The Atmospheric General Circulation

Lecture 11: The Low Frequency Extratropical Transients

热带外低频瞬变

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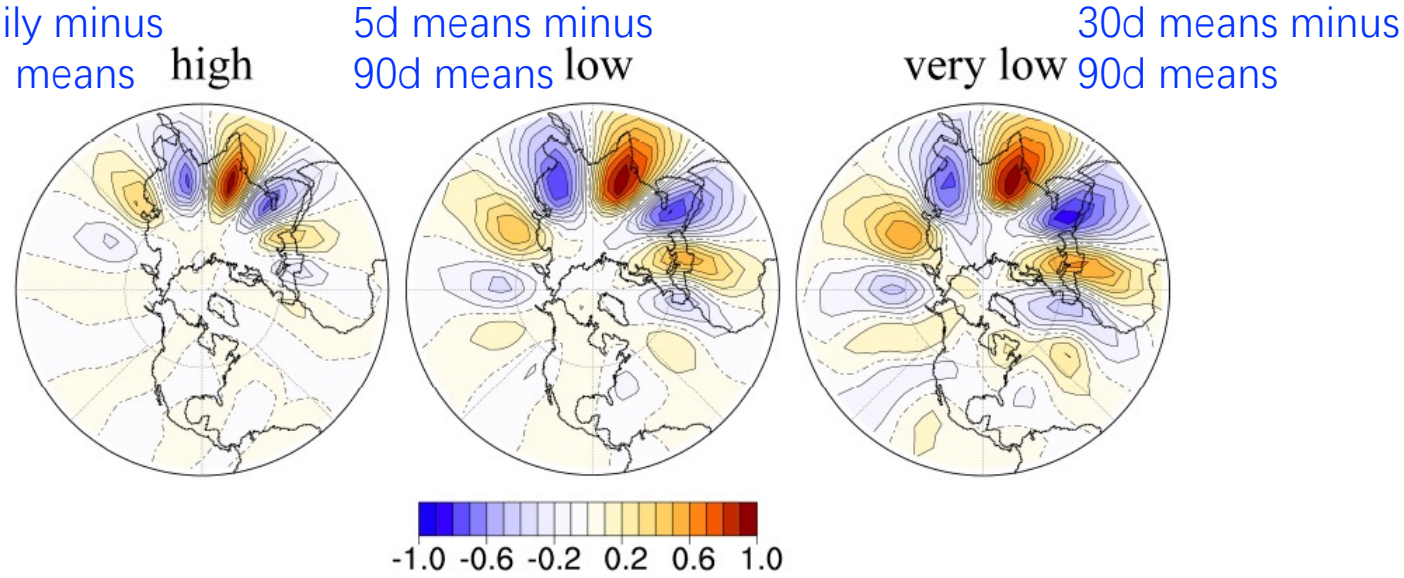
1.Rossby Wave Dispersion

- We will make extensive use of what we refer to as *teleconnectivity* 遥相关性 maps. Teleconnectivity is a measure of the degree to which fluctuations of a variable at a given grid point, say x_i , are linearly related to fluctuations in x at distant grid points.
- Various metrics are used to quantify teleconnectivity and identify prominent teleconnection patterns: (a) the absolute value of the largest negative value on the one-point correlation map for x_i ; (b) the *correlation teleconnectivity* : the area-weighted r.m.s. amplitude of the values on the one-point correlation map for that grid point; and (c) the *covariance teleconnectivity* : the area-weighted r.m.s. amplitude of the covariances between standardized x_i and non-standardized x at all grid points.
- Also making use of empirical orthogonal function (EOF) analysis and empirical orthogonal teleconnections (EOTs).

1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

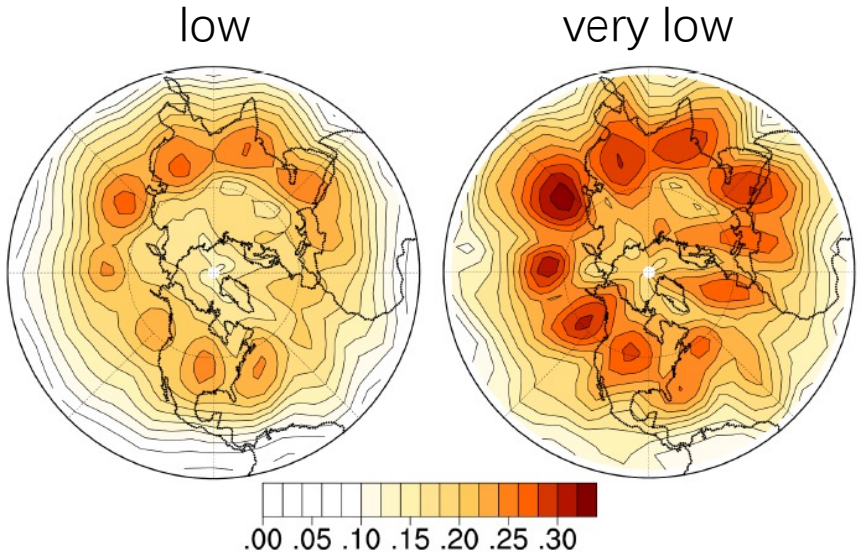
- One-point correlation maps for v_{200} at a typical grid point along an extended westerly waveguide, which coincides with the axis of the wintertime jet stream that extends across North Africa, southern Asia and into the western Pacific.
- The wave trains for the low and very low frequency variability are almost circumglobal in extent. Zonal wavelengths range from zonal wavenumber $k \sim 8$ for the high frequency transients to $k \sim 5$ for the very low frequency transients.



1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

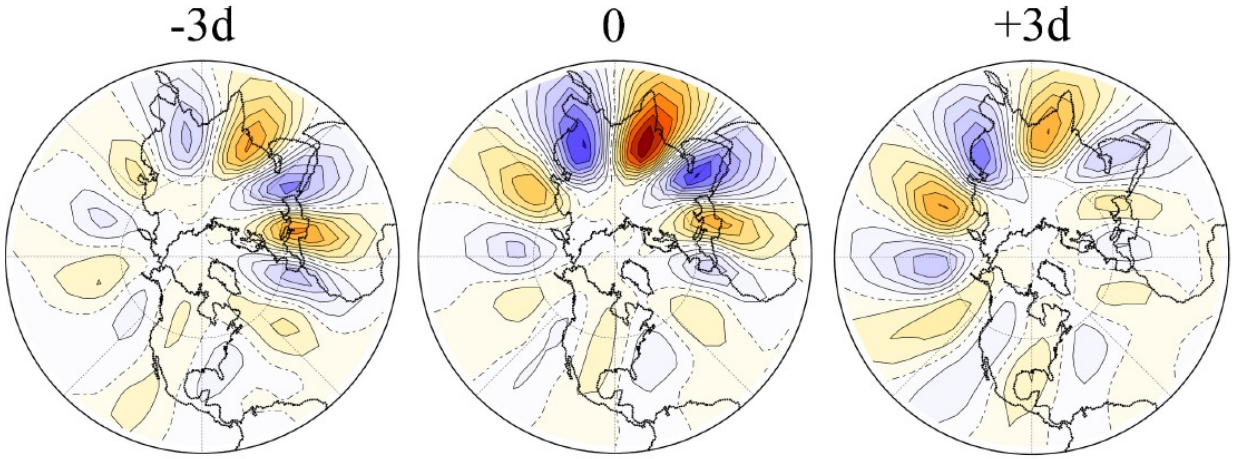
- The distribution of correlation teleconnectivity for the low frequency transients in v_{200} exhibits a maximum along the axis of the climatological mean jet stream (left). These undulations in teleconnectivity are a weak reflection of the much stronger features in the teleconnectivity patterns for very low frequency transients (right).
- The undulations in teleconnectivity are indicative of a preferred phase of the nearly circumglobal wave, which we will refer to as the *circumglobal teleconnection* (CGT) *pattern*.



1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

- The evolution of wave trains along the westerly waveguide is frequency dependent. Eastward phase propagation is dominant in the day-to-day variability, as shown in the last lecture, but not in the low frequency variability. Eastward dispersion is clearly evident in the week-to-week variability, as illustrated in the lag-correlation plots shown below, in which features on the western end of the wave-train decay with time while features on the eastern end amplify. The corresponding lag-correlation patterns for the month-to-month variability (not shown) do not exhibit any notable phase propagation.

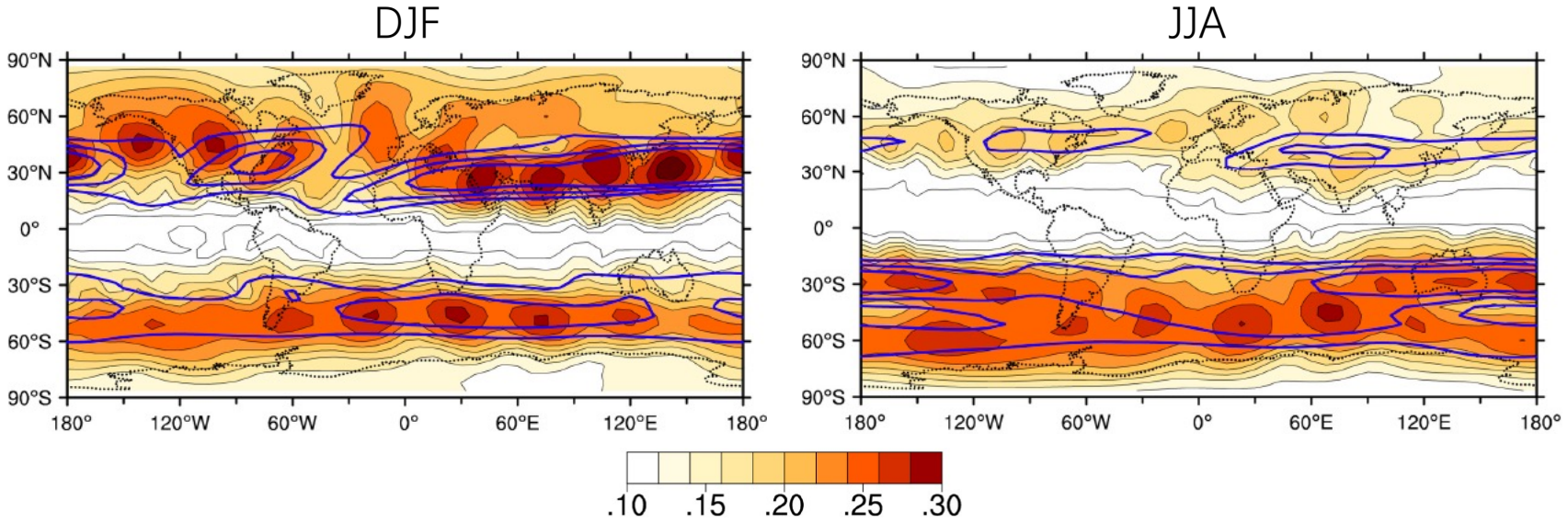


week-to-week variability is defined as centered 5d means minus centered 30d means

1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

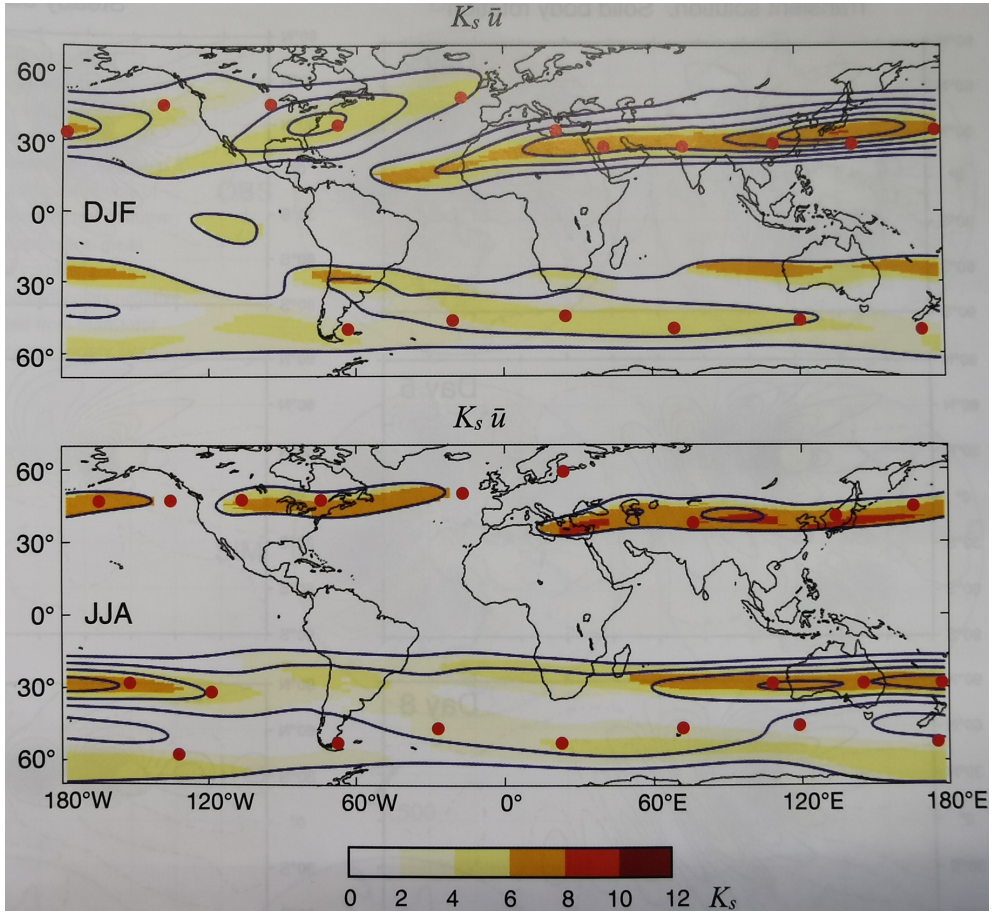
- A comprehensive survey of the role of westerly waveguides in the global general circulation is presented in the observed distributions of correlation teleconnectivity of v_{200} in both hemispheres during both DJF and JJA.
- A SH counterpart of the CGT pattern, with centers of action anchored over the southern tip of South America and south of Africa and western Australia, is present year-round. CGT-like patterns in the NH summer tend to be weaker than during winter.



1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

- Many aspects of the structure and evolution of low frequency atmospheric variability can be understood in terms of barotropic Rossby wave dispersion on a sphere in the presence of a basic state flow that includes strong westerly jets with well-defined exit regions.
- The maxima of the stationary wave number K_s tend to occur in zonally oriented bands, often, but not always, aligned with the mean jets. For a waveguide teleconnection pattern to exist, not only must its meridional propagation be meridionally confined but it needs to be located in a region of high eastward group velocity so that its energy will disperse a long distance before it dissipates.

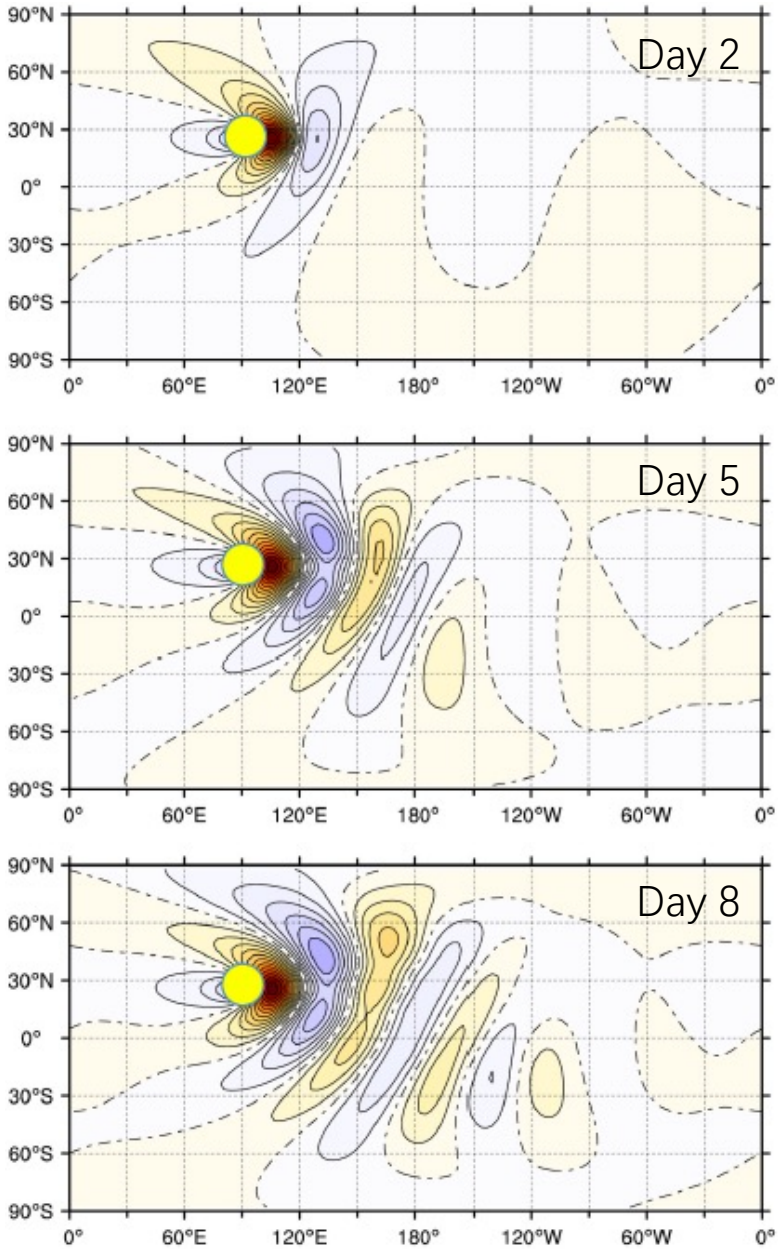


1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

- Simple solutions of linearized barotropic models provide examples of the waveguide behavior predicted by K_s.
- Perturbations in the v field that develop in a linear barotropic model at times t = 2, 5, and 8 days after a small circular vorticity source is inserted into the flow in an atmosphere with zonally symmetric flow consisting of pure solid body superrotation ([u] > 0).
- Within a few days, wavelike circulation anomalies develop downstream of the source. In succeeding days additional centers appear along the leading edge of the flux of wave activity emanating from the source and remaining geographically fixed as the “signal” disperses downstream and crosses the equator into the SH.

Transient solution. Solid body rotation

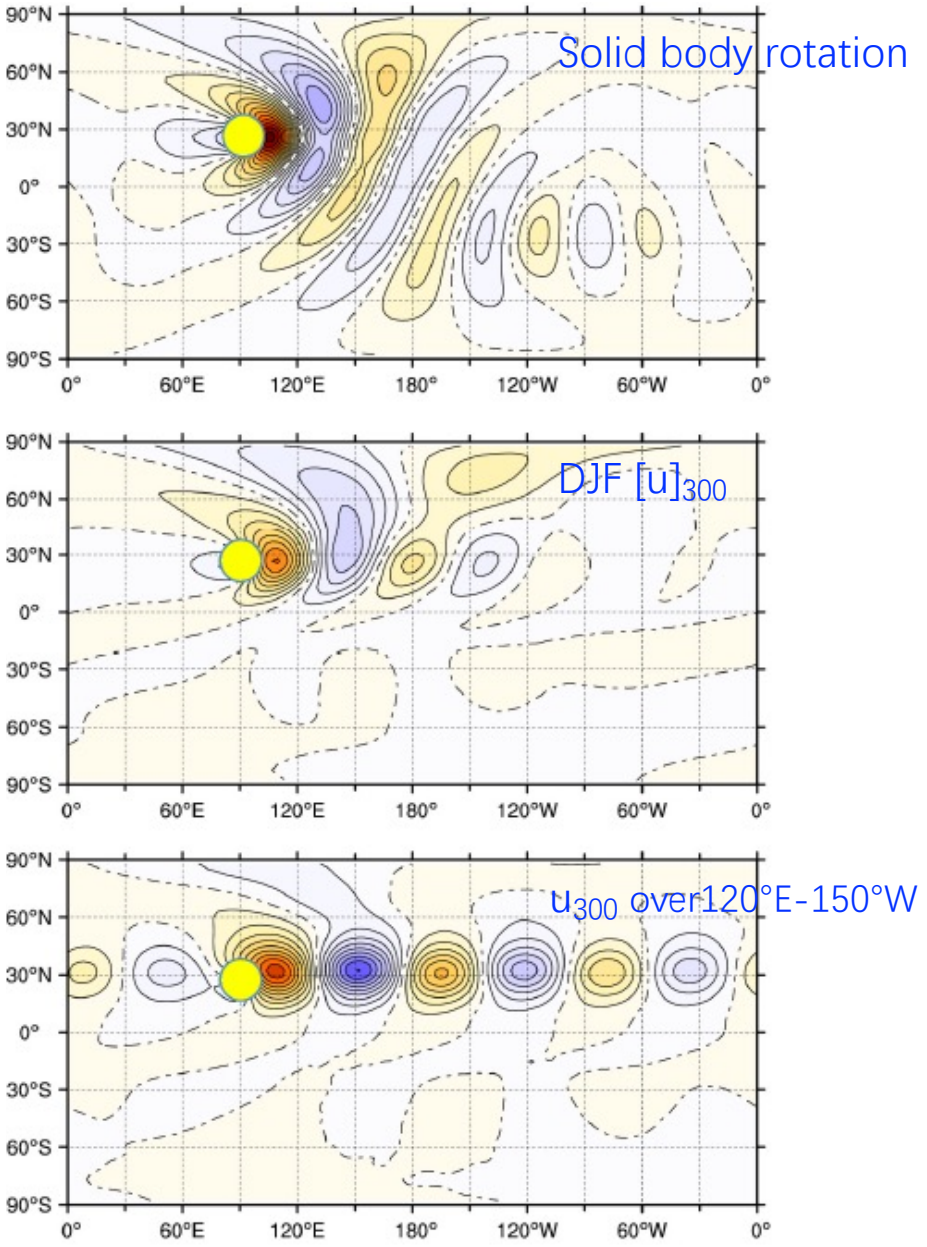


1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

- The steady state solution for a basic state flow in solid body rotation together with solutions for two flows with westerly jets that mimic the climatology.
- In the more realistic basic state flows in the two bottom panels, the strong poleward gradient of absolute vorticity along the axes of the climatological mean jets acts as a waveguide for low frequency Rossby waves of intermediate zonal scale (k = 4-6). Near these jets the low frequency disturbances are not able to propagate meridionally in arching patterns oriented along great circles as in the previous figure: their group velocity is constrained to be eastward.

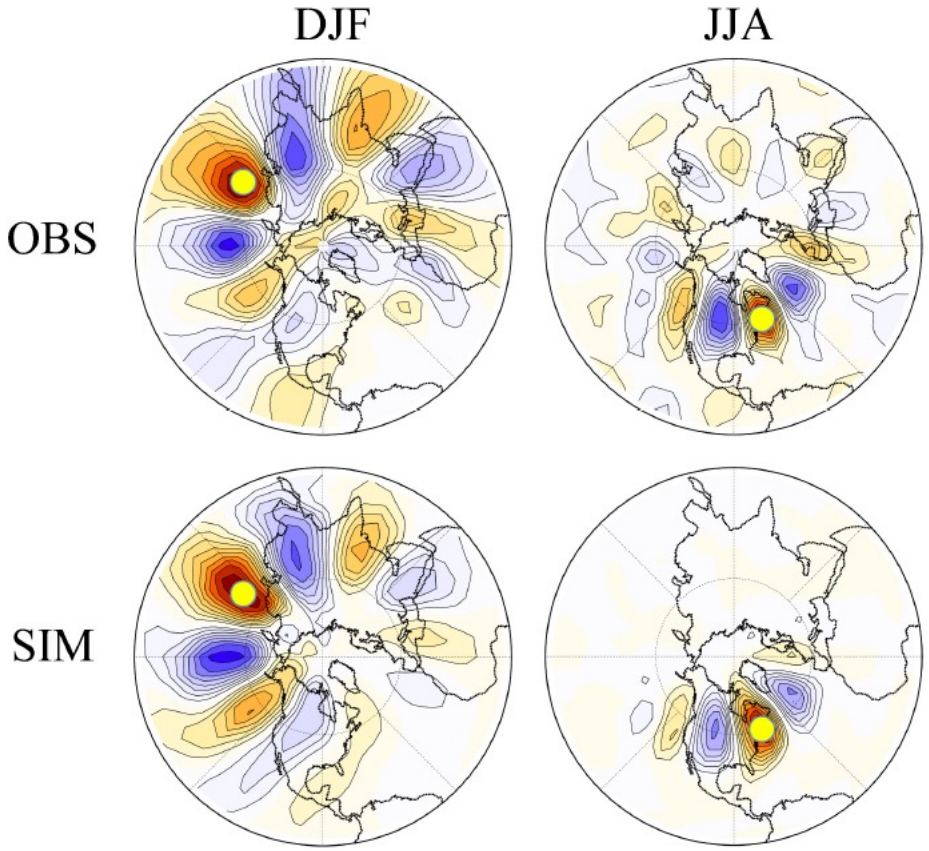
Steady state solutions



1.Rossby Wave Dispersion

1.1 Dispersion along westerly waveguides

- The importance of the mean state is more quantitatively demonstrated by a set of experiments with a more realistic model in which the patterns develop in response to steady forcing that has no particular spatial organization.
- That the simulated patterns are remarkably realistic and the seasonality is well simulated confirms that it is not necessary to invoke any kind of special forcing to explain the existence of the CGT pattern: its structure derives from Rossby wave propagation and dispersion in the presence of the observed basic state flow.



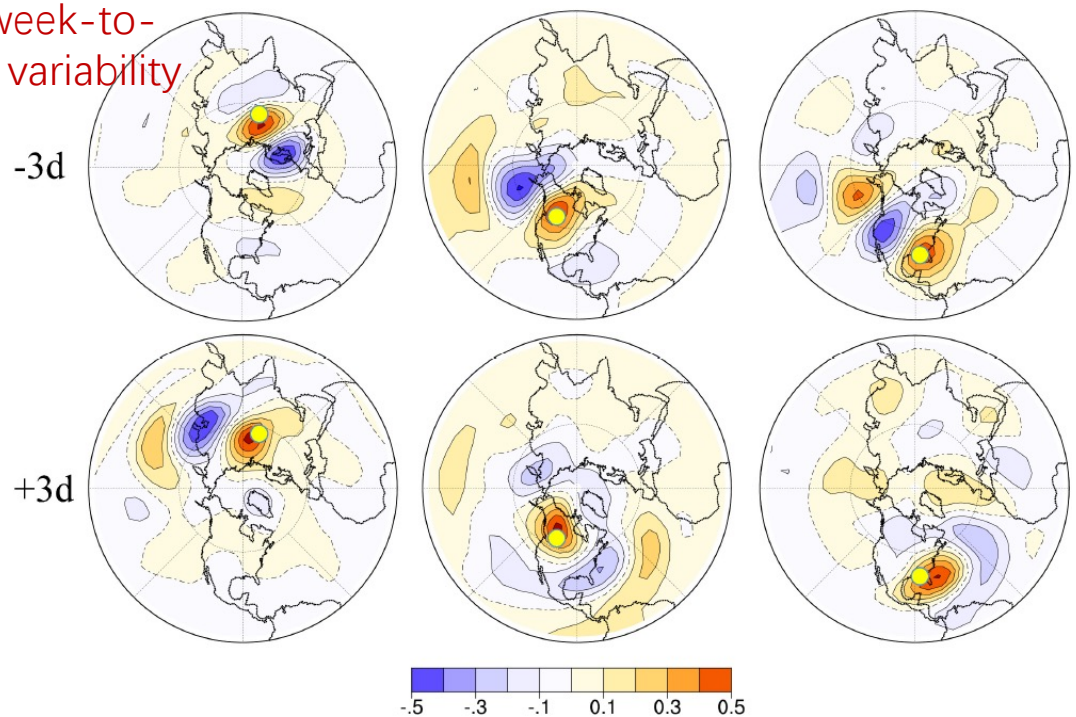
1.Rossby Wave Dispersion

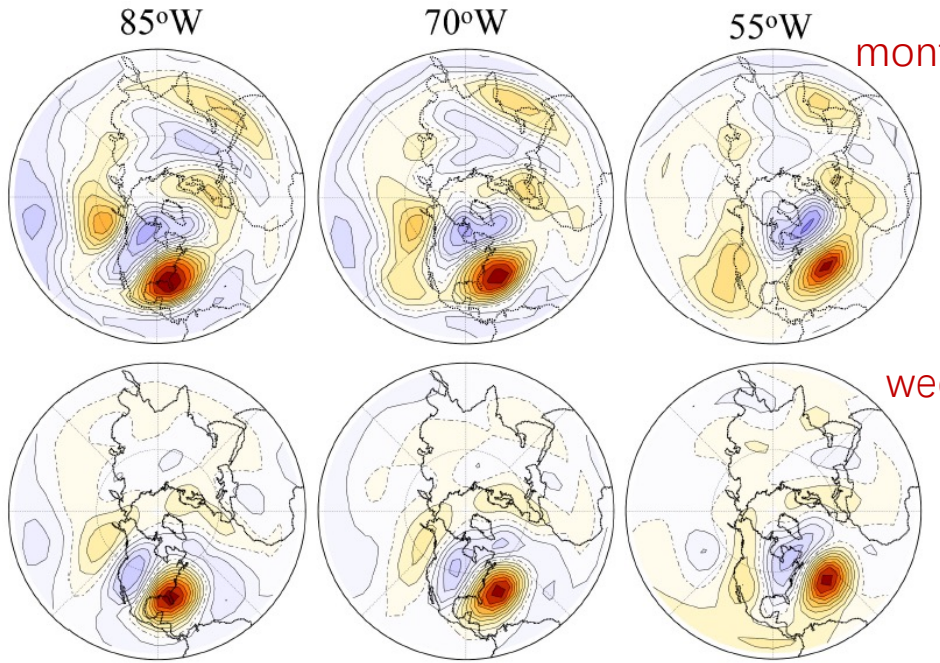
1.2 Dispersion away from westerly waveguides

- Away from westerly waveguides, Rossby waves are less constrained to propagate zonally and accordingly, they tend to propagate along great circles rather than along latitude circles.

- The structure is frequency dependent, with teleconnection patterns most clearly evident at the very low frequencies.

Z_{500} week-to-week variability





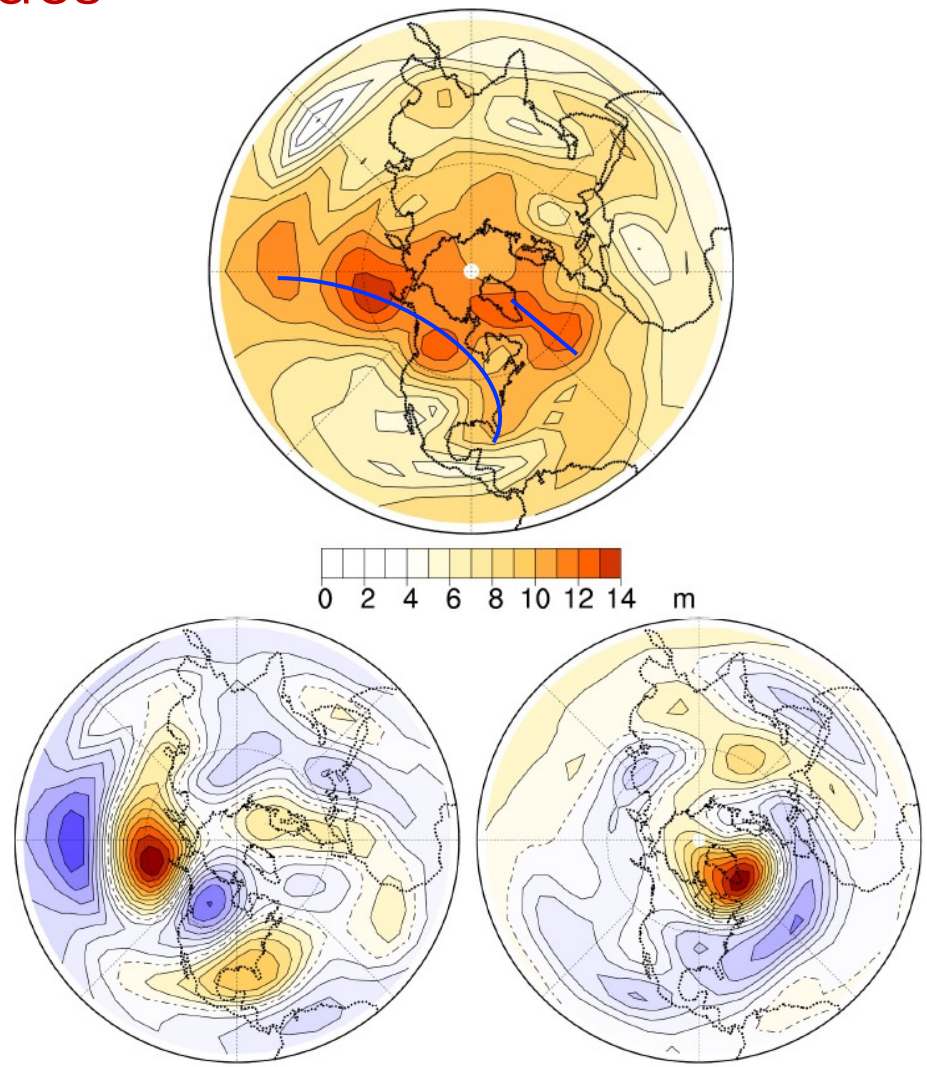
month-to-month

week-to-week

1.Rossby Wave Dispersion

1.2 Dispersion away from westerly waveguides

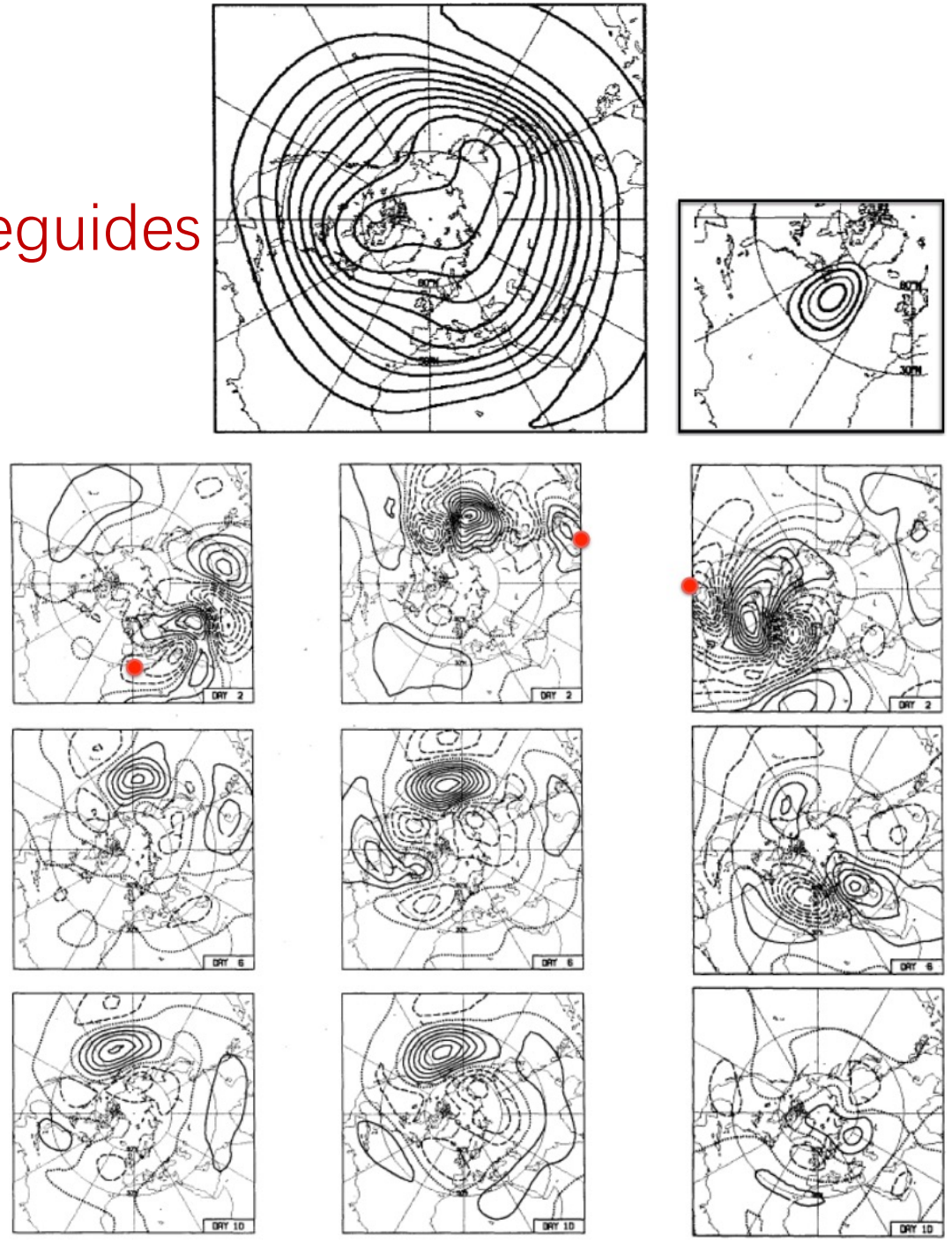
- Covariance teleconnectivity map in DJF Z_{500} for the very low frequency transients (top) shows that the pattern is dominated by (1) an arching wave train extending from the subtropical Pacific along a great circle across the Gulf of Alaska, and the Yukon, across Florida, and into the tropical Atlantic, and (2) a dumbbell over the North Atlantic with a northern center over the southern tip of Greenland.
- The geographically fixed teleconnection patterns that are responsible for these features are revealed by the one-point correlation maps: the arching wave train (bottom left) is the signature of the so-called *Pacific-North American* (PNA) pattern, and the dipole (bottom right) corresponds to the *North Atlantic Oscillation* (NAO).



1.Rossby Wave Dispersion

1.2 Dispersion away from westerly waveguides

- To demonstrate the dynamical plausibility of the existence of the PNA pattern, considering the results of the three numerical experiments with a barotropic model which is forced by a prescribed vorticity source on Day 0 and linearized about a zonally varying basic state flow — the observed January climatological mean streamfunction at the 300 hPa level.
- First and second resemble the PNA pattern, and the third resembles the EA pattern. That patterns similar to these are obtained in many such experiments regardless of where the initial perturbation is placed is suggestive of a normal mode type behavior.



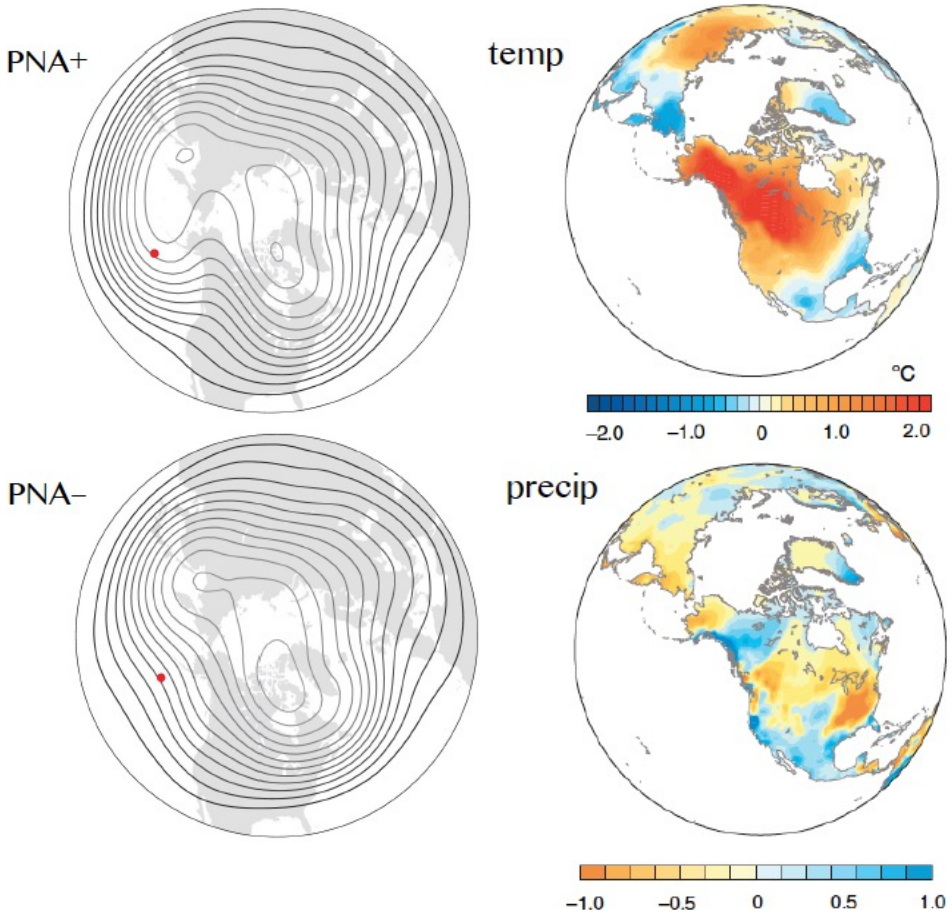
1.Rossby Wave Dispersion

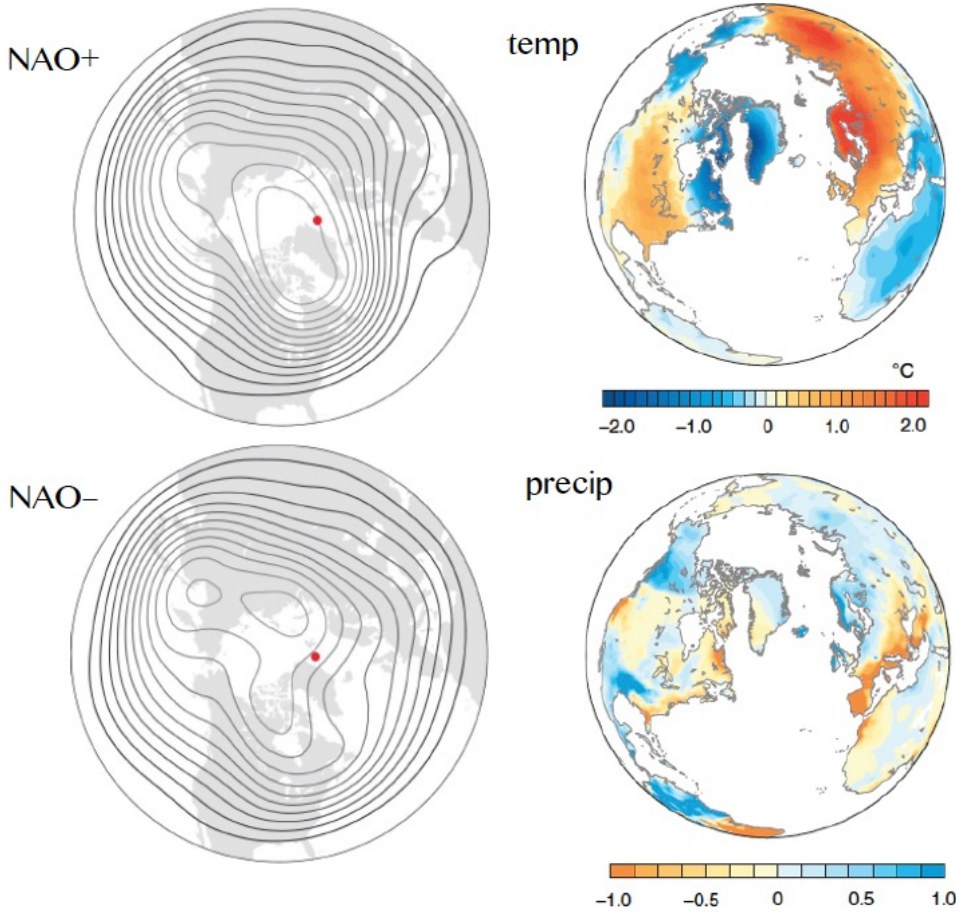
1.2 Dispersion away from westerly waveguides

- Patterns that resemble the NAO do not emerge either among the solutions of the linearized barotropic model or among the prominent one-point correlation patterns obtained when the more realistic multi-level linearized primitive equation model is subjected to stochastic forcing.
- The NAO also differs from the other patterns in that it exhibit a strong zonally symmetric component, with out-of-phase SLP fluctuations in polar and temperate latitudes. At very low frequencies, its time-varying index is so highly correlated with that of the NH barotropic annular mode (NAM).
- The positive feedback of the eddy fluxes in baroclinic waves upon the zonally averaged background flow, contributes to the prominence of this mode.

1.Rossby Wave Dispersion

1.2 Dispersion away from westerly waveguides

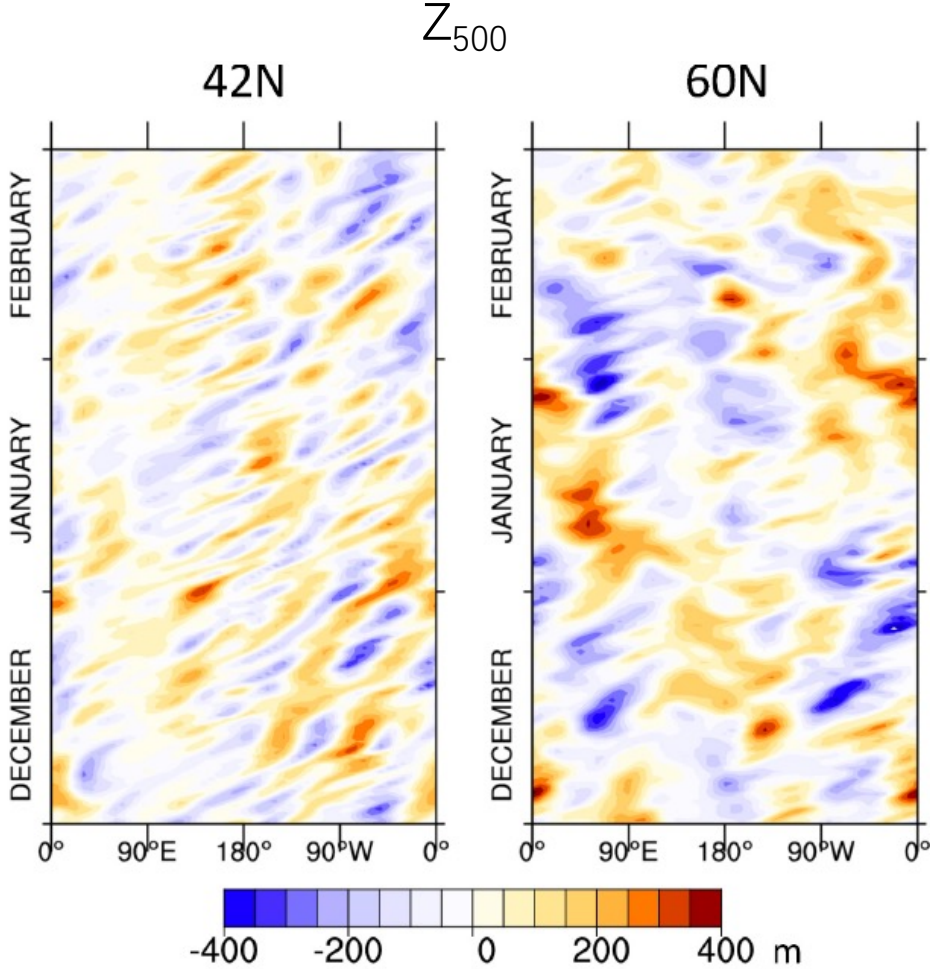




1.Rossby Wave Dispersion

1.3 Retrograding后退的 planetary-scale Rossby waves

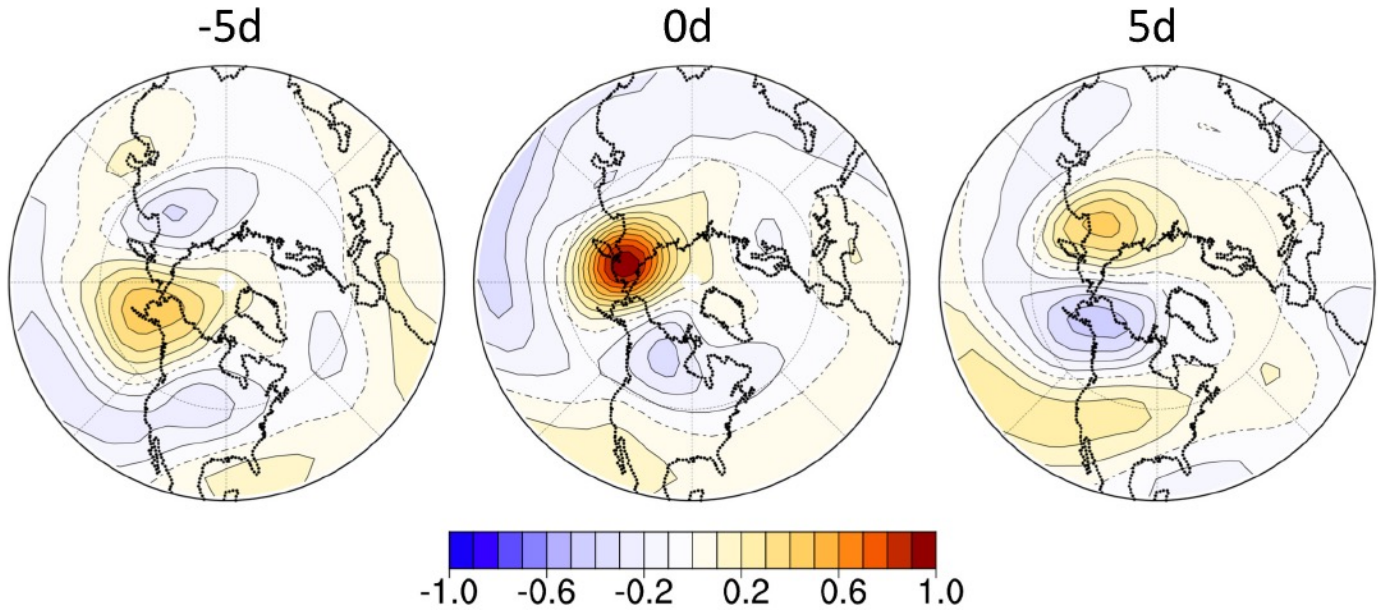
- Contrasting time-longitude sections of Z_{500} on the 42°N and 60°N latitude circles. In the former, eastward propagating disturbances are prevalent at all frequencies, whereas in the latter, westward propagating planetary waves are relatively more prominent, especially at the lower frequencies.
- The westerlies are so weak at 60°N that westward propagation is prevalent despite the weakness of the beta effect.



1.Rossby Wave Dispersion

1.3 Retrograding后退的 planetary-scale Rossby waves

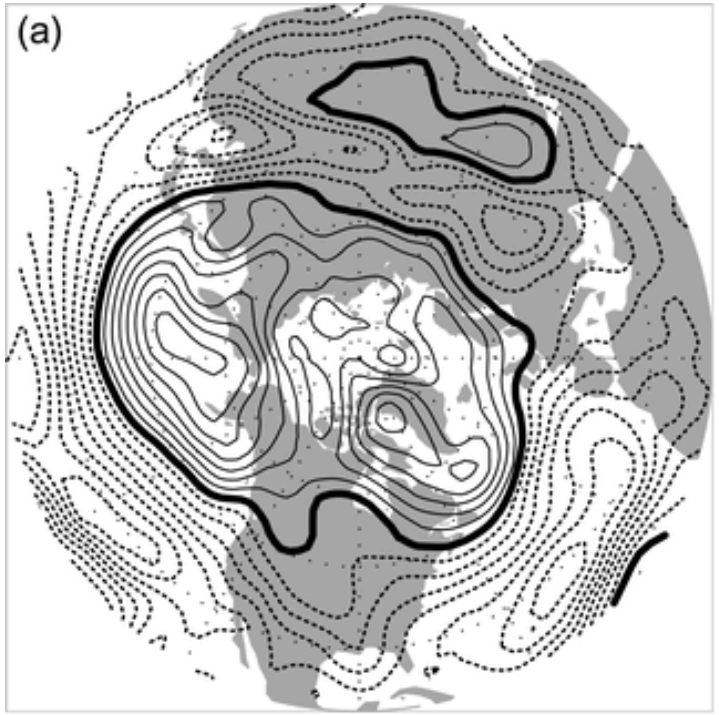
- One-point lag-correlation maps for the grid point at (64°N, 165°E) are shown below. The spatial patterns are dominated by zonal wavenumber $k = 2$ and the phase propagation is characterized by a prevalence of retrogression. That the patterns for lags of +5 days and -5 days are nearly equal and opposite is indicative of a tendency for cyclic evolution with a period of about 20 days.



2.Blocking阻塞

Blocking episodes have been of interest to weather forecasters dating back to the 1940s because they account for a disproportional share of record-breaking warm and cold events and severe weather events.

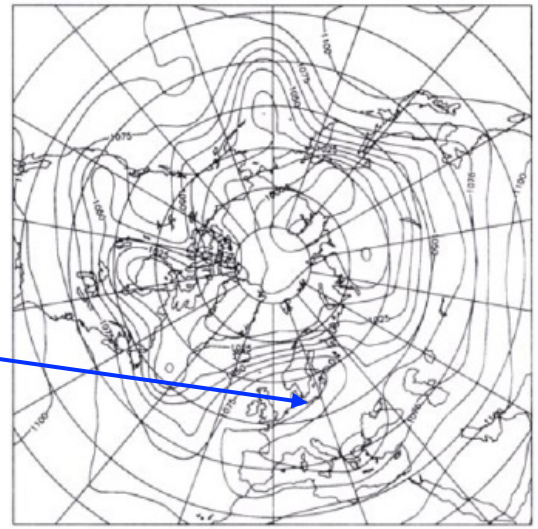
- Some aspects of the nonlinear behavior of the hemispheric circulation can be seen in blocking and flow regimes.
- In the climatological-mean distribution of skewness偏度 of the 6-day lowpass filtered NH DJF Z_{500} field, most of the values in the positive tail are associated with high amplitude ridges and so-called *blocking highs* (or *blocking anticyclones*) that exhibit one or more closed Z contours, with a patch of easterly flow on their equatorward flank that interrupts the westerly background flow in which they are embedded.
- In a similar manner, high amplitude negative values in the band of negative skewness to the south of the jet stream are associated with deep troughs or *cutoff lows* with a patch of easterlies on their poleward flank that “blocks” the westerlies.

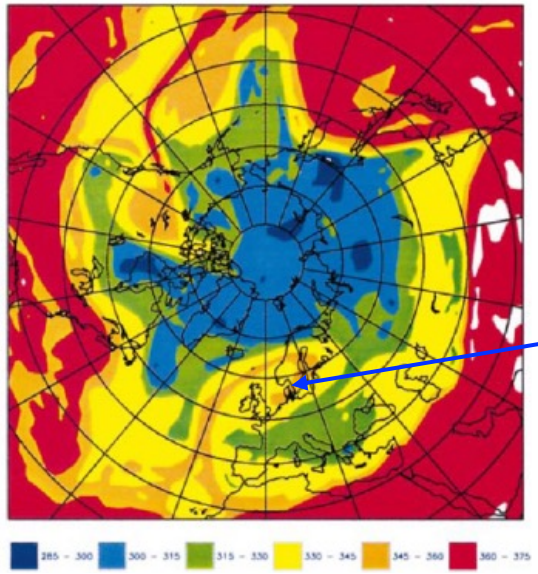


2.Blocking阻塞

- Blocking episodes tend to be long lasting for two reasons: (1) blocking flow configurations are marked by a near-balance between eastward advection of relative vorticity by the zonal flow and westward phase propagation due to the β effect, and (2) they are amplified and maintained by their interactions with the high frequency transients.
- Blocks exhibit a strong barotropic component of the flow that extends from the Earth's surface upward to the lower stratosphere. They are characterized by a local reversal of the meridional gradient of PV on potential temperature surfaces.

Fields associated with a prominent blocking event over northern Europe

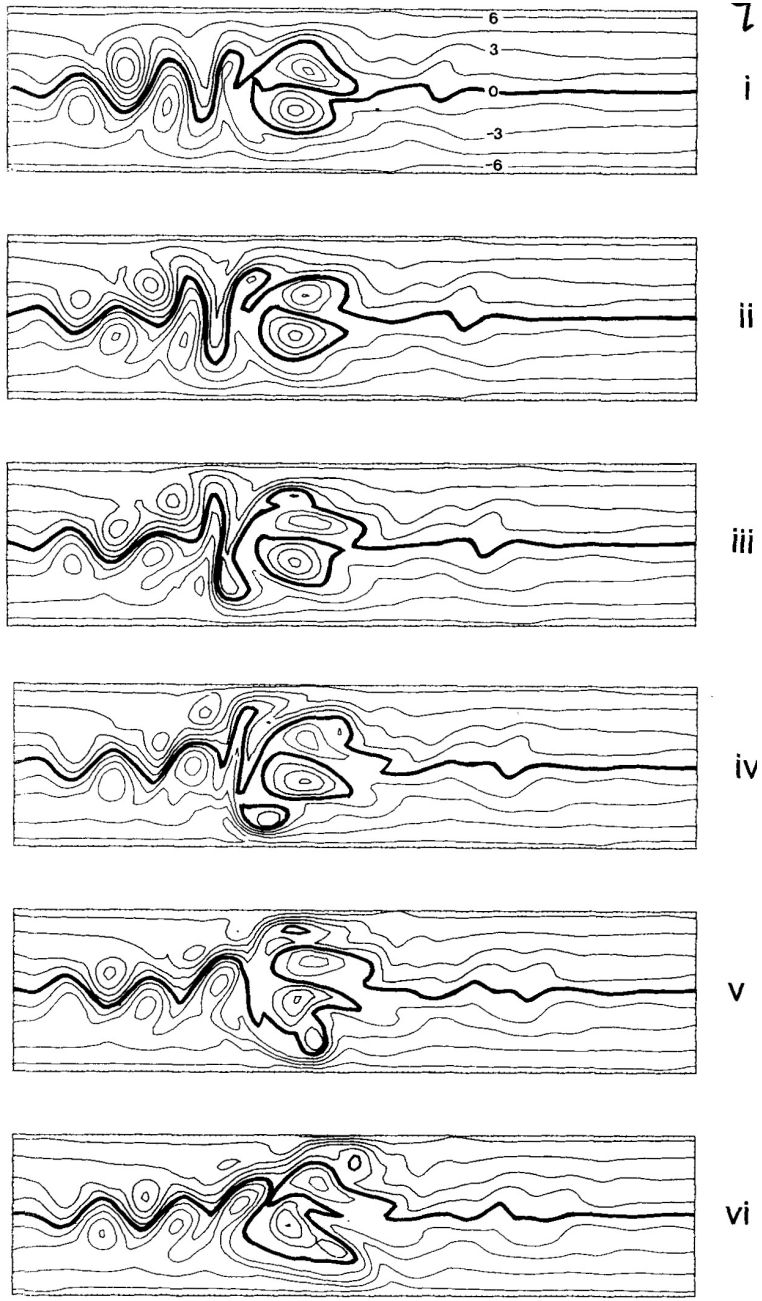




2.Blocking阻塞

- Numerical simulation can illustrate the processes that lead to the formation and maintenance of blocks.
- In this experiment, a barotropic flow in a channel was initialized with a modon偶极子 embedded in a uniform eastward flow and perturbed by a train of waves generated by an upstream wavemaker.
- As the waves approach the modon, they are meridionally stretched, zonally contracted, and twisted in such a way that anticyclonic blobs break off and circulate around the poleward flank of the anticyclonic gyre, re-enforcing it. In this manner, air parcels that formerly resided at low latitudes are transported poleward and become sequestered within closed, anticyclonic eddies and vice versa. This interpretation has been verified in observational studies of blocking episodes.

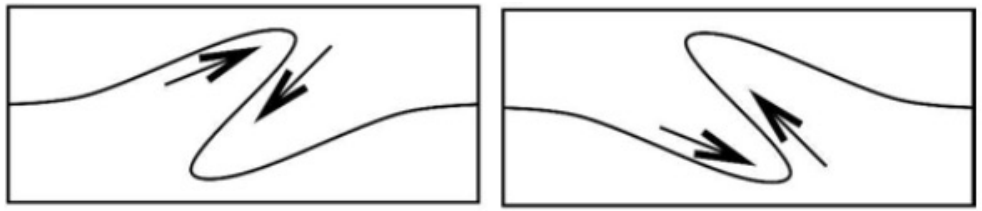
Contours of QG PV



2.Blocking阻塞

- The initiation of blocking anticyclones is often associated with anticyclonic wave-breaking, as shown in the schematic below. With a bit of twisting in either direction, the PV contours passing through a modon in a westerly flow assume a “yin-yang”阴阳 shape.

anticyclonic wave-breaking

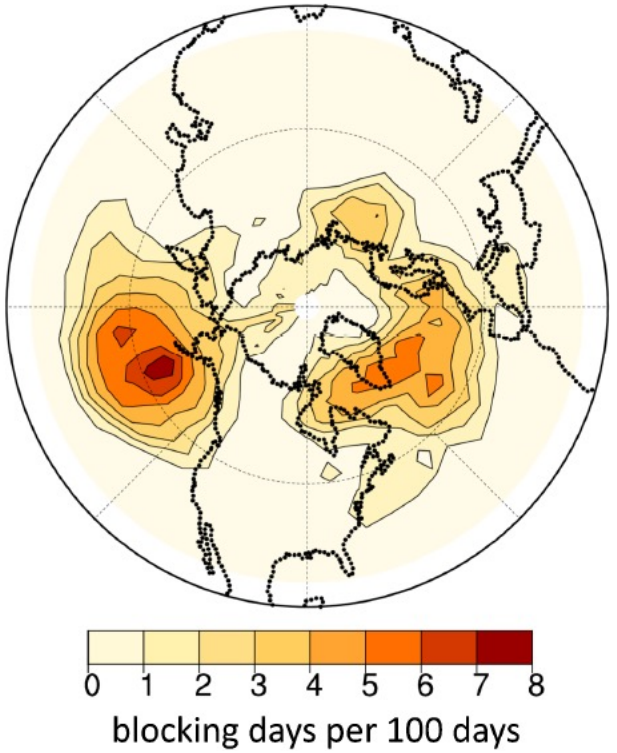


cyclonic wave-breaking

- The direction of the twisting determines whether the contour loops first around the high latitude ridge and then around the low latitude trough or vice versa. Former case is said to be anticyclonic wave-breaking (resulting in a poleward transport of westerly momentum) and the latter is said to be cyclonic wave-breaking (an equatorward transport of westerly momentum). Regardless of which way the waves break, they produce an equatorward transport of vorticity (and PV) along the axis of the developing block, weakening the zonally averaged zonal flow at that latitude.

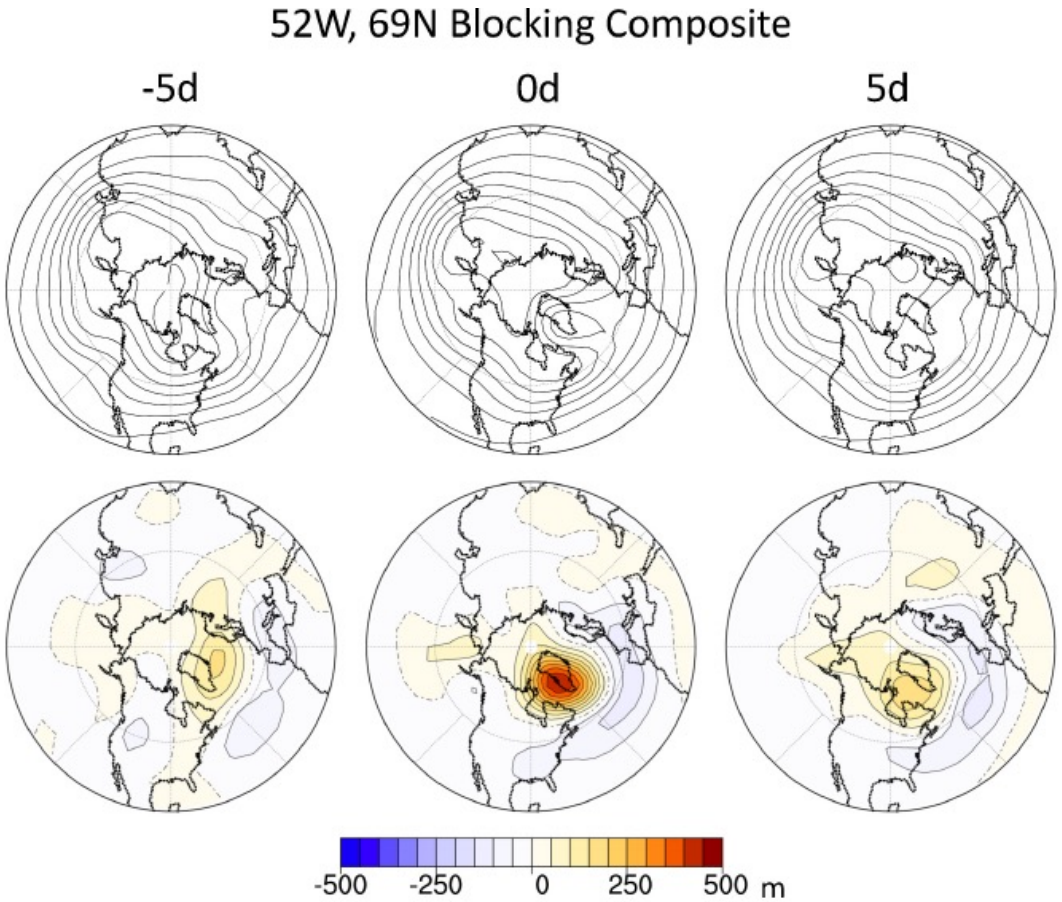
2.Blocking阻塞

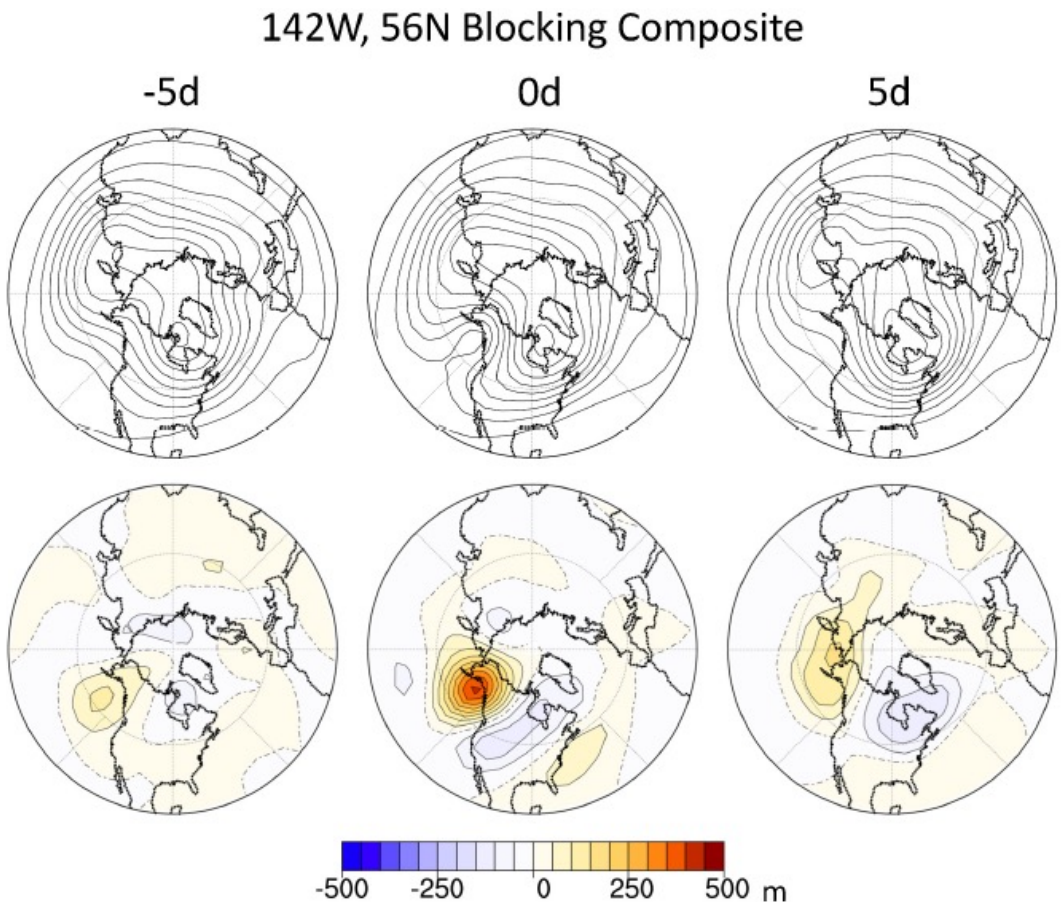
- An alternative criterion for defining blocking that has been widely used in the literature is the occurrence of strong, long-lived geopotential height anomalies at fixed grid points.
- Blocking frequency tends to be highest during winter in the regions of high skewness over and near Greenland and the Gulf of Alaska, downstream of the climatological-mean upper tropospheric troughs, where the background flow is strongly diffluent. Another favored location is downstream of the oceanic storm tracks, which play a role analogous to the wave-maker.



2.Blocking阻塞

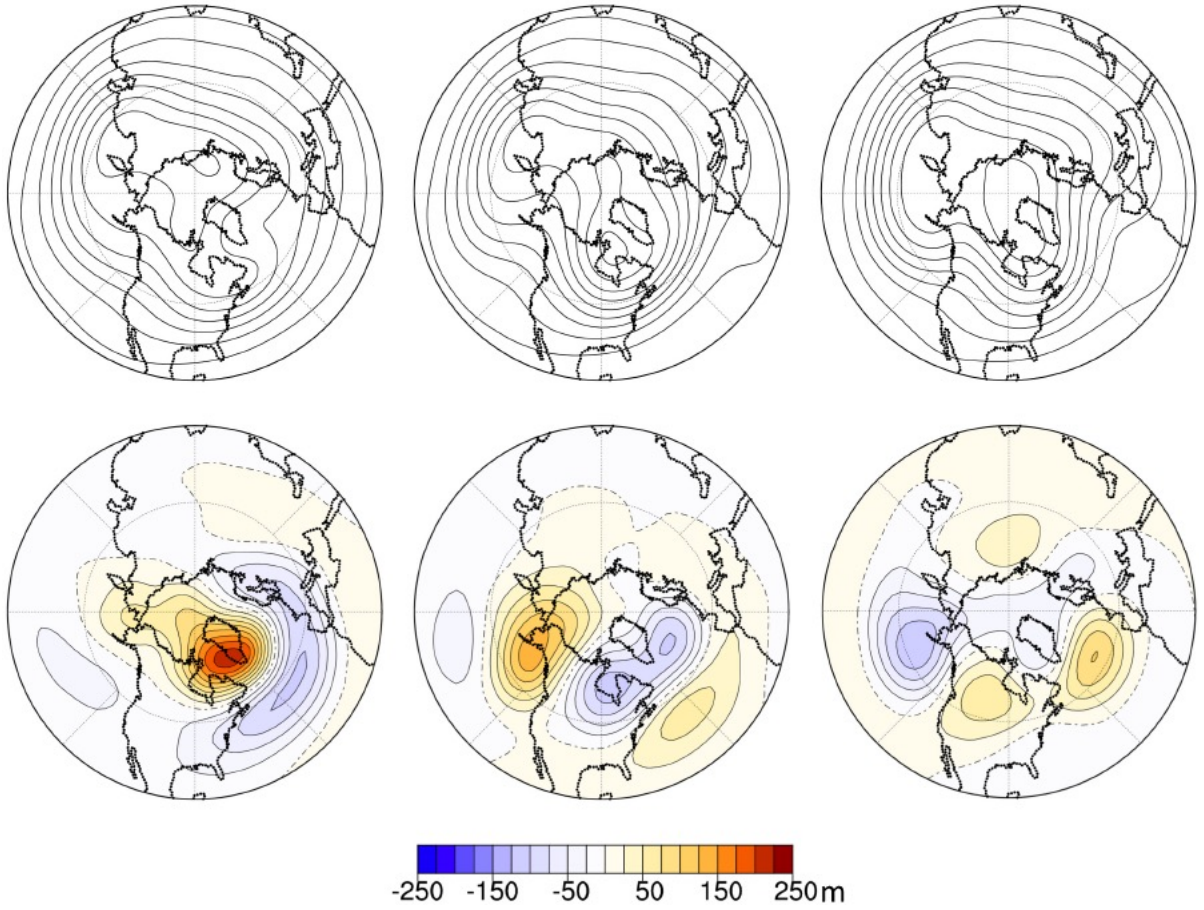
- Over their roughly week-long lifetimes, blocking ridges in both regions exhibit a tendency for retrogression.





3.Favored Flow Configurations

- The notion that there exist favored circulation regimes 流型 persists and is well supported by observational evidence. The most prominent of these regimes are related to blocking or the absence of it.
- The most widely used analysis technique for detecting favored circulation regimes is cluster analysis.
- Clusters are obtained when lowpass filtered DJF Z_{500} anomalies are partitioned using the method of self organizing maps (SOM).

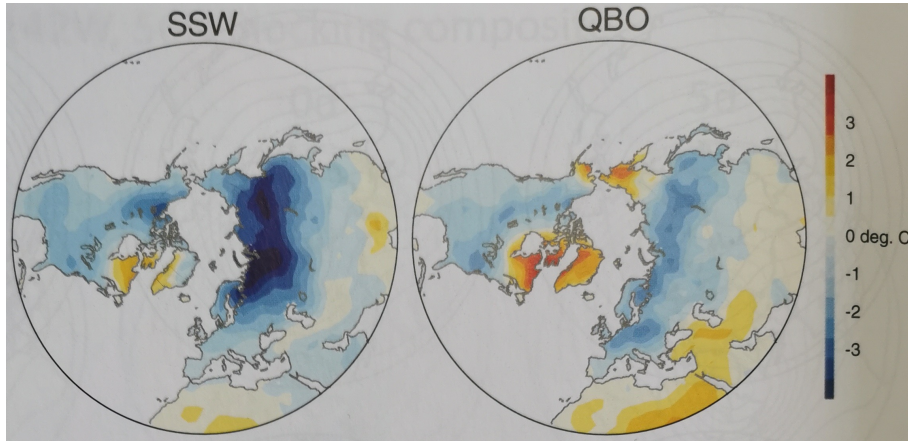


4.Externally Forced Low Frequency Variability

- Preferred patterns of variability play an important role in mediating externally forced climate variability and change. Just as a stretched violin string may emit a pure note — its normal mode of vibration — in response to white noise forcing, the extratropical circulation exhibits favored modes of variability, which assume the form of teleconnection patterns. The same positive feedbacks that maintain the patterns in the presence of frictional and thermal damping can serve to amplify the response to external forcings that project strongly onto them.

4.Externally Forced Low Frequency Variability

- An example — the influence of sudden stratospheric warmings (SSWs) and the quasi-biennial oscillation (QBO) upon the NH barotropic annular mode环状模, the NAM.



- Another example — the secular trend of “ozone hole”臭氧洞 and the SH annular mode (SAM).