

The Atmospheric General Circulation

Lecture 10: The High Frequency Extratropical
Transients

热带外高频瞬变

Ming Bao

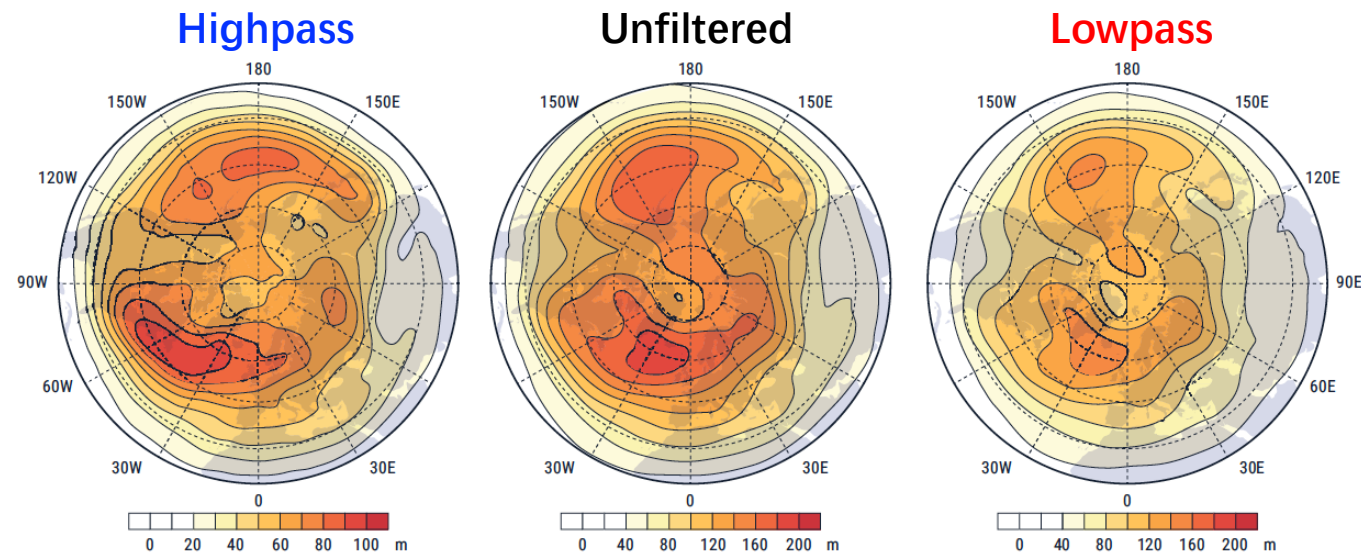
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Introduction

- **Transients:** variations about the seasonally varying climatological mean state
- At least 100 years ago, correlations statistics were restricted to the analysis of seasonal or annual mean time series at individual stations.
- From the late 1940s into 1960s, V. P. Starr and his colleagues were making extensive use of variance and covariance statistics based on daily data from a sparse and irregularly spaced global network of rawinsonde stations.
- During the early 1970s, it became feasible to calculate 3D fields of covariance statistics making use of newly available, objective analyzed, gridded data-sets archived by several of the world's operational centers for numerical weather prediction. Despite their limited accuracy, even the early operational analyses that were available prior to 1980 were capable of revealing the structure and evolution of the geopotential height and wind fields and qualitatively representing the gross features of the ageostrophic wind field.

1. Frequency Dependence and Anisotropy 各向异性: Observational Evidence

- **7 day highpass filtered data**: distinguishing the high frequency transients with periods shorter than about a week from the low frequency transients with longer periods.
- Variance maps expressed as standard deviation " $\sigma(Z_{500})$ ": **high frequency** perturbations exhibits zonally elongated maxima suggestive of "storm tracks" located slightly poleward and downstream of the climatological-mean jet streams; the maxima in variance of **low frequency** transients are farther downstream, extend farther poleward, and not as zonally elongated.



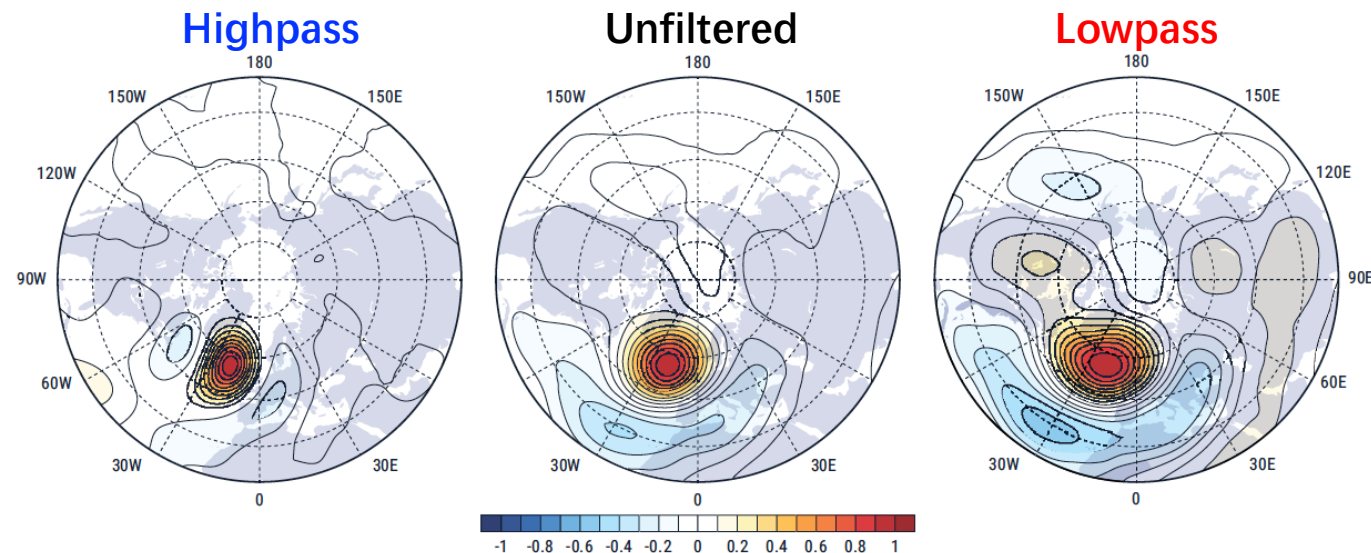
1. Frequency Dependence and Anisotropy 各向异性: Observational Evidence

- Making use of analysis techniques that reveal the structural distinctions between the low and high frequency fluctuations. The most basic of these tools is the *one-point correlation (or regression) map*.
- One-point correlation maps are created by correlating the time series of a prescribed variable at a prescribed “reference grid point” with time series of the same (or another) variable at grid points extending over the entire hemisphere or globe and mapping the resulting field. By construction, the correlation coefficient at the reference grid point is 1.0 and the correlations drop off with increasing distance from the reference grid point.
- If the correlations drop off more rapidly in one direction than along an axis perpendicular to it, that constitutes evidence of *anisotropy*, a systematic departure from isotropic behavior.
- A composite one-point correlation map (referred as a “horizontal structure function”) may be generated by “registering” a number of individual one-point correlation maps (i.e., shifting them so that their reference grid points coincide) and averaging them.

1. Frequency Dependence and Anisotropy 各向异性: Observational Evidence

- High (low) frequency transients are both quite anisotropic: meridionally (zonally) elongated.
- The structure of the high frequency transients is suggestive of a train of waves with a wavelength of about 4000 km. In contrast, the low frequency pattern is larger in horizontal scale and its shape is suggestive of a north-south dipole configuration.
- That the high and low frequency transients exhibit contrasting forms of anisotropy is a reflection of fundamental properties of Rossby wave propagation.

Z_{500} One-point correlations maps

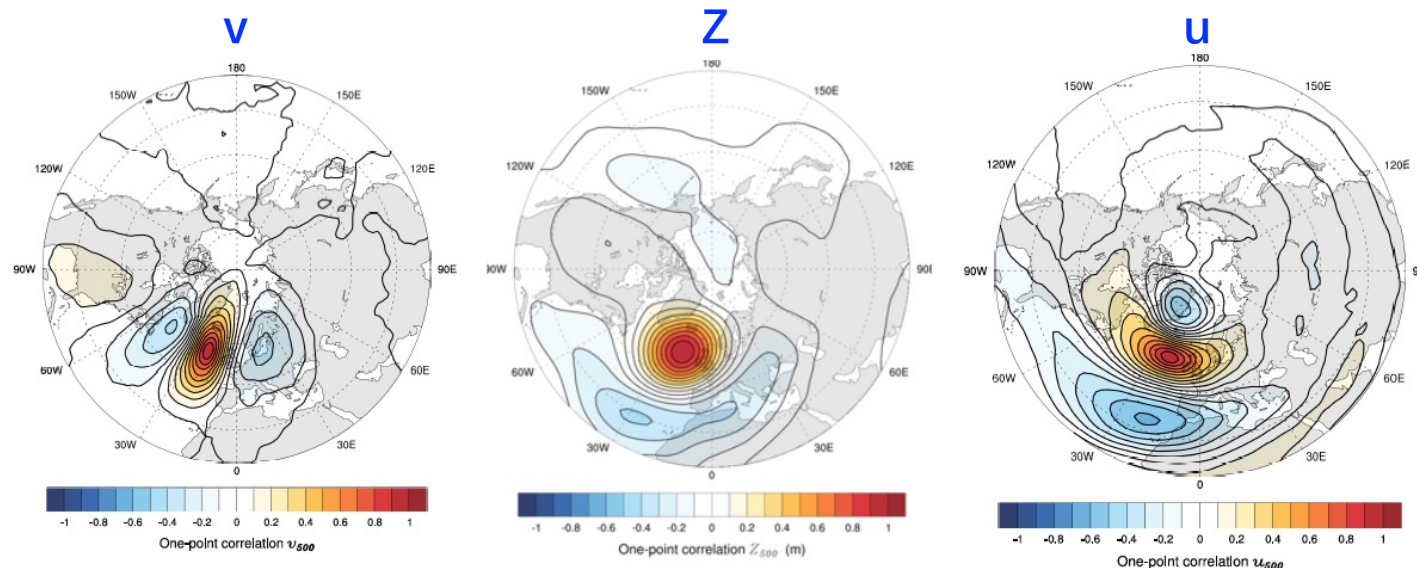


2. Phase Velocity vs. Group Velocity: Theory

- In the absence of a zonal flow, Rossby waves propagate westward with phase speed $c = -\frac{\beta^*}{k^2+l^2}$. The frequency of the zonally propagating waves is thus $\omega = -\frac{k\beta^*}{k^2+l^2}$.
- For waves of a given 2D scale $\sqrt{k^2 + l^2}$, c is independent of the ratio of k to l , but ω depends on it because it takes waves of a given c longer to propagate past a geographically fixed reference point if they are zonally elongated than if they are meridionally elongated. Even if the perturbations consisted of isotropic “red noise”, the high frequency transients would contain a disproportionate share of meridionally elongated waves and vice versa.
- For Rossby wave propagation in the atmosphere with the background zonal wind field U , $c = U - \frac{\beta^*}{k^2+l^2}$. The waves are stationary when the 2D wavenumber $K = \sqrt{k^2 + l^2} = \sqrt{\beta^*/U} = K_S$, and waves with scales close to that value propagate quite slowly and therefore exhibit low frequencies. For waves of a given 2D scale, those that are meridionally elongated exhibit higher frequencies than those that are zonally elongated: hence the contrasting anisotropy of the observed high and low frequency transients.

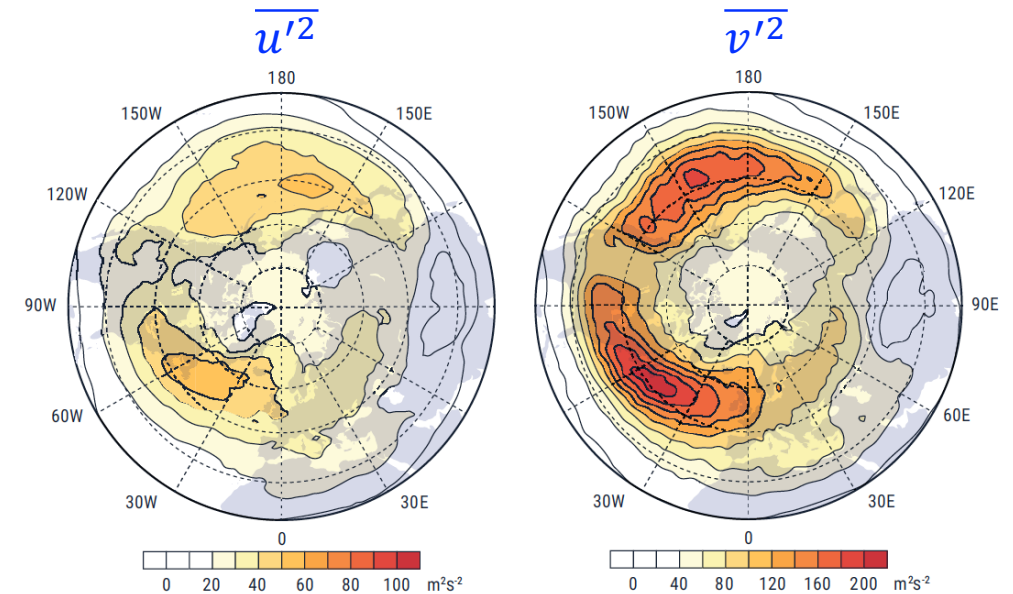
2.Phase Velocity vs. Group Velocity: Theory

- One-point correlation maps of **unfiltered** pattern for Z_{500} is quite isotropic. In contrast, the centers of action in the pattern for v_{500} are meridionally elongated, as in the pattern for the high frequency transients in Z_{500} . The succession of positive and negative centers is suggestive of a zonally oriented wave train. In contrast, the centers of action in the pattern for u_{500} are zonally elongated like those in the pattern for the low frequency transients in Z_{500} .



2.Phase Velocity vs. Group Velocity: Theory

- The variances $\overline{u'^2}$ and $\overline{v'^2}$ in the high frequency transients based on 500 hPa DJF data exhibit distinctive features associated with the storm tracks over the western Pacific and western Atlantic sectors.
- In interpreting these fields, it should be kept in mind that u' and v' are nearly geostrophic and nondivergent. Because of the marked anisotropy of the high frequency transients with meridionally elongated features in the Z field, the variance of the v is about three times as strong as that of u .
- The shape of the u and v patterns are also quite different: patches of v are concentrated along the axes of the storm tracks, whereas u are less so.



2.Phase Velocity vs. Group Velocity: Theory

- These distinctions can be understood in terms of the schematic in Figure, in which the zonal wind perturbations derive from the meridional gradient of wave amplitude along the flanks of the idealized storm track.

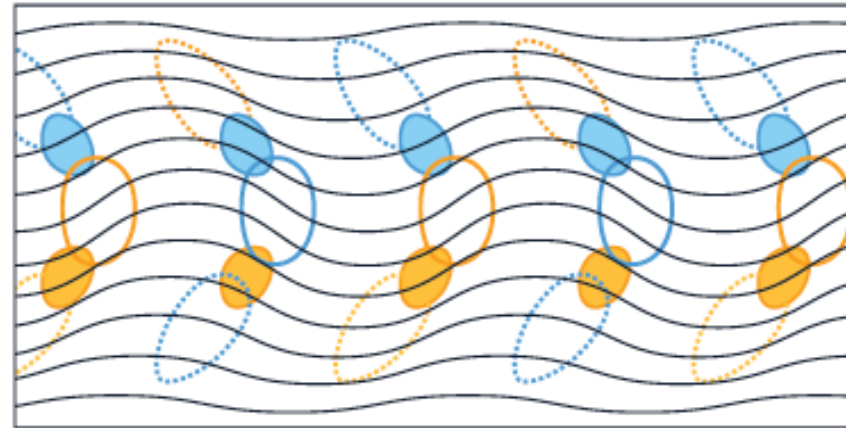


Figure 11.7: Idealized sinusoidal waves in westerlies confined within a channel, as represented by geopotential height field. The waves exhibit a meridional tilt similar to those in the schematic in Fig. 3.7. Locations of extrema in the u and v perturbations are denoted by dashed and solid contours, respectively. Extrema in the zonal momentum transport $\overline{u'v'}$ are denoted by shading. Gold shading denotes positive and blue denotes negative.

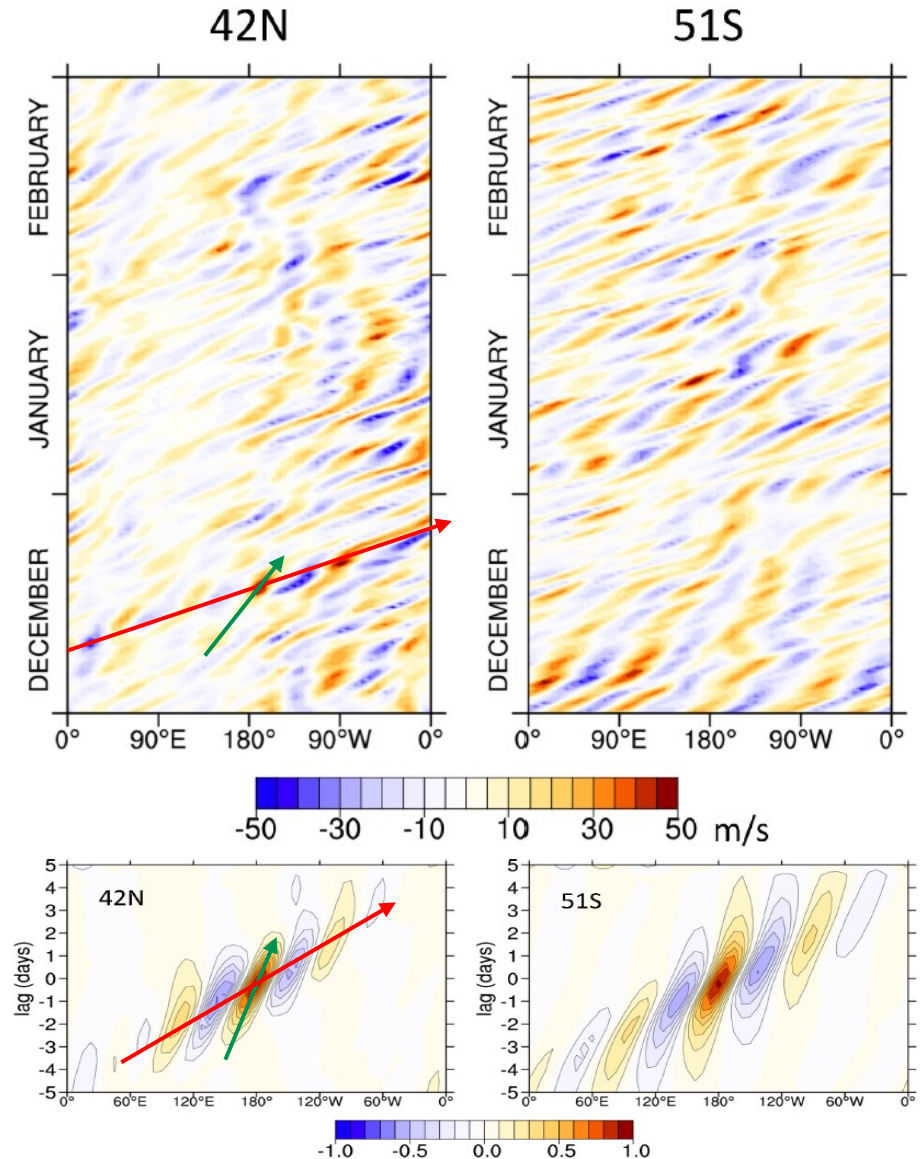
2. Phase Velocity vs. Group Velocity: Theory

- The Doppler-shifted zonal group velocity of a Rossby wave is $c_{gx} - U = \frac{\beta(k^2 - l^2)}{(k^2 + l^2)^2}$. It is evident that waves with $k > l$ (i.e., with centers of action elongated in the meridional direction, e.g., as in baroclinic waves) have an eastward Doppler-shifted group velocity and a westward Doppler-shifted phase velocity. So a wave packet of finite (zonal) extent that is embedded in an eastward zonal background or “steering flow” will disperse eastward more rapidly than the waves that comprise it; that is new ridges and troughs will develop to the east of the existing ones. *so-called downstream development* 槽脊的下游发展
- Conversely, zonally elongated features with $k < l$ have westward group velocity relative to the mean wind, but it is not as large as their phase velocity. Hence, for example, the group velocity of a stationary Rossby wave embedded in a westerly background flow is eastward, but smaller than U . 定常波位相不变但能以群速度向东传播形成波列
- Irrespective of the direction in which they are propagating, Rossby waves tend to disperse in the direction parallel to their minor axis: hence the tendency for them to be oriented along great circles. *Rossby wave spherical dispersion* 罗斯贝波的球面频散

3. Phase Velocity vs. Group Velocity: Observations

3.1 Phase velocity vs. group velocity

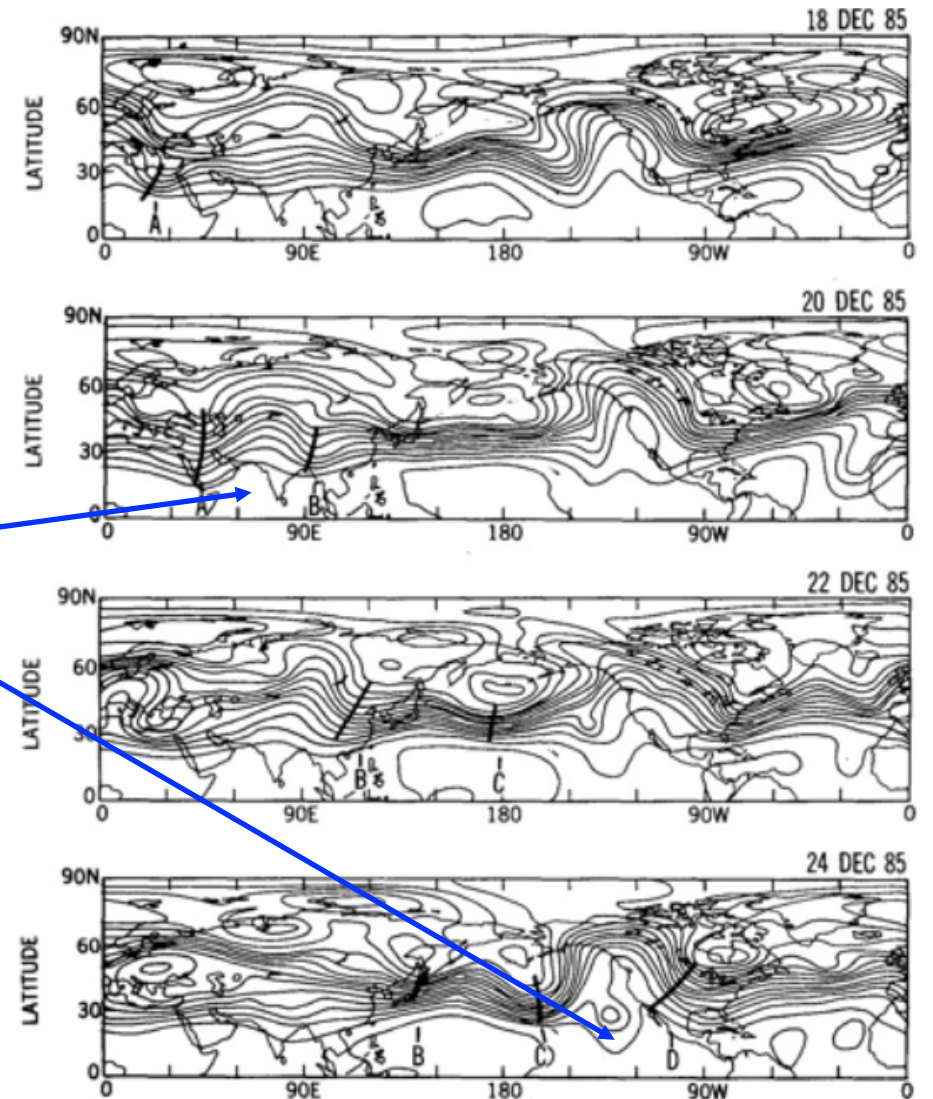
- Time-longitude sections of v_{200} on the 42°N and 51°S latitude circles for DJF 2013/14
- Eastward **phase speeds** c on the order of 10°/day
- Eastward **group velocities** c_g on the order of 30°/day
- Lag correlation plots were constructed based on reference grid points near the Date Line.
- It is a fundamental property of Rossby wave dispersion that $c_g > c$. Hence, wave packets overtake the individual waves. Synopticians 天气学家 refer to this phenomenon as “**downstream development**” 下游发展.



3. Phase Velocity vs. Group Velocity: Observations

3.1 Phase velocity vs. group velocity

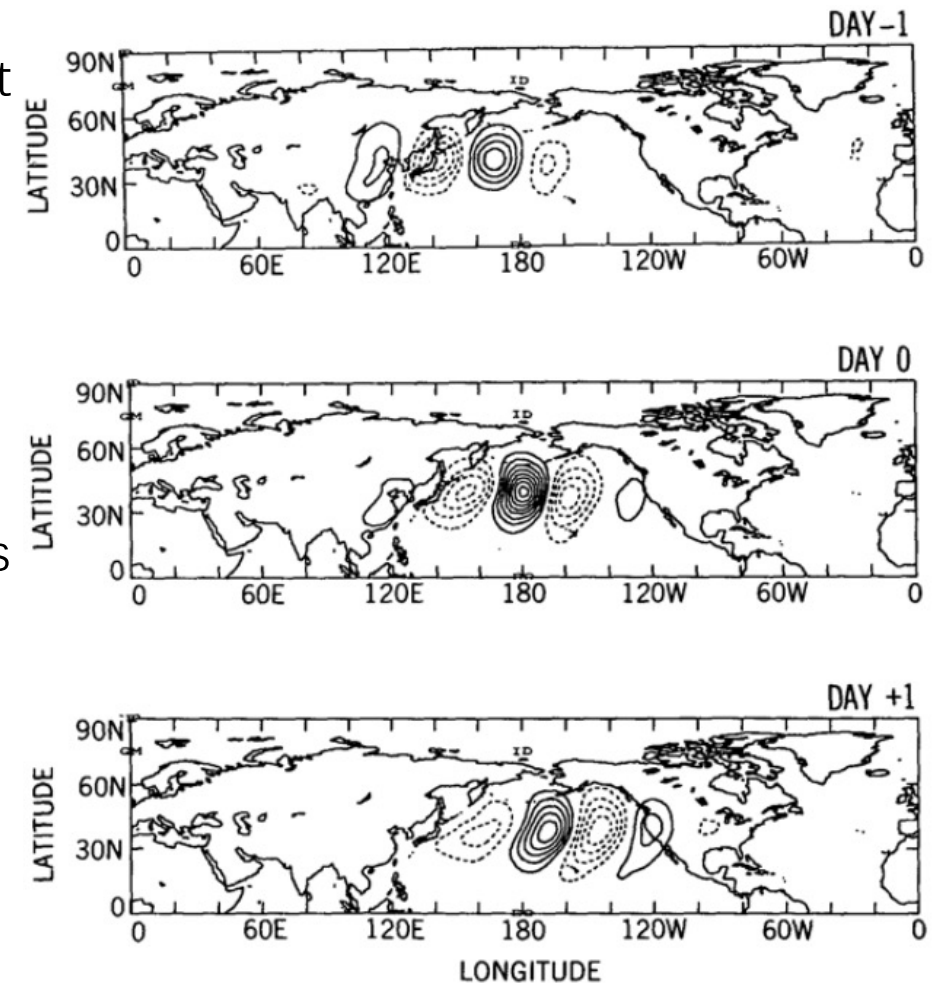
- A synoptic perspective on the individual waves in one specific wave packet. Letters designate specific trough lines that can be tracked from one panel to the next as they propagate eastward.
- Note how new trough lines (C and D), originally on the downstream end of the packet, become increasingly prominent, while A and B fall behind the advancing wave packet and dissipate.



3. Phase Velocity vs. Group Velocity: Observations

3.1 Phase velocity vs. group velocity

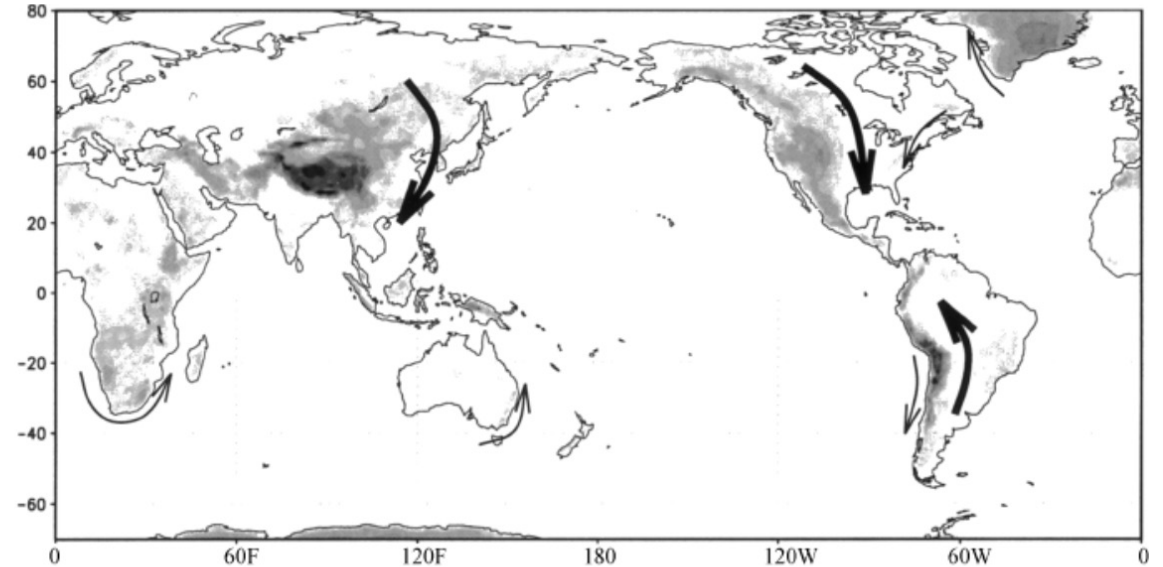
- Another perspective on the downstream development phenomenon — a series of [one-point lag-correlation](#) maps based on a reference time series for v_{300} on the Date Line.
- It can be understood by considering the horizontal equations of the motion in a frame of reference moving with the phase velocity of the waves, bearing in mind that air parcels are moving through the waves from west to east.



3.Phase Velocity vs. Group Velocity: Observations

3.2 Orographic influences on wave propagation

- At lower troposphere levels the propagation of the transients is influenced by orography. Baroclinic waves and other wavelike features tend to **propagate anticyclonically around regions of high terrain.**
- **Two factors** contribute to the tendency: one involves the **geostrophic flow** in Rossby waves, and the other involves the **orographically induced ageostrophic flow.**
- In Rossby wave dynamics the **terrain slope acts as a waveguide** analogous to the β effect.



4. The Extended Eliassen-Palm Flux

- Barotropic energy conversion from the time-mean flow into the transients is given by

$$C_K = \overline{u'^2} \frac{\partial \bar{u}}{\partial x} + \overline{v'^2} \frac{\partial \bar{v}}{\partial y} + \overline{u'v'} \left(\frac{\partial \bar{v}}{\partial x} + \frac{\partial \bar{u}}{\partial y} \right) \quad (12.13)$$

- If the mean flow is nondivergent, this expression can be rewritten as

$$C_K = -2M \frac{\partial \bar{u}}{\partial x} - N \left(\frac{\partial \bar{v}}{\partial x} + \frac{\partial \bar{u}}{\partial y} \right), \quad (12.14)$$

- For realistic climatological mean atmospheric flows, which are characterized by narrow, zonally oriented jet streams, $\partial \bar{u} / \partial y \gg \partial \bar{v} / \partial x$ and therefore, the conversion reduces to

$$C_K = \mathbf{E} \cdot \nabla \bar{u}, \quad (12.15)$$

$$\text{Where } \mathbf{E} = -2M \mathbf{i} - N \mathbf{j} = (\overline{v'^2} - \overline{u'^2}) \mathbf{i} - \overline{u'v'} \mathbf{j} \quad (12.16)$$

- Equations (12.15-12.16) serve to introduce what is referred to the *extended Eliassen-Palm flux vector*, or “*E vector*” for short, where “extended” connotes taking into account the zonally varying structure of the transients. Like their 2D (zonally averaged) counterparts \mathbf{v} (denoted \mathbf{F}), the \mathbf{E} vectors trace the flow of zonal momentum and wave activity.

4. The Extended Eliassen-Palm Flux

- Consider first the horizontal flow at one level, for which the \mathbf{E} can be regarded as horizontal, a function of (x, y) . It can be shown (Hoskins et al. 1983) that if the second spatial derivatives $N_{xx} \ll N_{xy}$, as in the vicinity of the zonally elongated storm tracks, the acceleration of the mean flow induced by the transients through the momentum (or vorticity) fluxes can be approximated by the divergence of \mathbf{E} ,

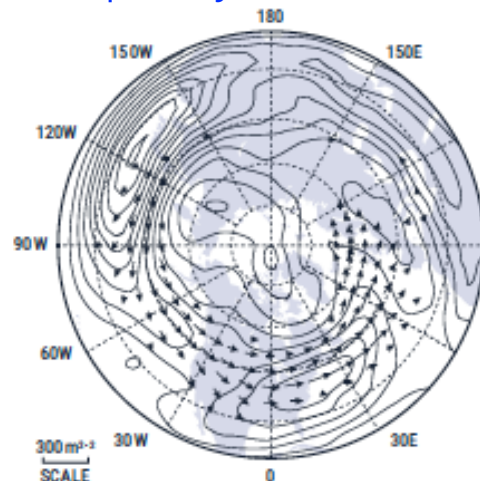
$$\frac{\partial \bar{u}}{\partial t} \approx \overline{v' \zeta'} \approx \nabla \cdot \mathbf{E} \quad (12.17)$$

- Like variances and covariances, \mathbf{E} may be partitioned into contributions from various frequency bands; *its orientation may be frequency dependent.*
- \mathbf{E} is an indicator of the group velocity relative to the mean flow, tracing the flux of wave activity like the zonally averaged EP flux.

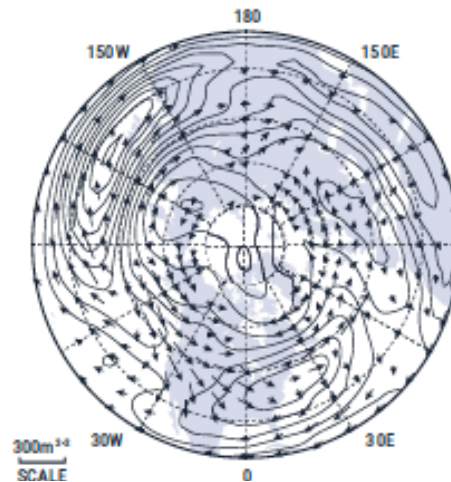
4.The Extended Eliassen-Palm Flux

- The **high frequency transients in the left panel** are dominated by **eastward-pointing E vectors**, strongest within and just downstream of the storm tracks, a reflection of the pronounced anisotropy $M < 0$ ($\overline{v'^2} \gg \overline{u'^2}$). The transport of westerly momentum in these regions by the high frequency transients is westward and it is evident that it is mainly countergradient. That the E vectors are strongly divergent in the storm tracks indicates that the eddy transports are imparting a strong westerly acceleration to the basic state flow. In terms of group velocity, the eastward-pointing E vectors in the storm tracks are indicative of eastward dispersion (i.e., group velocity) of the high frequency transients.

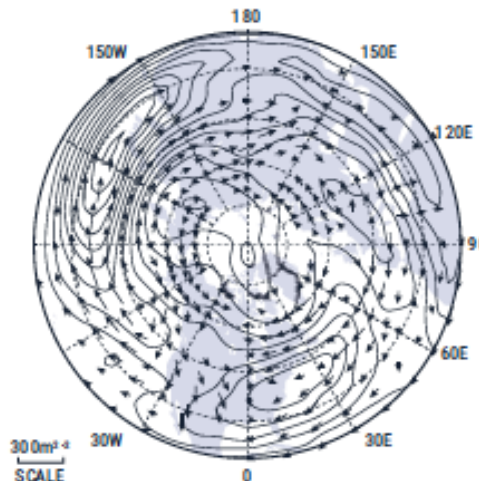
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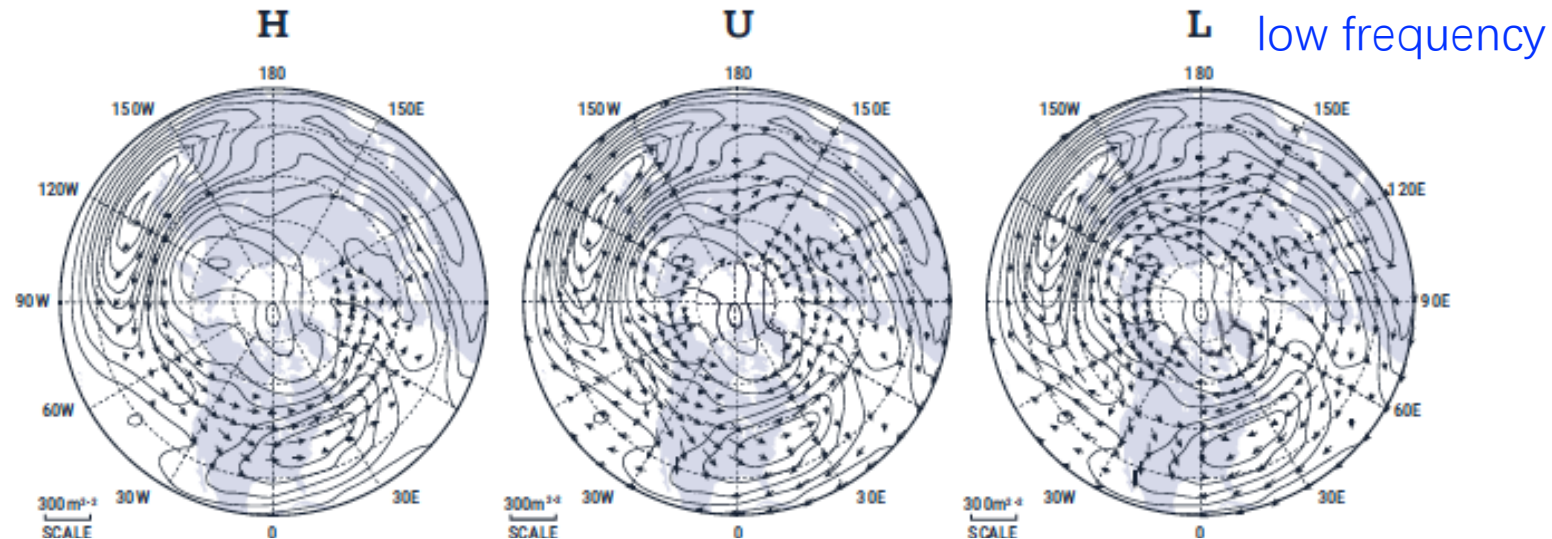


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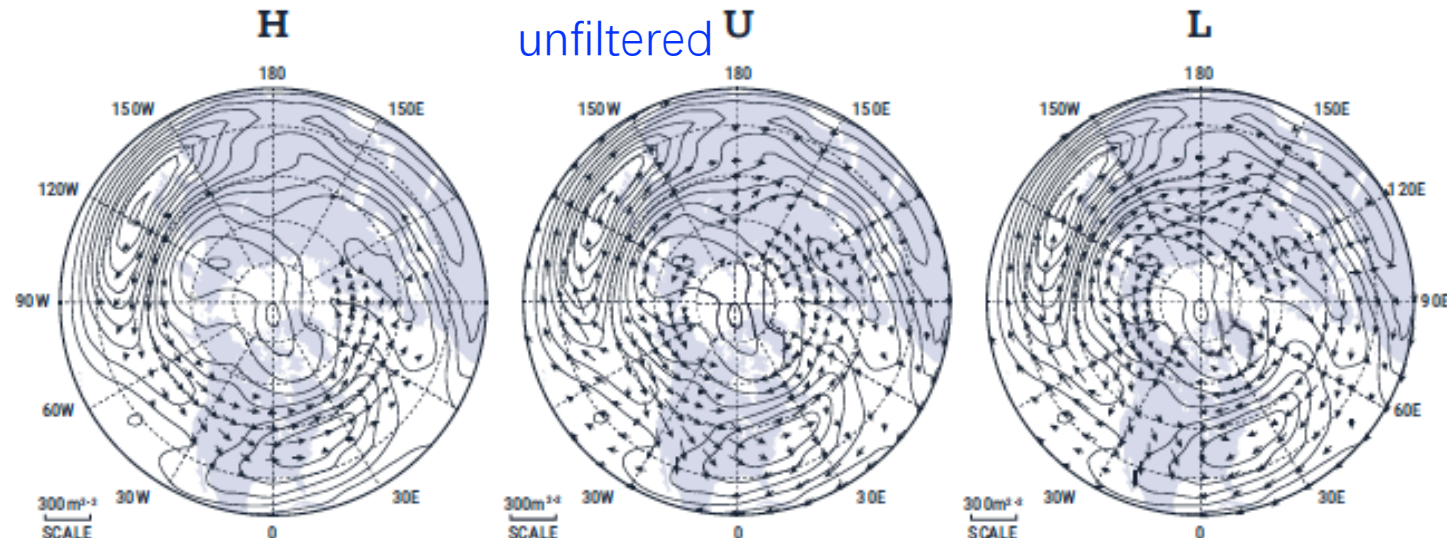
4. The Extended Eliassen-Palm Flux

- The **low frequency transients in the right panel** are dominated by the **westward-pointing E vectors**, strongest in the jet exit regions, directed up the gradient of \bar{u} . Bearing in mind that the E vectors point in the direction opposite to the flux of westerly momentum, this configuration is indicative of a down-gradient momentum flux and a barotropic conversion from the climatological mean flow into the low frequency transients in the energy cycle. Interpreted in terms of group velocity, the westward-pointing E vectors in the jet exit regions are indicative of westward dispersion of the low frequency transients.



4.The Extended Eliassen-Palm Flux

- The pattern of E vectors based on unfiltered $\overline{u'^2}$, $\overline{v'^2}$, $\overline{u'v'}$ shown in the middle panel, is a hybrid of the contrasting patterns for the low and high frequency transients and is thus more difficult to interpret. There is some cancellation between the predominately westward E vectors in the low frequency component and the eastward E vectors in the high frequency component such that the meridional fluxes, in particular, the southward vectors at $\sim 35^\circ\text{N}$ over the United States and the Mediterranean are quite prominent, accounting for the pronounced maxima in $[\overline{u^*v^*}]$.



4. The Extended Eliassen-Palm Flux

- It remains to be explained why a positive value of $M = (\overline{u'^2} - \overline{v'^2})/2$ should induce a zonal transport of westerly momentum.
- It is clear that $\overline{u'^2}$ must be producing an eastward transport of westerly momentum analogous to the way in which $\overline{u'v'}$ produces a northward transport of it. The **westward transport** of westerly momentum in the storm tracks is thus **attributable to** the meridional flux of meridional momentum $\overline{v'^2}$.

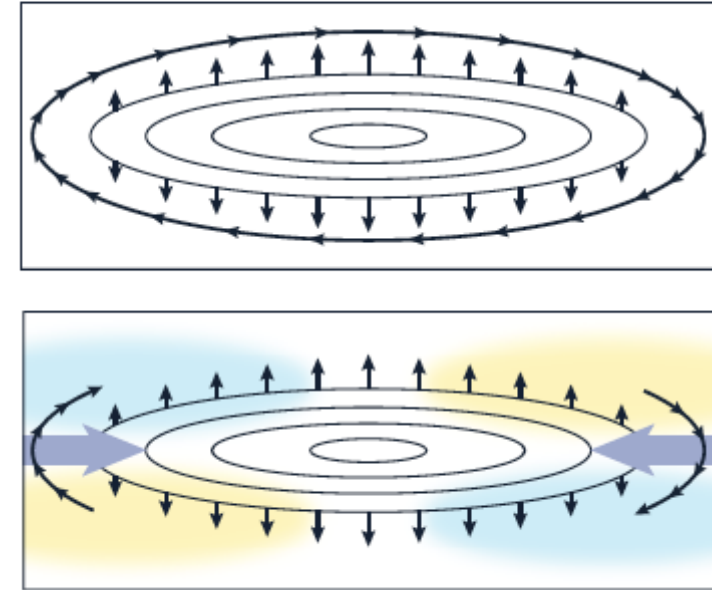


Figure 11.11: Response to the meridional fluxes of meridional momentum $\overline{v'^2}$ in the vicinity of an isolated storm track. *Top:* the direct response, a diffluent meridional circulation which is not, in and of itself, geostrophically balanced. *Middle:* the ageostrophic circulation cell that develops in response to the departures from geostrophic balance. *Bottom:* The zonal wind accelerations (dark arrows) and temperature tendencies (colored shading, blue cold and yellow warm) that develop in response to the ageostrophic circulation in the middle panel and the associated vertical motions in the layer below.

4. The Extended Eliassen-Palm Flux

- A heuristic explanation of how the maximum in $\overline{v'^2}$ along the axis of the storm track induces an ageostrophic time-mean circulation that, in turn, induces a westerly acceleration at the upstream end of the storm track and an easterly acceleration at the downstream end, which amounts to a westward transport of westerly momentum.
- The direct effect of the transport of meridional momentum is to produce a poleward (equatorward) acceleration of the air on the poleward (equatorward) flank of a storm track (top panel). The Coriolis force induced by this diffluent meridional flow, in turn, induces an eastward (westward) ageostrophic circulation on the poleward (equatorward) flank of the storm track.

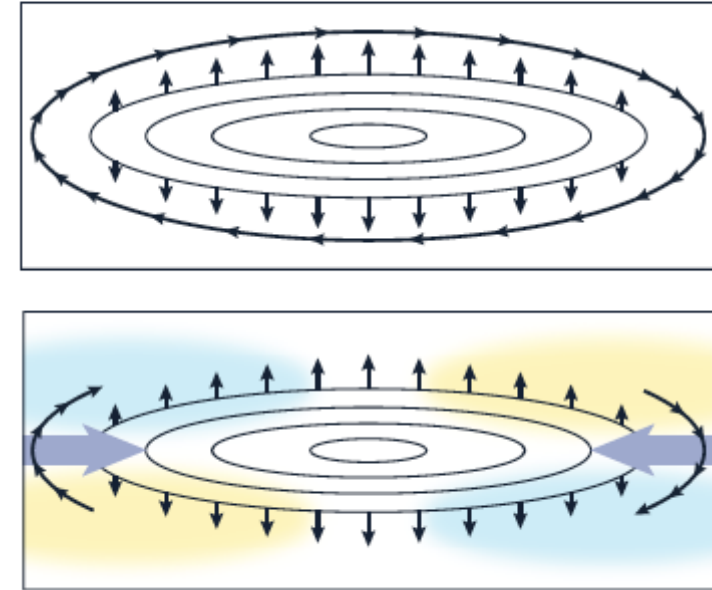


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4. The Extended Eliassen-Palm Flux

- In order to conserve mass, the ageostrophic flow must assume the form of an anticyclone gyre, with poleward (equatorward) flow at the upstream (downstream) end of the storm track (**bottom panel**). These transverse ageostrophic circulations and the associated vertical velocities in the layer below them conspire to produce the pattern of geostrophically balanced zonal accelerations and temperature tendencies.
- In this manner, the dominance of $\overline{v'^2}$ in the high frequency transients in the storm track results in a diffluent meridional acceleration together with a confluent zonal acceleration, inducing a circulation that is quasi-nondivergent.

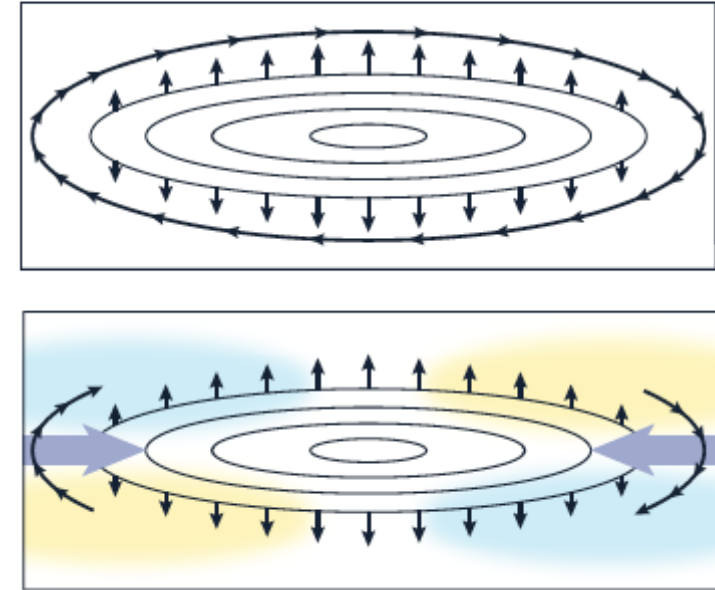


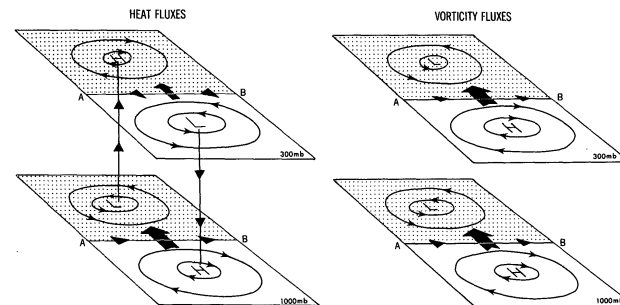
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4. The Extended Eliassen-Palm Flux

- In the 3D formulation of the EP flux, the local vertical component of the E vector is directly proportional to $\overline{v'T'}$, so that \mathbf{E} for the horizontal flow in (12.16) can be extended to 3D

$$\mathbf{E} = (\overline{v'^2} - \overline{u'^2}) \mathbf{i} - \overline{u'v'} \mathbf{j} + \overline{v'\alpha'}/\sigma \mathbf{k} \quad (12.18)$$

- Upward-directed E vectors are indicative of an upward flux of wave activity and a downward flux of westerly momentum. E vectors directed up the vertical gradient of \bar{u} are indicative of energy conversion $A_M \rightarrow A_T$ in the energy cycle and vice versa. The upward-directed E vectors in the storm tracks are the signature of amplifying baroclinic waves. They are consistent with the reinforcement of the surface westerlies in the storm tracks by high frequency transients, as deduced from the geopotential tendency equation and summarized in the figure in the last lecture.



5.Characteristics of Baroclinic Waves

- Numerous observational studies are based on several different approaches. Time series of variables are [linearly regressed upon](#) a common reference time series. An alternative approach is to identify features on the basis of [tracking algorithms](#) applied to fields such as SLP or PV.
- Other published findings establish that baroclinic waves exhibit ... (1~10 see next page)
- The structure and evolution of baroclinic waves as inferred from these analyses is generally consistent with the picture that has emerged in the synoptic meteorology literature. It reflects the structure of the [normal modes标准模](#) associated with [baroclinic instability](#), but it is also influenced by incidences of [nonmodal behavior](#) in the early stages of their development, and by [nonlinearities](#) that develop after they achieve finite amplitude.

5.Characteristics of Baroclinic Waves

仅了解

- A westward tilt of the wave axes in the geopotential height field with height, strongest in the lower troposphere
- An in-phase relationship between upward vertical velocity and temperature in the lower troposphere versus a quarter cycle phase difference between them in the upper troposphere.
- In most cases an upward development and a transition from a more baroclinic to a more barotropic vertical structure as the waves evolve through their life cycles while they grow and propagate eastward along the oceanic storm tracks.
- Systematic departures from geostrophic balance, including super-geostrophic zonal flow in the ridges and sub-geostrophic flow in the troughs, which account for the meridional accelerations experienced by air parcels passing through the waves.
- A tendency for cyclones at the Earth's surface to track poleward and anticyclones to track equatorward, a reflection of the westward acceleration of the surface winds during the baroclinic wave life cycle.
- A positive correlation between zonal wind and geopotential height, indicative of an eastward transport of mechanical energy.
- The tendency for anticyclonic wave-breaking in regions where the climatological mean flow exhibits anticyclonic relative vorticity and vice versa.
- An enhancement of the generation of transient (or eddy) kinetic energy due to the release of latent heat, especially in the more intense systems.
- An upward displacement of the tropopause in the ridges of the waves relative to the troughs, as evidenced by the distribution of total ozone.
- Well-defined patterns of cloudiness and cloud types in satellite imagery.