

The 1978 shift in the NCEP reanalysis stratospheric quasi-biennial oscillation

Amihan S. Huesmann and Matthew H. Hitchman

Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, Wisconsin, USA

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[1] The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP) reanalysis exhibits interdecadal changes in the structure of the quasi-biennial oscillation (QBO) and annual mean fields in the tropical stratosphere during 1958–2001. A sudden temperature increase occurred around 1978, with equatorial maxima of ~ 3 K at 10 hPa and near the tropopause. When this 1978 jump is removed, a moderate cooling trend is found throughout the tropical lower stratosphere, with an equatorial maximum cooling of 3 K over 40 years near 30 hPa. While the QBO in zonal wind is similar in both the 1958–1978 and 1979–2001 periods, the QBO in temperature is significantly reduced in amplitude and latitudinally contracted after 1978, and the QBO meridional circulation is stronger. Vertical temperature variations in the annual mean and QBO have been underestimated since the introduction of nadir-sounding satellites. A mechanism is suggested for how this may affect meridional circulations in data assimilation models. **INDEX TERMS:** 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 1620 Global Change: Climate dynamics (3309). **Citation:** Huesmann, A. S., and M. H. Hitchman, The 1978 shift in the NCEP reanalysis stratospheric quasi-biennial oscillation, *Geophys. Res. Lett.*, 30(2), 1048, doi:10.1029/2002GL016323, 2003.

1. Introduction

[2] The NCEP reanalysis provides the opportunity to investigate interannual climatological variations from 1948 to the present [Kalnay *et al.*, 1996; Kistler *et al.*, 2001]. Recently, several authors have described a shift in the annual cycle and the nature of the stratospheric quasi-biennial oscillation (QBO) in this data set [Pawson and Fiorino, 1999; Randel *et al.*, 2000; Huesmann and Hitchman, 2001]. Spatial and temporal coverage improved dramatically around 1978 with the introduction of satellite data, particularly in the polar and oceanic regions. However, the vertical resolution of satellites is substantially lower than that of radiosondes in the stratosphere.

[3] The dominant mode of variability in the tropical stratosphere is the QBO, which is approximately zonally symmetric. Figure 1 shows the equatorial zonal mean zonal wind (\bar{u}_{eq}) at 30 hPa. These and all other data used in this study are monthly and zonal averages of the NCEP reanalysis daily data. During the first decade, observations were insufficient to adequately capture the QBO, but by 1958 the

QBO in \bar{u}_{eq} was fairly uniform. However, the QBO variability in temperature and meridional circulation differ notably between 1958–1978 (record 1, hereinafter “R1”) and 1979–2001 (record 2, hereinafter “R2”). Since the QBO cycle in \bar{u}_{eq} is fairly stable, we will use the QBO indices of Huesmann and Hitchman [2001] (10–20, 20–30, 30–50, and 50–70 hPa differences of \bar{u}'_{eq} , where the prime indicates that the annual cycle has been removed) to relate the QBO in zonal wind to these other fields.

2. Time Mean Fields

[4] Figure 2 illustrates some of the changes that took place around 1978 and statistical quantities used in this study. Figure 2a shows the departure of NCEP reanalysis equatorial tropopause temperature from the annual climatology ($\bar{T}'_{\text{eq,tp}}$) versus 50–70 hPa \bar{u}'_{eq} difference. The QBO interannual variability in $\bar{T}'_{\text{eq,tp}}$ is smaller after 1978 (the slope of the R2 fit line is smaller than that of the R1 fit line) and the non-QBO interannual variability is significantly larger (rms_2 is larger than rms_1). The fraction of the overall variability that is QBO-related is the square of the correlation coefficient, which is smaller after 1978. Figure 2b shows the time series of $\bar{T}'_{\text{eq,tp}}$. Although there is a cooling trend in both records, a significant change occurred near 1978. The existence of a cooling trend motivates our definition of the “jump” as the difference in the two least-squares fit lines at December 1978, which is 3.5 K at the tropopause.

[5] Figure 3 shows the 1958–2001 time mean and R2–R1 time mean difference for \bar{T} , \bar{u} , and meridional wind (\bar{v}). At the sharp tropical tropopause (Figure 3a), the R2–R1 time mean difference is ~ 2.5 K, which compares favorably with results from Pawson and Fiorino [1999] and Randel *et al.* [2000]. Near 10 hPa in the tropics NCEP temperatures are also ~ 2.5 K warmer after 1978, while temperatures are slightly cooler near 30–50 hPa. Time mean differences are somewhat smaller than the jump as defined above.

[6] Figure 3b shows the westerly jets and tropical stratospheric easterlies which emerge in the time mean. Expansion of the westerly jet near 30°N (Figure 3e) after 1978 is related to the enhanced poleward temperature decrease (Figure 3d).

[7] The time mean structure of \bar{v} (Figure 3c) shows a predominant Hadley flow from the northern to the southern hemisphere. This structure is markedly changed after 1978 (Figure 3f), with a northward increase near the equator. Assuming partial conservation of angular momentum, this is compatible with the westerly increase in Figure 3e. Pawson and Fiorino [1999] concluded that this structure in \bar{v} is related to spuriously weak southward flow in the Indonesian sector during boreal summer after 1978.

[8] Figure 4 shows the time-weighted mean trend (m) and the jump for \bar{T} . Figure 4a suggests that the tropical strato-

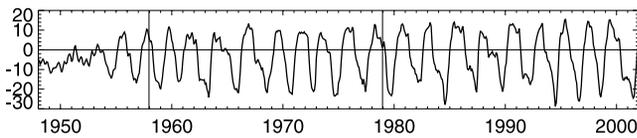


Figure 1. Zonal average equatorial zonal wind in (\bar{u}_{eq}) m/s at 30 hPa during 1948–2001. Tick marks indicate the January of that year. Vertical lines delineate record 1 (1958–1978, hereinafter “R1”) and record 2 (1979–2001, hereinafter “R2”).

sphere has cooled by up to 3 K in 40 years, in agreement with other studies [e.g., Pawson *et al.*, 1998]. However, a systematic warm jump appears in the data (Figure 4b) that is largest and most significant at the tropopause and near 10 hPa. In both these regions, the temperature lapse rate exhibits sharp upward increases which are blunted in satellite data. The warm jump is larger than the cooling trend near the tropopause and 10 hPa, while the cooling trend dominates near 30–50 hPa (Figures 4a, 4b). The result is apparently warmer time mean temperatures at the tropopause and at 10 hPa and cooler time mean temperatures near 30–50 hPa (Figure 3d). These results highlight the inability of a time mean difference to distinguish between a trend and a temporal discontinuity.

3. QBO Signal

[9] Figure 5 shows the peak-to-peak range in the QBO for 1958–2001 and the R2–R1 range difference for \bar{T} , \bar{u} , and \bar{v} . The range at each point is calculated as in Figure 4 of

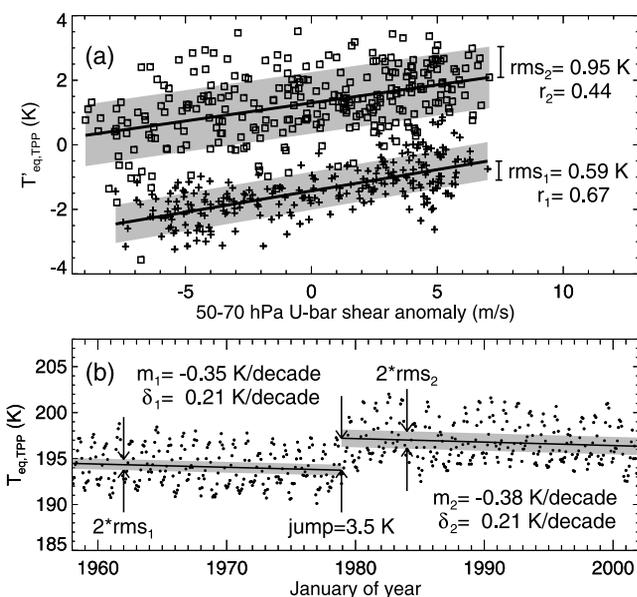


Figure 2. (a) Scatterplot of zonal average equatorial tropopause temperature anomaly ($\bar{T}'_{\text{eq,TPP}}$) versus 50–70 hPa \bar{u}'_{eq} difference. The least-squares fit lines for R1 and R2 are plotted. Root mean square deviations from each fit line (rms) are shaded. (b) $\bar{T}'_{\text{eq,TPP}}$ during 1958–2001. The least-squares fit lines for R1 and R2 (of slope m and uncertainty δ) are plotted and the $\pm rms$ values are shaded. The jump is indicated. Subscripts “1” and “2” on m , δ , rms , and r indicate a quantity calculated for R1 or R2.

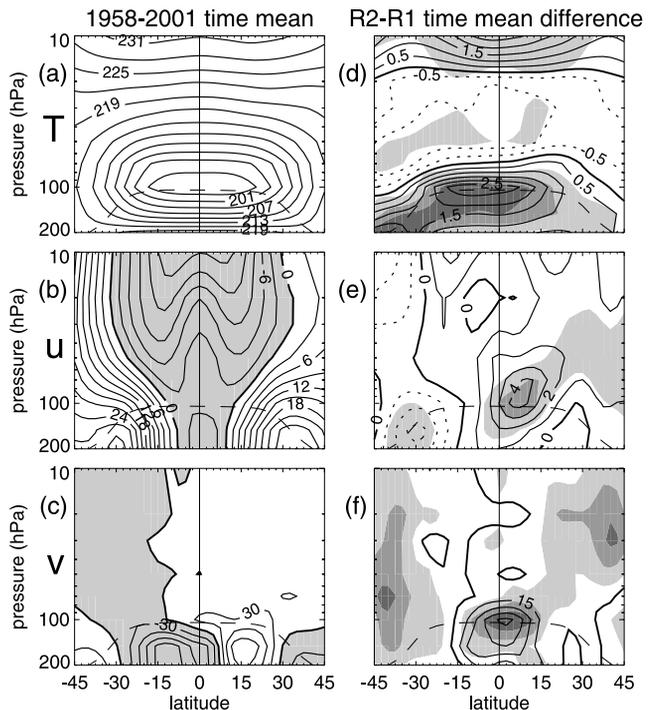


Figure 3. (a)–(c) 1958–2001 time mean \bar{T} , \bar{u} , and \bar{v} as functions of latitude and pressure. Contour intervals are (a) 3 K, (b) 3 m/s, and (c) 30 cm/s. The dashed line is at the climatological tropopause. (d)–(f) Time mean R2–R1 difference in \bar{T} , \bar{u} , and \bar{v} . Contour intervals are (d) 0.5 K, (e) 1 m/s, and (f) 15 cm/s. Progressively darker shading indicates differences exceeding 1σ , 2σ , and 3σ . Here, σ is the geometric mean of the interannual standard deviations for R1 and R2 [Bevington and Robinson, 1992].

Huesmann and Hitchman [2001]. The QBO ranges in \bar{u} during R1 and R2 have very similar patterns, as evidenced by the small values in Figure 5e.

[10] In contrast, the QBO ranges in \bar{T} and \bar{v} change markedly. Figure 6 compares the R1 and R2 QBO ranges for \bar{T} (Figures 6a, 6b), the R1 and R2 QBO ranges for \bar{T} and \bar{u} at the equator (Figure 6c), and the meridional structure of the QBO signal in \bar{T}' and $\frac{\partial \bar{T}'}{\partial z}$ (Figure 6d). The \bar{T} range decreases by $\sim 1/3$ in the tropics, but the reductions are as much as 80% of the R1 range near $\pm 10^\circ$ at 70 hPa, where the range is small and the range difference is large. The result is an overall reduction in QBO range (Figure 5d) as well as a

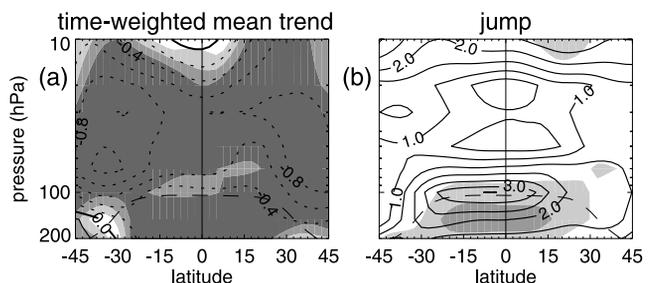


Figure 4. (a) The time-weighted mean trend, m , in \bar{T} , contour interval is 0.2 K. (b) The jump in \bar{T} , contour interval is 0.5 K. Shading is as in Figure 3. Here, σ is (a) the geometric mean of time-weighted δ_1 and δ_2 and (b) the geometric mean of rms_1 and rms_2 .

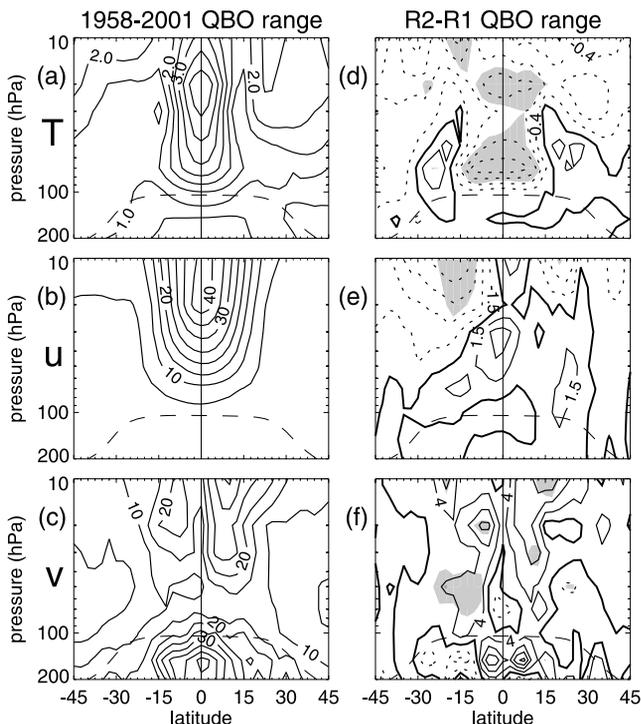


Figure 5. (a)–(c) 1958–2001 peak-to-peak QBO range in \bar{T} , \bar{u} , and \bar{v} . Contour intervals are (a) 0.5 K, (b) 5 m/s, and (c) 10 cm/s. (d)–(f) R2–R1 difference in QBO range. Contour intervals are (d) 0.4 K, (e) 1.5 m/s, and (f) 4 cm/s. Shading is as in Figure 3. Here, σ is the geometric mean of sd_1 and sd_2 , where sd is the standard deviation of the individual cycle ranges.

meridional contraction of the signal (Figure 6d). The QBO range in \bar{v} increases by $\sim 50\%$ (Figures 5c, 5f), but the patterns for R1 and R2 are similar (not shown).

[11] The large QBO range in upper tropospheric \bar{v} (Figure 5c) appears in both records. This signal may reflect separate quasi-biennial variability indigenous to the troposphere or it may simply be the residual of large natural variability. Compare the peak-to-peak QBO range of ~ 45 cm/s in Figure 5c with twice the rms in the same region, ~ 360 cm/s, (where rms is calculated as for Figure 2a).

[12] To explore the temporal dependence of the relationship among QBO variables, running correlation coefficients were calculated between the anomalies of several variables and QBO wind shear indices (Figure 7). For month N the correlation coefficients were calculated using the 45 months from $N-22$ through $N+22$. The QBO indices and lags were selected which gave the highest overall correlations for the smallest lag. The $\bar{u}'_{eq,20hPa}$ correlation is nearly 1.0 and constant in time. The $\bar{T}'_{eq,20hPa}$ correlation exceeds 0.8 during R1 but exhibits a more variable and reduced correlation during R2, consistent with a smaller QBO range in Figure 5d. There is a drastic reduction in the $\bar{T}'_{eq,tpp}$ correlation after 1978; at times it is essentially zero.

4. Discussion

[13] In the NCEP record, vertical temperature variations in the tropics are reduced after 1978. In October 1978 the TIROS-N satellite was launched, which included the High

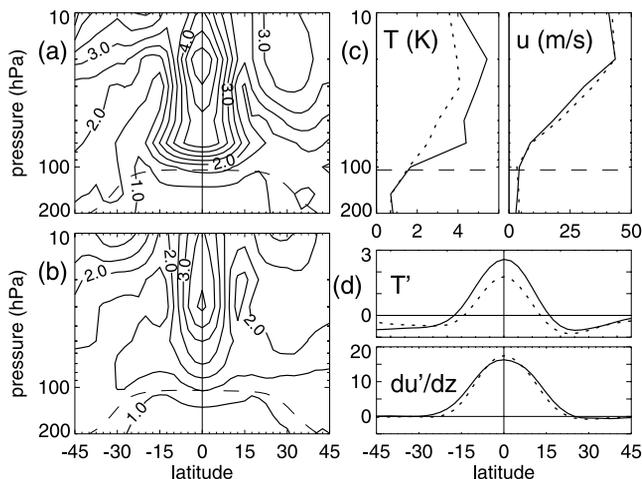


Figure 6. (a) The QBO range in \bar{T} for (a) R1 and (b) R2, contour interval is 0.5 K. (c) Vertical profiles of R1 and R2 QBO ranges (solid and dotted lines, respectively) for \bar{T} (left) and \bar{u} (right). (d) Westerly minus easterly \bar{T}' (top, K) and du'/dz (bottom, m/s per 20 hPa) in the 30–50 hPa layer as functions of latitude. R1 (R2) data are in solid (dotted) lines. Note that these are differences of composite means rather than peak-to-peak ranges.

Resolution Infrared Sounder (HIRS) [Smith *et al.*, 1979]. November 1978 is the month when these data began to strongly affect the NCEP reanalysis (cf. Figure 1 of Kistler *et al.* [2001]). Other nadir-sounding devices were launched on the NOAA-6 satellite in June 1979. HIRS channels peak near 100, 60, 30, and 5 hPa, giving an effective vertical resolution of about one density scale height. This is larger than the vertical scale of variation of the tropopause and comparable to that of a QBO anomaly.

[14] A typical HIRS vertical weighting function centered at 100 hPa has half-power levels near 250 and 30 hPa. Due to the few stratospheric channels and their broad half-widths, one would expect the time mean tropopause and QBO in temperature to be vertically smoothed in satellite data. Figure 6c suggests that the temperature QBO is reduced by $\sim 1/3$.

[15] How can the QBO in \bar{u} remain fairly constant while the QBO in \bar{T} is reduced in amplitude after 1978? The relative uniformity of the \bar{u} QBO may be due to the continued primacy of balloon winds in the reanalysis. Thermal wind balance, $|\frac{\partial \bar{u}}{\partial z}| \propto |\frac{\partial \bar{T}}{\partial y}|$, can be maintained for

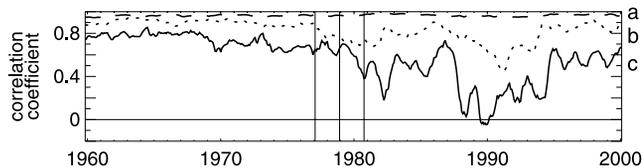


Figure 7. Running correlation coefficient between several zonal average anomalies and a QBO index. The vertical lines near the center indicate December 1978 and 22 months before and after. The indices are chosen to maximize the correlation for the smallest lag. The variables are (a) $\bar{u}'_{eq,20hPa}$ (30–50 hPa index, lag = 0), (b) $\bar{T}'_{eq,20hPa}$ (20–30 hPa index, lag = -1), (c) $\bar{T}'_{eq,tpp}$ (50–70 hPa index, lag = 0).

a smaller \bar{T} QBO if the meridional scale is also smaller. This is consistent with Figure 6d.

[16] One may consider the idealized zonal mean potential temperature equation over the equator to assess the effects of underestimated QBO temperature anomalies on the QBO mean meridional circulation:

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{w} \frac{\partial \bar{\theta}}{\partial z} = \bar{Q}_{rad} + \bar{Q}_{sat}, \quad (1)$$

where \bar{Q}_{rad} represents net radiative heating and \bar{Q}_{sat} the effects of introducing satellite temperatures.

[17] The QBO is wave driven, with a westerly body force leading to meridional convergence and subsidence over the equator ($\bar{w} < 0$). The resulting warm anomaly will lead to enhanced infrared cooling to space ($\bar{Q}_{rad} < 0$). If this warm anomaly ($\bar{\theta}_{actual}$) is underestimated by satellite measurements ($\bar{\theta}_{sat}$), this introduces a spuriously cool temperature forcing: $\bar{Q}_{sat} \propto \bar{\theta}_{sat} - \bar{\theta}_{actual} < 0$. To balance this requires a larger rate of descent. Similarly, spuriously warm temperatures in QBO easterly shear zones can be balanced by spuriously rapid ascent. Underestimation of actual temperature anomalies by satellites can lead to exaggerated meridional circulations for dynamically-driven phenomena such as the QBO. For radiatively-driven meridional circulations, the sign of \bar{w} and \bar{Q}_{rad} are again the same, but rising occurs in a warm anomaly. In this case underestimation of the warm anomaly would lead to a reduced meridional circulation.

[18] We hypothesize that the QBO meridional circulation is spuriously enhanced in a data assimilation system when QBO temperature anomalies are underestimated by satellite data. One may also anticipate that the upward motion in the

tropical stratosphere may be spuriously large and result in larger poleward mixing in a general circulation model coupled with a data assimilation system.

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A. S. Huesmann, Department of Atmospheric and Oceanic Sciences, 1225 West Dayton Street, Madison, WI 53706, USA. (amihan@xena.aos.wisc.edu)

M. H. Hitchman, Department of Atmospheric and Oceanic Sciences, 1225 West Dayton Street, Madison, WI 53706, USA. (matt@aos.wisc.edu)