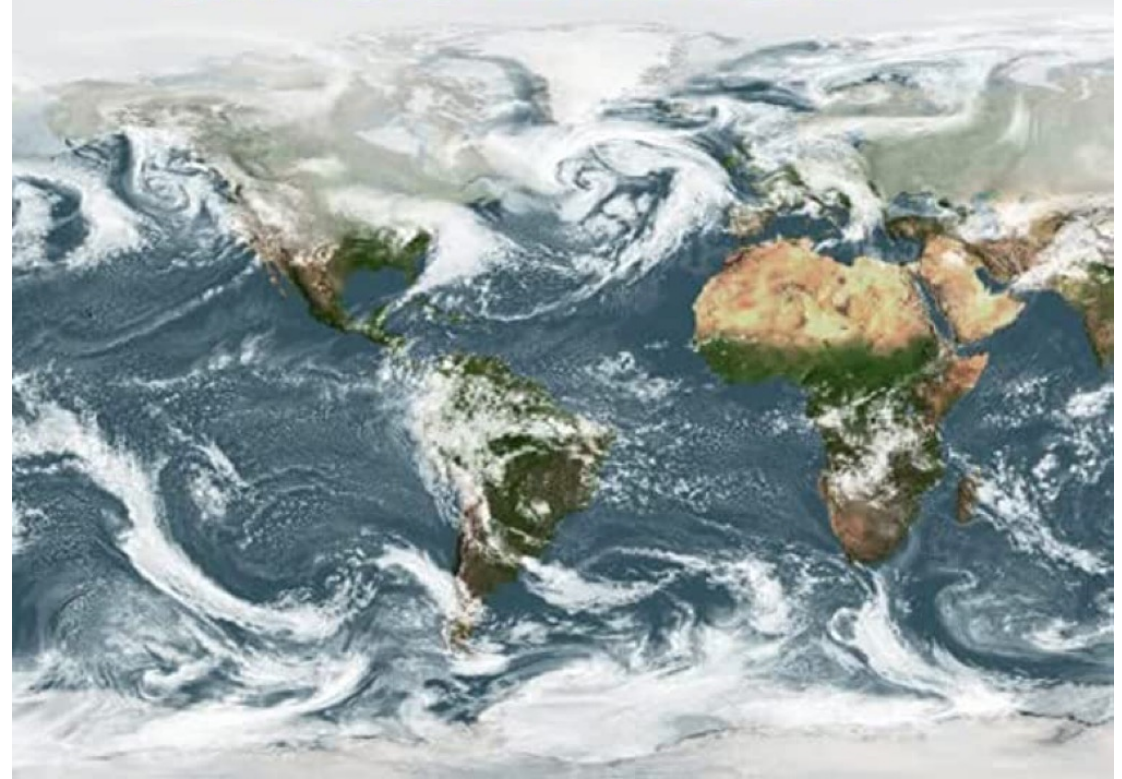


The Atmospheric General Circulation

Nanjing-Helsinki Institute
Nanjing University
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THE ATMOSPHERIC GENERAL CIRCULATION



The Atmospheric General Circulation

- Resources for the Book

<https://agc.atmos.uw.edu/index.html>

- Solutions to most of the exercises in the textbook

<https://www.cambridge.org/highereducation/api/resources/33DDE1003D6FB7E124A8C9A2BD17886E>



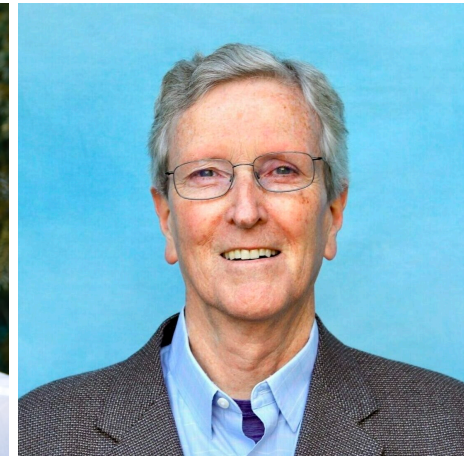
John M. Wallace



David Battisti



David Thompson



Dennis Hartmann

The Atmospheric General Circulation

Lecture 9: The Northern Hemisphere winter
zonally varying climatology

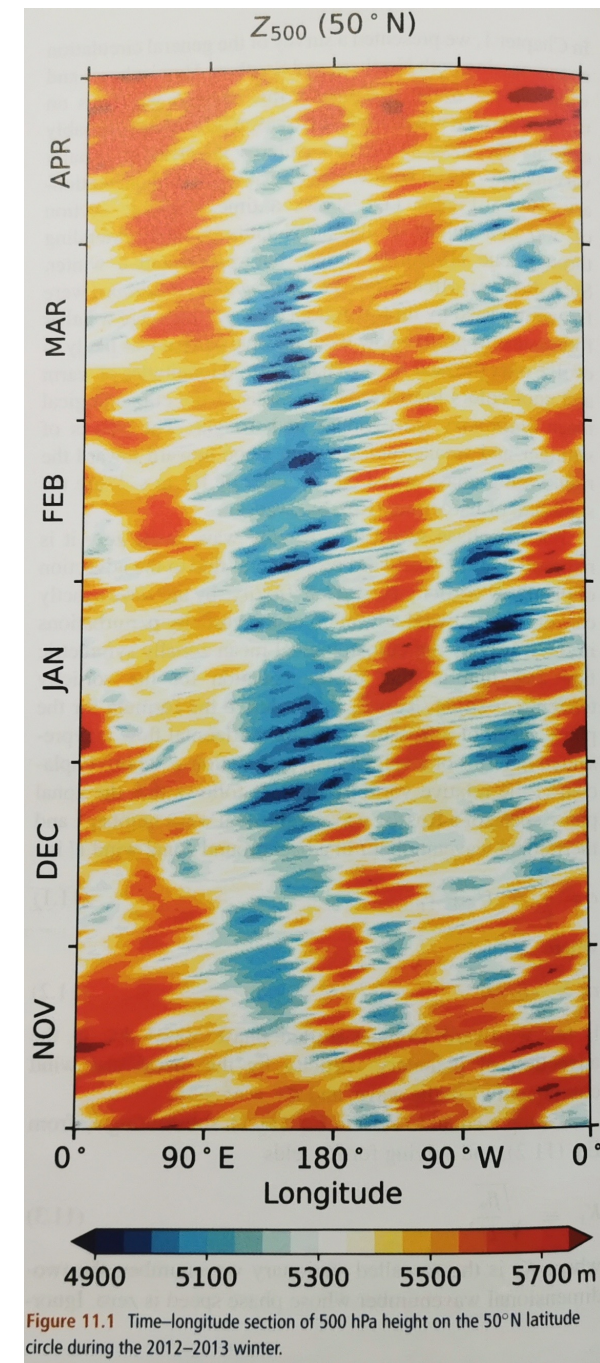
北半球冬季纬向变化的气候态

Ming Bao

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Introduction

- NH winter season DJF arguably exhibits the most distinctive patterns in terms of zonally varying jets, storm tracks, and climatological mean stationary waves.
- Right figure shows a time-longitude section of Z_{500} on the 50°N latitude circle during the 2012–2013 winter. Such displays, often referred to as *Hovmöller diagrams*. The preferred longitudes of warm and cool colors indicate the positions of the climatological mean *stationary wave ridges and troughs*.
- K_s is the so-called stationary wavenumber; $K_s \sim 4$ corresponding to a stationary zonal wavenumber $k_s \sim 2-3$.



1. Observed & Simulated structure in DJF

- The positions of the storm tracks, represented by the [standard deviation of the 700 hPa vertical velocity](#) field based on unfiltered daily data, are slightly stronger in observation (ERA-I) than in CTL (control simulation) and in CTL than in NM (no mountain experiment).

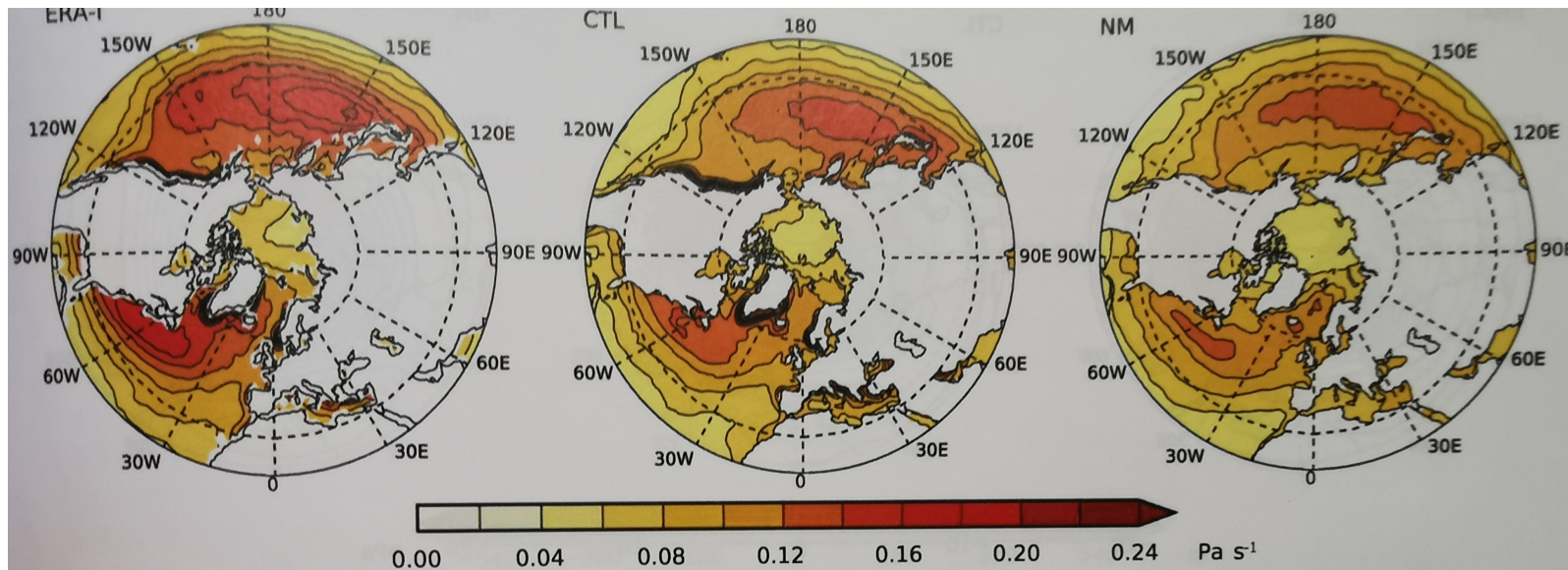
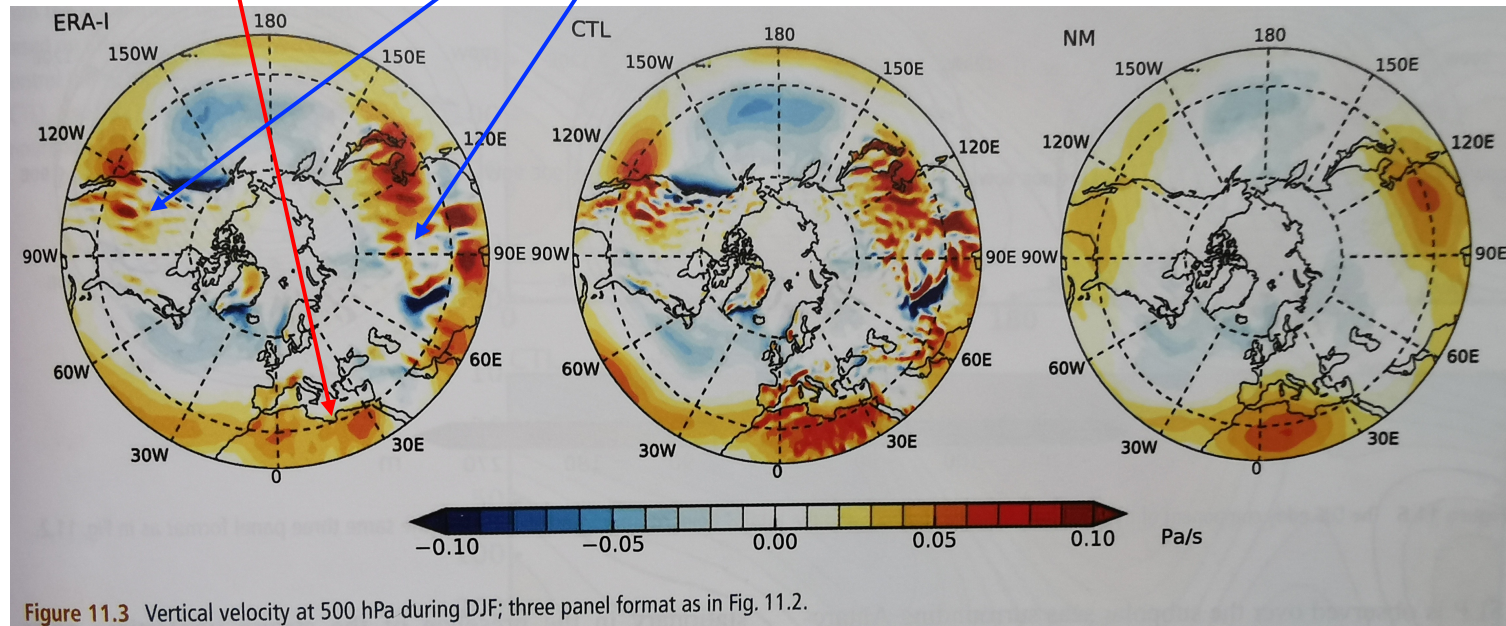


Figure 11.2 The standard deviation of the 700 hPa vertical velocity field during DJF based on unfiltered daily data. (Left) ERA-Interim reanalysis; (middle) as simulated in the control run of the Whole Atmosphere Community Climate Model (WACCM) with realistic orography (CTL) and (right) in a run of the same model in which the orography is entirely flattened and the parameterized frictional drag is the same as it would be on a planet with the same continent–ocean configuration, but with all land surfaces at sea level (NM). Unless otherwise noted, the domain in these polar stereographic projections is poleward of 20°N.

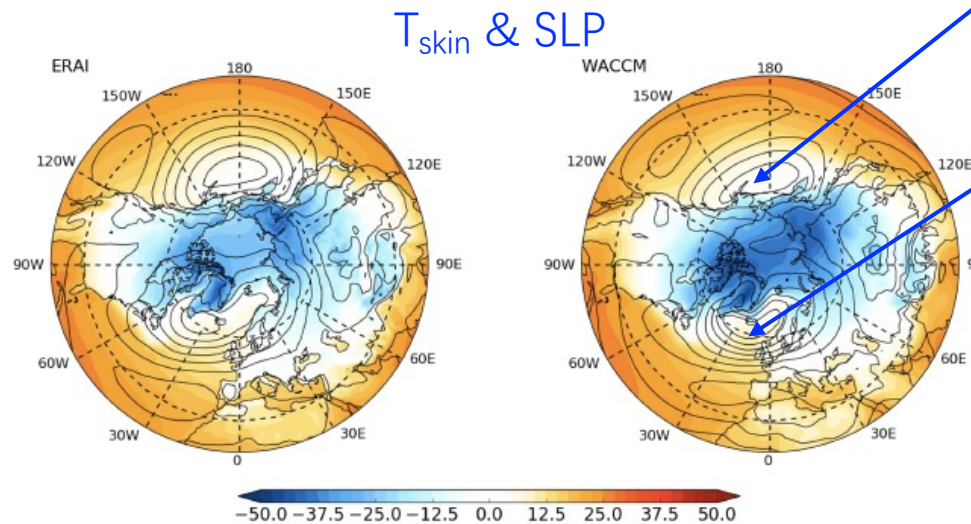
1. Observed & Simulated structure in DJF

- The subsidence around the periphery of the map (20-30°N) is a reflection of the **sinking branch of the Hadley cell**. Prominent zonally varying features include patches of **ascent upstream and descent downstream of the mountain ranges** of central and eastern Asia and North America. Embedded in the planetary-scale orographic signature are bands imprinted by the individual mountain ranges. Over the open oceans there are patches of ascent at the eastern end of the storm tracks.

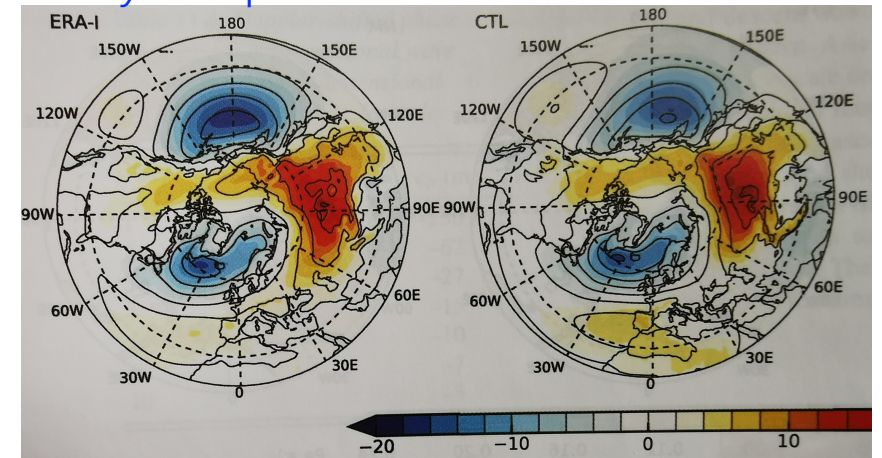


1. Observed & Simulated structure in DJF

- At the higher latitudes, land, with its low heat capacity, tends to be much colder than the ocean at the same latitude. The subpolar **Aleutian and Icelandic lows** are prominent features of the SLP field.



Eddy component of SLP & the total SLP

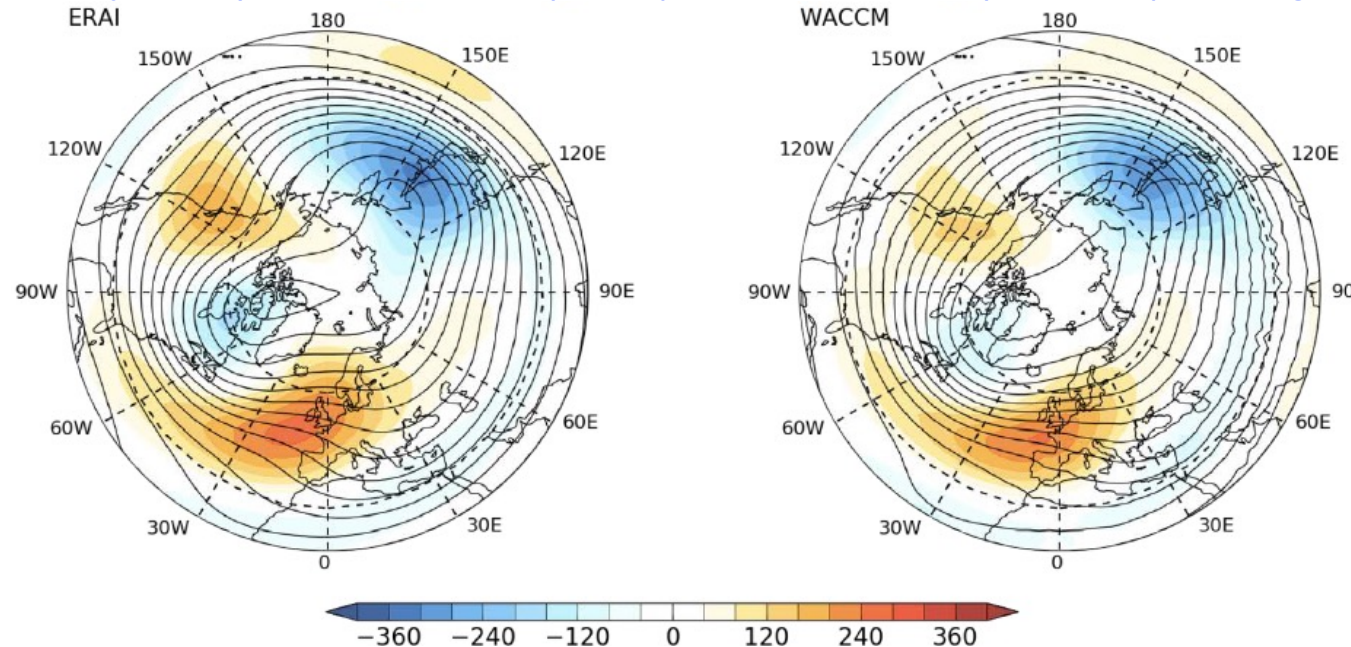


- The NH near-surface subpolar features assume the form of closed cyclones rather than a series of troughs in the westerlies because the axially symmetric flow at subpolar latitudes is almost zero, as evidenced by the strong correspondence between SLP contours and shading.

1. Observed & Simulated structure in DJF

- Z_{300} patterns exhibit pronounced ridges over the west coasts and troughs over the east coasts of the continents. The westerlies are particularly strong along the base of the troughs, where the height contours are pinched together. The storm tracks are located along the poleward flanks of these jets and somewhat downstream of them.

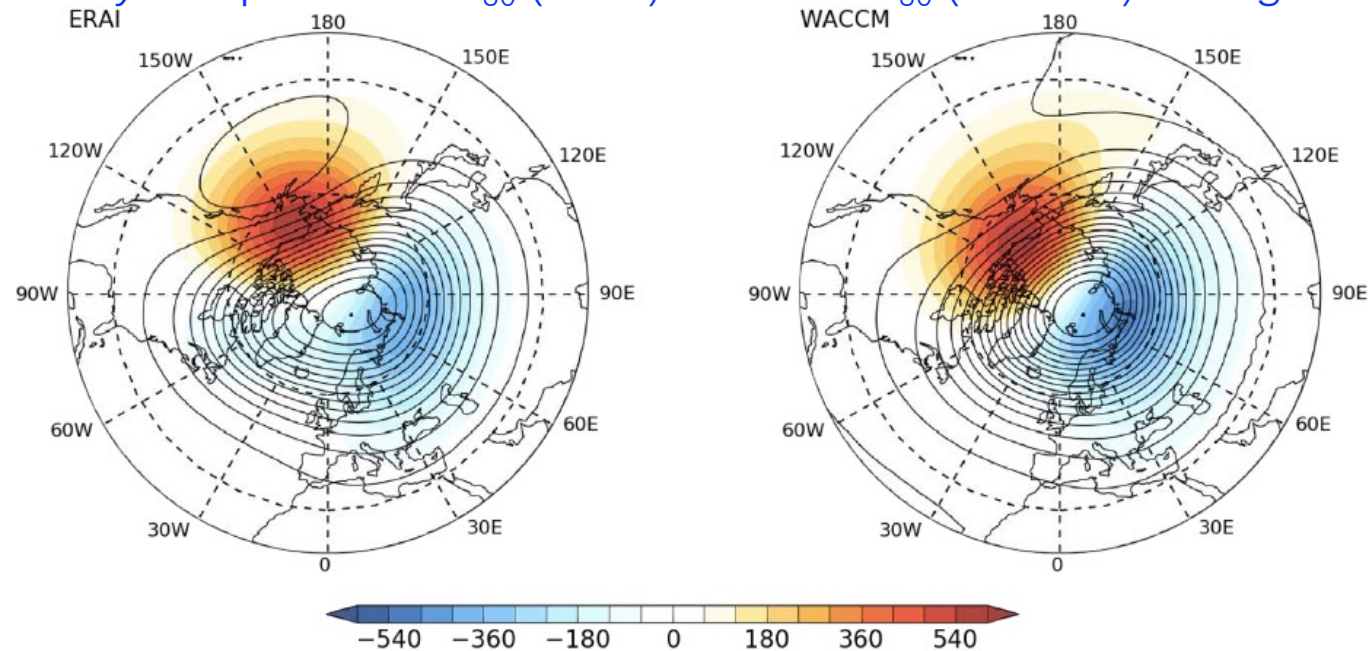
Eddy component of Z_{300} (color) and total Z_{300} (contour) during DJF



1. Observed & Simulated structure in DJF

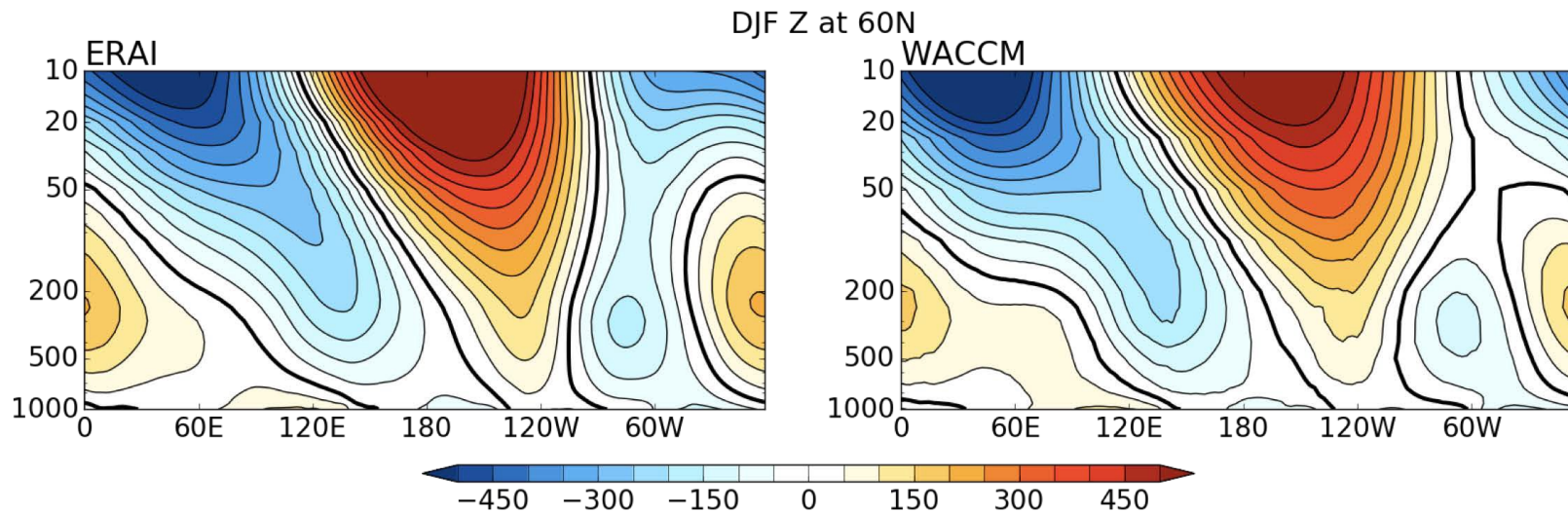
- The boreal wintertime planetary waves **disperse upward into the stratosphere**, but it is only the lowest zonal wavenumbers ($k = 1, 2$) that are capable of remaining stationary in the presence of the strong wintertime polar night jet. The climatological mean ridge centered over Alaska is a persistent feature of the wintertime stratospheric polar vortex and it evidently plays a role in the **midwinter warming**. (see Lecture 12)

Eddy component of Z_{30} (color) and total Z_{30} (contour) during DJF



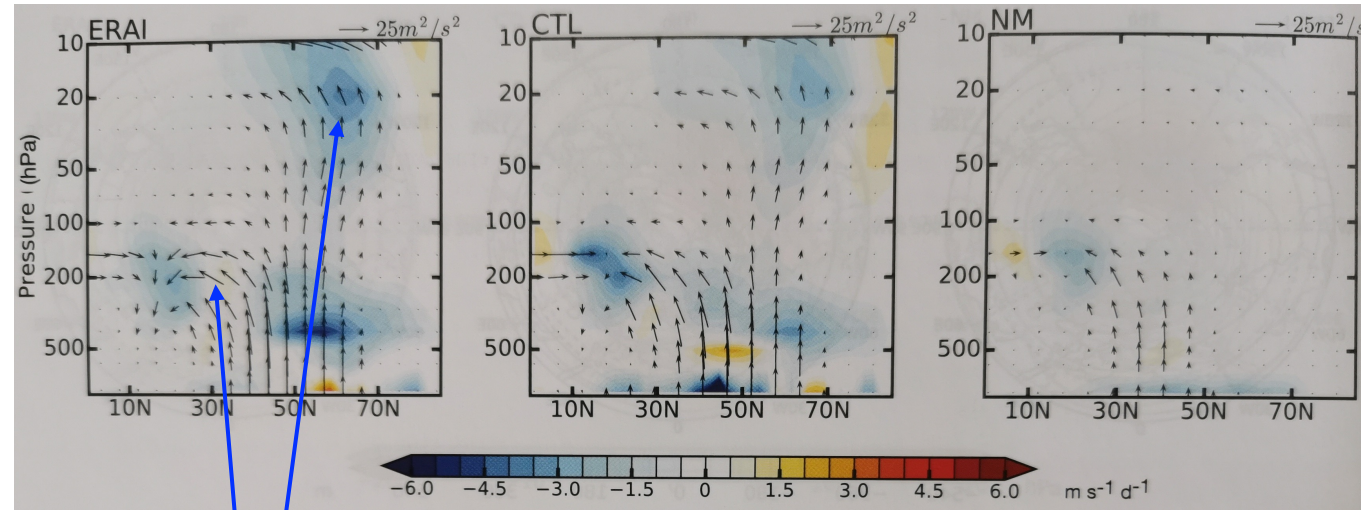
1. Observed & Simulated structure in DJF

- The longitude-height cross section at 60°N illustrates a vertical structure that **tilts westward with height**. The amplification of the waves and the transition toward lower zonal wavenumbers with increasing height are also evident.

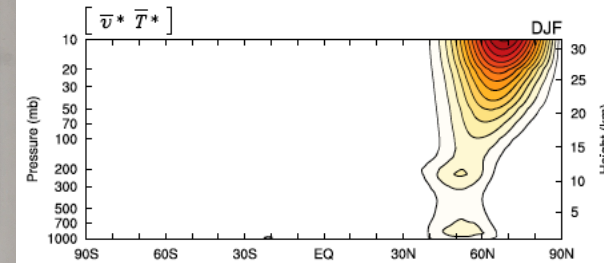


Departure of the Z at 60N from the zonal mean

1. Observed & Simulated structure in DJF



EP fluxes by the stationary waves and its divergence



- The continuous westward tilt with height is consistent with the observed poleward heat flux by the stationary waves in DJF (right) and the upward EP fluxes in the stationary waves. The EP fluxes split into two branches — one dispersing equatorward into the subtropics at the tropospheric jet stream level (~200 hPa) and the other one dispersing straight upward and converging into the polar night jet. The region of EP flux convergence (blue shading) are characterized by breaking planetary waves, which extract westerly momentum from the zonal mean flow in accordance with the properties of EP flux.

1. Observed & Simulated structure in DJF

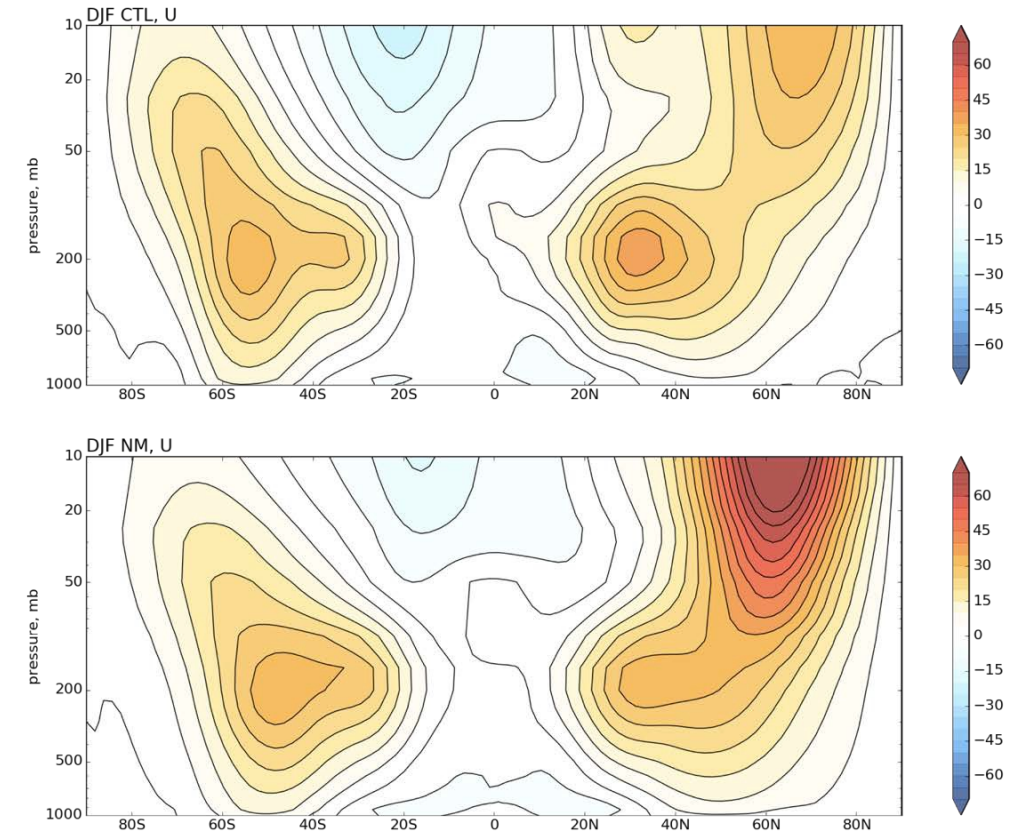
- Although the conversions in the mechanical energy cycle in the stationary waves are qualitatively similar to those in baroclinic waves, the dynamical interpretation is somewhat different.
- Rather than playing the central role in maintaining the waves and being responsible for their existence, the conversion from zonal to eddy available potential energy in the stationary waves can be viewed as a positive feedback that serves to amplify the response to whatever wave forcing is present.
- To understand why the stationary waves exist and why they assume the form that they do, it is necessary to consider the **responses to the various forcings: orography, diabatic heating, and the transports by the transients.**

2. Orographic Forcing 地形强迫

2.1 Impact on the zonally symmetric flow

- The westerlies are substantially stronger in the NM run than in the control run, especially in NH. The strengthening is most pronounced at the uppermost levels but it is discernible all the way down to the Earth's surface.
- The influence of the orography in reducing the amplitude of the stratospheric polar night jet was partitioned into the **drag from the EP flux convergence by resolved waves**, and the **drag associated with subgrid scale orographic feature that are parameterized in the model**. Neither the forcing by the resolved or the unresolved waves, acting alone, can account for more than a small fraction of the marked weakening of the jet in the control experiment CTL as compared with NM.

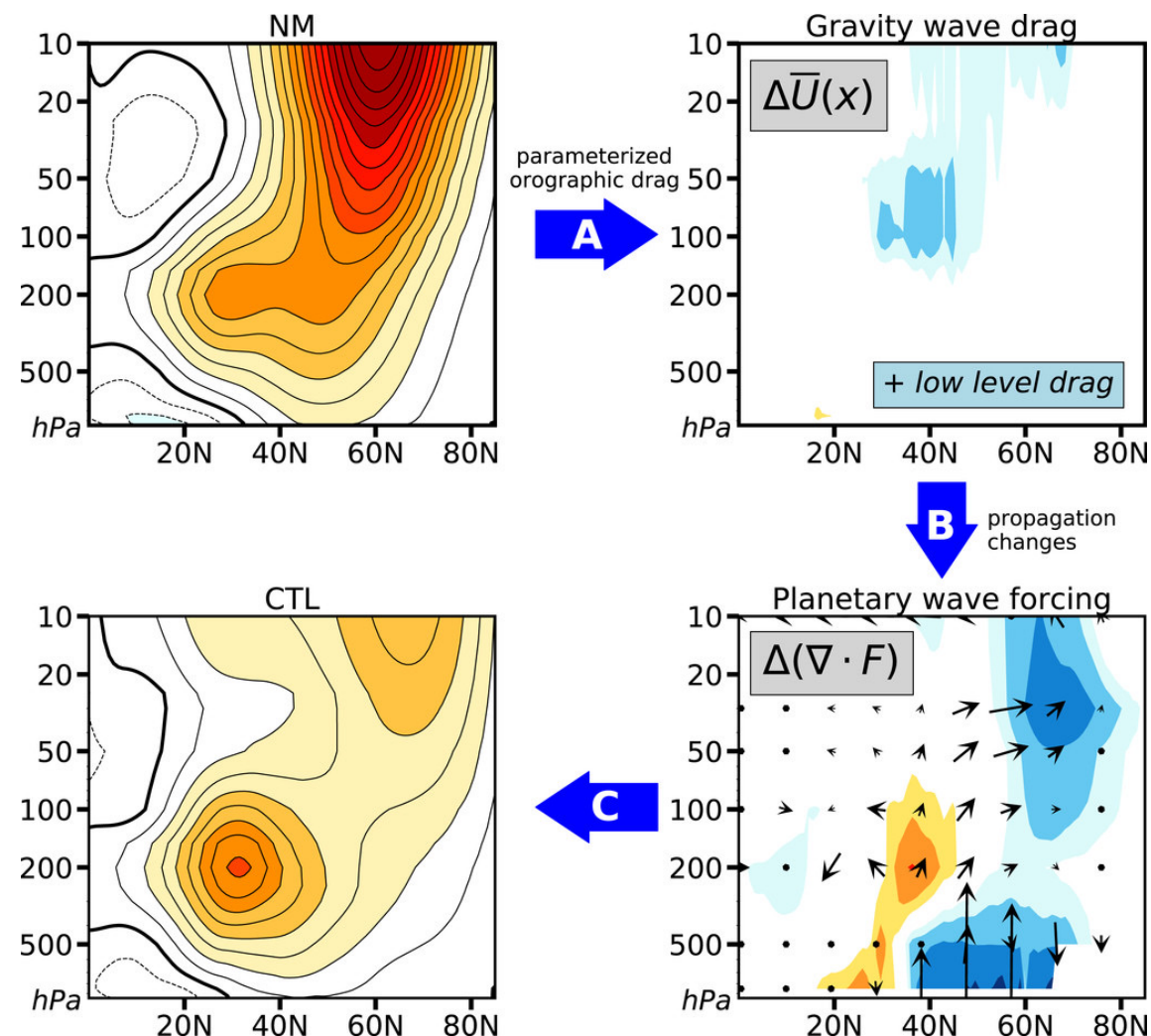
NM ("no mountain"): the land surface is completely flattened and the orographic forcing is entirely eliminated in both the resolved dynamics and in the parameterizations that involve gravity wave drag.



2. Orographic Forcing 地形强迫

2.1 Impact on the zonally symmetric flow

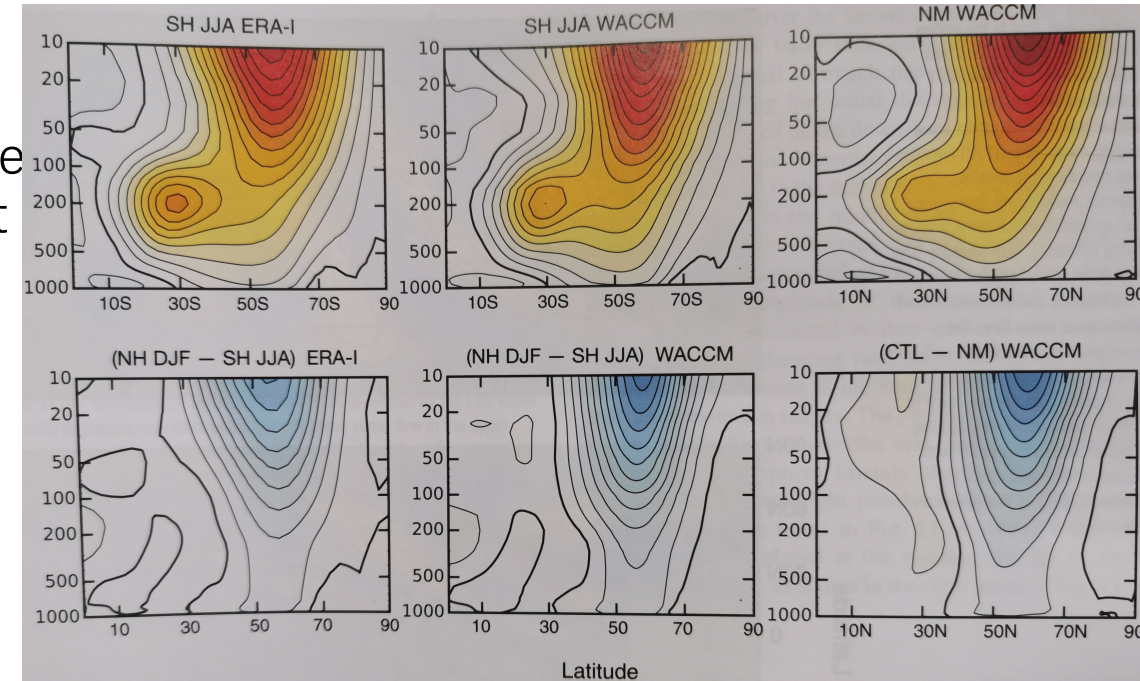
- The direct effect of drag from unsolved gravity waves slightly reduces the strength of the westerlies just above the tropospheric jet stream.
- The weakening of the westerlies at this level renders the stratospheric polar night jet more susceptible to the breaking of planetary waves dispersing upward from the troposphere, resulting in enhanced EP flux and EP flux convergence.
- It is this positive feedback between the forcing by resolved and unresolved orography that makes the whole so much greater than the sum of the parts.



2. Orographic Forcing 地形强迫

2.1 Impact on the zonally symmetric flow

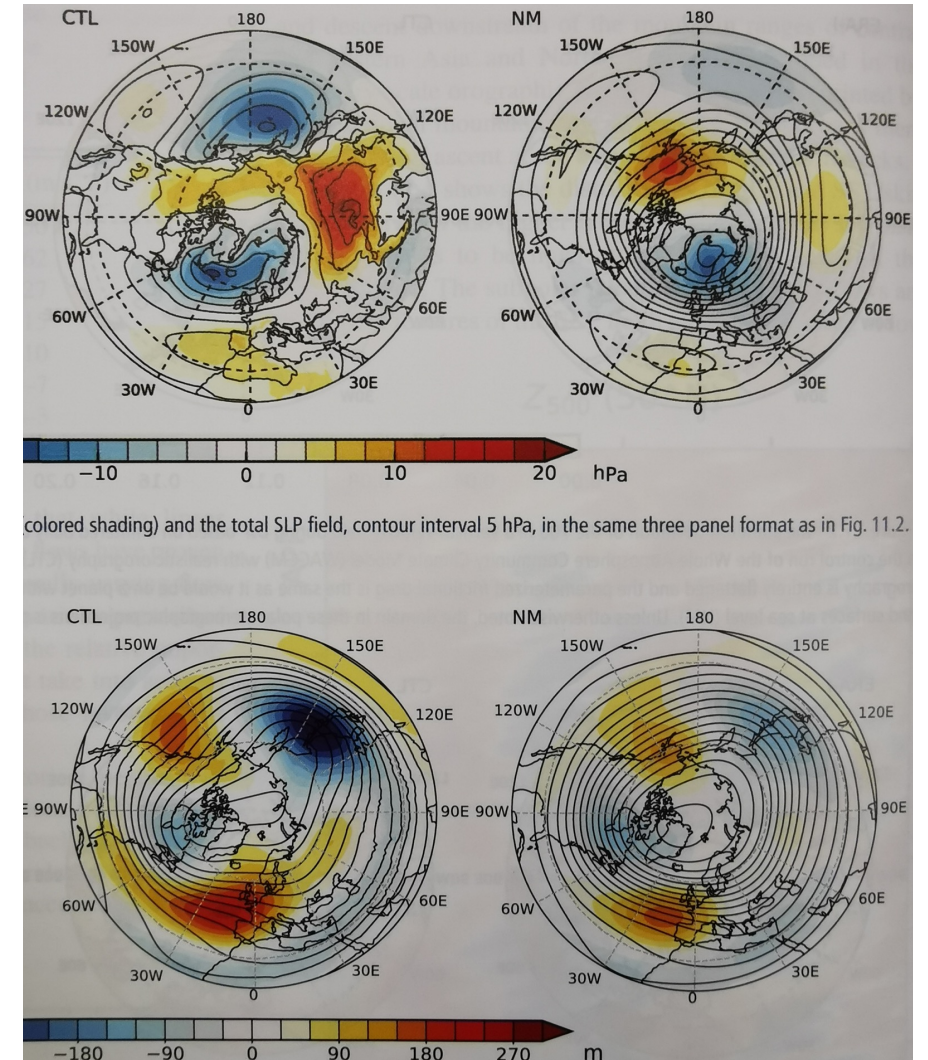
- Since the SH's high mountain range in the latitude belt of the westerlies, the Andes, is much more limited in longitudinal extent than the ranges on the NH continents, and the Andes achieve their highest altitudes equatorward of the westerly wind belt, comparing CTL and NM simulations in a climate model can be considered as analogous.
- In some respects, to comparing NH and SH wintertime climatologies, using the latter as an indicator of that the zonally symmetric circulation would be like on a planet without mountains.
- The similarity of the patterns in the three panels confirms that the zonally symmetric circulation in the NM experiment mimics the SH wintertime zonally symmetric circulation, and that the [Andes range has little impact on the zonal mean zonal wind](#).



2. Orographic Forcing 地形强迫

2.2 Impact on the stationary waves

- It is evident from a comparison of the left and right panels that including mountains in the WACCM simulations substantially increases the prominence of the stationary waves.
- The strong influence of the mountains on the boreal winter general circulation also derives from the [symbiotic relationship between the mechanical and thermal influences](#) that exists by virtue of the particular positioning of the mountain ranges on the NH continents.
- The presence of orography and the extensive NH mountain ranges greatly enhances the zonal asymmetries in the boreal wintertime climate at all level (from surface subpolar low, east-west T contrasts, to polar night jet).

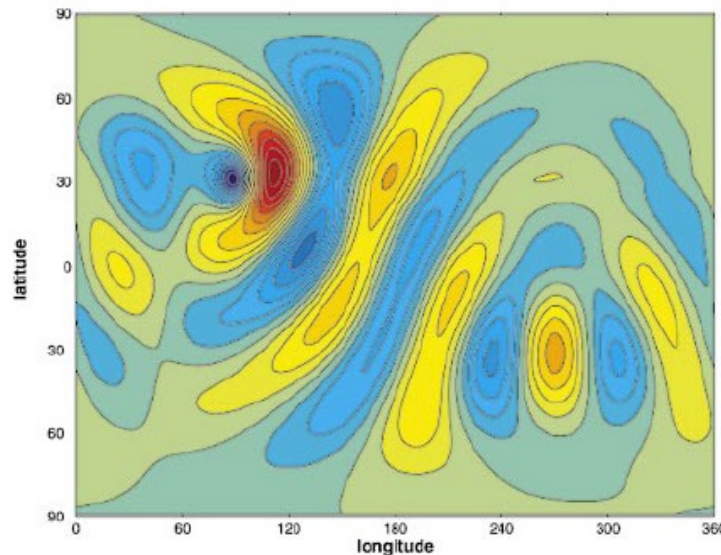


2. Orographic Forcing 地形强迫

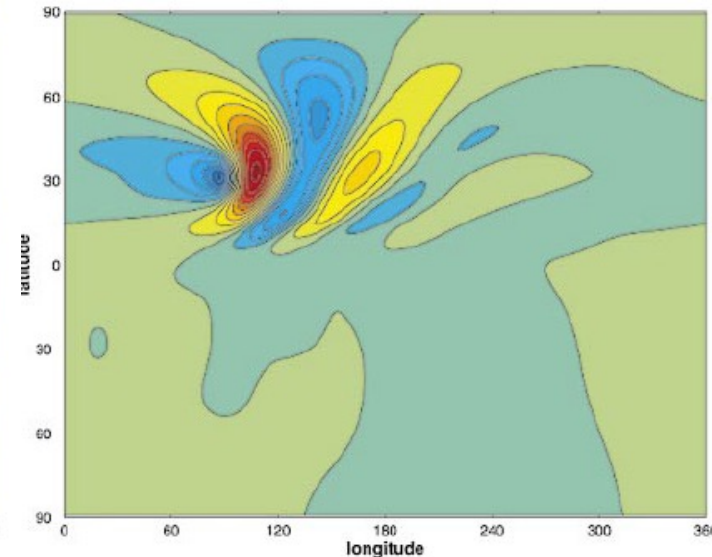
2.3 Insights derived from experiments with a 2D model

- Since orography influences the stationary waves **indirectly**, by slowing down the zonally symmetric flow, and thereby enabling the stationary waves to disperse upward more readily, the differences between the CTL and NM simulation **cannot be interpreted as a linear wave response** to the orographic forcing.
- Velocity streamfunction field in the eddies induced by flow over **an idealized circular mountain** as inferred from **a model based on the barotropic vorticity** linearized about two different zonally symmetric background flows.

Pure superrotation
(constant angular
velocity $[u]\cos\phi$)



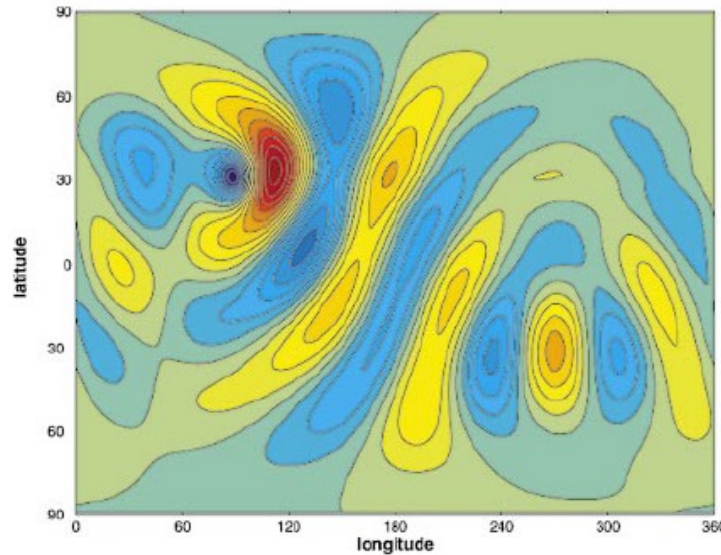
More realistic
zonal mean flow



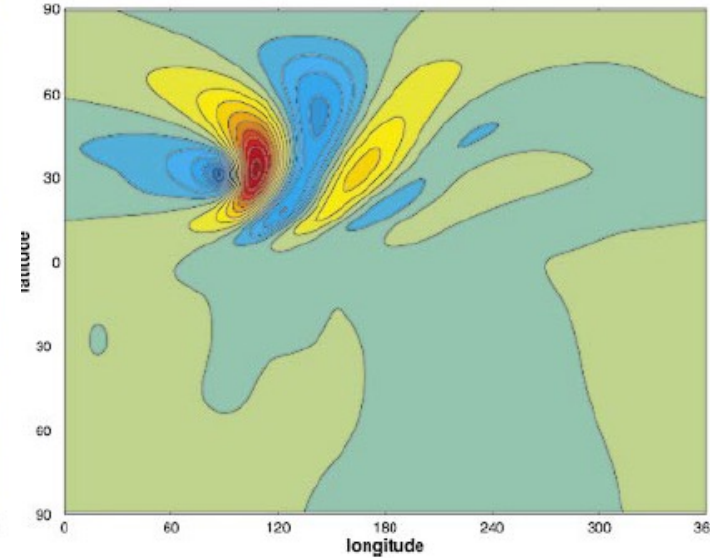
2. Orographic Forcing 地形强迫

2.3 Insights derived from experiments with a 2D model

Pure superrotation
(constant angular
velocity $[u]\cos\phi$)



More realistic
zonal mean flow

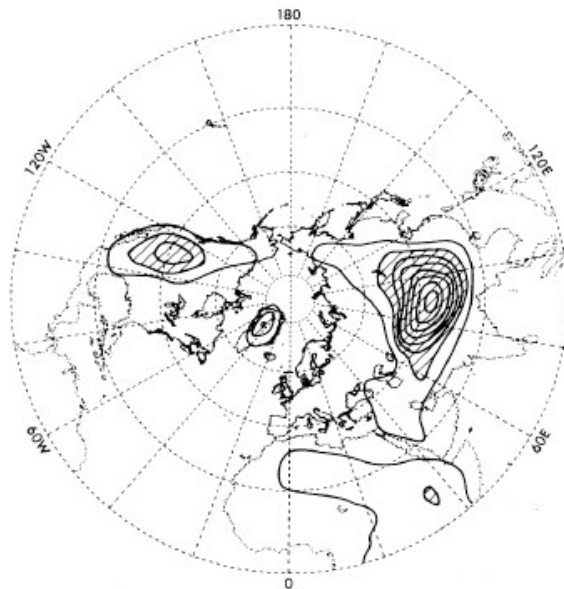


- $\frac{\partial \zeta}{\partial t} = -V_h \cdot \nabla(\zeta + f) - r\zeta$ The barotropic vorticity equation can be integrated forward in time until the flow reaches a steady state.
- For basic state flow to be **pure superrotation**, the streamfunction field for the Rossby wave response consists of a wave train that disperses eastward along a great circle.
- For a **more realistic zonal mean zonal flow**, the wave train is absorbed when it encounters the zero zonal wind in the zonal mean flow, at $\sim 10^\circ\text{N}$.

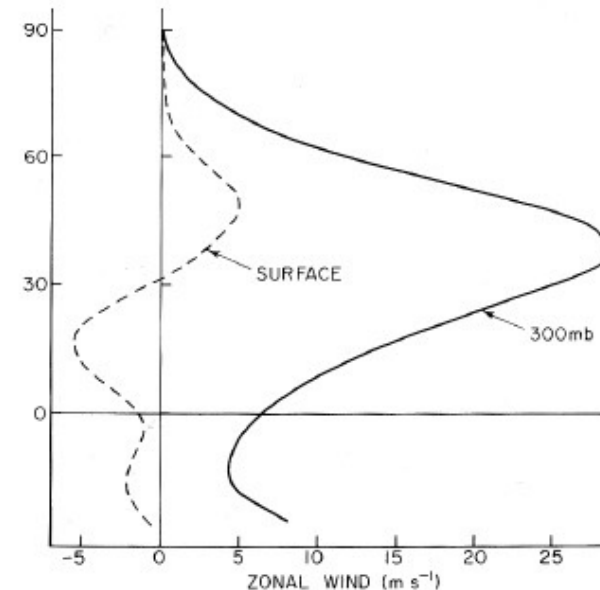
2. Orographic Forcing 地形强迫

2.3 Insights derived from experiments with a 2D model

- Consider the response to **more realistic orographic forcing**, a highly smoothed version of the NH orography (left panel). The meridional profile of climatological zonal mean zonal wind is prescribed (right panel).
- Forcing in barotropic model:



Mountain ranges

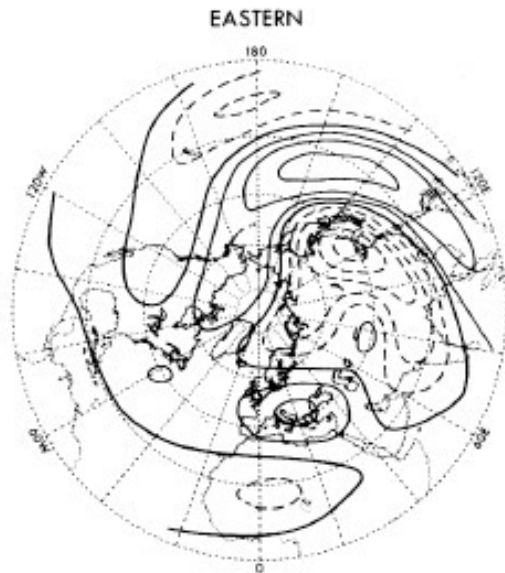


Meridional profiles of the prescribed zonally averaged winds

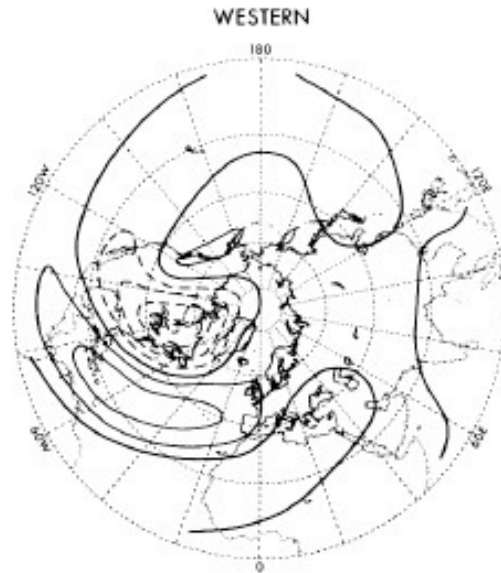
2. Orographic Forcing 地形强迫

2.3 Insights derived from experiments with a 2D model

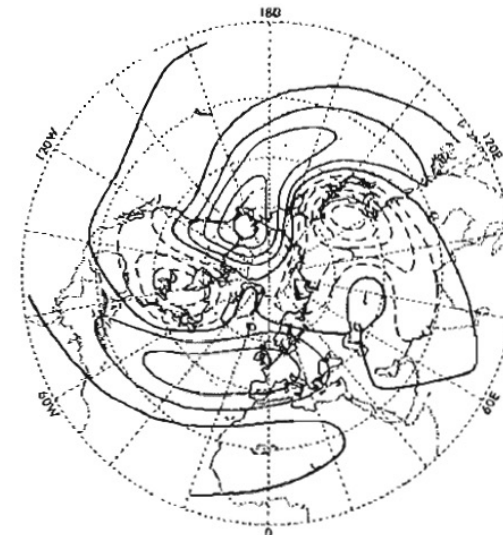
- Orographic forcing gives rise to Rossby wave trains to the east of each of the major mountain ranges. Since the model is linear, the simulated response is the sum of the responses to the individual mountain ranges.



Mountains of EH



Mountains of WH

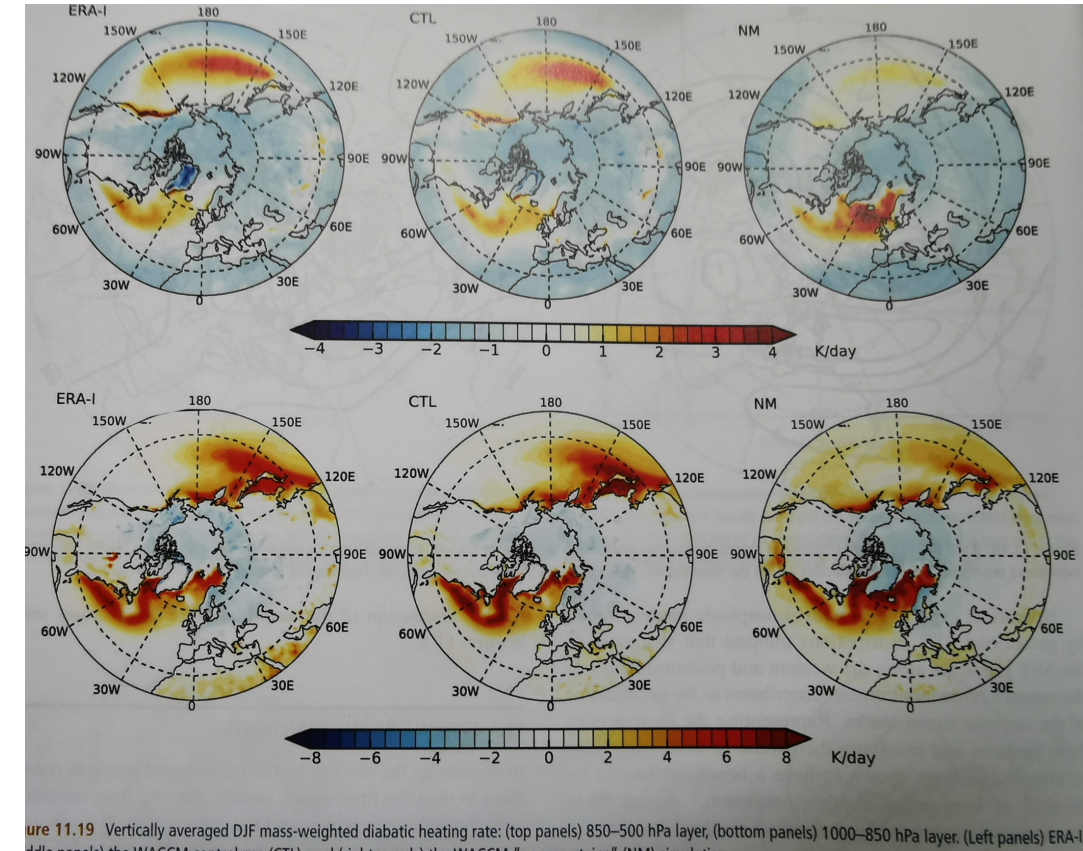


All Mountains

3. Diabatic Forcing 非绝热强迫

3.1 The observed heating

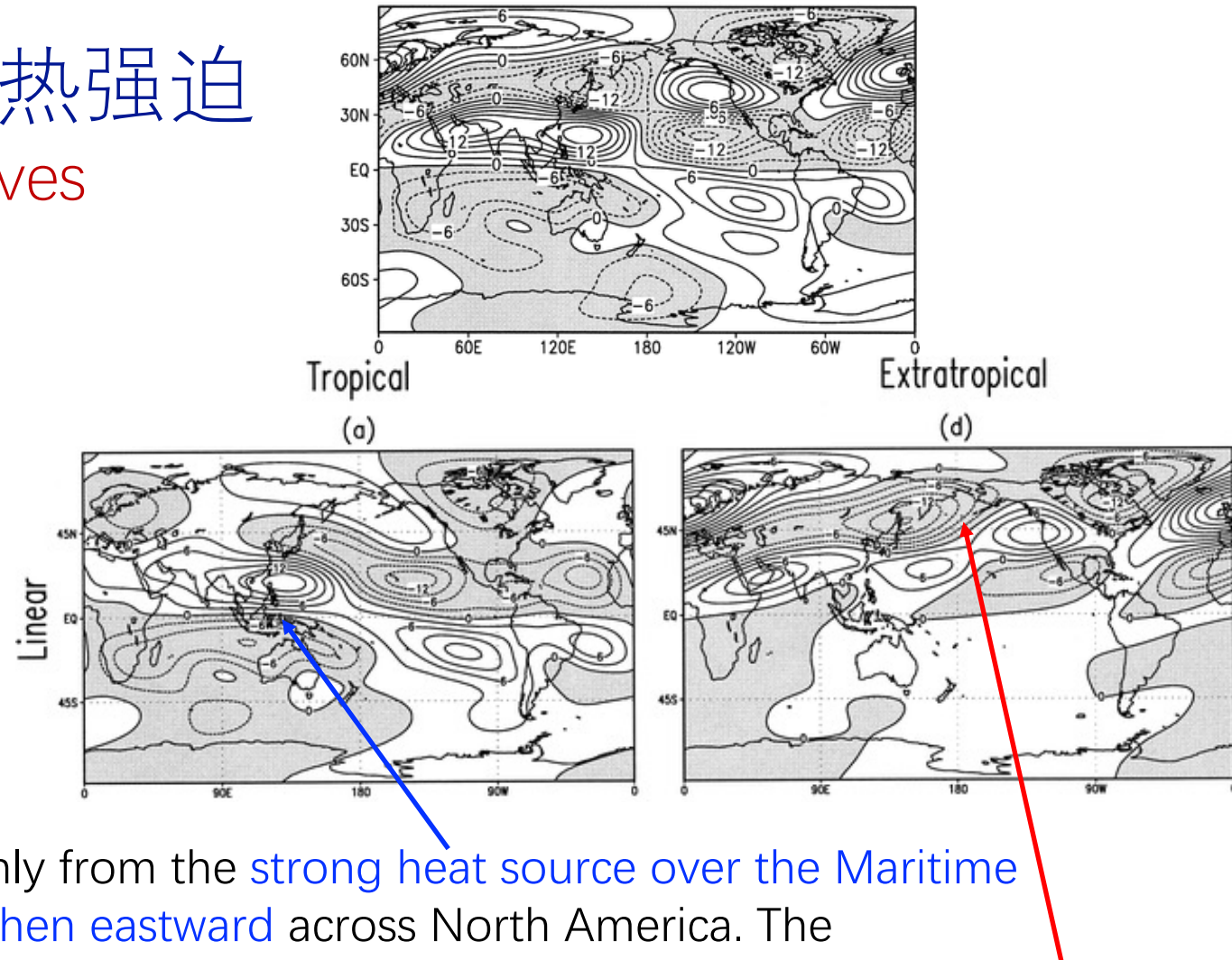
- The boundary layer heating shown in the bottom panels is strongest off the eastern seabords of Asia and North America, where the ocean surface is much warmer than the air flowing off the continents during wintertime. They are enhanced by the existence of the warm, wind-driven western boundary currents in these regions, [the Gulf Stream \(墨西哥湾流\)](#) in the Atlantic and [the Kuroshio-Oyashio current \(黑潮-亲潮\)](#) system in the Pacific.



3. Diabatic Forcing 非绝热强迫

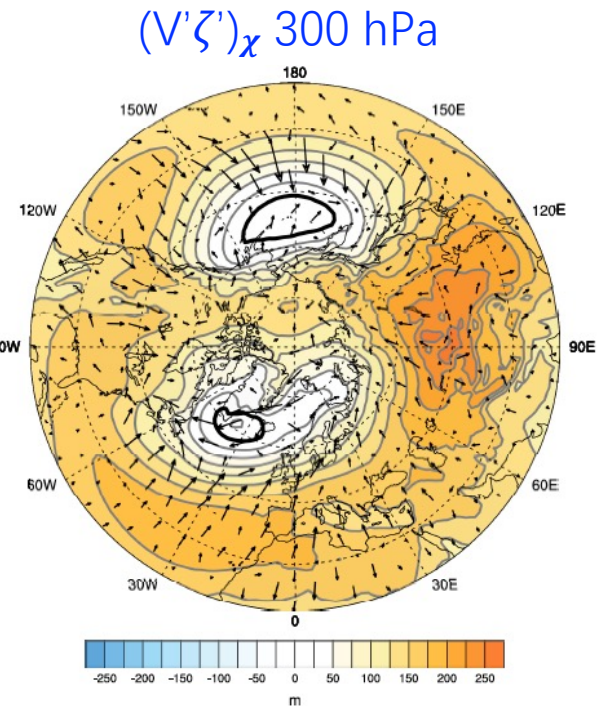
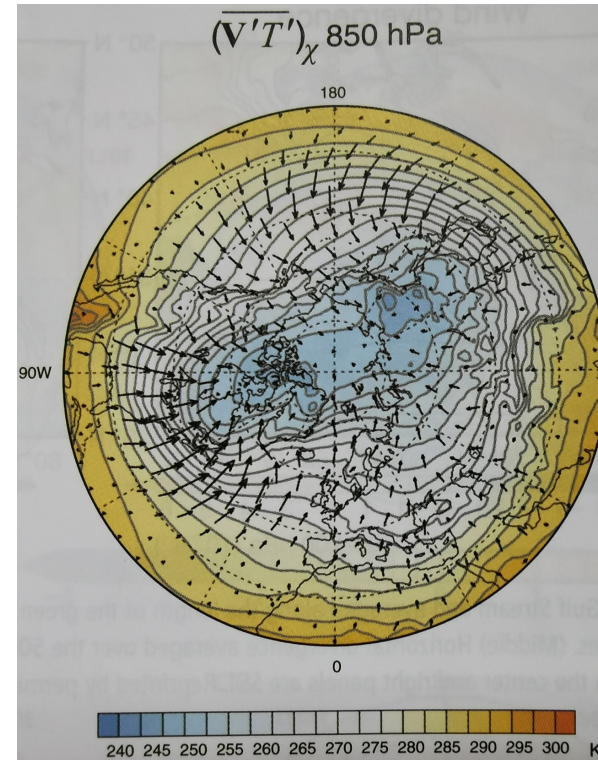
3.2 Impact on the stationary waves

- The stationary wave response to the diabatic forcing has been estimated using a linearized primitive equation model, prescribing the eddy component of the diabatic heating in accordance with the observations or with the climatology of an AGCM run with realistic boundary conditions.
- The tropical contribution emanates mainly from the **strong heat source over the Maritime Continent and disperses poleward and then eastward** across North America. The extratropical heating yields a **response with wave troughs upstream and ridges downstream of the storm tracks**, consistent with linear theory.



4. Forcing by the Transients 瞬变强迫

- Left panel shows the irrotational transport of heat at the 850 hPa level, superimposed upon the time-mean temperature gradient. The transport is mainly poleward, but it exhibits a zonal component directed down the zonal temperature gradient. The poleward transport is larger over the oceanic storm tracks than over the continents, where the strongest meridional temperature gradients are observed.
- The transport of relative vorticity at the jet stream level tends to be directed down the Z_{1000} gradient (right) into the Icelandic and Aleutian lows, balancing the frictional sink in the vertically integrated, zonally varying vorticity budget.

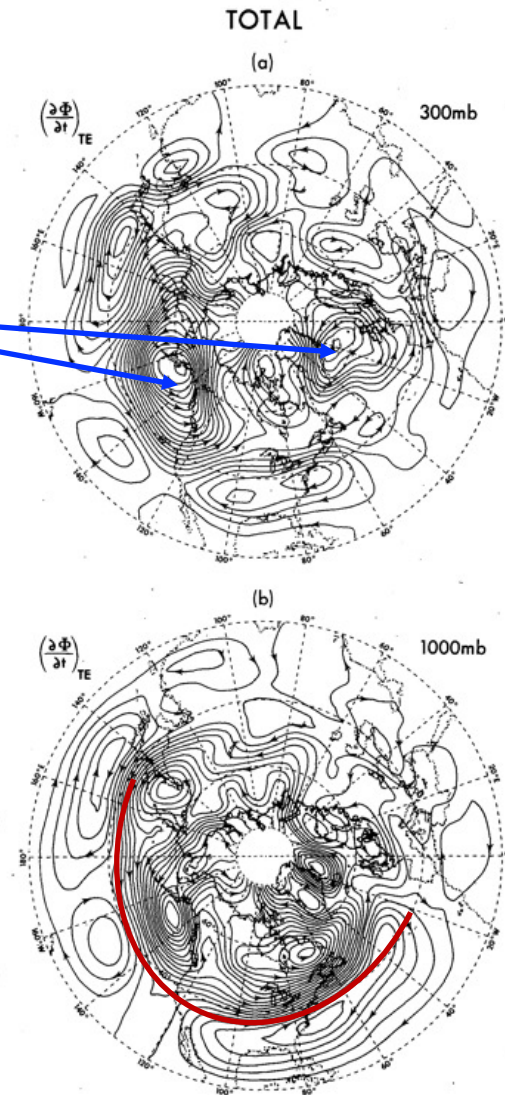


4. Forcing by the Transients 瞬变强迫

- The forcing of the time-mean flow by the transients (mainly the transient eddies) in the extratropics can be diagnosed quantitatively using the [quasi-geostrophic formulation](#). The geopotential tendency equation is written as $A \frac{\partial \Phi}{\partial t} = D + R$,
- where A is an elliptic operator that appear in the tendency equation, D is the forcing due to the transients as detailed below, and R is collection of terms involving advection of vorticity and potential temperature by the time-mean flow. Since the tendency of the time mean flow is zero, it follows that the terms of the right-hand side must be equal and opposite ($D+R=0$).
- The forcing by the transients is given by $D = D^{VORT} + D^{HEAT}$,
- where $D^{VORT} = -\nabla \cdot \overline{\mathbf{V}'\zeta'}$ and $D^{HEAT} = f \frac{\partial}{\partial p} \frac{\nabla \cdot \overline{\mathbf{V}'T'}}{\bar{S}}$, where $\bar{S}$ is the hemispheric mean of the static stability, here defined as $-\partial\bar{\theta}/\partial p$.

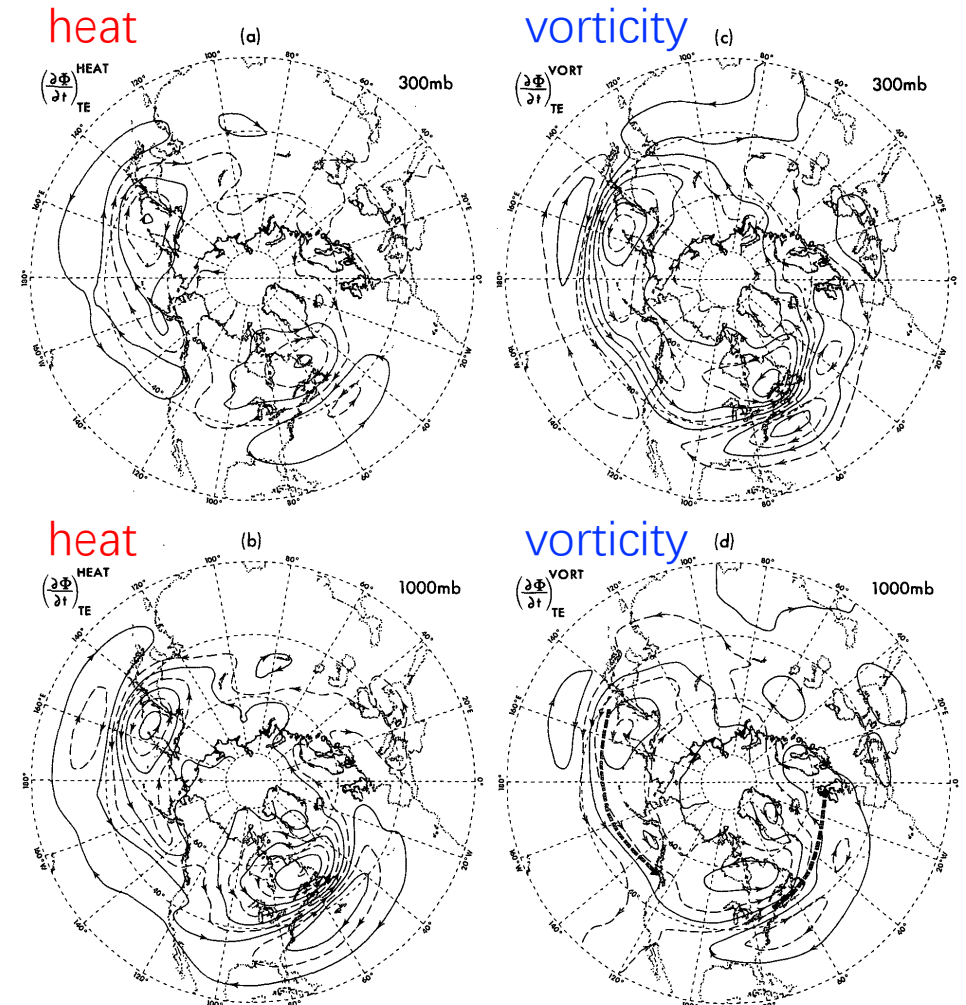
4. Forcing by the Transients 瞬变强迫

- The geopotential tendencies induced by the transients at the 300 hPa and 1000 hPa levels are shown.
- The transients induce **negative geopotential tendencies over the Aleutian and Icelandic lows** at the 300 hPa level.
- The stronger pattern at the 1000 hPa level consists of a series of **dipoles with nodes centered along $\sim 45^\circ\text{N}$** , with negative tendencies to the north and positive tendencies to the south. The force eastward wind tendency is particularly strong at the longitudes of the oceanic storm tracks, which are subject to boundary forcing by the strong poleward eddy heat transport at the Earth's surface.
- The robust pattern at the 1000 hPa level is almost exclusively due to the **forcing by the high frequency transients** with period shorter than a week.



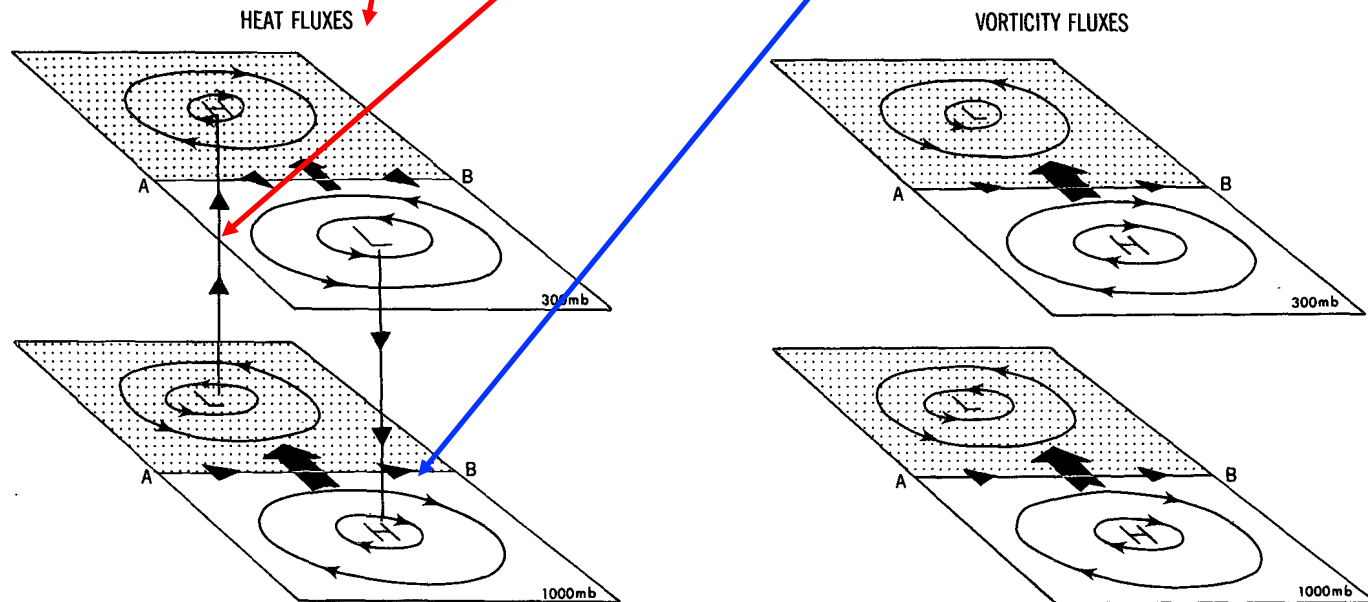
4. Forcing by the Transients 瞬变强迫

- The eddy-induced tendencies are partitioned into the contributions from the **heat transport** and the **vorticity transport**.
- The heat transport acts to reduce the baroclinicity of the time-mean flow, the geopotential tendencies induced by the heat transports are in the opposing directions at the two levels, so that to the north of $\sim 45^\circ\text{N}$ the 1000-300 hPa thickness is increasing and to the south of that latitude it is decreasing.
- In contrast, the **vorticity transports induce a barotropic response**, which is of the same polarity at the two levels. At the upper level the tendencies induce by the heat and vorticity transport tend to cancel, whereas at the lower level they tend to reinforce one another. This explains why the 1000 hPa pattern is stronger.



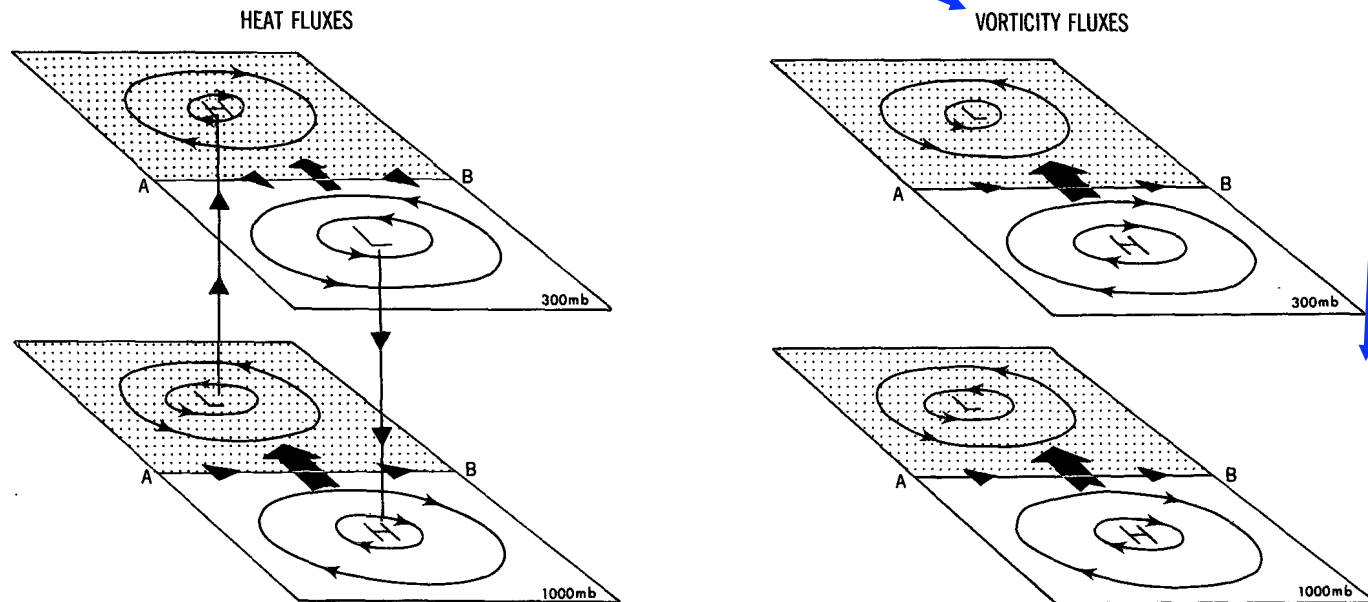
4. Forcing by the Transients 瞬变强迫

- Schematic offers a further dynamical interpretation of the geopotential tendencies induced by the transients. The **heat transports** induce a **thermally indirect meridional circulation cell** in the same sense as the zonally averaged Ferrel cell, but locally much stronger. The poleward flow in the lower branch of this cell induces **a strong westerly acceleration** at the Earth's surface at latitudes $\sim 45^\circ\text{N}$.



4. Forcing by the Transients 瞬变强迫

- The **vorticity transports** are concentrated at the jet stream level, but by virtue of the elliptical operator in the geopotential tendency equation, they induce negative (positive) height tendencies poleward (equatorward) of the storm tracks at both levels. The eddy-induced mean meridional circulation at the jet stream level is instrumental in spreading the tendencies through the depth of the troposphere, resulting in a **more barotropic response** to the poleward vorticity transports.



5. Response to the Combined Forcing

- Which of the forcings is most important? One analysis protocol is to compare the response to the three forcings in the same **linearized** primitive equation model. Such a comparison based on the 300 hPa streamfunction indicate that diabatic heating induces by far the strongest linear response of the three forcings.
- As it turns out, **this comparison is misleading** because the zonally symmetric background flow in the linear models is prescribed to match the observations, whereas in reality it is profoundly influenced by the presence of the wave forcings, and, in particular, by the orography.
- In the presence of such **strong nonlinearity**, it really isn't meaningful to decompose the stationary waves into components attributable to the different forcings. But numerical experiments performed using today's state-of-the-art models that are capable of realistically simulating the observed stationary waves can nonetheless provide valuable dynamical insights.

6. A Historical Note

- The GCM in use in the late 1970s with $5^\circ \times 5^\circ$, were surprisingly successful in capturing the structure of the zonally symmetric flow and the climatological-mean stationary waves. Not until much later was it recognized that the agreement was fortuitous. The higher resolution models that came into use during the early 1980s, which better resolved the baroclinic waves in the storm tracks, exhibited unrealistically strong surface westerlies in midlatitudes. It soon became apparent that **this systemic bias was due to the neglect of the drag exerted on the atmosphere by the breaking of orographically induced gravity and inertia-gravity waves** on horizontal scales far too small to be resolved by the models. In order to obtain a realistic simulation, it was found to be necessary to resort to a **gravity wave drag parameterization scheme**. When this refinement was introduced, the fidelity of the models increased quite dramatically and continued to improve with further increases in resolution.
- Many of the pioneering studies in which CTL and NM simulations were used to diagnose the relative importance of diabatic heating and orography in forcing the stationary waves were carried out around 40 years ago, during the period when **the models were getting the right answer for the wrong reason** — **the eddy forcing of the westerlies and the gravity wave drag were both being underestimated**, resulting in compensating errors.