Mid-Latitude Transient fluctuations in the atmosphere – baroclinic instability, storm tracks and their transports

*(or: **How do they transport energy ?**)*

-- Barotropic and Baroclinic instability of zonally averaged basic state

-- Local zones of high baroclinicity (vertical shear) influences locus of storms (storm tracks)

-- Method of statistically focusing on baroclinic disturbances

-- Structure of synoptic disturbances is such as to transport heat and moisture

-- Estimates of growth rates

-- Difference in behavior of cyclones and anticyclones

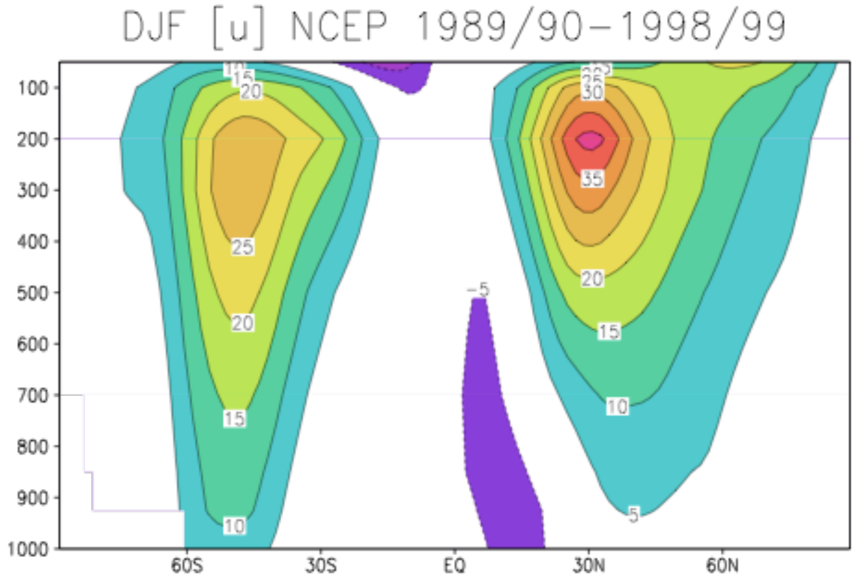
-- Feedback of baroclinic high frequency fluxes of heat and momentumto the time mean general circulation

-- The origin of the Ferrel Cell (or at least one origin)

Vertical shear
Baroclinic instability

Horizontal shear
Barotropic instability

pressure



Sub-tropical jets are present in both hemispheres.

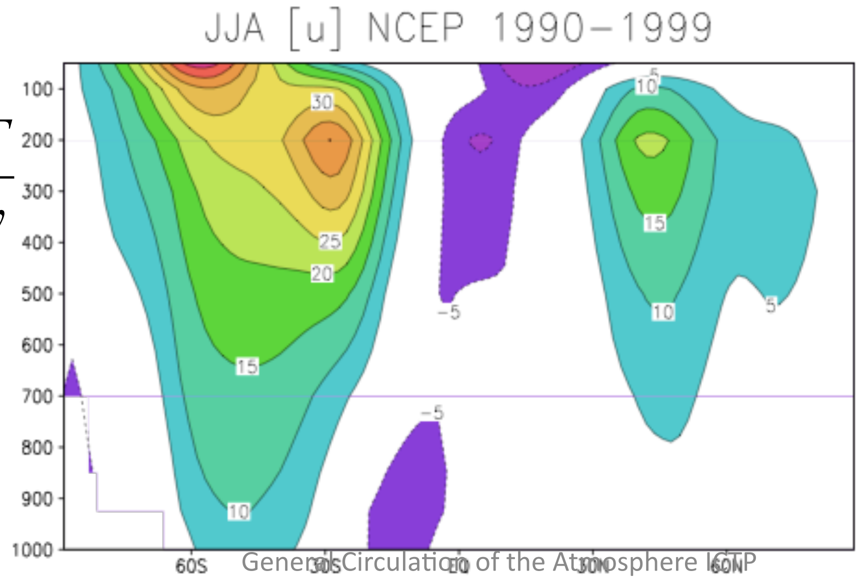
The vertical wind shear is maximum at those latitudes where d[T]/dy is most negative (thermal wind relationship)

The jets shift poleward in summer, equatorward in winter

[u] vs. p from NCEP reanalysis: DJF mean, JJA mean

$$\frac{\partial U}{\partial z} = -\left(\frac{R}{Hf}\right)\frac{\partial T}{\partial y}$$

$$f = 2\Omega \sin(\phi)$$



Note the easterlies in the tropics. Since the surface wind acts as a stress on the surface, the distribution of surface easterlies and westerlies is connected to the angular momentum budget of the earth-atmosphere system.

Instability of zonally symmetric *basic states* to small wave-like perturbations

Barotropic instability:

- Growth of kinetic energy of eddies from zonal mean momentum [u]
- *Necessary* conditions for barotropic instability:

    One possibility it that the meridional gradient of barotropic potential vorticity $(\beta - [u]_{yy})$ changes sign in the interior

    This does not usually happen!

-Baroclinic instability:

- Growth of eddy available potential and kinetic energy from available potential energy of the full zonal mean state [u], [T]
- Necessary condition is that meridional gradient of (quasi-geostrophic) potential vorticity change sign in the interior: This does happen!

1 Quasi-geostrophic potential vorticity

The meridional gradient of potential vorticity in quasi-geostrophic dynamics is:

$$\frac{\partial[q]}{\partial\mu} = \left(2\Omega - \frac{1}{a}\frac{\partial^2}{\partial\mu^2}\left([u]\cos\phi\right)\right) \tag{1}$$

$$+ \frac{aH^2 f^2}{RP}\frac{1}{(1-\mu^2)}\frac{\partial}{\partial Z}\left(\frac{e^{-Z/H}}{S}\frac{\partial}{\partial Z}\left([u]\cos\phi\right)\right) \tag{2}$$

where μ is the sine of latitude, ϕ latitude, Ω the rotation frequency of the earth about its axis, a the earth's radius, $P = p/p_0$, and $Z = H\,log\left(\frac{p_0}{p}\right)$ with $H = 10$ km, and $p_0 = 1000\,hPa$. The static stability S is:

$$S = \frac{d[T]}{dZ} + \frac{R}{C_p}[T] \tag{3}$$

where R is the gas constant and C_p the specific heat of air at constant pressure.

Application to the observed atmosphere? What do we use for the basic state?

(a) Even ignoring stationary waves, a zonally symmetric atmosphere without transient eddies could not exist, because such an atmosphere would be baroclinically unstable to wave-like disturbances – which would grow in the presence of a strong temperature gradient, and would act to reduce that temperature gradient.

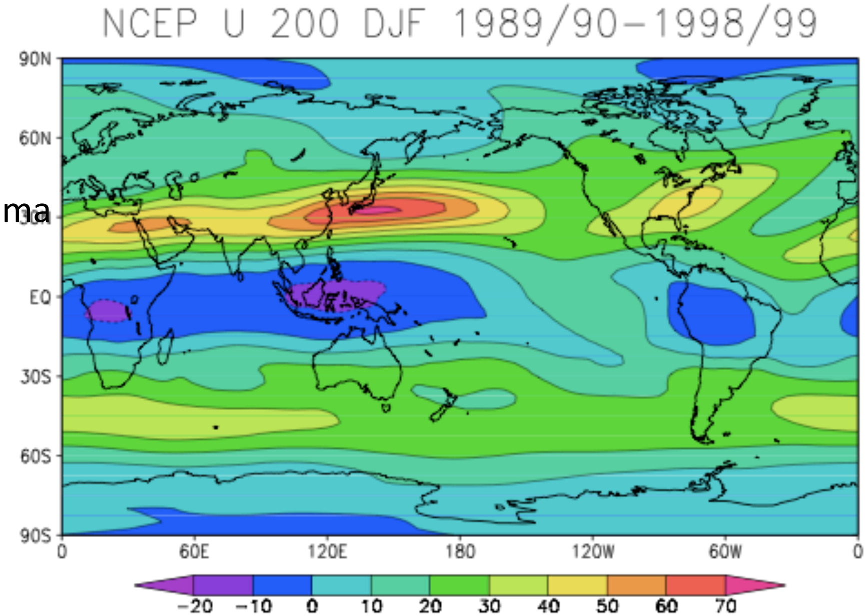
(b) The final *statistical* equilbrium would have transient waves growing and decaying, and a smaller temperature gradient (i.e. the one that we observe).

(c) But even this temperature gradient is unstable some places and at same times.

(d) So the basic state of relevance is probably the observed time mean.

(e) Furthermore, the instabilities of greatest interest are not those of the zonally averaged time mean, but of the local time mean. Here there *is* some relevance for barotropic instability.

Well defined local maxima (jets) in NH winter are regions of high vertical shear du/dz and hence instability

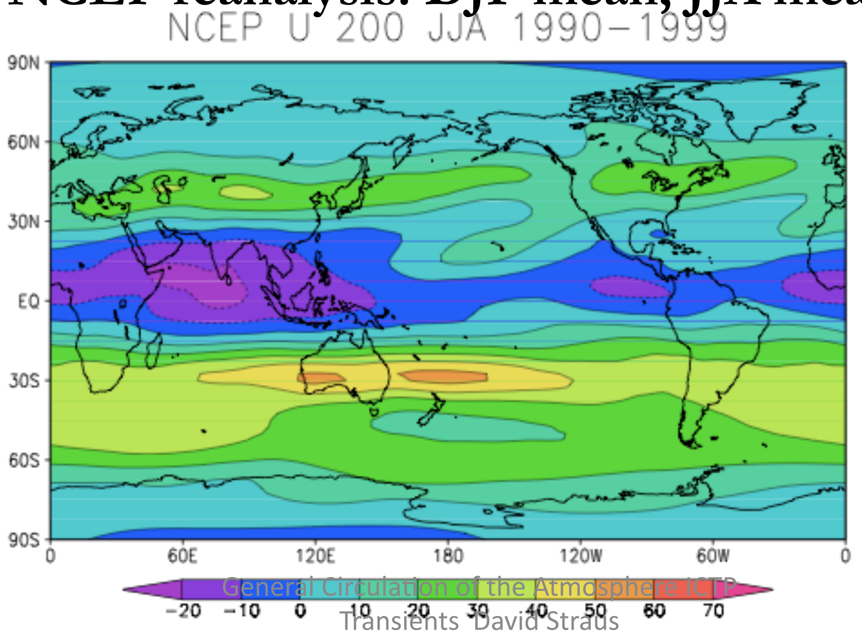


More complete indicator of baroclinically unstable regions would be the ratio of du/dz to the static stability S.

But this does not change the qualitative nature of the picture

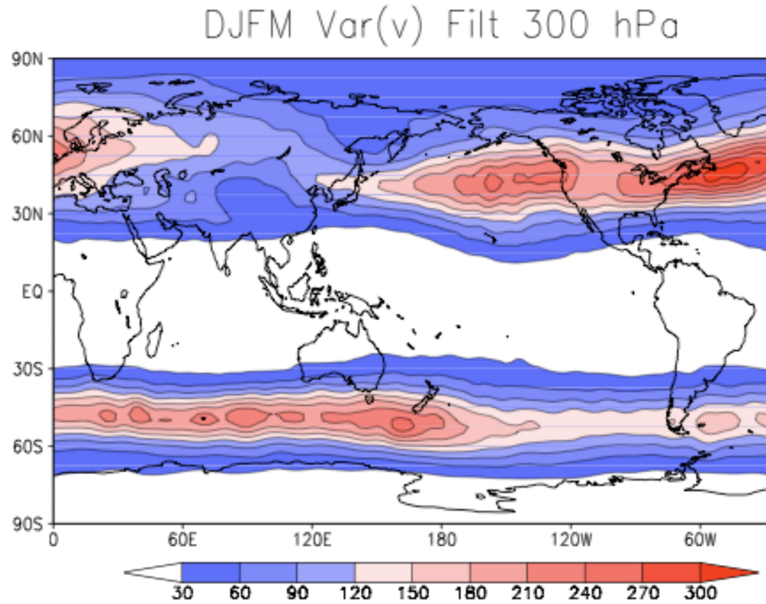
200 hPa u-wind NCEP reanalysis. DJF mean; JJA mean

Broader maxima (jets) in SH winter



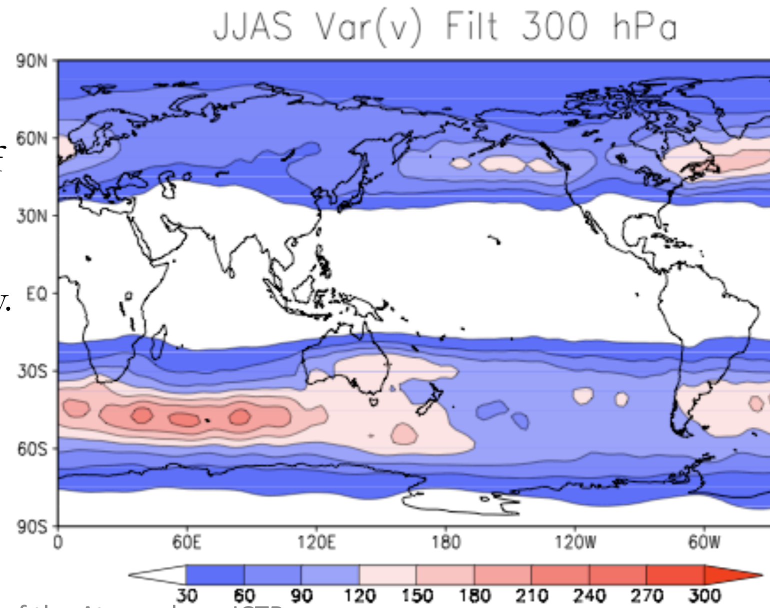
Baroclinic Transient Fluctuations (periods of 2-10 days)

"Storm Tracks"



300 hPa filtered v-wind variance gives one indication of where baroclinic activity is the strongest.

In NH winter, see strong activity downstream and poleward of maximum shear. (In SH there we see no correspondence between longitude of maximum baroclinic activity and longitude of maximum u).



Measured by focus on fluctuations with time scales of 2 - 10 days:

- For each point and each winter (or summer), remove signalof the annual cycle in meridional wind v.
- Apply digital filter to anomalies to retain only periods of 2 to 10 days (approximately).
- Compute variance of filtered anomalies for each of 18 winters: 1981/82 - 1998/99 from NCEP reanalysis (or 18 summers: 1982-1999).
- Average variance map over 18 seasons

One paradigm of a developing baroclinic system

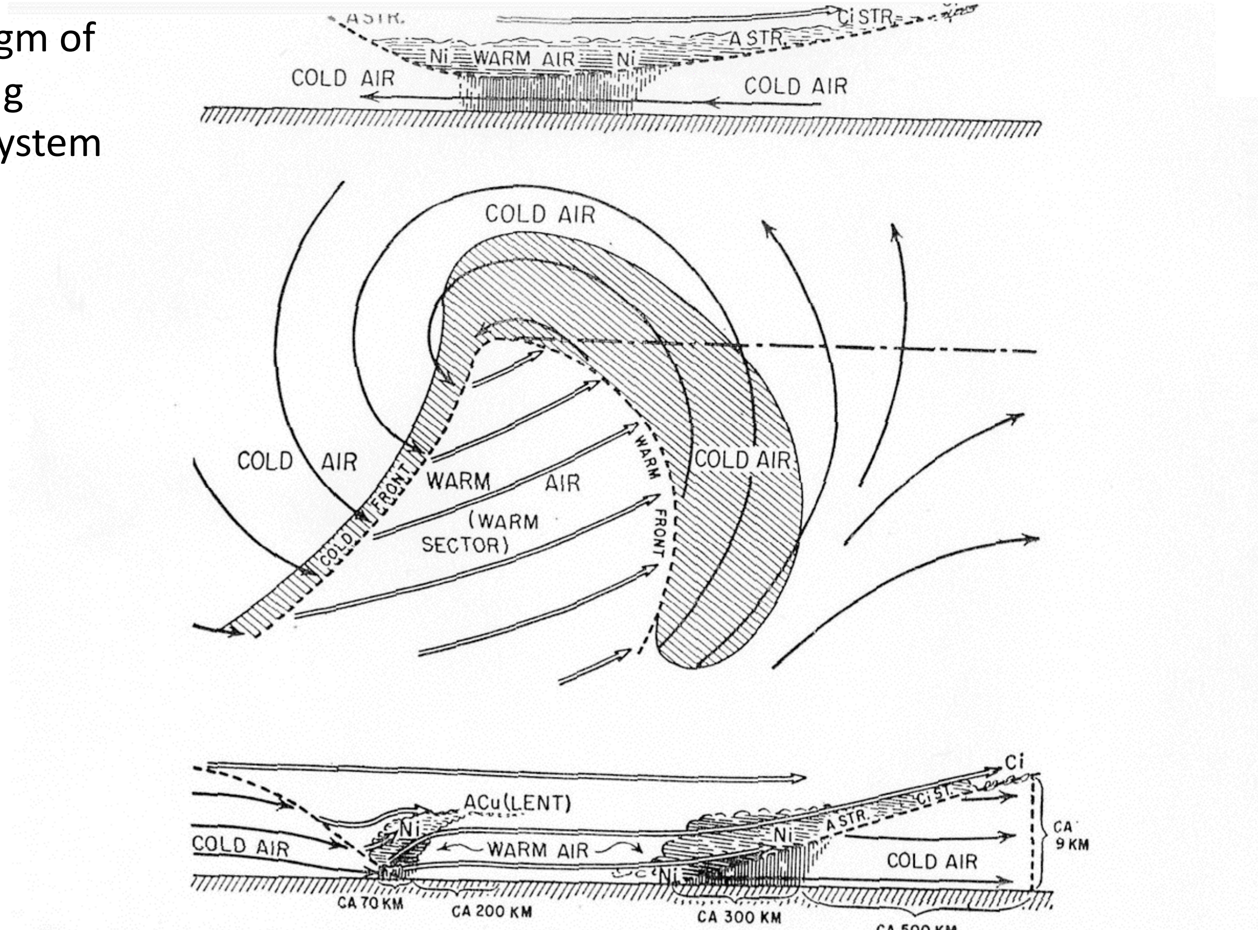
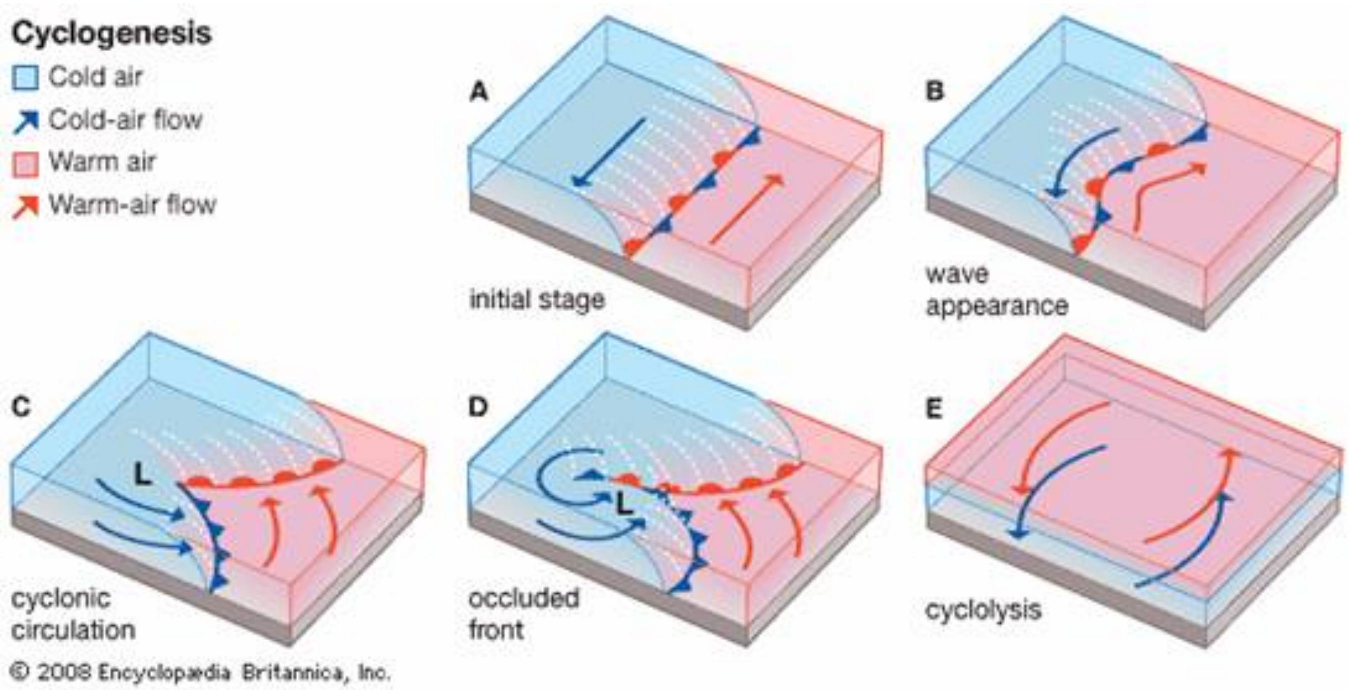


FIG. 12.1.4. Bjerknes' cyclone model. For convenience, this diagram has been reproduced from Bjerknes and Solberg (1921); it contains slight modifications as compared with the original model of J. Bjerknes, 1918.

From: "Weather Analysis and Forecasting, Vol I" by Sverre Petterssen, McGraw-Hill, New York, 1956

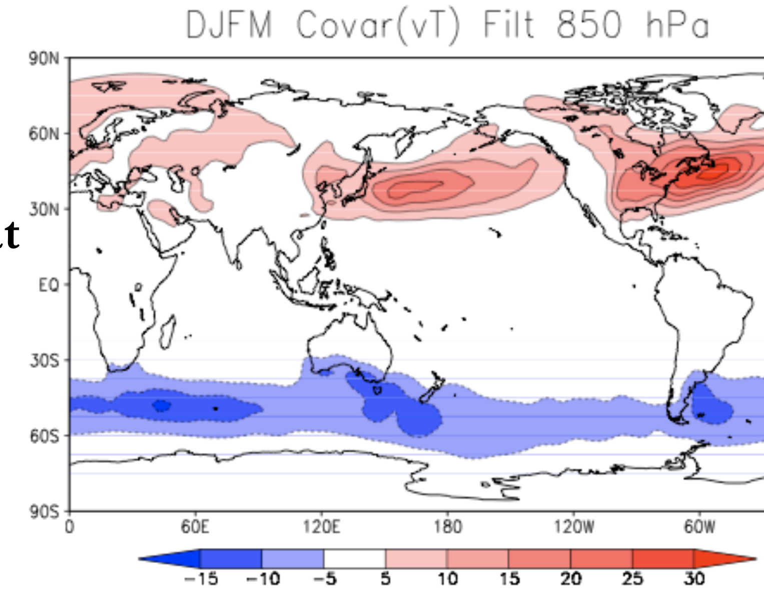


http://www.people.fas.harvard.edu/~pkatai/midlat_structure.htm

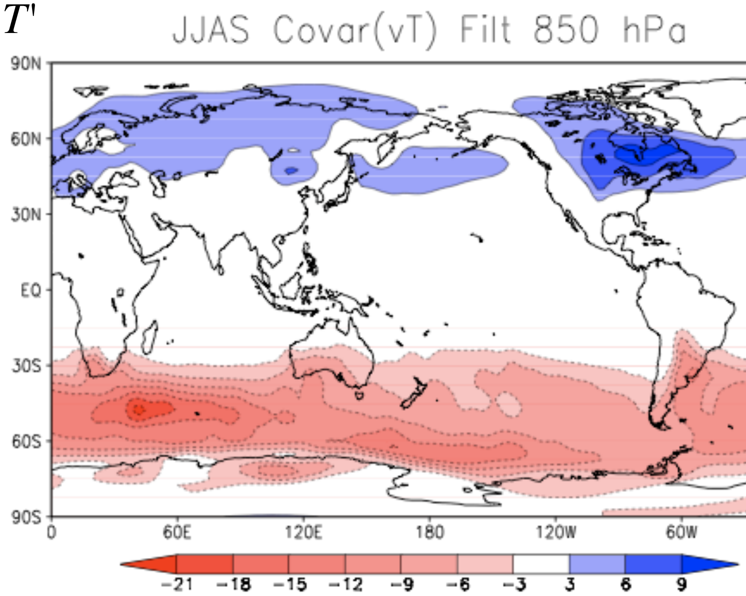
Baroclinic Transient Fluctuations: Their role in the general circulation. Meridional transport of sensible heat

850 hPa covariance between filtered v-wind and temperature T gives another indication of where baroclinic activity is the strongest. This shows a major contribution to the poleward flux of sensible (thermodynamic) heat by the transient eddies.

Units: m/sec °K



$\overline{v'T'}$

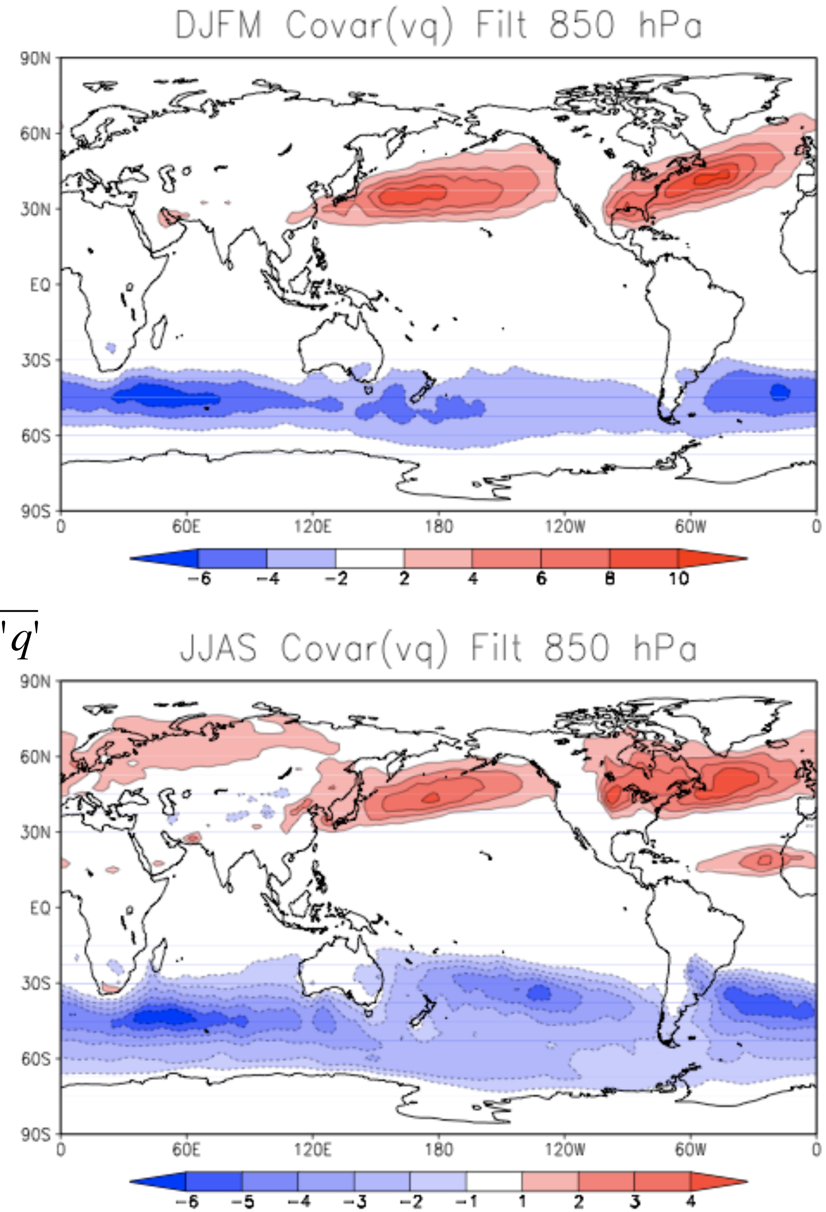


Baroclinic Transient Fluctuations: Their role in the general circulation. Meridional transport of moisture

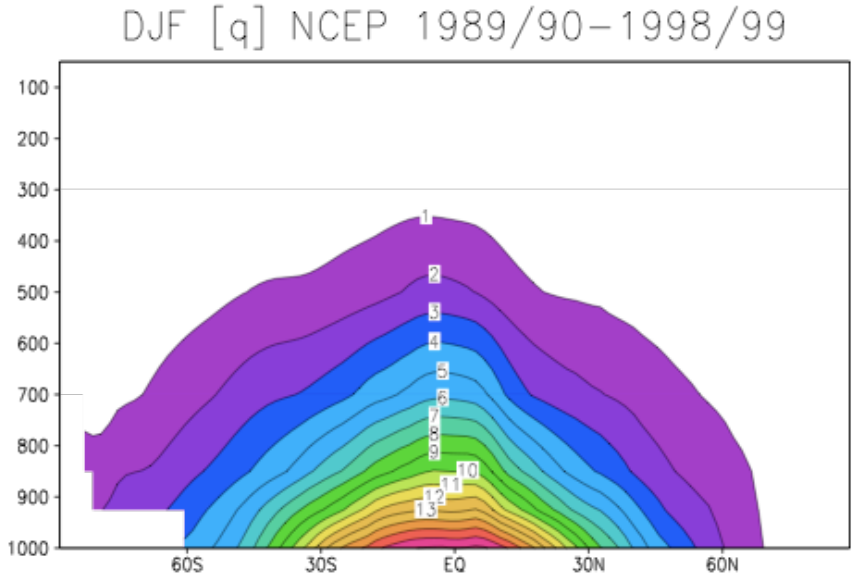
850 hPa covariance between filtered v-wind and moisture q gives an alternate indication of where baroclinic activity is the strongest. Compared to the heat flux, the maxima are further equatorward. Please note the continental extensions of the maximum flux over Asia and especially eastern North America.

Units: m/sec x g/kg

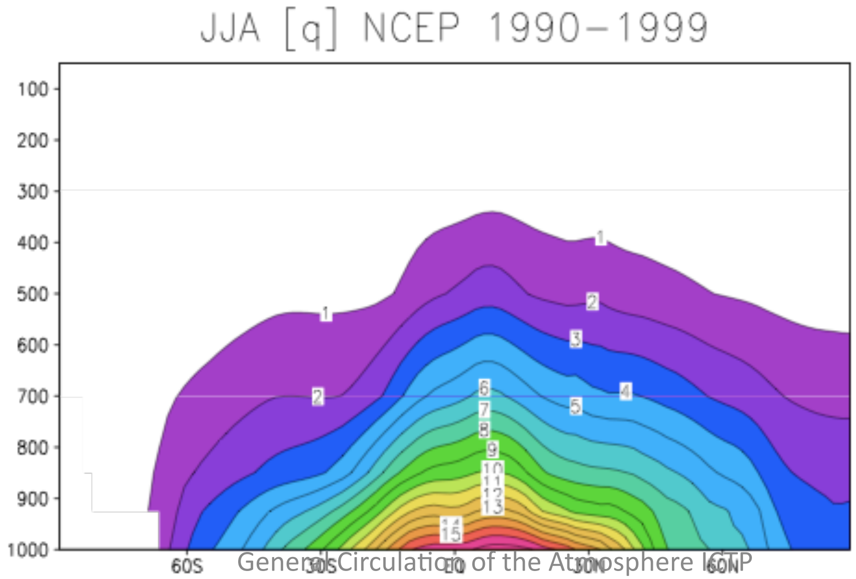
$\overline{v'q'}$



Units: g (water) per kg (air)



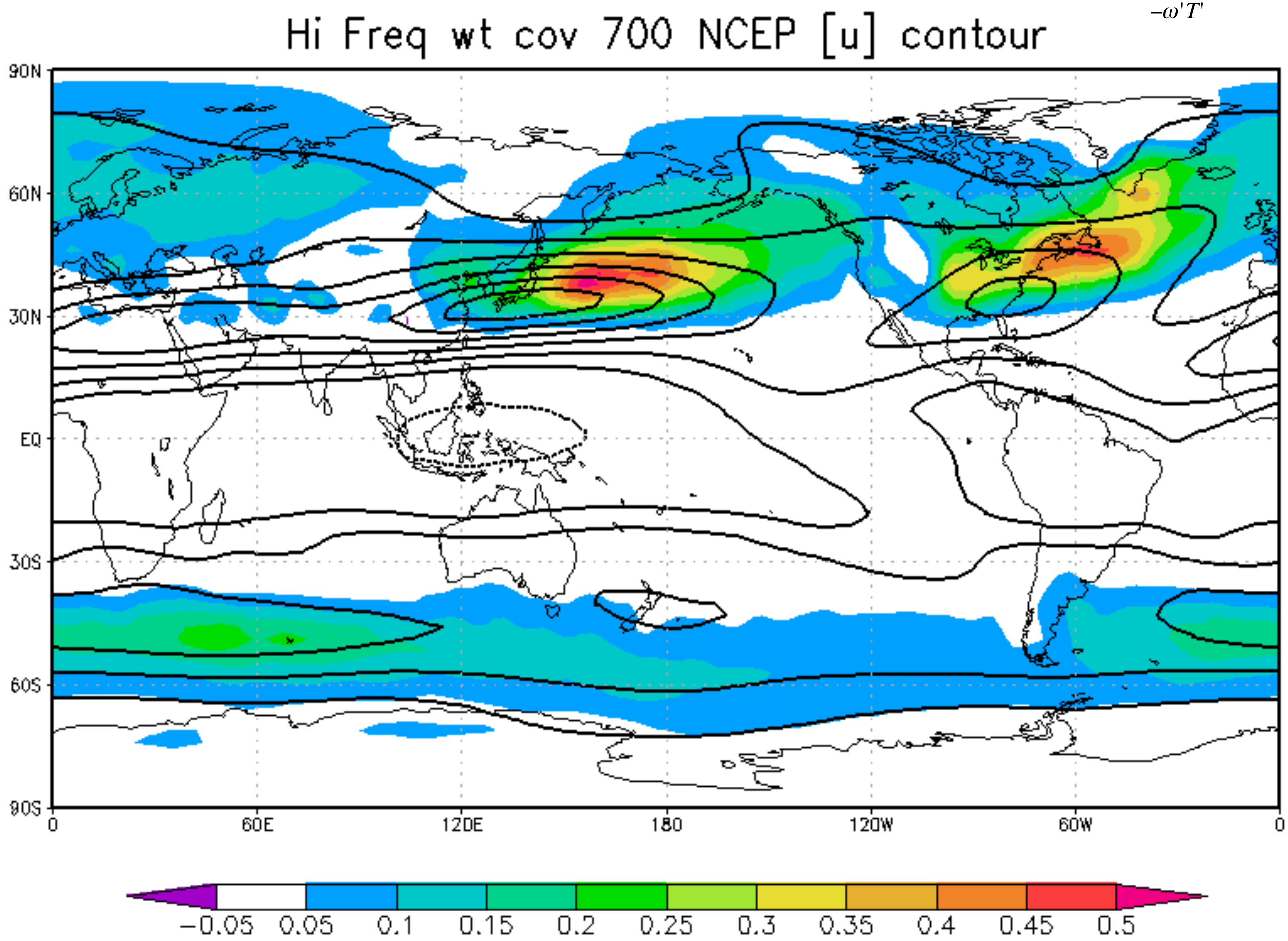
[q] vs. p from NCEP reanalysis: DJF mean, JJA mean



Specific humidity: typical value in tropics = 0.02 kg/kg

Upward sensible heat transport

$-\overline{\omega' T'}$



1 FEBRUARY 1988 JOHN M. WALLACE, GYU-HO LIM AND MAURICE L. BLACKMON 439

Relationship between Cyclone Tracks, Anticyclone Tracks and Baroclinic Waveguides

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(Manuscript received 24 March 1987, in final form 4 September 1987)

(1) Statistical estimate of average growth rates
(2) The difference in the behavior of cyclones and anti-cyclones

Simple statistical analysis of *average* growth rates of barclinic disturbances at a single grid point in mid-latitiudes (westerly flow)

(a) Form the filtered series of geopotential height Z
(b) Remove seasonal mean of Z to obtain Z', and divide by its temporal standard deviation (σ) to obtain $z = Z' / \sigma$. This is called a standardized series.
(c) Compute the lag correlation of zs at this point with all other grid points a day earlier (lag = - 1) and a day later (lag = +1)
(c) For lag = - 1, you will find the maximum correlation occurs at an upstream point – call the standardized series at this grid point zu
(d) For lag = +1, you will find the maximum correlation occurs at a downstream point – call this series zd
(e) Then form the linear regressions:

$zu = \alpha z + \varepsilon u$ α is the regression coefficient εu the error to be minimized

$zd = \beta z + \varepsilon d$

(f) The growth rate, or estimated rate of amplification at our single grid point is then given by:

$(\beta - \alpha) / 2$ (units are meters/day)

Note the rate of amplification in the portions of the storm tracks downstream from the jet maxima (largest vertical shear) tends to be negative!
In these regions baroclinic disturbances decay!

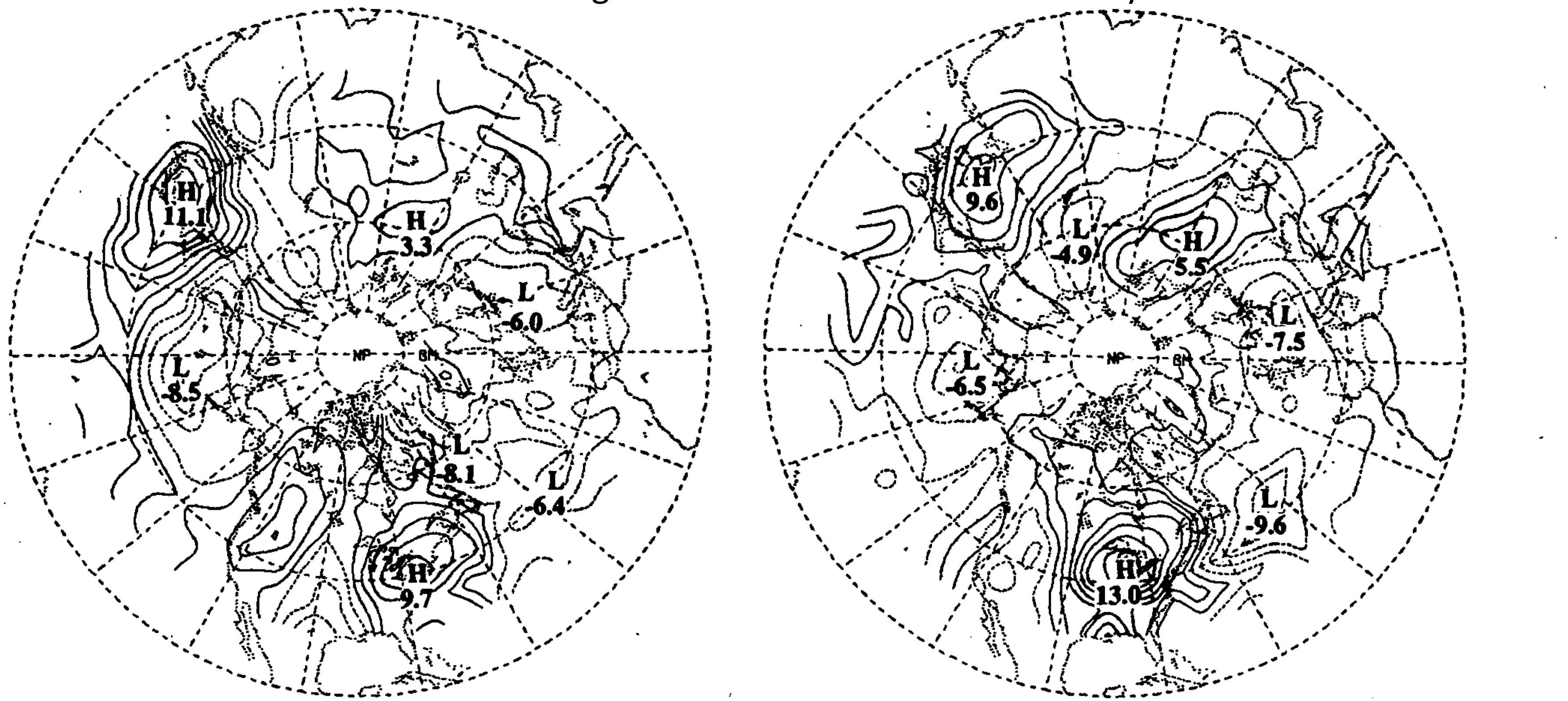


FIG. 10. Rate of amplification or decay of moving disturbances in the highpass-filtered (left panel) 1000 and (right panel) 500 mb height field as inferred from the method described in section 4d. Contour interval 2 m of geopotential height per day; negative contours are dashed.

Distingushing evolution of anticylones (high pressure systems) from cyclones (low pressure systems). A simple method.

Cyclones:

Find all dates at which the filtered 1000 hPa height field at one grid point are more than two standard deviations <u>below</u> normal:

Z' < 2s

Then average the maps obtained for those dates, and also the dates 2 days previously, 1 day previously, 1 day subsequently and 2 days subsequently.

This gives you an average evolution of a *low pressure system*

Anticyclones:

Find all dates at which the filtered 1000 hPa height field at one grid point are more than two standard deviations <u>above</u> normal:

Z' > 2s

Then average the maps obtained for those dates, and also the dates 2 days previously, 1 day previously, 1 day subsequently and 2 days subsequently.

This gives you an average evolution of a *high pressure system*

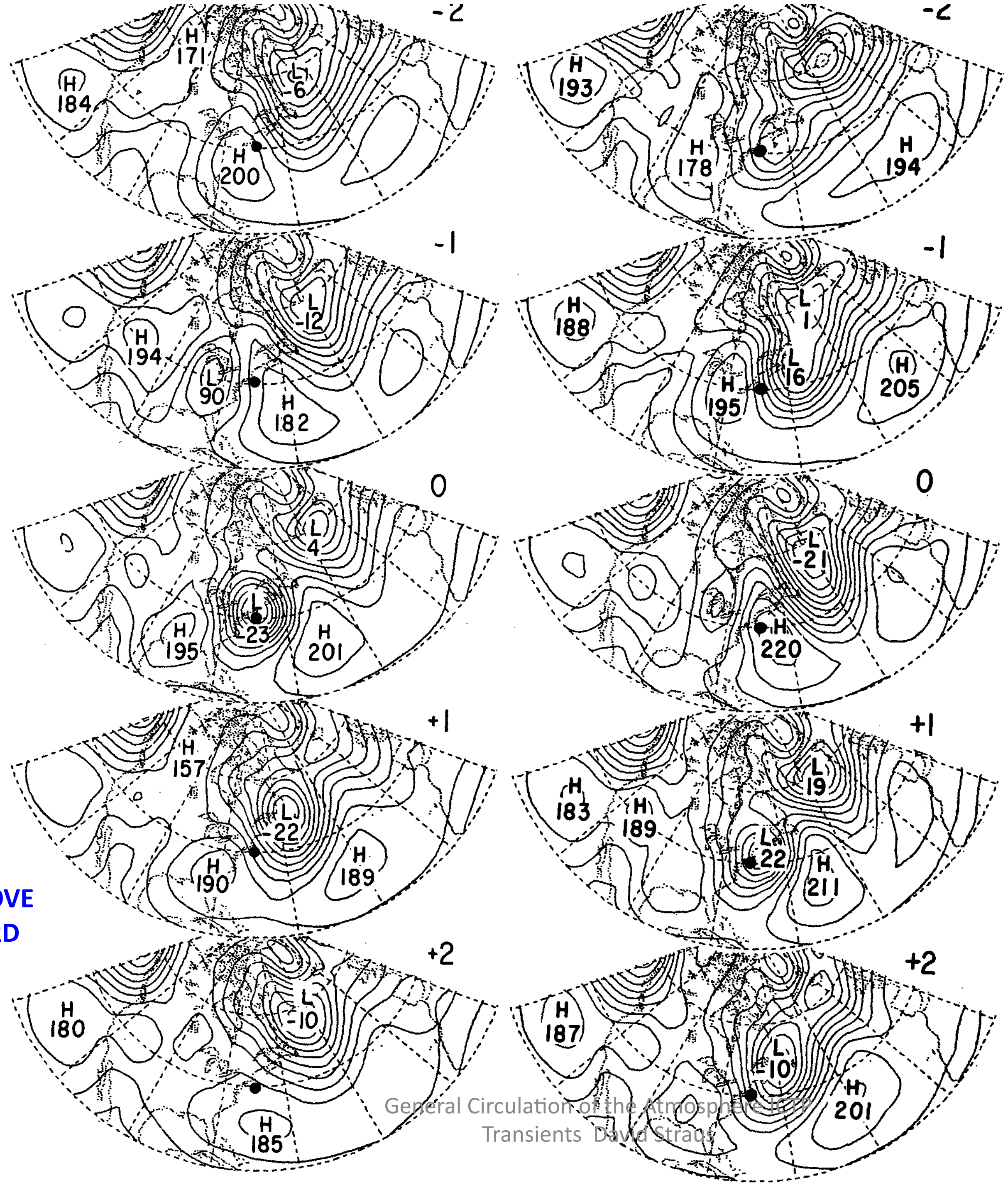


FIG. 14. Composite maps for the unfiltered 1000 mb height field based on key dates at which highpass-filtered 1000 mb height at the base gridpoint (40°N, 70°W) is more than two standard deviation below zero (left panels) and above zero (right panels). Lag in days, relative to

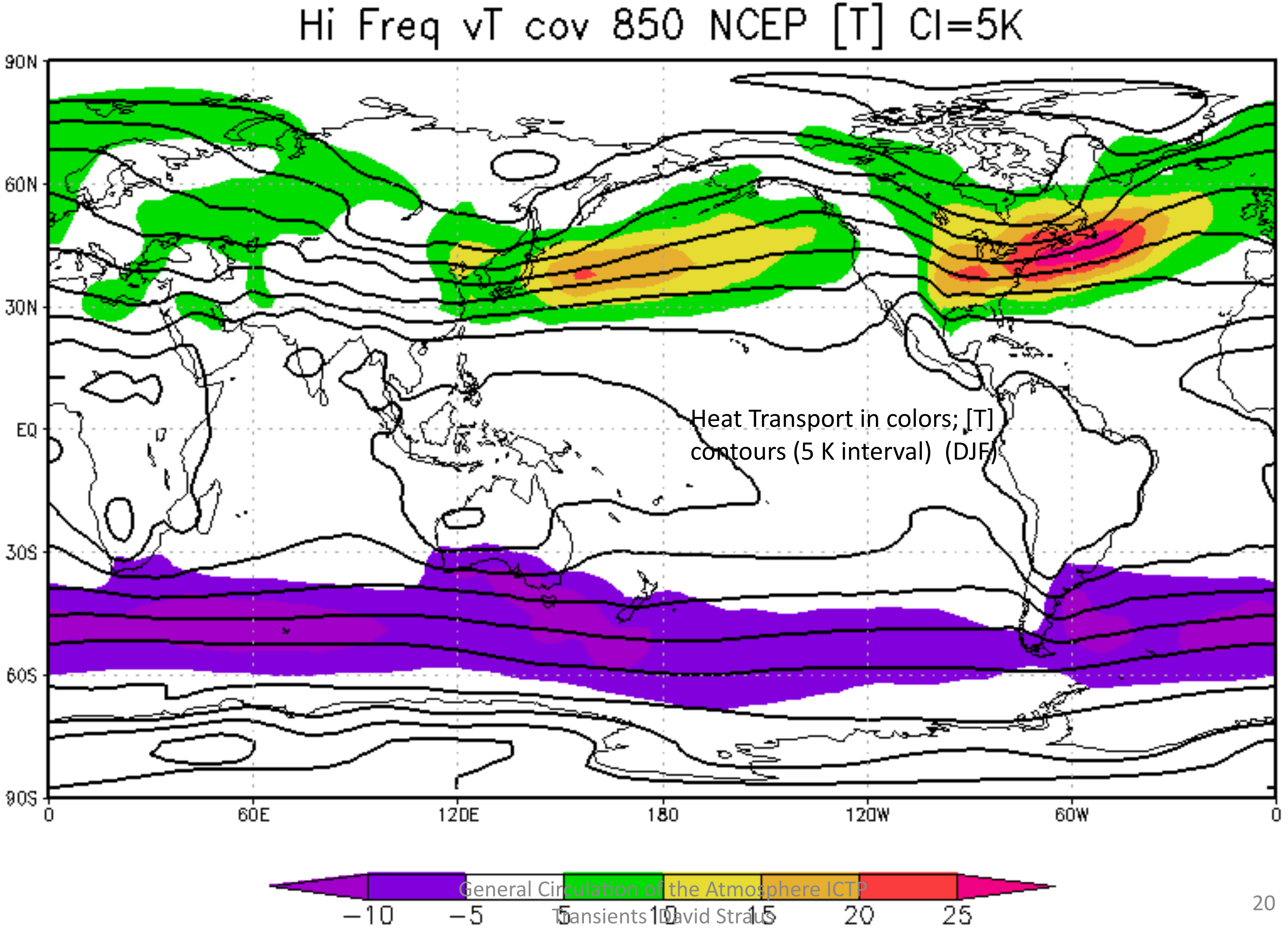
LOWS MOVE POLEWARD

HIGHS MOVE EQUATORWARD

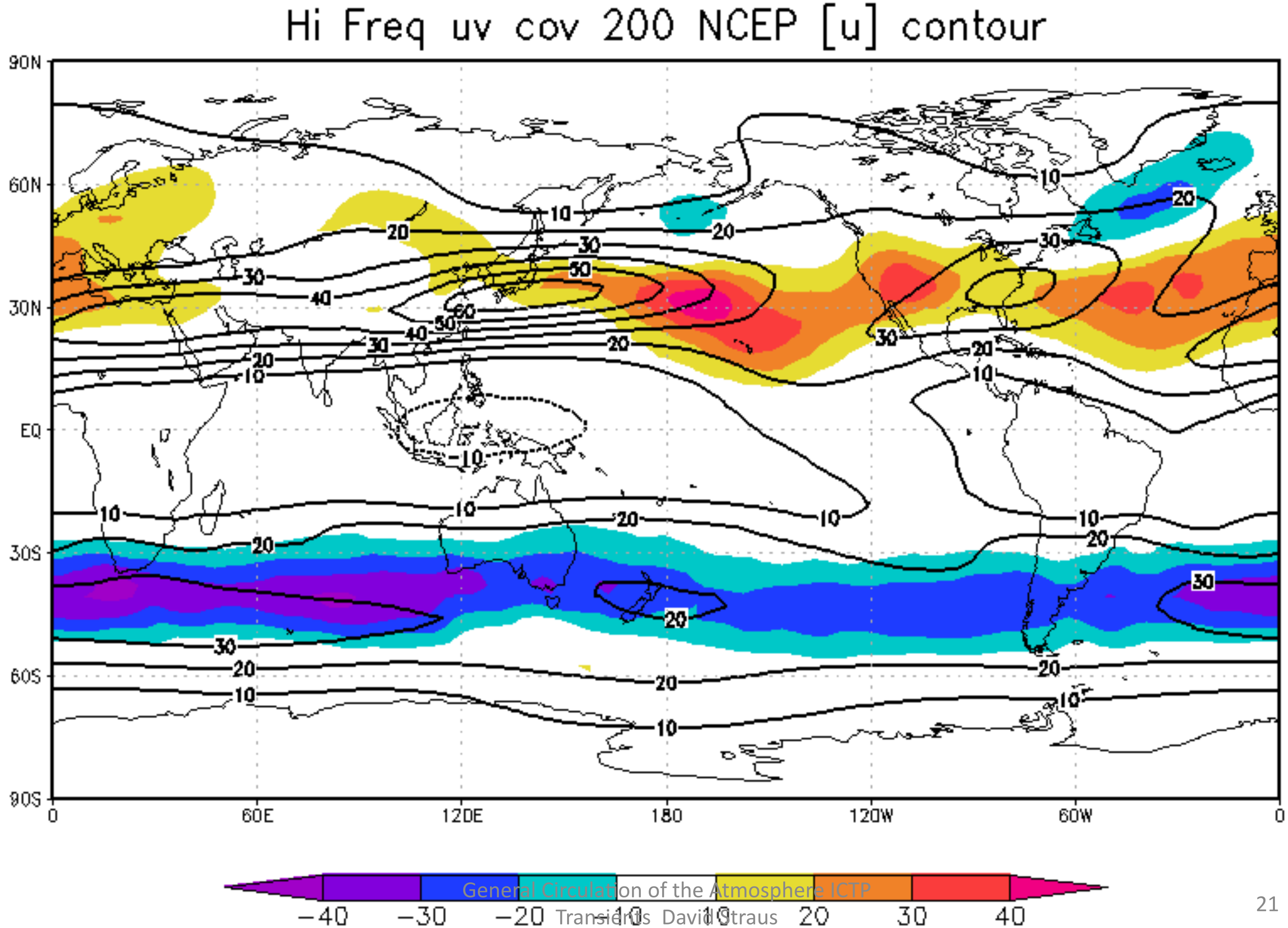
Grid point is 40N 70W (near NYC)

Feedback of baroclinic high frequency fluxes of heat and momentum to the time mean general circulation

Horizontal Heat transport by baroclinic waves tends to smooth out temperature gradient



Horizontal transport of eastward momentum by baroclinic waves tends to move jets poleward

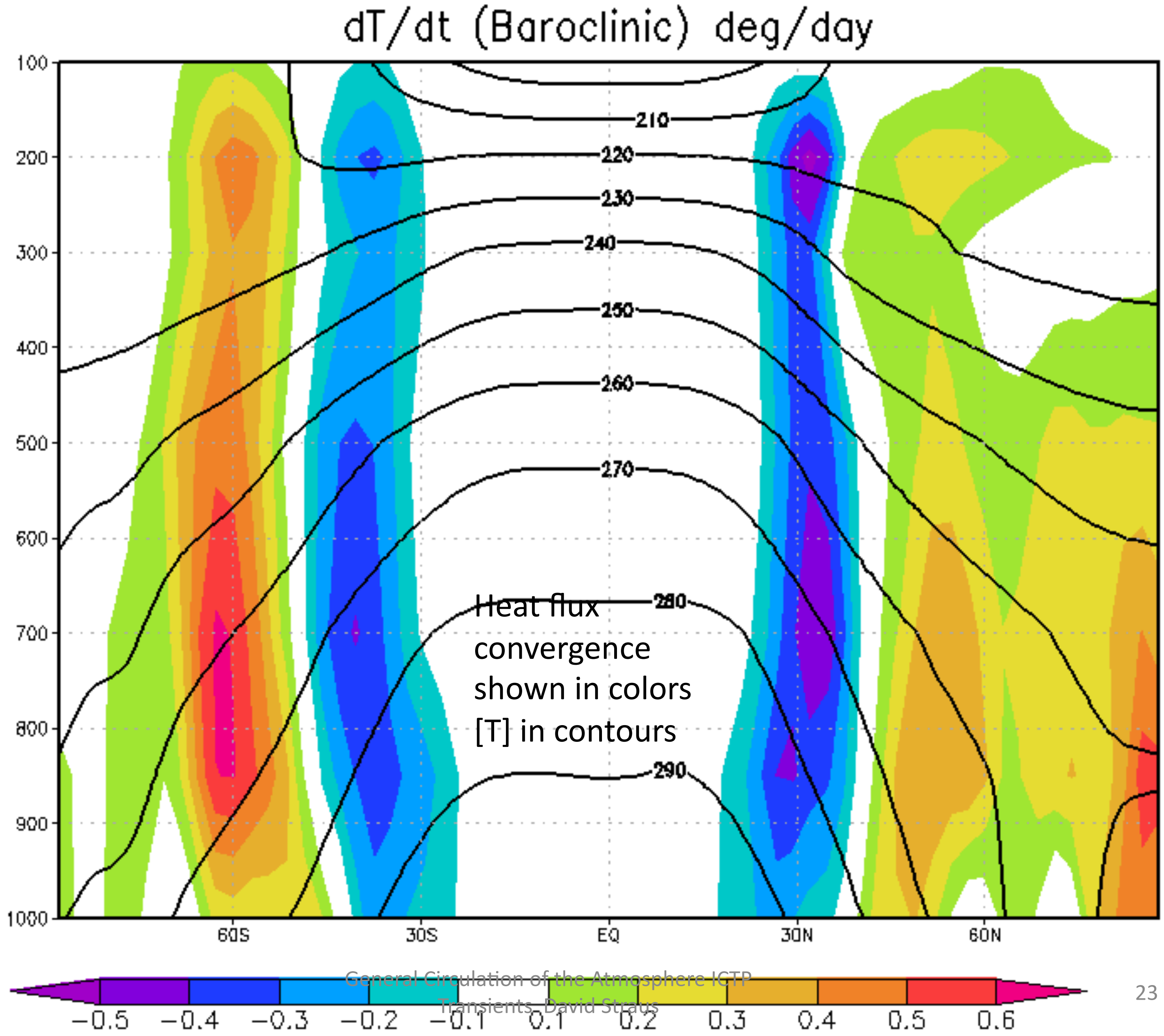


“Direct” effect of baroclinic waves on zonal mean of temperature [T} and barotropic component of [u]:

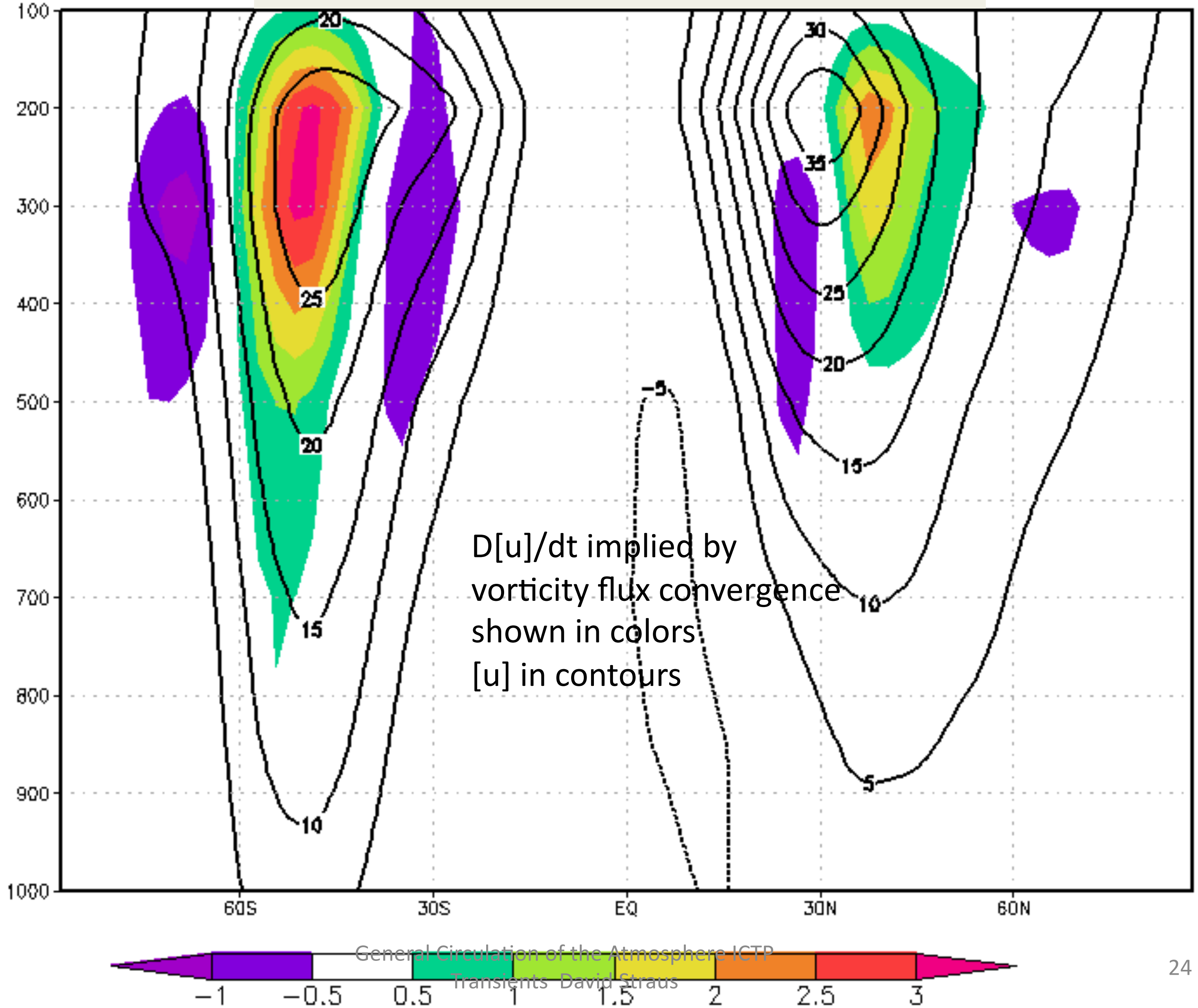
$$\frac{\partial[T]}{\partial T} = \ldots - \frac{1}{a\cos(\phi)}\frac{\partial}{\partial\phi}\left(\left[\overline{v'T'}\right]\cos(\phi)\right)$$

$$\frac{\partial[\psi]}{\partial t} = \ldots - \nabla^{-2}\frac{1}{a\cos(\phi)}\frac{\partial}{\partial\phi}\left(\left[\overline{v'\zeta'}\right]\cos(\phi)\right)$$

There is also an “indirect” effect due to the mean meridional circulation induced by the baroclinic waves (we will see an example of this later)


dT/dt (Baroclinic) deg/day
100
200
300
400
500
600
700
800
900
1000
60S
30S
EQ
30N
60N
210
220
230
240
250
260
270
280
290
Heat flux
convergence
shown in colors
[T] in contours
−0.5
−0.4
−0.3
−0.2
−0.1
0.1
0.2
0.3
0.4
0.5
0.6

du/dt barotropic) m/sec/day



An Observational Study of the Northern Hemisphere Wintertime Circulation[1]

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(Manuscript received 17 November 1976, in revised form 29 March 1977)

Induced mean meridional circulations

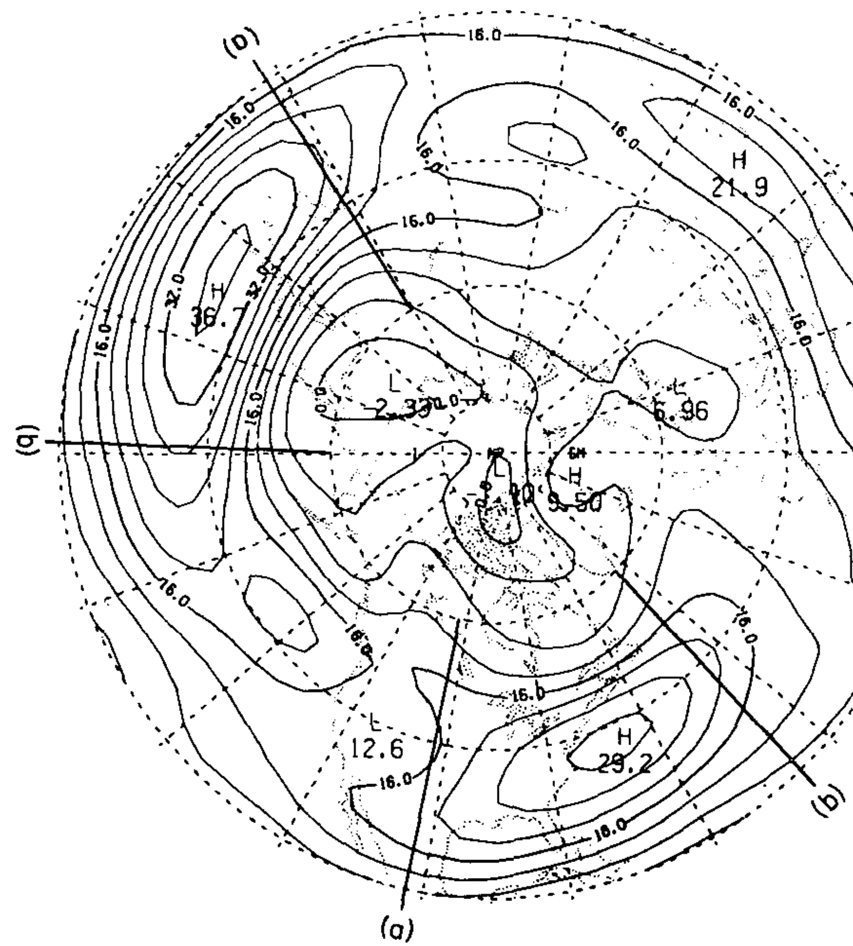
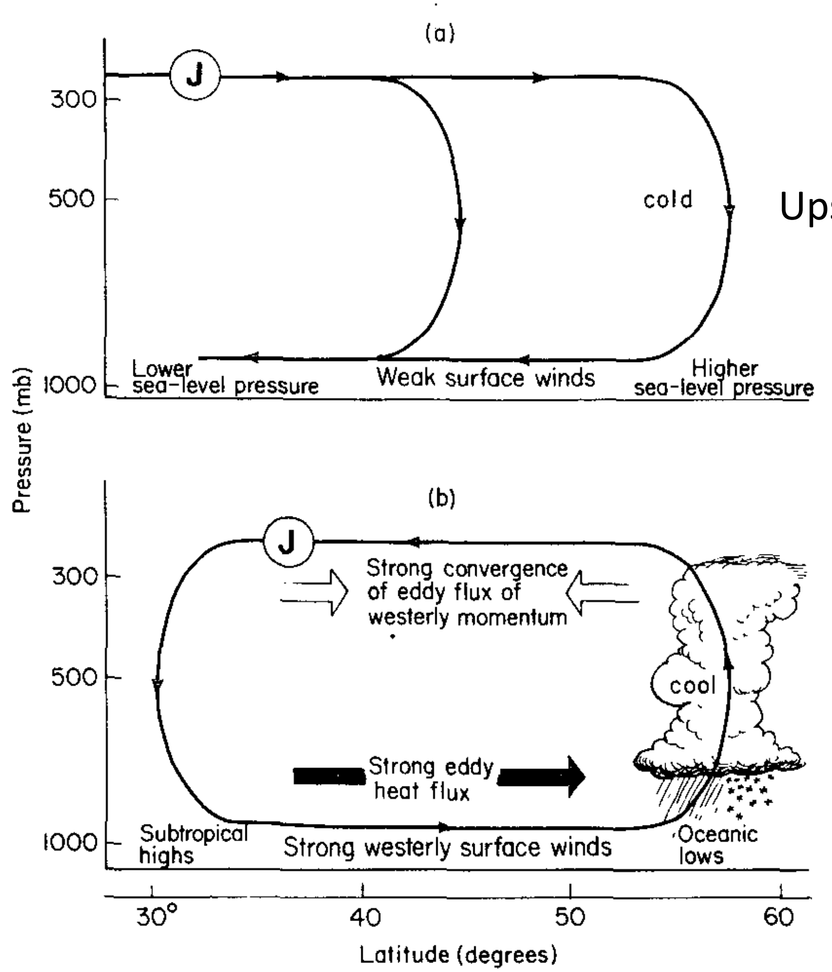


FIG. 6a. Nine-winter average 500 mb zonal wind speed; contour interval 4 m s^{-1}. See text (Section 8d) for interpretation of letters (a) and (b) on periphery of figure.

Upstream from jet core

Same sense as Ferrel Cell
Meridional circulation
helps to enforce thermal
wind relationship by
reducing horizontal wind
shear



Downstream from jet core

FIG. 15. Schematic illustration showing relationship between the jet streams (denoted by the letter J), the time-mean circulation transverse to the jet streams (continuous thin line with arrows), and the band-pass eddy fluxes of westerly momentum at the jet stream level (heavy white arrows) and heat at the 850 mb level (heavy black arrow), in cross-sections (a) upstream and (b) downstream from the jet cores.

$$\theta = \left(\frac{p_0}{p}\right)^{\kappa} T$$

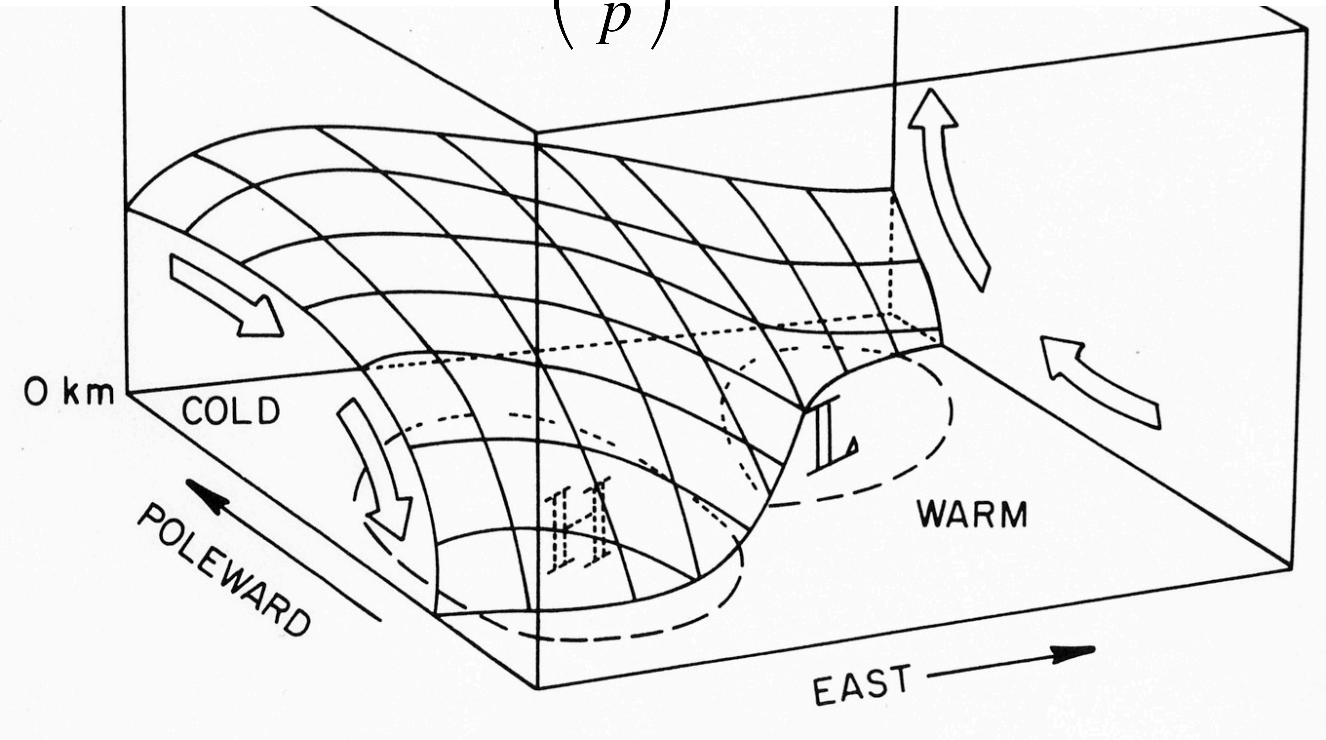


FIG. 3.18 Schematic diagram showing a sloping, three-dimensional isentropic surface and its relationship to developing high (H) and low (L) pressure centers. Schematic contours on the box bottom illustrate the surface pressure pattern. The double-shafted arrows show the meridional motion of air parcels in the warm and cold air sectors.

From: “Global Atmospheric Circulations: Observations and Theories”, Richard Grotjahn
Oxford University Press, New York, 1993