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# MODES OF INTERANNUAL VARIABILITY IN THE STRATOSPHERE

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*Abstract.* During 1964-91, stratospheric temperature and circulation in northern hemisphere winter varied interannually on time scales from 2 to ~12 years. A substantial percentage of December-February (DJF) interannual variance was correlated with the quasi-biennial oscillation (QBO). Additional monthly variance could be accounted for by quasi-decadal oscillation and QBO/low-frequency modulation. The QBO was the largest and most consistent of these signals, and its decadal modulation explains an apparent correlation with the solar cycle depending on the sign of the QBO – an interpretation supported by principal component analysis.

## Introduction

The record of temperature and circulation in the northern stratosphere is now becoming long enough to reveal dominant modes of interannual variability. Three possible signals have been identified. (i) In 1964-91 the tropical quasi-biennial oscillation (QBO) was significantly correlated with extratropical flow (Holton and Tan, 1980; Dunkerton and Baldwin, 1991). (ii) Low-frequency 'quasi-decadal' variation (QDV) correlated with the solar cycle was discovered by Kodera and Yamazaki (1990) and Kodera *et al* (1990) in the midlatitude upper stratosphere, 1975-87. (iii) According to Kodera *et al* (1991) the QDV extended to the polar lower stratosphere and modulated the QBO's influence there, or was modulated by the QBO (Labitzke and van Loon, 1988).

The question may be asked about the relative importance of these interannual 'modes', how their influence evolved during the winter season, and whether they are in fact genuine and describe interannual variability in the most efficient way. Two approaches may be taken. One is to search for a physical mechanism (e.g., QBO) significantly correlated with extratropical data. This has already been done for modes individually, but not collectively as a multivariate correlation. The other is to perform principal component analysis and identify statistical modes of variability (Nigam, 1990).

## Simple Model

A 'model' of interannual variability could be constructed from possible signals identified in the data:

$$\bar{T}(y,z,t) = a(t)f(y,z) + b(t)g(y,z) + \operatorname{sgn}[a(t)] \cdot b(t)h(y,z) + \cdots \qquad (1)$$

where $a(t)$ and $b(t)$ represent quasi-biennial and quasi-decadal oscillations (QBO and QDV); the third term is a modulation of QDV by the QBO ('LvL'). The spatial pattern of variability is contained in $f$, $g$, and $h$. We defined $a(t)$ as the tropical QBO (40 mb Singapore wind) and used 10.7 cm solar flux for QDV term $b(t)$. $\bar{T}(y,z,t)$ is seasonally-averaged (DJF) zonal mean temperature. In what follows, reference signals had the long-term mean removed and were normalized by their standard deviation. It should be understood that we are not ready to endorse (1) as a explanation of variability but will instead use it to illustrate a basic point.

An example of $\bar{T}$ at 82°N, 30 mb is shown in Figure 1a. It reveals the Holton-Tan oscillation (HTO; cold winters in QBO west phase, and vice versa) and – much less obvious – the Labitzke-van Loon modulation (LvL). (Hint: Connect triangles and circles separately.) The LvL term in (1) was written as a product to describe the nonlinear modulation: temperatures were warm in QBO

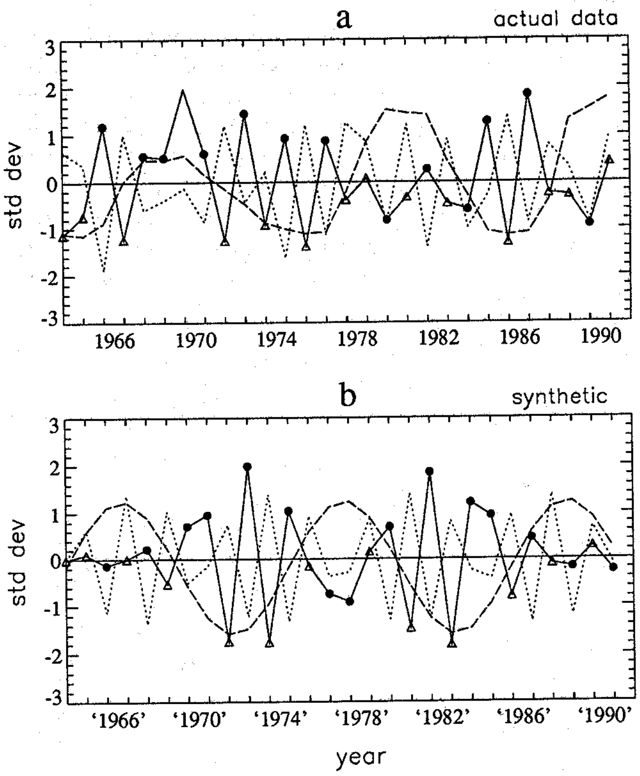

Fig. 1: (a) Time series of DJF zonal mean temperature at 82°N, 30 mb (solid line), solar flux (dashed line), and tropical QBO (dotted line). Symbols denote 40 mb QBO west phase (triangles) and east phase (circles). (1970 was in west phase at 50 mb.) (b) As in (a), but for synthetic time series.

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west phase near solar maximum, cold in west phase near solar minimum, and so on. By definition, LvL interfered destructively with HTO near solar maximum, and constructively near solar minimum. At this grid point, the linear term $b(t)g(y,z)$ was small in DJF.

To visualize the interference effect a little more clearly, we obtained time series from an idealized model where $a(t)$ and $b(t)$ were sine waves of quasi-biennial (28-month) and quasi-decadal (11-yr) period, respectively, having equal amplitude ($-f = h = 1$). This is shown in Figure 1b, with linear QDV term excluded ($g = 0$). The combined series is basically an HTO modulated on the 11-yr time scale. At 'solar minimum' there is large HTO; at 'maximum', the oscillation is absent or slightly reversed (e.g., at year '1977').

The degree of interference depends on the relative magnitude of $f$ and $h$. Small $h$ implies little modulation of HTO and vice versa. In the data, interference due to LvL helps explain the imperfect HTO correlation with tropical QBO. By eliminating high solar flux years in Figure 1a the correlation is improved substantially. Succinctly put, interference implies modulation. However, a basic point should be noted from what follows: LvL did not exceed HTO (with the possible exception of February data, near 100 mb north pole). Therefore a simpler interpretation is suggested, in which HTO and LvL terms are combined into a single HTO with decadal modulation.

The spatial patterns $f$, $g$, and $h$ and their net contribution to $\bar{T}$ variance were calculated by multivariate regression. As it turned out, the total percent variance could be well approximated by adding squares of individual correlations, since input signals (QBO, solar cycle, and their product) were nearly orthogonal. (Cross-correlations were below .04 in magnitude). Figure 2 shows the total percent variance explained by the three components, for DJF season, derived from 28 years of National Meteorological Center (NMC) data. In the polar stratosphere, and at midlatitudes near 10 mb, the total exceeded 40%.

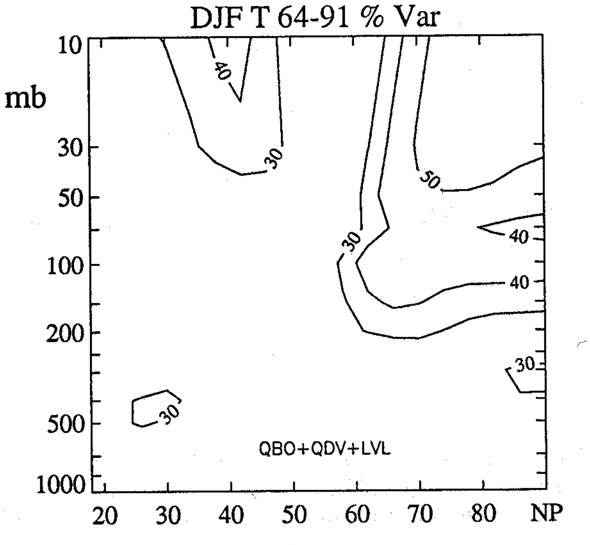

Fig. 2: Total percent variance of DJF temperature explained by three-component model (QBO, QDV, and interaction term).

The dipole pattern in middle stratosphere resembled that of the QBO component alone, but was slightly larger in magnitude. The QBO was a dominant component of variance in DJF, explaining up to ~40% in both halves of the dipole (not shown). The QDV contribution was insignificant and confined primarily near 20-30°N, 10 mb and 40-70°N, 700 mb. LvL added ~10-20% to total DJF variance in the polar lower stratosphere.

### Seasonal Progression

Figure 3 shows the correlation with NMC temperature for QBO, QDV, and LvL terms in individual months (D,J,F). The QBO was largest in December and January; LvL was prominent in February only. The QBO temperature dipole straddled the latitude band 50-60°N – the location of maximum HTO zonal wind anomaly (with stronger westerlies in 40 mb QBO west phase and vice versa). The subtropical half of HTO wind dipole lay to the south of the midlatitude HTO temperature anomaly. The entire pattern shifted northward in January (Dunkerton and Baldwin, 1991) before descending and weakening in February.

The QDV correlation in December was also a dipole, most prominent in this month, near 10 mb. The corresponding wind anomaly at ~40°N was positively correlated with solar cycle (although we found it to be weaker in 1964-91 than in Kodera and Yamazaki's 1975-87 data). This correlation seems plausible because solar heating is partly responsible for the middle atmosphere Hadley circulation. In fact, large variations of solar heating are required to achieve the observed variation (Kodera *et al*, 1990).

One can imagine four possible causes of decadal variability in the middle atmosphere: (1) external forcing from above, e.g., solar cycle; (2) internal forcing from below, associated with decadal variations of the earth-atmosphere system; (3) interference effects, e.g., between QBO and annual or biennial cycles; (4) random variations of the Holton-Tan oscillation. Of these only (2) requires any 'memory' of the earth-atmosphere system on decadal time scales.

### Principal Components

The simple model worked well because input signals were known *a priori* to be correlated with NH temperature, and were nearly orthogonal. However, there are many orthogonal bases, and it is not obvious which one is best. The problem could be illustrated by van Loon and Labitzke's (1987) discussion of ENSO correlations.

Orthogonal series can be obtained from the data via principal component analysis in the time domain (Fraedrich, 1986). Prior to doing this it is useful to extract the principal components of spatial variability by conventional EOF analysis (Nigam, 1990) and then apply a similar technique in the time domain. The combined procedure was illustrated by Ghil and Mo (1991).

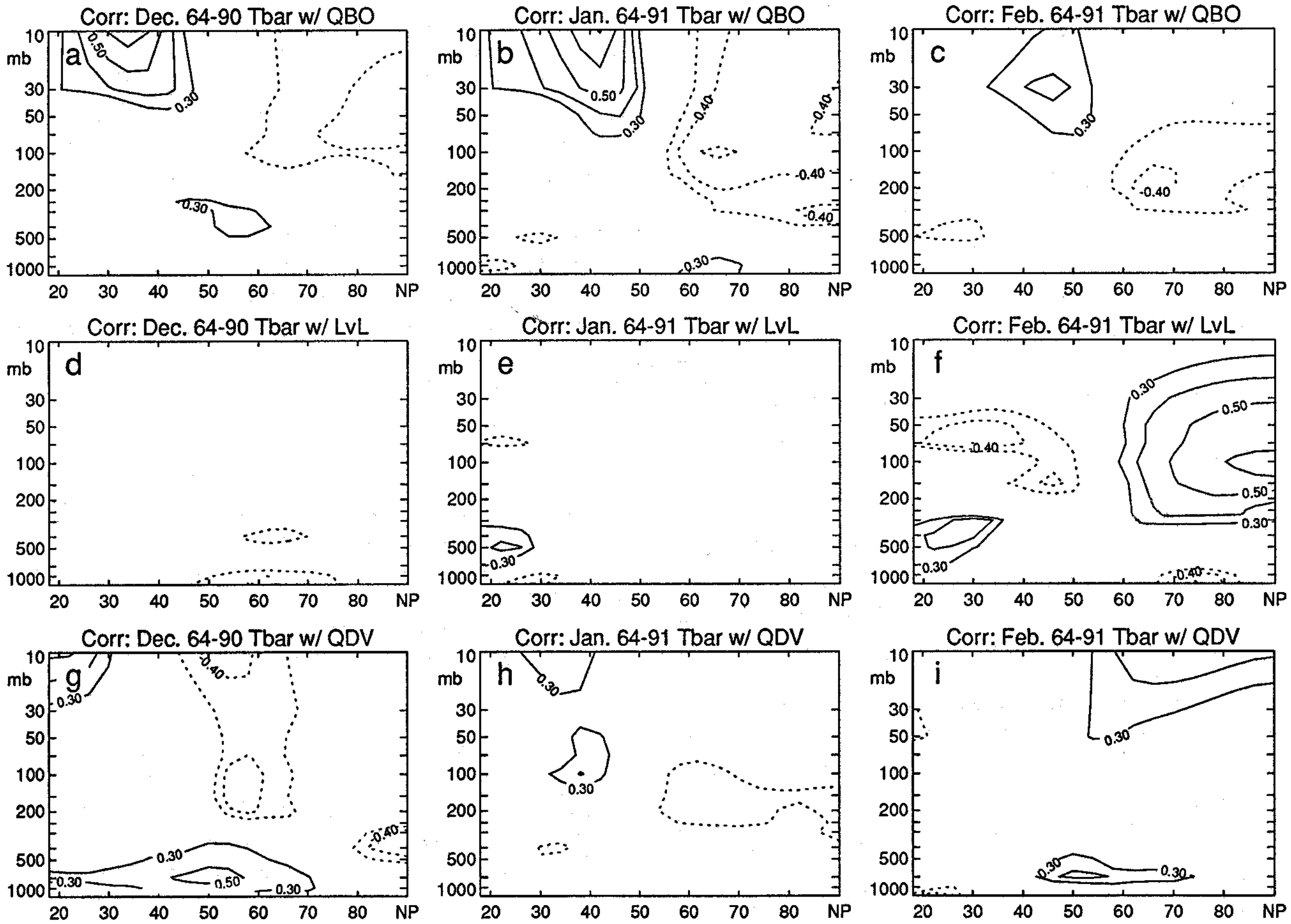

Fig. 3: Correlation between monthly mean temperature and reference signals QBO (top), LvL (middle), and QDV (bottom) for December (left), January (middle), and February (right).

Spatial empirical orthogonal functions (S-EOFs) are particularly useful in NH stratosphere because the lowest mode, shown in Figure 4, explained 60.7% of the spatial variance of $\bar{T}$. (This is larger than Nigam's since we did not normalize data by the standard deviation.) The dominant S-EOF was a dipole centered near 55°N. Its time series or associated principal component (S-PC) is shown by the solid line in Figure 5. This S-PC was almost perfectly correlated with the lowest S-PC of zonal wind, which explained a similar fraction of total variance, and resembled the HTO dipole.

The second S-EOF of zonal wind (9.1%) described a latitudinal shift in polar night jet axis, while the second S-EOF of temperature (12.9%) was due mainly to a change in lower stratosphere static stability. The two appear unrelated.

The time series of temperature S-PC #1 was remarkably similar to polar 30 mb temperature (Figure 1a). This is not surprising since S-EOF #1 maximized at the pole just below 30 mb. We infer that the lowest S-EOF contained both HTO and LvL signals. This result favors the view that LvL, rather than being a separate signal, is actually a modulation of HTO on the 10-12 yr time scale. Evidently the linear QDV component in DJF was too weak to appear in the leading EOFs.

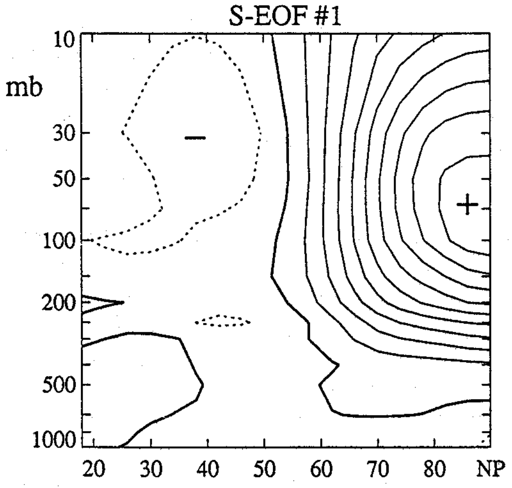

Fig. 4: Structure of lowest spatial EOF of temperature (nondimensional, contour interval $.02\times\sqrt{266}$).

When principal component analysis in the time domain was applied to the S-PC in Figure 5 we found that only 3 temporal EOFs were necessary to describe the combined HTO/LvL behavior. For this purpose the maximum lag was taken as 11 years. The sum of the

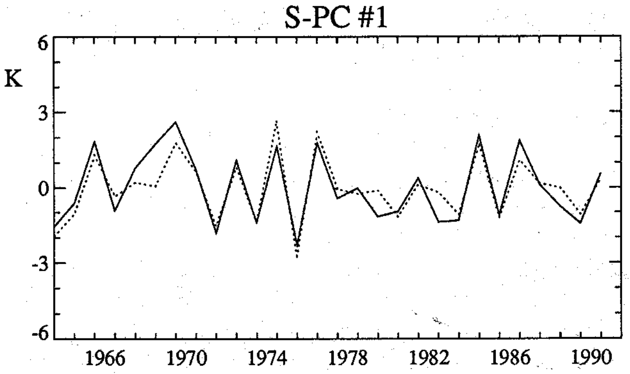

Fig. 5: Time series of principal component of lowest spatial EOF (solid) and sum of first three temporal PCs (dashed).

first 3 temporal principal components (T-PCs) is shown by the dotted line in Figure 5. Together they explained 56% of the total variance averaged over all lags (although a much larger percentage at zero lag as shown in the figure).

Further decomposition into T-PCs 1 and 2+3 revealed that the lowest component was a nearly biennial oscillation, and that mode 2+3 was quasi-biennial; in fact, 2+3 was better correlated with the lowest two T-PCs of tropical QBO (-.77) than the correlation between raw temperature and QBO series (-.57). This suggests an alternative statistical interpretation, that LvL modulation is due to the superposition of nearly biennial and quasi-biennial signals.

## Conclusion

By examining 28 years of NMC data in NH winter it was shown that a substantial percentage of DJF variance could be explained by the tropical quasi-biennial oscillation (QBO). Additional monthly variance could be accounted for by a quasi-decadal variation (QDV) apparently correlated with the solar cycle, and QBO/QDV interaction term (LvL). Unlike the QBO, these signals were inconsistent from month to month. The largest contribution in early and mid-winter was the QBO component (Holton-Tan oscillation). The interaction term was prominent only in February. There was less evidence of poleward and downward propagation of QDV in the 28-year dataset than found by Kodera *et al* (1990) in a shorter record. Nevertheless, QDV in early winter was substantial. Since it was largest in the upper stratosphere, a longer dataset will be required to establish its significance and whether solar forcing is important.

Principal component analysis supports the interpretation that the nonlinear LvL term represents a modulation of HTO on the 10-12 yr time scale. The lowest spatial EOF contained both HTO and its modulation. Decomposition into temporal EOFs did not separate the time series into the form (1) but rather a superposition of nearly biennial and quasi-biennial signals.

It is likely that the dipole pattern of HTO represents the effect of planetary wave activity (Dunkerton and Baldwin, 1991). Because of this, it is doubtful that external forcings, as reference time series $a(t)$, $b(t)$, etc., can ever provide a complete explanation of interannual variability in the stratosphere.

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