The Atmospheric General Circulation

Lecture 12: The Global Stratospheric Circulation
全球平流层环流

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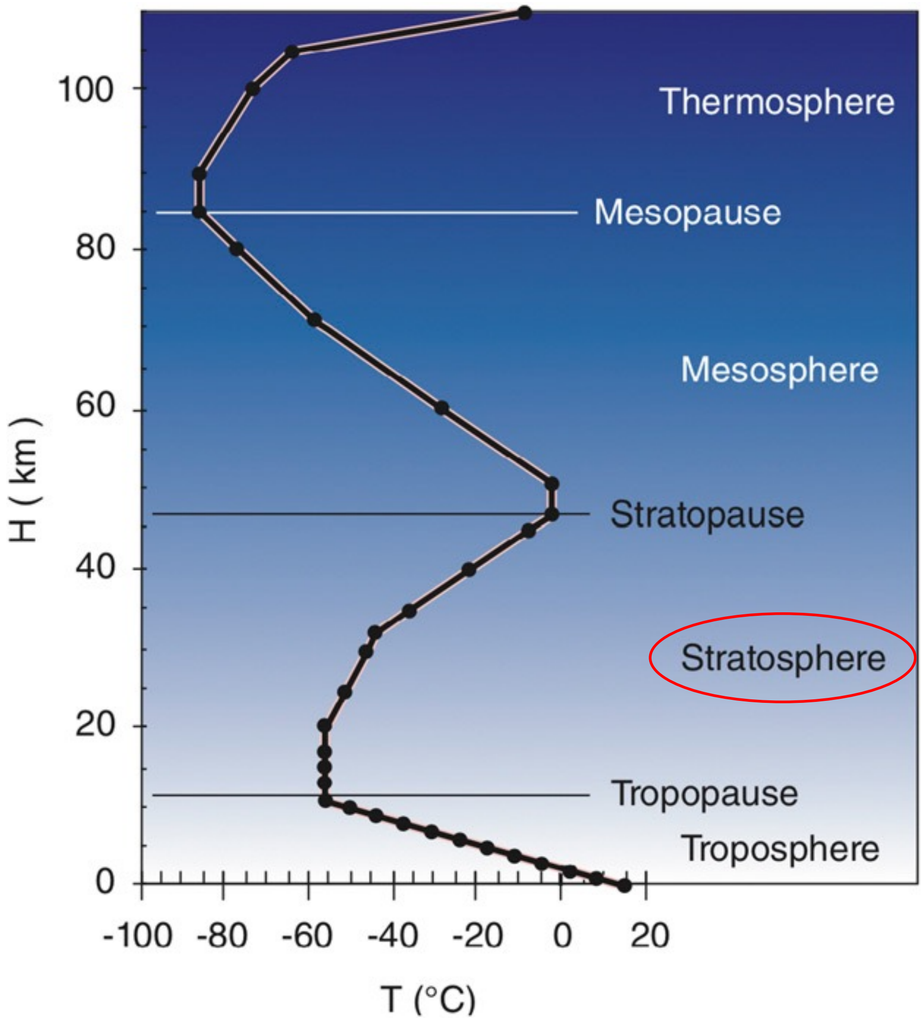
Introduction

- The middle atmosphere encompasses the stratosphere and the mesosphere. Its geometric midpoint at ~50 km corresponds roughly to the stratopause, the top of the stratosphere and the level of strongest heating due to the absorption of solar ultraviolet radiation by ozone molecules.



Temperature variation with height according to the U.S. Standard Atmosphere. Temperatures represent idealized, midlatitude, annual average conditions.

Introduction

$$\frac{\partial[u]}{\partial t} = f[v]^* + \nabla\cdot\mathbf{F} + [\mathcal{F}_x] \quad (8.6)$$

$$\frac{\partial[\alpha]}{\partial t} = \sigma[\omega]^* + [\mathcal{Q}]\,, \quad (8.7)$$

where

$$[v]^* \equiv [v] + \frac{\partial}{\partial p}\frac{[v^*\alpha^*]}{\sigma} \quad \text{and} \quad [\omega]^* \equiv [\omega] - \frac{\partial}{\partial y}\frac{[v^*\alpha^*]}{\sigma} = [\omega] + \frac{\mathcal{P}}{\sigma} \quad (8.8)$$

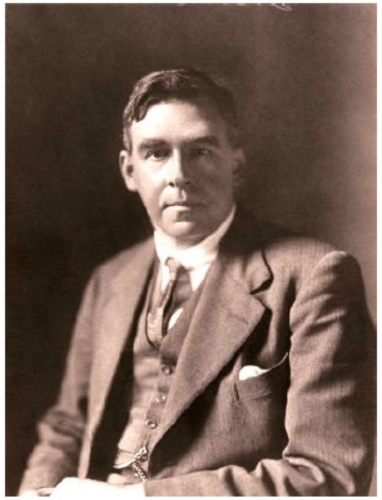
are referred to as the transformed Eulerian mean meridional (TEM) circulations and

- The development of the transformed Eulerian mean (TEM) formalism was arguably one of the most important advances in dynamical meteorology in the late twentieth century. It provides:
    - An estimate of the Lagrangian MMC based on grid point data that closely resembles the circulation computed in isentropic coordinates and interpolated onto a pressure grid,
    - A representation of the eddy forcing of the [u] field that takes into account the direct forcing by the momentum transports $[u^*v^*]$ and the indirect forcing by the eddy heat transports $[v^*T^*]$ by way of the MMC,
    - A metric that can be used to trace the dispersion of waves in the meridional plane from regions of generation to regions of dissipation.
- The TEM circulation takes into account (i) the Eulerian MMC, (ii) the eddy-induced Stokes drift, and (iii) a component that cancels the Stokes drift through the bottom boundary, as required to satisfy the conservation of mass. It is an estimate of the Lagrangian meridional motions of tagged air parcels, derived from Eulerian measurements: hence the label “TEM”.

1.The Stratospheric Circulation

1.1 Lagrangian mean meridional circulation (TEM circulation)

- The climatology and most of the non-seasonal variability of the zonally averaged, middle atmospheric circulation is wave-driven and can be understood in terms of the TEM formalism. In the stratosphere it is dominated by Rossby waves whose upward dispersion is proportional to the poleward eddy heat transport.
- The pole-to-pole TEM circulation, referred to as the *Brewer-Dobson circulation* (BDC), ventilates the stratosphere with troposphere air that enters by ascending through the tropical tropopause and exits at higher latitudes, carrying water vapor, carbon monoxide and other tropospheric traces upward and carrying ozone that originated in the stratosphere downward (stratosphere-troposphere exchange).



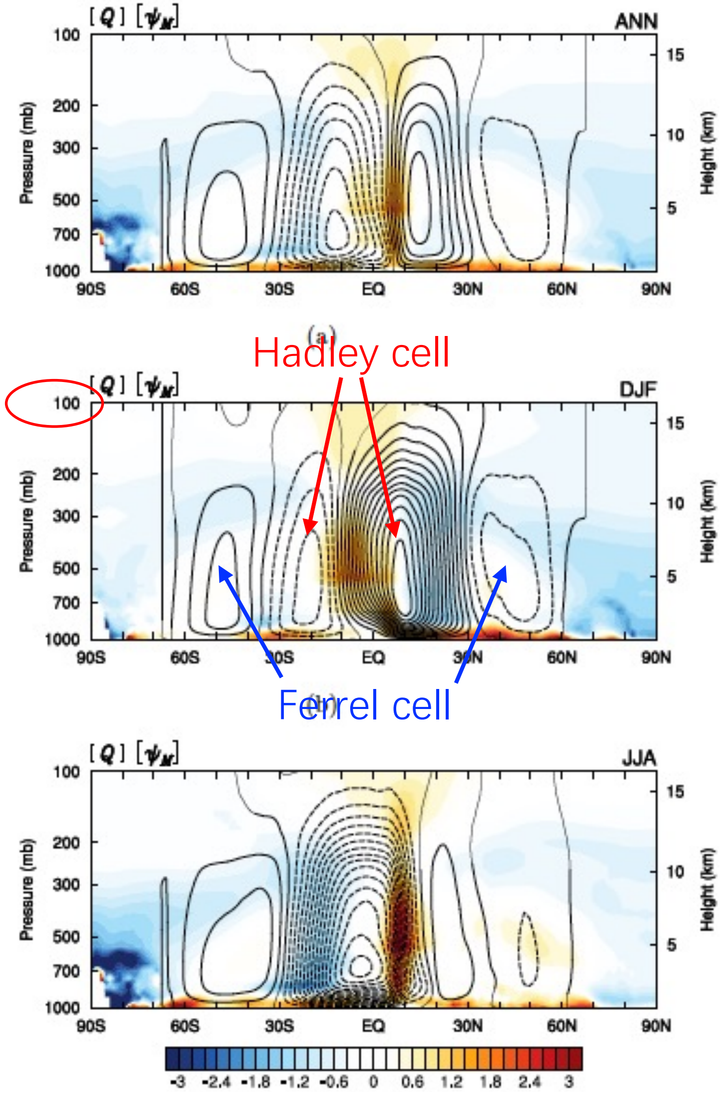
Left: Alan W. Brewer (1915-2007). Deduced that the dryness of the stratosphere is due to the condensation of water vapor in air parcels ascending through the tropical cold point. Right: G.M.B. Dobson (1899-1975). Recognized the relative warmth of the stratopause and attributed it to the absorption of solar ultraviolet radiation by ozone. Pioneered the development of the spectrophotometer for making ground-based measurements of total column ozone concentration, established a network of observing stations, and carried out groundbreaking research on the structure and variability of the ozone layer.

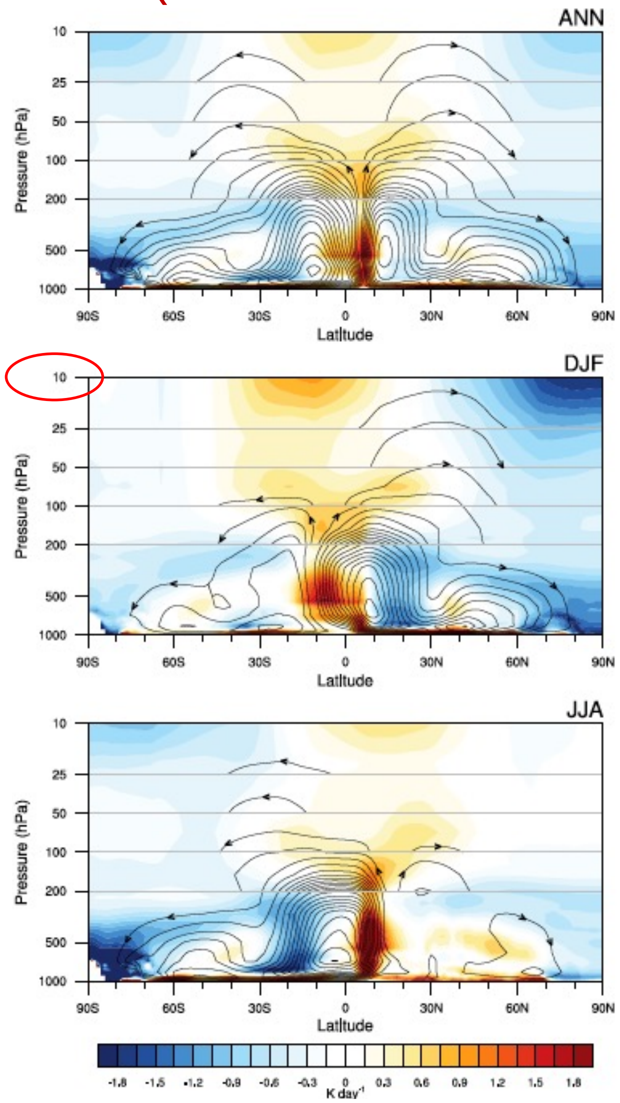
1.The Stratospheric Circulation

1.1 Lagrangian mean meridional circulation (TEM circulation)

Eulerian mean meridional circulation & diabatic heating

Eulerian MMC meridional mass streamfunction





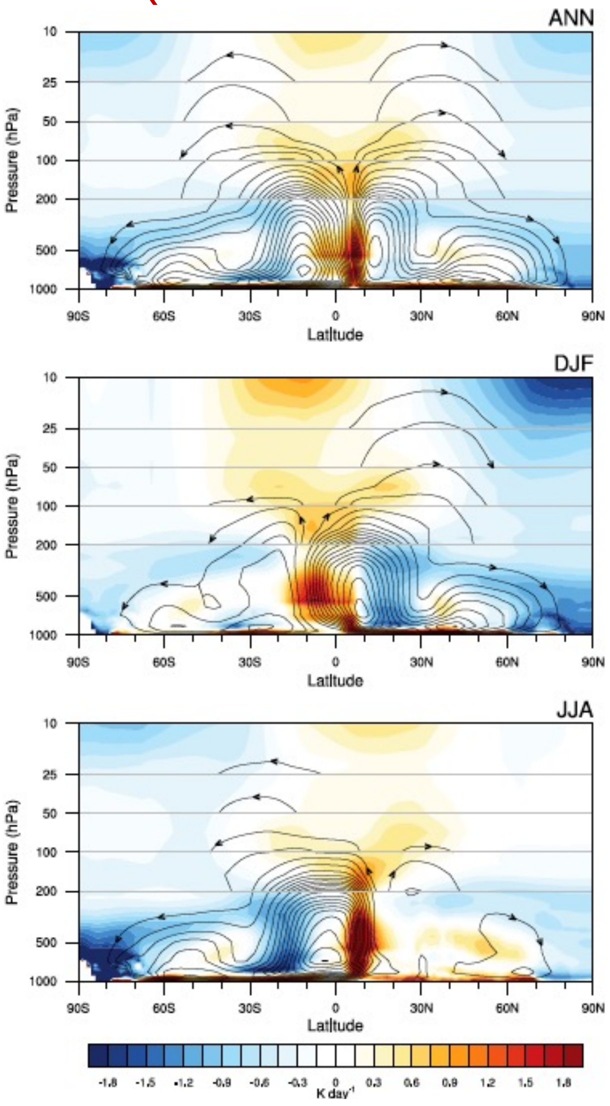
Lagrangian mean meridional circulation & diabatic heating

Lagrangian MMC based on the TEM formulation

1.The Stratospheric Circulation

1.1 Lagrangian mean meridional circulation (TEM circulation)

- The Lagrangian MMC represents an estimate of the zonally averaged motions, not at a set of fixed grid points in the meridional plane, but following the centroids of hypothetical ”clouds” of tagged air parcels initially located at those grid points. It is thus an estimate of the Lagrangian as opposed to the Eulerian mean meridional motions.
- It corresponds closely to the mean meridional motions in isentropic等熵 coordinates, that is zonally averaged along constant potential temperature surfaces rather than pressure surfaces. The method for making this estimate, which is referred to as the TEM circulation.



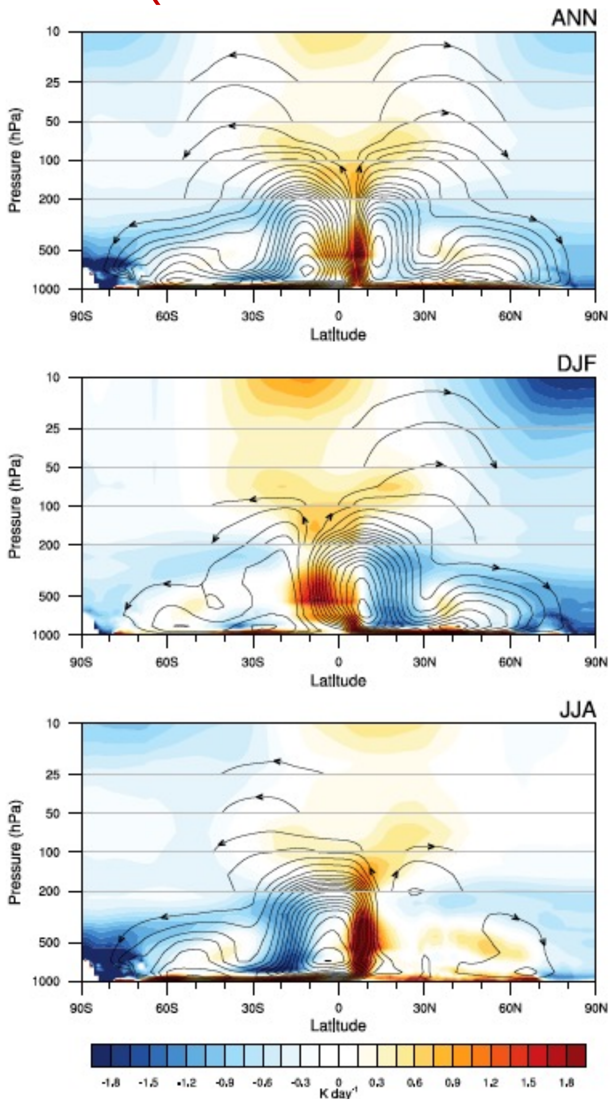
Lagrangian mean meridional circulation & diabatic heating

Lagrangian MMC based on the TEM formulation

1.The Stratospheric Circulation

1.1 Lagrangian mean meridional circulation (TEM circulation)

- The Lagrangian MMC that ventilates the stratosphere — upward at low latitudes, meridionally directed toward the winter pole, and downward in the wintertime polar night region — is referred to as the Brewer-Dobson circulation because long before reliable stratospheric wind measurements became available, its existence was inferred on the basis of Brewer's measurements of stratospheric water vapor and Dobson's measurements of stratospheric ozone.



Lagrangian mean meridional circulation & diabatic heating

Lagrangian MMC based on the TEM formulation

1.The Stratospheric Circulation

1.1 Lagrangian mean meridional circulation (TEM circulation)

- The true Lagrangian mean mass transports in the meridional plane in a flow with eddies are difficult to visualize.
- In the numerical simulation based on a tracer transport model, the spread of the traces from its source in the tropical boundary layer reveals both the lateral diffusion by the eddies on isentropic surfaces and the upward and subsequent poleward transport of the centroid of the "cloud" of tracked air parcels by the Lagrangian MMC. Three years after the release, the remnants of the tracer are confined to the high latitudes of the upper stratosphere.

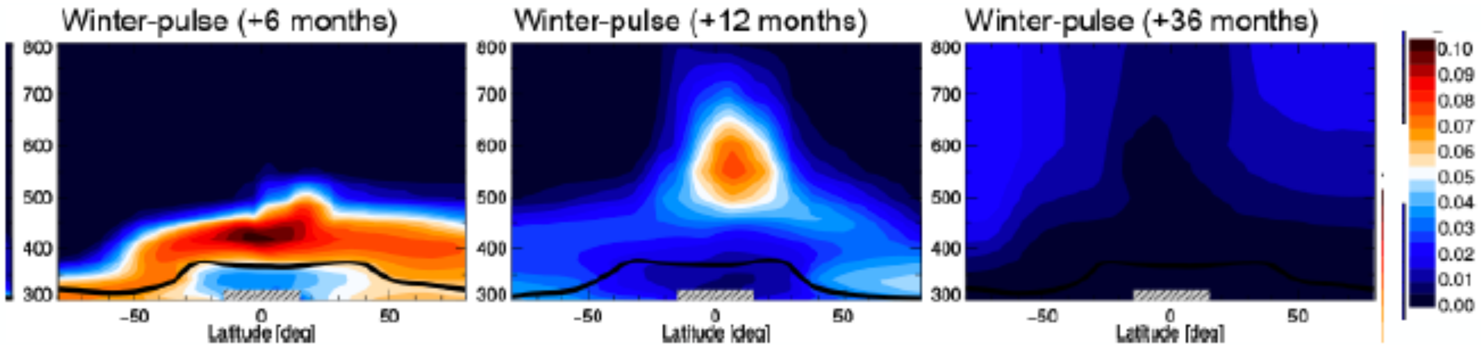


Figure 4.17: Dimensionless "mixing ratio" of tagged air parcels released in the tropical boundary layer (gray shading) in a month-long pulse January 2000 and advected by the three-dimensional wind field in ERA-I. Parcels that remain in or return to the tropical boundary layer after the end of the month are terminated From Ploeger

1.The Stratospheric Circulation

1.1 Lagrangian mean meridional circulation (TEM circulation)

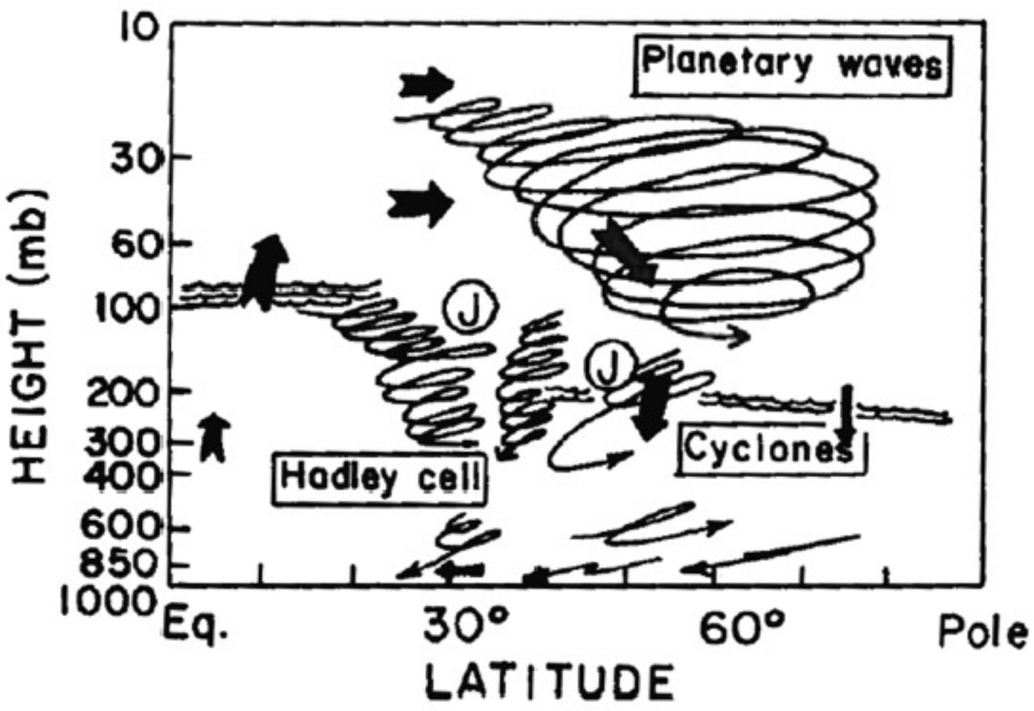
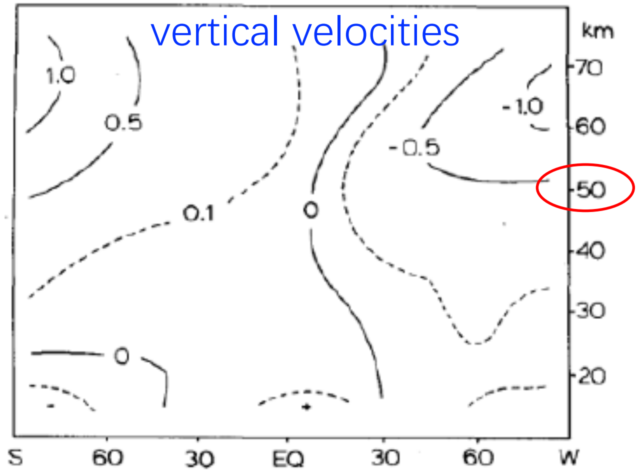
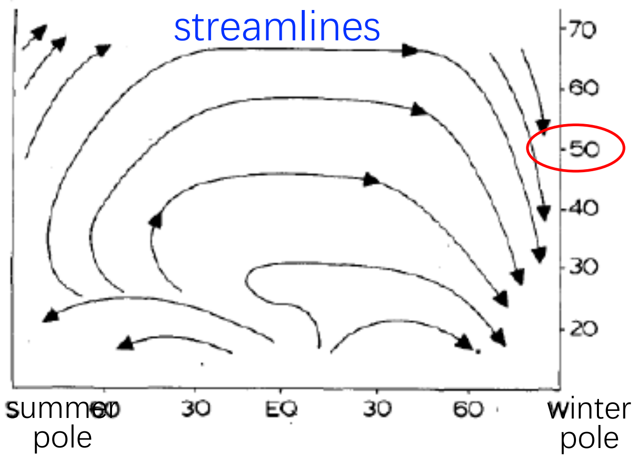


Figure 4.18: Schematic illustration of the Lagrangian mean meridional motion as inferred from the motions of the of tracers inserted into the flow in a simple general circulation model. Looping arrows show tracks of individual tracers and heavy arrows show tracks of centroids of clouds of tracers emanating from points in the meridional plane. From Kida (1977).



The vertical velocity component was inferred from the distribution of diabatic heating rate based on radiative transfer calculations

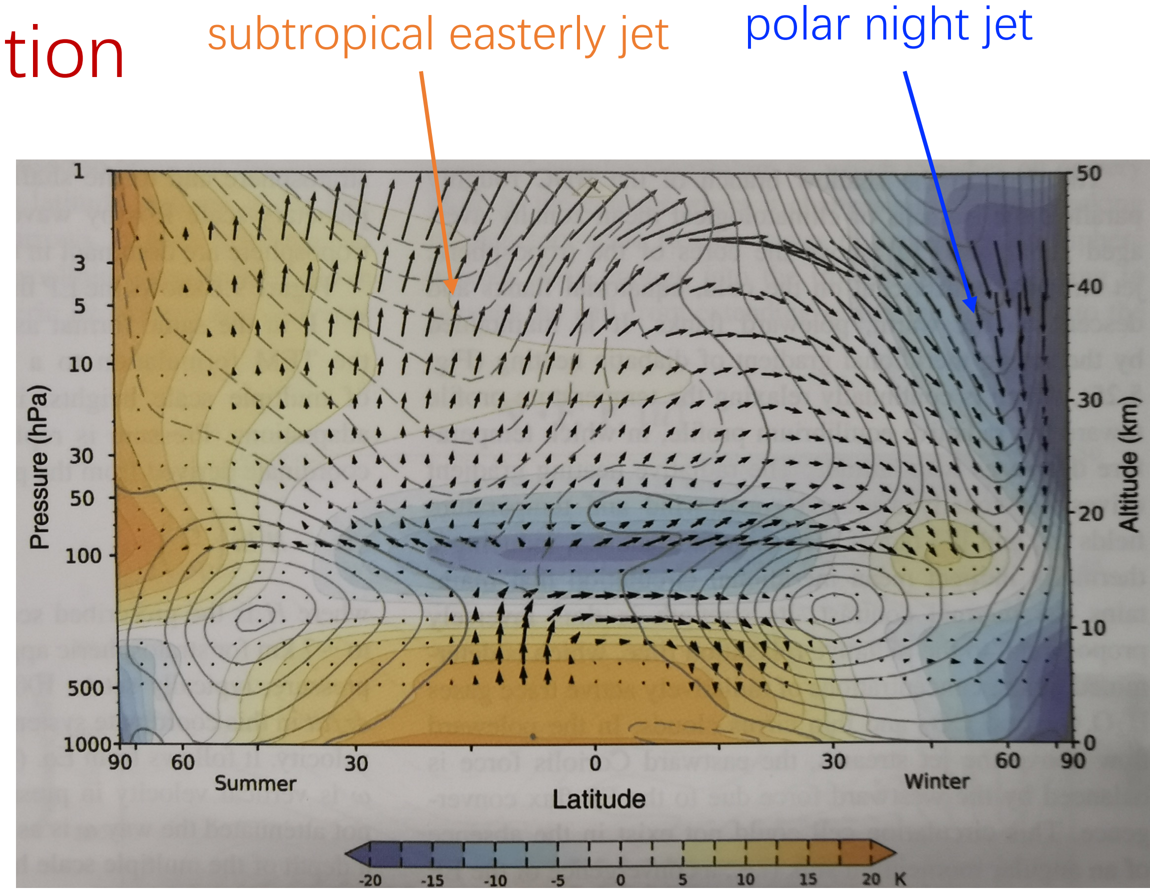


An estimate of the Lagrangian MMC based on the TEM formalism

1.The Stratospheric Circulation

1.2 The seasonally varying TEM circulation

- The zonal flow is seen to be dominated by two matched pairs of jets: the tropospheric jet streams at the base of the stratosphere, and the westerly polar night jet of the winter hemisphere in combination with the subtropical easterly jet in the summer hemisphere, both of which achieve their peak amplitudes near the stratopause level.
- The temperature field can be inferred from the [u] field, with which it is in thermal wind balance:



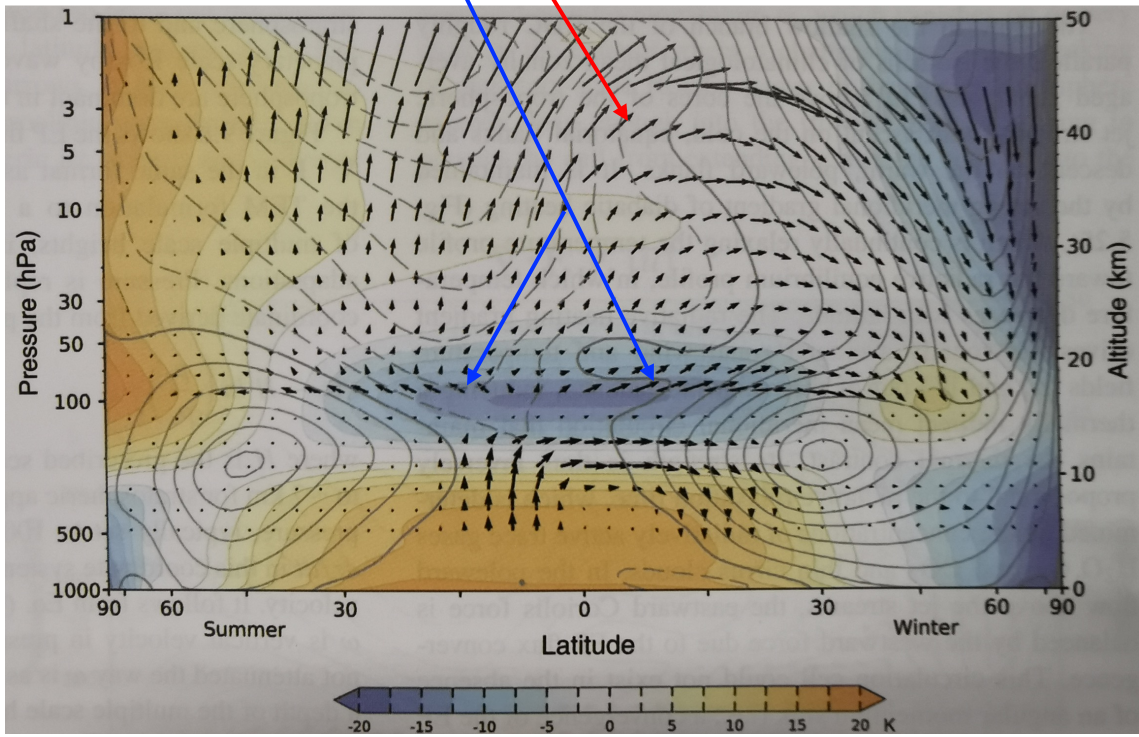
Meridional cross section extending from the summer pole (left) to the winter pole (right) constructed by averaging the DJF fields and the JJA fields, after transposing the latter in latitude. The climatological fields shown are the departure from the global mean temperature at each level (colored shading), the TEM circulation (arrows) and zonal wind (contour). The circulation at 100 hPa and above is referred to as the Brewer-Dobson circulation. The arrows correspond to different scaling above and below 100 hPa.

1.The Stratospheric Circulation

1.2 The seasonally varying TEM circulation

- The ascent in the shallow branch of the BDC is almost symmetric about the equator and the flow is poleward year-round in both NH and SH. The flow in the shallow branch roughly parallels the isotachs of climatological mean zonally averaged zonal wind above the cores of the tropospheric jet streams. It is maintained by the strong meridional gradient of diabatic heating.
- The ascent in the deep branch is biased toward the SH and virtually all of the descent occurs over the winter polar cap. Hence, the cell is thermally direct, with rising of warmer air and sinking of colder air, but it could not exist in the absence of wave-breaking.

The TEM circulation is seen to consist of a *shallow branch* extending from the tropopause up to about 50 hPa and a *deep branch* extending upward into the mesosphere.



Meridional cross section extending from the summer pole (left) to the winter pole (right) constructed by averaging the DJF fields and the JJA fields, after transposing the latter in latitude. The climatological fields shown are the departure from the global mean temperature at each level (colored shading), the TEM circulation (arrows) and zonal wind (contour). The circulation at 100 hPa and above is referred to as the Brewer-Dobson circulation. The arrows correspond to different scaling above and below 100 hPa.

1.The Stratospheric Circulation

1.3 The breaking of planetary-scale Rossby waves

- Westerly jet streams serve as waveguides. The tropospheric jet streams serve as waveguides for Rossby wave with zonal wavenumbers ranging from $k = 5$ to about 10, which are generated mainly by baroclinic instability, while the Stratospheric polar night jet serves as a waveguide for planetary-scale Rossby waves, with zonal wavenumbers $k = 1$ and 2. Planetary waves include stationary waves forced by flow over mountain ranges and continent-ocean thermal contrasts.
- The Rossby waves generated by baroclinic instability are thus largely confined to the lower stratosphere and to the shallow branch of the BDC, while planetary-scale Rossby waves dispersing upward from the troposphere are dominant in the deep branch.

1.The Stratospheric Circulation

1.3 The breaking of planetary-scale Rossby waves

- To apply the TEM formulation to a layer extending over a depth of multiple scale heights, it is necessary to make some adaptations. Pressure is replaced by a height-like vertical coordinate derived from the pressure field $z \equiv -H\ ln\left(\frac{p}{p_s}\right)$ [对数p坐标代替p坐标].
  - H is the prescribed scale height, RT/g, typically set to ~7 km for applications. p_s is the surface pressure, typically set to 1000 hPa. Vertical velocity $w = dz/dt$ resembles geometric vertical velocity. It follows that $\omega/w \approx e^{-z/H}$, where ω is vertical velocity in pressure coordinates.
- The counterparts to TEM Equations in spherical coordinates are Eqs. (9.2)-(9.5)

$$\frac{\partial [u]}{\partial t} = \left(f - \frac{1}{R_E\, cos\phi}\frac{\partial}{\partial \phi}[u]cos\phi\right)[v]^* - [w]^*\frac{\partial [u]}{\partial z} + \frac{\nabla \cdot \mathbf{F}}{\rho_o R_E\, cos\phi} + [\mathcal{F}_x], \qquad (9.2)$$

$$\frac{\partial [T]}{\partial t} = [w]\ (\Gamma_d - \Gamma), \qquad (9.3)$$

$$[v]^* = [v] - \frac{1}{\rho_o}\frac{\partial}{\partial z}\left(\rho_o \frac{[v^*T^*]}{\Gamma_d - \Gamma}\right),$$

$$[w]^* = [w] + \frac{1}{R_E\, cos\phi}\frac{\partial}{\partial \phi}\left(\frac{[v^*T^*]}{\Gamma_d - \Gamma}cos\phi\right), \qquad (9.4)$$

where $\Gamma_d - \Gamma = g/c_p - d\overline{T}/dz$ is the height-dependent static stability and $\mathbf{F}$ is given by (c.f., Eq. (8.10))

$$\mathbf{F} = \rho_o R_E cos\phi\left(-[u^*v^*]\mathbf{j} + \left(f - \frac{1}{R_E\, cos\phi}\frac{\partial}{\partial \phi}[u]cos\phi\right)\frac{[v^*T^*]}{\Gamma_d - \Gamma}\mathbf{k}\right), \qquad (9.5)$$

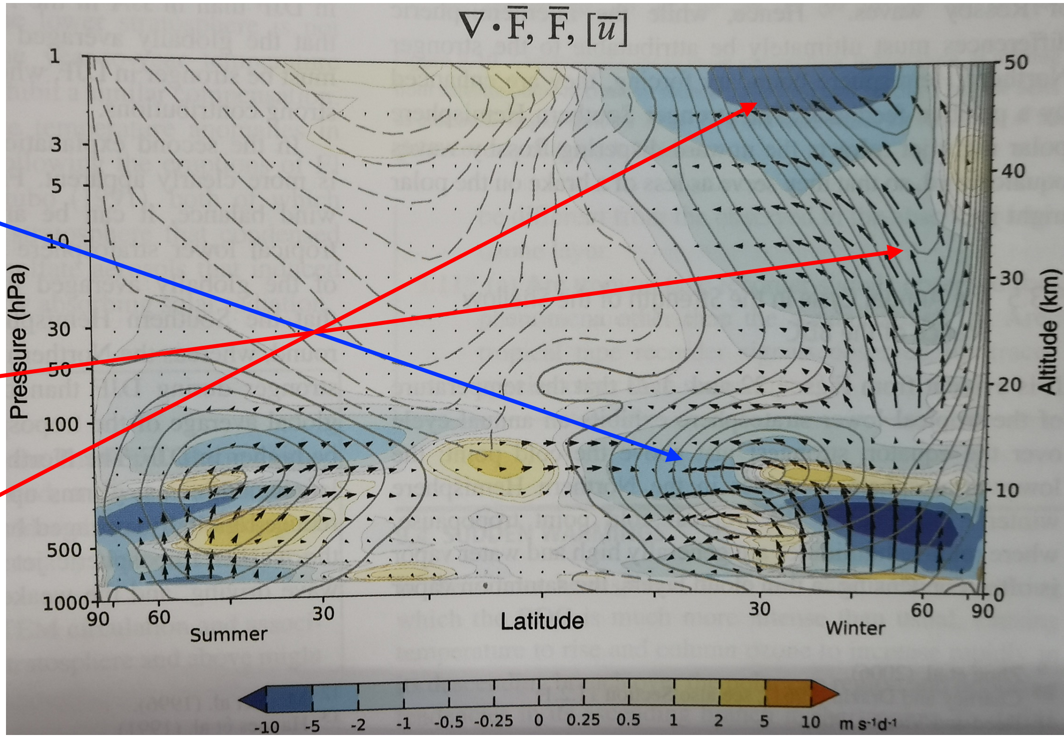
where ρ_o is a reference density, which is prescribed to decrease exponentially with height and $\mathbf{j}$ and $\mathbf{k}$ are unit vectors northward and upward, respectively. We have already made use of this scaling in plotting Fig. 8.13. Note that with the inclusion of the reference density, the EP flux vectors $\mathbf{F}$ have units of kg s^{-2}.

1.The Stratospheric Circulation

1.3 The breaking of planetary-scale Rossby waves

- The lower branches of arrows in both hemispheres, which represent the flux of baroclinic wave activity, curve equatorward into the tropospheric jet streams and converge on their equatorward flanks. A deep branch representing the flux of planetary-scale Rossby wave activity is also clearly discernible, ascending into the polar night jet, curving equatorward, and converging on its equatorward flank.
- The breaking of these waves, indicated by the broad, blue-shaded band of EP flux convergence, is the principal momentum sink that enables the poleward flow in the winter hemisphere in the deep branch of the BDC.

The EP flux **F** and the EP flux divergence **∇·F**



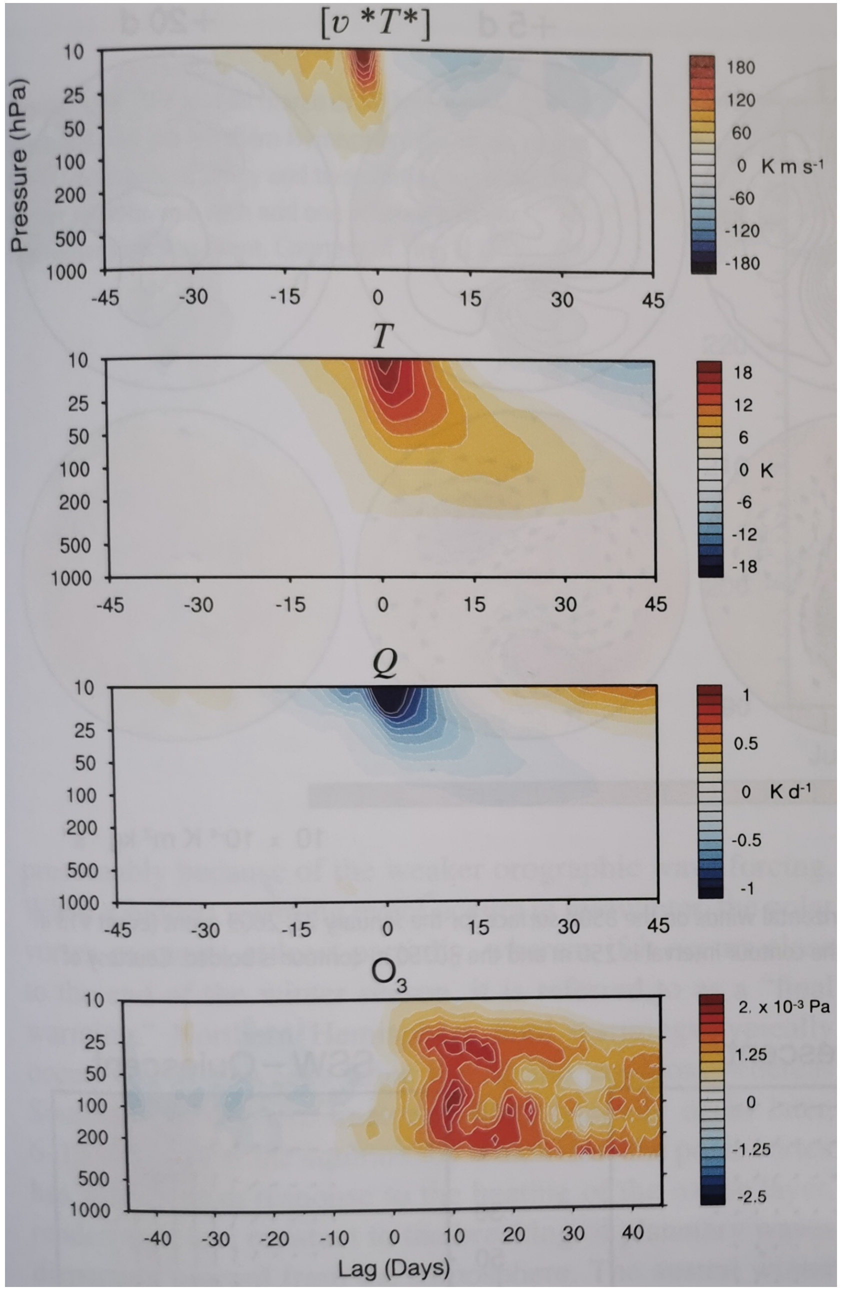
1.The Stratospheric Circulation

1.4 NH vs. SH asymmetries

- The wintertime stationary waves are much stronger in the NH than in the SH: their r.m.s. amplitudes are stronger and they produce much stronger poleward heat transports, indicative of a stronger upward EP flux into the middle and upper stratosphere. The poleward TEM circulation is accordingly stronger during DJF than in the SH during JJA. The stronger upward EP flux results in a stronger angular momentum sink for the poleward-flowing air in the BDC, accommodating a stronger TEM circulation. A stronger TEM circulation, in turn, favors a weaker equator-to-pole temperature difference and hence a weaker polar night jet.
- Another factor accounts for the greater strength of the NH wintertime circulation. Theory and numerical experiments indicate that excessively strong westerlies inhibit the dispersion of Rossby waves (Charney & Drazin 1961). Hence, while the interhemispheric differences must ultimately be attributable to the stronger NH boundary forcing, they are enhanced by a positive feedback. The stronger SH polar night jet refracts the upward dispersing Rossby waves equatorward, so that they serve as less of a brake on the polar night jet.

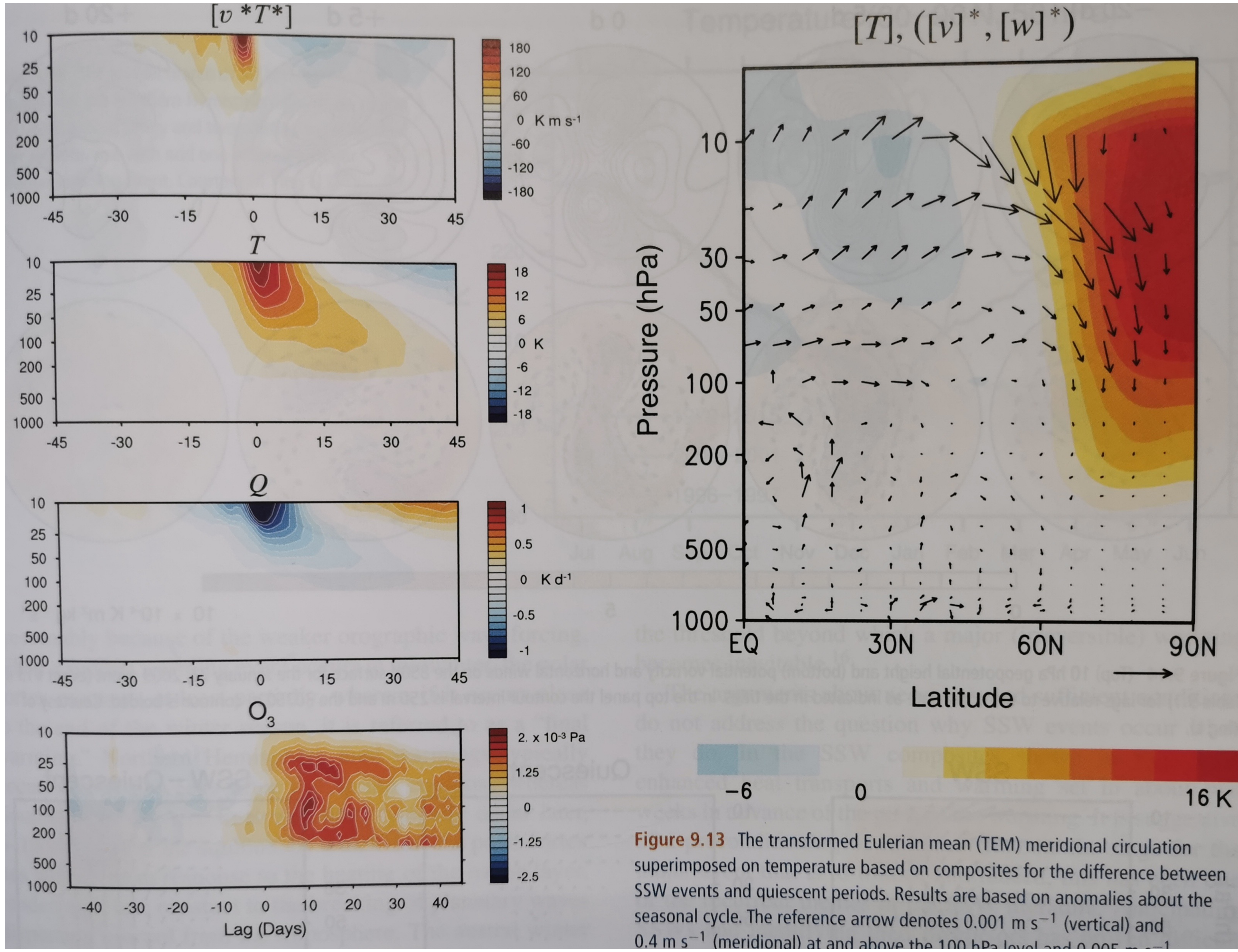
2.Stratospheric Sudden Warmings

- In the winter hemisphere, there are short intervals during which the BDC is much intense than usual, causing temperature to rise and column ozone to increase rapidly in its descending branch over the polar cap region and opposing tendencies in its ascending branch in the tropics. To define these events, we use time series of daily 10 hPa geopotential height anomalies averaged over the NH polar cap region 60°-90°N. When a stratospheric sudden warming (SSW) event occurs, this index rise rapidly in response to the warming in the underlying layer.
- Temperature over the polar cap region begin rising around Day -20, coincident with a strengthening of the poleward eddy heat transport and it rises abruptly by as much as 20 K at the uppermost levels on or around Day -2, coincident with a sharp spike in the transport.



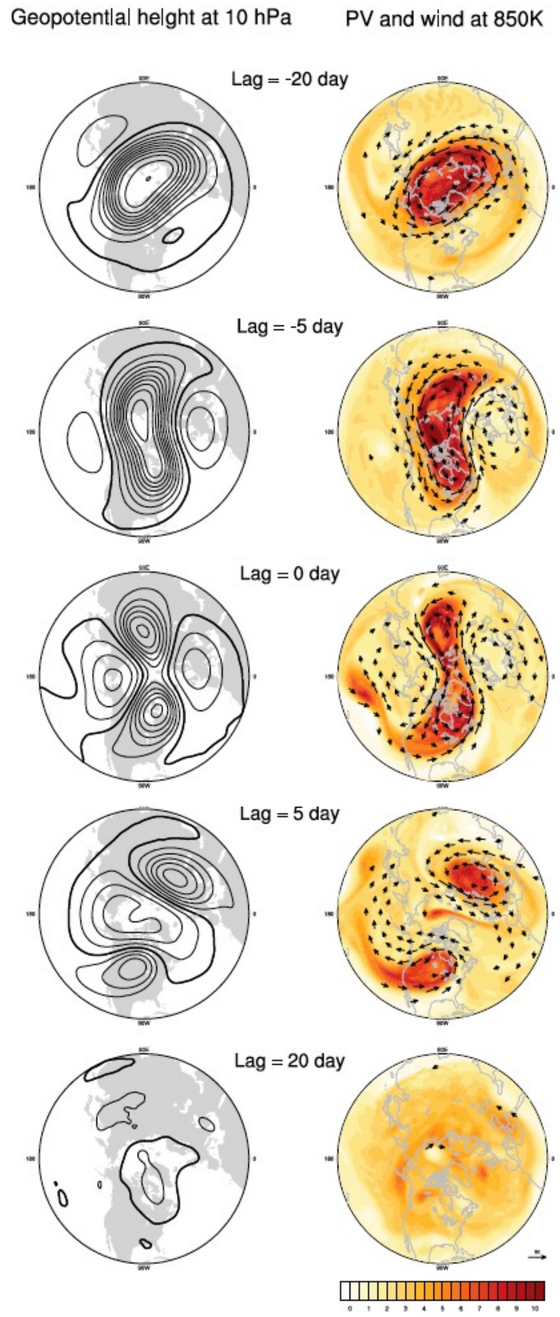
2.Stratospheric Sudden Warmings

- Radiative cooling acts to damp the positive temperature anomalies. Hence, it is clear that the temperature perturbations are dynamically induced and radiatively damped. The anomalously high ozone concentrations over the polar cap that develop during the warming persist even longer than the temperature anomalies.
- The meridional extent of the SSW signature is revealed by the fact that the onset of the warming in high latitudes is accompanied by low latitude ascent and cooling that extends deep into the tropics.



2.Stratospheric Sudden Warmings

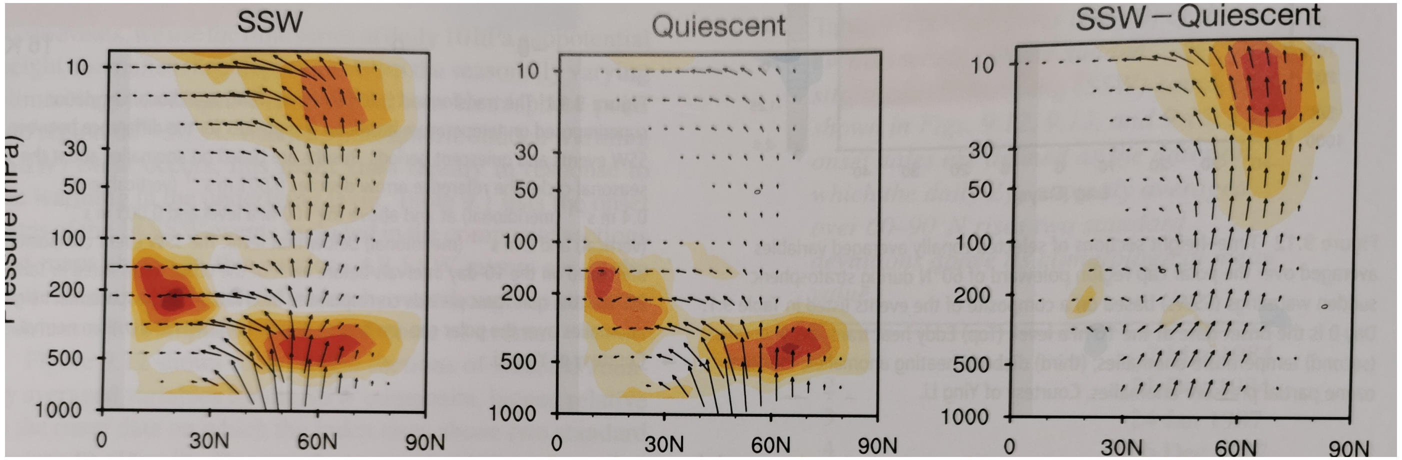
- The amplified eddies observed during SSWs assume a variety of shapes. Some warmings are dominated by zonal wavenumber $k = 1$, some by $k = 2$, and some by the mixture of the two.
- Figure: A warming dominated by $k = 2$. As the warming proceeds, the polar vortex shrinks as the zero-wind line intrudes into the polar cap region.
- Even in this planetary-scale flow, clusters of neighboring air parcels are drawn out into thin filaments that lose their identities as the air within them mixes irreversibly with the surrounding air.



2.Stratospheric Sudden Warmings

2.1 The role of wave driving

- The dynamics of SSWs can be understood in terms of the governing equations for a geostrophically balanced, zonally symmetric flow, prescribing the time-varying eddy forcing in accordance with the observed EP fluxes.



- The big increase in the upward flux of wave activity during SSWs relative to quiescent periods are in the layer above 200 hPa. Much of the wave activity is directed almost straight upwards, where wave-breaking occurs, decelerating the polar night jet.

2.Stratospheric Sudden Warmings

2.2 Climatology and timing

- SSWs can occur at any time during the winter season, on average, about 6 times per decade in the NH. Midwinter warming events occur much less frequently in the SH, presumably because of the weaker orographic wave forcing.
- When a sudden warming event occurs in midwinter, the polar vortex recovers, at least partially, whereas if it occurs close to the end of the winter season, it is referred to as a "final warming." NH final warmings typically occur within 6 weeks after the spring equinox, whereas SH final warmings typically occur later, 6-12 weeks after the equinox, by which time the polar vortex has weakened in response to the heating of the ozone layer, rendering it less resistant to the breaking of planetary waves dispersing upward from the troposphere.
- The austral winter season often ends precipitously with a major warming in which polar temperatures rise from near their lowest values of the year to their highest values of the year in a matter of a few weeks.

2.Stratospheric Sudden Warmings

2.2 Climatology and timing

- Much of what appears to be interannual variability in stratospheric temperature is related to the occurrence or non-occurrence of SSWs. Winters without strong midwinter warmings tend to be colder than normal over the polar cap region.

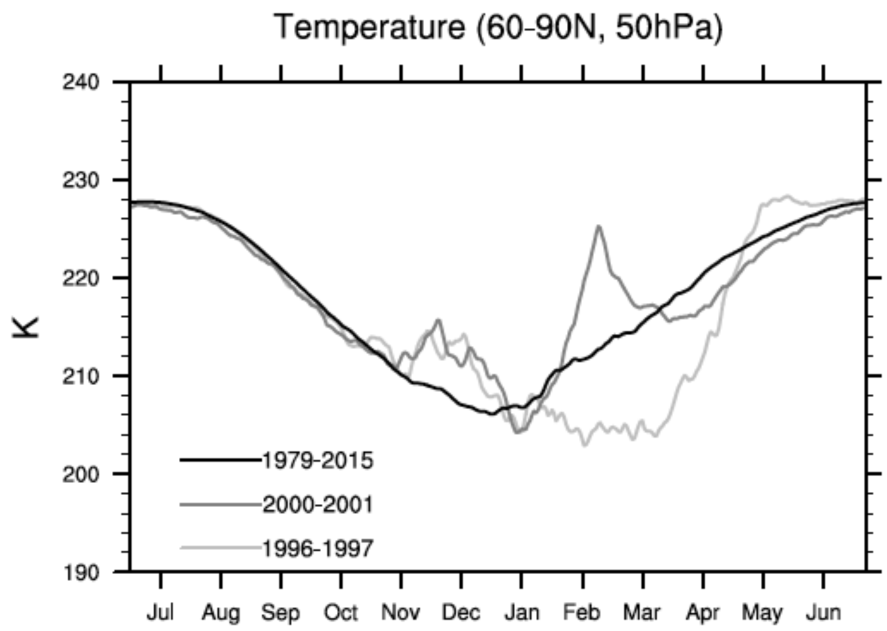


Figure 4.21: The annual march of 50 hPa temperatures averaged over the polar cap region 60-90°: the climatology and two contrasting individual winter seasons, one with and one without a major midwinter warming.

2.Stratospheric Sudden Warmings

2.2 Climatology and timing

- What are the necessary and sufficient conditions for SSW events to occur? The strength of the planetary wave forcing appears to be an important factor. But they do not address the question why SSW events occur when they do.
- In the SSW composites, enhanced heat transports and warming set in about two weeks in advance of the peak of the warming. It is suggestive of a preconditioning of the flow that sets the stage for the major event that is to follow, and indeed, this has been one of the recurrent themes in the SSW literature. Please see papers by Yang et al. (2023a; 2023b; 2024).
- Anticipating SSWs and identifying their precursors has proven difficult because their development is influenced by the amplitude and configuration of both the wave forcing and the zonal mean flow, and because positive feedbacks render their development and evolution highly sensitive to the initial conditions.