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Seasonal variations of Water Vapor in the Tropical Lower Stratosphere

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Abstract. Measurements of stratospheric water vapor by the Microwave Limb Sounder aboard the Upper Atmosphere Research Satellite show that in the tropical lower stratosphere, low-frequency variations are closely related to the annual cycle in tropical tropopause temperatures. Tropical stratospheric air appears to retain information about the tropopause conditions it encountered for over a year as it rises through the stratosphere. We use a two-dimensional Lagrangian model to relate MLS measurements to the temperature that tropical air parcels encountered when crossing the 100 hPa surface.

Introduction

Recent satellite observations of stratospheric trace constituents by the Upper Atmosphere Research Satellite (UARS) permit the investigation of seasonal variations in these constituents. Because of its importance in stratospheric photochemistry and radiation, water vapor is of particular interest. The Microwave Limb Sounder (MLS) instrument observed stratospheric water vapor for approximately 19 months and provides a unique picture of its seasonal variations. In the upper stratosphere, variations of MLS water vapor are related to the semi-annual oscillation, while in the lower stratosphere, variations have a period of slightly more than a year, suggesting that the quasi-biennial oscillation (QBO) may be modulating an annual cycle [*Carr et al.*, 1995]. Carr et al. did not discuss the cause of the

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annual cycle or the connections between variations at different levels. In this article we show that the water vapor mixing ratio of air in the tropical lower stratosphere is closely related to the temperature the air encountered when it crossed the tropical tropopause. Using Lagrangian residual velocities calculated from observations, we show that the timing of extremes in the water vapor observed by MLS is consistent with advection of the annual cycle in saturation mixing ratio at 100 hPa. We also show that the same feature appears in water vapor results from a general circulation model.

That the annual cycle of tropical tropopause temperatures should influence lower stratospheric water vapor is not a new suggestion [e.g. Newell *and Gould-Stewart, 198* 1] but direct evidence from satellite observations of seasonal variations in tropical lower stratospheric water vapor has not hitherto been presented, except for a few seasonally averaged cross-sections [*Rind et al., 1993]. McCormick et al. [1993]* showed that the annual cycle in Stratospheric Aerosol and Gas Experiment (SAGE) II H_20 between 30° and 40° in both hemispheres has a minimum in about March, consistent with the fact that the observed minimum tropopause temperatures occur in January-February [*Reed and Vlcek,* 1969] and with rapid mixing to middle latitudes of both hemispheres below the 400K isentropic surface [*Chen et* al., 1994].

The Microwave Limb Sounder

MLS vertically scans the limb and measures atmospheric thermal radiance at millimeter wavelengths, from which vertical profiles of atmospheric parameters are retrieved. The measurement technique was described by *Waters [1993],* and the instrument by *Barath et al.* [1993]. Stratospheric water vapor profiles were obtained from the MLS 183 GHz radiometer which operated from late September 1991 through late April 1993. The tropics were observed continuously (with few exceptions) during this period, and approximately 400 profiles between 12° N and 12°S were obtained each day. The retrieved vertical profiles are piece-wise linear, with breakpoints occurring every $10^{1/3}$ change in atmospheric pressure. We use MLS version 3 data and examine stratospheric water vapor at the three lowest profile points (10, 22 and 46 hPa) considered reliable. The estimated accuracy is better than 20%, and individual profile points have precision of 0.2 to 0.4 ppmv (W.A. Lahoz et al., manuscript submitted to JGR). Since hundreds of profiles are averaged for our analyses, the results we present should have very good precision.

Gaps in the data record appear at various points, including a protracted instrument shutdown from June 2 to July 15,1992 clue to a problem with the UARS solar array drive. Data shown here have been linearly interpolated across all gaps, a crude approach that nonetheless seems to be satisfactory since we examine only low-frequency variations. We show five-clay means which have been smoothed twice using a 1-2-1 filter.

Models

As a diagnostic tool for evaluating the MLS observations, we employ a simple Lagrangian-mean two-dimensional (L2D) model. The model [*Rosenlof,* 1995] calculates monthly mean transformed Eulerian-mean residual stream function for 1992-1993 based on the method of *Solomon et al.* [1986] which includes heating rates in the stream function calculation. Input to the radiative calculation included temperature from the U.K. Meteorological Office (UKMO) stratospheric data assimilation, archived as part of the UARS correlative data base, and ozone and water vapor measurements from M 1,S; climatological values were used for other trace species and for ozone in the lowest part of the stratosphere. Sensitivity studies showed that the calculated heating rates were nearly the same for climatological ozone as for MLS ozone, and for HALOE $H_2$0 as for MLS H_2O in January 1993. For this radiative calculation only, gaps in the MLS observations were filled using climatology and water vapor data from the Halogen Occultation Experiment *[Russell et al., 1993]* were used for the time period after the MLS 183 GHz radiometer failed.

We interpolated the monthly mean stream functions to daily values and then derived residual velocities from the daily stream functions to satisfy mass continuity, We ran back trajectories starting every two weeks from latitudes between 12° S and 12° N at 2° intervals and at altitudes between 100 hF'a and 5 hPa at -1 km intervals, until the parcels crossed the 100 hPa surface, Using the latitude and date of parcel crossing and the UKMO assimilated 100 hPa temperatures, we took the minimum temperature in that latitude band which occured within a week of the crossing date and computed a saturation mixing ratio q_s.Q_s results between 12° S and 12° N were averaged, and results for 1992 and 1993 were averaged to reduce interannual variability caused, e.g., by the QBO.

The simulation of stratospheric water vapor in the National Center for Atmospheric Research Community Climate Model (CCM2), described by Mote [1995], ineluded an upper stratospheric water vapor source and had a reasonable zonal mean water vapor distribution and annual cycle. We include (monthly mean) CCM2 results to show that our explanation of MLS H_2O variations is plausible, since the CCM2 shows the same sort of variations and we can be certain of the physical mechanism causing them.

Results.

Figure 1 compares the evolution of tropical water vapor between the MLS observations, the CCM2, and the L2D model, For MLS and CCM2 we have subtracted the time-mean vertical profile for the period shown in order to account, crudely, for the effects of methane oxidation on the vertical gradient. The most striking feature of the MLS observations (Figure la) is the relatively moist air (red) which appears to move upward with time; it is found at 46 hPa in March and April 1992, at 22 hPa in September 1992, and at 10 hPa in January-February 1993. Relatively low values (blue) are present at 46 hPa in October 1991, and at 22 hPa in January–March 1992, though there is no corresponding feature at 10 hPa. Later, a minimum appearing in November- December 1992 at 46 hPa appears to reach 22 hPa in April 1993. These features seem to be upward-moving oscillations whose period is somewhat more than a year. In the CCM2 (Figure lb), which gives results for altitudes below 46 hPa not available from current MLS data, qualitatively similar features clearly indicate an annual cycle moving upward from the tropical tropopause. The phase of the CCM2's water vapor annual cycle at the tropopause agrees well with the observed annual cycle of tropopause temperatures.

A reasonable hypothesis to explain the oscillations is that they reflect the seasonal variations in tropopause mixing ratio, passively transported upward by the mean motion. 10 test this "unmixed ascent" hypothesis, in Figure 1c we show the variation in mixing ratio diagnosed by the L2D model. The major features of Figure la are well reproduced, except the 10 hPa variations early in the record which may be attributable to the impact on the circulation of volcanic aerosol from the June 1991 eruption of hit. Pinatubo. It is worth noting that if the data in Figure 1c are plotted on the same vertical grid as the MLS observations, the plot resembles Figure la more closely since extreme values can only appear at grid levels.

The phase correspondence between the MLS water vapor and that of the models can he seen more clearly in Figure 2. At each level, the L2D mode] water vapor values have been shifted and scaled so that the maximum and minimum equal the maximum and minimum MLS observations, because the L2D model values are considerably larger than the MLS observations for reasons which we discuss below. The agreement of the phase is quite good at 46 hPa, but diminishes with height; at 46 and 22 hPa the MLS variation is approximately annual, while at 10 hPa there seems to be a trend from low to high values during the record with a weak annual cycle superposed. (The oscillations of period ~ 1 month, which are especially visible at 22 hPa after August 1992, are not fully understood, but we believe they are an artifact of the periodic yaw maneuvers that the UARS must execute.)

The phase differences between MLS observations and CCM2, which are greatest at 46 hPa (Figure 2c) can be understood as differences not of mechanism but of circulation. The CCM2 is known to have a lower stratospheric circulation about 60% stronger than deduced from observations [*Rosenlof and Ho/ion, 1993];* compare the slopes of the contours in Figures lb and 1c. The attenuation with height, which is slight in the MLS data but more pronounced in the CCM2, could reflect different degrees of meridional or vertical mixing between the CCM2 and the atmosphere. The L2D model exhibits no attenuation of annual signal by the nature of its construction.

Discussion.

The coherence of the lower stratospheric signature of the annual cycle in tropopause water vapor mixing ratio (Figure 1) is striking. Evidently air passing through the tropical tropopause carries with it information about the conditions under which it entered the stratosphere and retains this information throughout its long journey upward to about 10 hPa, while remaining mostly unmixed. In the lowest few kilometers of the stratosphere, some air is mixed poleward, as noted before [*McCormick et* al., 1993; *Chen et* al., 1994], but the amplitude of the seasonal-scale variations of MLS water vapor is virtually unchanged between 46 and 22 hPa (Fig, 2), indicating negligible mixing. Water vapor is unique among commonly observed trace constituents in retaining this degree of information, because of its strong dependence on temperature when entering the stratosphere. Measurements of CO_2, which has an annual cycle as well as a long term trend, may provide an independent check on the "unmixed ascent" hypothesis.

The timing of the minima and maxima of MLS water vapor are fairly well diagnosed by the L2D model, but the shapes of the MLS and L2D model annual cycles are quite different, especially at the upper level shown. In the model, the seasonal variations of saturation mixing ratio are sharply peaked, while the seasonal variations in MLS data and CCM2 output have a more sinusoidal shape. The sharpness of the peak increases with height (compare Figures 2a and 2c), apparently because the annual maximum of the residual mean vertical velocity coincides with the annual minimum of 100 hPa temperatures, which acts to spread out the minimum values of saturation mixing ratio q_s. Before scaling, L2D model mixing ratios were much higher than MLS mixing ratios for parcels which crossed 100 hPa in northern summer, but were closer at other times of the year. The sharp peak in the L2D model occurs partly because the height of the tropical tropopause varies seasonally, from pressures less than 100 hPa in northern winter to pressures greater than 100 hPa in northern summer [*Reid and Gage*, 1981]. As *Frederick and Douglass [1983]* pointed out, when the temperature minimum occurs above the 100 hPa level, the minimum q_s is overestimated by the 100 hPa temperature but underestimated by the 100 hPa pressure, resulting in a small net error. But when the temperature minimum is below 100 hPa, both the 100 hPa temperature and pressure overestimate q_s, so errors in profile minimum q_s would be greatest in northern summer.

Measurements of water vapor and methane by other instruments, notably the Halogen Occultation Experiment (H ALOI?) aboard UARS, confirm the link between tropopause temperatures and seasonal variations of lower stratospheric water vapor as suggested by the MLS observations presented here. In a more comprehensive paper, we shall examine these and other stratospheric water vapor measurements, elaborate on the impact of tropopause height on estimates of q_s, and elucidate the role of the QBO in distorting the annual cycle.

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MOTE ET AL.: WATER VAPOR IN THE TROPICAL LOWER STRATOSPHERE

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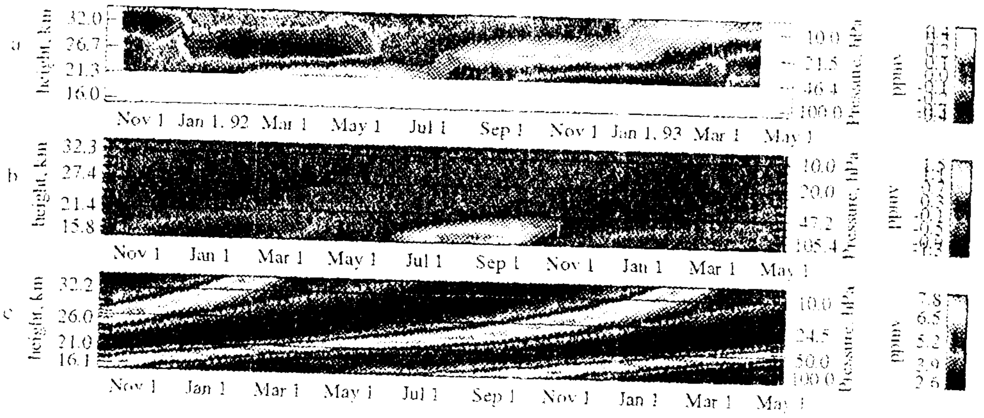
Figure 1. Time-height sections of (a) MLS, (b) CCM2 and (c) Lagrangian 2D model tropical (roughly 12° S to 12° N) mean water vapor. In panels b and c, MLS levels are indicated by horizontal bars, and model grid levels by tick marks with the levels closest to MLS levels labeled. Color scales are somewhat different for each panel due to the differing definitions of the plotted fields: in panels a and h, the mean profile has been subtracted

Figure 2. Tropical water vapor at (a) 10 hPa, (b) 21.5 hPa and (c) 46.4 hPa. MLS, CCM2, and Lagrangian 2D model curves are indicated by 'M',' C', and 'L' respectively. The maximum and minimum values of the 2D model curve have been scaled to the MLS values at each level.

a
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46.4
100.0
Pressure, hPa
ppmv
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b
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21.4
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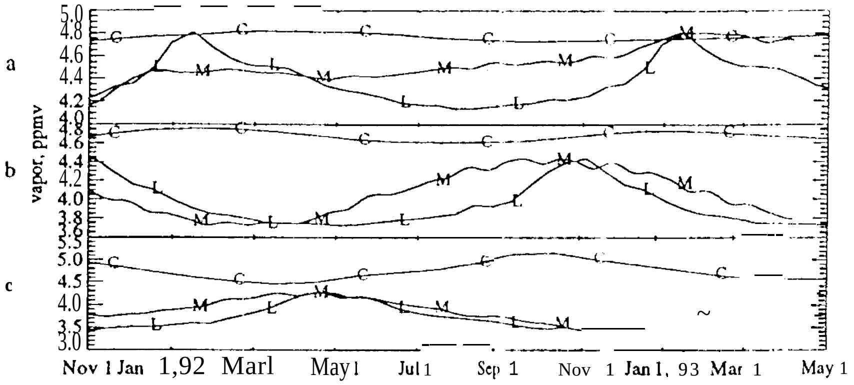
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