GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 13, PAGES 2445-2448, JULY 1, 1998

Sub-seasonal variations in lower stratospheric water vapor

Philip W. Mote and Timothy J. Dunkerton

Northwest Research Associates, Bellevue, Washington

Hugh C. Pumphrey

Department of Meteorology, University of Edinburgh

Abstract. Observations of water vapor with high temporal and spatial resolution and good horizontal coverage just above the tropical tropopause have been scarce, but a preliminary version of such data has been developed using radiance measurements of the Microwave Limb Sounder. These data reveal distinct variations with periods in the ranges 10–25 days and 30–70 days, consistent with (respectively) slow Kelvin waves and the tropical intraseasonal oscillation.

1. Introduction

Signatures of equatorial Kelvin waves were first found in lower stratospheric temperature [*Wallace and Kousky,* 1968] and have also been found in trace constituents using satellite data [*Canziani et al.* 1994; *Ziemke and Stanford* 1994]. By studying ozone and water vapor profiles from the Limb Infrared Monitor of the Stratosphere (LIMS), *Kawamoto et al.* [1997] identified Kelvin-wave signatures in the lower stratosphere, though for water vapor the results were compromised by poor-quality data in the lower stratosphere.

In addition to possible Kelvin-wave signatures in lower stratospheric water vapor, we also wish to investigate in this paper the possibility of a stratospheric signature of the tropical intraseasonal oscillation (TIO). For both kinds of sub-seasonal variations we turn to a relatively new water vapor data set from the Microwave Limb Sounder (MLS) instrument aboard the Upper Atmosphere Research Satellite (UARS). While MLS stratospheric water vapor data have previously been used in a number of studies, the data set used here is based on a new retrieval that extends the data down to 100 hPa, as explained in section 2. We analyze the spectral characteristics of sub-seasonal anomalies in MLS water vapor at the 100 and 68 hPa UARS levels.

2. Data

MLS measures water vapor in two spectral bands, 183 GHz and 205 GHz, with best sensitivity in the stratosphere and upper troposphere respectively. With the standard retrieval, the 183 GHz radiometer yields data at and above 46 hPa with a resolution of about 5 km. A nonlinear retrieval has been developed that extends the sensitivity to 100 hPa and doubles the vertical resolution; results from an earlier version of the nonlinear retrieval were presented and discussed by *Mote et al.* [1996]. The retrieval has been improved, primarily by eliminating systematic errors and by speeding up the code to allow all available days to be processed. The range of available days lies between late September 1991, the launch of UARS, and late April 1993, when the 183 GHz radiometer failed. There are several one-day gaps, a four-day gap, and a long gap in June–July 1992 when only a few days of data were taken. We bridge the shorter gaps by linear interpolation, and the long gap forces us to divide the record into two segments for most analyses.

In contrast to solar occultation instruments, MLS, because it measures emissions at the limb, can gather over 1300 profiles per day. We have formed a zonal, equatorial cross-section of water vapor data in time and longitude by binning profiles within 2.5° of the equator in 24° longitude bins for each day, after quality control. All equatorial data values at 100 hPa are flagged by the retrieval as suspicious (meaning that the error of the retrieved product is greater than one half of the error of the a-priori data) but are nonetheless reasonable in some respects: the seasonal variations agree with 100 hPa temperatures and with HALOE water vapor [*Mote et al.,* 1996]. The higher-frequency, zonally-varying fluctuations of MLS water vapor at 100 hPa also seem reasonable, and do not arise from the (zonal mean) a-priori data, but may be affected by the values at 68 hPa, the next UARS level above 100 hPa. To be on the safe side, we concentrate here on the data at 68 hPa.

3. Results

As shown by *Mote et al.* [1996], water vapor has a large annual cycle at the tropical tropopause. In fact, low-frequency variability accounts for more than 90% of the variance. In order to reveal the subtler signature of higher-frequency variations, we high-pass filter the data removing periods longer than about 90 days. We then remove variations in the zonal-mean component and consider two 256-day intervals, one on each side of the data gap in June–July 1992.

For the 68 hPa level (Figure 1a), a clear signature of mostly eastward-traveling disturbances emerges. Unlike the slower disturbances at 215 hPa reported by *Clark et al.* [1998], which usually vanished above the eastern Pacific, these disturbances occur at all longitudes, and sometimes circle the globe. For example, the positive anomaly (light shading) apparent near 0° at the end of September 1991 can be traced more than once around the globe, returning to 0° in mid-October and possibly again in early November.

In order to elucidate the characteristics of these oscilla-

Paper number 98GL51847.
0094-8534/98/98GL-51847$05.00

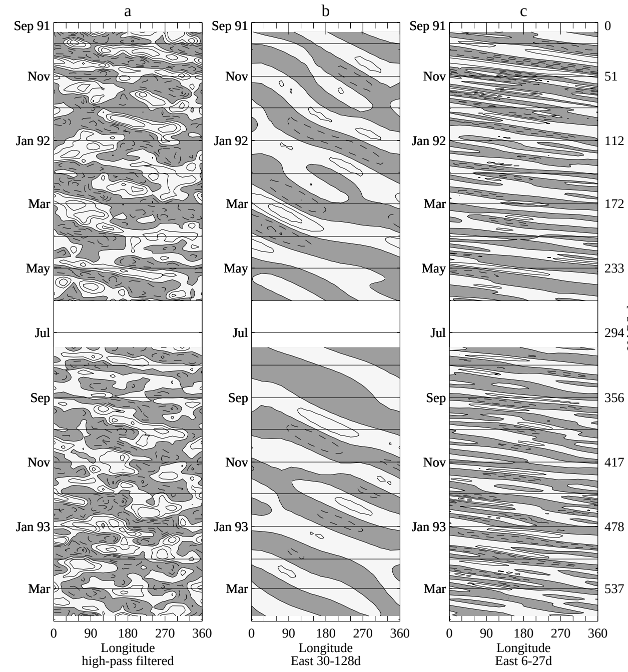

Figure 1. Hovmöller diagrams of (a) equatorial (2.5°S–2.5°N) 68 hPa water vapor, high-pass (period < 90d) filtered; (b) the same, reconstructed using only eastward wavenumbers 1–3 and temporal periods 30–128 days (see lower box in Figure 2a) and (c) as in (b) but for temporal periods 6–27 days (see upper box in Figure 2a). Dark shading indicates negative anomalies. Contour interval is 0.04 ppmv in (a) and (c), 0.02 ppmv in (b).

tions, we calculate wavenumber-frequency power spectra of the 256-day segments of data shown in Figure 1a and also of the corresponding data at 100 hPa. At each longitude the time series data are tapered at the endpoints to assure continuity when applying the spectral analysis. (The results are virtually identical without tapering.) Then the time-longitude data are regressed to find coefficients of terms like $\cos(kx - nt)$ where x and t are defined so that k and n are integers; k varies from -7 to 7 (since there are 15 grid points) and n varies from 1 to 128, corresponding to periods between 256 and 2 days.

The results are shown in Figure 2. The dominant spectral peaks are at eastward-traveling wavenumber 1 with periods between 10 and 70 days and a weak minimum at 30 days, suggesting a division into two spectral bands, 10–25 day period and 30–70 day period. We discuss the significance of these two bands separately, tentatively associating them respectively with Kelvin waves and with the tropical intraseasonal oscillation (TIO), also known as the Madden-Julian Oscillation.

3.1. 30–70 day band

Clark et al. [1998] studied MLS water vapor (from the 205 GHz channel) at 215 hPa; they too found considerable spectral power in the 30–70 day band, and identified it with the TIO. While a signature of the TIO in the lower stratosphere has not generally been acknowledged, it seems reasonable to identify the spectral peaks at 30–70 days at the 68 and 100 hPa levels (Figure 2) with those at 215 hPa, thus connecting them to the TIO as well. Figure 1b shows a reconstruction of the water vapor variations using the limited space-time coefficients enclosed in the lower dashed box in Figures 2a and 2b, that is, limited to wavenumbers 1–3 and to periods of 30–128d. Some features (e.g., in March 1992) clearly correspond to features in Figure 1a, and are anticorrelated with the variations at 215 hPa (figures not shown, but cf. *Clark et al.* [1998]).

The spectral power in the 30–70d band drops by approximately four orders of magnitude between 215 and 100 hPa, due partly to the corresponding decrease in water vapor mixing ratio, and another order of magnitude between 100 hPa and 68 hPa, where the mixing ratios are comparable. The attenuation with height is consistent with our interpretation of the variations at 100 and 68 hPa as an evanescent stratospheric response to the TIO.

3.2. 10–25 day band

In the 10–25 day spectral band, the disturbances are only attenuated by a factor of 2 between 100 and 68 hPa. The fact that shorter periods dominate at higher altitudes is consistent with the observations of *Canziani et al.* [1994] showing distinct spectral bands of slow (roughly 10–20 day), fast

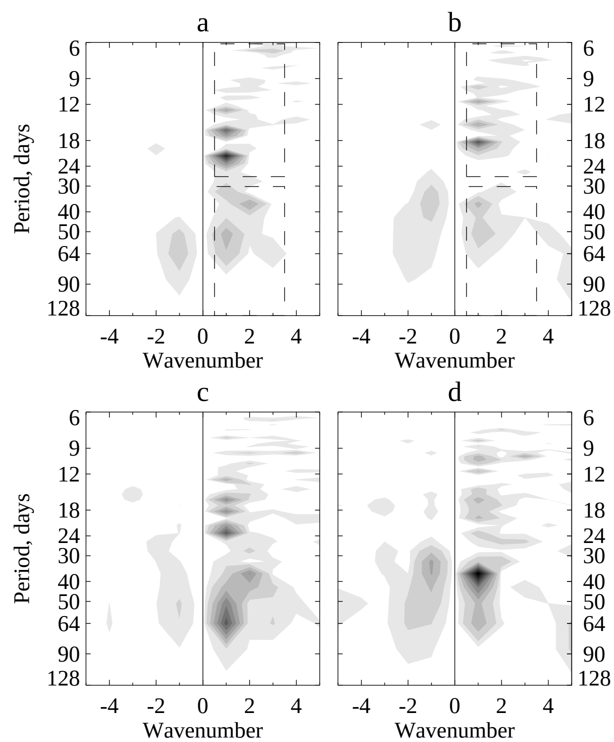

Figure 2. Power spectra, by wavenumber and frequency, of the water vapor variations shown in Figure 1a for 68 hPa (top two panels) and of the corresponding variations at 100 hPa (bottom two panels). Positive wavenumbers refer to eastward waves, and negative wavenumbers to westward waves. Figures 2a and 2c refer to the first 256-day interval in Figure 1, and figures 2b and 2d refer to the second interval in Figure 1.

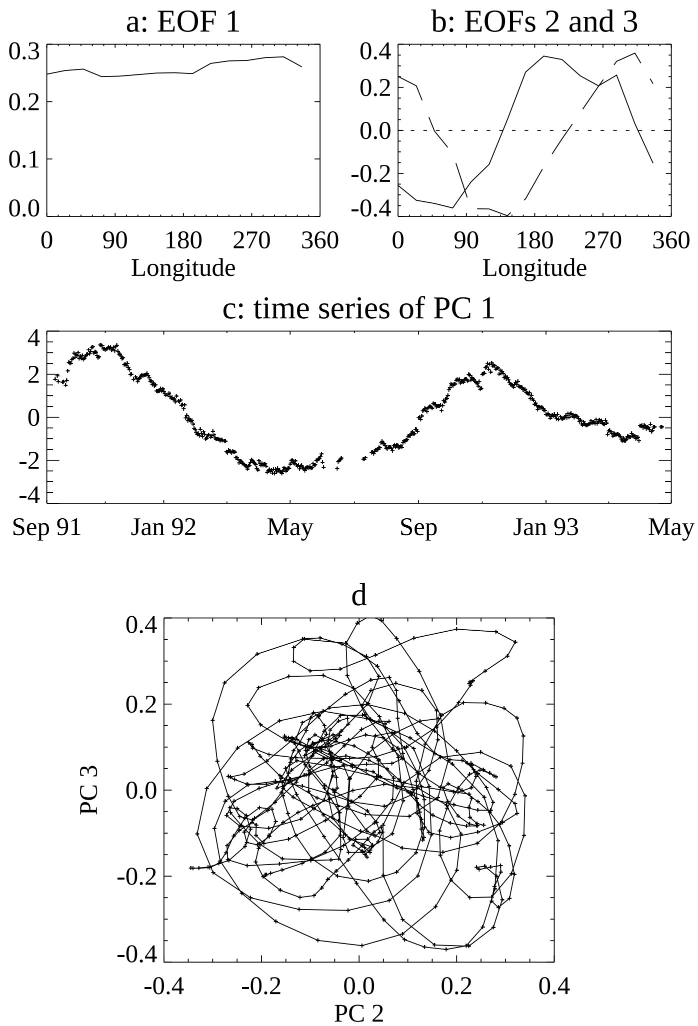

Figure 3. Empirical orthogonal functions of equatorial water vapor at 68 h Pa (a–b) and the time series of their principal components (c–d). In Figure 3b, EOF 2 is indicated by the solid curve, EOF 3 by the dashed curve. In Figure 3d, the (slightly smoothed) principal component time series of EOFs 2 and 3 are plotted against each other to emphasize their phase relationship.

(5–9 day), and ultrafast (3–4 day) waves; slow waves dominated in the lower stratosphere and fast waves in the middle and upper stratosphere (their figures 8 and 11). *Tsuda et al.* [1994] also found a roughly 20-day spectral peak in radiosonde data, confined mainly to the 15–20 km altitude range, and identified it as a Kelvin wave. We also find (figures not shown) that the equatorial water vapor disturbances at these levels are coherent with (but stronger than) disturbances at both higher latitudes and higher altitudes. These attributes, with the correct phase relationship, could be manifestations of Kelvin waves in the water vapor field, though the interpretation is complicated by the fact that the vertical gradient of water vapor typically changes sign twice between 100 and 10 hPa [see *Mote et al.*, 1996, their Plate 1].

To emphasize the contribution of the 10–25 day band to the variations shown in Figure 1a, we reconstruct the variations using only wavenumbers 1–3 and periods between 6 and 27 days (the upper dashed box in Figure 2). The results, shown in Figure 1c, highlight the coherence of features in this spectral band and provide an aid in interpreting Figure 1a. At times (e.g., September–November 1991) the resemblance between Figure 1c and Figure 1a suggests that the higher-frequency eastward disturbances predominate.

An alternative approach for isolating the eastward-traveling variations seen in Figure 1 is to calculate empirical orthogonal functions (EOFs). We do this for the entire data record (not just the two intervals of Figure 1) at 68 and 100 hPa separately; the results for 68 hPa are shown in Figure 3, and the results for 100 hPa (not shown) are very similar. The first EOF (Figure 3a) is nearly zonally symmetric and accounts for approximately 94% of the variance, and its associated time series (Figure 3c) represents the seasonal variation in the zonal mean; this seasonal variation is formed by the seasonally varying tropopause temperature, and advected upward as discussed by *Mote et al.* [1996]. The second and third EOFs (Figure 3b) each explain about 1% of the variance, have comparable eigenvalues, have wavenumber-1 structure, and are temporally in quadrature, as revealed by the prevalence of circular patterns in Figure 3d. These characteristics all describe a conjugate pair of EOFs, indicating that they describe a traveling oscillation. Their time series indicate variations at a range of periods but mostly near 20 days, as shown by visual inspection and by spectral and autocorrelation analysis. The largest cross-correlation is at a lag of 4 days, indicating a combined period near 16 days.

4. Discussion

Tsuda et al. [1994] stated that "upward flux of water vapor...into the equatorial stratosphere can also be modulated by the activity of Kelvin waves." The variations in tropical tropopause temperature shown in their figure 17 (approximately 185K to 193K) correspond to a variation in saturation mixing ratio from 1.5 to 5 ppmv. MLS water vapor variations in the sub-seasonal frequency range, on the other hand, are only a few tenths of a ppmv; this discrepancy could be attributed to a number of causes, including the vertical resolution and sensitivity of the MLS retrieval.

It seems likely that the data at 100 hPa contain useful information not just at low frequencies, as already demonstrated by *Mote et al.* [1996], but also at sub-seasonal frequencies. These data provide an important link between lower stratospheric and upper tropospheric water vapor, a link that will be investigated further. In the present paper we have shown that sub-seasonal variations in lower stratospheric water vapor are probably due to the joint influence of slow Kelvin waves and the TIO, but we have not established that this interpretation is correct. Subsequent papers will investigate (1) the relationships of the Kelvin-wave signatures shown here to those in water vapor at higher levels, as well as to those in temperature; (2) the relationship between lower stratospheric and upper tropospheric water vapor in the 30–70 day band.

Acknowledgments. We are grateful to Bob Harwood for his input on this paper. Work in the U.S.A. was supported by NASA contracts NAS1-96071 and NAS5-32862, and work in the U.K. by NERC.

References

Canziani, P.O., J.R. Holton, E. Fishbein, L. Froidevaux, and J.W. Waters, Equatorial Kelvin waves: a UARS MLS view. *J. Atmos. Sci., 51,* 3053–3076, 1994.

Clark, H.L., R.S. Harwood, P.W. Mote, and W.G. Read, Variability of water vapor in the tropical upper troposphere as measured by the Microwave Limb Sounder. *submitted to J. Geophys. Res.,* 1998.

Kawamoto, N., M. Shiotani, and J.C. Gille, Equatorial Kelvin waves and corresponding tracer oscillations in the lower stratosphere as seen in LIMS data. *J. Meteorol. Soc. Japan, 75,* 763–773, 1997.

Mote, P.W., K.H. Rosenlof, M.E. McIntyre, E.S. Carr, J.C. Gille, J.R. Holton, J.S. Kinnersley, H.C. Pumphrey, J.M. Russell III, and J.W. Waters, An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor. *J. Geophys. Res., 101,* 3989–4006, 1996.

Tsuda, T., Y. Murayama, H. Wiryosumarto, S.W.B. Harijono, and S. Kato, Radiosonde observations of equatorial atmospheric dynamics over Indonesia, 1. Equatorial waves and diurnal tides. *J. Geophys. Res., 99,* 10,491–10,505, 1994.

Wallace, J.M., and V.E. Kousky, Observational evidence of Kelvin waves in the tropical stratosphere. *J. Atmos. Sci., 25,* 900–907, 1968.

Ziemke, J.R., and J.L. Stanford, Quasi-biennial oscillation and tropical waves in total ozone. *J. Geophys. Res., 99,* 23,041–23,056, 1994.

T.J. Dunkerton and P.W. Mote, Northwest Research Associates, PO Box 3027, Bellevue WA 98009. (e-mail tim@nwra.com, mote@nwra.com)

H.C. Pumphrey, Department of Meteorology, University of Edinburgh, King's Buildings, Mayfield Road, Edinburgh EH9 3JZ UK. (e-mail hcp@met.ed.ac.uk)

(Received February 27, 1998; revised April 20, 1998; accepted May 8, 1998.)