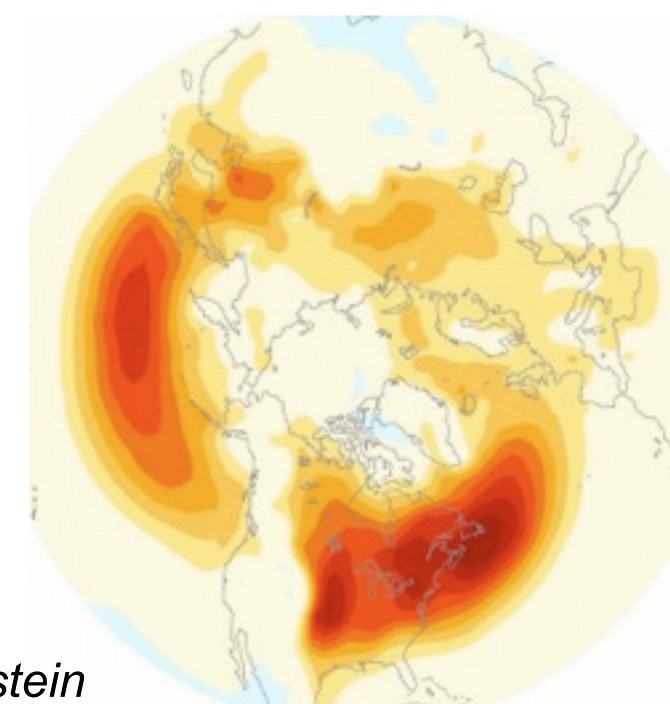
500 hPa height variance DJF



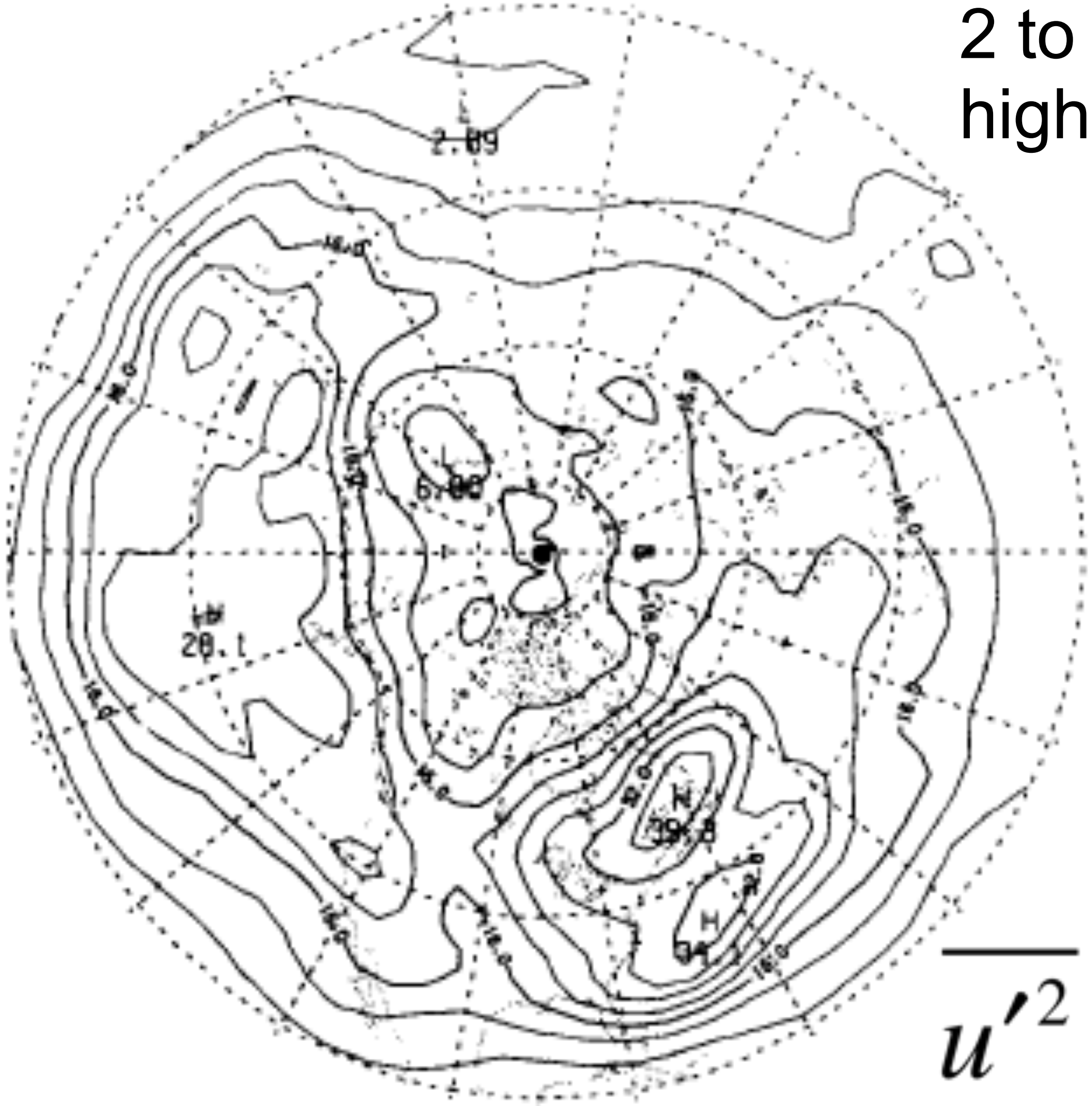
after Rennert and Wallace JAS, 2009

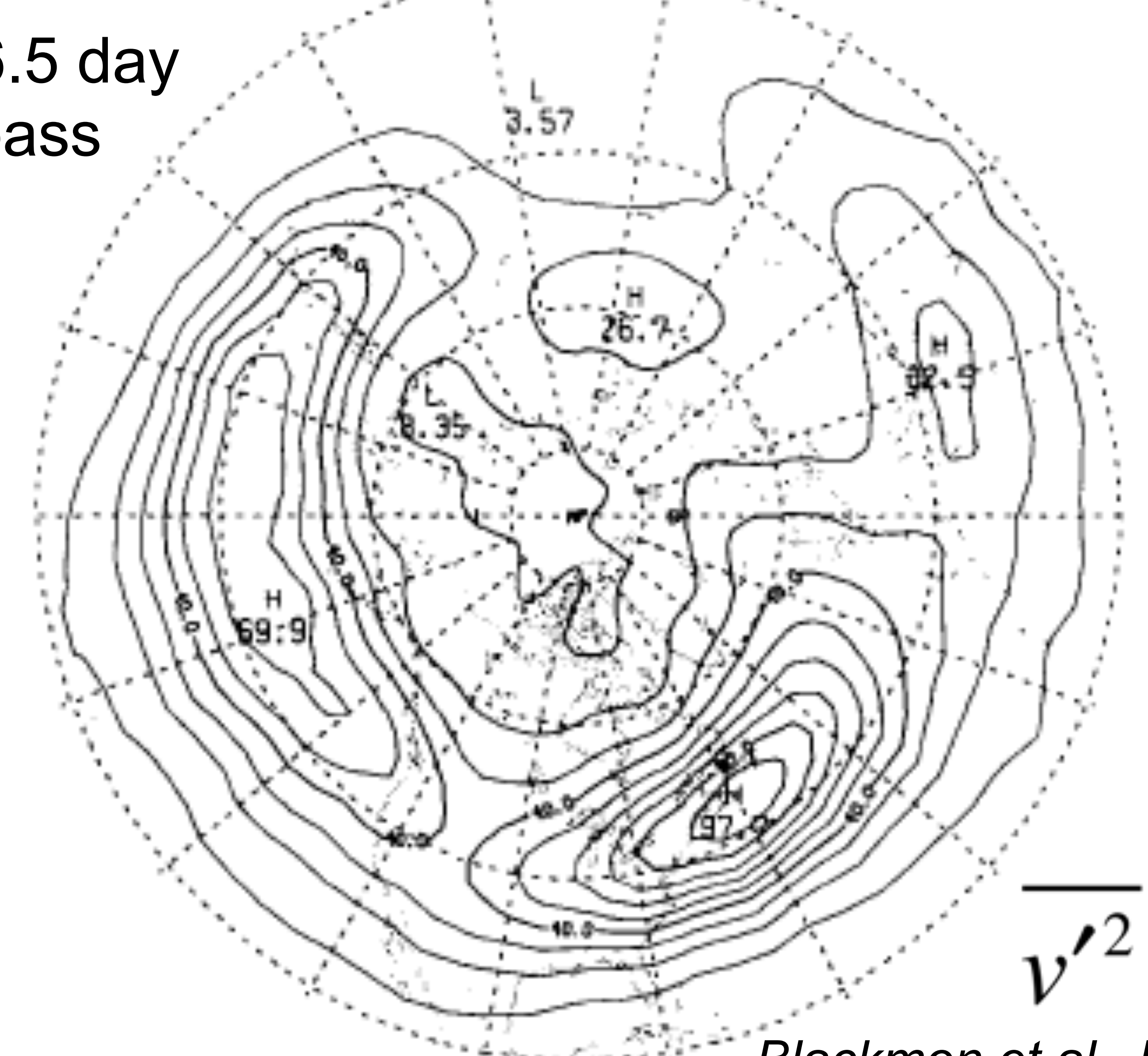
eddy heat flux
850 hPa



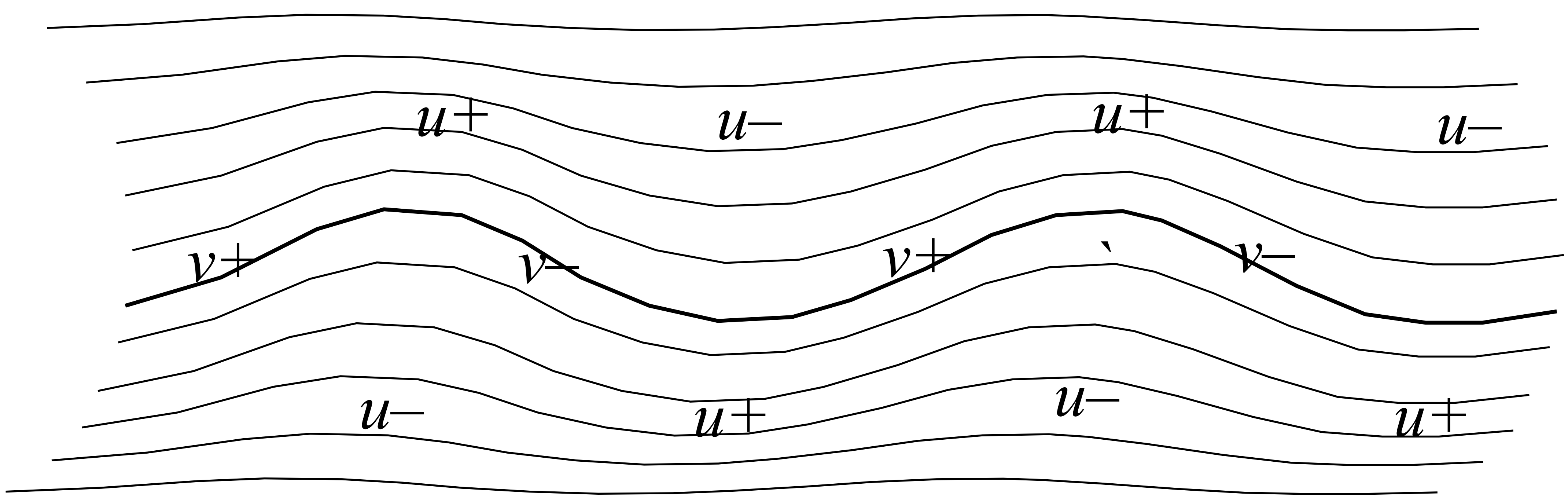
courtesy of Justin Wettstein

2 to 6.5 day highpass

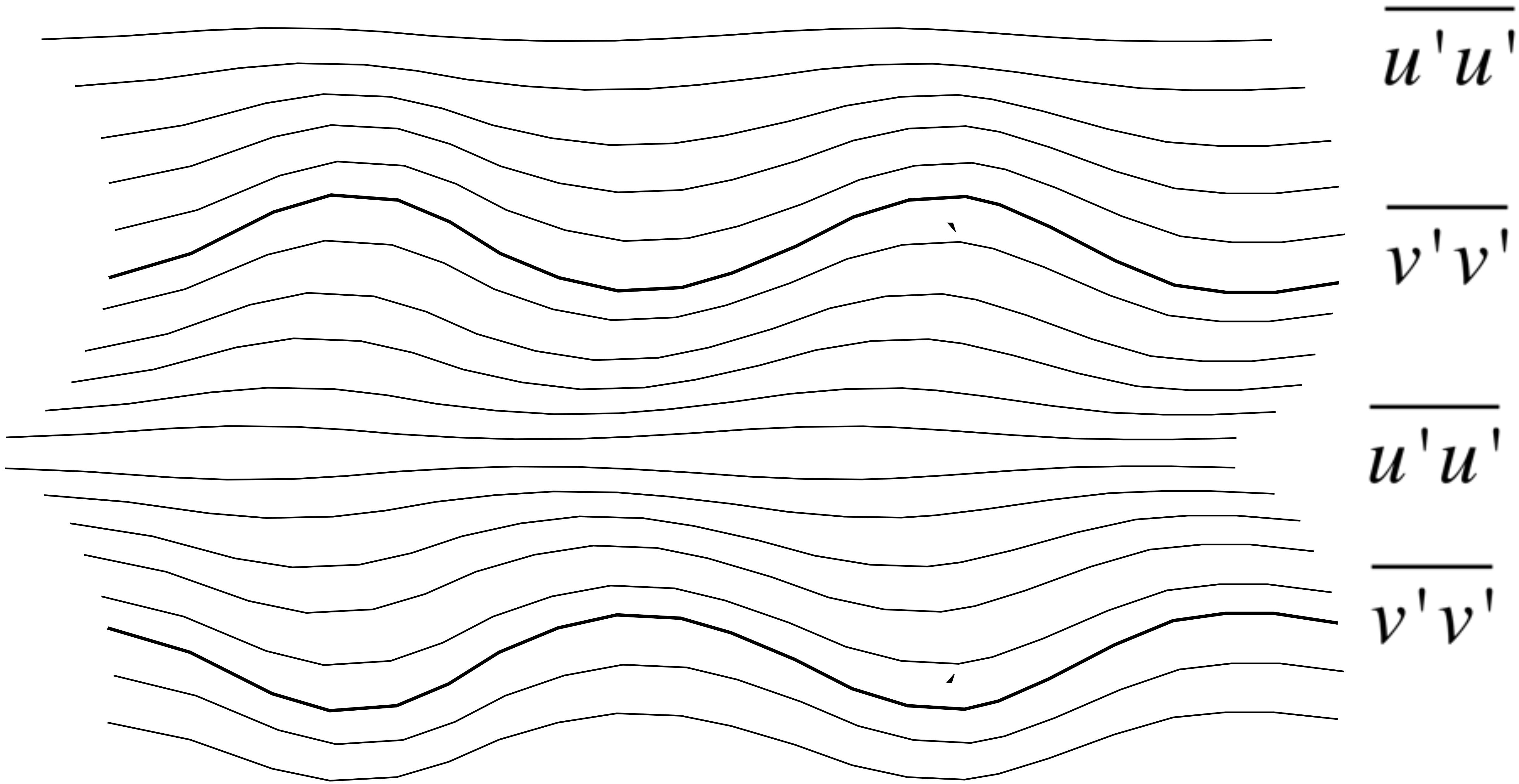


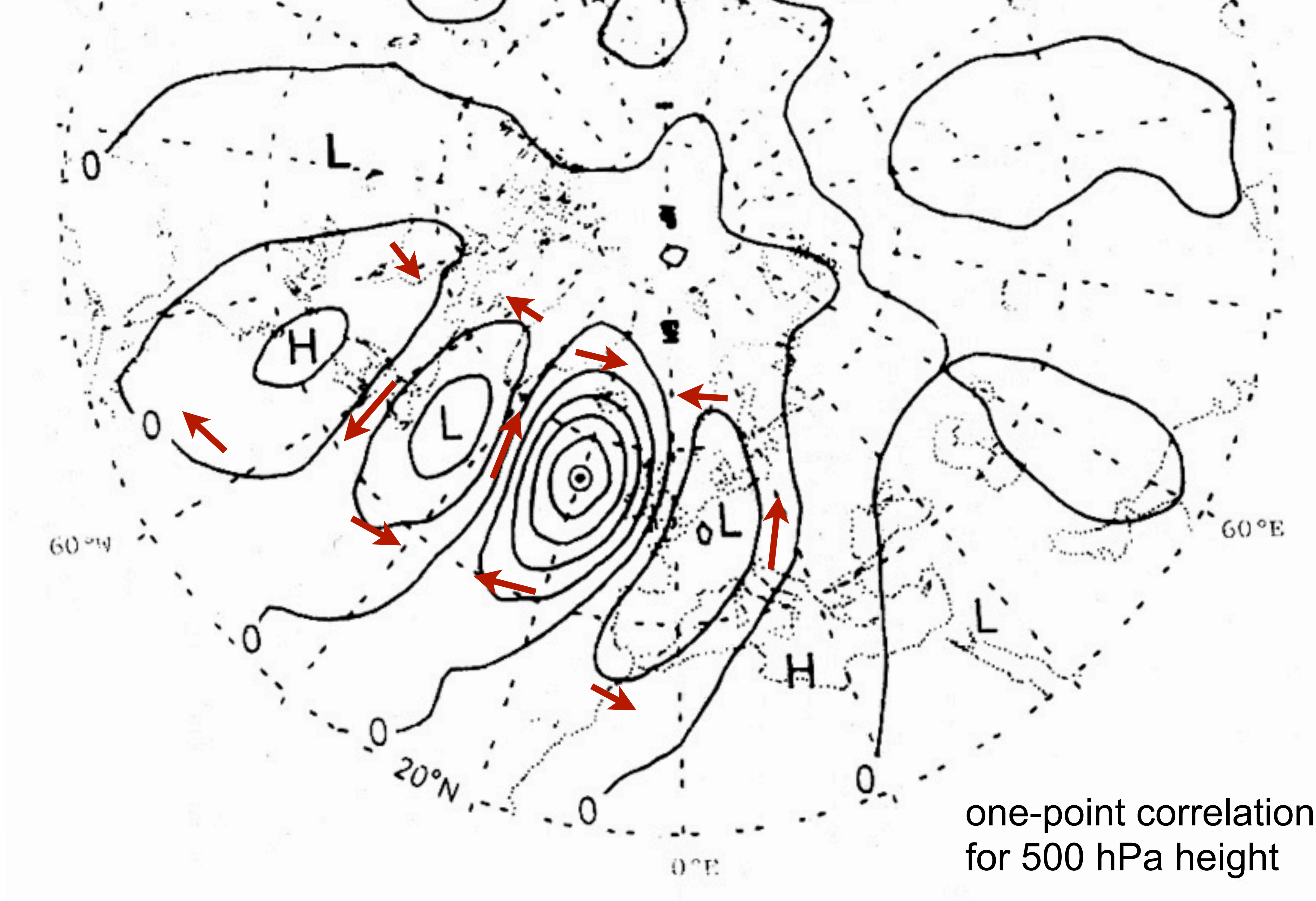


Blackmon et al. JAS 1977



2 to 6.5 day
highpass

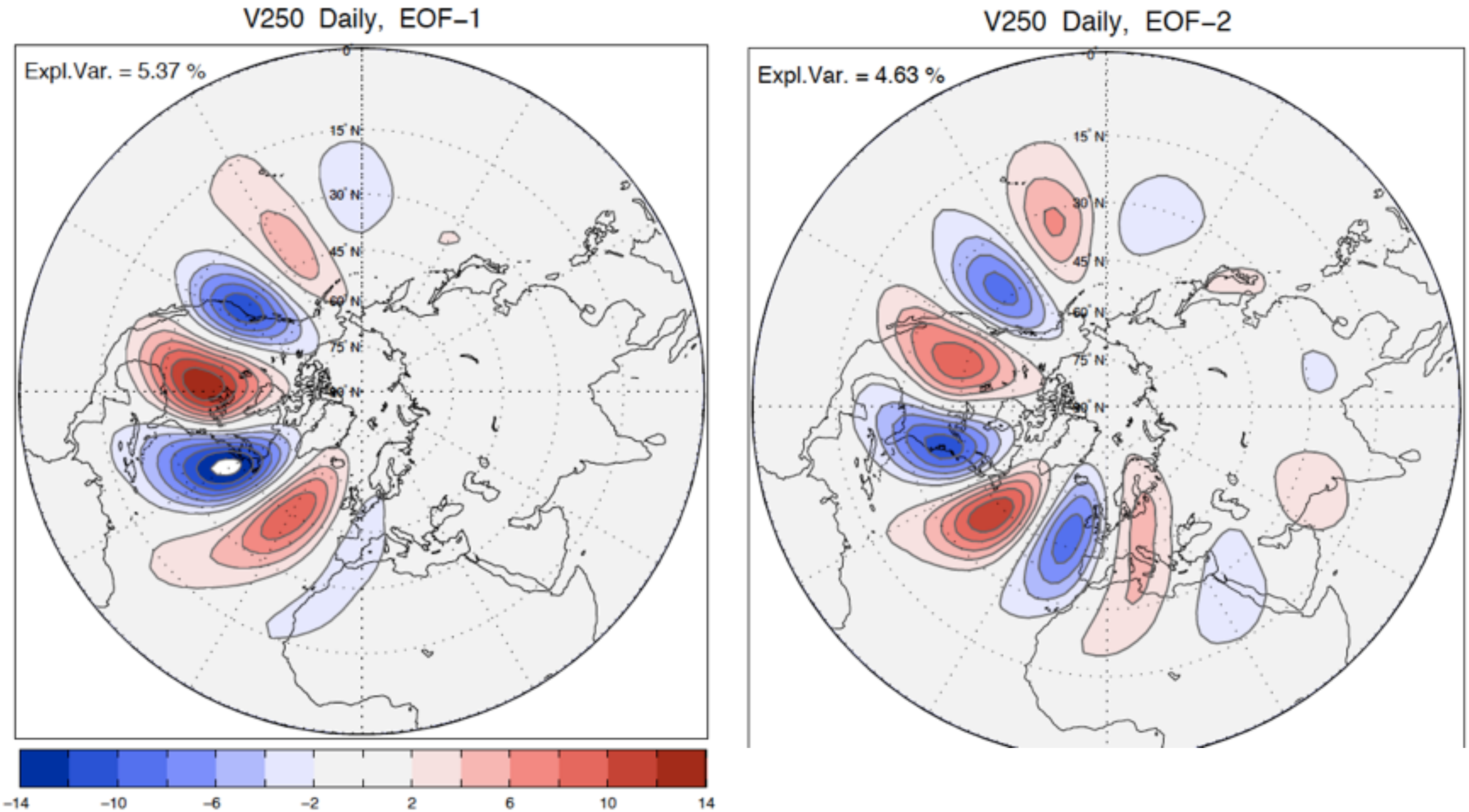




one-point correlation map
for 500 hPa height

Anisotropy of high frequency transients

$$\overline{v'v'} > \overline{u'u'}$$



Leading wintertime EOFs, Courtesy of Panos Athanasiadis based on daily unfiltered data

Anisotropy of high frequency transients

$$\overline{v'v'} > \overline{u'u'}$$

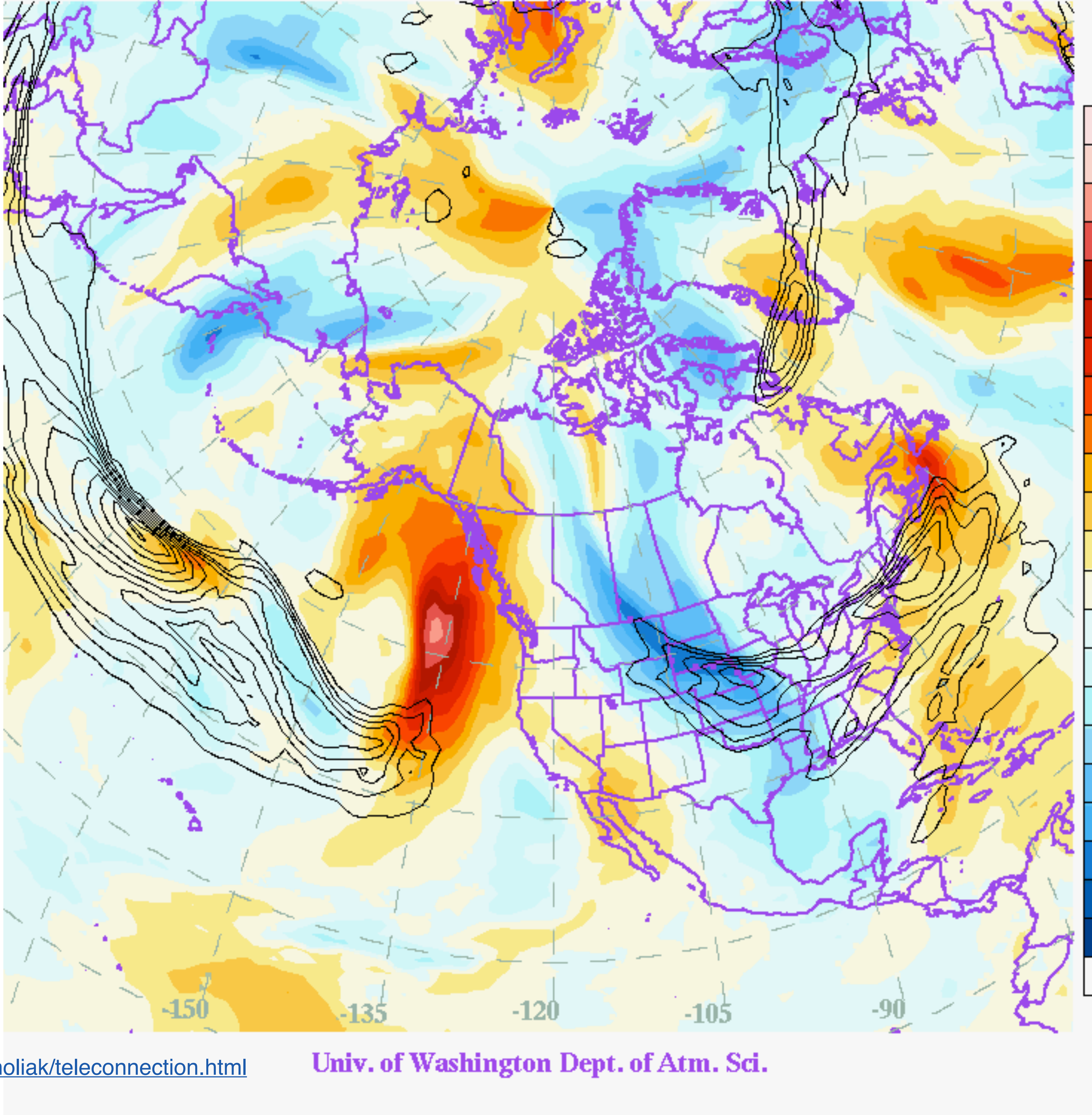
u' contours

positive anomalies only

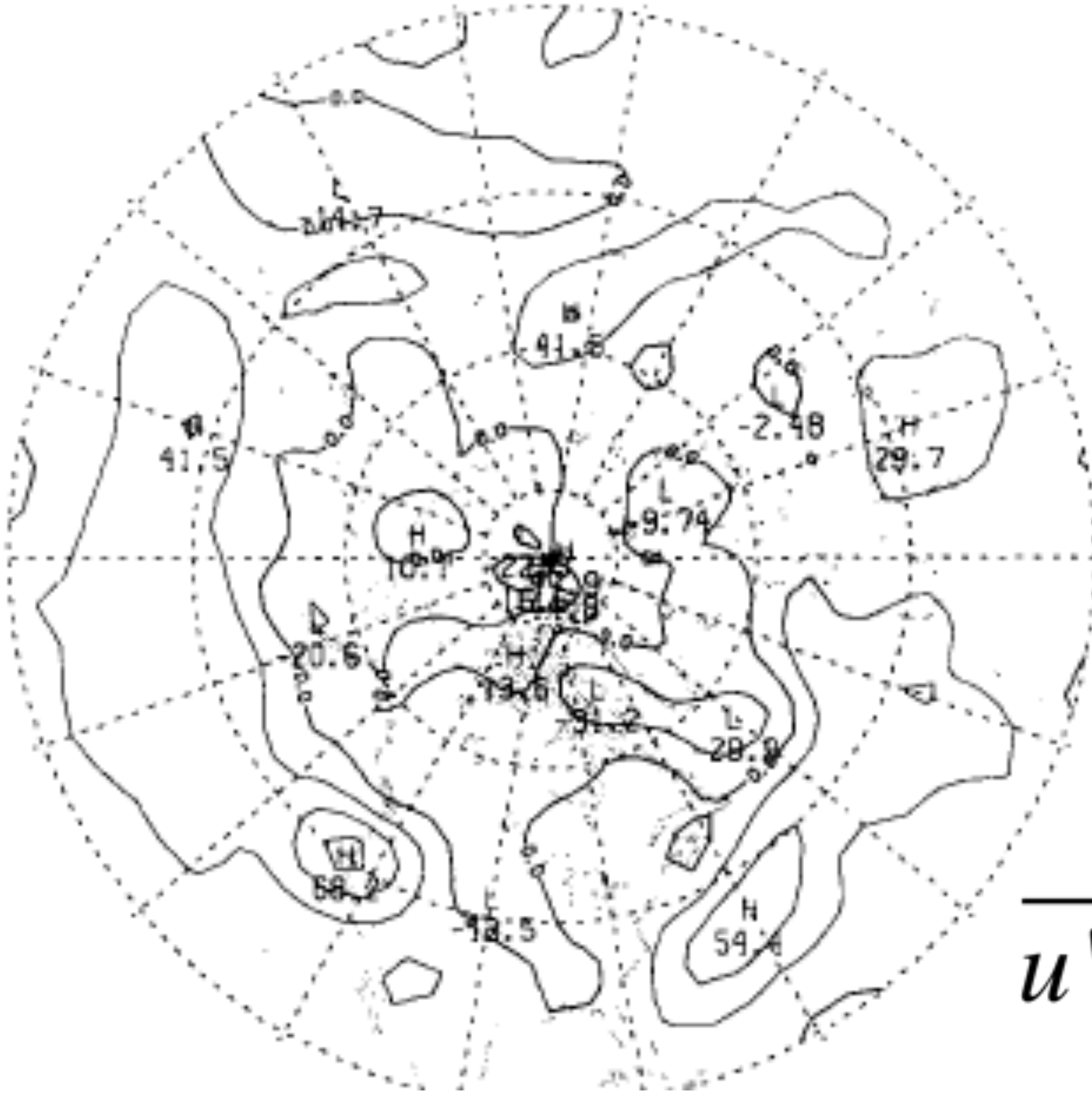
v' colored shading

tan poleward

courtesy of David Ovens

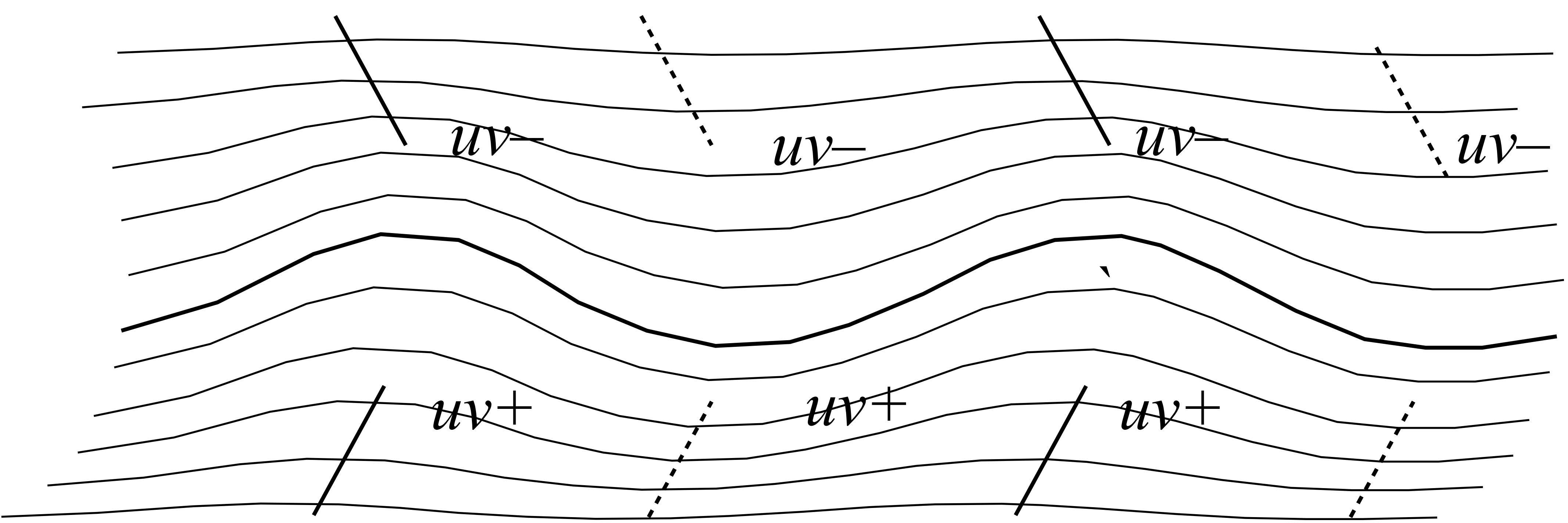


http://www.atmos.washington.edu/~bsmoliak/teleconnection.html

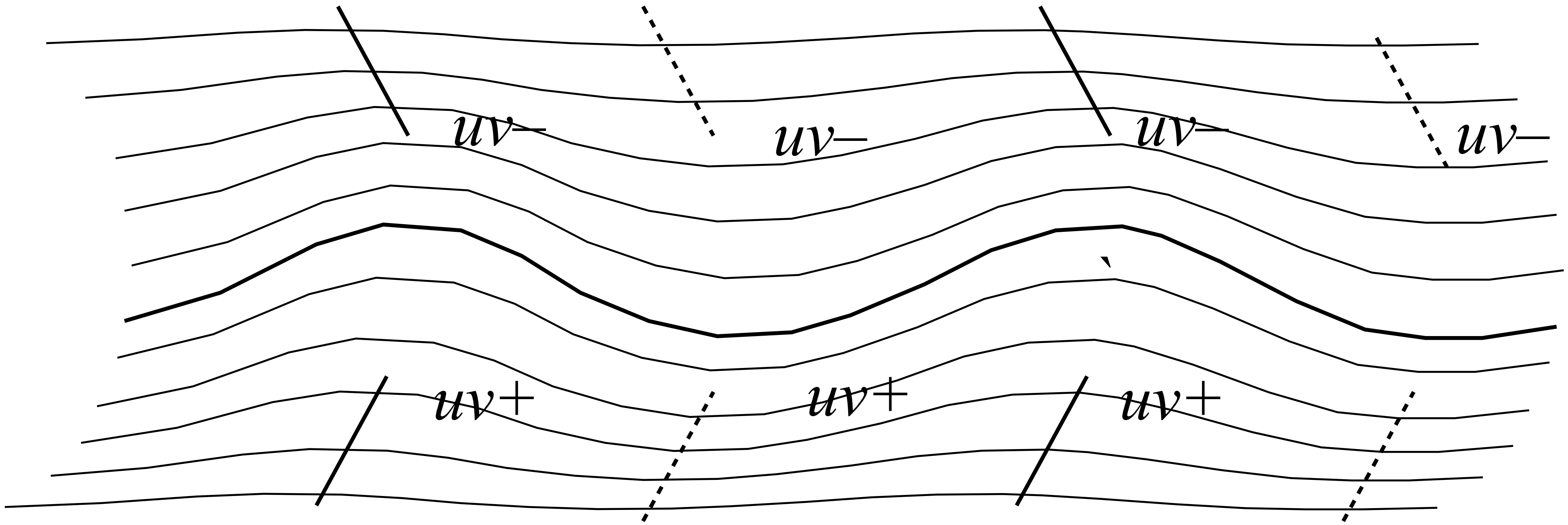


2 to 6.5 day
highpass

$\overline{u'v'}$



$$-\frac{\partial}{\partial y}\left[\overline{u'v'}\right] > 0$$



Using $\overline{u'v'}$ as an example, consider the distributions of

$$\overline{u_g'\Phi'},\ \overline{v_g'\Phi'},\ \overline{u_a'\Phi'},\ \overline{u_g'\zeta'}$$

for a full length paper about this, see Lau and Wallace JAS 1979

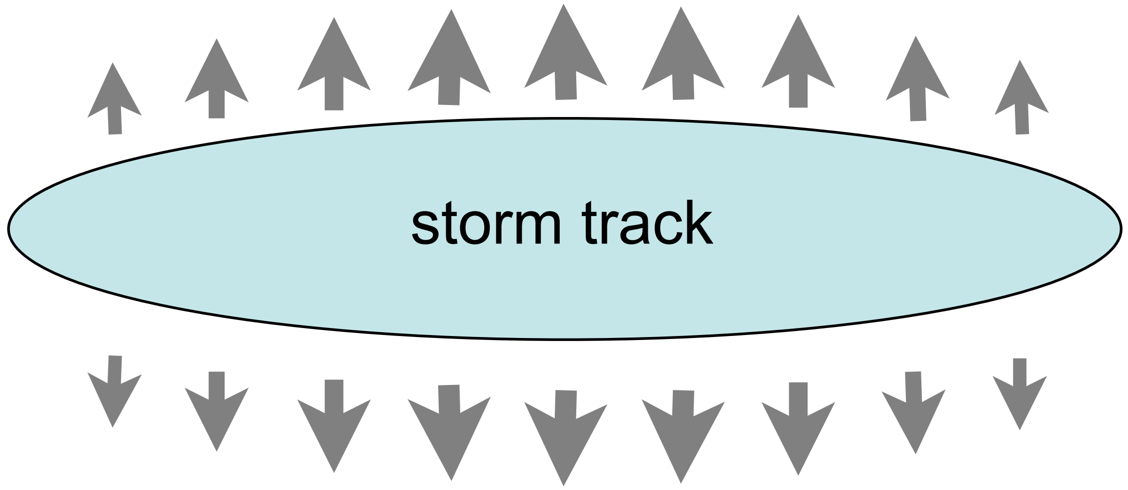
Interaction between the eddies and the time-mean flow in a barotropic flow

$$\frac{\partial \bar{u}}{\partial t} = -\bar{u}\frac{\partial \bar{u}}{\partial x} - \bar{v}\frac{\partial \bar{u}}{\partial y} - \frac{\partial}{\partial x}\overline{u'u'} - \frac{\partial}{\partial y}\overline{u'v'} + fv_a + F_x$$

$$\frac{\partial \bar{v}}{\partial t} = -\bar{u}\frac{\partial \bar{v}}{\partial x} - \bar{v}\frac{\partial \bar{v}}{\partial y} - \frac{\partial}{\partial x}\overline{u'v'} - \frac{\partial}{\partial y}\overline{v'v'} - fu_a + F_y$$

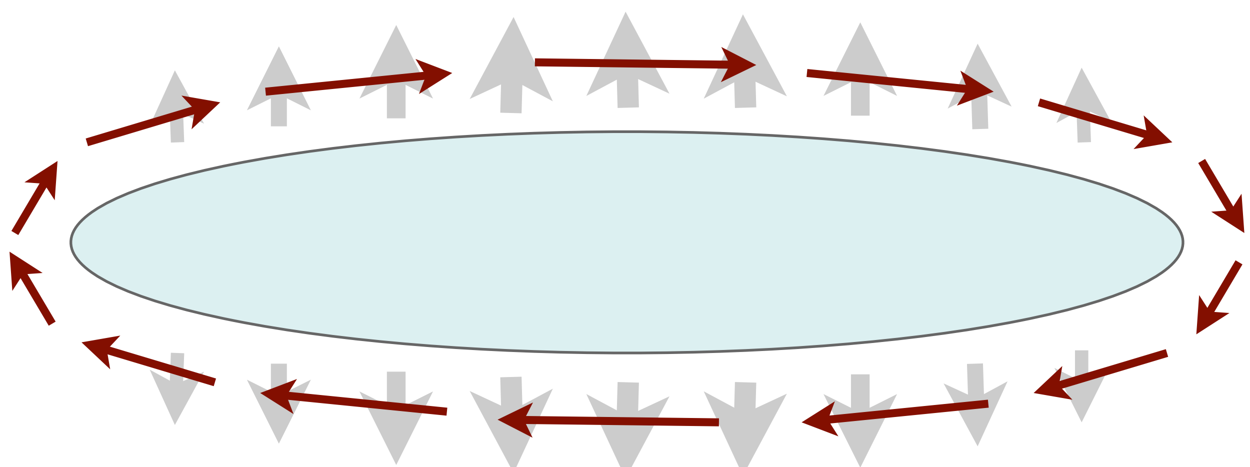
The eddy forcing is difficult to interpret because of the eddy-induced ageostrophic circulation

We can get around this problem by considering the eddy forcing of the vorticity field.

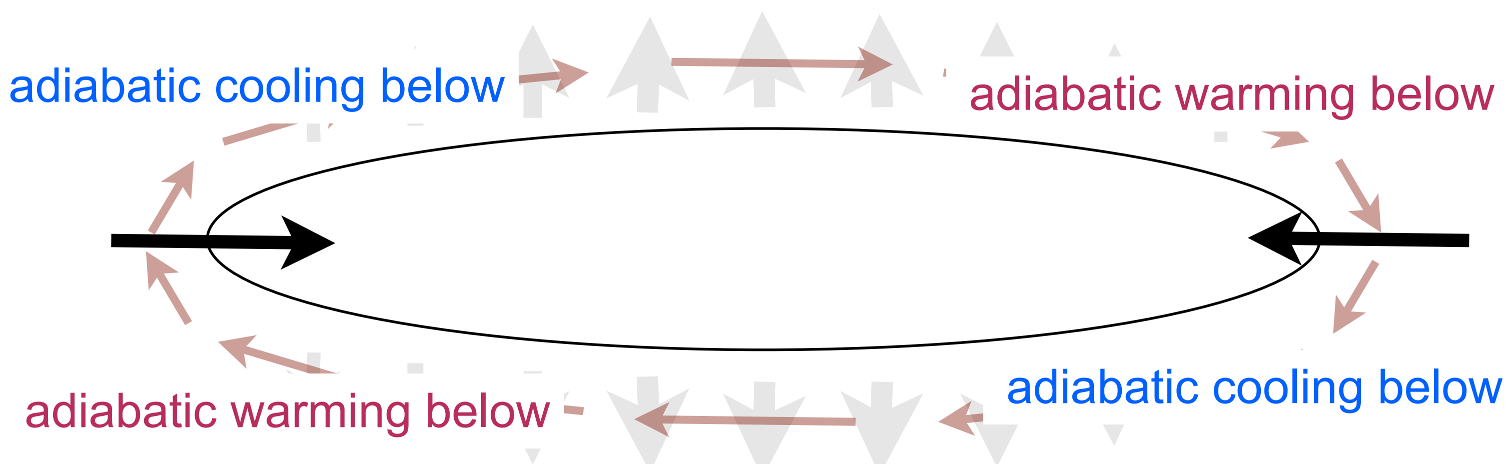


direct effect of eddy forcing

$-\partial/\partial y\left(\overline{v'v'}\right)$ only



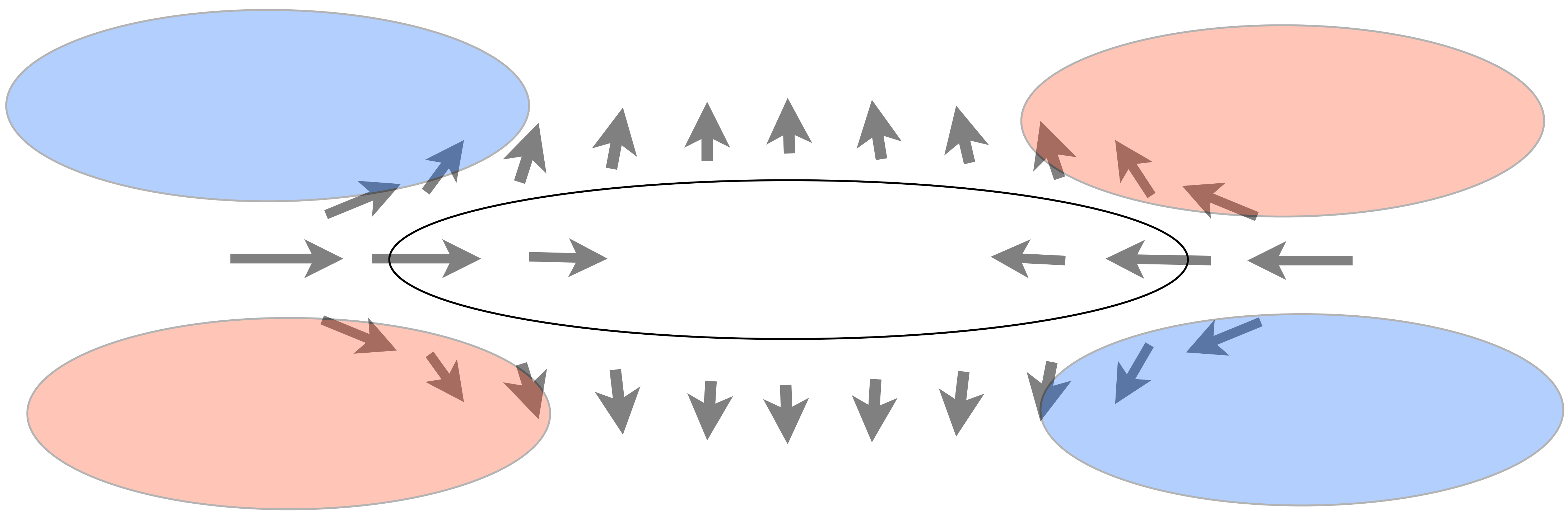
induced ageostrophic circulation



indirect effects of eddy forcing

after Hoskins, James and White JAS 1983

The balanced geostrophic response



Note that the eddies produce an effective *westward transport* of westerly momentum through the storm track

We can see this effect more clearly by considering the vorticity transport by the eddies

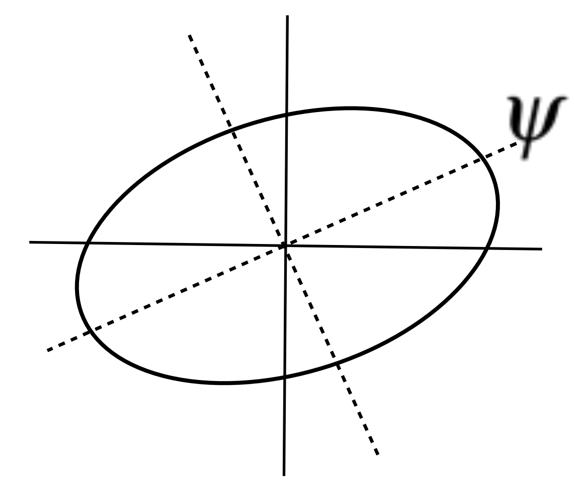
after Hoskins, James and White JAS 1983

The eddy covariance tensor

after Hoskins, James and White JAS 1983

$$\begin{pmatrix} \overline{u'^2} & \overline{u'v'} \\ \overline{u'v'} & \overline{v'^2} \end{pmatrix} = \begin{pmatrix} K & 0 \\ 0 & K \end{pmatrix} + \begin{pmatrix} M & N \\ N & -M \end{pmatrix}$$

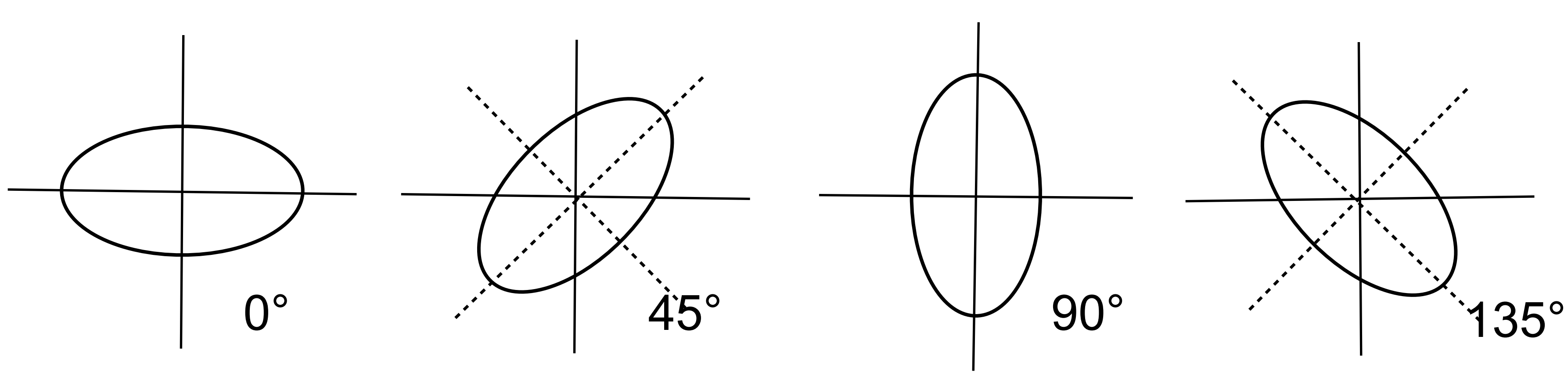
$$K = \frac{\overline{u'^2} + \overline{v'^2}}{2} \qquad M = \frac{\overline{u'^2} - \overline{v'^2}}{2} \qquad N = \overline{u'v'}$$



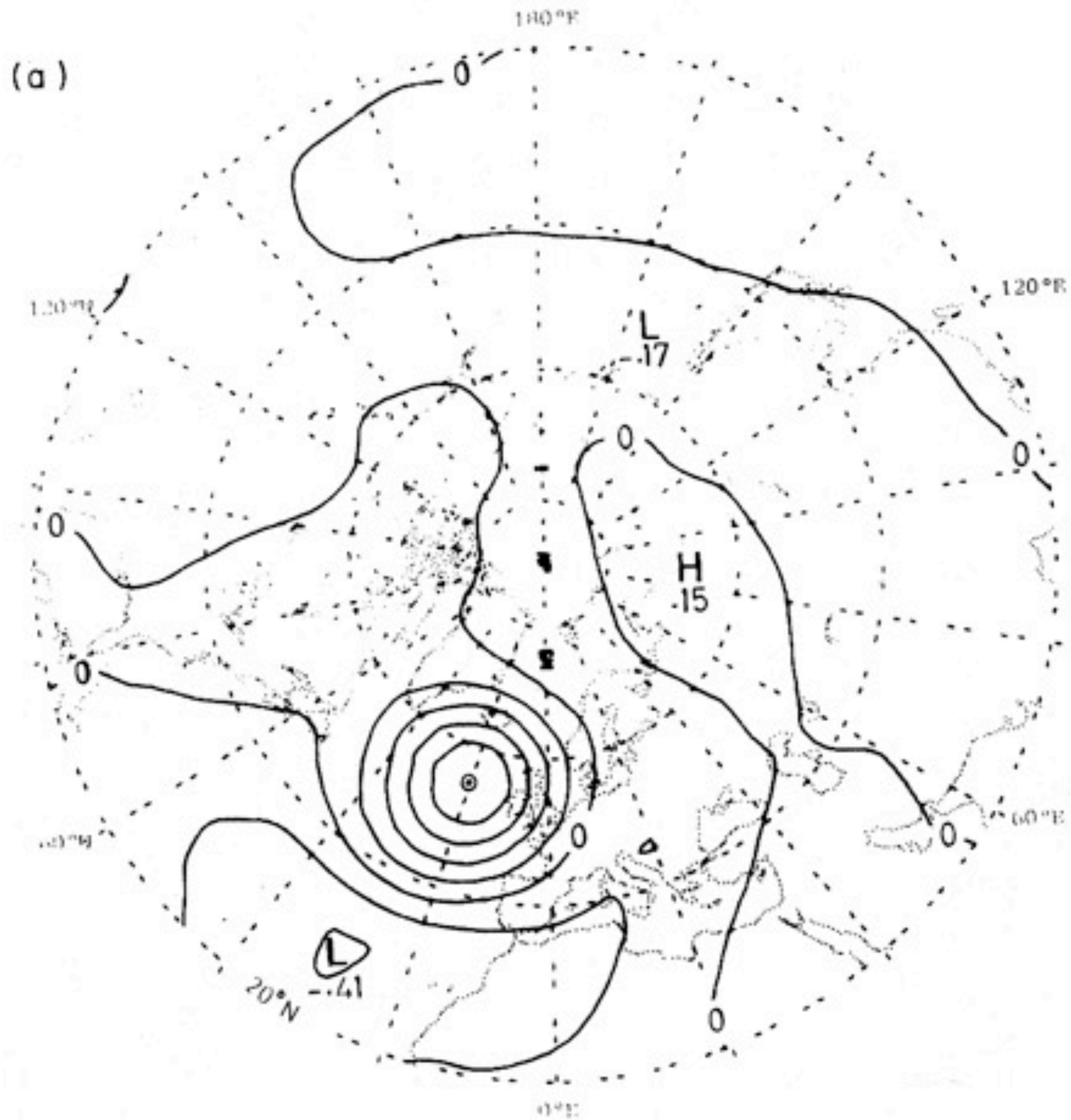
$$\widehat{M} = \sqrt{M^2 + N^2}$$

$\alpha \equiv \widehat{M} / K$ dimensionless coefficient of anisotropy

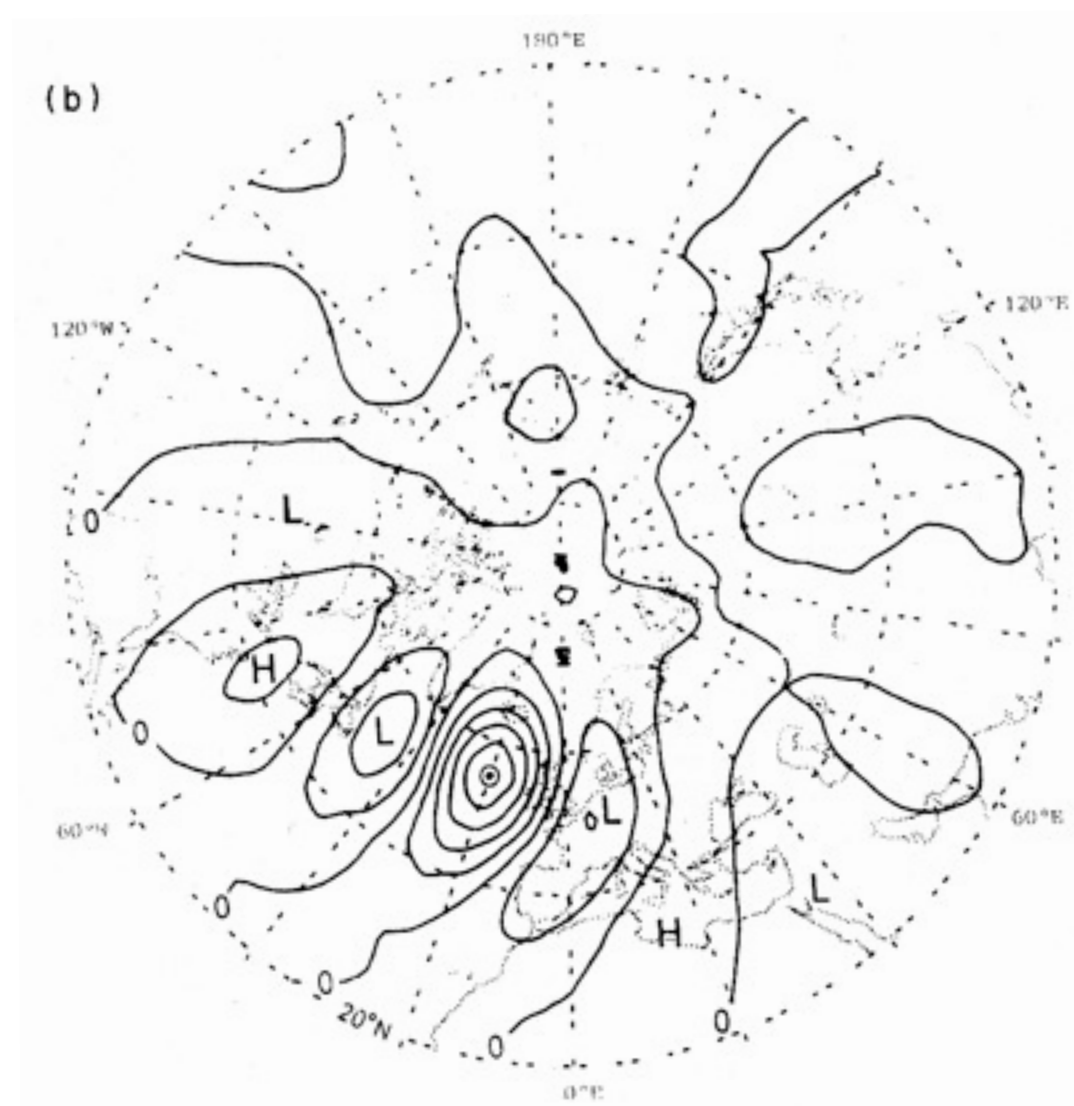
$\psi = \frac{1}{2}\tan^{-1}\frac{N}{M}$ angle of major axis relative to *x* axis



One point correlation maps

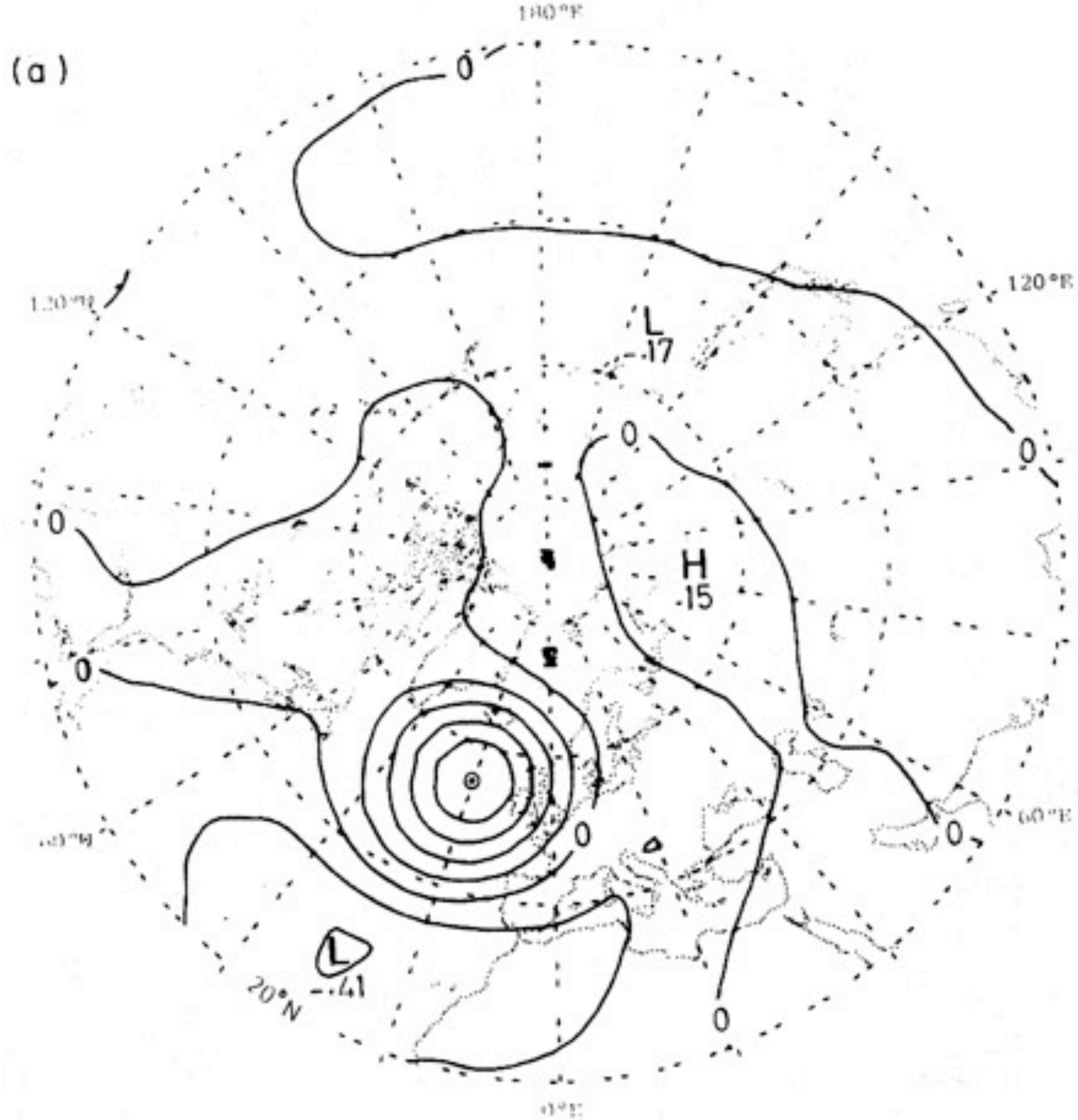


Unfiltered



< 6 d

After Wallace and Blackmon, Large scale Dynamucal Processes in the Atmosphere, 1983



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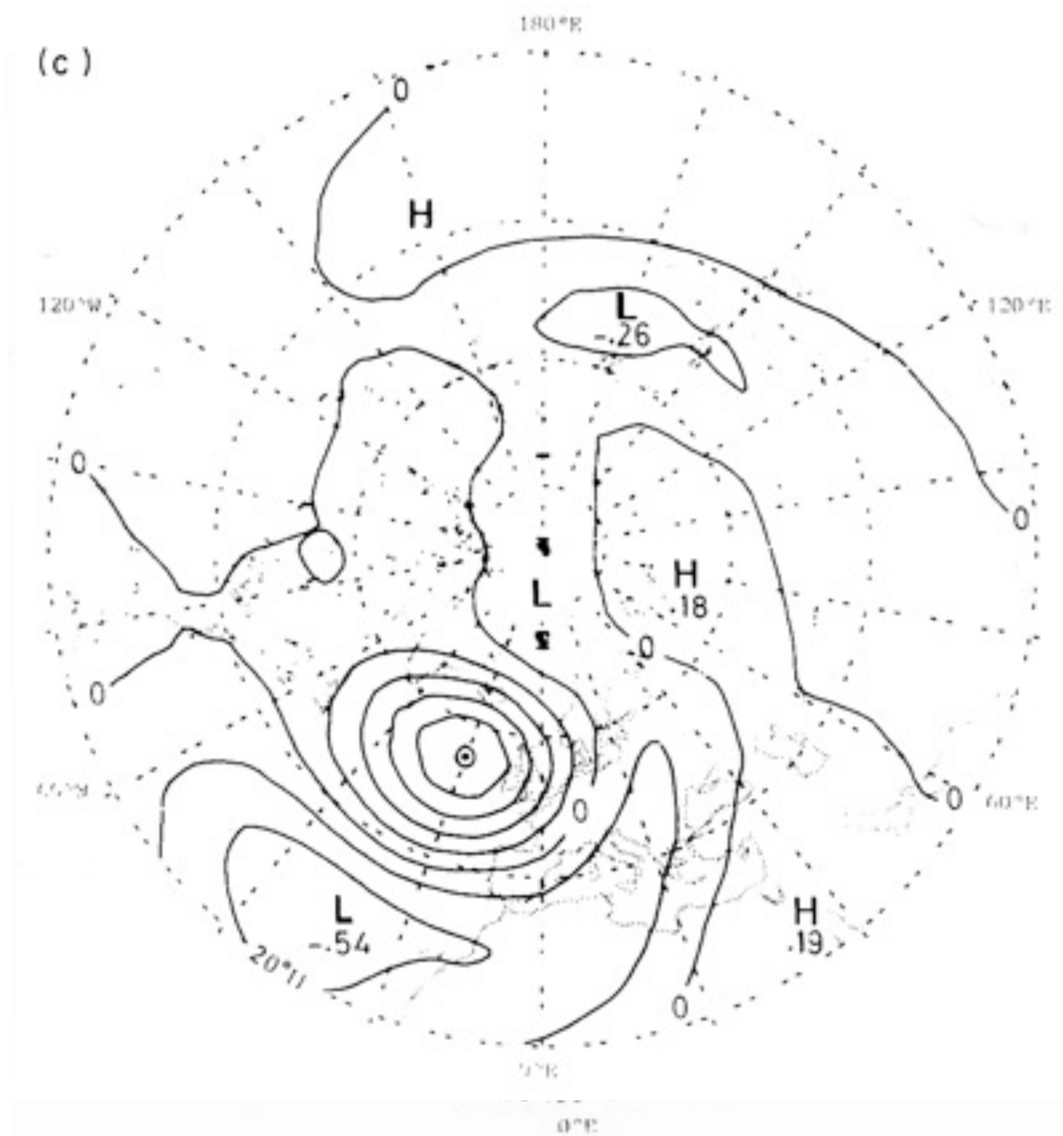
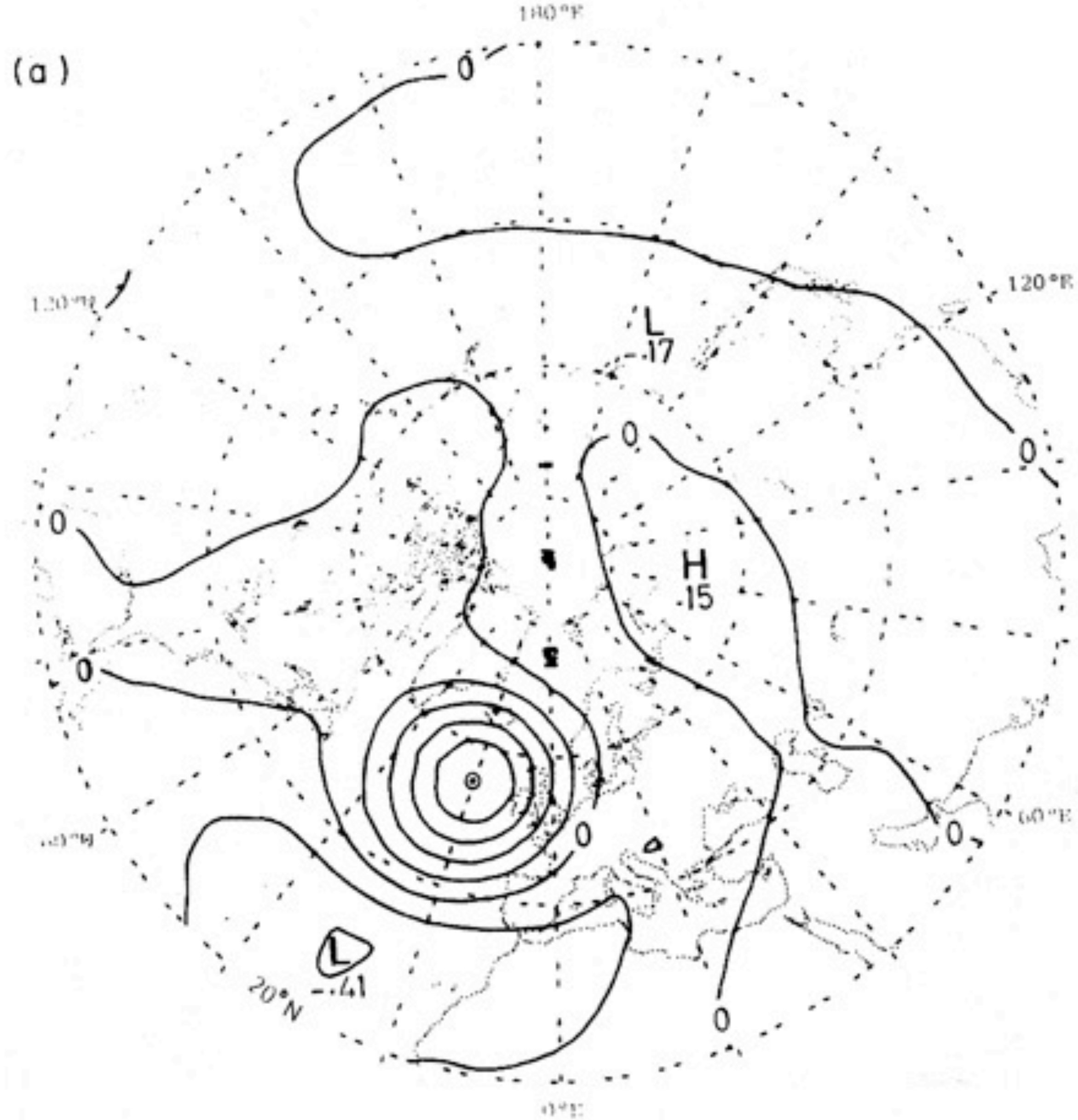
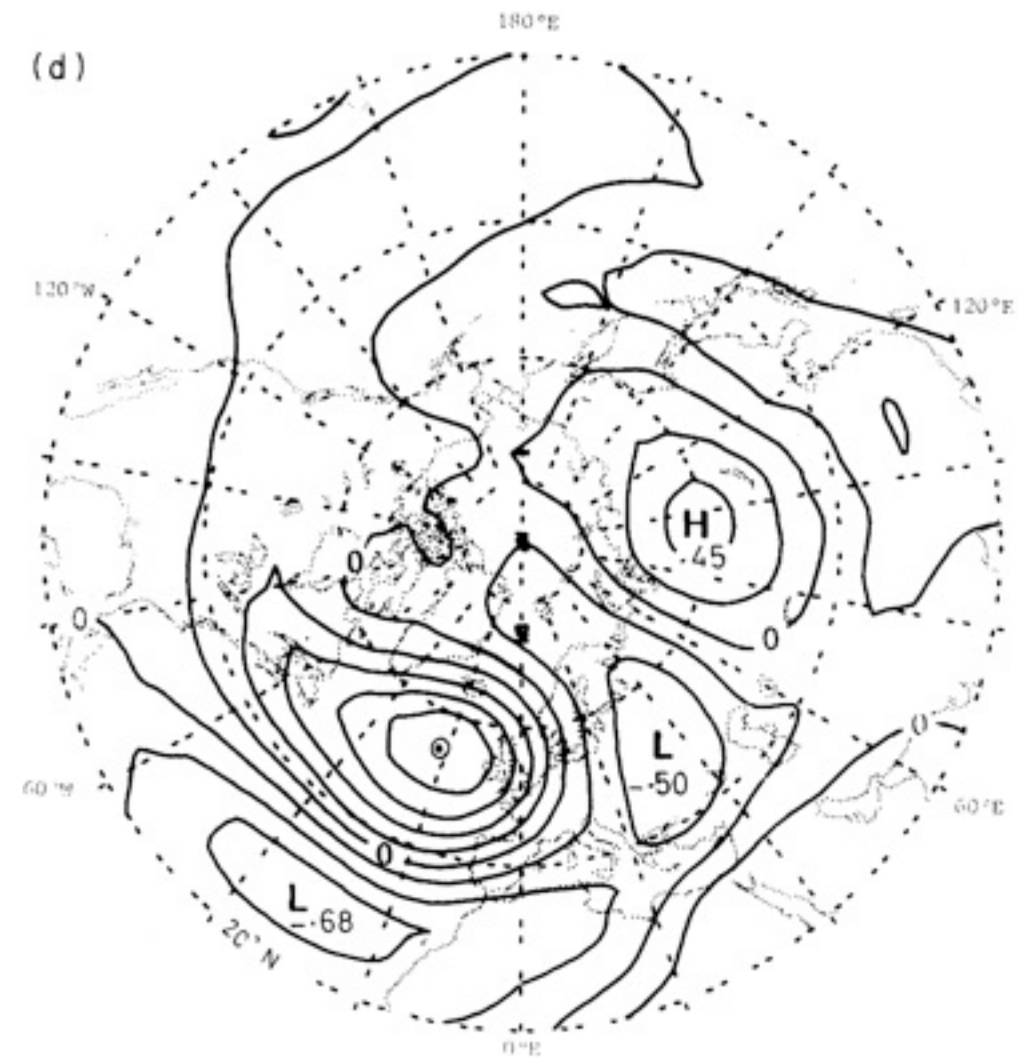


> 10 d

After Wallace and Blackmon, Large scale Dynamucal Processes in the Atmosphere, 1983



Unfiltered



>30 d

After Wallace and Blackmon, Large scale Dynamucal Processes in the Atmosphere, 1983

Feedback of transients upon the background flow

1. Determining how the eddies change the $\overline{q}$ field

Estimate $$\frac{\partial \overline{q}}{\partial t} = -\nabla \cdot \overline{q'\vec{V}'} = -\frac{\partial}{\partial x}\overline{q'u'} - \frac{\partial}{\partial y}\overline{q'v'}$$

2. Use invertibility principle (solving elliptic equation)

For barotropic flow we can use ζ in place of q in (1) and (2) reduces to solving Poisson's equation

$$\frac{\partial \overline{\Phi}}{\partial t} = \nabla^{-2}\left(\frac{\partial \overline{\varsigma}}{\partial t}\right)$$

after Hoskins, James and White JAS 1983

Nondivergent eddies

$$\overline{\varsigma' u'} = -M_y + N_x; \quad \overline{\varsigma' v'} = -M_x - N_y$$

$$\frac{\partial \bar{\varsigma}}{\partial t} = -\nabla \cdot \overline{\vec{V}'\varsigma} = 2M_{xy} - N_{xx} + N_{yy} \qquad (1)$$

but the features in the $\overline{u'v'}$ field tend to be zonally elongated along storm tracks. It follows that $N_{xx} << N_{yy}$ so (1) can be rewritten as

$$\frac{\partial \bar{\varsigma}}{\partial t} = -\nabla \cdot \overline{\vec{V}'\varsigma'} \simeq \frac{\partial}{\partial y}\left(\frac{\partial}{\partial x} 2M + \frac{\partial}{\partial y} N \right) \qquad (2)$$

or

$$\frac{\partial \bar{\varsigma}}{\partial t} \simeq -\frac{\partial}{\partial y}\left(\nabla \cdot \vec{E}\right) \quad \text{where} \quad \vec{E} \equiv \left(-2M, -N\right) \qquad (3)$$

Features in the mean flow also tend to be zonally oriented, so

$$\frac{\partial \bar{u}}{\partial y} >> \frac{\partial \bar{v}}{\partial x}$$

Hence, (3) can be written as $$\frac{\partial}{\partial t}\left(-\frac{\partial \bar{u}}{\partial y}\right) = -\frac{\partial}{\partial y}\left(\nabla \cdot \vec{E}\right)$$

or $$\frac{\partial}{\partial y}\left(\frac{\partial \bar{u}}{\partial t}\right) = \frac{\partial}{\partial y}\left(\nabla \cdot \vec{E}\right)$$

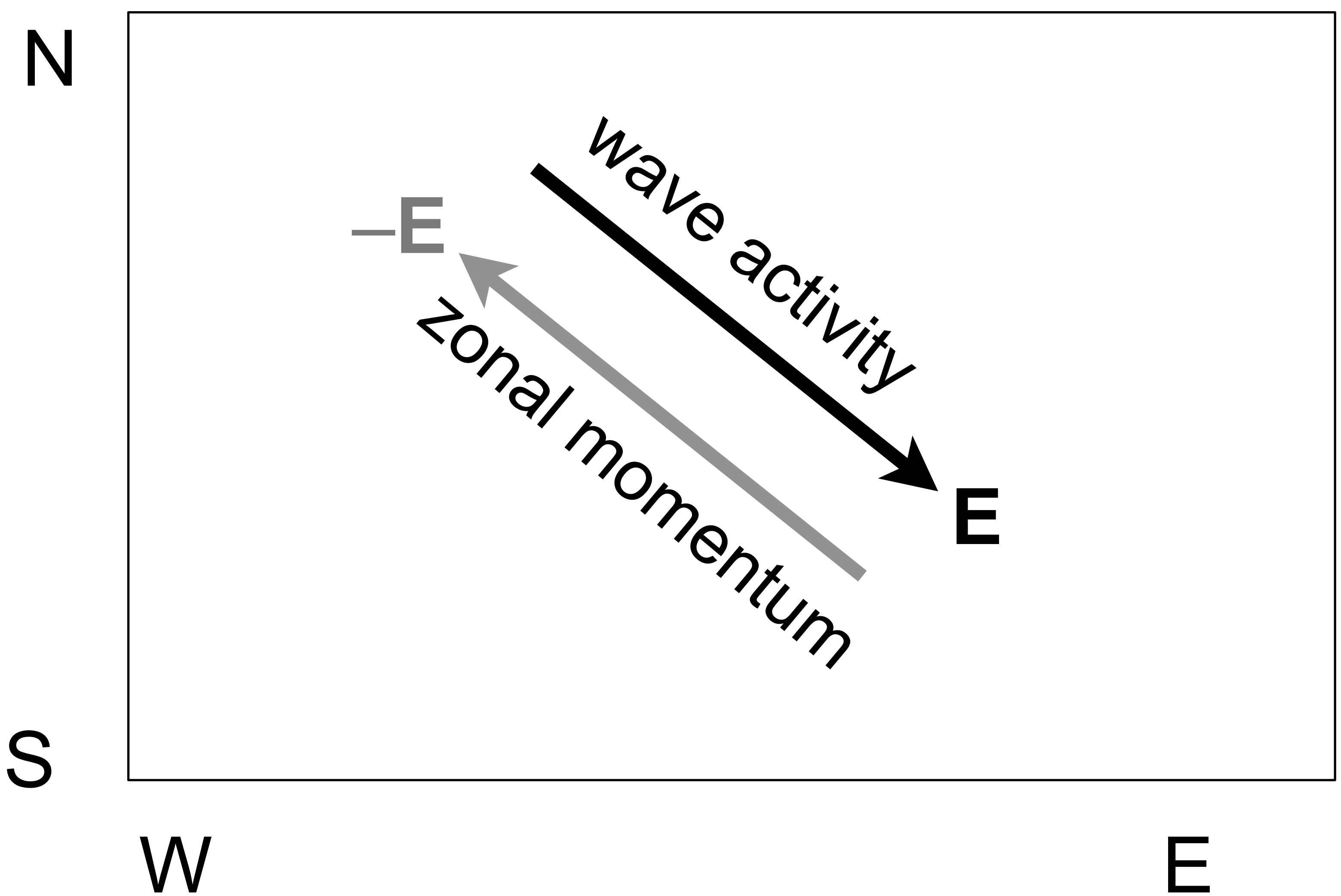
It follows that $$\frac{\partial \bar{u}}{\partial t} = \nabla \cdot \vec{E}$$

where $$\vec{E} \equiv -\left(\overline{u'^2} - \overline{v'^2},\ \overline{u'v'}\right)$$

The "*E* vector" in this horizontal (barotropic) flow, with sign reversed, traces the 2-dimensional flux of *u* by the transient eddies.

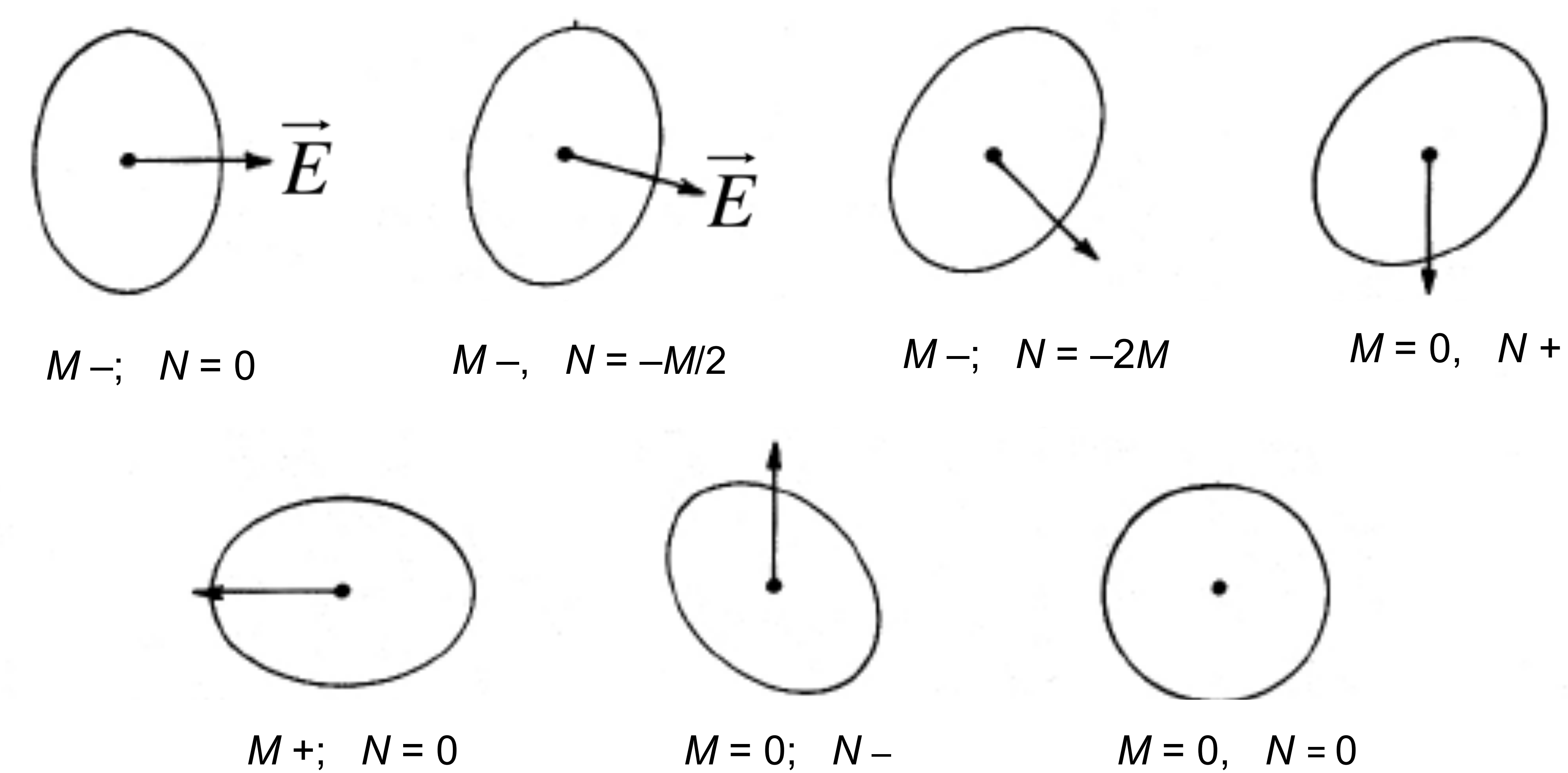
Analogous to the Eliassen-Palm flux vector in the meridional plane.

Like the EP flux, it can also be identified with the *group velocity*

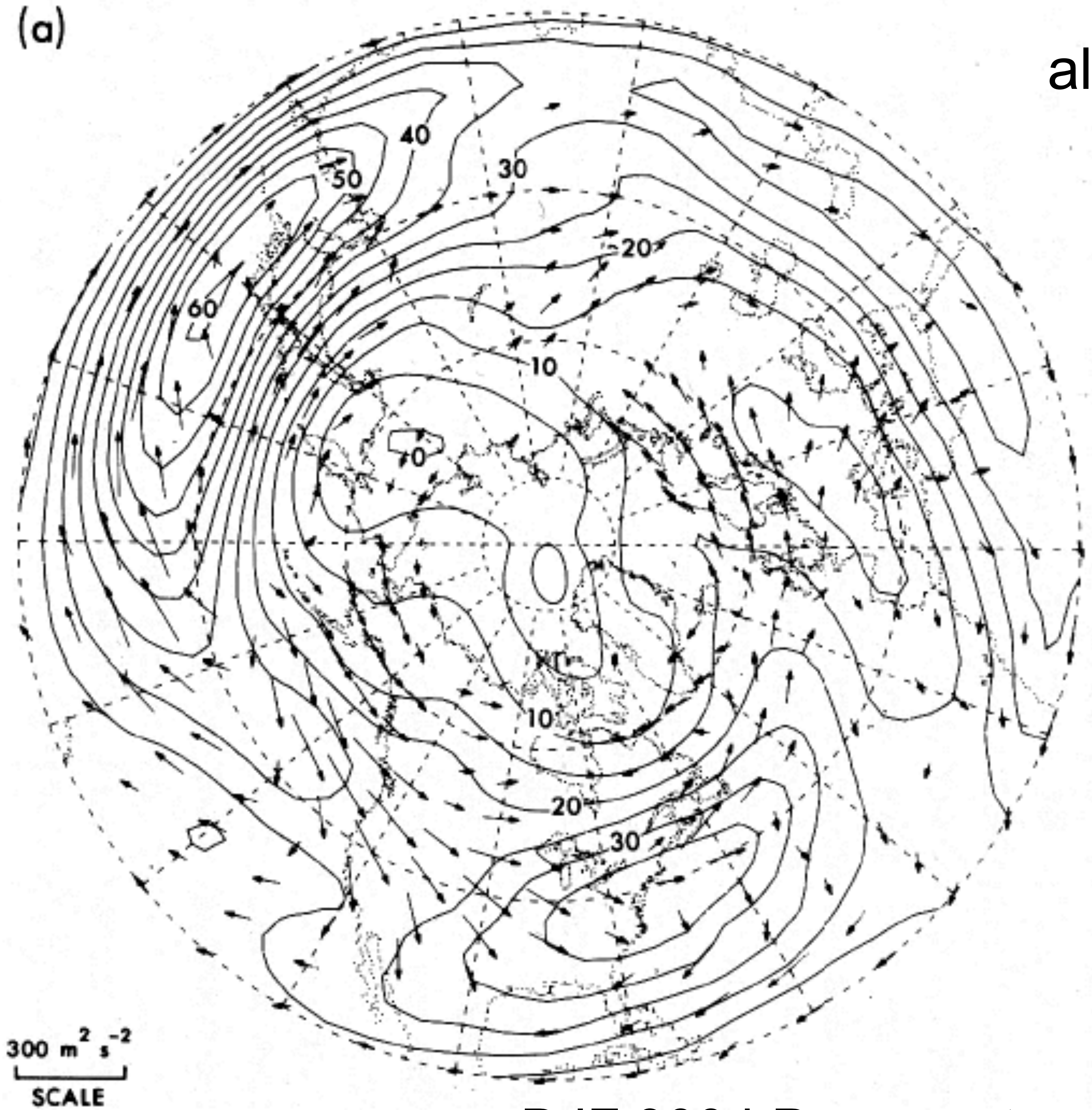


$$\vec{E} \equiv -\left(\overline{u'^2} - \overline{v'^2},\ \overline{u'v'}\right)$$

involves the anisotropy of the eddies.



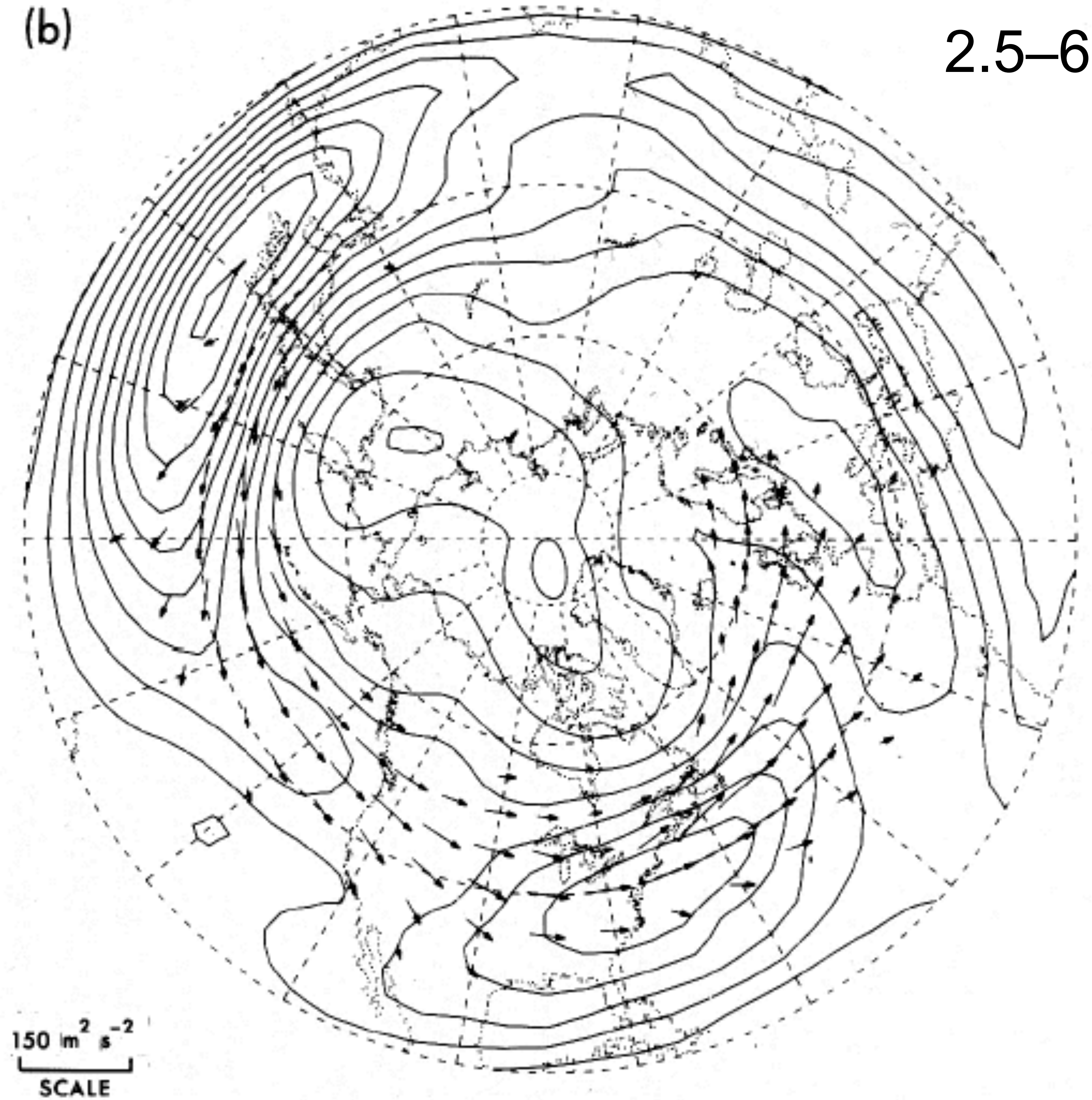
all frequencies



DJF 300 hPa. *u* contours; E vectors

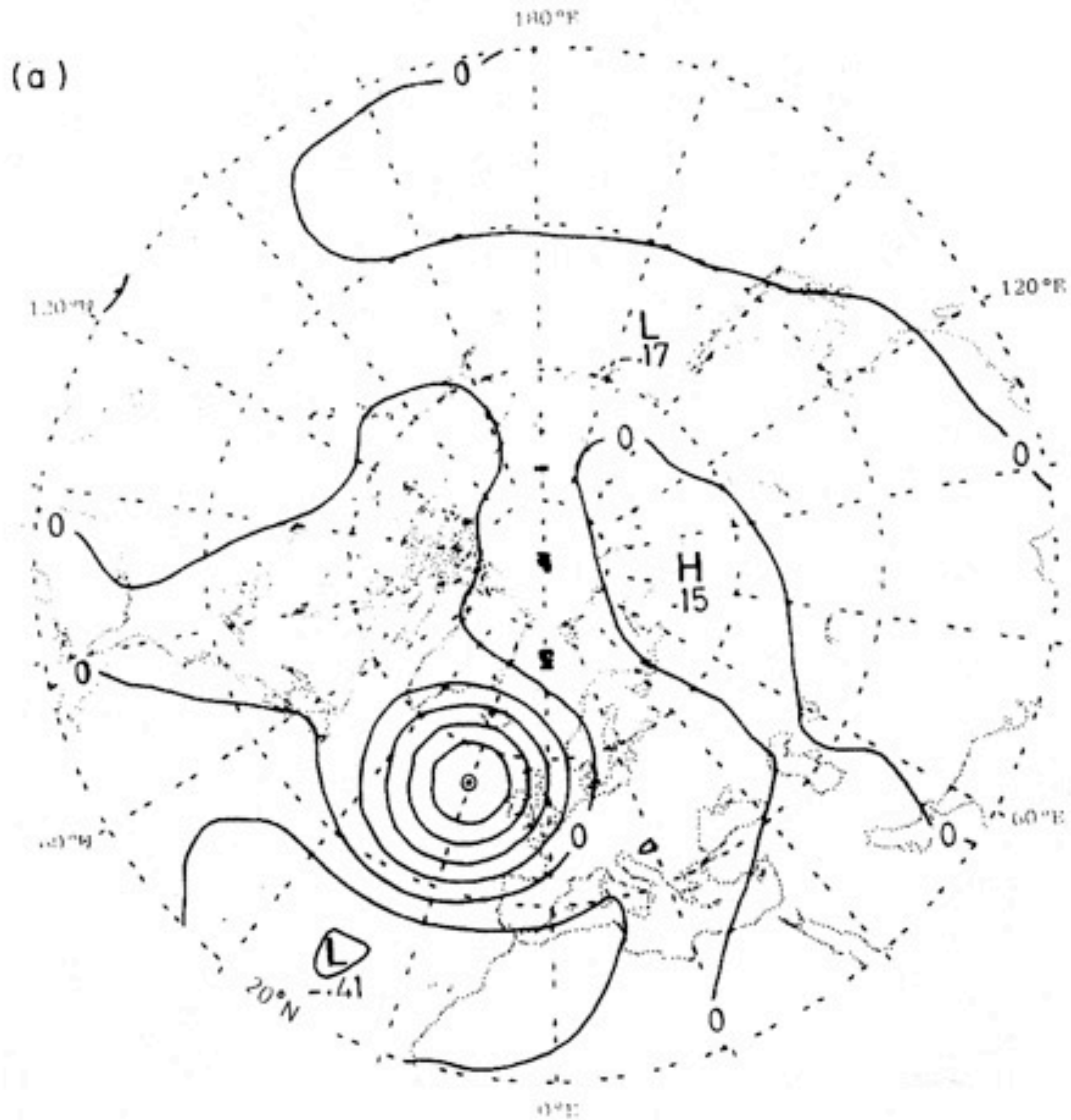
after Wallace and Lau, Issues in Atmospheric and Oceanic Modeling 1985

2.5–6 d highpass

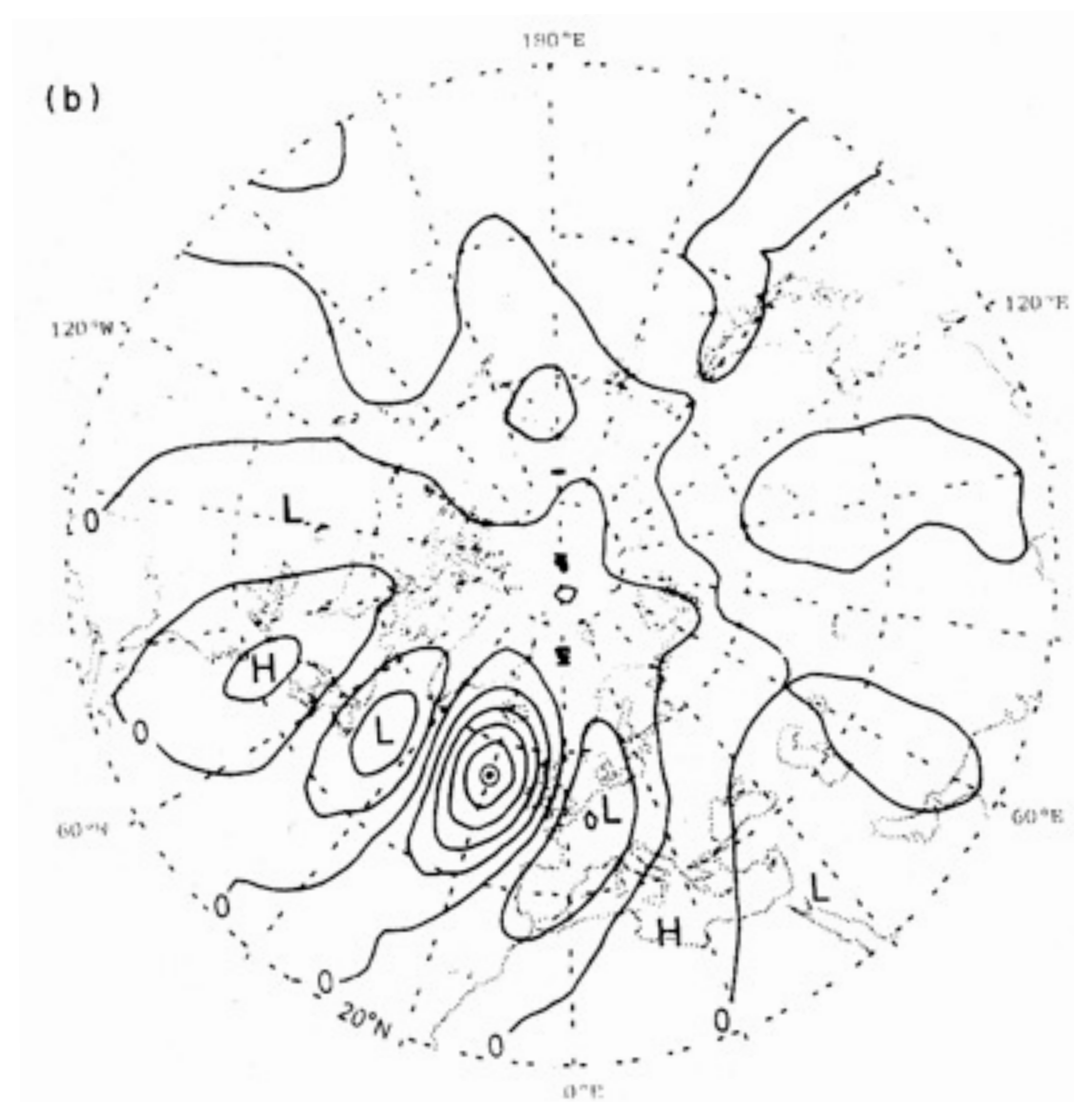


after Wallace and Lau, Issues in Atmospheric and Oceanic Modeling 1985

One point correlation maps



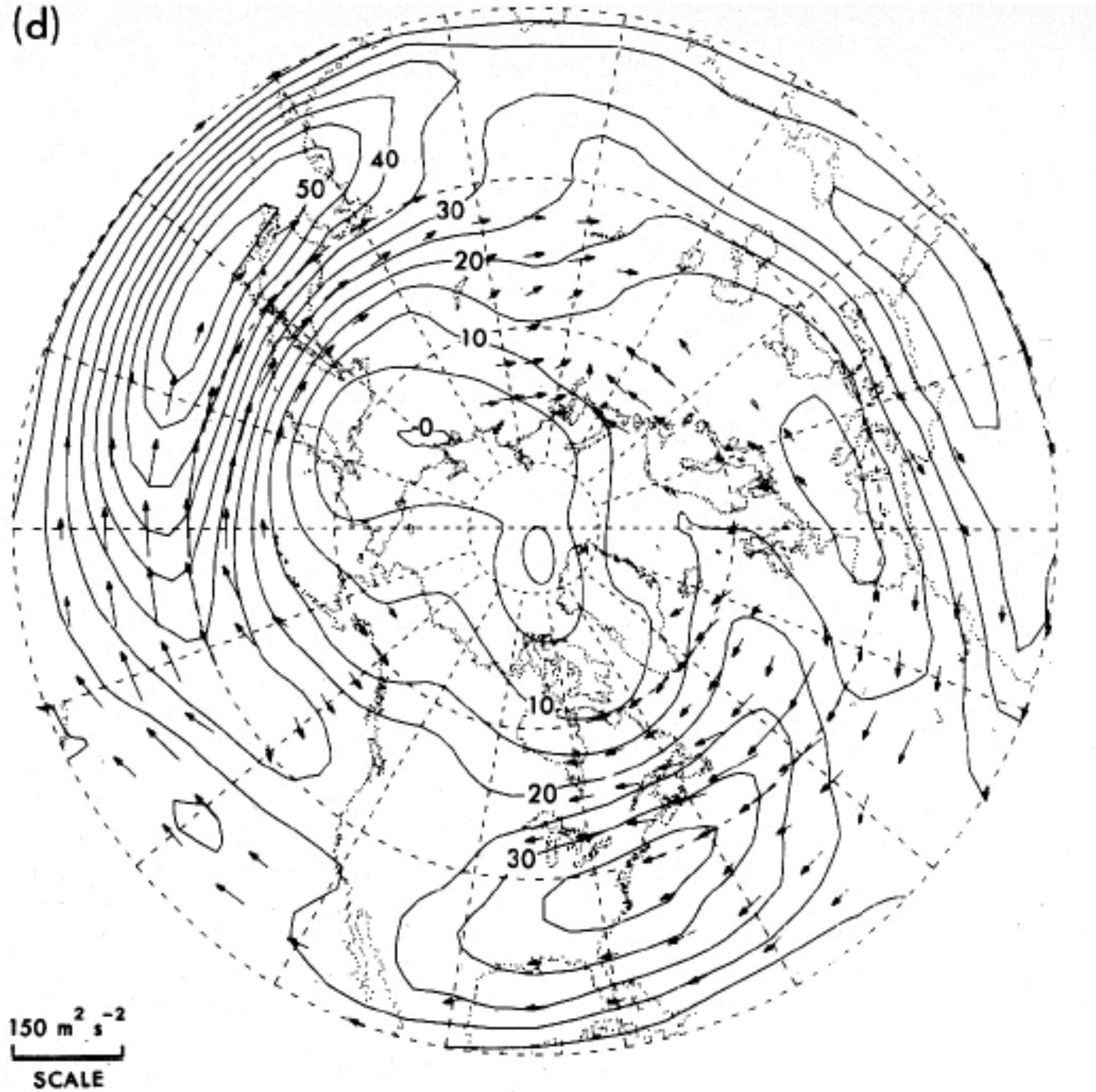
Unfiltered



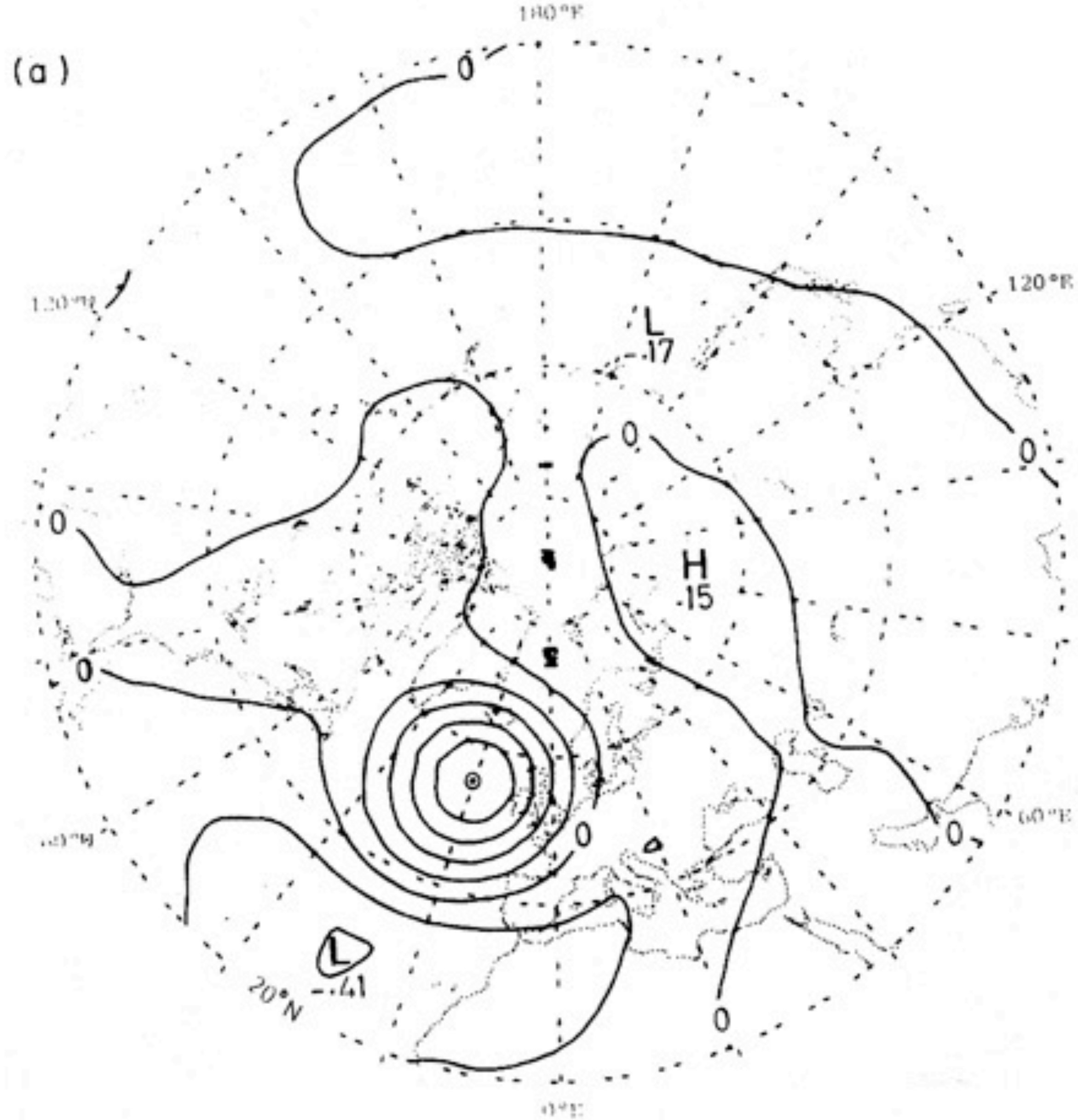
< 6 d

After Wallace and Blackmon, Large scale Dynamucal Processes in the Atmosphere, 1983

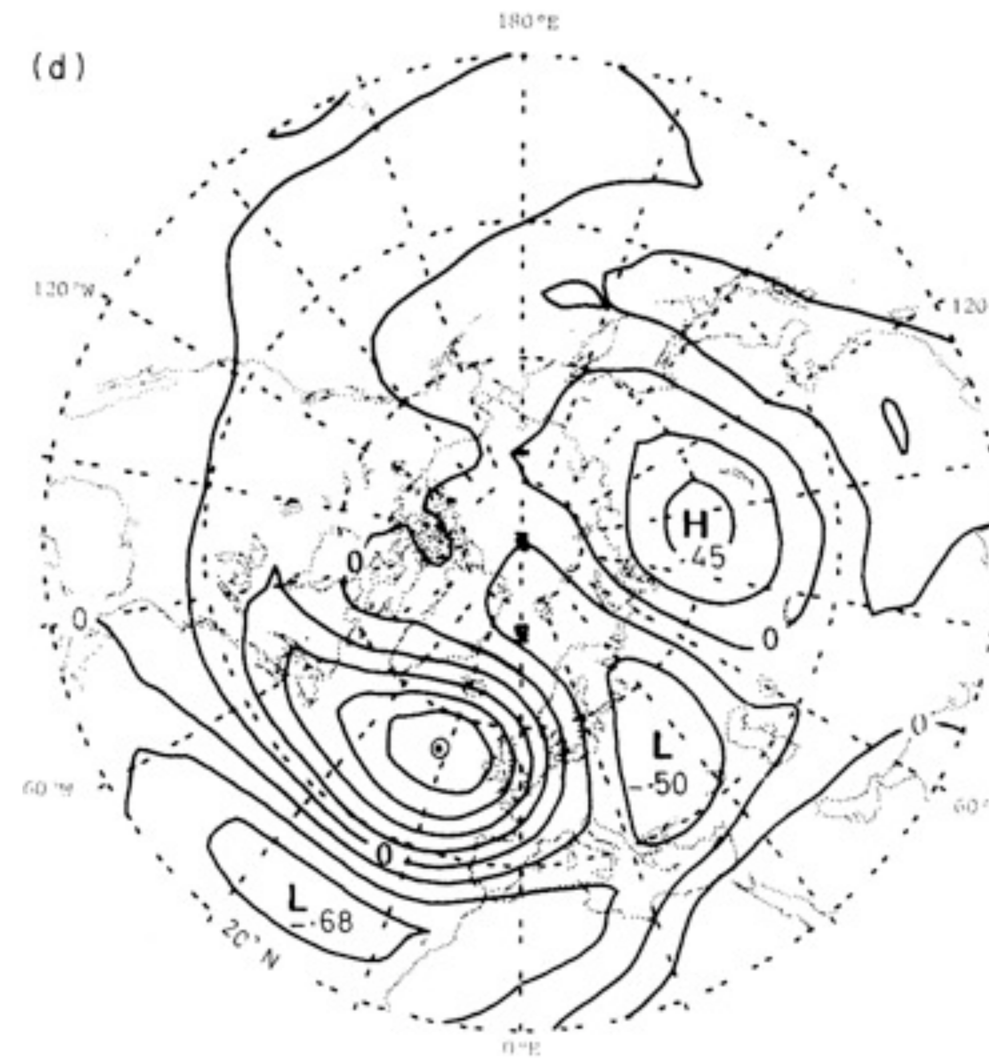
30 d lowpass



after Wallace and Lau, Issues in Atmospheric and Oceanic Modeling 1985

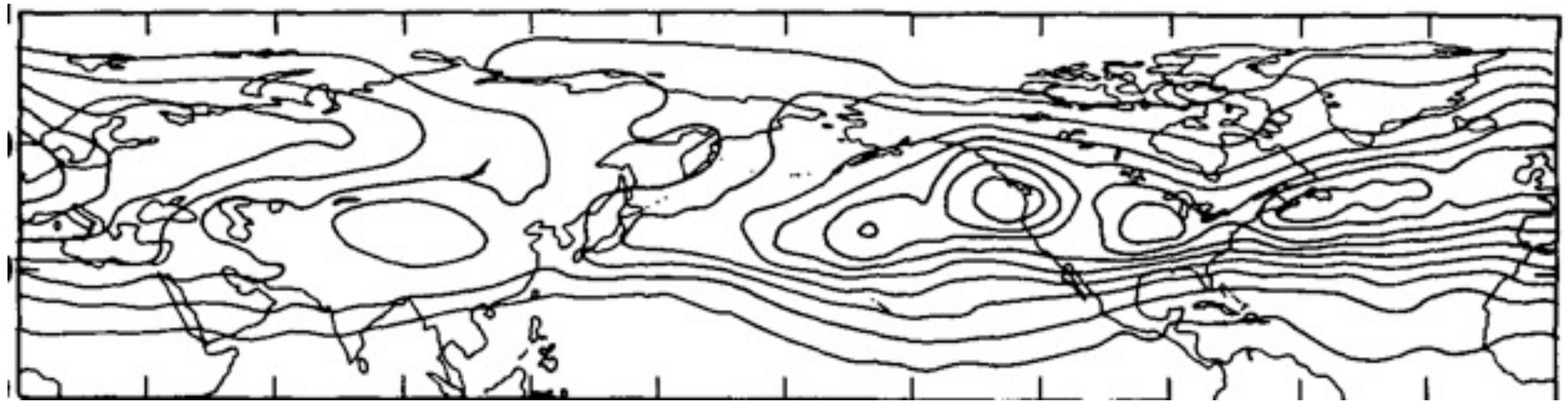


Unfiltered

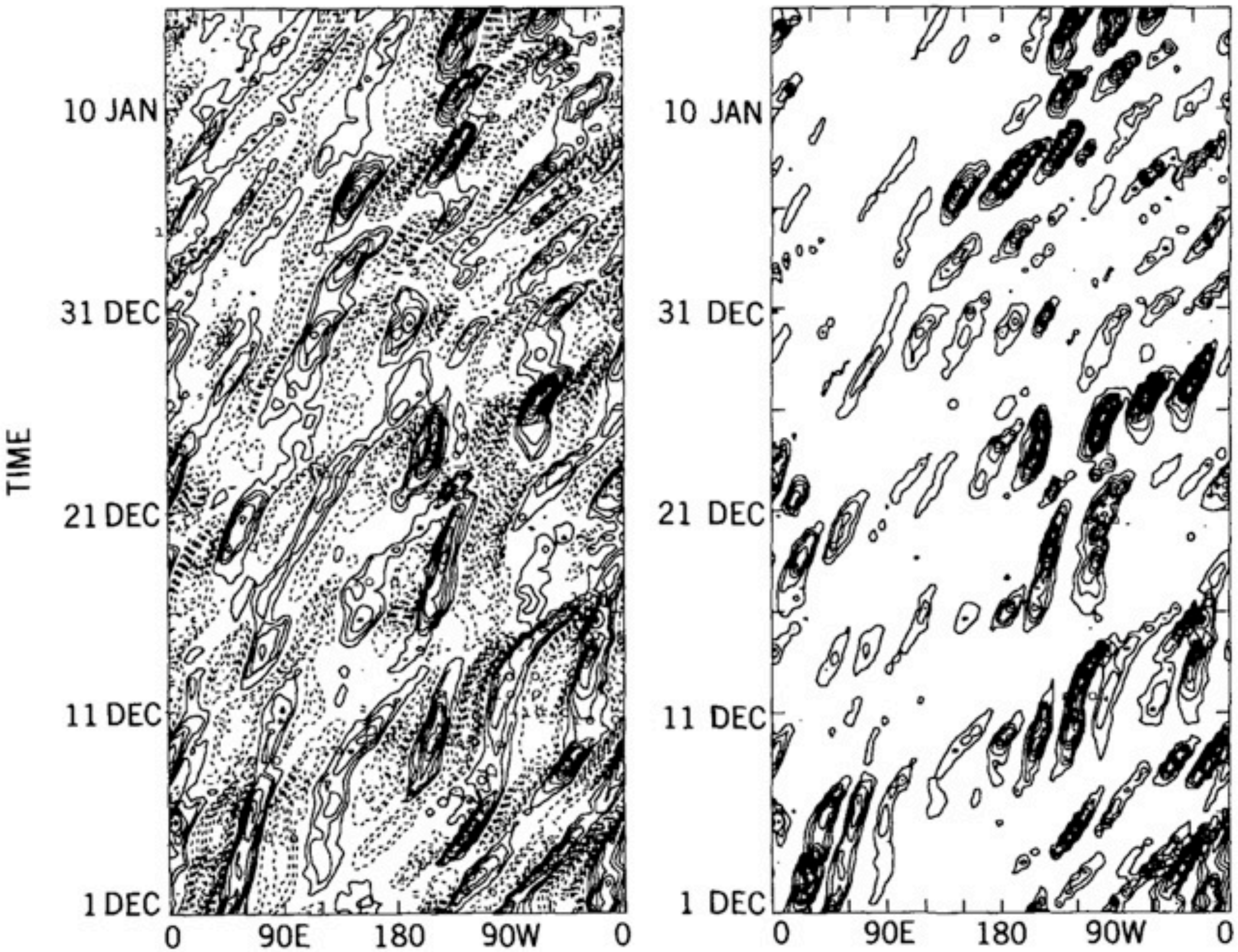


>30 d

After Wallace and Blackmon, Large scale Dynamucal Processes in the Atmosphere, 1983



$\overline{v'^2}_{300hPa}$



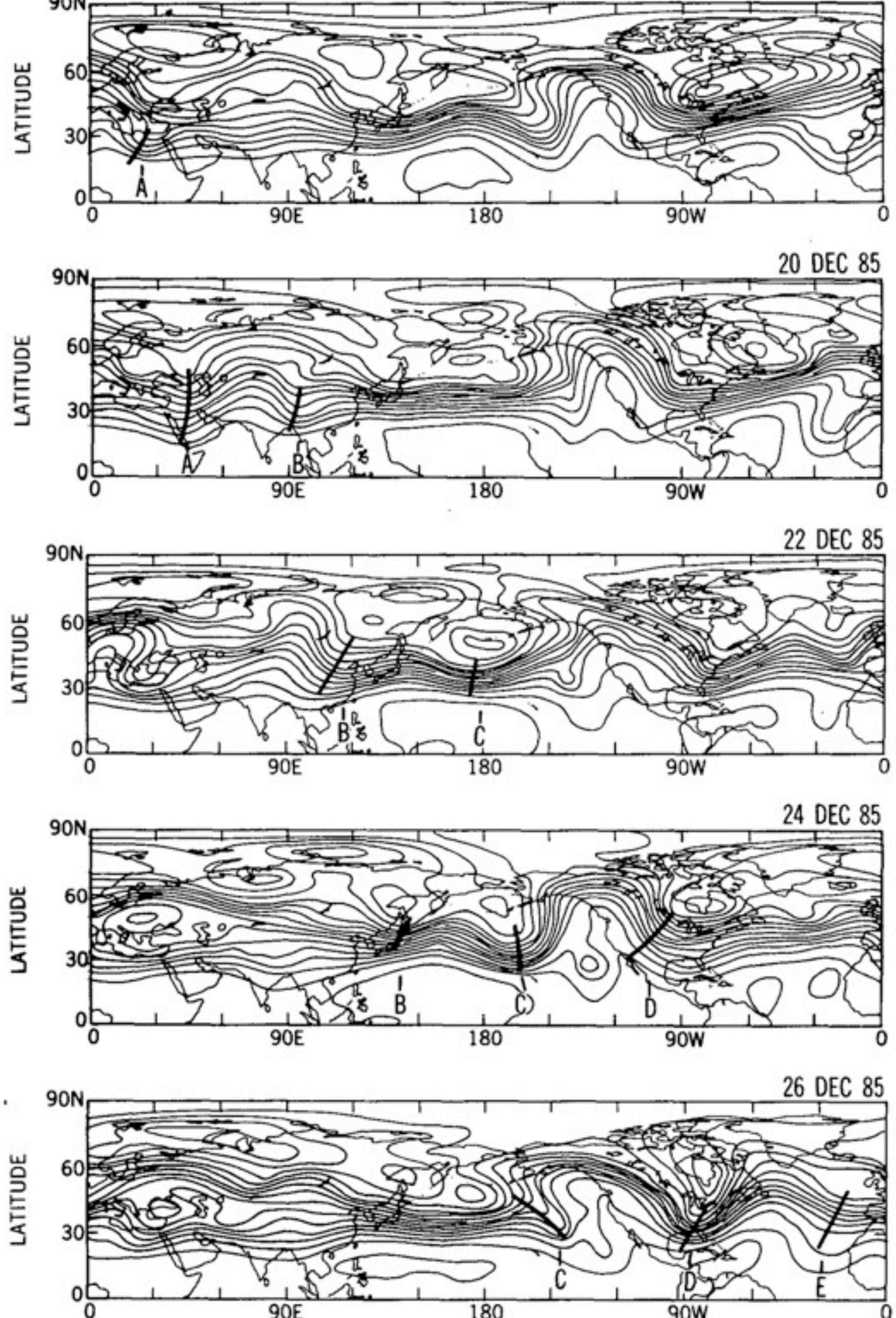
v_{300hPa} $\overline{v'^2}_{300hPa}$

time-longitude sections

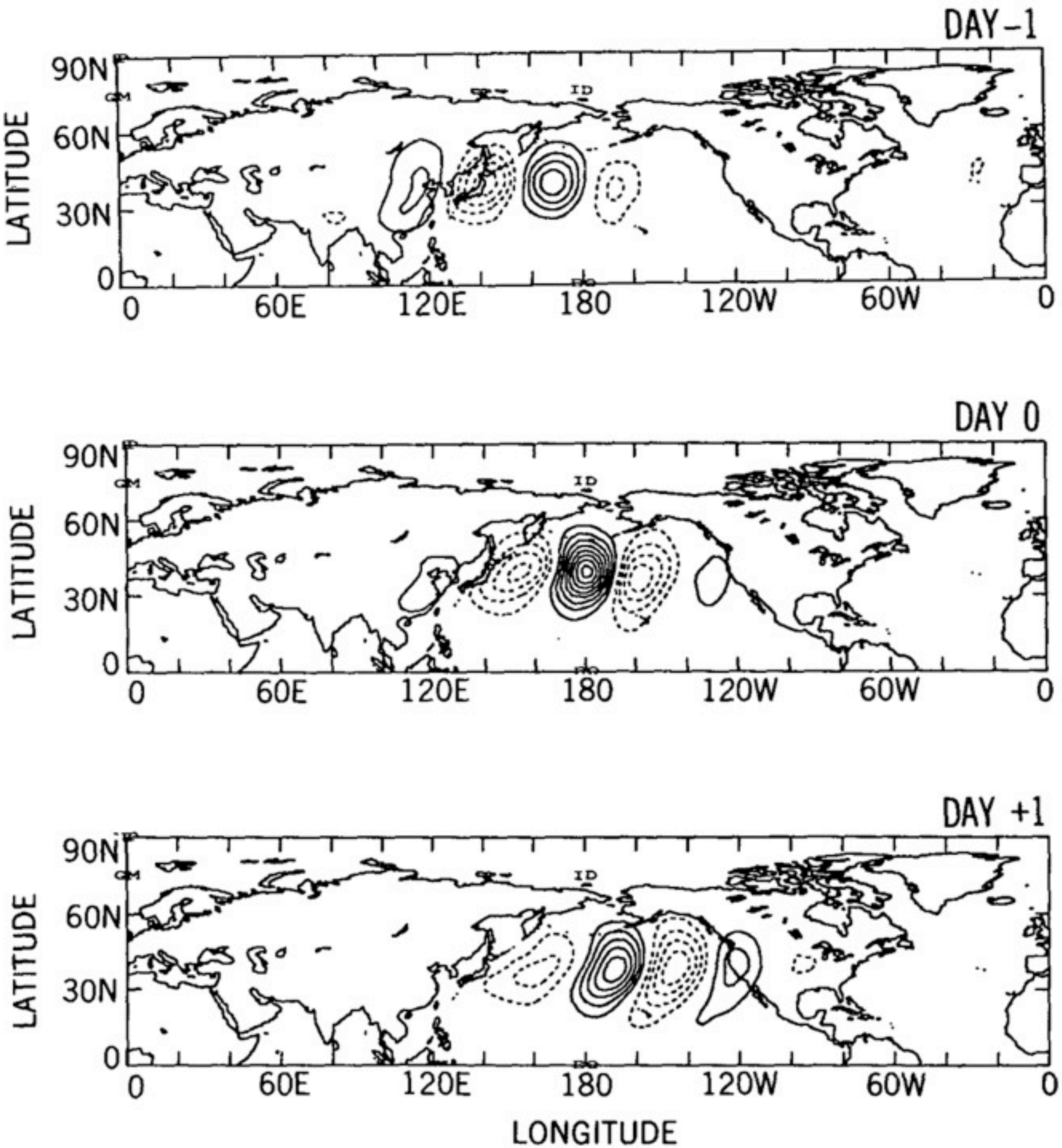
30° to 60°N

1985-86

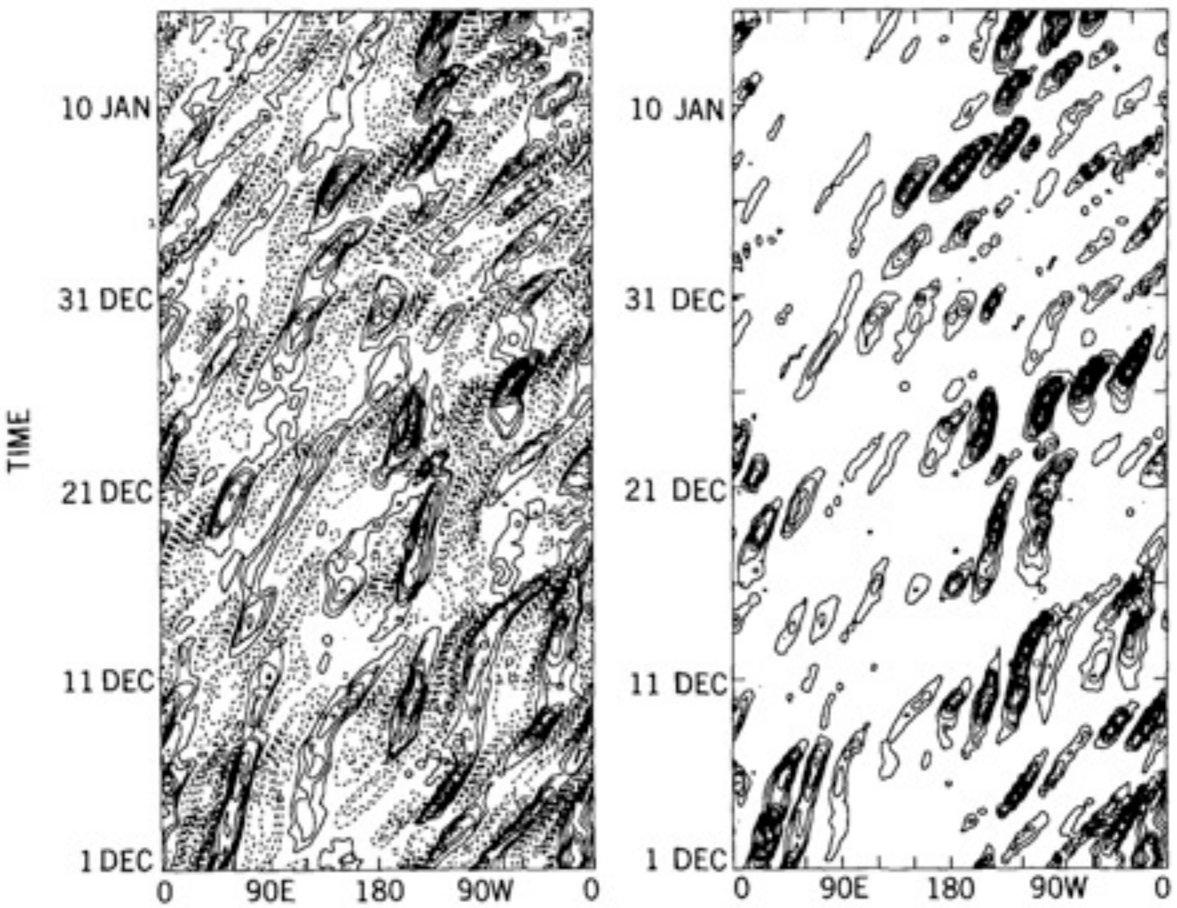
Edmund K.M. Chang,
J. Atmos. Sci. 1993



90N
60
30
0
LATITUDE
0
90E
180
90W
0
A
20 DEC 85
A
B
22 DEC 85
B
C
24 DEC 85
B
C
D
26 DEC 85
C
D
E

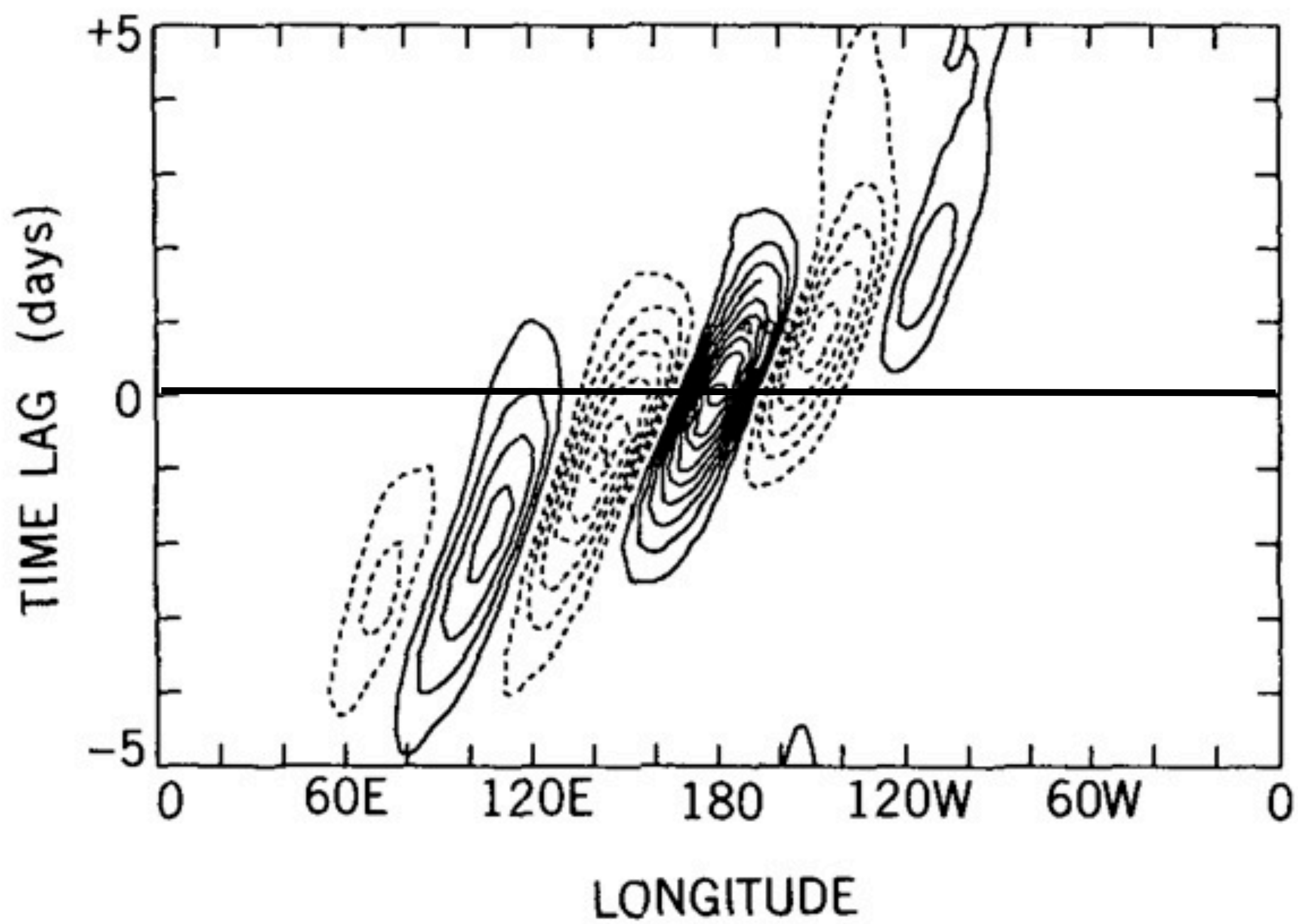


Edmund K.M. Chang,
J. Atmos. Sci. 1993

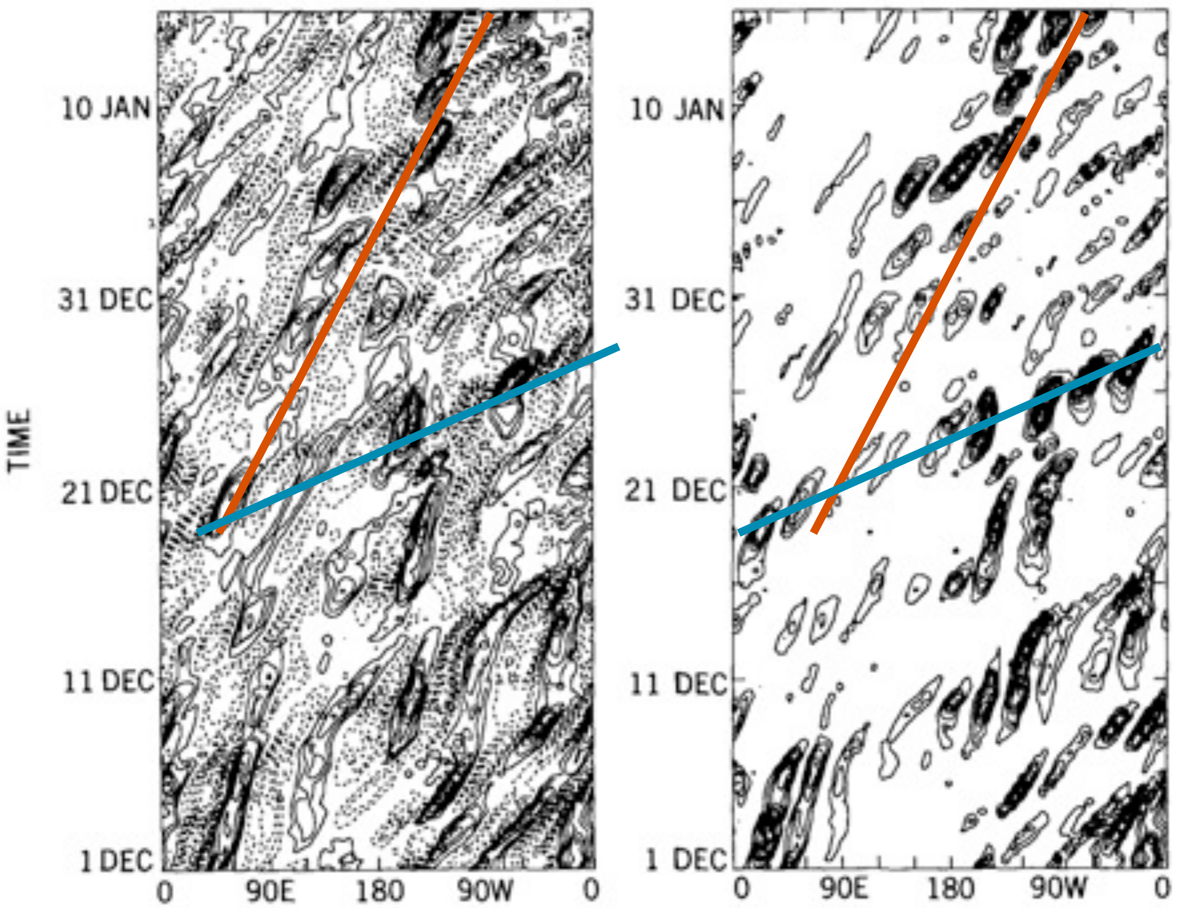


30° to 60°N

lag correlations

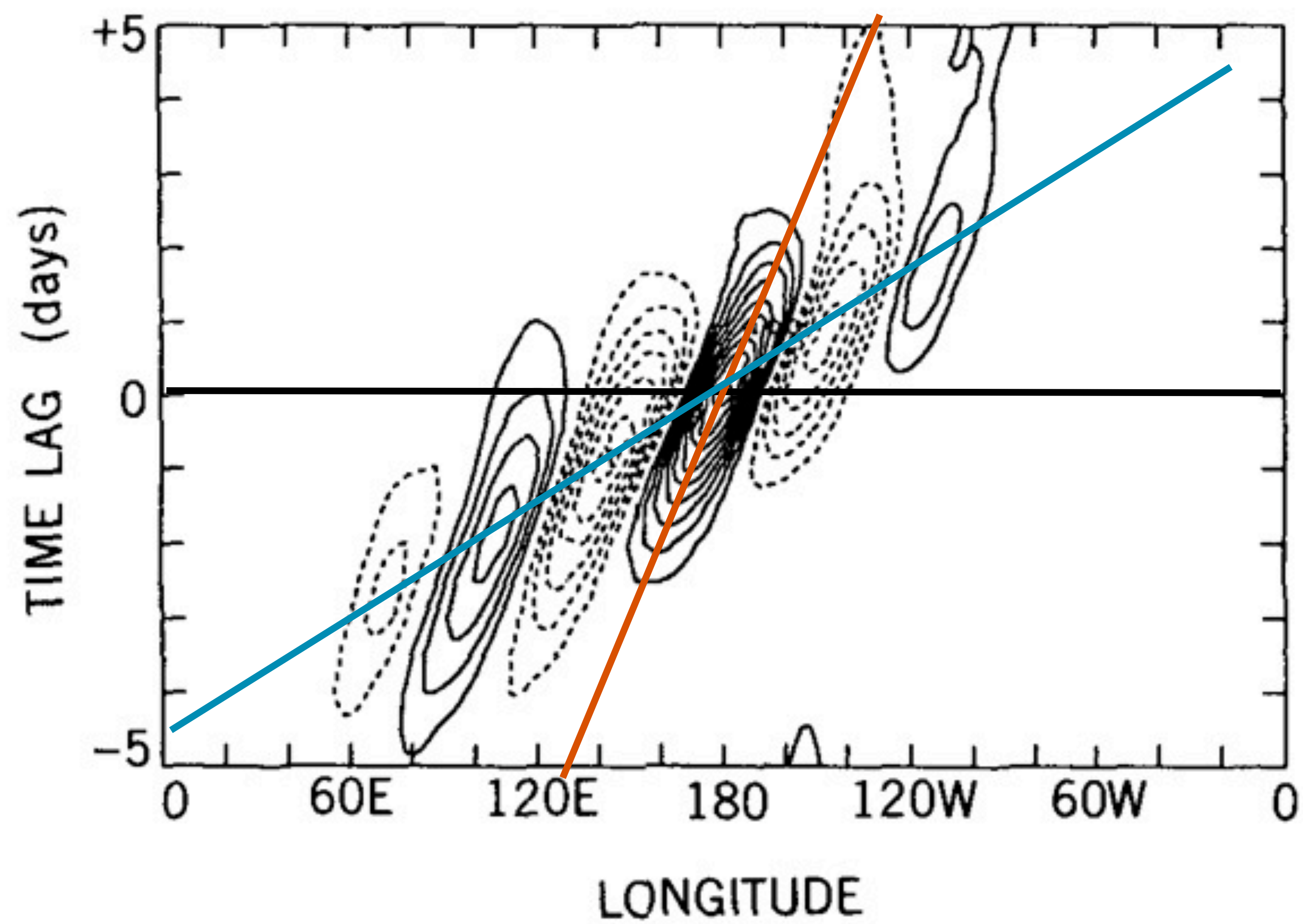


Edmund K.M. Chang,
J. Atmos. Sci. 1993



rate of downstream phase propagation

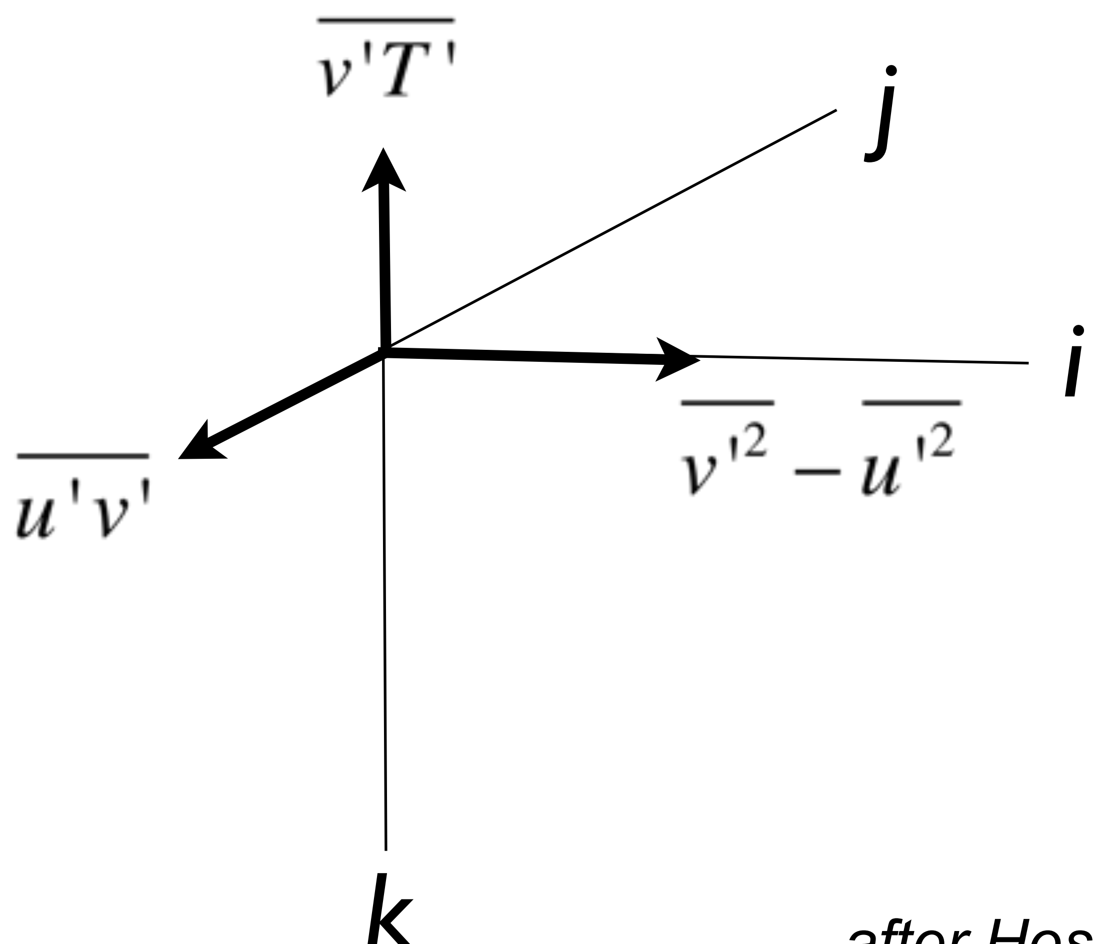
rate of downstream dispersion
(group velocity)



Generalization of *E*-vector formalism to three dimensions

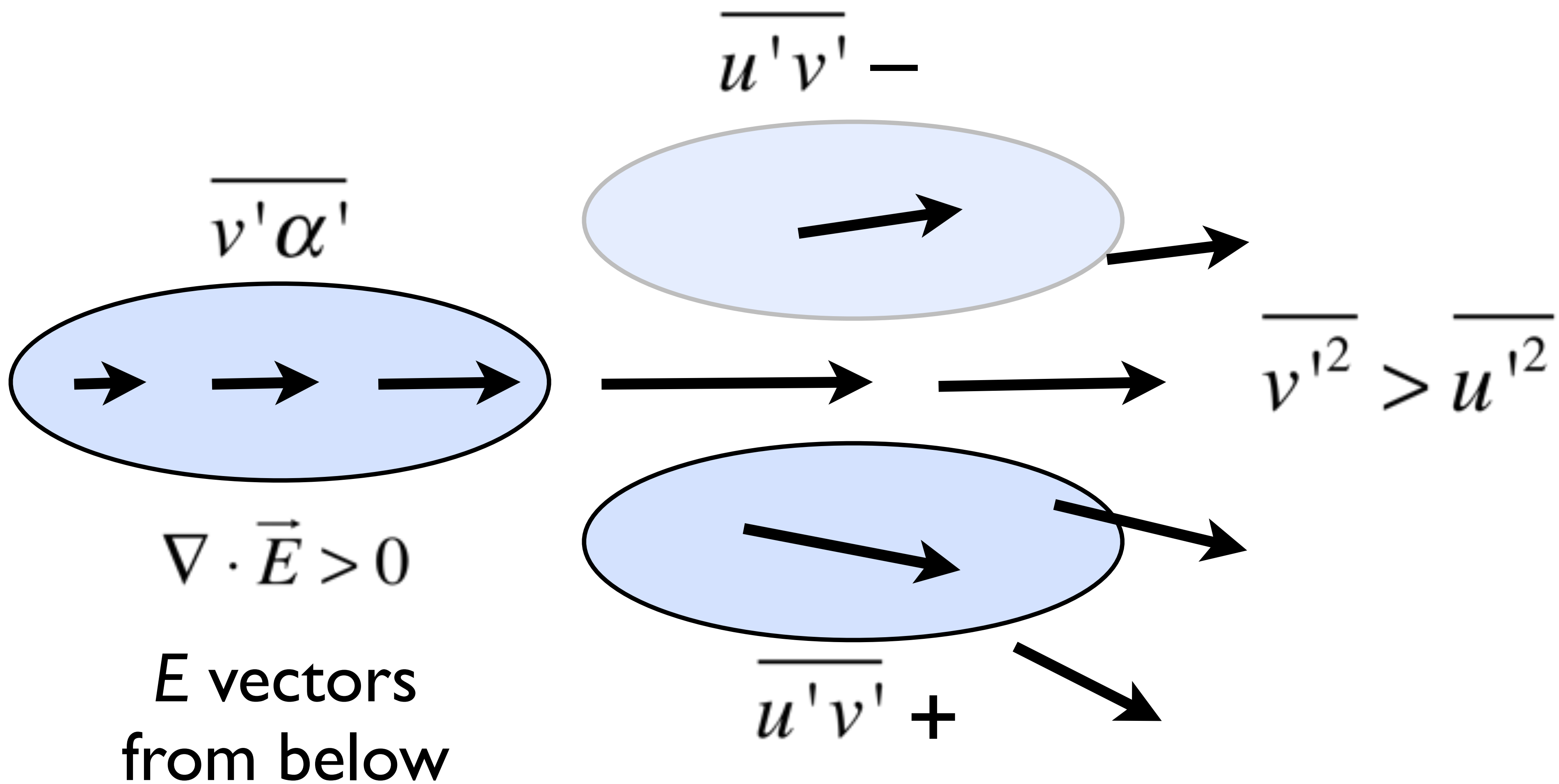
In analogy with $\frac{\partial \bar{\varsigma}}{\partial t} \simeq -\frac{\partial}{\partial y}\left(\nabla \cdot \vec{E}\right)$ where $\vec{E} \equiv \left(\overline{v'^2} - \overline{u'^2}, -\overline{u'v'}\right)$

we can write $\frac{\partial \bar{q}}{\partial t} \simeq -\frac{\partial}{\partial y}\left(\nabla_3 \cdot \vec{E}\right)$ where $\vec{E} \equiv \left(\overline{v'^2} - \overline{u'^2}, -\overline{u'v'}, -\frac{\overline{v'\alpha'}}{\sigma}\right)$



after Hoskins, James and White JAS 1983

Idealized storm track showing *E* vectors



After Lau and Holopainen *JAS* 1984

Transient eddy forcing of the climatological-mean flow

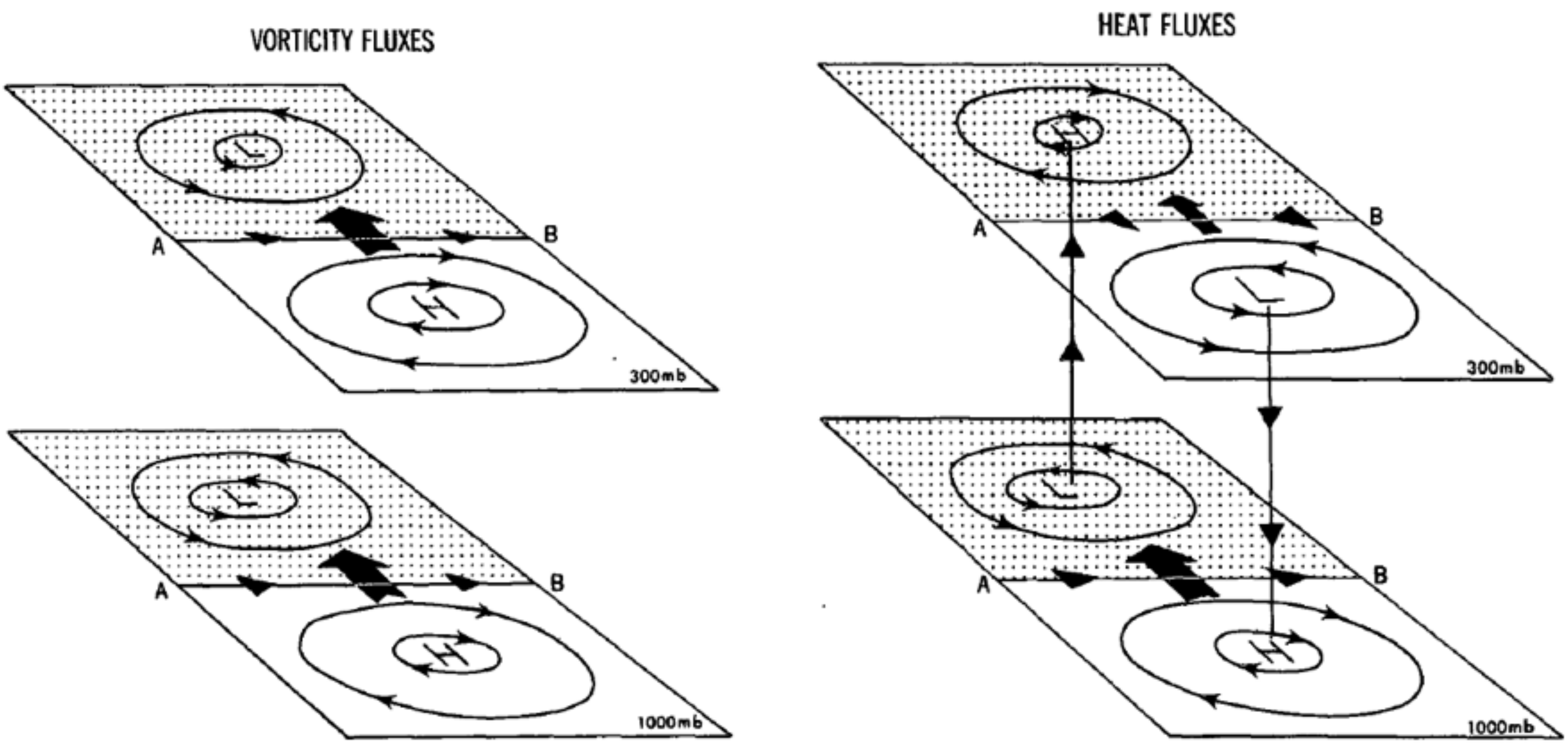
$$\left\{\frac{1}{f}\nabla^2 + f\frac{\partial}{\partial p}\left(\frac{1}{\sigma}\frac{\partial}{\partial p}\right)\right\}\frac{\partial \Phi}{\partial t} = D + R_1,$$

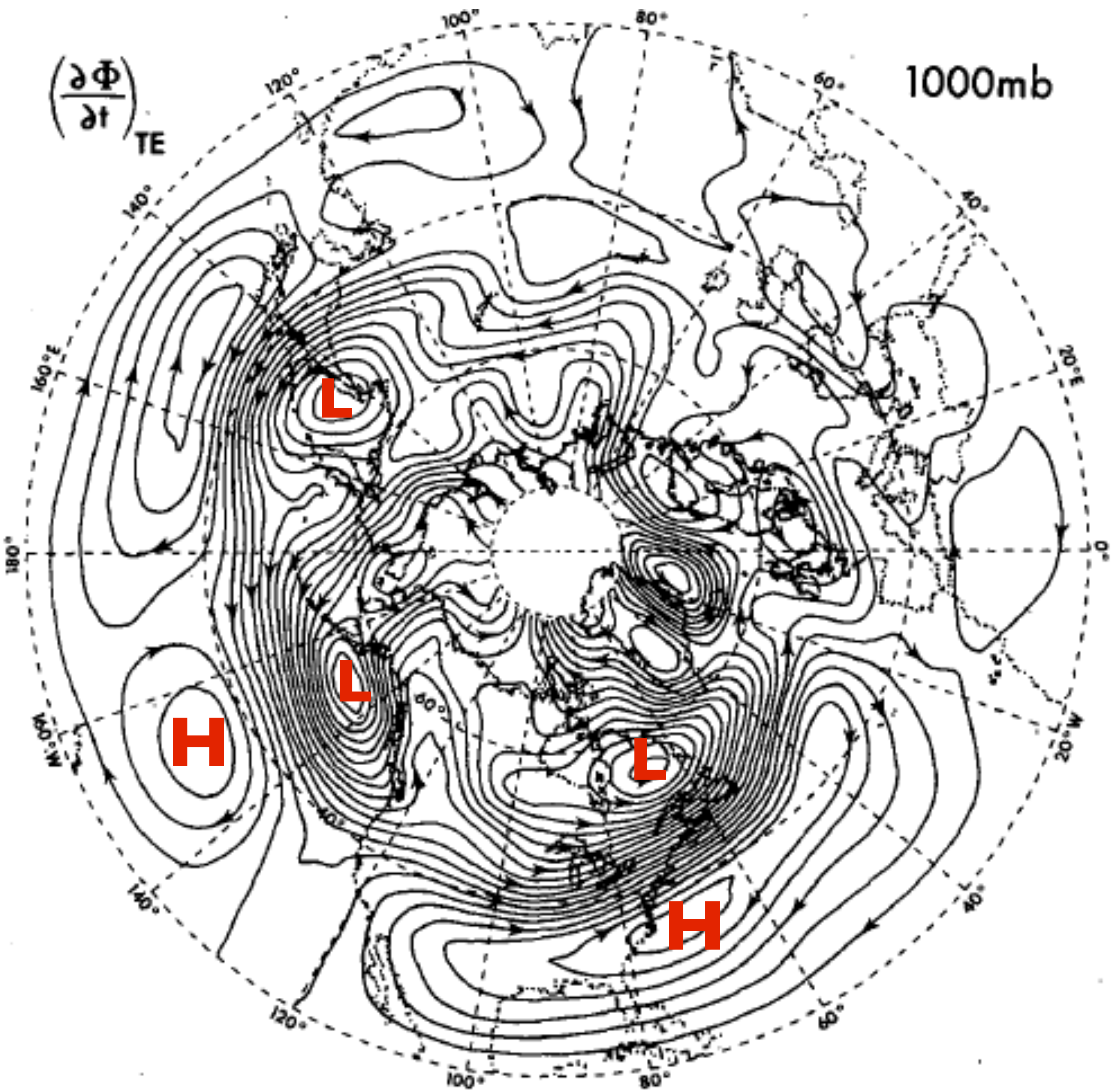
Time-averaged geopotential tendency equation

$$D = D^{\mathrm{HEAT}} + D^{\mathrm{VORT}},$$

$$D^{\mathrm{HEAT}} = f\frac{\partial}{\partial p}\left(\frac{\nabla \cdot \overline{\mathbf{V}'\theta'}}{\bar{\bar{S}}}\right)$$

$$D^{\mathrm{VORT}} = -\nabla \cdot \overline{\mathbf{V}'\zeta'}.$$

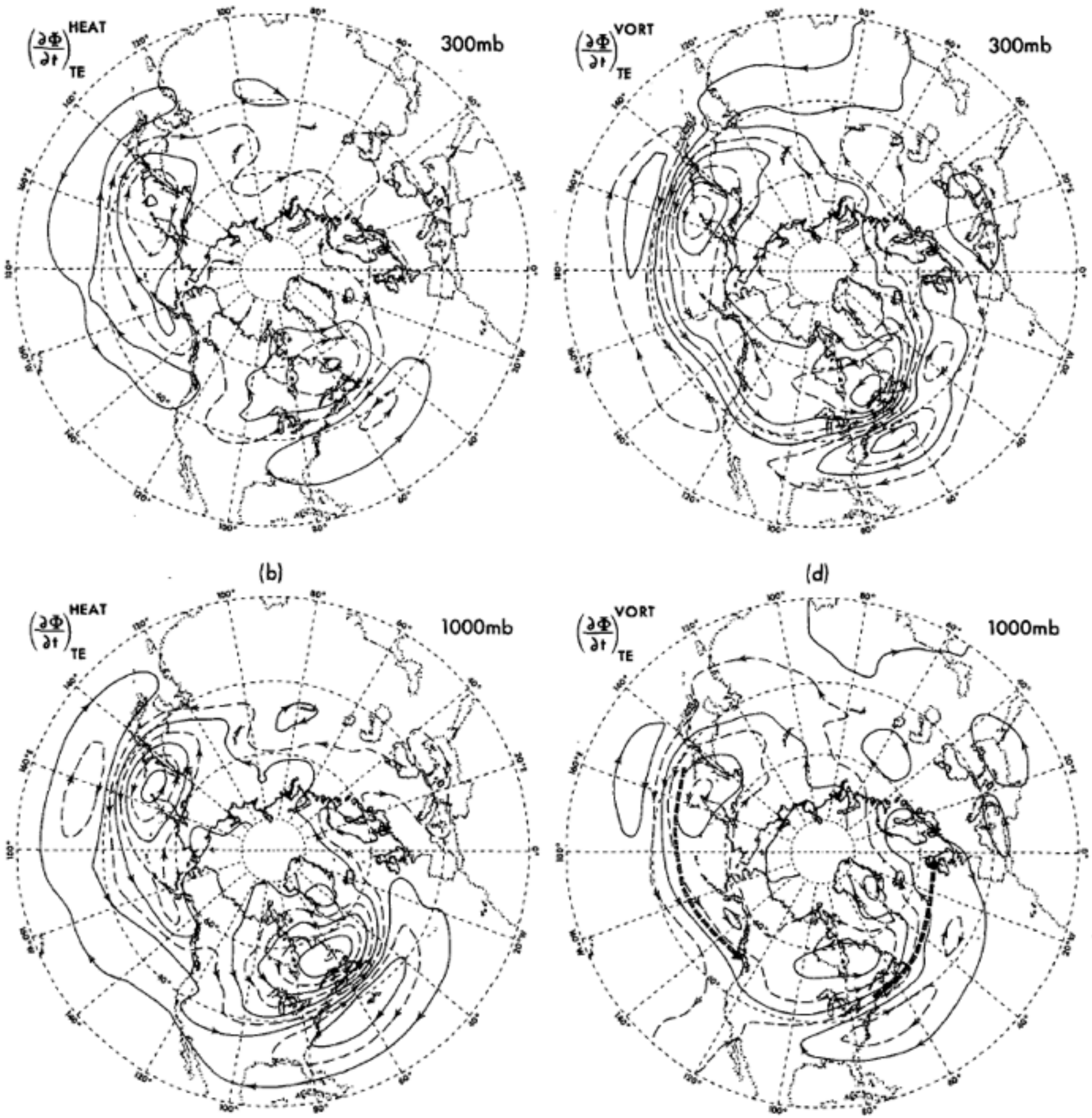




Tendency induced by all transients: high frequencies dominate

After Lau and Holopainen JAS 1984

tendency induced by high frequency transients



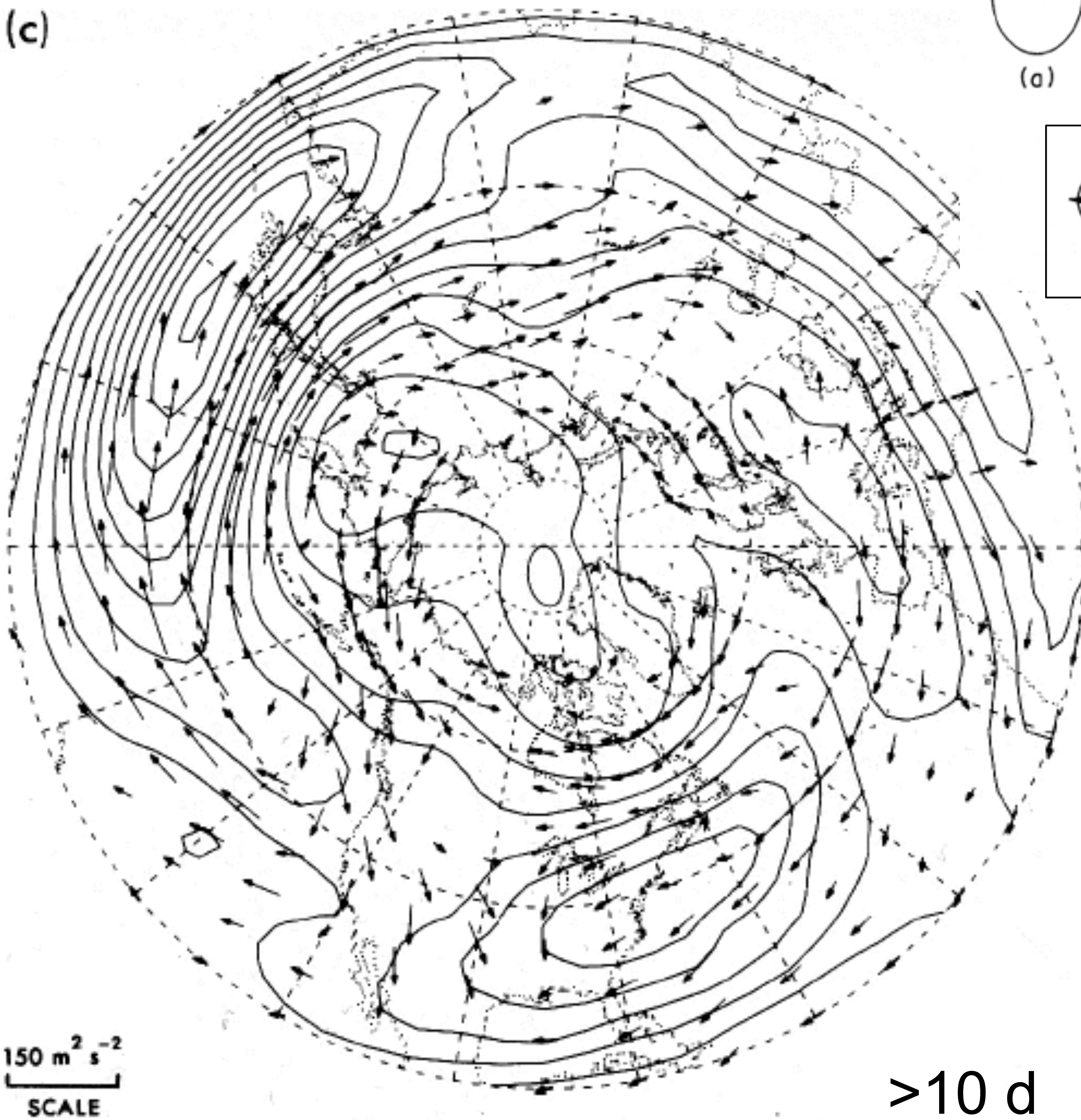
at 300 hPa the tendencies induced by the heat and vorticity fluxes by the transient eddies oppose one another so the net forcing is rather small.

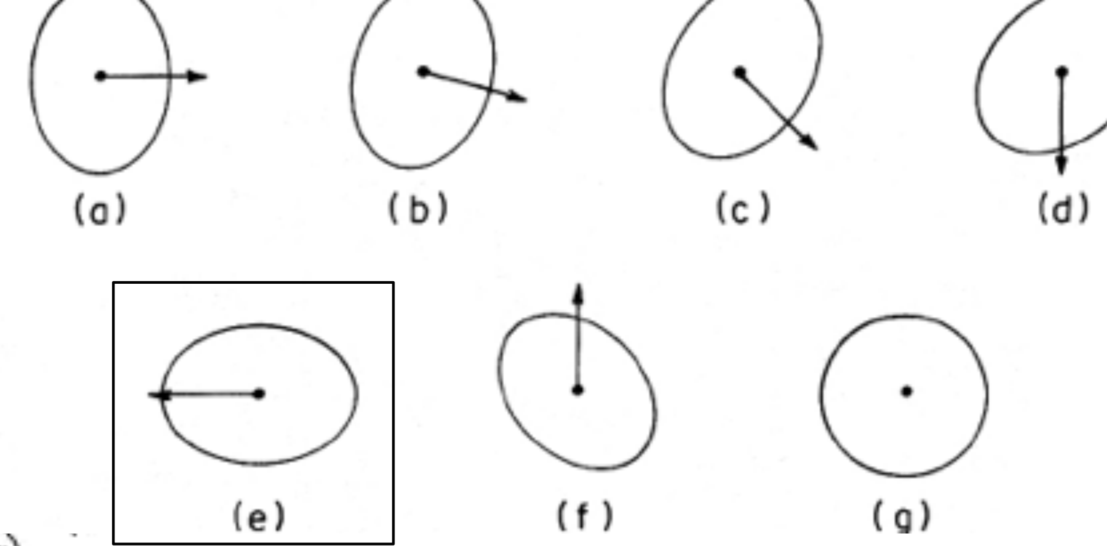
at 1000 hPa they reenforce one another so the eddy-induced tendency is much larger. Note how the heat fluxes dominate.

After Lau and Holopainen JAS 1984

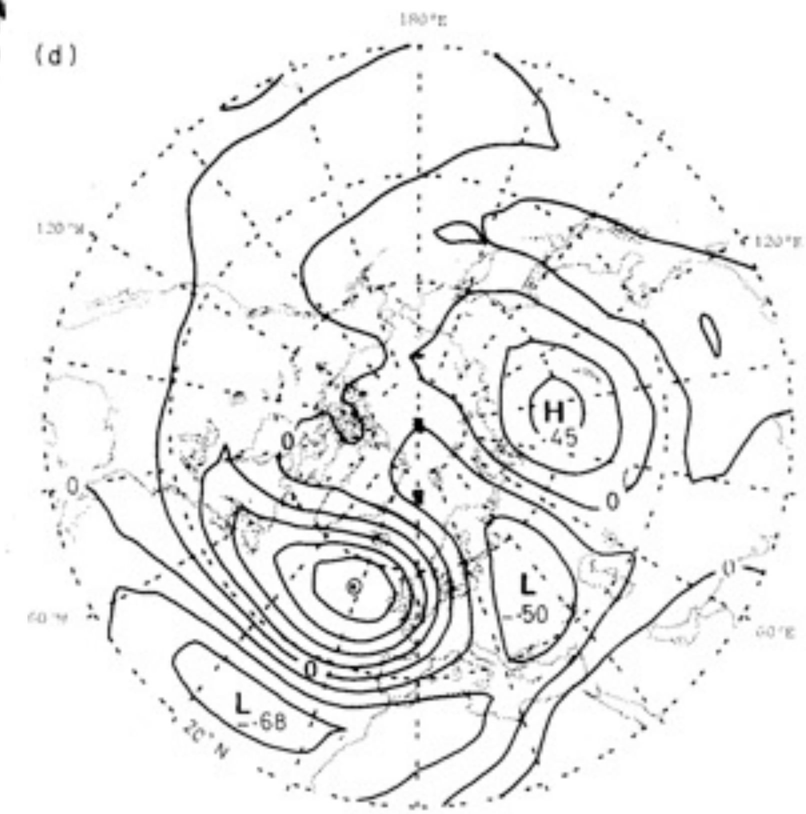
More about the evolution of the transients

(c)





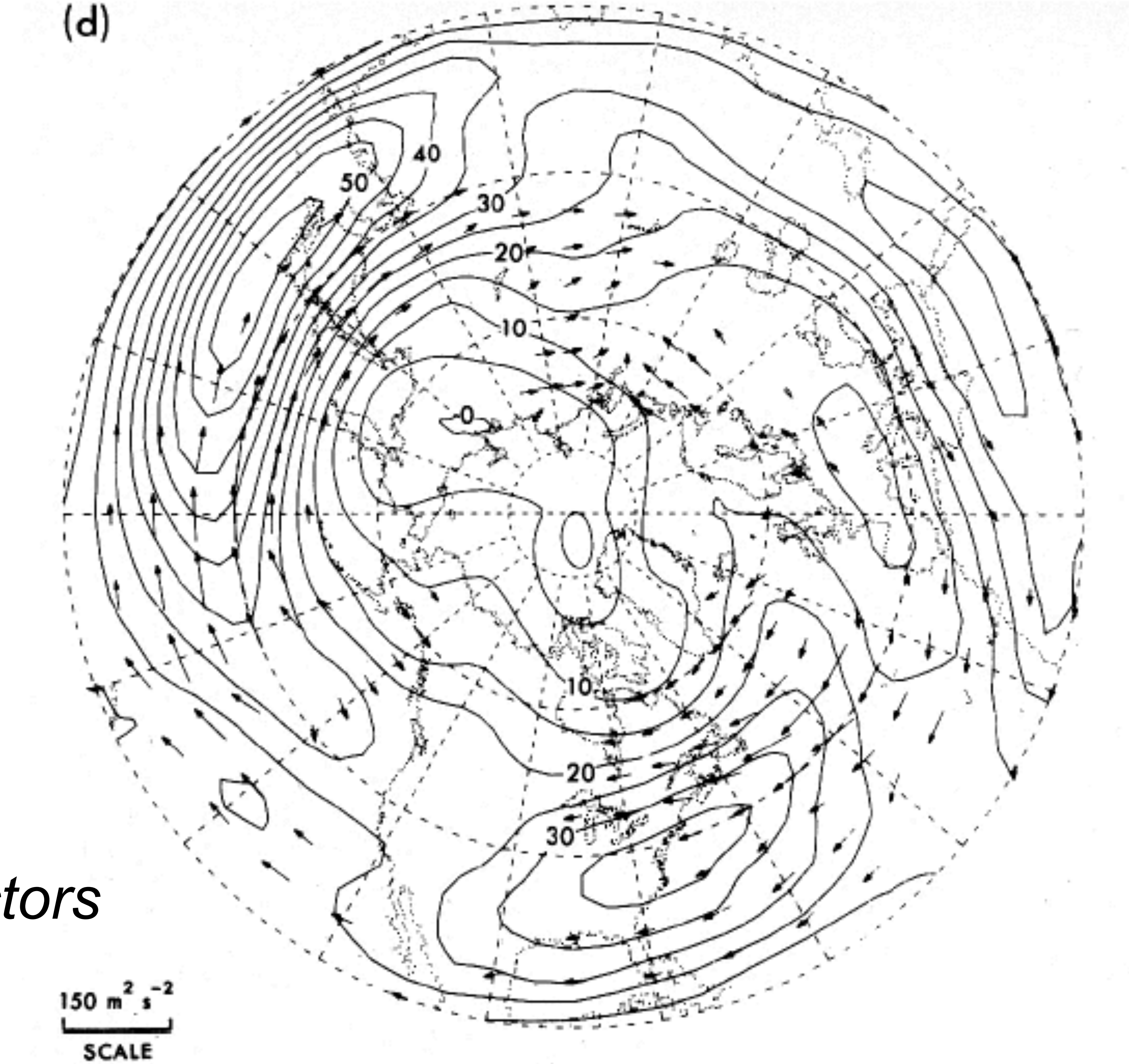
(d)



>10 d

after Wallace and Lau, Issues in Atmospheric and Oceanic Modeling 1985

>30 d



E vectors

Note dominance of westward arrows: zonally elongated perturbations localized in climatological-mean jet exit regions

after Wallace and Lau, Issues in Atmospheric and Oceanic Modeling 1985

Why do transient disturbances become more elongated as we go toward lower frequency?

First consider the situation in the ocean in which there is no zonal background flow. All transient perturbations propagate westward for to the beta effect. The phase speed is given by

$$c = \frac{\beta}{k^2 + l^2}$$

and the frequency apparent to a fixed observer by

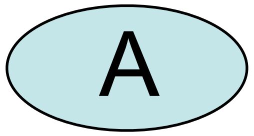
$$\omega = \frac{k\beta}{k^2 + l^2}$$

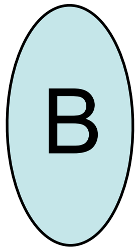
where *k* is the zonal wavenumber (the inverse of wavelength) and *l* is the meridional wavenumber.

Longer waves (i.e., waves with smaller two-dimensional wavenumber $k^2 + l^2$ propagate westward faster than shorter waves.

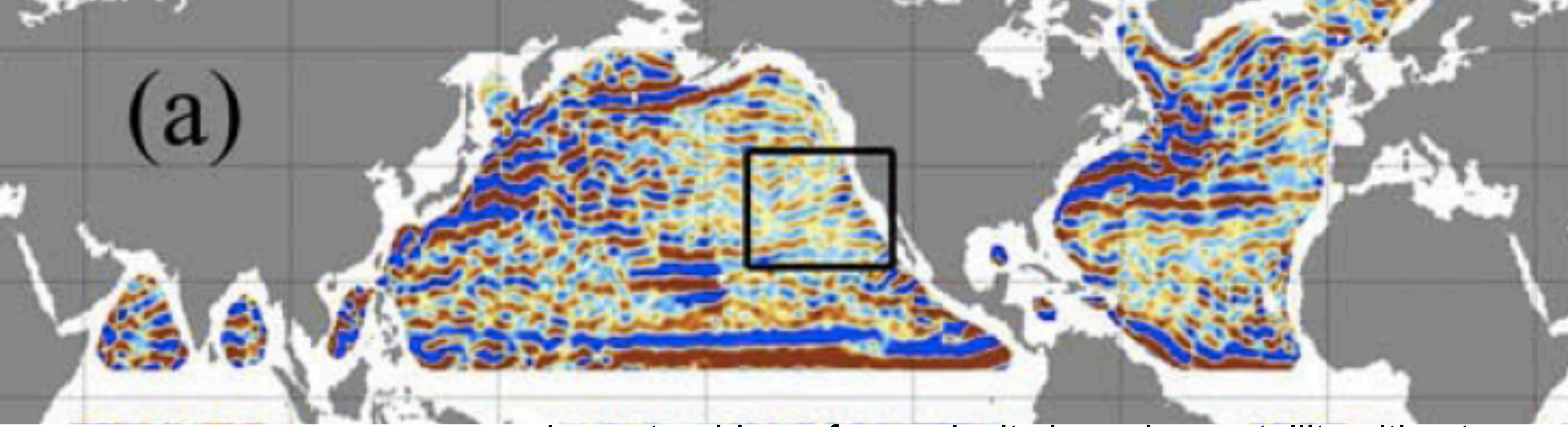
Why do transient disturbances become more elongated as we go toward lower frequency?

Now consider two disturbances with the same two-dimensional wavenumber $k^2 + l^2$

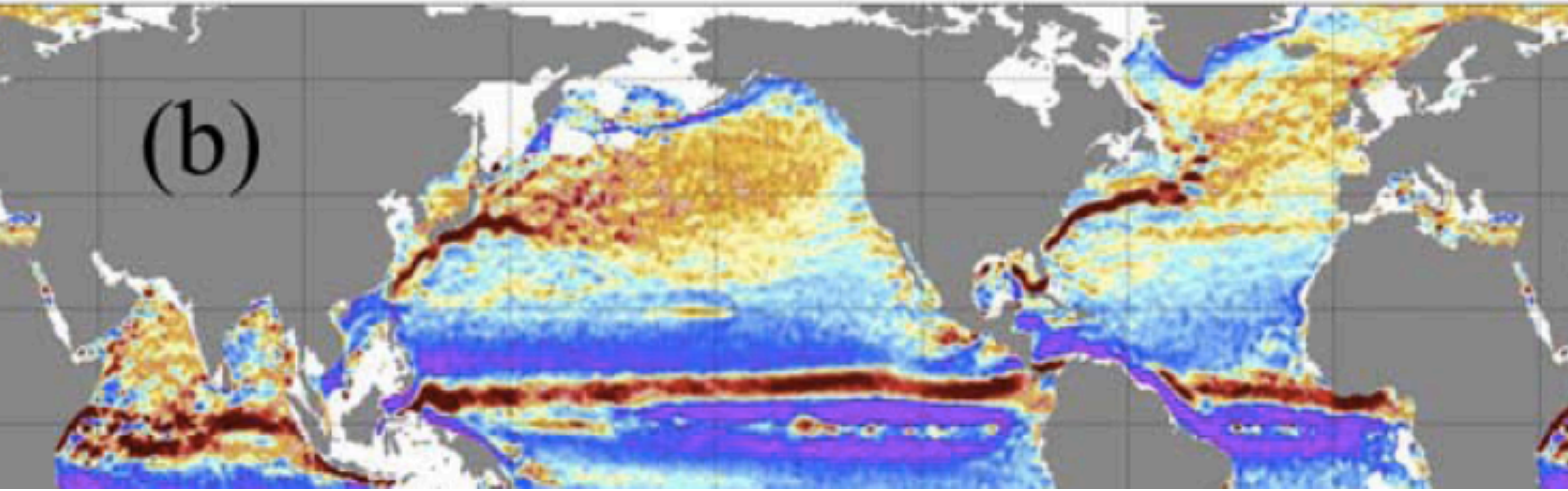
One shaped like 

and the other shaped like 

A takes longer to pass the fixed observer, so it has a lower frequency. If a spectrum of waves is present, with some being zonally elongated, like A and some meridionally oriented like B. The more strongly we lowpass filter the data, the more the zonally elongated disturbances will be favored. In the limit of zero frequency, the wind perturbations will be nearly purely zonal.



zonal geostrophic surface velocity based on satellite altimetry

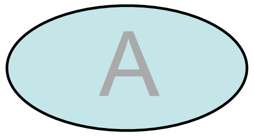


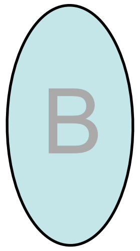
zonal geostrophic surface velocity based drifters

Maximenko et al. GRL, 2008

Why do transient disturbances become more elongated as we go toward lower frequency?

Now consider two disturbances with the same two-dimensional wavenumber $k^2 + l^2$

One shaped like 

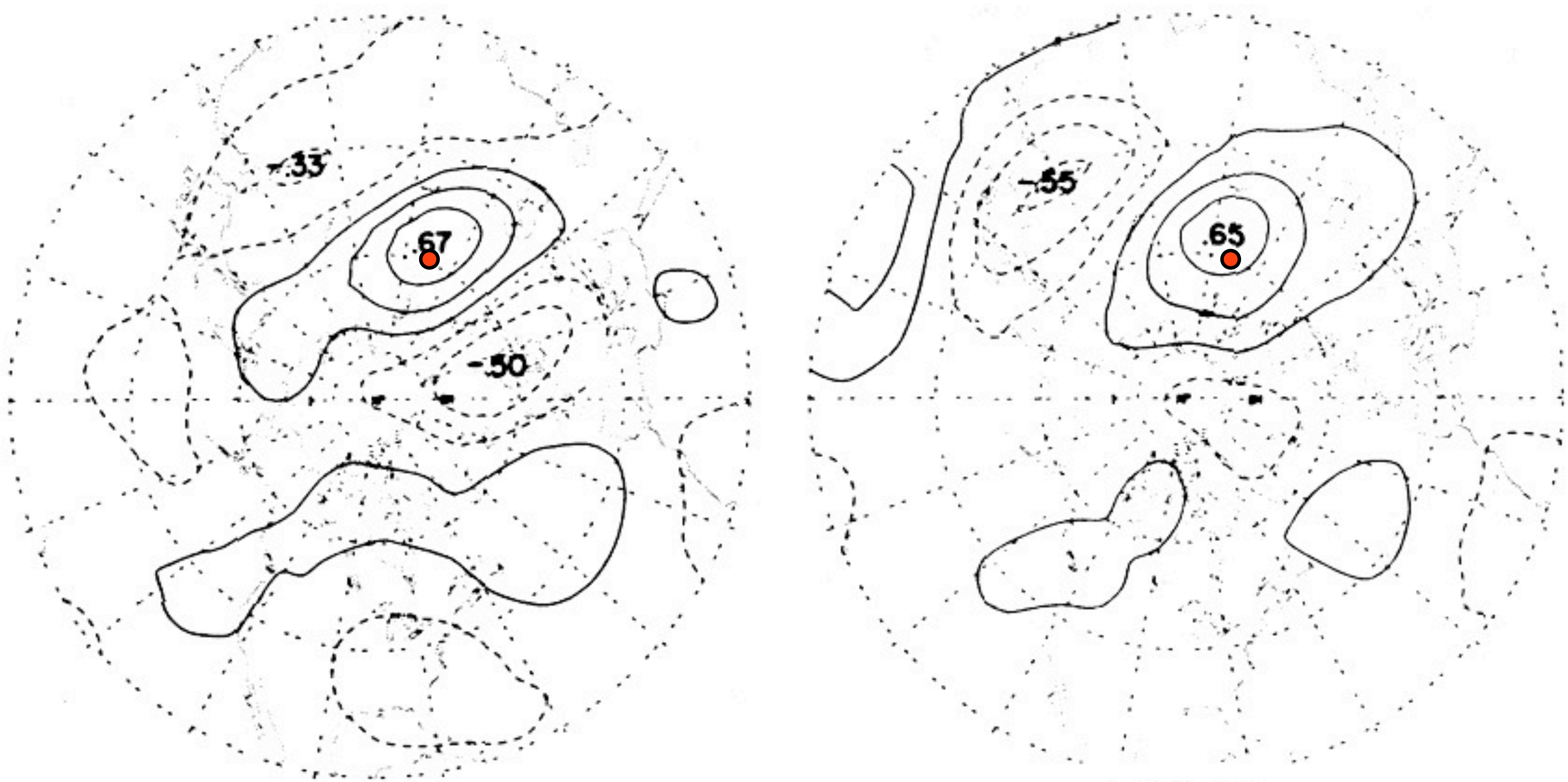
and the other shaped like 

A takes longer to pass the fixed observer, so it has a lower frequency. If a spectrum of waves is present, with some being zonally elongated, like A and some meridionally oriented like B. The more strongly we lowpass filter the data, the more the zonally elongated disturbances will be favored. In the limit of zero frequency, the wind perturbations will be nearly purely zonal.

The argument carries over to the atmosphere where $\omega = k\left(u - \dfrac{\beta}{k^2 + l^2}\right)$
In this case, the most slowly propagating disturbances will be the ones for which the term in parentheses is smallest, but for a prescribed spectrum of $k^2 + l^2$, the zonally elongated ones will still have the lowest frequencies.

More about the evolution of the transients

10-30d bandpass DJF 500 hPa height

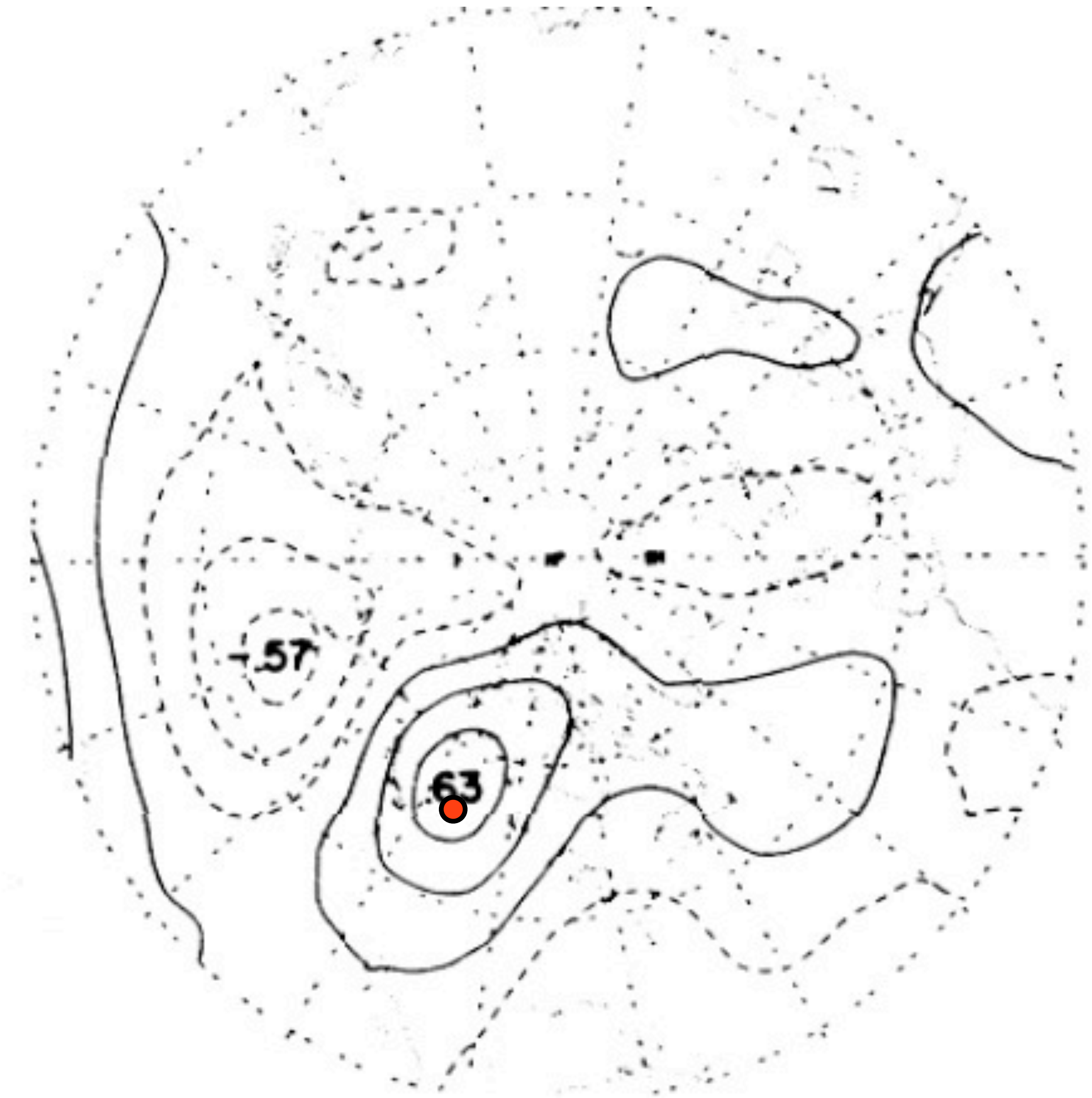


5 days earlier

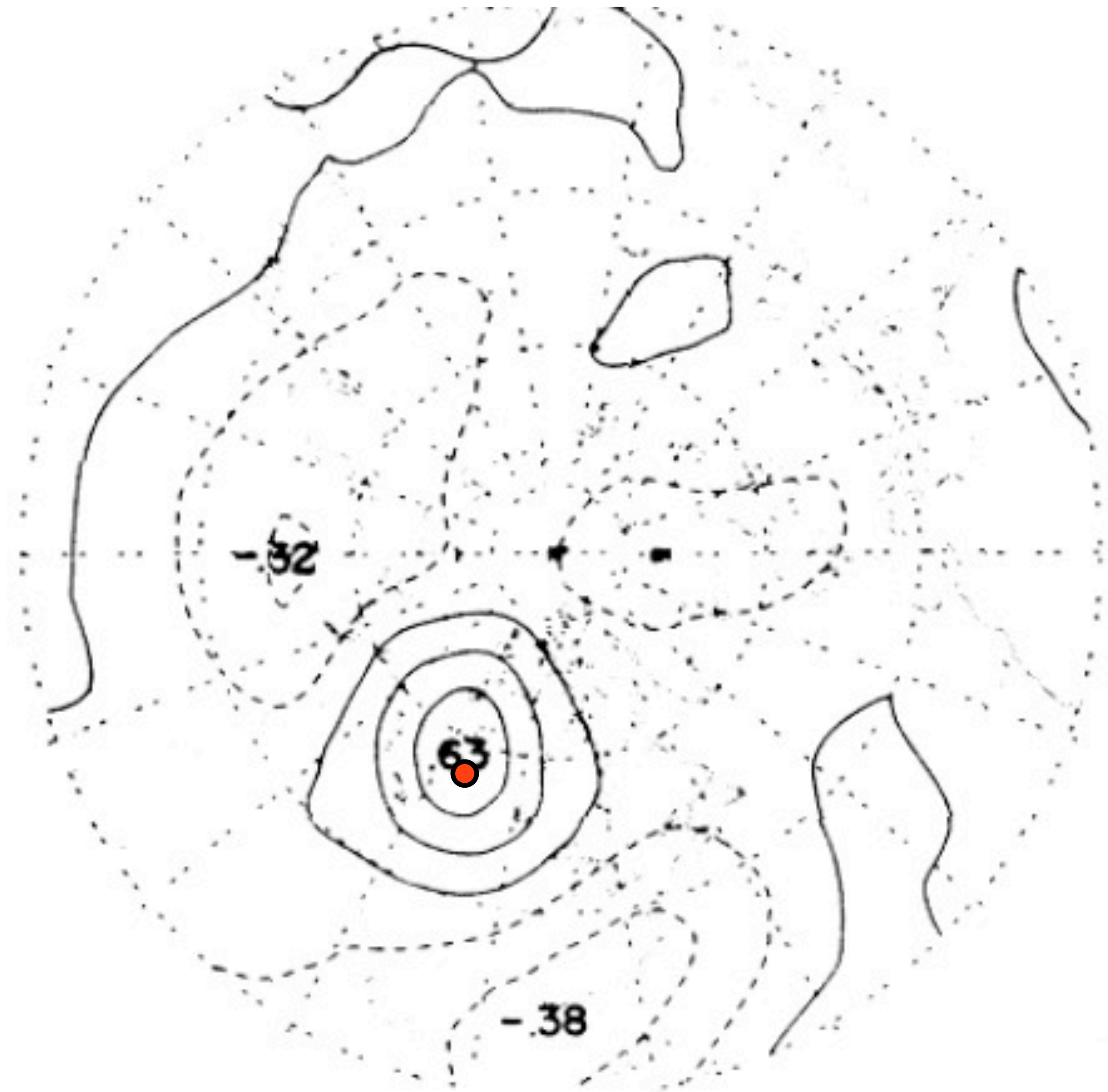
5 days later

lag correlations with 500 hPa height at reference grid point

after Blackmon et al. JAS (1984b)

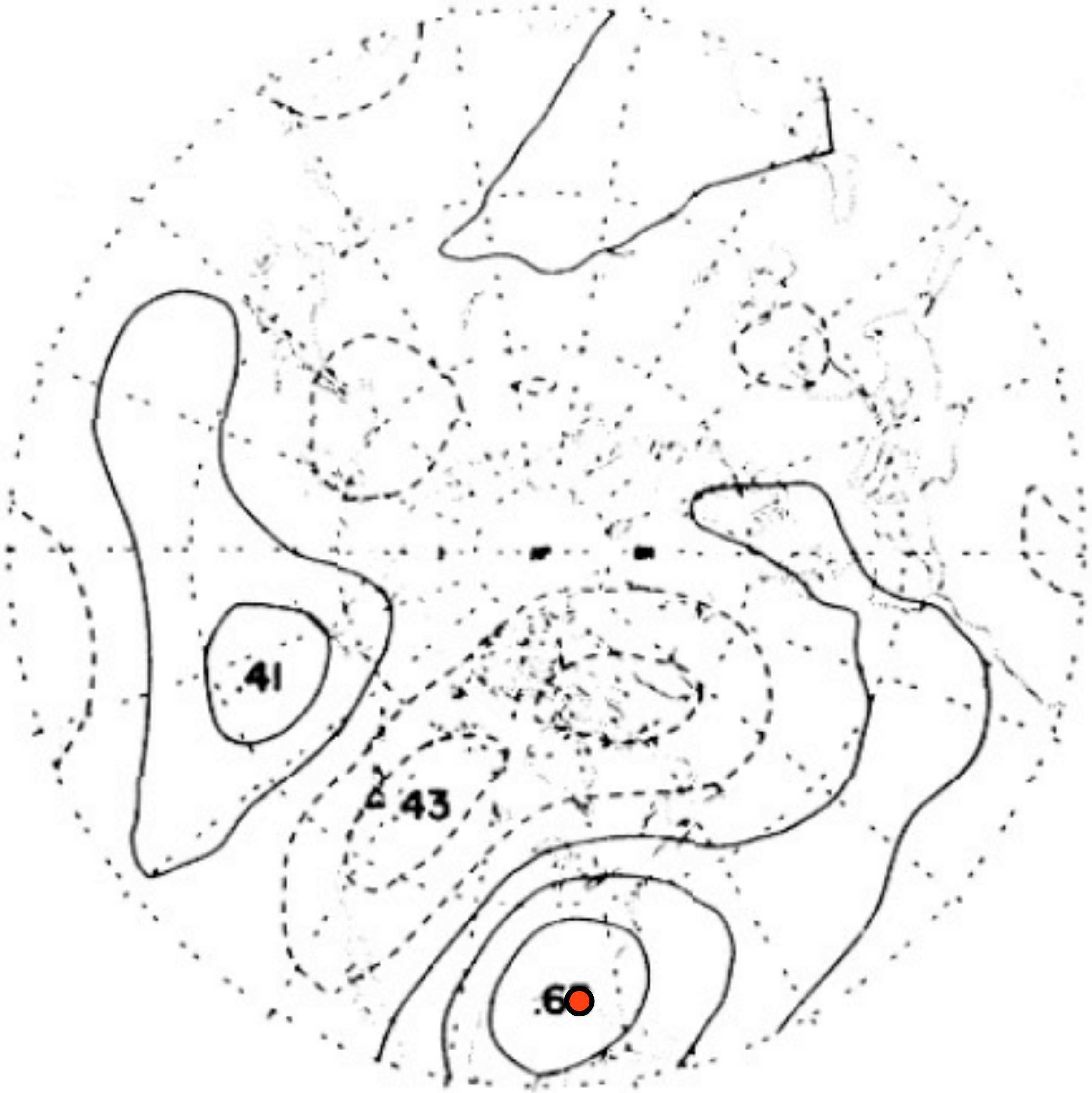


5 days earlier

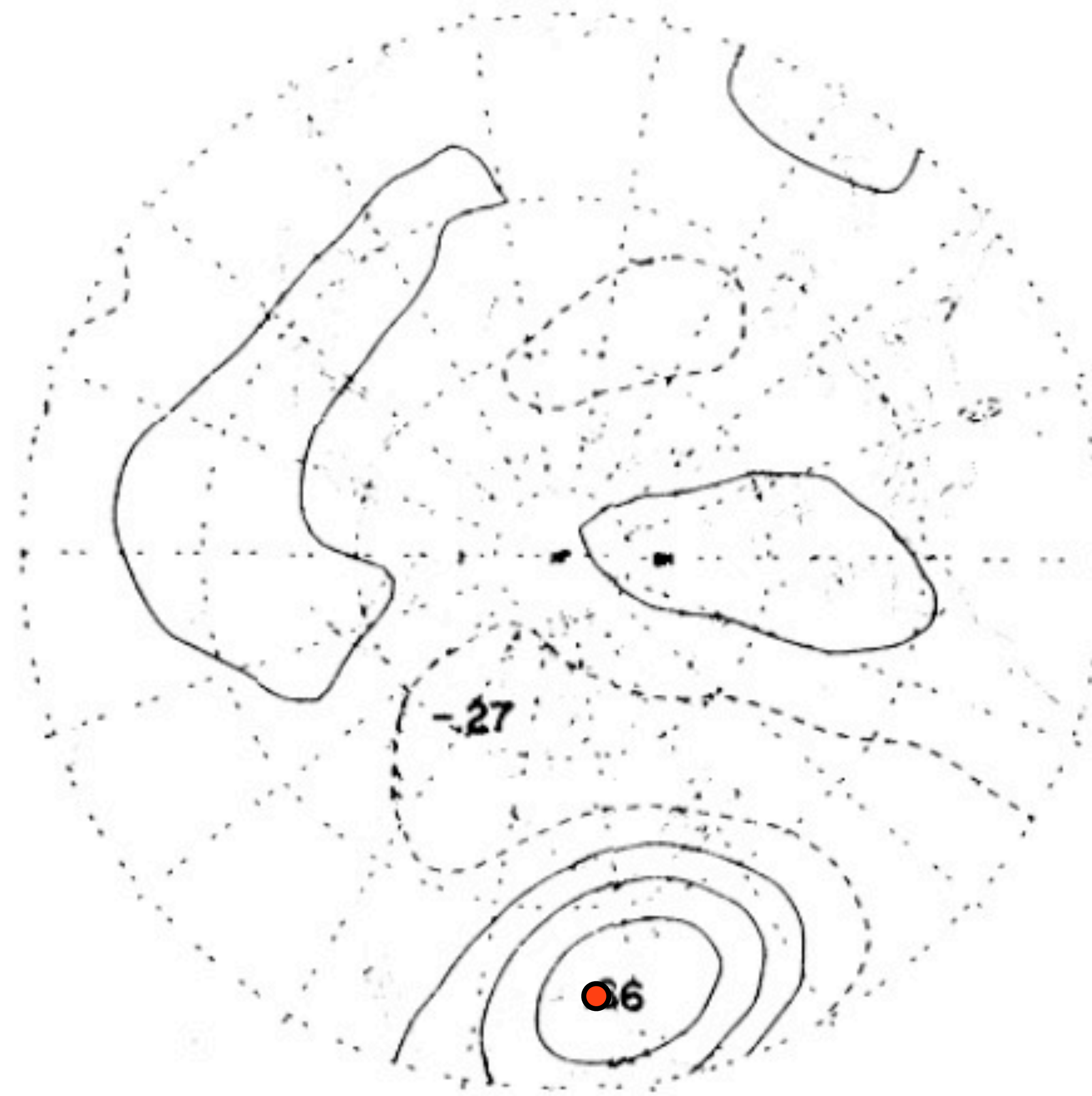


5 days later

after Blackmon et al. JAS (1984b)



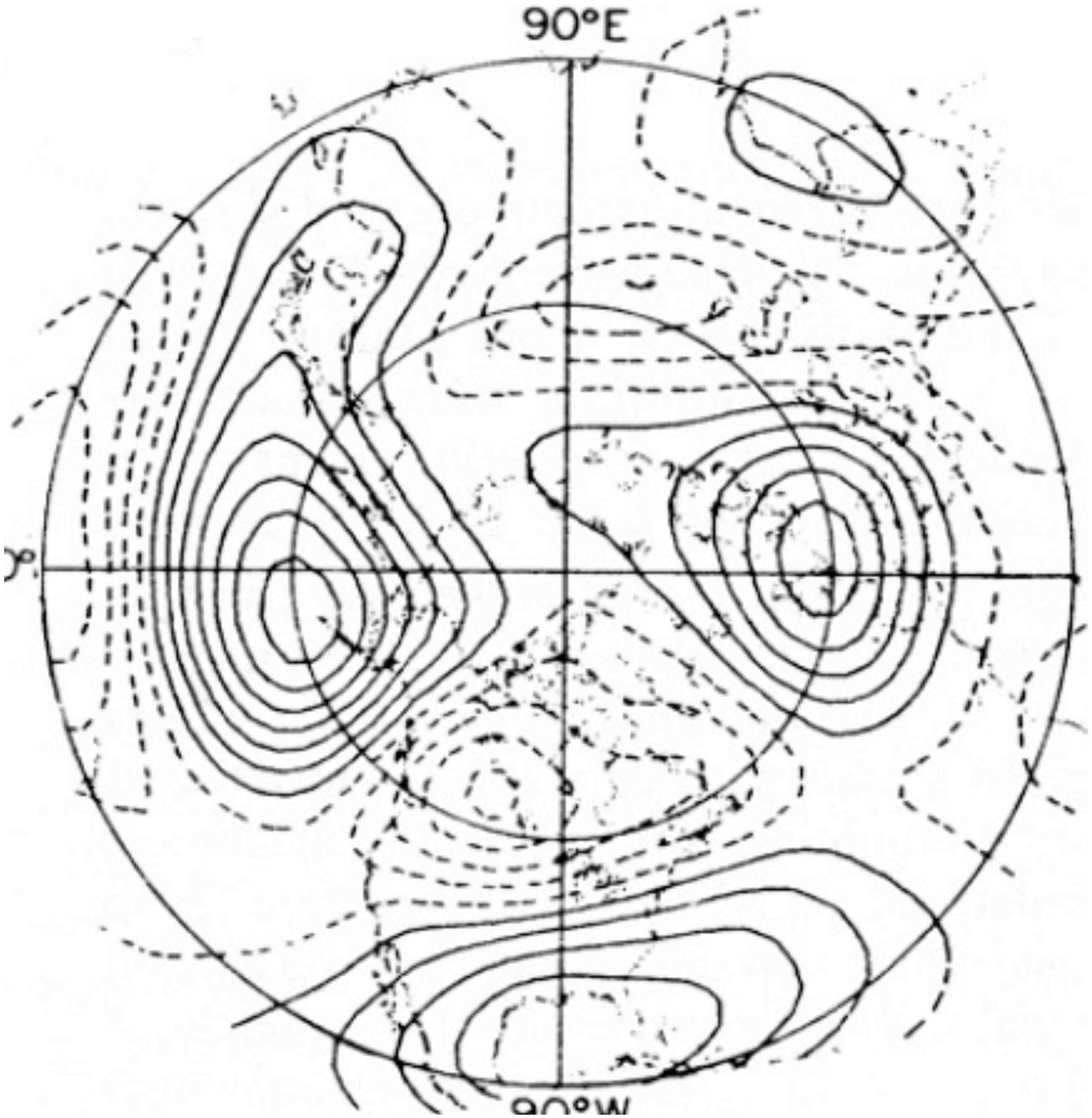
5 days earlier



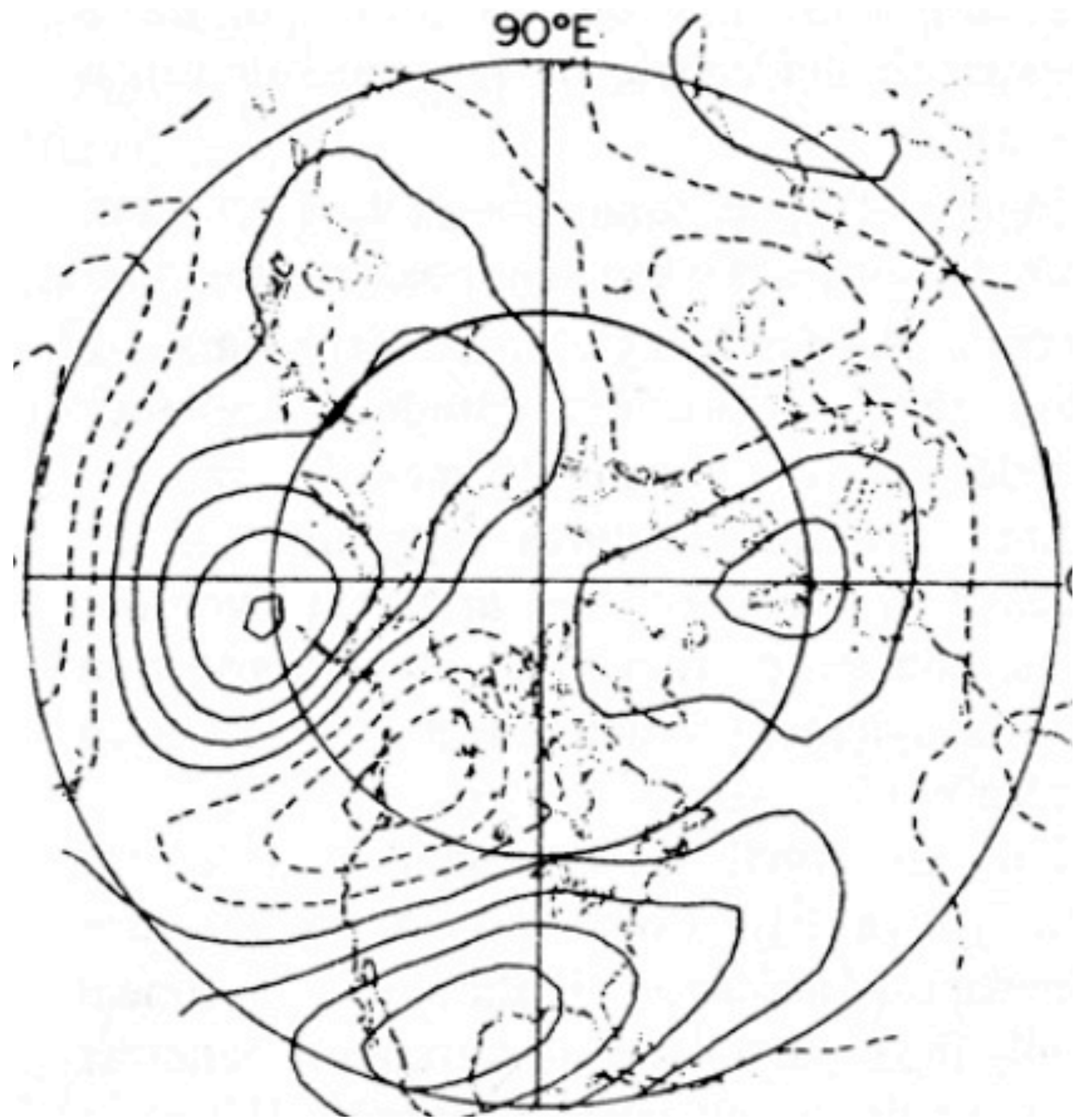
5 days later

after Blackmon et al. JAS (1984b)

Regressed onto the cosine coefficient of zonal wavenumber 2 on 50°N

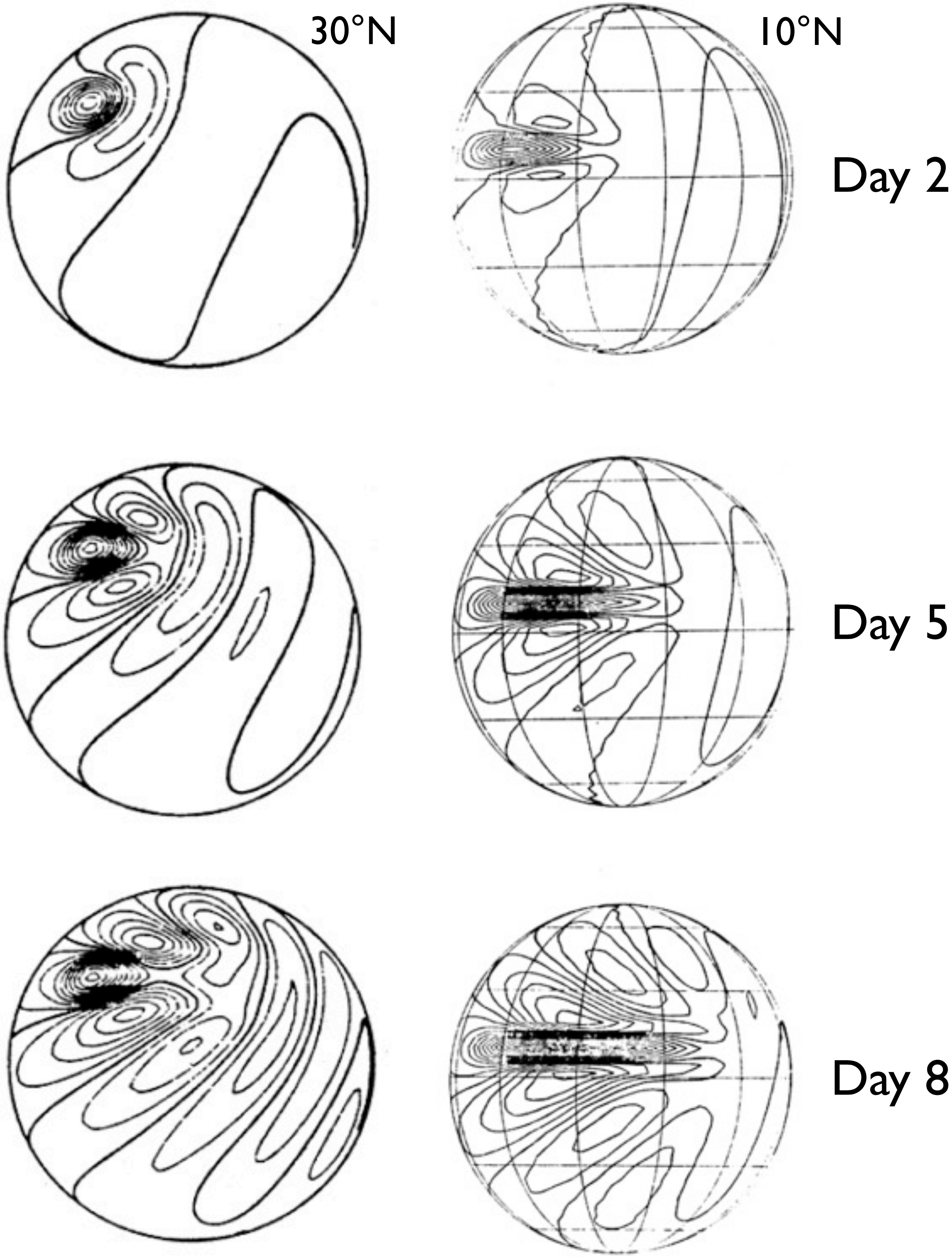


As in left panel but 5 days later



Consecutive 5-day mean wintertime 500 hPa height

After Wallace and Hsu, JAS, 1983



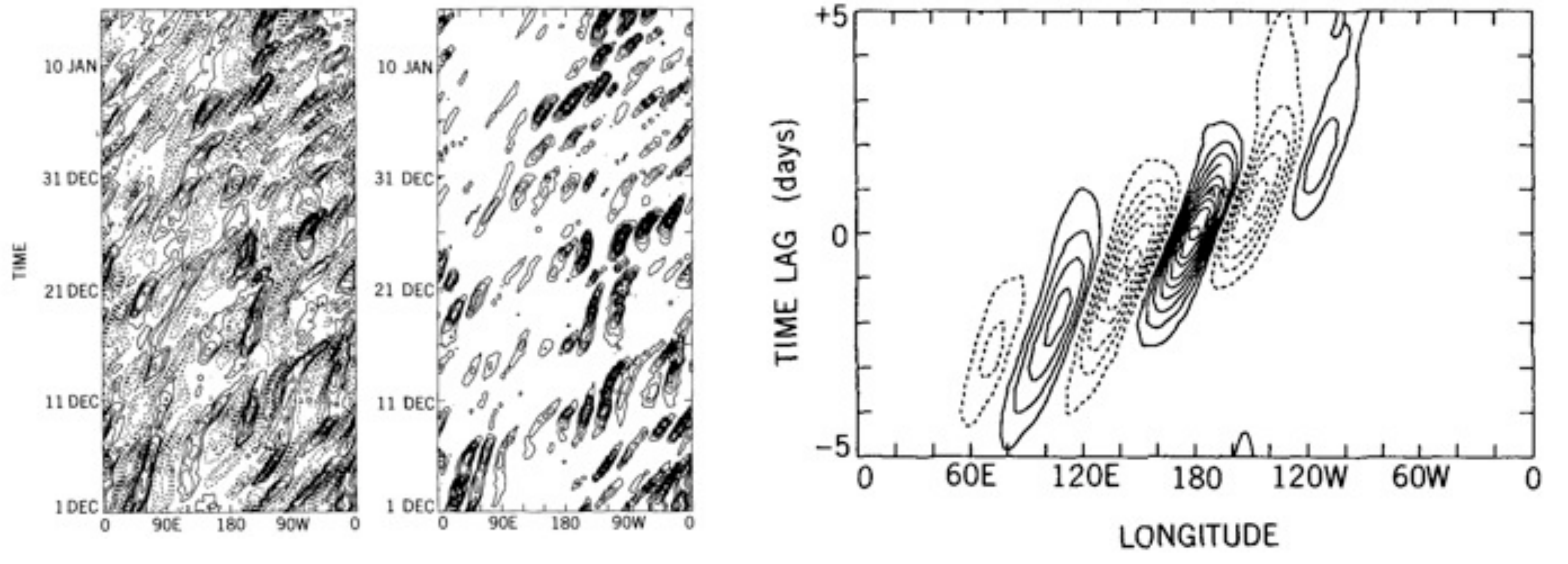
Barotropic vorticity equation

Basic state flow consisting of superrotation

“Mountain” turned on on Day 0

Courtesy of B. J. Hoskins

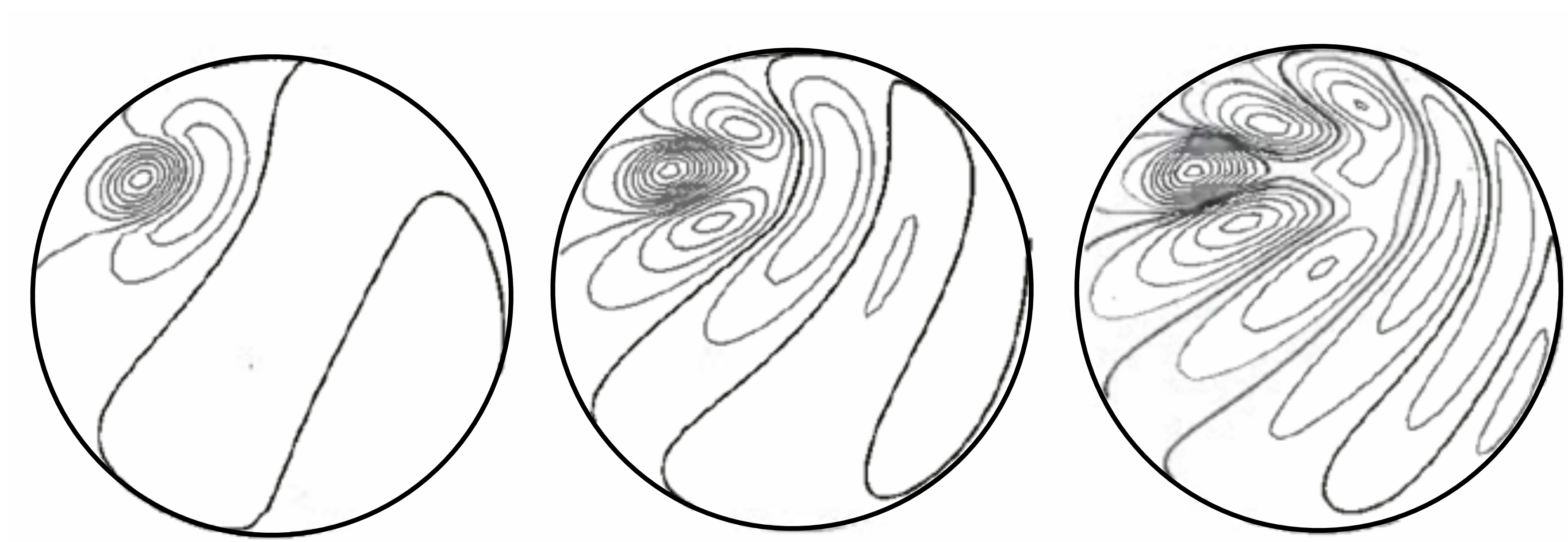
Highpass: periods shorter than a week



Summary:

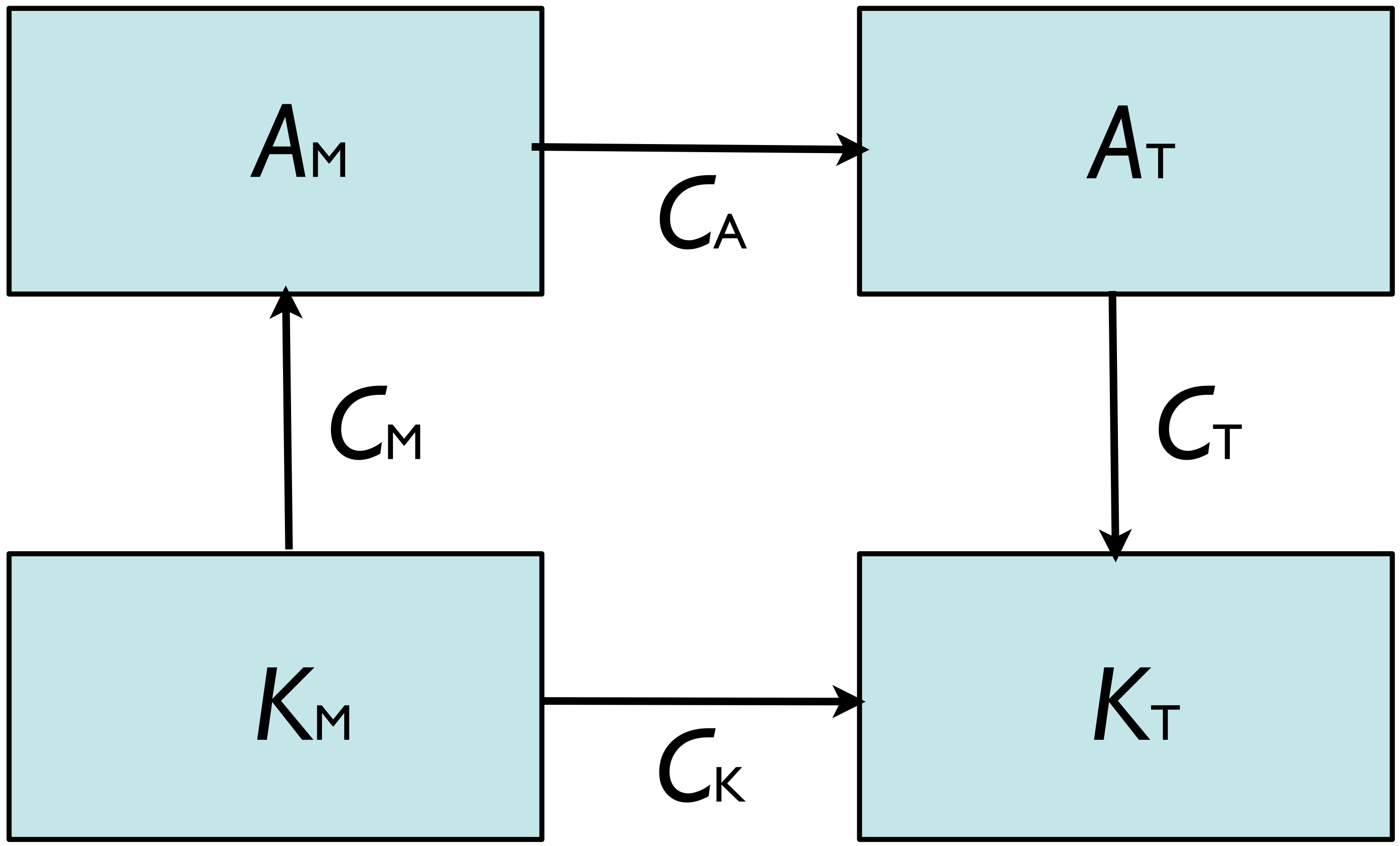
Phase propagation $\bar{u}\dfrac{\partial}{\partial x}$ dominates; $\overline{v'^2} > \overline{u'^2}$

10-30d bandpass



Eastward dispersion dominates; great circle routes

Energetics of the transients

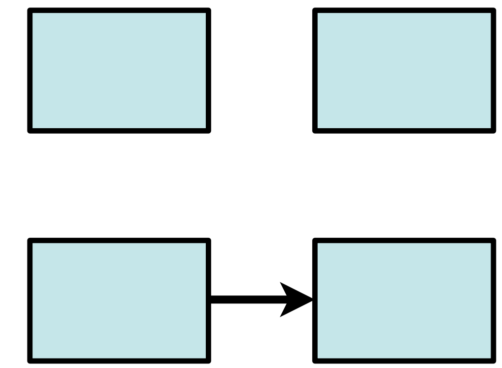


Lorenz kinetic energy cycle: time mean vs. transients

Time mean includes both zonally symmetric flow and stationary waves.

Transients may be decomposed into frequency ranges.

$$C_K = -\overline{u'u'}\frac{\partial \bar{u}}{\partial x} - \overline{u'v'}\left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x}\right) - \overline{v'v'}\frac{\partial \bar{v}}{\partial y}$$



If we assume that the time mean flow is nondivergent,

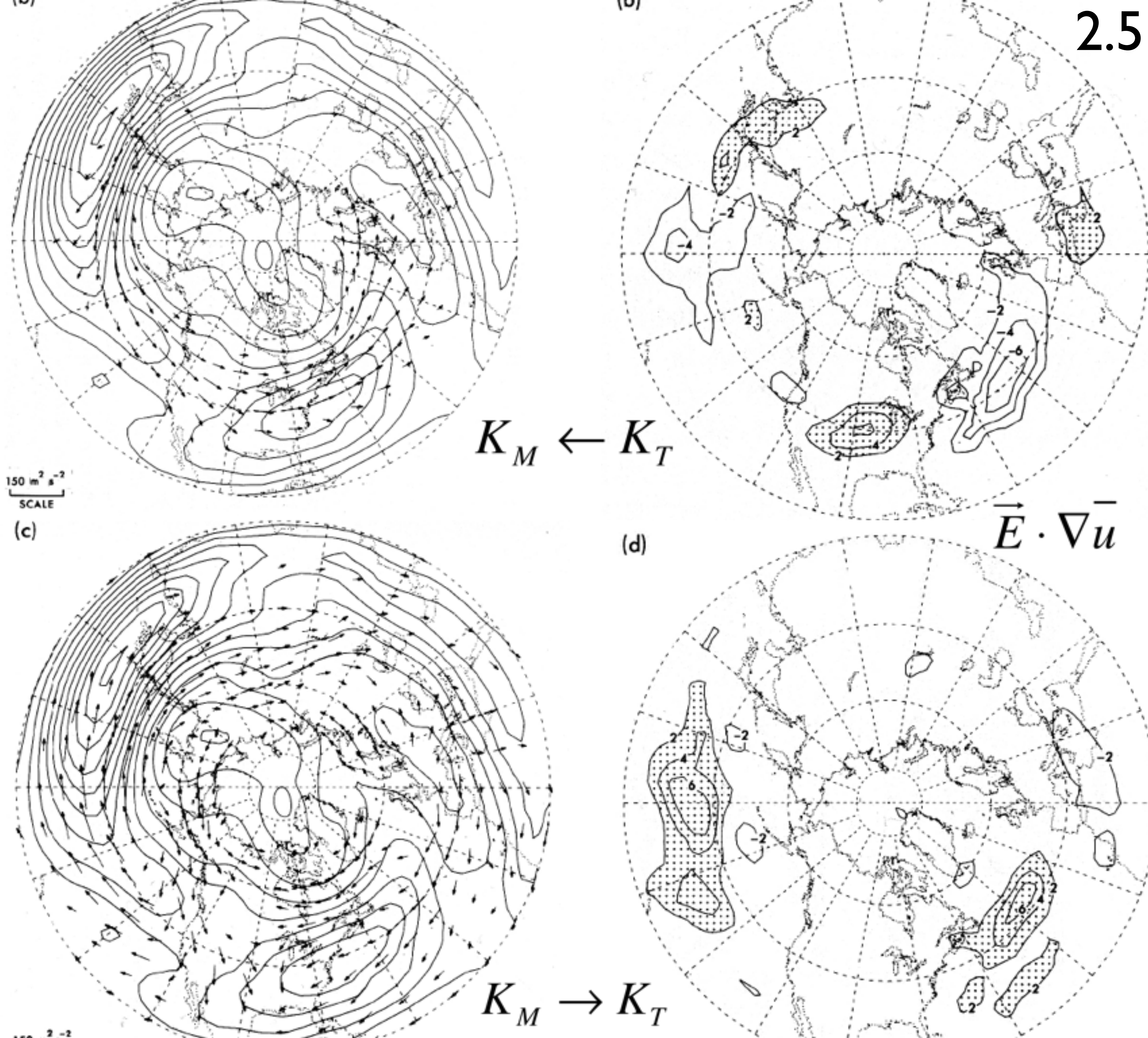
$$C_K = \left(\overline{v'v'} - \overline{u'u'}\right)\frac{\partial \bar{u}}{\partial x} - \overline{u'v'}\left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x}\right)$$

and that $\partial \bar{u} / \partial y >> \partial \bar{v} / \partial x$

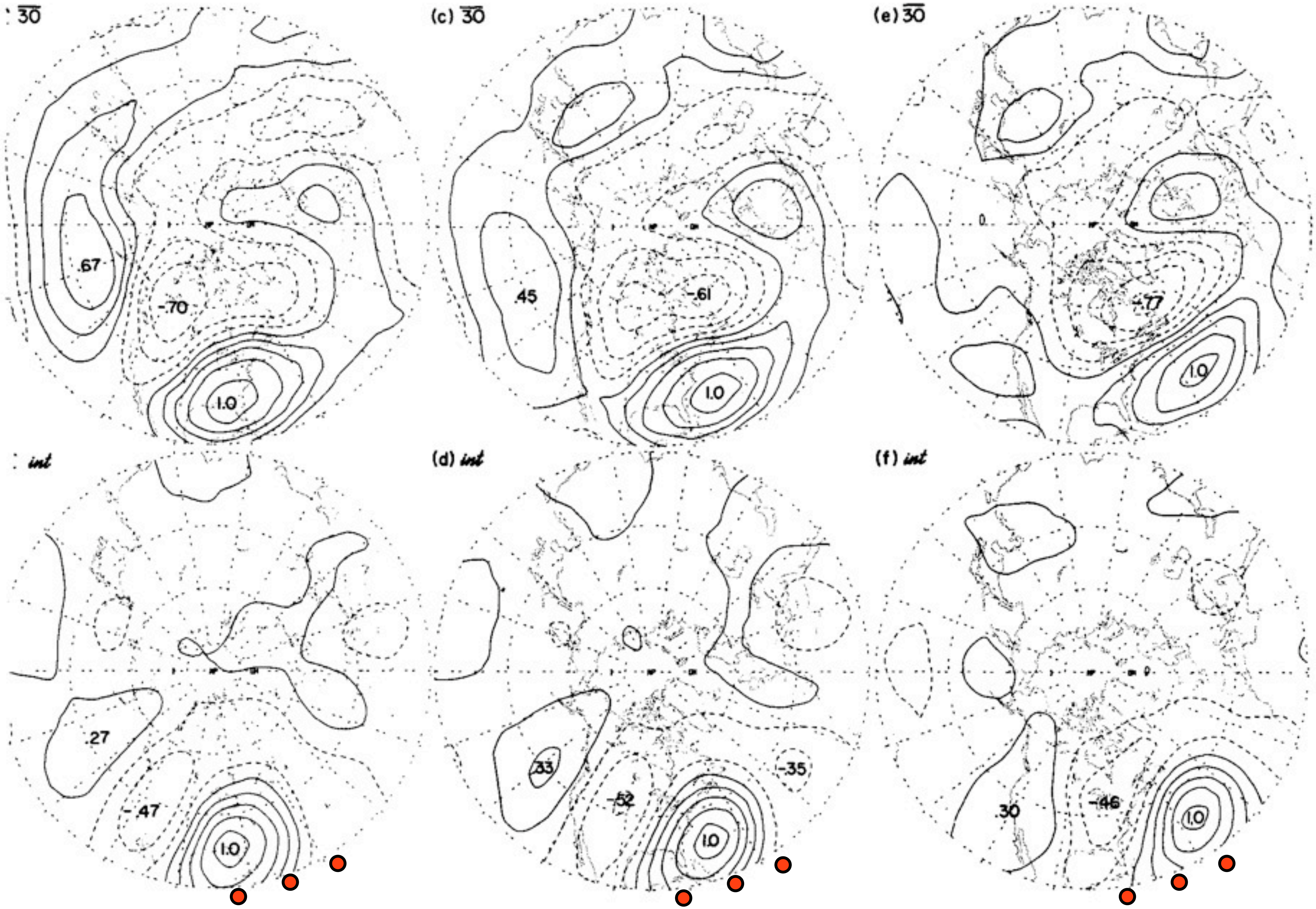
Then

$$C_K = \left(\overline{v'^2} - \overline{u'^2}\right)\frac{\partial \bar{u}}{\partial x} - \overline{u'v'}\frac{\partial \bar{u}}{\partial y} = \vec{E} \cdot \nabla \bar{u}$$

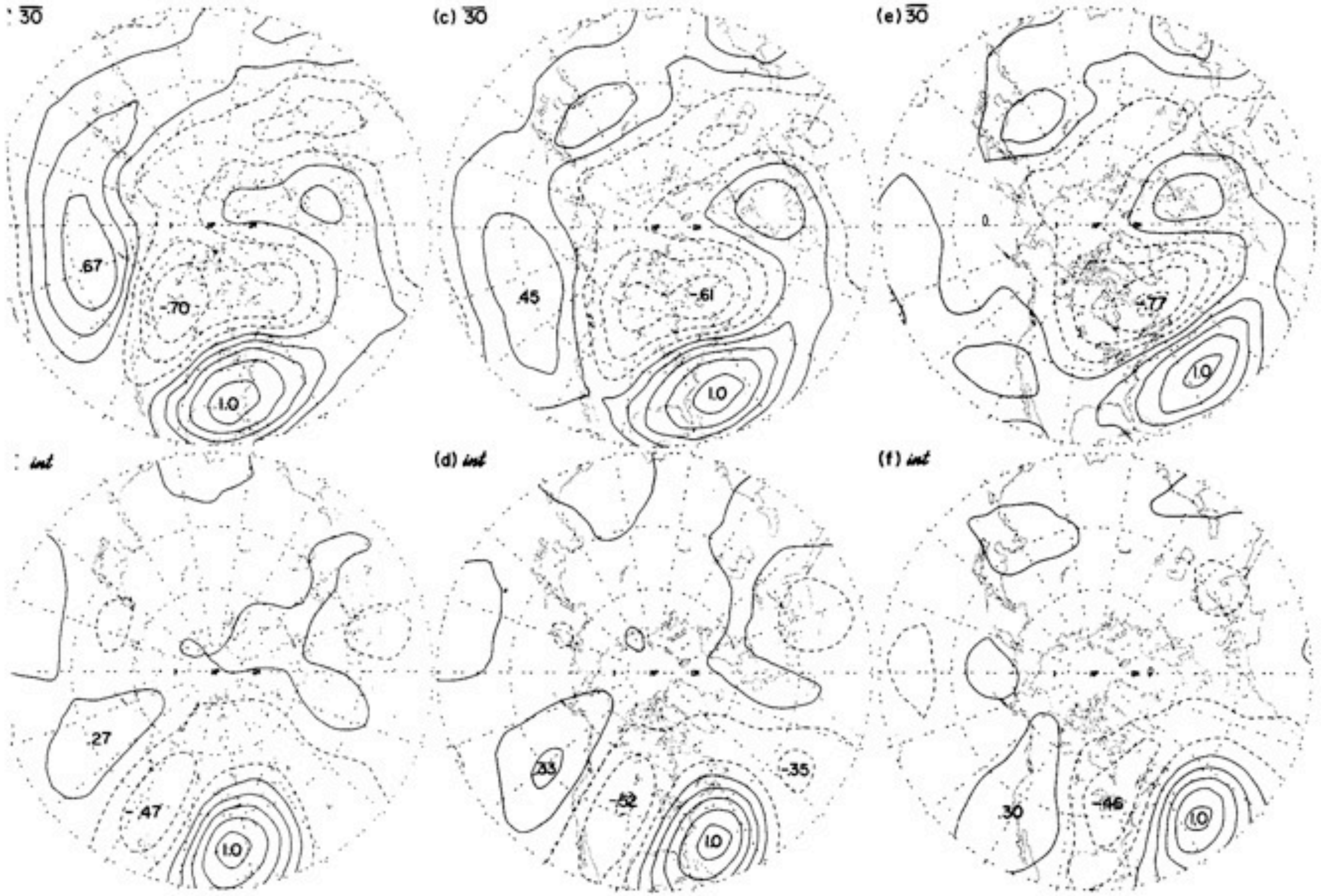
If $\vec{E}$ is up the gradient of $\bar{u}$, then the flux is downgradient and the transients are gaining KE at the expense of the time mean flow.



2.5 to 6 d
(c)
(d)
150 m² s⁻²
SCALE
$K_M \leftarrow K_T$
< 6 d
$\vec{E} \cdot \nabla \bar{u}$
$K_M \rightarrow K_T$
>30 d



After Blackmon et al., JAS, 1984a



Indication of geographically-fixed patterns

Pattern moves with reference grid point

Suggests the existence of "teleconnection patterns"

After Blackmon et al., JAS, 1984a