

The Atmospheric General Circulation

Lecture 13: Wave-Mean Flow Interaction in the
Tropical Stratosphere

热带平流层的波流相互作用

Ming Bao

Nanjing University

1. The Zonal Wind Climatology

- The feature of interest is the **downward propagating westerly shear zone**, which is a reflection of low-frequency variations in the zonally averaged zonal wind component [u]. The higher frequency oscillations mark the **passage of equatorial wave**.

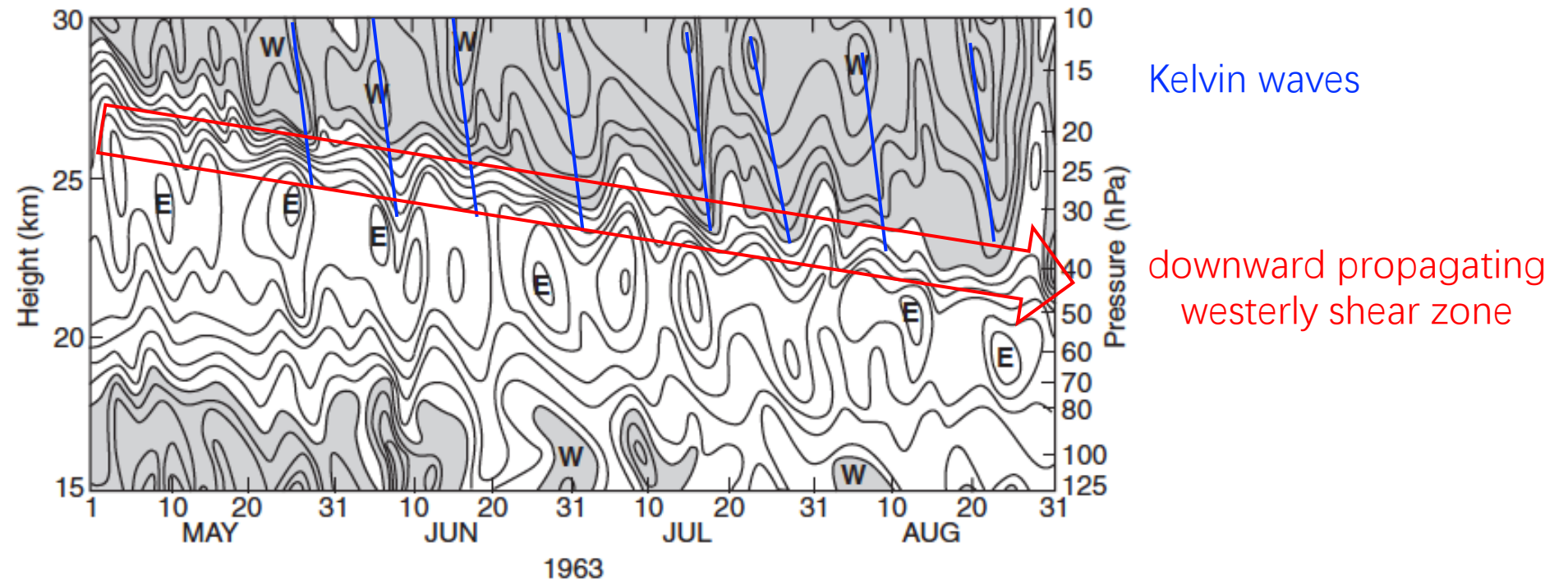
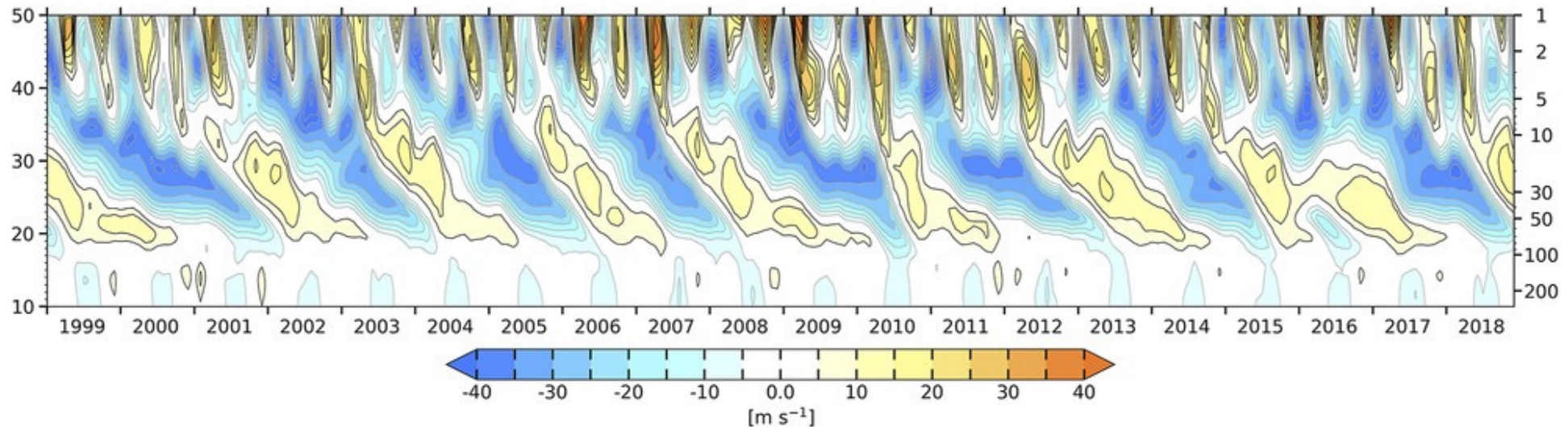


Fig. 12.14 Time-height section of zonal wind at Canton Island (3°S). Isotachs at intervals of 5 m s^{-1} . Westerlies are shaded. (Courtesy of J. M. Wallace and V. E. Kousky.)

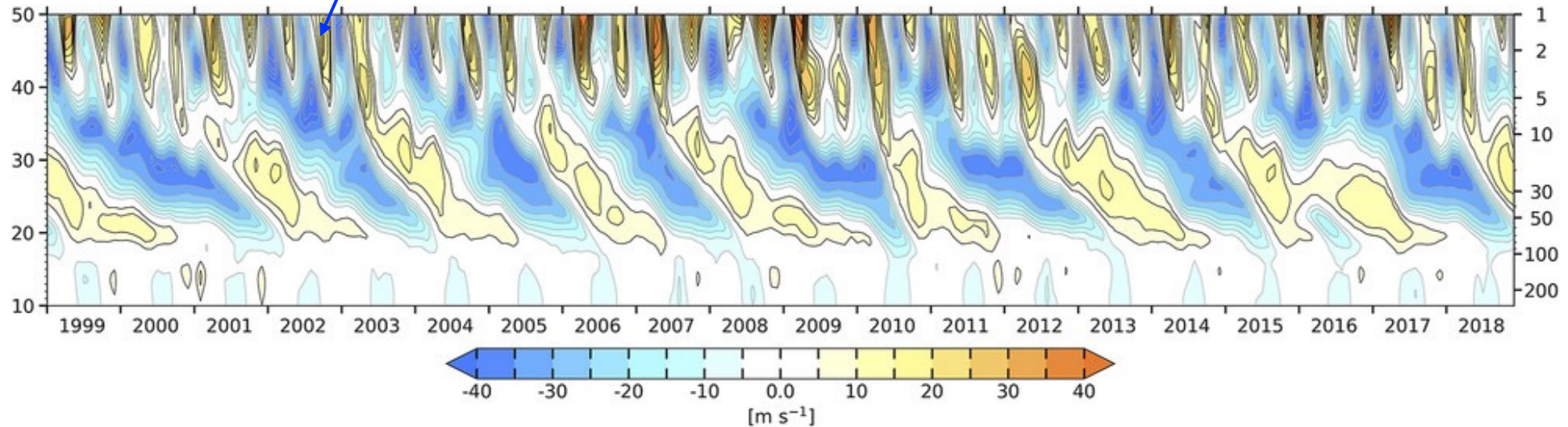
1.The Zonal Wind Climatology

- Fluctuations with zero-to-peak amplitude range up to 28 m s^{-1} at the 25 km (25 hPa) level. Successive easterly and westerly wind regimes, separated by **strong shear zones**, propagate **downward** at an average rate of $\sim 1 \text{ km per month}$. The westerly shear zones are sharper and propagate downward somewhat faster than the easterly shear zones. Apart from a short lapse in 2016-2017, the variations have been **quasi-periodic** with similar vertical structures recurring at intervals of $\sim 27 \text{ months}$: hence the name **quasi-biennial oscillation (QBO)**.



1. The Zonal Wind Climatology

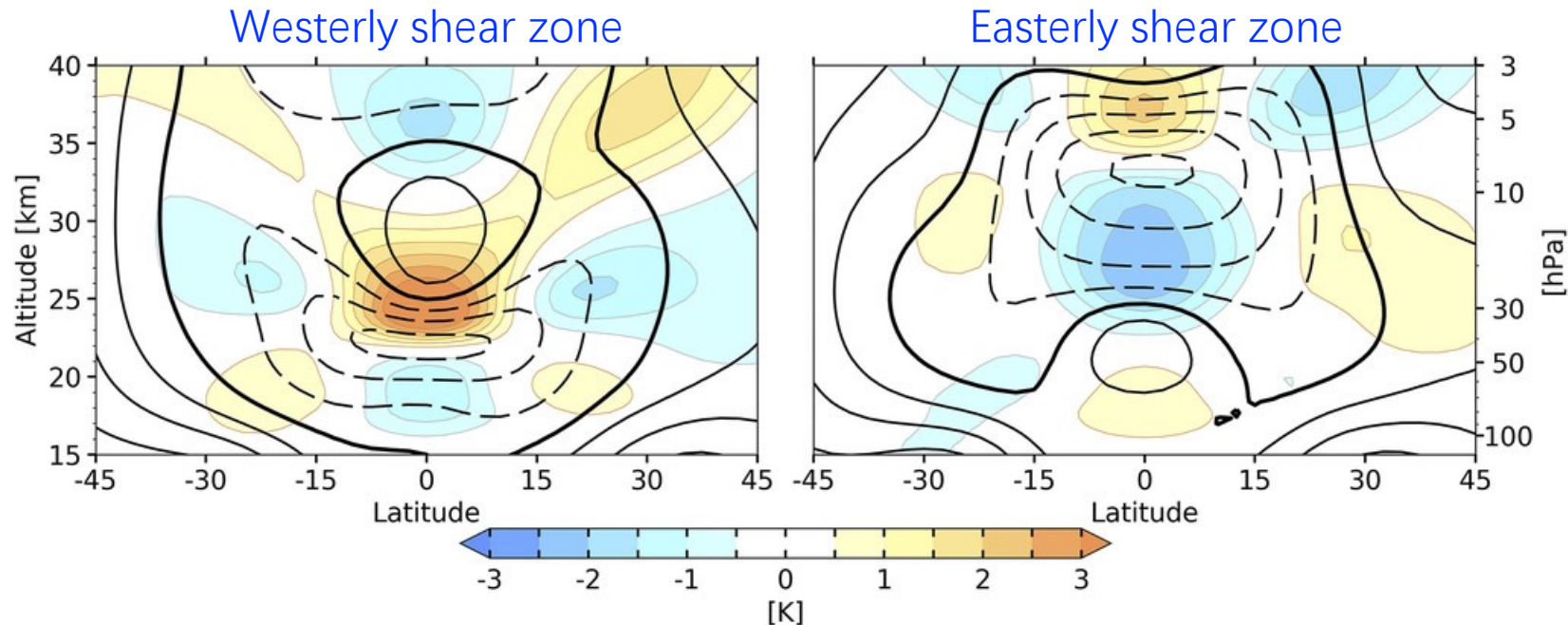
- QBO is the dominant mode of [u] variability throughout the tropical lower stratosphere. The downward propagating easterly and westerly wind regimes are rapidly attenuated as they approach the cold point tropopause ~ 17 km (100 hPa). Above 35 km, the QBO coexists with a [semiannual oscillation \(SAO\)](#). Most westerly shear zones of the QBO originate as leading edges of westerly wind regions of the SAO.



1.The Zonal Wind Climatology

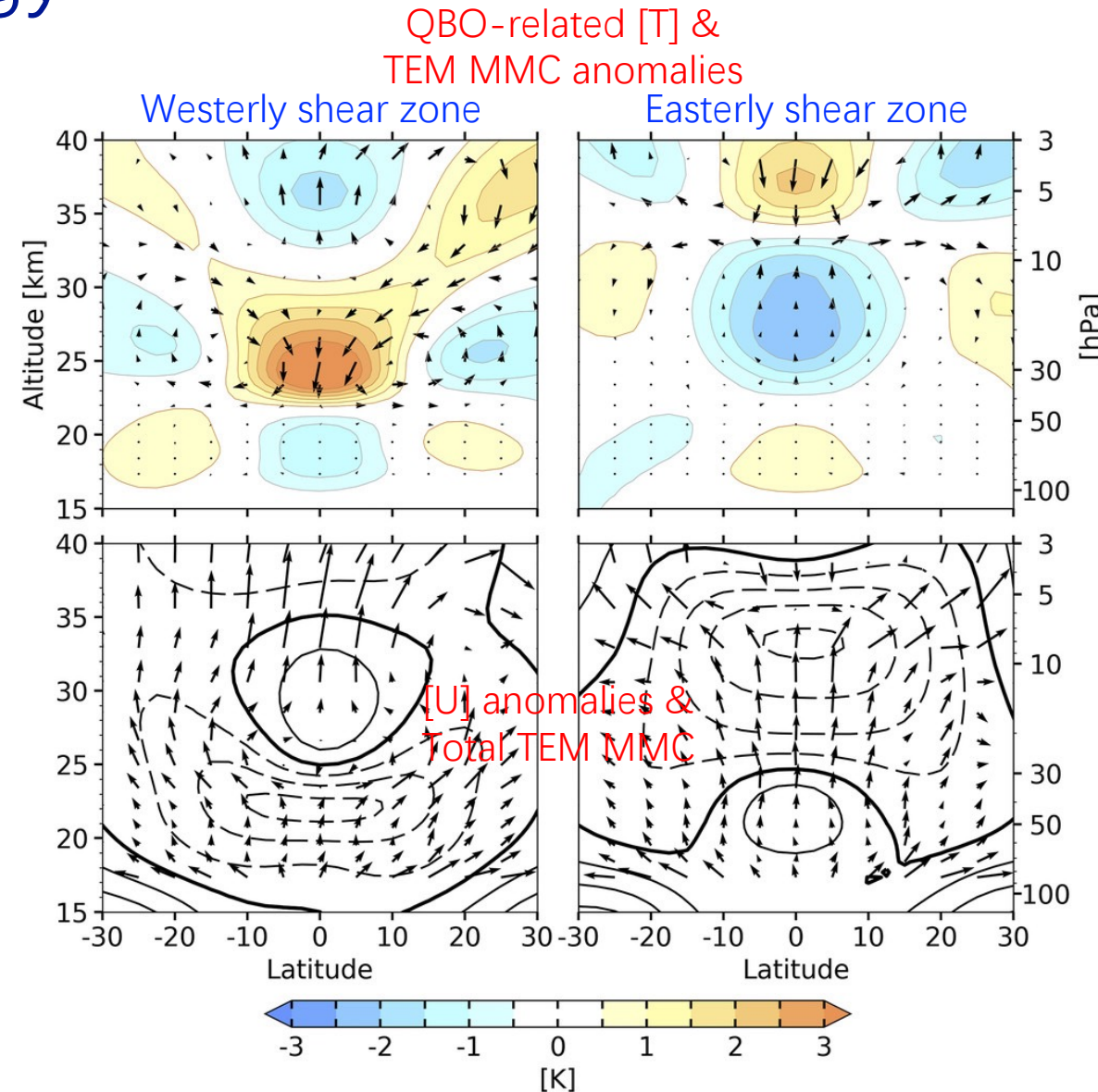
Not long after the discovery of the QBO, it was hypothesized that the observed downward propagation of easterly and westerly shear zones is due to vertical advection, but it is now well established that the mean vertical velocity in the tropical lower stratosphere is upward, not downward, in association with the rising branch of the BDC. Since the downward propagation is not associated with downward mass transport, it must be in response to downward propagating sources and sinks of westerly momentum.

- Meridional cross-sections of zonally averaged zonal wind and temperature are shown for descending westerly and easterly shear zones of the QBO.



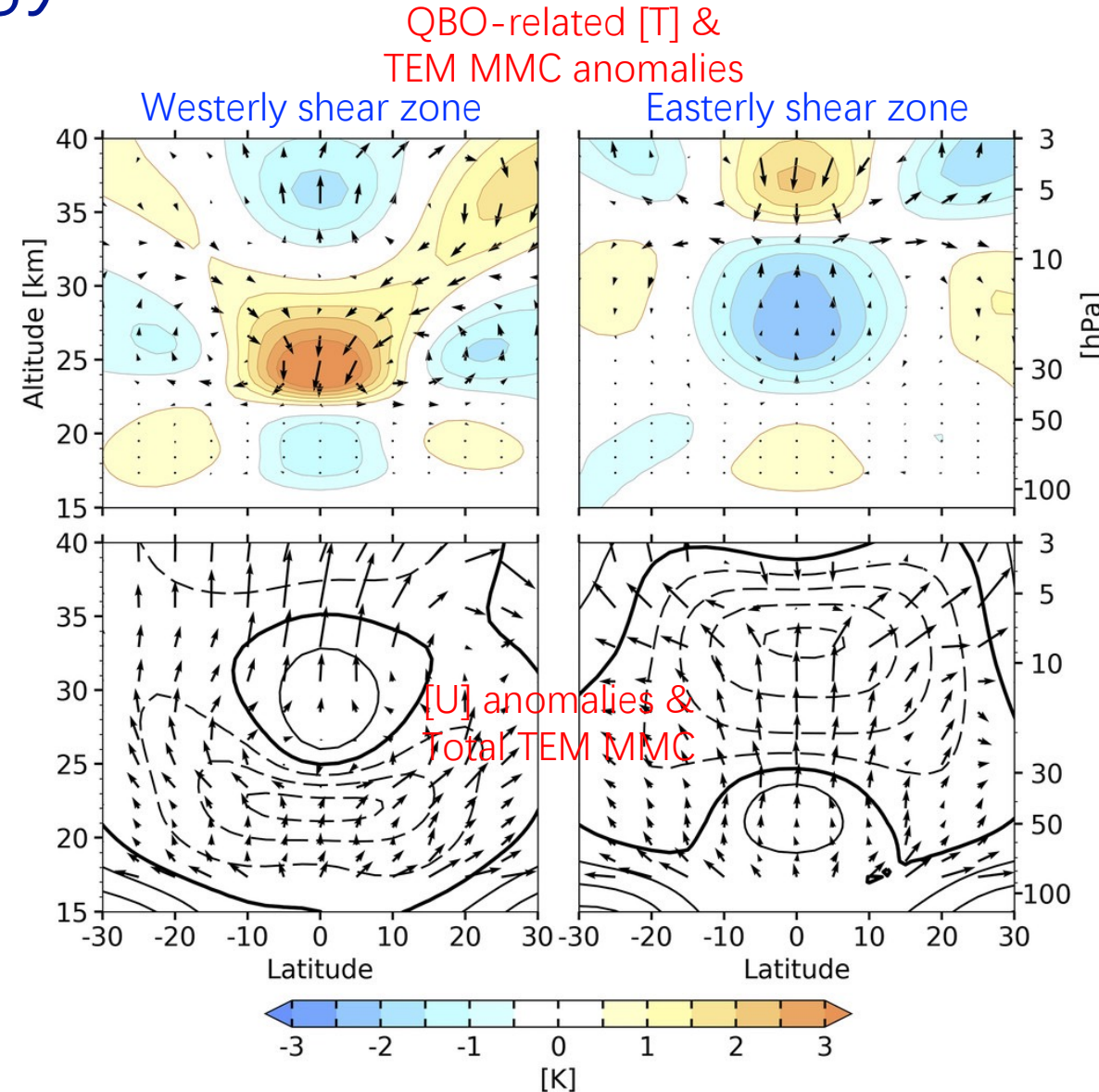
1. The Zonal Wind Climatology

- That the QBO-related $[T]$ and $[w]$ perturbations are linearly congruent and out of phase with one another indicates that the $[T]$ perturbations are adiabatically induced and radiatively damped.
- The QBO-related $[T]$ anomalies are concentrated in the shear zones between the easterly and westerly wind regimes. The $[T]$ and (not shown) $[Z]$ anomalies are strongest on the equator and exhibit weaker centers of opposing sign at $\sim 20^\circ\text{N/S}$. The $[u]$ and $[T]$ fields are in quadrature with one another, with the warmest air below the westerly maxima, as required for thermal wind balance, which prevails to within a few kilometers of the equator.



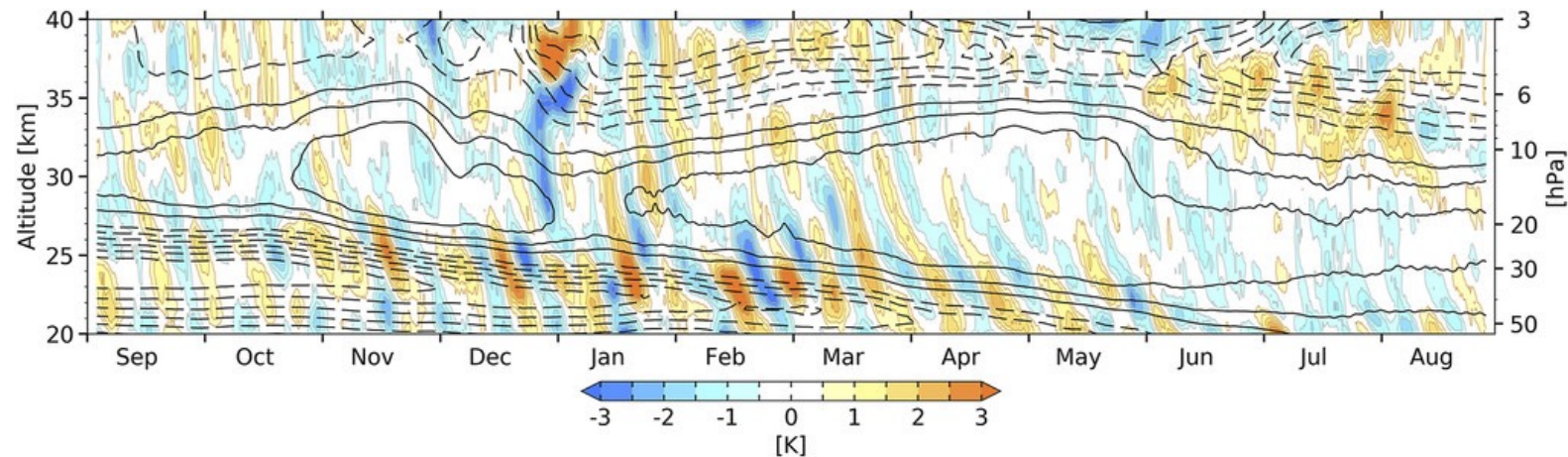
1. The Zonal Wind Climatology

- On the basis of the continuity equation, it can be inferred that the QBO-related MMC consist of downward propagating cells with equatorward flow in the westerly wind regimes and poleward flow in the easterly regimes. The QBO-related vertical velocity perturbations are as large as the mean rate of ascent in the BDC at these levels.
- Hence, at the times when westerly shear zones are descending through the lower stratosphere, the shallow and deep branches of the BDC are separated. Hence, the strength and structure of the BDC varies not only seasonally, but also from one year to the next.



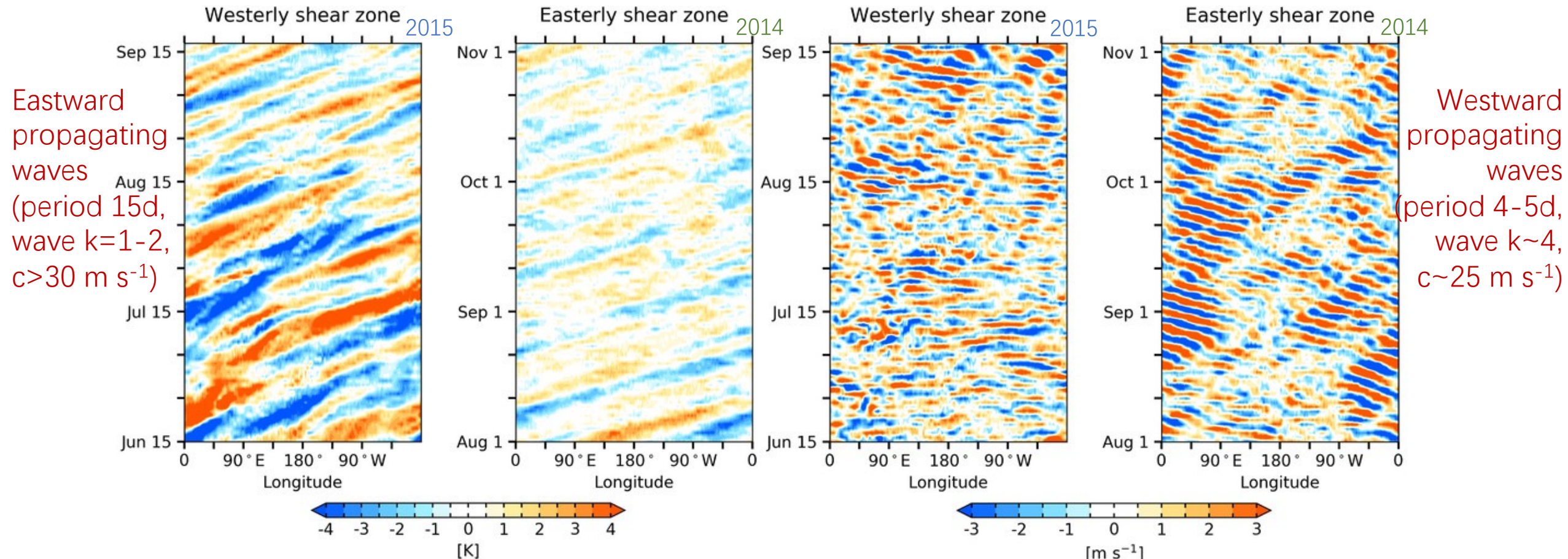
2. Equatorially Trapped Planetary Waves

- In the end of the 1960s with the discovery of a family of equatorially trapped planetary waves in the lower stratosphere, it was recognized almost immediately that these waves are most prominent within layers of strong vertical shear of the zonally symmetric background flow and that they play an important role in wave-mean flow interaction in connection with the QBO.
- Downward propagating waves with periods on the order of 10-15 days are present in T^* or u^* for $(0^\circ, 180^\circ)$, and that they are particularly well organized within the westerly shear zone.



2. Equatorially Trapped Planetary Waves

- Time-longitude sections of the eddy component of T_{50} (left) and v_{50} (right) over the equator for selected seasons. One is in a westerly shear zone and the other in an easterly shear zone.



2. Equatorially Trapped Planetary Waves

Theory (see the textbook):

2.1 The shallow water wave equations

2.2 The shallow water wave solutions

2.3 Vertical structure

2.4 Wavenumber-frequency spectra

2.5 Kelvin and mixed Rossby-gravity (MRG) waves

2.6 Rossby waves

2.7 Gravity waves and Inertio-gravity (IG) waves

3.The Generalized Eliassen-Palm Flux

- To diagnose the wave-mean flow interaction in the QBO it will be necessary to use the generalized完整的 TEM formulation, which take into account the contributions of vertically propagating Kelvin waves, MRG waves, IG waves, and smaller scale gravity waves, as well as equatorially trapped Rossby waves.
- The general expression for the EP flux \mathbf{F} in $z = -H \ln(p/p_s)$ coordinates is (10.6-10.7) and for the wave forcing term $\nabla \cdot \mathbf{F}$ is (10.8-10.9).

$$\mathbf{F} = F^{(y)}\mathbf{j} + F^{(z)}\mathbf{k} \quad (10.6)$$

where

$$F^{(y)} = \rho_o R_E \cos\phi \left(\frac{\partial[u]}{\partial z} \frac{[v^*T^*]}{\Gamma_d - \Gamma} - [u^*v^*] \right),$$

$$F^{(z)} = \rho_o R_E \cos\phi \left(\left(f - \frac{1}{R_E \cos\phi} \frac{\partial}{\partial \phi} [u] \cos\phi \right) \frac{[v^*T^*]}{\Gamma_d - \Gamma} - [u^*w^*] \right), \quad (10.7)$$

where ρ_o is a reference density, which decreases exponentially with height, and \mathbf{k} is the vertical (upward) unit vector.

The wave forcing term $\nabla \cdot \mathbf{F}$ in Eq. (9.2) can be written as the sum of the direct forcing by the eddy transports of zonal momentum

$$-\nabla \cdot \mathbf{F}_M = \frac{\rho_o}{\cos\phi} \frac{\partial}{\partial \phi} \left([u^*v^*] \cos^2\phi \right) + R_E \cos\phi \frac{\partial}{\partial z} \left(\rho_o [u^*w^*] \right) \quad (10.8)$$

and the indirect forcing associated with the mean meridional circulations induced by the poleward eddy heat transports,

$$-\nabla \cdot \mathbf{F}_H = -\frac{\rho_o}{\cos\phi} \frac{\partial}{\partial \phi} \left(\cos^2\phi \frac{\partial[u]}{\partial z} \frac{[v^*T^*]}{\Gamma_d - \Gamma} \right) - R_E \cos\phi \frac{\partial}{\partial z} \left(\rho_o \left(f - \frac{1}{R_E \cos\phi} \frac{\partial}{\partial \phi} [u] \cos\phi \right) \frac{[v^*T^*]}{\Gamma_d - \Gamma} \right). \quad (10.9)$$

3. The Generalized Eliassen-Palm Flux

- In this generalized form, the EP flux is still in the direction opposite to the flux of westerly momentum, but it is not quite as simply related to the flux of wave activity as it is in the diagnosis of Rossby waves.
- For Kelvin waves and eastward propagating IG and gravity waves, the transport of both westerly momentum and wave activity is upward, as evidenced by the observed in-phase relationships between u , w , and Z , yet it is evident from Eq. (10.7) that they produce a downward EP flux despite their upward group velocity. Hence, **in the case of eastward propagating Kelvin and IG waves the vertical fluxes of wave activity and westerly momentum are in the same direction; i.e., they are both upward.**

$$\mathbf{F} = F^{(y)}\mathbf{j} + F^{(z)}\mathbf{k} \quad (10.6)$$

where

$$F^{(y)} = \rho_o R_E \cos\phi \left(\frac{\partial[u]}{\partial z} \frac{[v^*T^*]}{\Gamma_d - \Gamma} - [u^*v^*] \right),$$

$$F^{(z)} = \rho_o R_E \cos\phi \left(\left(f - \frac{1}{R_E \cos\phi} \frac{\partial}{\partial\phi} [u] \cos\phi \right) \frac{[v^*T^*]}{\Gamma_d - \Gamma} - [u^*w^*] \right), \quad (10.7)$$

where ρ_o is a reference density, which decreases exponentially with height, and \mathbf{k} is the vertical (upward) unit vector.

The wave forcing term $\nabla \cdot \mathbf{F}$ in Eq. (9.2) can be written as the sum of the direct forcing by the eddy transports of zonal momentum

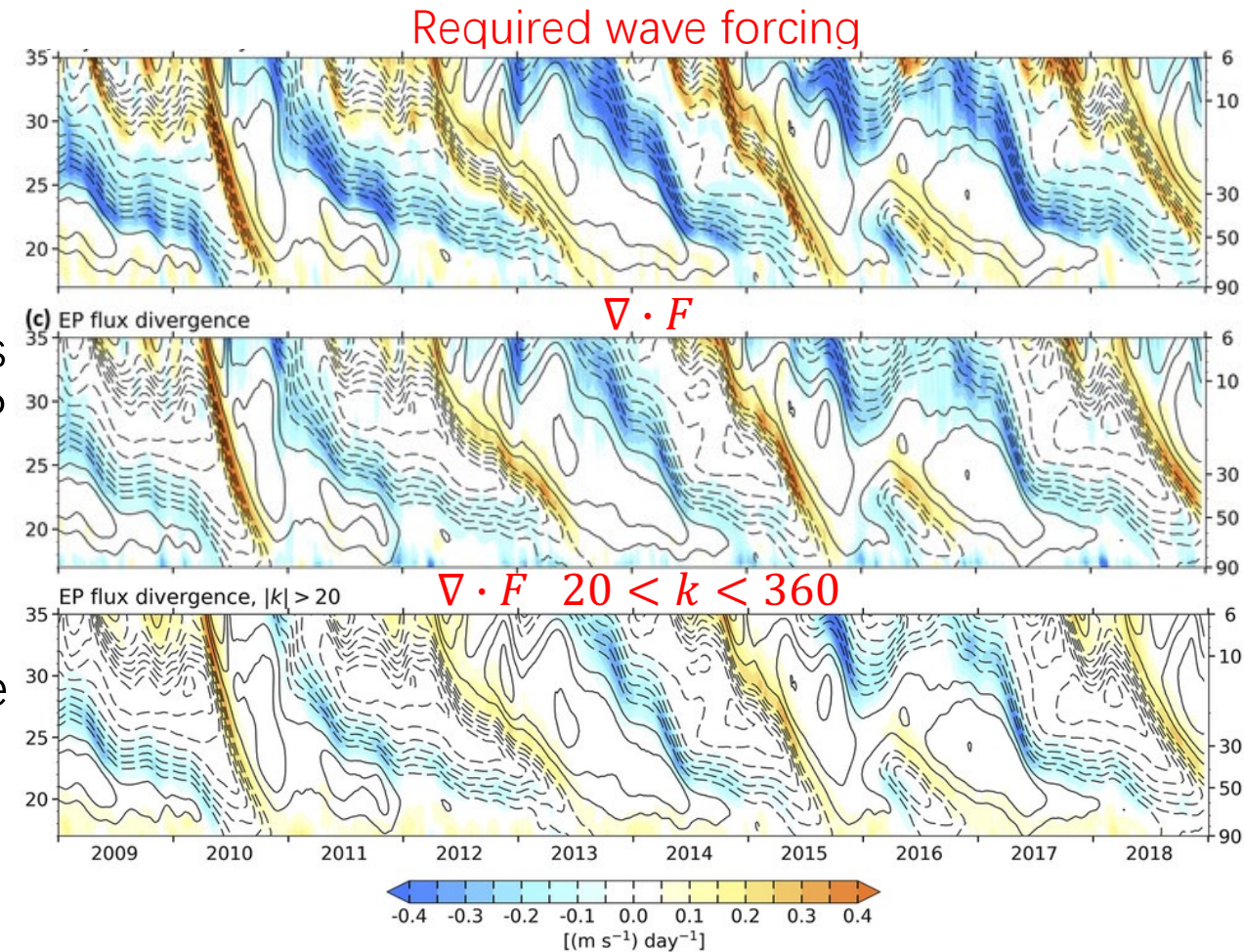
$$-\nabla \cdot \mathbf{F}_M = \frac{\rho_o}{\cos\phi} \frac{\partial}{\partial\phi} \left([u^*v^*] \cos^2\phi \right) + R_E \cos\phi \frac{\partial}{\partial z} \left(\rho_o [u^*w^*] \right) \quad (10.8)$$

and the indirect forcing associated with the mean meridional circulations induced by the poleward eddy heat transports,

$$-\nabla \cdot \mathbf{F}_H = -\frac{\rho_o}{\cos\phi} \frac{\partial}{\partial\phi} \left(\cos^2\phi \frac{\partial[u]}{\partial z} \frac{[v^*T^*]}{\Gamma_d - \Gamma} \right) - R_E \cos\phi \frac{\partial}{\partial z} \left(\rho_o \left(f - \frac{1}{R_E \cos\phi} \frac{\partial}{\partial\phi} [u] \cos\phi \right) \frac{[v^*T^*]}{\Gamma_d - \Gamma} \right). \quad (10.9)$$

4. Wave-Mean Flow Interaction in the QBO

- Top panel shows the **required forcing** (color shading); that is, the observed acceleration estimated using $\partial[u]/\partial t$ minus the vertical advection $-[w]\partial[u]/\partial z$
- Middle panel shows the forcing by the waves resolved by the reanalysis, as given by the EP flux divergence. **It accounts an appreciable fraction of the required forcing.**
- Bottom panel shows the contribution of waves with zonal wavenumber $k > 20$. These waves behave in a similar manner and **their contribution to the observed accelerations is not inconsequential.**



4. Wave-Mean Flow Interaction in the QBO

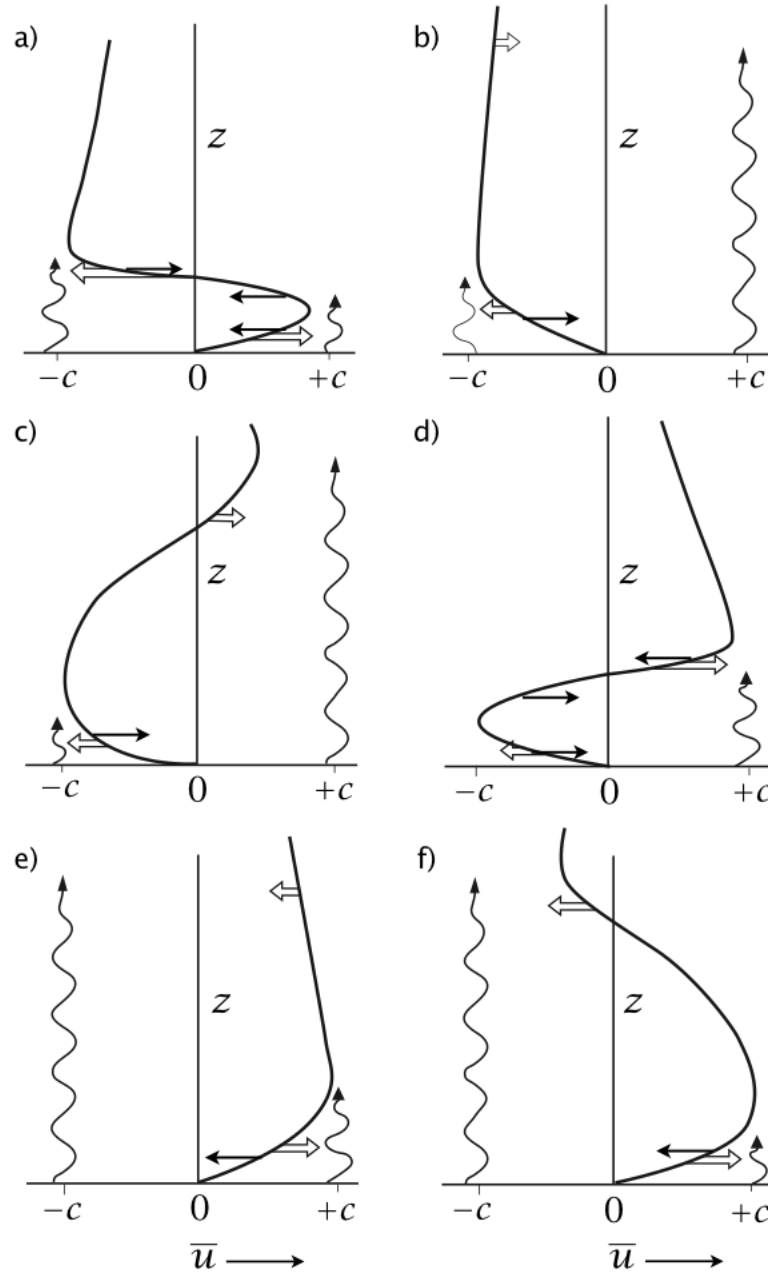
- The vertical component of the group velocity c_g , a measure of the rate at which wave activity disperses upward from below, is proportional to the Doppler-shifted phase speed $[u] - c$.
- It follows that eastward propagating Kelvin waves, eastward propagating IG and gravity waves disperse upward much more rapidly through easterly regimes (when $[u]$ and c are of opposing sign so that $[u] - c$ is large) than through westerly regimes and that their wave activity thus tends to be accumulated in westerly shear zones, where their group velocity is decreasing rapidly with height, **causing them to break and transfer their westerly momentum to the zonal flow**. It is the eastward acceleration due to this wave forcing that causes the westerly shear zones to descend.
- In a similar manner, westward propagating IG and MRG waves tend to accumulate and break in easterly shear zones, causing them to descend.

4. Wave-Mean Flow Interaction in the QBO

- The results based on ERA5 reanalysis can be summarized as follows.
 - Resolved waves with wavenumbers k ranging up to 360 account for slightly more than half of the wave forcing required to account for the observed zonal wind accelerations in the QBO. The remainder is presumably due to IG and gravity waves with shorter wavelengths and higher frequencies than those resolved by the reanalysis.
 - On the equator, the resolved forcing is dominated by the divergence of vertical transports of $[u^*w^*]$, whereas in the latitude bands from 5° to 15°N/S , the MMC induced by the poleward $[v^*T^*]$ in MRG waves and the $[u^*v^*]$ in extratropical Rossby waves also make appreciable contributions.
 - The forcing by the resolved waves is roughly evenly divided between waves with wavenumber k greater or less than 20. The former are mainly IG waves with periods on the order of a day or less, while the latter are lower frequency Rossby waves, Kelvin waves, and MRG waves.
 - The planetary wave contribution to the forcing comprises Kelvin, MRG, and IG waves. Kelvin waves are dominant in the westerly shear zones, while westward propagating IG waves are the most important contributors in the easterly shear zones, with a secondary contribution from MRG waves.
 - Eastward propagating IG waves contribute to the descent of westerly wind regimes and westward propagating IG waves contribute to the descent of easterly wind regimes.

4. Wave-Mean Flow Interaction in the QBO

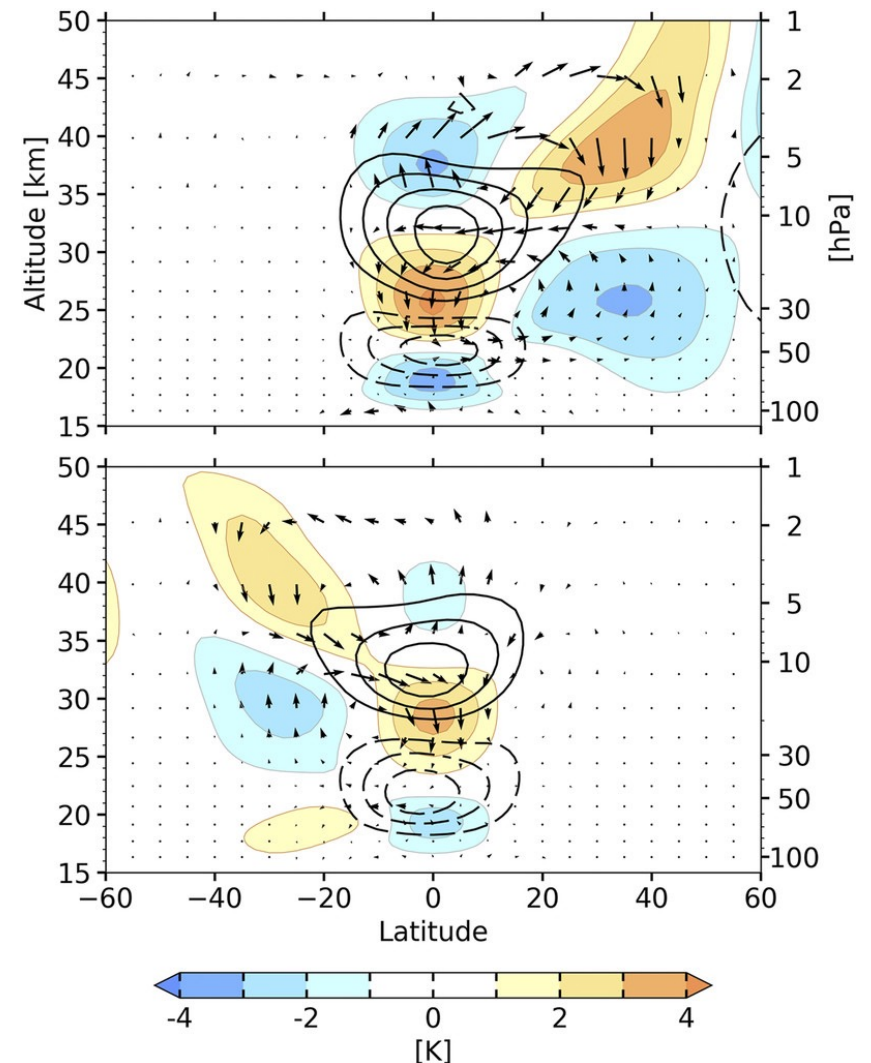
- The recent observational results serve to validate a mechanism, proposed over 50 years ago, for explaining why the QBO cycles back and forth between easterly and westerly wind regimes (Lindzen & Holton 1968; Holton and Lindzen 1972). The forcing in a simple, mechanistic model was prescribed as consisting of upward dispersing gravity waves with a continuum of phase speeds, both eastward and westward, ranging up to a maximum of $\pm c_{max}$. The waves give up their zonal momentum to the zonal flow when they reach a level in the atmosphere at which their phase speed matches the zonal wind speed, at which point their group velocity goes to zero and the momentum that they carry with them is imparted to the zonal flow, causing the shear zone to propagate downward. Waves propagating in the opposite direction are unaffected by this shear zone and are able to disperse upward without absorption until they encounter a mean flow that matches their phase speed. Successive easterly and westerly shear zones continue to propagate downward until they reach the wave source, which is presumed to lie at 19 km, just above the equatorial cold point. Integrations of the model yielded alternating, downward propagating easterly and westerly wind regimes with wind speeds ranging up to $\pm c_{max}$.



Plumb 1984

5. Influence of QBO on the Wintertime Polar Vortex

- The patterns in the meridional cross sections based on year-round data are nearly equatorially symmetric. In contrast, the midlatitude centers of action in the QBO-related temperature field and MMC anomalies are largely **confined to the winter hemisphere**.
- A likely explanation for this pronounced seasonality is that poleward of 15°N/S , the existence of MMCs is contingent upon the presence of “wave driving” (i.e., the divergence of the EP flux), which is appreciable only during the winter season when the background flow at these levels is westerly. This constraint applies to the climatological mean as well as to the QBO-related variations about the mean.



5. Influence of QBO on the Wintertime Polar Vortex

- The QBO modulates the strength of the NH wintertime stratospheric polar vortex (**Holton-Tan effect**). The difference field (**right**) exhibits an interesting structure. In the easterly phase, the polar vortex is weaker and the flux of wave activity into the stratosphere from below is stronger. A secondary feature is the redirection of the high latitude EP flux into the polar vortex in the easterly composite, reflecting a higher frequency of incidence of stratospheric sudden warmings.

