Quasi-Biennial Oscillation:

(Role of the equatorial waves)

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QUASI-BIENNIAL OSCILLATION (QBO)

Resources:

Ref: ***Middle Atmosphere Dynamics***, **by Andrews, Holton and Leovy, 1987, Academic Press. 489pp (Chap.8)**

- Baldwin et al., 2001: Quasi-Biennial Oscillation, Reviews of Geiphysics, 39 (2) 179-229

- Wallace J. M. 1973: General Circulation of the Tropical Lower Stratoshere, Reviews of Geophysics and Space Physics,V OL. 11, No. 2, PP. 191-222, MAY 1973

QUASI-BIENNIAL OSCILLATION (QBO)

Before discussing this phenomenon, let us recall some features of the distribution of mean temperature and wind in the stratosphere.

- The annual cycle of solar forcing gives rise to a strong annual cycle in almost all fields in the troposphere. In the troposphere the temperature is symmetric about the equator.
- In the stratosphere the temperature distribution in the extratropics is asymmetric about equator (Fig.1). It is also associated with asymmetric distribution of zonal wind in the stratosphere (Fig.2).
- In the tropics, above 35 Km the temperatrue variations is dominated by a *semiannual oscillation*.

TEMPERATURES in °K up to 90 KM

JULY

JAN

Oct

APRIL

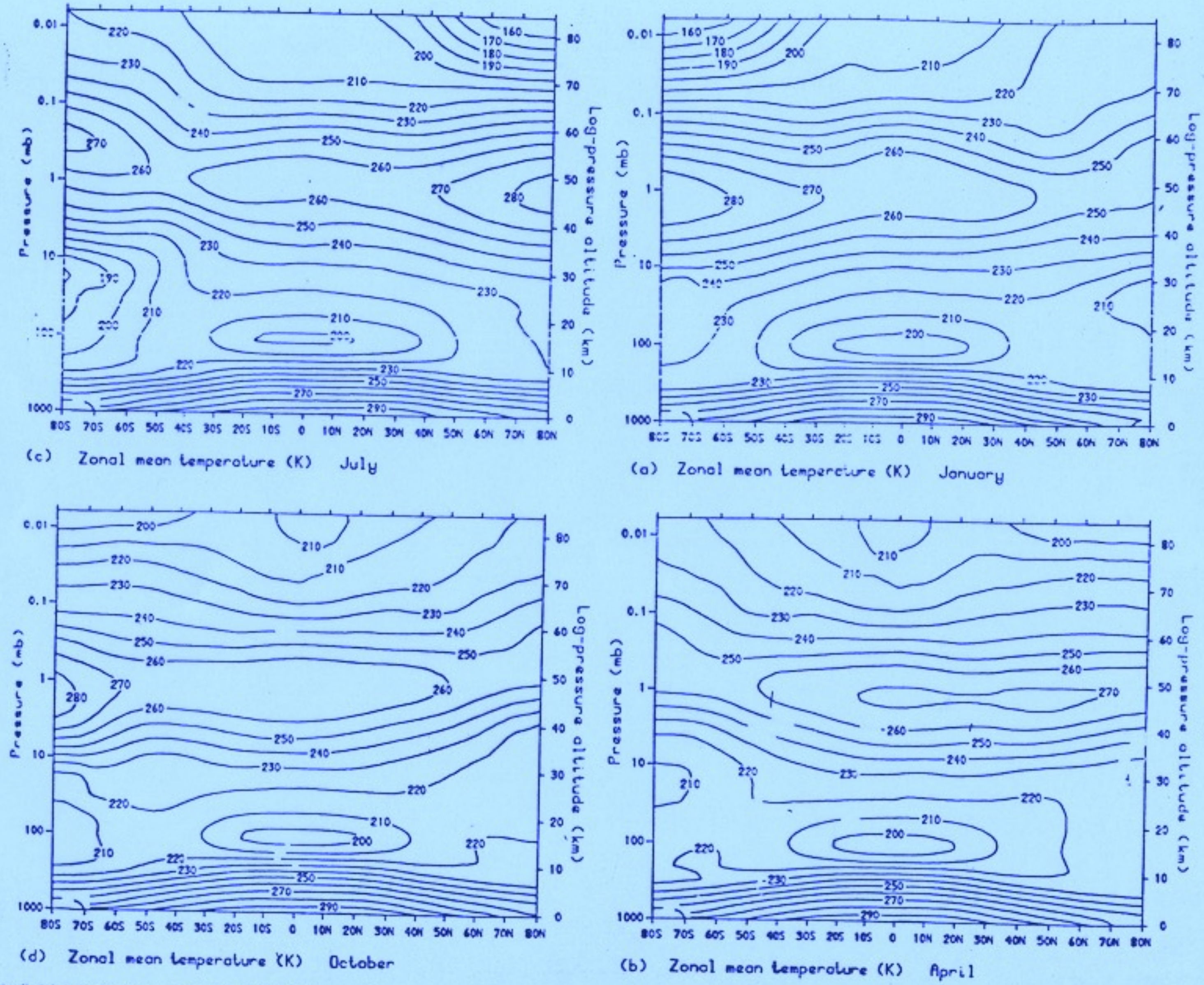
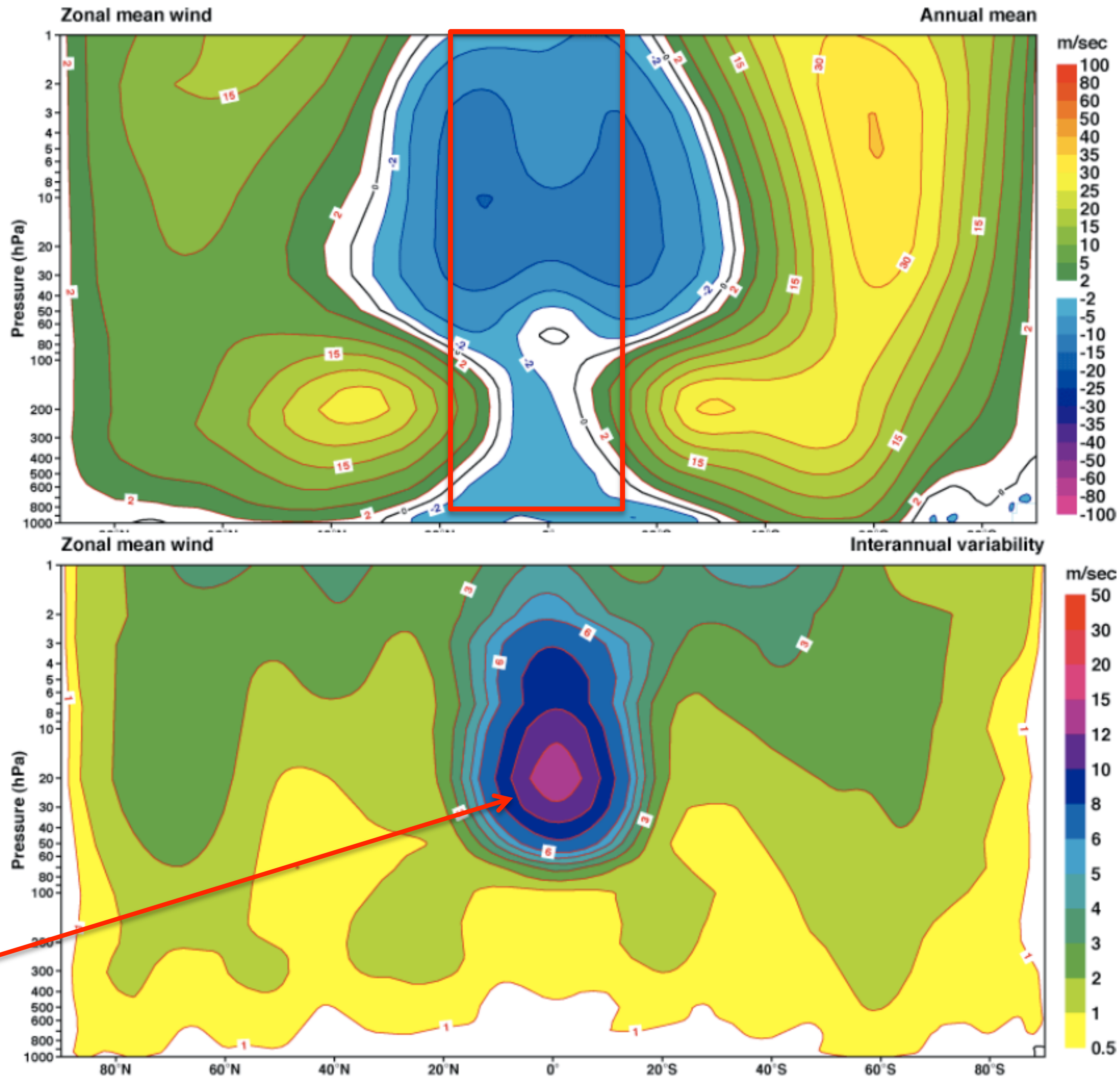


Fig. 5.1. Monthly and zonally averaged temperature (K) for altitudes up to approximately 90 km, based on about 5 years of data from the *Nimbus* 5 and 6 satellites (January 1973–December 1974 and July 1975–June 1978, respectively) above 30 mb; data supplied by Berlin Free University at 30 mb and Oort's (1983) climatology for 50 mb and below. (a) January, (b) April, (c) July, (d) October. From the 1986 CIRA compilation, courtesy of J. J. Barnett and M. Corney, Department of Atmospheric Physics, Oxford University. (See also Barnett and Corney, 1985a.)

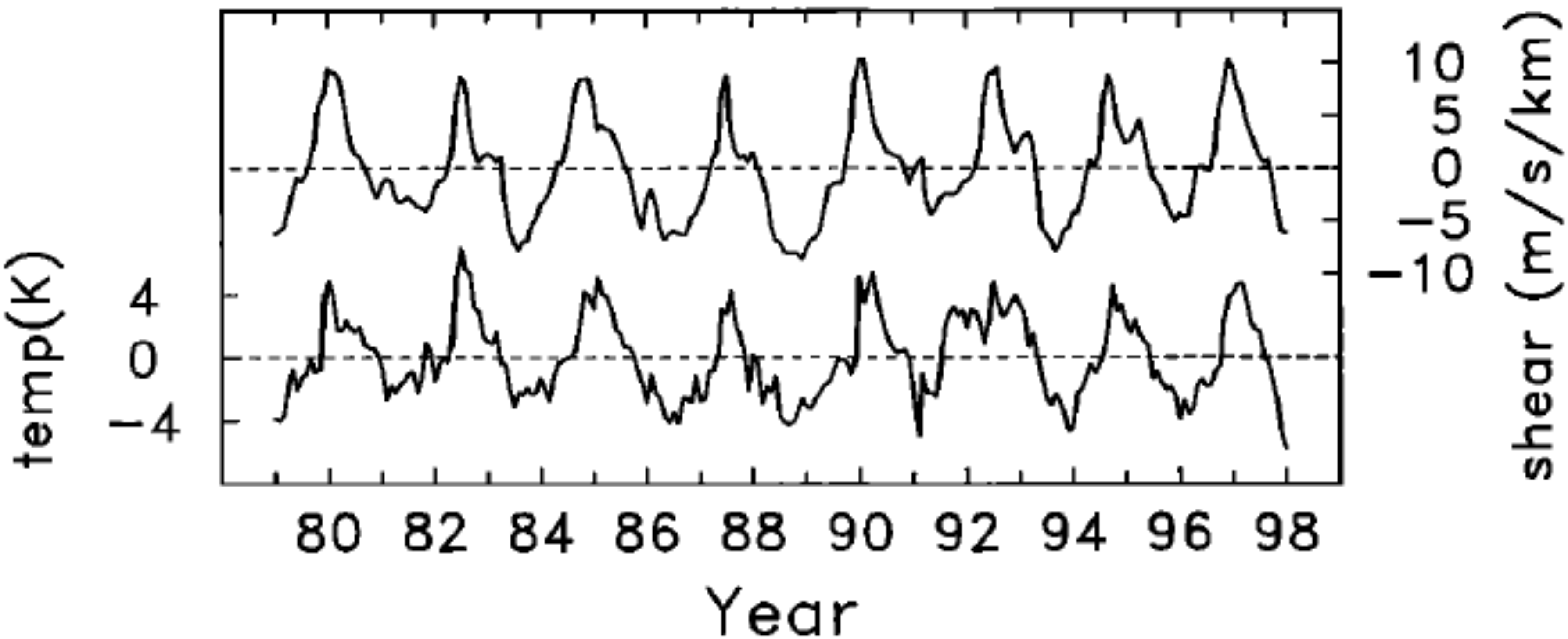
Climatological annual mean zonal winds

S.D. of interannual variability (IAV) annual mean zonal winds
➔Note very high IAV equatorial lower strastosphere



That is because,

- Below 35 Km, the equatorial stratosphere is dominated by long period oscillation known as *"Quasi-Biennial Oscillation"* with an approximate period of 27 months. As we shall shortly show, the amplitude of the zonal wind oscillation associated with QBO is very large.
- As the period of QBO has nothing to do with solar forcing, what forces this very large amplitude oscillation? First discovered by Reed in 1960 and independently by Veryard and Ebdon (Reed et al, 1961 JGR,**66**, 813-898, Veryard and Ebdon, 1961, Meterol.Mag.**90**, 125-143) is best displayed in the zonal winds.



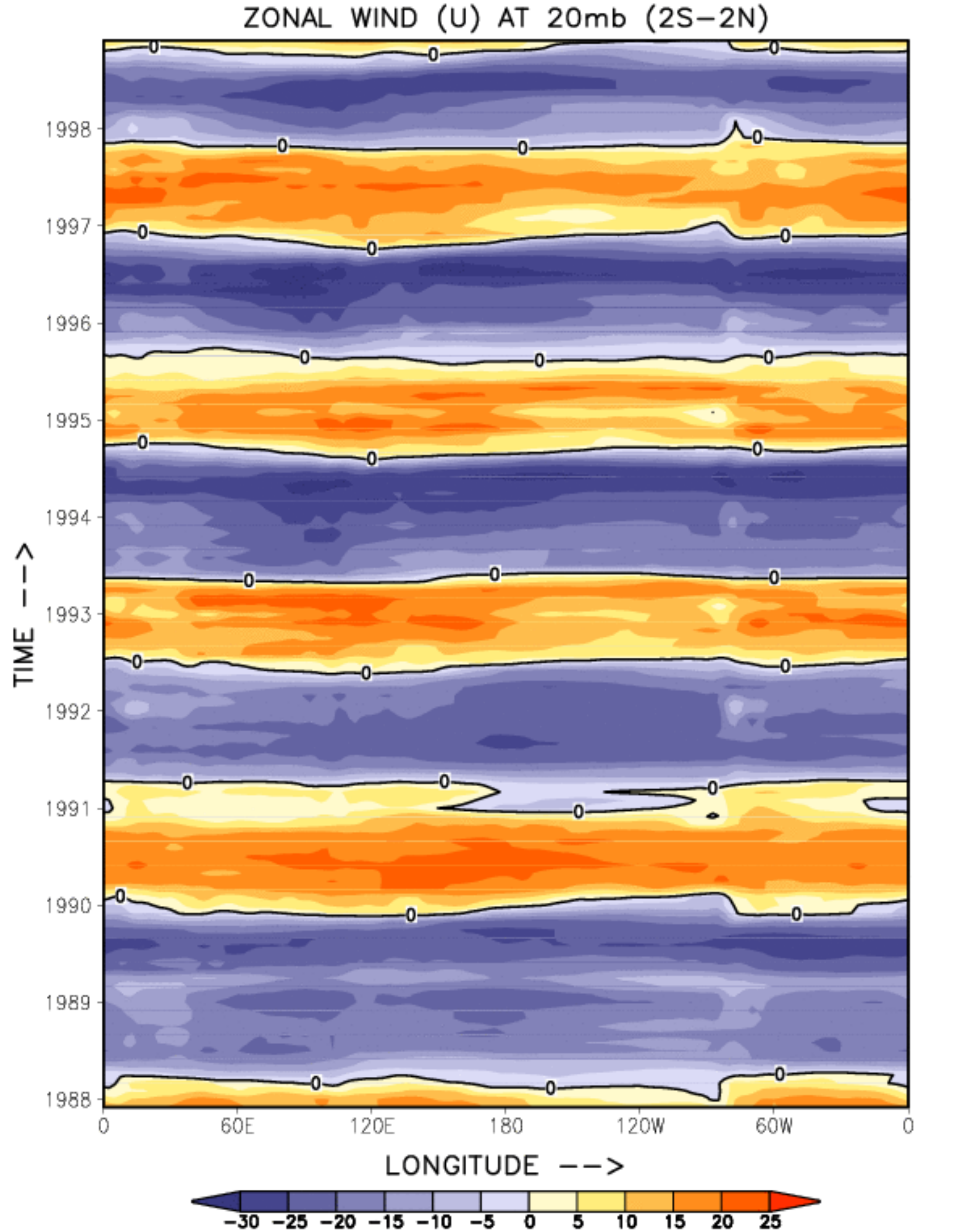
Equatorial temperature associated with the QBO in the 30- to 50-hPa layer (bottom curve) and vertical wind shear (top curve) at any station.

➔Note regular oscillation of the vertical shear of U-wind with large amplitude +-10 m/s/km and temperature +- $4^{O}K$

Baldwin et al. (2001): Rev. Geophysics

- The zonal wind fluctuation are coherent throughout the equatorial belt. In the next Fig. zonal wind averaged around the equator (2^oS-2^oN) are plotted as a function of longitude and time.
- Zonal winds fluctuate between a strong easterly regime and a strong westerly regime. When it is easterly (or westerly), it is so throughout the equatorial belt.

Time – longitude section of zonal winds at 20 hPa averaged between 2^{o}S and 2^{o}N. This is from NCEP/ NCAR reanalysed winds (m s^{-1}).



• **Time-height cross section of zonal wind**.(Fig.¯)

⇒ Many important features are seen in this cross section.

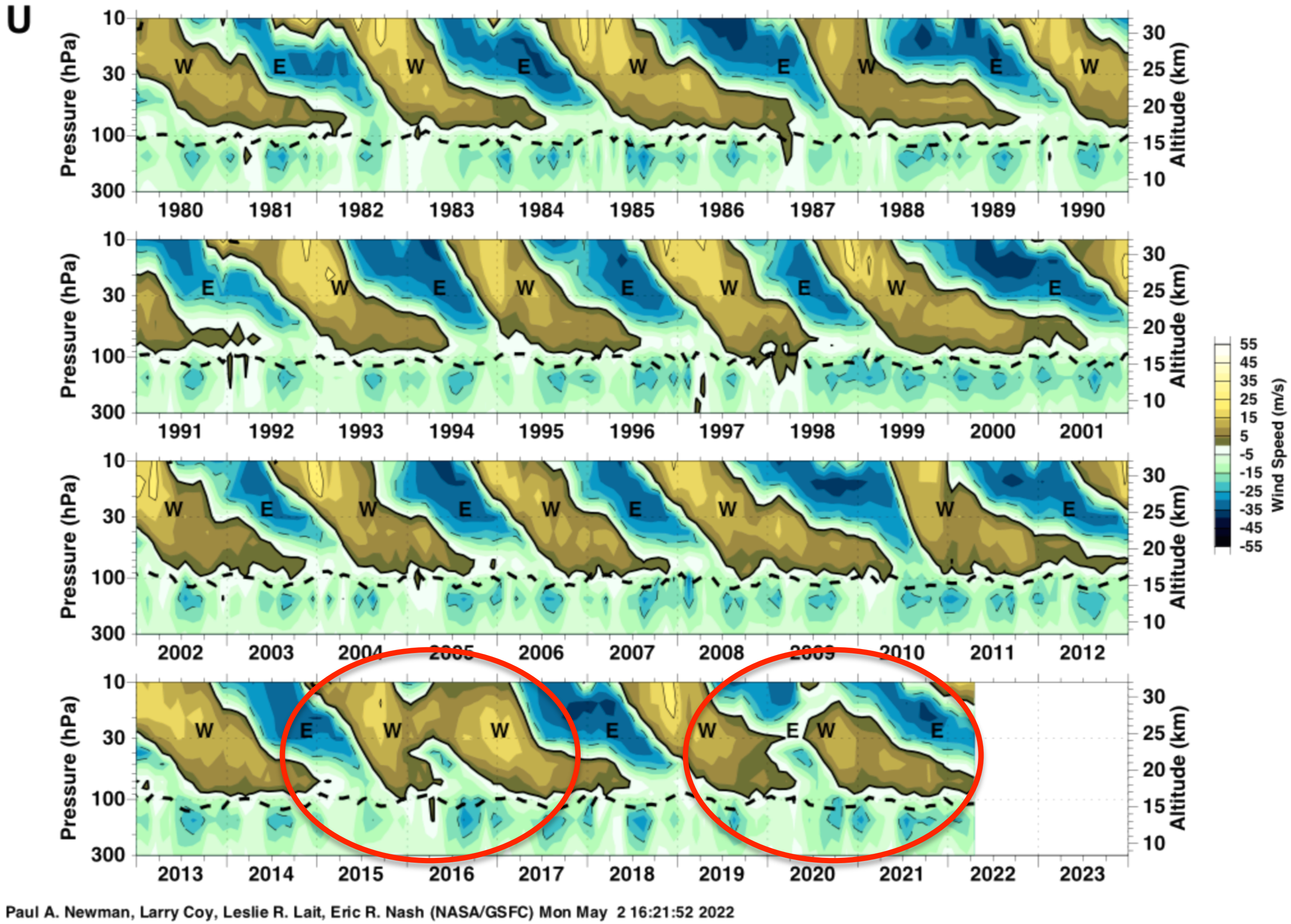
⇒ Largest amplitude of the oscillation is around 20hpa.

⇒ Periodicity is about 2 years.

⇒ Downward phase propagation. Both easterly and westerly phase first starts at upper stratosphere and descends slowly downward.

⇒ The easterly phase seems to descend faster than the westerly phase.

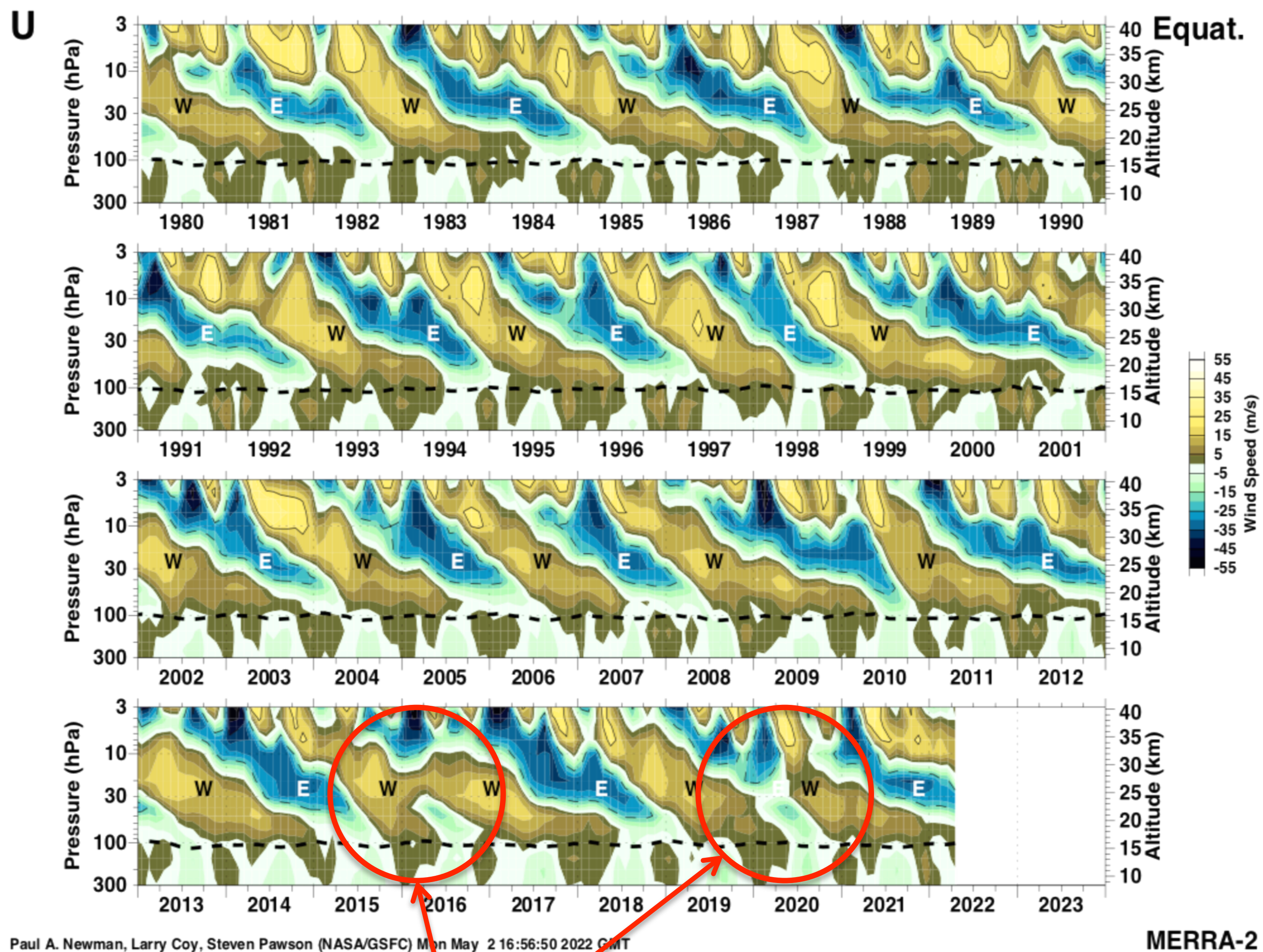
⇒ Peak of easterly phase ($\sim$ 30-35 ms^{-1}) is larger than the peak of westerly phase ($\sim$ 15-20 ms^{-1}).



Singapore sonde 1980-present QBO from monthly mean zonal wind

The plot is made by: 1) reading all daily sondes for the full month (generally twice per day at 0Z and 12Z), 2) vertically interpolating the zonal wind to missing levels (no extrapolation to levels above balloon burst altitudes), and 3) time interpolating for missing levels above the top of the balloon profile. The thick dotted line shows the tropopause calculated from the thermal lapse rate. Units are meters per second (m/s).

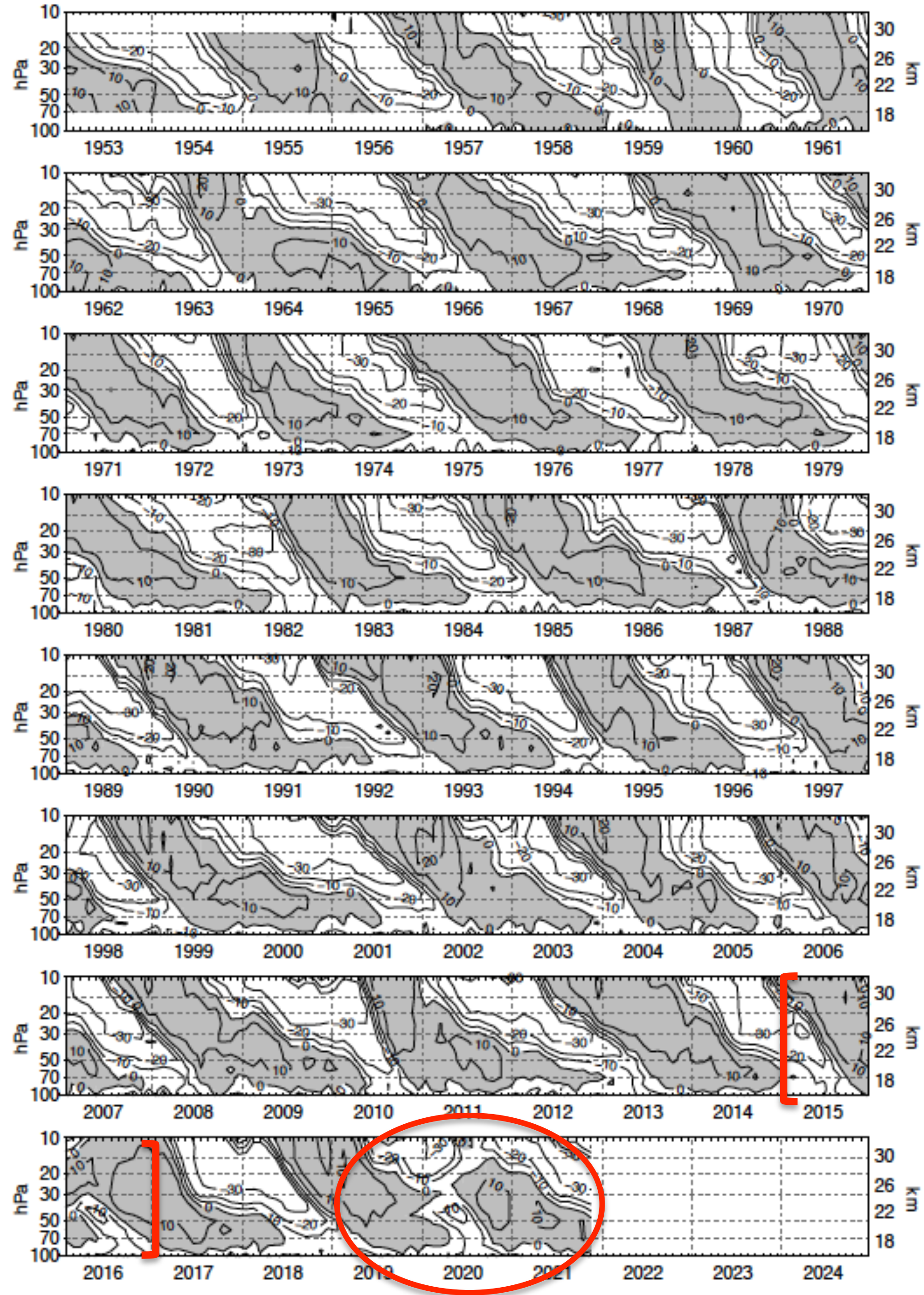
MERRA-2 1980-present QBO monthly mean zonal wind at the Equator



Anomalous behavior during 2016 and 2020

Longer history is created by combining observations on several equatorial stations

Time-height section of monthly mean zonal winds (m/s) at equatorial stations: Canton Island, 3°S/172°W (Jan 1953 - Aug 1967), Gan/Maledive Islands, 1°S/73°E (Sep 1967 - Dec 1975) and Singapore, 1°N/104°E (since Jan 1976). Isopleths are at 10 m/s intervals; westerlies are shaded (updated from Naujokat, 1986)



Latitude-height dependence of the Amplitude and Phase of QBO

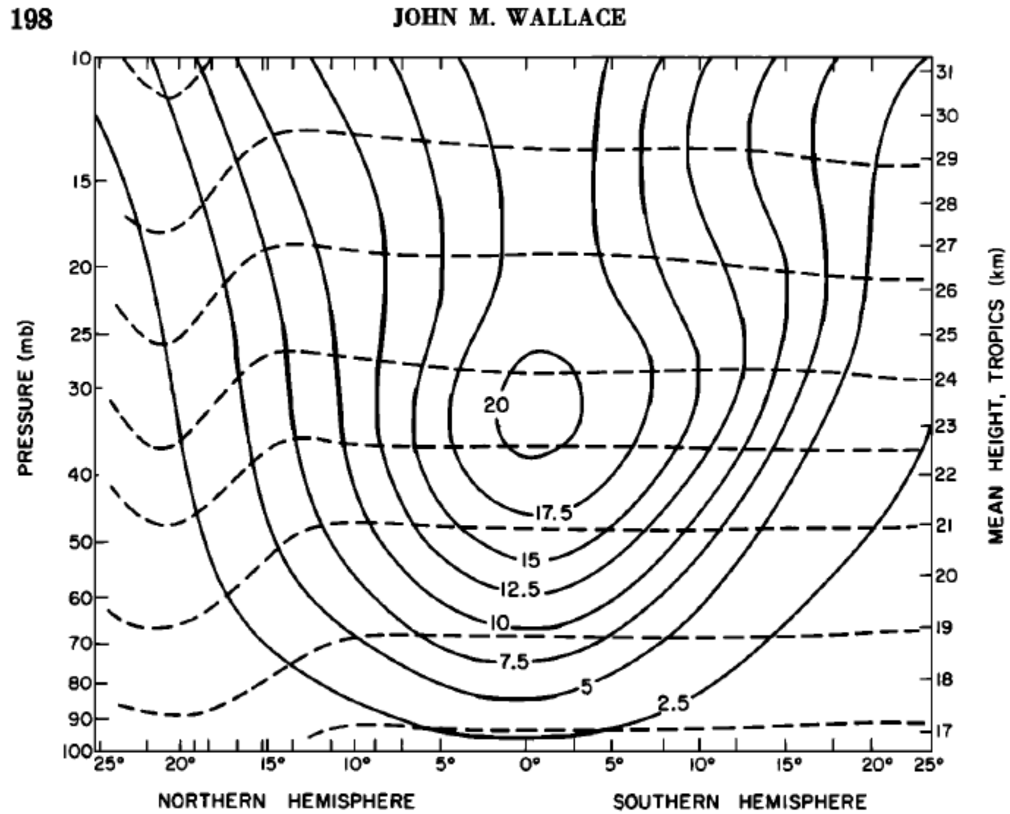


Fig. 6. Phase and amplitude of the quasi-biennial oscillation in zonal wind (adapted from *U.S. Navy Weather Research Facility* [1964]). Phases are indicated by dashed lines spaced at intervals of 1 month, where time increases downward. Amplitude in meters per second is given by solid lines.

- Amplitude is largest at Equator at height of about 30hPa (24km). Decreases downward and becomes negligible at tropopause.
- Equatorially trapped phenomenon. Amplitude decreases away from the equator, half width about 12 degrees.
- Phase propagates downward. No phase dependence latitude.

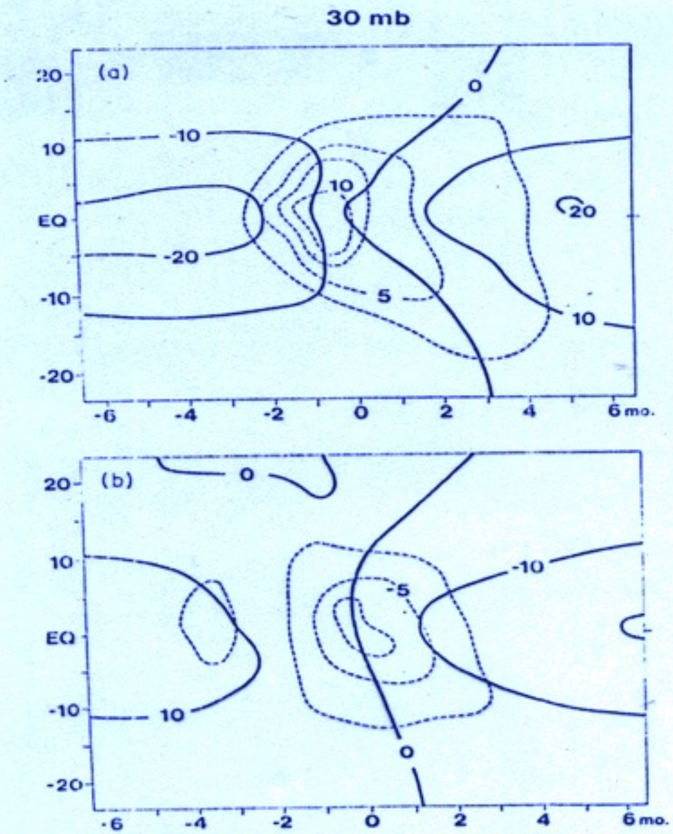


Fig. 8.3. Composite latitude-time section of zonal wind at 30-mb for westerly (upper) and easterly (lower) phases of the QBO. Zonal winds (solid lines) in m s^{-1}; acceleration (dashed lines) in m s^{-1}month^{-1}. [From Dunkerton and Delisi (1985). American Meteorological Society.]

- Westward and eastward acceleration are asymmetric.
- Westerly acceleration is stronger than easterly acceleration.
- Westerly acceleration starts at the equator and spreads to higher latitude.
- Easterly acceleration starts almost simultaneously at latitude between 10S and 10N.

- As we have seen in the time-height section of Zonal wind, different phases of QBO is associated with different large vertical shear of Zonal winds.
- As these are slow variations, Zonal wind are in thermal wind balance. This must lead to latitudinal variation in temperature accordingly as shown.
- Adiabatic adjustment of these meridional temperature gradients indicate that there must be secondary meridional circulation.

Implied meridional overturning circulation

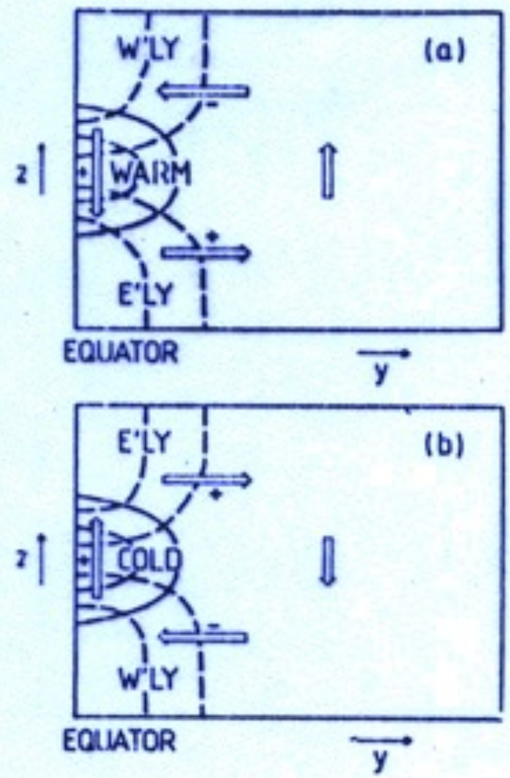


Fig. 8.5. Schematic latitude-height sections showing the mean meridional circulation associated with the equatorial temperature anomaly of the QBO. Solid contours show temperature anomaly isotherms, dashed contours are zonal wind isopleths. Plus and minus signs designate signs of the zonal wind accelerations driven by the mean meridional circulation. (a) Westerly shear zone, (b) easterly shear zone. [From Plumb and Bell (1982), with permission.]

Zonal winds are in Thermal wind balance

$$\frac{\partial u}{\partial z} = \frac{-R}{H\beta}\frac{\partial^2 T}{\partial y^2}$$

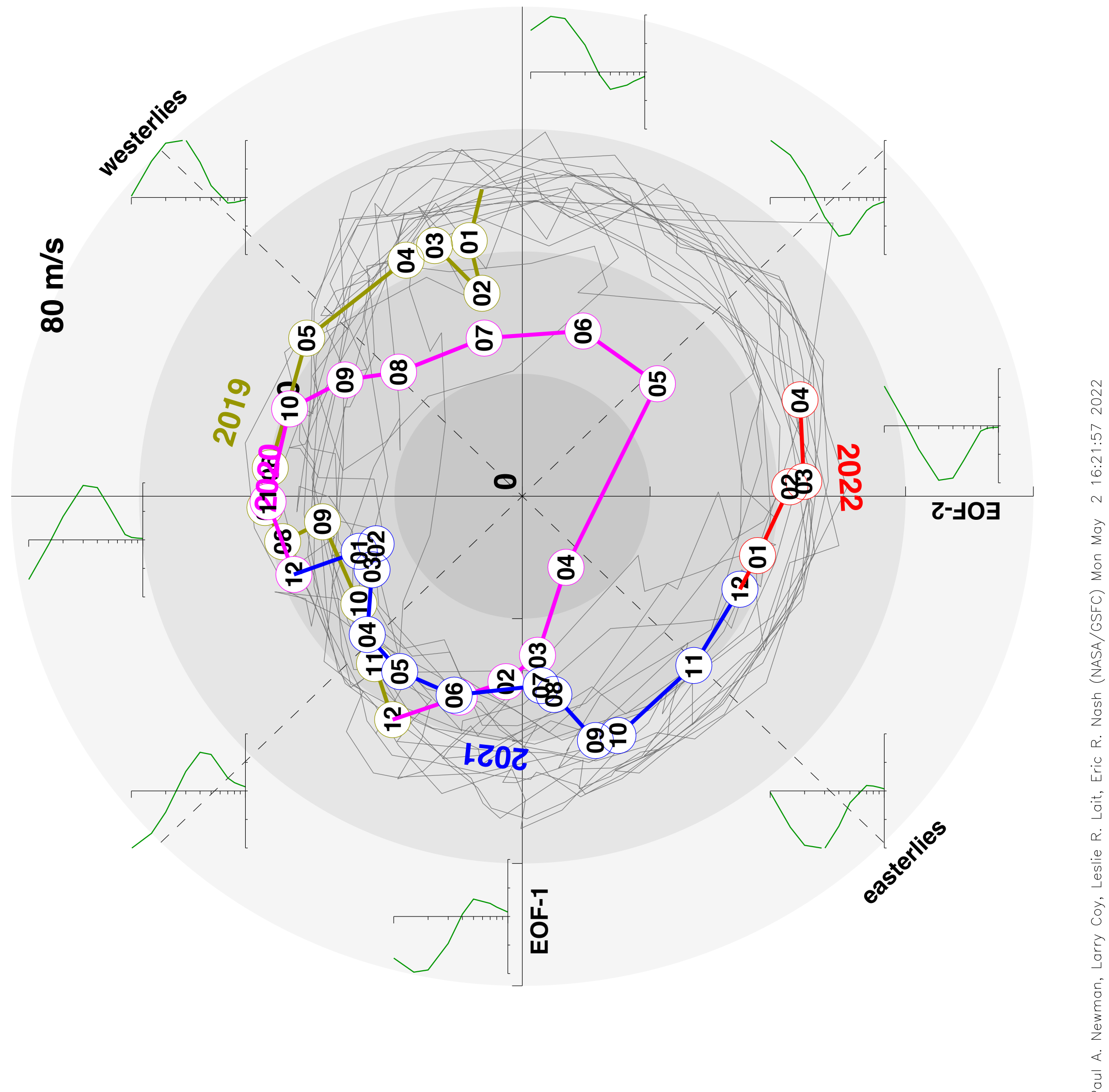
At Equator ➔ $\frac{\partial u}{\partial z} \sim \frac{R}{H\beta}\frac{T}{L^2}.$

Nearly Periodic (~28 months) Character of the QBO

The EOFs of the 1979-present QBO from the Singapore sonde monthly mean winds between 10 and 100 hPa.

EOF1 and EOF2 explain large variance and explain the periodic component.

- While PC1-PC2 make near circular orbits, anomalous behavior during 2020 is notable



Theory of QBO

Must explain ;

- Quasi-biennial periodicity
- Occurrence of Zonally symmetric westerlies at the equator
- Downward phase propagation
- Asymmetric in phase propagation of westerly and easterly phase

Early attempts to explain QBO as due to adiabatic heating or due to lateral exchange of momentum were unsuccessful in explaining the above feature. A model of QBO based on vertically propagating waves was originally proposed by Lindzen and Holton(1968) and refined by Holton and Lindzen (1972). Holton and Lindzen proposed that QBO results from wave mean flow interaction that occurs when vertically propagting Kelvin and Mixed Rossby gravity wave are radiatively or mechanically damped in the lower stratosphere.

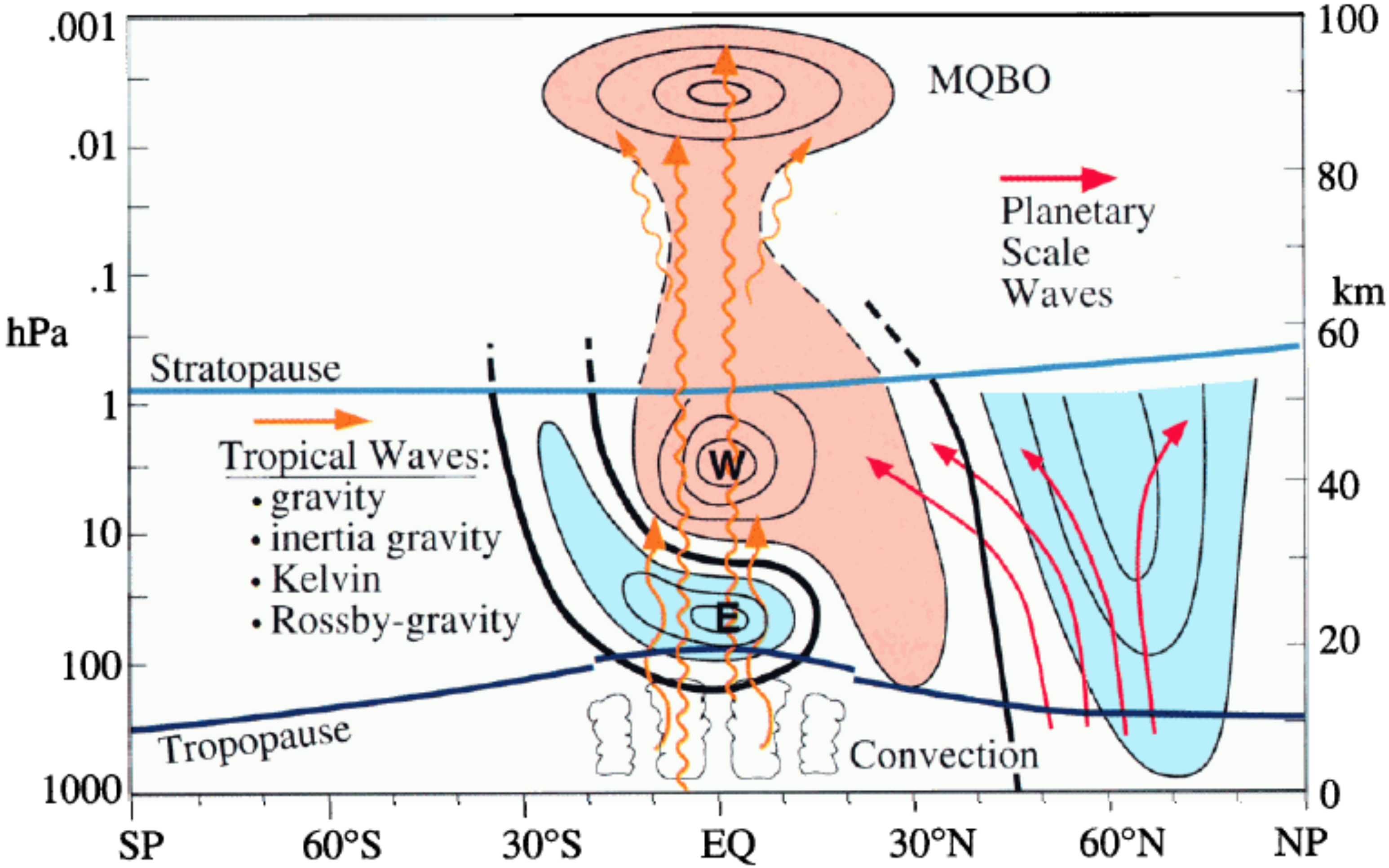


Plate 2. Dynamical overview of the QBO during northern winter. The propagation of various tropical waves is depicted by orange arrows, with the QBO driven by upward propagating gravity, inertia-gravity, Kelvin, and Rossby-gravity waves. The propagation of planetary-scale waves (purple arrows) is shown at middle to high latitudes. Black contours indicate the difference in zonal-mean zonal winds between easterly and westerly phases of the QBO, where the QBO phase is defined by the 40-hPa equatorial wind. Easterly anomalies are light blue, and westerly anomalies are pink. In the tropics the contours are similar to the observed wind values when the QBO is easterly. The mesospheric QBO (MQBO) is shown above ~80 km, while wind contours between ~50 and 80 km are dashed due to observational uncertainty.

Baldwin et al., 2001

Two Important Components of QBO theory:

1. Vertically propagating equatorial waves ,

2. Wave-Mean flow interaction

VERTICAL PROPAGATION OF EQUATORIAL WAVES

Recall the basic linear equation in the absence of any mean flow ($\bar{u}$ = $\bar{v}$ = 0),

$$u'_t - \beta y v' + \phi'_x = 0 \tag{1}$$

$$v'_t + \beta y u' + \phi'_y = 0 \tag{2}$$

$$u'_x + v'_y + \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 w') = 0 \tag{3}$$

$$\phi'_{zt} + N^2 w' = 0 \tag{4}$$

where $N^2(z) = \frac{1}{H} R\bar{\theta}_z e^-(kz/H) \longrightarrow$ Brunt Vaisala Freqency.

Assume N = constant.We look for propagating wave solutions both in x and z directions.

$$\begin{pmatrix} u' \\ v' \\ w' \\ \phi' \end{pmatrix} = e^{\frac{z}{2H}} \begin{pmatrix} u(y) \\ v(y) \\ w(y) \\ \phi(y) \end{pmatrix} e^{i(kx+mz-\omega t)}$$

From (4) we can write

$$w(y) = -\frac{\omega}{N^2}\left(m - \frac{i}{2H}\right)\phi(y) \tag{5}$$

and from (1)-(3) we get

$$-i\omega u - \beta y v + ik\phi = 0 \tag{6}$$

$$-i\omega v + \beta y u + \phi_y = 0 \tag{7}$$

$$iku + v_y - i\omega m^2 N^{-2}\phi = 0 \tag{8}$$

In getting (8) from (3) we have used (5) and the factor $m^2 + 1/4H^2$ is replaced by m^2. This is justified for many equatorial waves for which vertical wave length is less than 15 Km. For these waves $4H^2m^2 \geq 34$. (6)-(8) gives us the equatorial wave that we discussed earlier.

THE KELVIN WAVE

$$-\omega u + k\phi = 0$$

$$\beta y u + \phi_y = 0$$

$$ku - \frac{\omega m^2}{N^2}\phi = 0$$

or

$$\phi = \frac{\omega}{k}u$$

therefore

$$ku = \frac{\omega m^2}{N^2}\phi = \frac{\omega m^2}{N^2}\frac{\omega}{k}u$$

$$\omega^2 = \frac{N^2 k^2}{m^2}$$

or

$$\omega = \pm\frac{Nk}{m}$$

It can be shown that the wave with upward phase velocity ($\omega = +Nk/m$) has downward energy propagation. This mode is rejected as there is no source of energy at infinity. Therefore, in the absence of a mean current $\bar{u} = 0$

$$\omega = -\frac{Nk}{m}$$

$$C_g^{(z)} = \frac{\partial \omega}{\partial m} = \frac{Nk}{m^2} = \frac{\omega^2}{Nk}$$

where $N^2(z) = \frac{k}{H}\frac{d\bar{\theta}}{dz}e^{-kz/H}$ = Brunt Vaisala frequency.

In the presence of a mean current with vertical shear $\bar{u}(z)$, using WKBJ approximation, the local frequency and group velocity may be written as

$$\omega - k\bar{u}(z) = -\frac{Nk}{m(z)} \tag{9}$$

and

$$\boxed{C_g^{(z)}(z) = \frac{NK}{m(z)^2} = \frac{\omega - k\bar{u}(z)}{Nk}} \tag{10}$$

- When phase speed $\frac{\omega}{k} \approx \bar{u}(z)$ the vertical wave length $\frac{2\pi}{m(z)} \approx 0$
- Also $C_g^{(z)} \approx 0$
- Thus the wave spends a VERY VERY long time in that height and is susecptible for dissipation.

WESTWARD PROPAGATING ROSSBY-GRAVITY WAVE

Again under WKBJ approximation

$$m(z) = \frac{N\left\{\beta + \left[\omega - k\bar{u}(z)\right]k\right\}}{\omega - k\bar{u}(z)}$$

and

$$\boxed{C_g^{(z)}(z) = -\frac{\left\{\omega - k\bar{u}(z)\right\}^3}{N\left\{2\beta + \left[\omega - k\bar{u}(z)\right]k\right\}}}$$

Let us recall that the spatial structure of the Kelvin and MRG waves are given by

KELVIN:

$$u = u_0 e^{-\frac{y^2}{4L^2}}$$

$$v = 0$$

$$\phi = \phi_0 e^{-\frac{y^2}{4L^2}}$$

MRG:

$$u = u_0 y e^{-\frac{y^2}{4L^2}}$$

$$v = v_0 e^{-\frac{y^2}{4L^2}}$$

$$\phi = \phi_0 y e^{-\frac{y^2}{4L^2}}$$

where L is a length scale.

Wave – Mean flow interactions

How do the waves change the mean Flow.

The mean flow acceleration is given by the equation (one dimensional)

$$\boxed{\frac{\partial \bar{u}}{\partial t} = \frac{1}{\rho_0} \sum \frac{\partial F_i}{\partial z} + \nu \frac{\partial^2 \bar{u}}{\partial z^2}}$$

where F_i = Elliassen-Palm Flux of a wave = $-\rho_0 \overline{u'w'}$

$$F^{(z)} = \sum_{i=1}^{2} F_i(z) = \sum_{i=1}^{2} F_i(z) exp \left[- \int_0^z g_i(z') dz' \right]$$

$$g_i(z) = \alpha N \left[k(\bar{u} - C_i)^2 \right]^{-1}$$

$\nu \longrightarrow$ represents the viscosity.

Here we assume this arise due to the radiative damping.

Characteristics of Dominant Observed Planetary-Scale Waves in the Equatorial Lower Stratosphere

Theoretical Description	Kelvin wave	Rossby-gravity wave
Discovered by	Wallace and Kousky	Yanai and Maruyama
Period (ground-based) $2\pi\omega^{-1}$	15days	4-5 days
Zonal wave number $s = ka\cos\phi$	1-2	4
Vertical wavelength $2\pi m^{-1}$	6-10 km	4-8 km
Average phase speed relative to ground	+25ms^{-1}	-23ms^{-1}
Observed when mean zonal flow is	Easterly (max.$\approx -25ms^{-1}$)	Westerly (max. $\approx +7ms^{-1}$)
Average phase speed relative to maximum zonal flow	$+50ms^{-1}$	$-30ms^{-1}$
Approximate observed amplitudes		
u'	$8ms^{-1}$	$2-3ms^{-1}$
v'	0	$2-3ms^{-1}$
T'	2-3 K	1 K
Approximate inferred amplitudes		
ϕ'/g	30m	4m
w'	$1.5x10^{-3}ms^{-1}$	$1.5x10^{-3}ms^{-1}$
Approximate meridional scales $\left(\frac{2N}{\beta\|m\|}\right)^{1/2}$	1300-1700 km	1000-1500 km

- Wallace J. M. 1973: General Circulation of the Tropical Lower Stratoshere, Reviews of Geophysics and Space Physics,V OL. 11, No. 2, PP. 191-222, MAY 1973

With global satellite data we now know that a spectrum of Kelvin and MRG waves exist in the atmosphere (Wheeler and Kiladis, JAS,1999, vol.56,374pp)

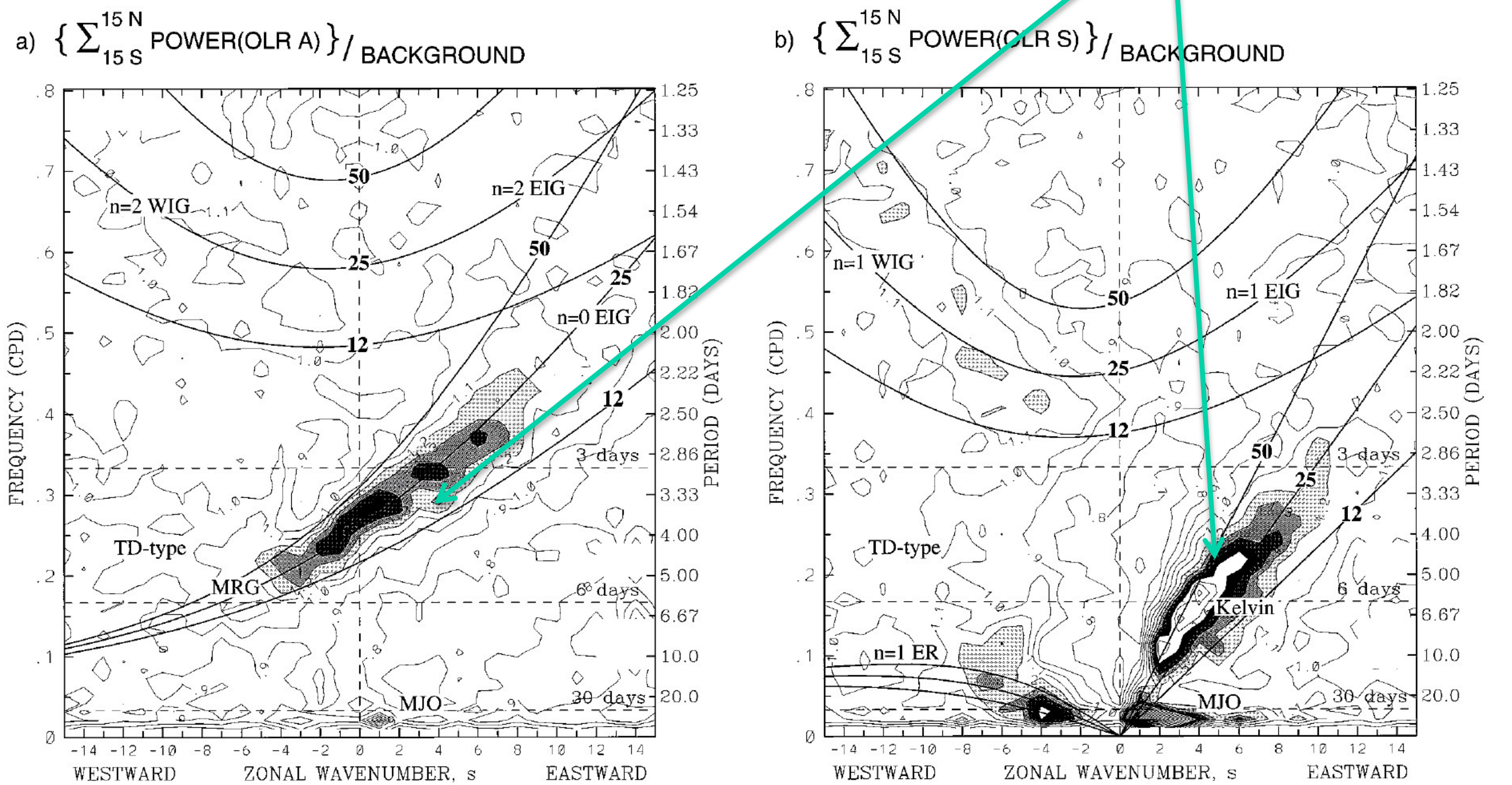


FIG. 3. (a) The antisymmetric OLR power of Fig. 1a divided by the background power of Fig. 2. Contour interval is 0.1, and shading begins at a value of 1.1 for which the spectral signatures are statistically significantly above the background at the 95% level (based on 500 dof). Superimposed are the dispersion curves of the even meridional mode-numbered equatorial waves for the three equivalent depths of h = 12, 25, and 50 m. (b) Same as in panel a except for the symmetric component of OLR of Fig. 1b and the corresponding odd meridional mode-numbered equatorial waves. Frequency spectral bandwidth is 1/96 cpd.

A Two-Dimensional Analog Model of the QBO

Essential mechanism can be understood with a simple model. Let us consider a vertically unbounded non rotating, stratified fluid subject to a standing wave forcing at the lower boundary of the form

$$\cos(kx)\cos(kct) = \frac{1}{2}\left[\cos k(x-ct) + \cos k(x+ct)\right]$$

$\Rightarrow$ equivalent to two traveling waves of equal amplitude but oppositely directed phase speed.

$\Rightarrow$ generates vertically propagating inertia gravity waves that propagates upward.

Two-dimensional analog model of QBO (after Plumb, 1982)

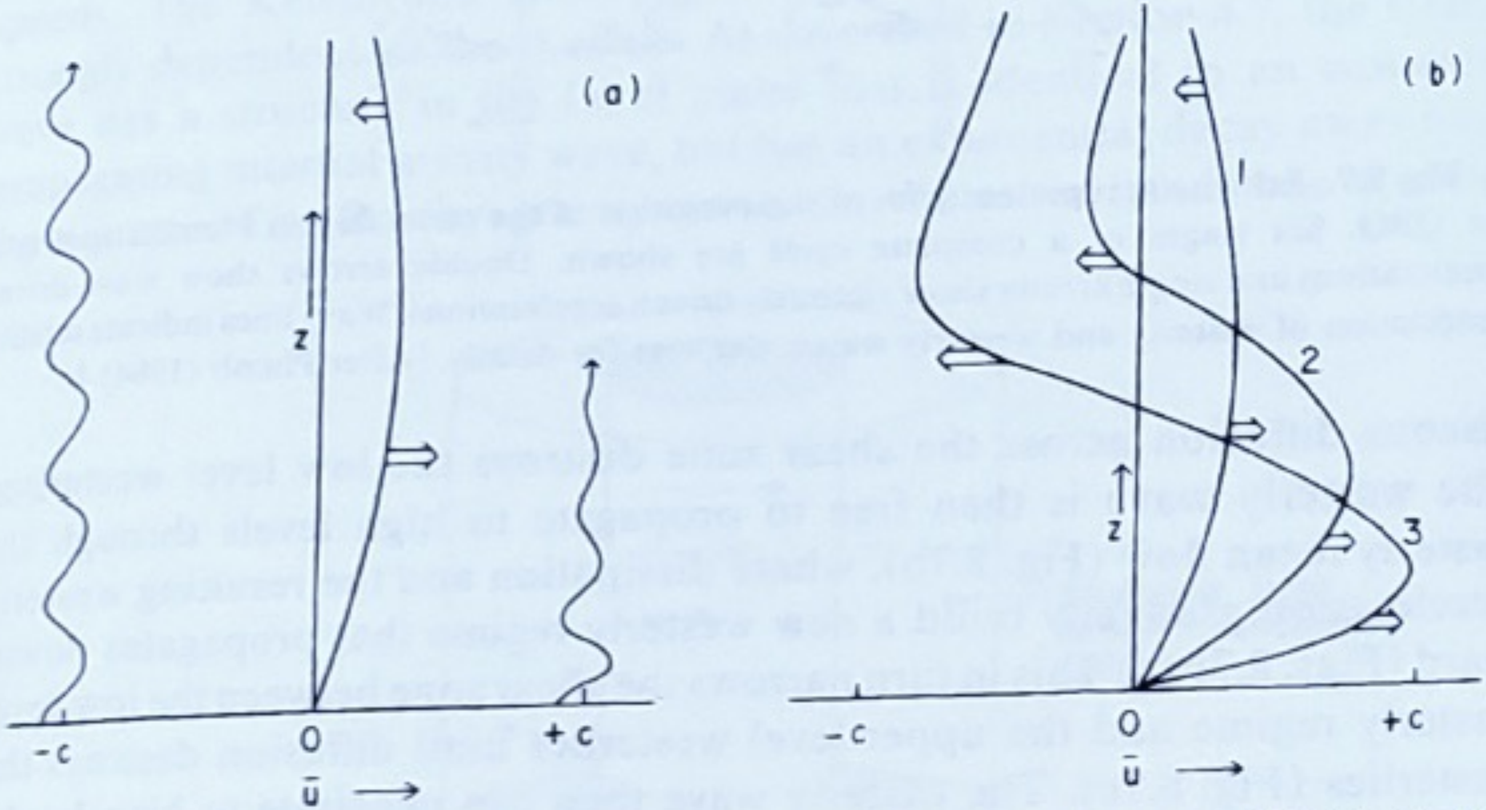


Fig. 8.6. Schematic representation of the instability of zonal flow in a stratified fluid with standing-wave forcing at a lower boundary. (a) Onset of instability from a small zonal flow perturbation. (b) Early stages of the subsequent mean-flow evolution. Broad arrows show locations and direction of maxima in mean wind acceleration. Wavy lines indicate relative penetration of wave components of positive and negative phase speeds *c*. [From Plumb (1982), with permission.]

From Andrews, Leovy and Holton, 1987

How does the vertical shear of the mean flow changes sign?

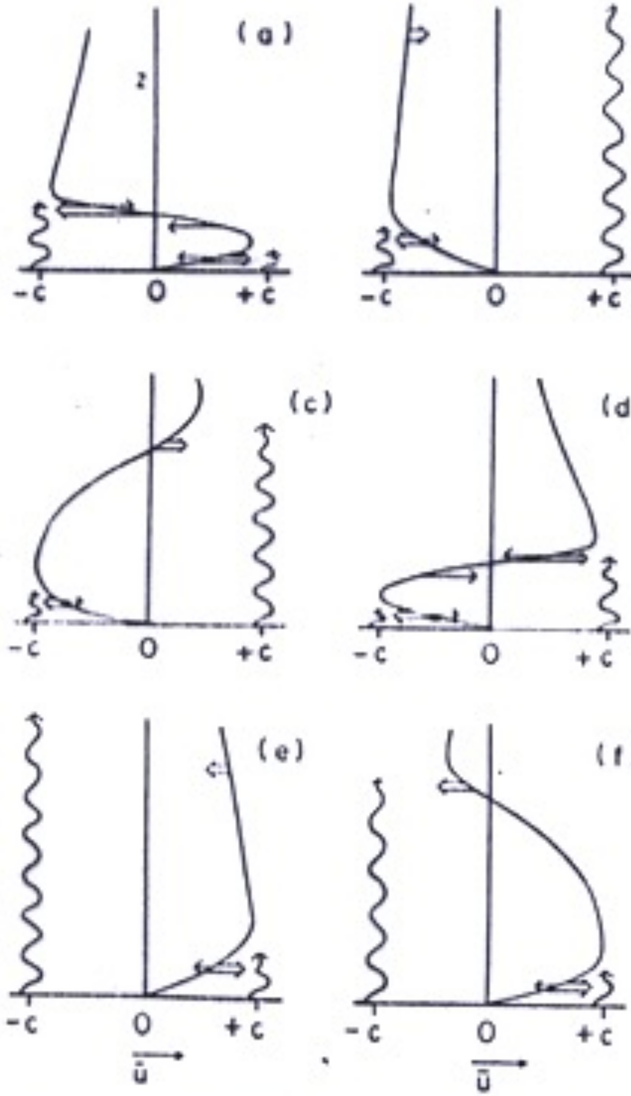


Fig. 8.7. Schematic representation of the evolution of the mean flow in Plumb's analog of the QBO. Six stages of a complete cycle are shown. Double arrows show wave-driven accelerations and single arrows show viscously driven accelerations. Wavy lines indicate relative penetration of easterly and westerly waves. See text for details. [After Plumb (1984).]

Laboratory demonstration of the concept

Plumb and McEwan, 1978, J. Atmos. Sci., 35, 1827-1939

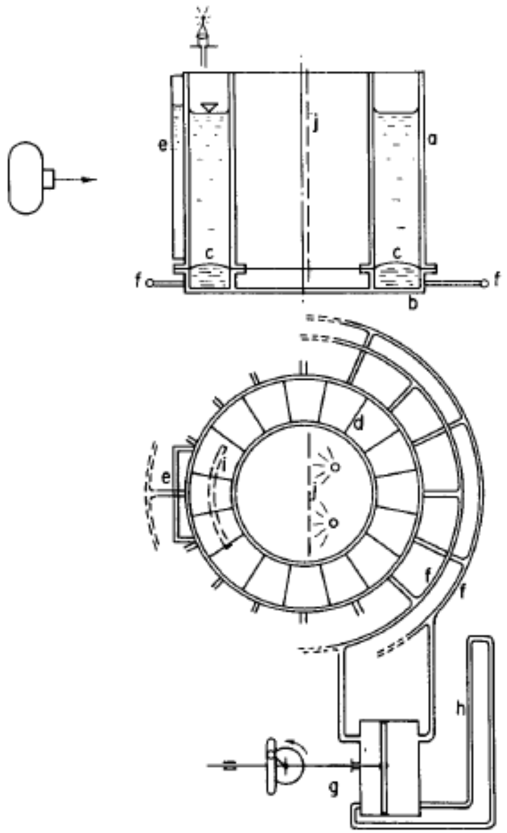
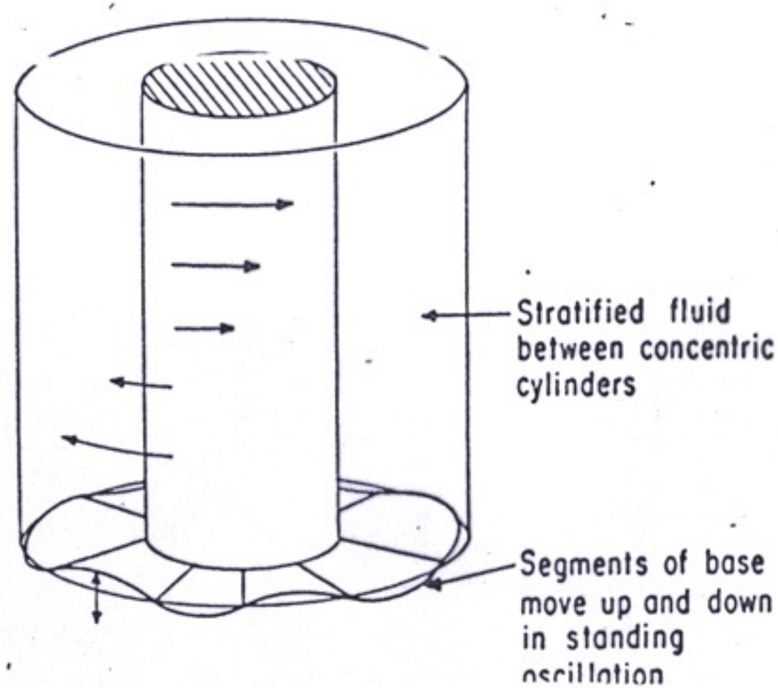


FIG. 2. The experimental apparatus: (a) annular cylinder (b) lower annular chamber, (c) rubber membrane, (d) radial dividers in lower chamber, (e) window, (f) distribution manifolds, (g) broad piston, scotch yoke and crank, (h) equalizing tube, (i) illuminated circumferential band, (j) illuminated diffusing screen (used to obtain the dye traces shown in Fig. 9).



ig. 8.8. Schematic representation of the apparatus used in the Plumb and McEwan ratory analog of the QBO.

This mechanism was demonstrated in a Laboratory by Plumb and McEwan (1978), schematic representation of the aparatus is shown in the next figure.

• An annular vessel filled with salt stratified water with a flexible membrane divided into a number of equal segments at the base.

• Membrane was oscillated to produce a standing wave forcing that excited two vertically propagating internal gravity wave of equal but opposite horizontal phase speed.

• Dissipation by viscosity

• For forcing above a critical value generated, strong mean flow consisting of downward propagating alternating westerly and easterly regimes.

• Experiment provides convincing evidence that HL mechanism contains essential physics of QBO.

In the Plumb model, the two waves are symmetric. As a result, the acceleration of the westerly and easterly are also symmetric. However, the rotation of the earth introduces important asymmetry in the waves with easterly and westerly phase speed. In the atmosphere, Kelvin and MRG waves also have different spatial structure in the y-direction. Therefore, instead of simple momentum flux, we have to consider what is known is Eliassen-Palm fluxes (EP fluxes). The divergence of the EP fluxes give rise to mean flow acceleration.

Holton and Lindzen, 1972 : An updated Theory for the Quasi-Biennial Cycle of Tropical Stratosphere, J. Atmos. Sci, 29, 1076- 1080

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}\bar{F}_{MW} + K\frac{\partial^2 \bar{u}}{\partial z^2} + G, \tag{1}$$

where:

$\bar{u}$	mean zonal flow (positive to the east)
$\rho_0(z)$	mean density
$\bar{F}_{MW}$	average vertical flux of mean zonal momentum due to synoptic-scale equatorial waves
K	an eddy diffusion coefficient
G	semiannual forcing
t	time
z	altitude

Holton and Lindzen (1972) used,

- Newtonian cooling coefficient that is 1/(21 days) at $z = 0$ (17 km) and linearly increased to 1/(7 days) at 30 km and remained constant after that.

- EP fluxes at $z = 0$ for both Kelvin and Rossby gravity wave were taken to be

$$\frac{F_i(o)}{\rho_0} = \pm 4 \times 10^{-3} m^2 s^{-2}$$

- Phase speed were taken to be $c_1 = -c_2 = 30 m s^{-1}$

- Zonal wave number 1 for Kelvin and 4 for MRG.

- Eddy diffusivity ν was assigned a small value of $0.3 m s^{-1}$

Equation(1) was intergrated numerically and the time evolution is showed in next fig.

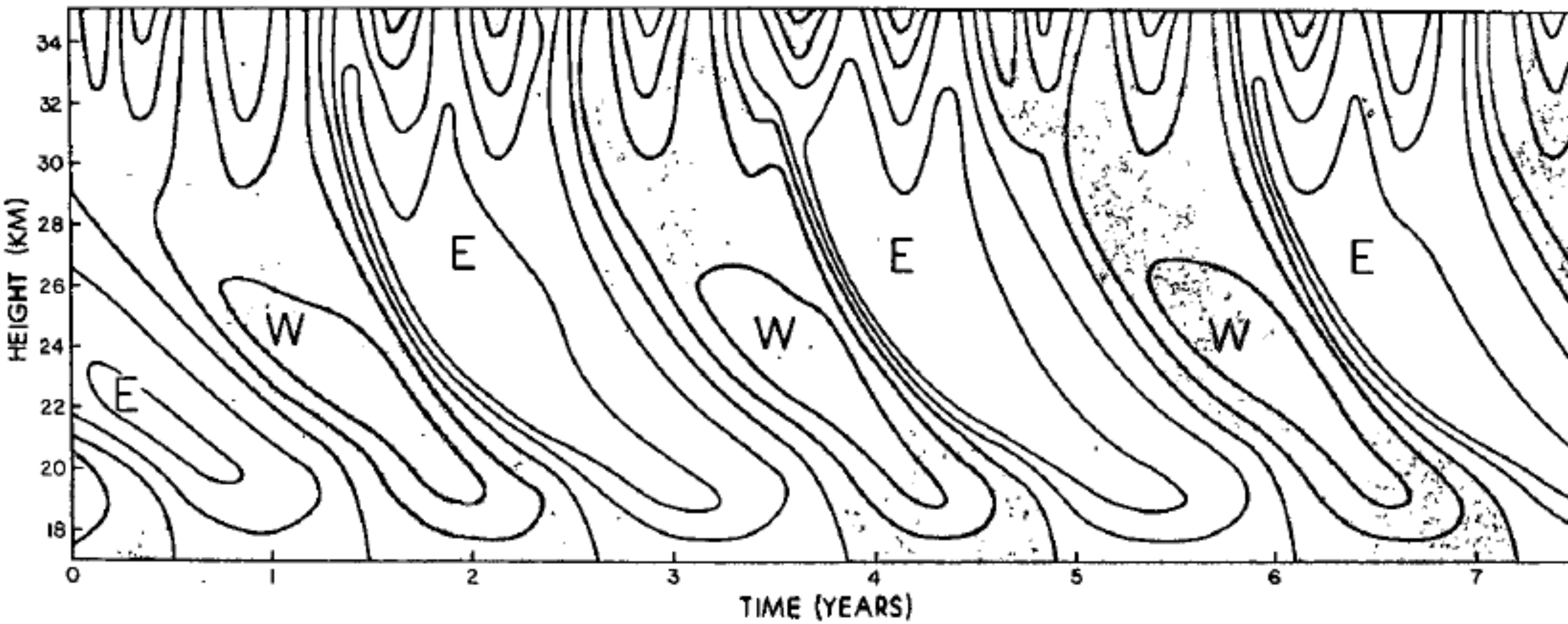
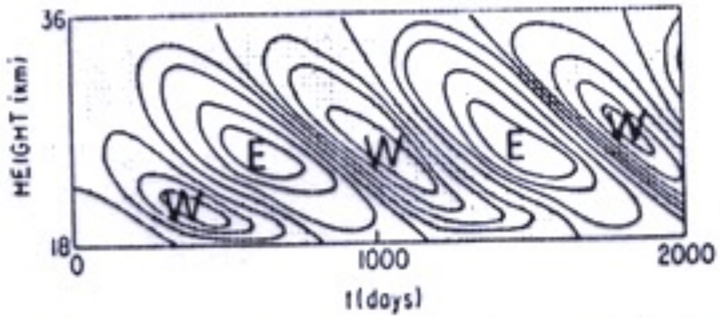


FIG. 1. Time-height cross section of mean zonal wind. Contours have been drawn at 10 m sec^{-1} intervals. Regions of westerly flow have been shaded.

HL model sumulates most features. But has a major drawback.

$\Rightarrow$ the easterly shear zone is stronger than westerly shear zone, contrary to observation.

Plumb & Bell (1982)
QJRMS, 108, 335



Inhomogeneous
Meridional
Variation
of $\bar{u}$, $\bar{T}$

Fig. 8.11. Time-height section of mean zonal wind at the equator in the two-dimensional model of the QBO of Plumb and Bell. Contours at 2-m s^{-1} intervals, easterlies are shaded [After Plumb and Bell (1982).]

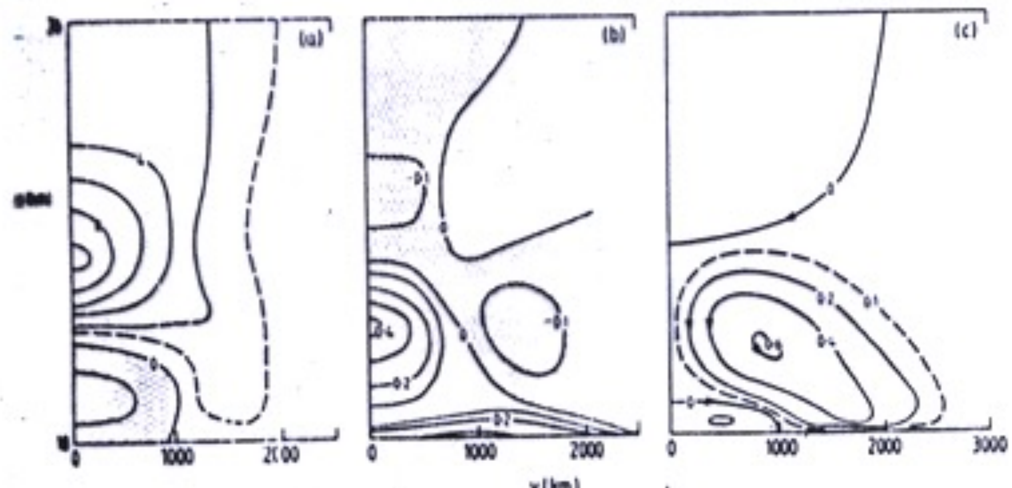
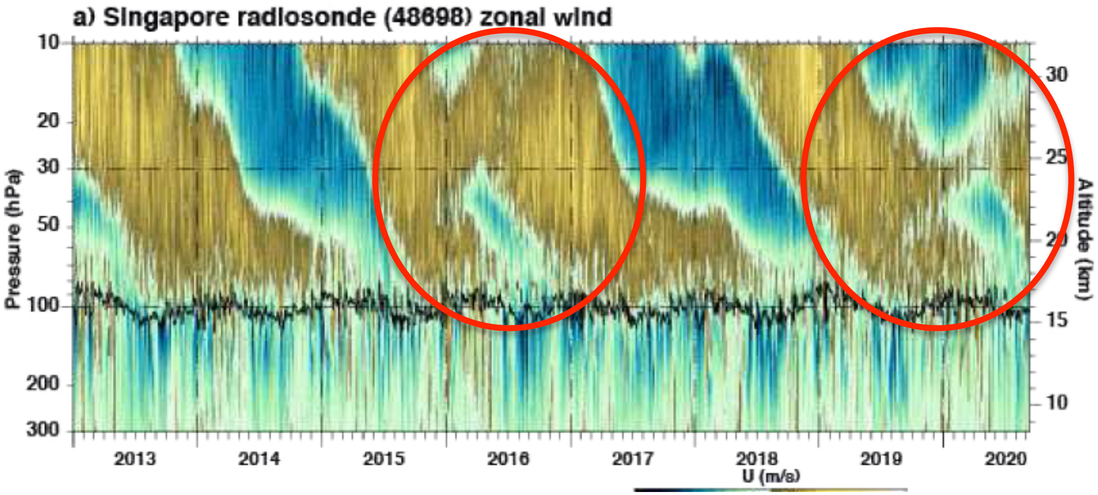


Fig. 8.12. Latitude-height sections showing the mean circulation at the time of the west wind maximum in the Plumb and Bell model of the QBO. (a) Zonal wind in m s^{-1}. (b) Potential temperature deviation in kelvins. (c) Mean meridional mass stream function in m^2 s^{-1}. Compare with the schematic in Fig. 8.5. [From Plumb and Bell (1982), with permission.]

Increasing disruptions in the QBO

- So far, only took into account vertical momentum flux from planetary EWs ,
- $\delta/\delta z(\rho_0\overline{v'w'})$



- To understand the 'disruptions' we need to
- Include, horizontal flux fluxes,
- $\delta/\delta y(\rho_0\overline{v'u'})$
- Gravity wave activity as well

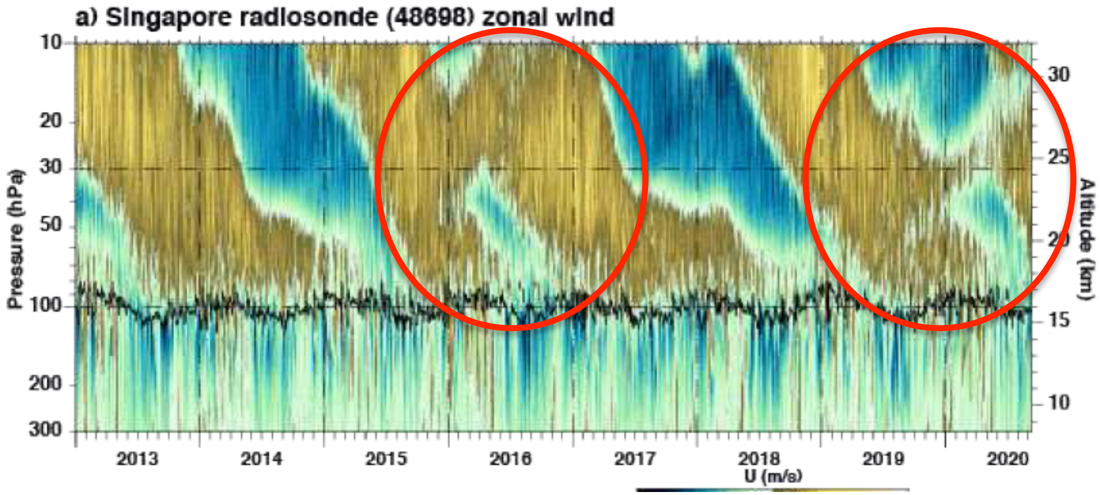
Studies show,

- during 2016 the EP fluxes in NH was very active in lower stratosphere
- While during 2020 SH fluxes were very active

Disruptions in the QBO is an active area of research currently

➔The disruptions of the QBO indicates that if they continue, the average period of the QBO is likely to shorten in future!

➔Highly predictable QBO ➔unpredictable



1. Match A., and S. Fueglistaler, 2021: J. Atmos. Sci., 78, 373-383
2. Anstey J. et al., 2021: Geophys. Res. Letts. https://doi.org/10.1029/2021GL093058
3. S. M. Osprey *et al.*, *Science* 10.1126/science.aah4156 (2016).
4.Newman, P. A., L. Coy, S. Pawson, andL. R. Lait (2016), The anomalous change in the QBO in 2015–2016,Geophys. Res.Lett.,43, 8791–8797, doi: 10.1002/2016GL070373.

Changes in QBO a Warming World

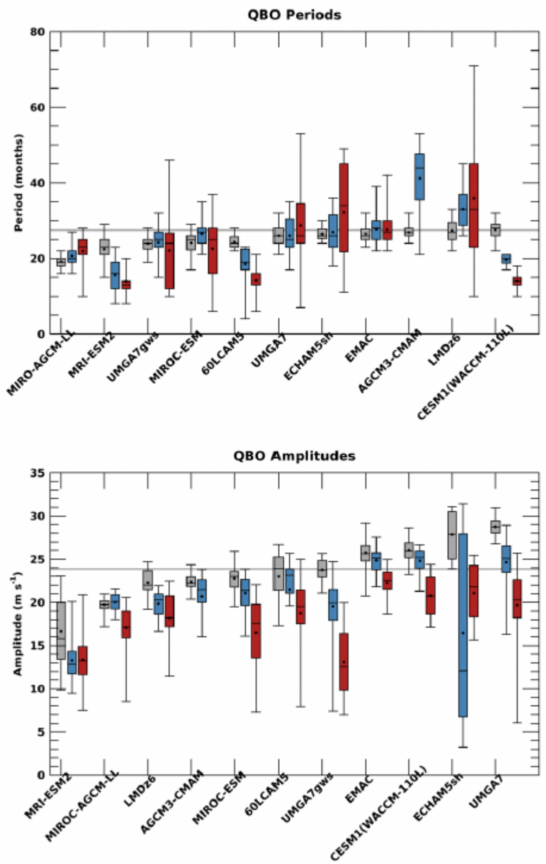


FIGURE 7 Distribution of QBO periods (top) and amplitudes (bottom) in Exp 2 (grey), Exp 3 (blue), and Exp 4 (red) derived using the TT method at 10 hPa. The distribution median is depicted by horizontal line in each box, box edges mark the lower quartile and upper quartiles, box whiskers mark the minimum and maximum values. Black dots represent mean values. Models are ordered according to Exp 2 mean period (top panel) amplitude (bottom panel). Horizontal grey lines indicate present day ERAI reanalysis values.

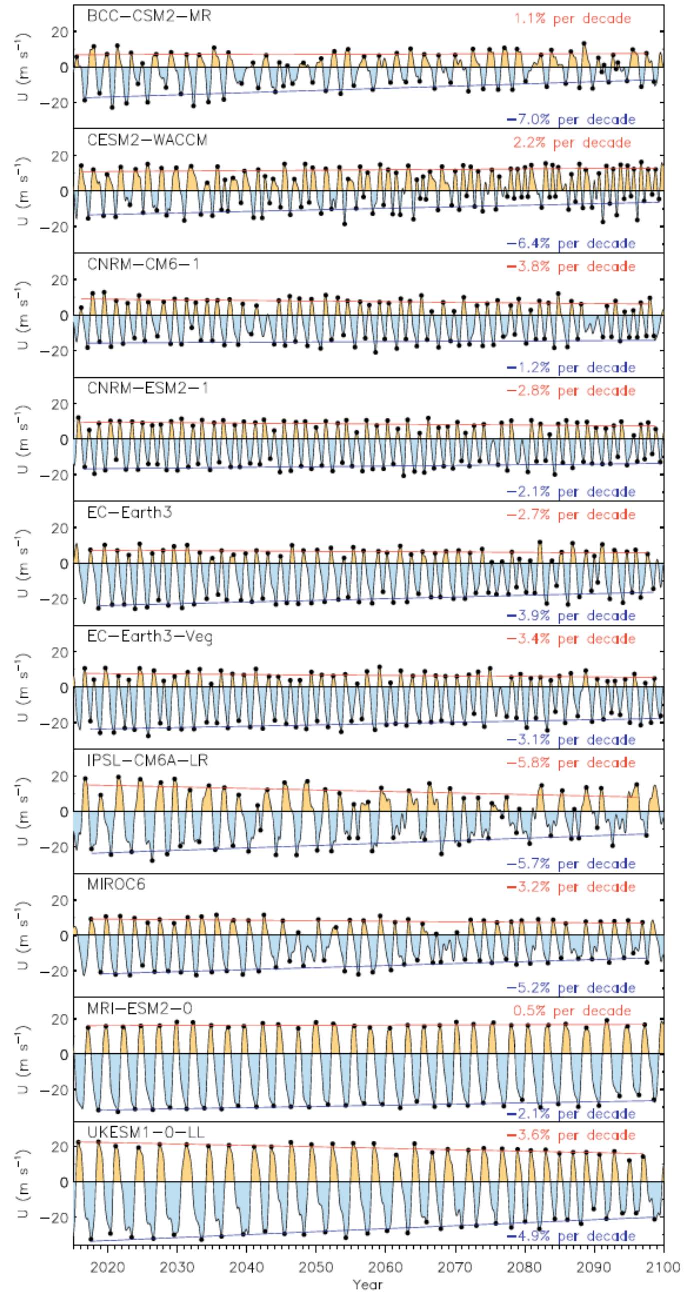
- Increased convective activity in tropics $2xCO_2$ and $4xCO_2$ experiments ➔ increase small scale GW activity ➔ influence QBO period and amplitude
- Period decreases by 8 months to 11 months
- Amplitude decreases by 36% to 51% at 60 hPa
- Model response is sensitive to GW drag parameterizations

1. Ritcher et al., 2020: QJRMS, https://doi.org/10.1002/qj.3749
2. Anstey, J. A., et al. (2021).. Geophysical Research Letters, 48, e2021GL093058. https://doi.org/10.1029/2021GL093058

QBO Changes in CMIP6 Climate Projections

- Only CMIP6 models have started simulating QBO reasonably
- 10 CMIP6 models are used
- Weakening @ 5.8 +- 0.5% to 4.3 +- 0.5% to 2.0 +- 0.5% per decade at 50 hPa for SSP585, SSP370, and historical simulations, respectively
- Period decreases in 7 out of 10 models

Butchart, N., Anstey, J. A., et al (2020). QBO changes in CMIP6 climate projections. GR, 47, e2019GL086903. https://doi.org/10.1029/2019GL086903



In Conclusion:

- QBO is a fascinating example of how equatorial waves and mean flow interaction can produce a near periodic oscillation of mean flow in lower stratosphere.

- Simplest theory can explain the 27 odd uninterrupted QBO cycles until it was disrupted in 2016 and then again in 2020.

- Global warming seems to be increasing the upward GW flux in tropics and increasing variability of equator ward flux of planetary waves from NH and SH.

- More disruptions of QBO may be expected in coming years!

Thank You