Simulations of the Interannual Variability of Stratospheric Water Vapor

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ABSTRACT

Observations and model results indicate that the quasi-biennial oscillation (QBO) modulation of stratospheric water vapor results from two causes. Dynamical redistribution of water vapor from the QBO-induced mean meridional circulation dominates the observed variability in the middle and upper stratosphere. In the lower stratosphere, the QBO water vapor variability is dominated by a ''tape recorder'' that results from the dehydration signal accompanying the QBO variation of the tropical cold point tropopause. It is suggested that another low frequency tape recorder exists due to ENSO modulations of the tropical tropopause, but insufficiently long observations of stratospheric water vapor exist to identify this in the observations.

1. Introduction

It is well known that the stratospheric quasi-biennial oscillation (QBO) dominates the interannual variability of the equatorial lower stratosphere. In particular, O'Sullivan and Dunkerton (1997) and Randel et al. (1998), hereafter referred to as OD97 and R98, respectively, have documented the QBO-induced changes in several stratospheric constituents—N_2O from the Cryogenic Limb Array Etalon Spectrometer (CLAES) instrument on Upper Atmosphere Research Satellite (UARS) and H_2O from the Microwave Limb Sounder (MLS) instrument on UARS in the case of OD97, and CH_4 and H_2O in the case of R98. In this paper, we compare the QBO variations in CH_4 and H_2O from R98, finding that CH_4 variations show QBO variations mainly in the middle and upper stratosphere, while significant H_2O QBO variations are seen throughout the depth of the stratosphere. Furthermore, we point out the QBO H_2O variations in the lower stratosphere have a very different nature than those in the middle and upper stratosphere. We show model results for QBO variations in CH_4 and H_2O using transport from the QBO mean meridional circulation. These calculations give CH_4 variations that match reasonably well with the observations of R98 and match the observed QBO variations of H_2O in the middle and upper stratosphere, but fail to match H_2O in the lower stratosphere.

Both Randel et al. (2000) and Zhou et al. (2001b) have analyzed the variability of the tropical tropopause. Randel et al. (2000) used National Centers for Environmental Prediction (NCEP) analyses and balloon soundings for comparison in their analysis of the lapse rate tropopause, while Zhou et al. (2001b) used European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses and balloon soundings in their analysis of the tropical cold point tropopause (CPT). Both found QBO and El Niño–Southern Oscillation (ENSO) signatures in the tropical tropopause temperatures, pressures, and altitudes.

One difference among water vapor (H_2O), methane (CH_4), and nitrous oxide (N_2O) is that H_2O is frozen out of tropospheric air as it rises through the tropical tropopause. Methane and nitrous oxide undergo no phase changes at these temperatures and pressures. We present modeling results that indicate the QBO modulation of cold point tropopause temperatures and pressures is what gives rise to most of the QBO water vapor variations in the lower stratosphere.

By analogy to the computations showing that QBO modulations of tropical tropopause temperatures and pressures are responsible for the sizable QBO modulations of lower stratospheric water vapor, the ENSO variations in the tropical tropopause also should give rise to modulations in lower stratosphere water vapor. No observational dataset exists that shows this unambiguously, however, since none extends over a sufficient number of ENSO cycles. We present some calculations to show how ENSO variations in the tropical tropopause should give rise to ENSO variations in lower stratospheric water vapor. Due to the uncertainty of how ENSO affects stratospheric dynamics, little can be said about variations in the middle and upper stratosphere. Also, a significant uncertainty exists as to the size of the ENSO variations in lower stratospheric water vapor

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due to unresolved questions of where and when tropospheric air enters the tropical stratosphere.

Our work expands upon the earlier results of Giorgetta and Bengtsson (1999). They performed atmospheric general circulation modeling experiments with an assimilated QBO and found a dehydration signal both due to the QBO variation in the dehydration of air rising through the tropical tropopause and the QBO modulation of the ascent rate of tropical air. The top of their model was at 10 hPa, however, and the methane oxidation source of water vapor was not included. Thus, they were not able to compare their results with data to any great extent. Also, because of their low model top, they were unable to separate the causes of QBO variations in water vapor in the lower portion of the stratosphere from those in the upper portion. Given the differences in their modeling and ours, the Giorgetta and Bengtsson (1999) results are very consistent with our results.

2. Observations

Figure 1 shows the tropical interannual anomalies of H_2O, CH_4, and H_2O + $2CH_4$ from the Halogen Occultation Experiment (HALOE) measurements. The early period (November 1991–December 1993) of HALOE measurements were not plotted since tropical lower stratospheric water vapor measurements had large uncertainty during this period due to heavy aerosol loading caused by the Mount Pinatubo eruption (e.g., Randel et al. 1999b). There are two aspects of Fig. 1 that are interesting but were not addressed by R98. One is that the CH_4 anomalies in the tropical lower stratosphere (e.g., below 30 km) are very weak, but significant H_2O anomalies exist in this region. Another is that the H_2O variations in the lower stratosphere have a very different nature than those in the middle and upper stratosphere (e.g., 30–50 km). The H_2O variations in the lower stratosphere slope upward with increasing time, whereas the variations in CH_4 and H_2O above show no such slope. There is another interesting aspect of Fig. 1. It is known that the annual ''tape recorder'' dies out above about 35 km (Mote et al. 1996). Thus, H_2O+2CH_4 should be almost constant with time above 35 km if only QBO variations in transport are affecting stratospheric water vapor and methane. What is seen, however, is that twice the anomalies of CH_4 only offset about half of the anomalies of H_2O in the tropical upper stratosphere, giving an H_2O+2CH_4 anomaly that exists at least up to 50 km (or about 1 mb).

3. Model description

The State University of New York at Stony Brook/St. Petersburg 2D Chemistry-Transport Model (SUNY-SPb 2D CTM; Smyshlyaev et al. 1998) is used to simulate stratospheric water vapor. This version of the SUNY-SPb 2D CTM extends from the surface up to about 78 km and from pole to pole, with a horizontal resolution of 5°. The vertical resolution is about 2 km, except near the tropopause where it has a finer resolution of about 0.15 km. The model meridional circulation and resolved eddy mixing were derived from the middle atmosphere version of the National Center for Atmospheric Research (NCAR) Community Climate Model (MACCM2). This was done by performing 3D transport numerical experiments with two orthogonal tracers (Yudin et al. 2000). The resulting meridional circulation and diffusion coefficients contain annual cycles but no interannual variabilities. The upwelling velocity and diffusion coefficients in the tropical lower stratosphere, as derived by Mote et al. (1998), are used so as to simulate a tape recorder signal that is consistent with HALOE observations.

The Brewer–Dobson circulation, with upward transport in the Tropics and downward transport in the extratropics, is known to dominate stratosphere–troposphere exchange (Holton et al. 1995), so we set the lower boundary for water vapor at the tropopause assuming that tropospheric air enters the stratosphere only in the Tropics. The entry value of the water vapor mixing ratio is specified at the altitude of the tropical tropopause (about 17.5 km between 15°S–15°N). Thus, the extratropical troposphere (at latitudes greater than 15°) simply serves as a passive reservoir for downward transport of water vapor. The water vapor entry values into the stratosphere are specified as follows. The entry values are taken to be the average (over 90°E–180°) saturation mixing ratios at the tropical CPT, where the CPT temperatures are calculated from the ECMWF analyses, taking into account the 2-K warm bias that has been pointed out by Zhou et al. (2001b). This treatment of the lower boundary condition is quite different from what has been used in previous simulations (e.g., Summers et al. 1997). For simplicity, we used a latitudinally varying tropopause, but one that does not vary with time. Model temperature fields were prescribed according to MACCM2 outputs. This affects chemistry only and does not affect the prescribed tropopause altitudes and the entry value of water vapor at the tropical tropopause. Figure 2 shows the seasonal cycle of the specified entry values for the water vapor entry mixing ratio, and the zonal means of the QBO and ENSO signatures in the Saturation Mixing Ratios (SMRs) at the tropical CPT. The SMRs were calculated using daily temperature fields. The choice of the averaging region (i.e., 90°E–180°) is arbitrary. Zhou et al. (2001b) indicated that the QBO signatures in the tropical CPT are zonally symmetric but the ENSO signatures are zonally asymmetric. The arbitrary choice of the averaging region has less effect on the QBO associated entry value interannual anomalies than it does on the ENSO related entry value interannual anomalies.

The chemistry is simplified, based on the JPL97 full chemistry (see DeMore et al. 1997), using the following prescription. The model with full chemistry and with

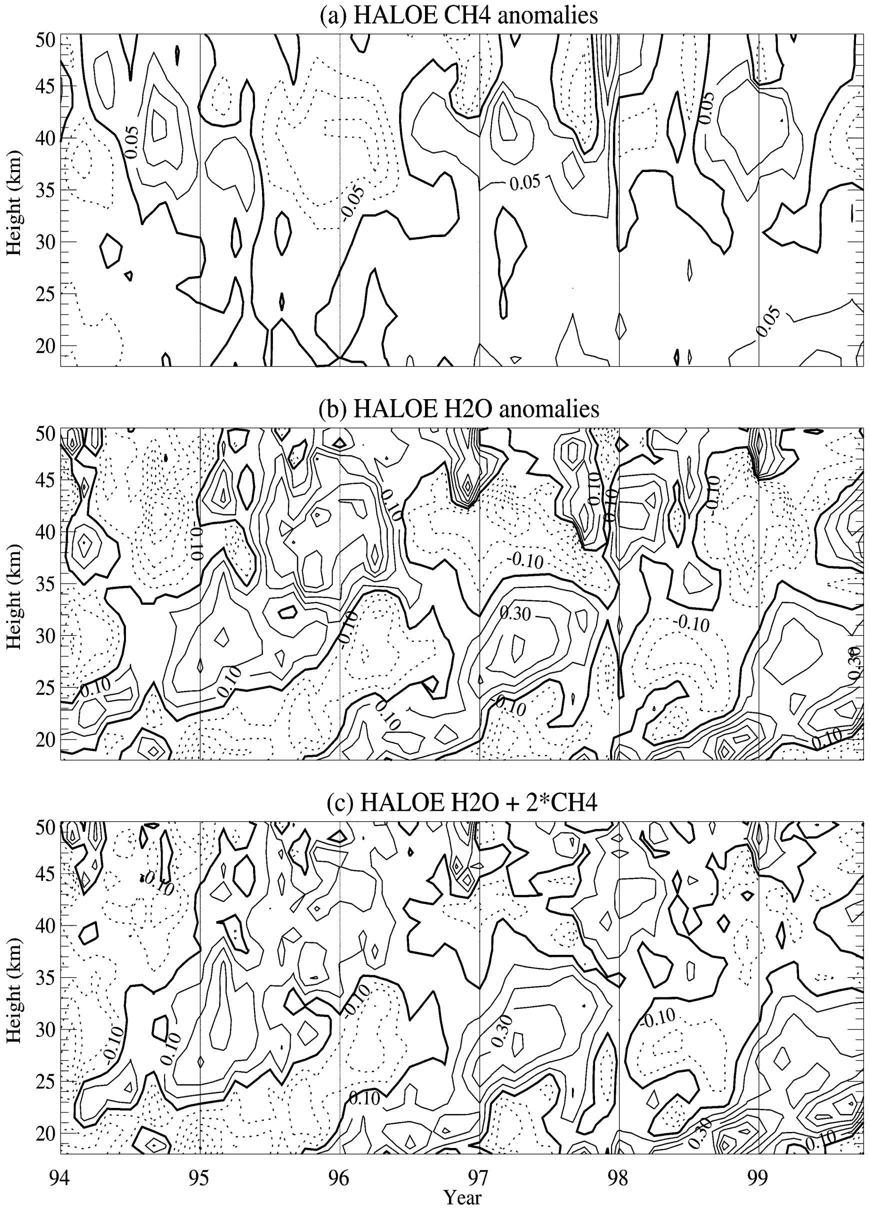

FIG. 1. Interannual anomalies of (a) CH_4, (b) H_2O, and (c) H_2O+2CH_4 over the equator. Contour interval is 0.05 ppmv for CH_4 and 0.10 ppmv for H_2O and H_2O+2CH_4. HALOE observations were analyzed between 80°N and 80°S on a 4° equivalent latitude grid (R98). Anomalies are about the seasonal cycle and figures were plotted using data provided by William Randel and Fei Wu (2000, personal communication).

all parameters (including the meridional circulation, eddy mixing, temperature, and entry value of water vapor) set to their annual cycle has been integrated for more than 15 years, which is long enough for the model to achieve an equilibrium state. The annual cycles of the production and loss rates for water vapor and methane are then saved every 5 days for subsequent simulations. This simplified system contains only two species, water vapor, and methane. This simplified model is a pure transport model with parameterized chemistry. It is very efficient in terms of CPU time compared with the full chemistry model and is suitable for the purposes of this study. This model will be used in both the control experiment and in perturbation experiments in which interannual variations for the atmospheric residual circulation and water vapor entry value are prescribed.

4. Model results

We first show in Fig. 3 model results for the seasonal cycles of water vapor and methane from a standard model run and their comparison with HALOE observations. In

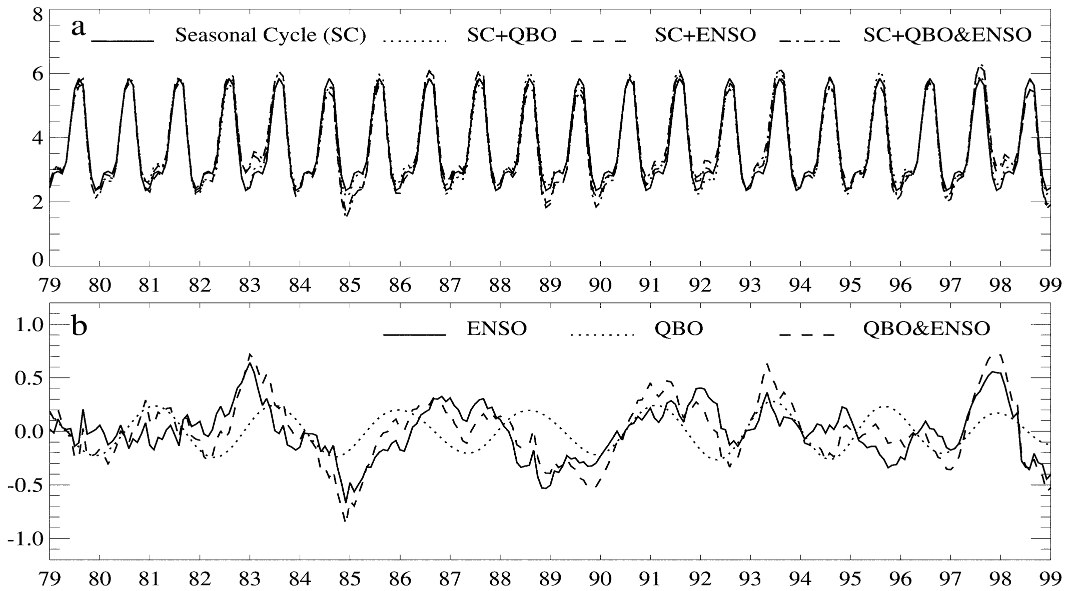

FIG. 2. Zonal mean (over 90°E–180°) seasonal cycle of the designed entry value of water vapor, and the QBO- and ENSO-induced anomalies of the CPT SMRs over 2.5°N. (a) The seasonal cycle that is repeated over 1979–99 with the QBO- and ENSO-induced anomalies superimposed. (b) The interannual anomalies.

the standard model run, all parameters were set to their seasonal cycles. HALOE uses the solar occultation technique and 30 measurements are obtained each day. Global coverage is obtained within a few weeks (Harries et al. 1996). For more details on HALOE, see Russell et al. (1993). The updated annual cycles of stratospheric water vapor and methane, and interannual anomalies of water vapor and methane plotted in Fig. 1, were derived from HALOE observations (version 19) during November 1991–May 1999 using the method as described in R98. The latitudinal variation with season of the water vapor mixing ratio isopleths, as shown in the HALOE observations, has been simulated quite well by the SUNY-SPb 2D model except that the Northern Hemisphere (NH) subtropical gradient is relatively weaker in the model (e.g., in April). Also, the winter Southern Hemisphere (SH) transport barrier is much stronger in the model than is seen in the observations. These defects can be traced back to deficiencies in the residual circulation and diffusion coefficients in the version of the Community Climate Model (CCM2), which the SUNY-SPb 2D model used (Yudin et al. 2000). Both the HALOE H_2O and CH_4 observations show a double-peak pattern in the upper stratosphere in April that is probably associated with the semiannual oscillation (SAO; R98). This double-peak pattern is very weak in the model simulation, however. This is quite consistent with the weak SAO in the MACCM2. Note that the 5.5 ppmv contour, the bold contour between 40 and 50 km over the equator as shown in Fig. 4, occurs at its lowest altitude in April, which is probably a result of the SAO meridional circulation. The modeled 5.5 ppmv contour for April does show a minor indication of this double-peak pattern, although it is not as clear as in the HALOE observations, and there is no double-peak feature above 45 km in the April simulation. The SUNY-SPb model simulates most of the features of the annual cycles in stratospheric water vapor and methane reasonably, namely, the annual evolution of the latitudinal variation of the contour pattern with time. The modeled tape recorder signal that is related to the annual cycle in the tropical CPT temperatures is shown in Fig. 4. It is consistent with Mote et al. (1996, 1998). This is not surprising since we have used their parameters in the model.

a. QBO simulations

QBO induced upwelling anomalies ($\overline{W^*_{\rm QBO}}$) were superposed on the annual cycle of the meridional circulation. The QBO induced upwelling anomalies were obtained by projecting the meridional circulation, derived from U.K. Met Office assimilated wind and temperature fields, to the first two orthogonal QBO reference time series derived from zonal winds over 70–10 mb (Wallace et al. 1993; Randel et al. 1999a). The anomalies of the horizontal component of the residual circulation were calculated for this model integration by solving the continuity equation. Thus, the QBO-induced 2D meridional circulation anomalies affect both vertical and horizontal transport. Figure 5 shows the $\overline{W^*_{\rm QBO}}$ and its induced H_2O, CH_4, and H_2O+2CH_4 anomalies over 2.5°N. Generally, negative $\overline{W^*_{\rm QBO}}$ maxima lead the positive anomalies of the stratospheric water vapor by about 1/4 period of the QBO. This phase relationship is not perfect in the middle to upper stratosphere, where horizontal transport by the QBO induced circulation and

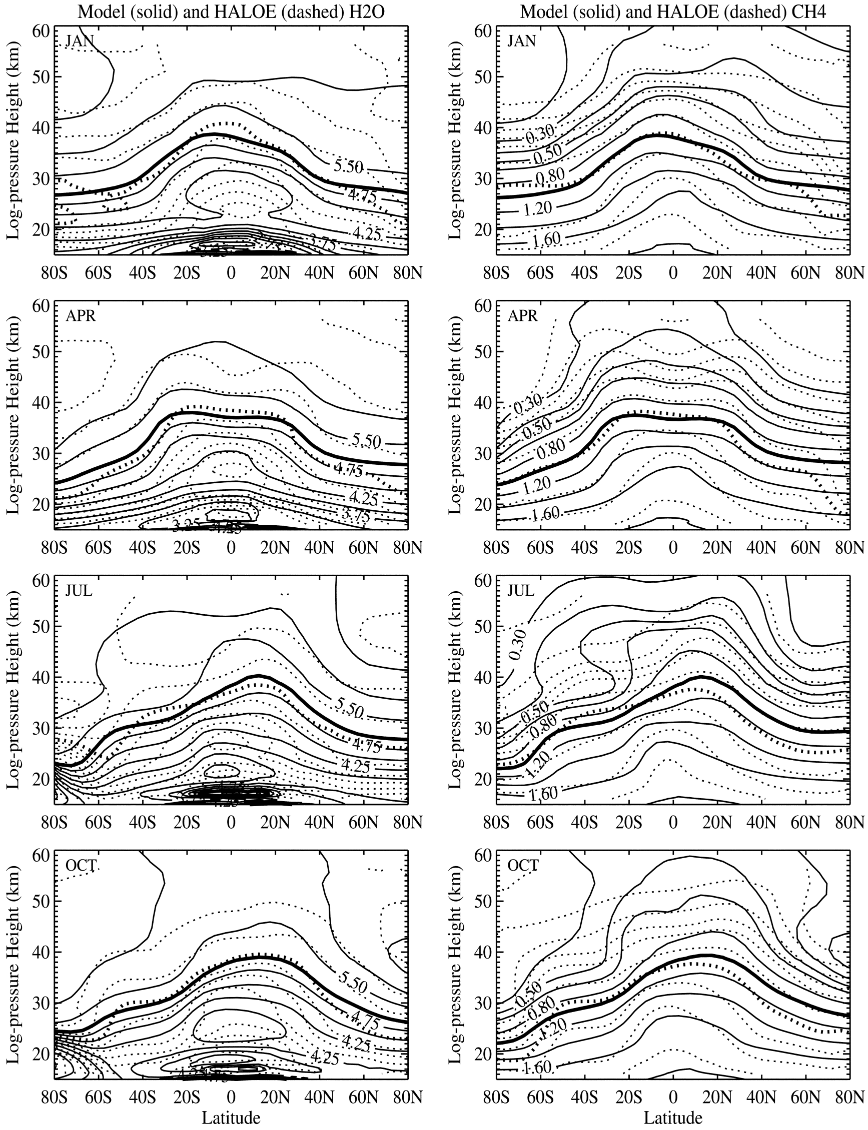

FIG. 3. Seasonal cycles of stratospheric (left) H_2O and (right) CH_4 from the standard model run (solid curves) and HALOE observations (dashed curves). From the top to the bottom are for Jan, Apr, Jul, and Oct, respectively. Contour interval for H_2O is 0.25 ppmv for the values smaller than 5.0 ppmv and 0.5 ppmv for the values greater than 5.0 ppmv. Contour interval for CH_4 is 0.1 ppmv for the values smaller than 0.6 ppmv, and 0.2 ppmv for the values greater than 0.6 ppmv. Contours 5.0 ppmv for H_2O and 1.0 ppmv for CH_4 are thickened.

horizontal diffusion play significant roles. Large H_2O and CH_4 anomalies occur in the middle to upper stratosphere, consistent with the findings of R98. However, the interannual anomalies in the tropical lower stratosphere are much weaker than the observations of R98 indicate.

In this numerical experiment, it is only the transport effects that produce the resulting anomalies. Given that there is no QBO variation in the entry value for the water vapor mixing ratio into the stratosphere, H_2O+2CH_4 shows little interannual variability (except for the weak coupling between the annual changes in the entry value of water vapor and the QBO variation in the transport; see Fig. 5d). Since the tape recorder resulting from the annual cycle of tropical tropopause temperatures dies out above 30–35 km, H_2O+2CH_4 is approximately conserved in the tropical upper stratosphere in this experiment. However, the observed anomalies of H_2O+2CH_4 are not small compared with either water vapor or methane anomalies in the tropical upper stratosphere according to the HALOE observations of R98. This discrepancy between observations and the model points to the fact that QBO variations in CPT temperatures play a large role in stratospheric water

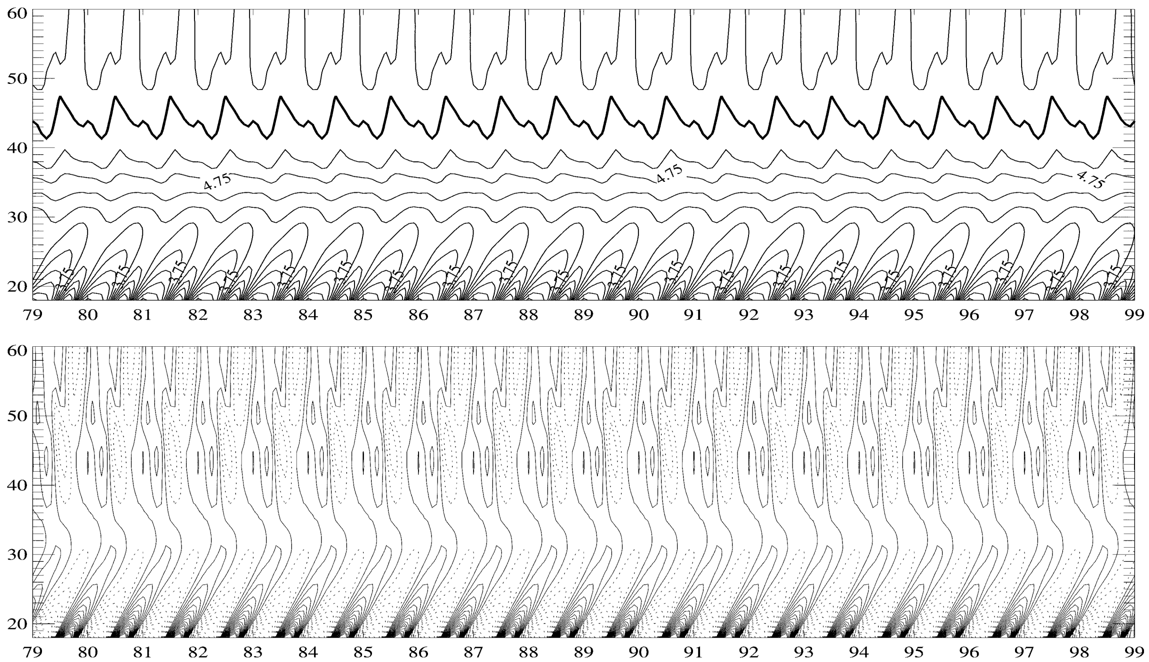

FIG. 4. Altitude–time sections of monthly mean (upper panel) and anomalies (lower panel) for stratospheric water vapor over 2.5°N for the standard run. The anomalies are the difference between monthly output and the mean of all monthly output (i.e., the sum of all monthly output divided by the numbers of months). The contour interval for monthly mean H_2O is 0.25 ppmv for values smaller than 5.0 ppmv, and 0.5 ppmv for the values greater than 5.0 ppmv. The contour interval for the monthly anomalies of H_2O is 0.2 ppmv. The bold curve indicates the influence of the semiannual oscillation in the model.

vapor variations. There is strong evidence that the mechanism that is missing from the simulations so far is the effect of dehydration by the QBO variations at the tropical CPT. The evidence for this is found in both the upward propagation of the lower stratospheric anomalies, which suggests that the source of this variation has its source at the tropopause region, and in the upward propagation of QBO anomalies in H_2O+2CH_4. Such variations would not occur unless there is a QBO modulation in the water vapor mixing ratio entry value.

Figure 6 shows results for both the H_2O and H_2O+2CH_4 anomalies when both the effects of the QBO induced circulation and the QBO variations in the entry value of water vapor mixing ratio are included. Above 30–35 km, the interannual anomalies come from the transport of the water vapor mean state by the QBO-induced anomalies of the residual circulation. Below about 30–35 km, the interannual anomalies of water vapor are mainly caused by the interannual variabilities of the CPT temperatures. If the amplitude of the QBO associated variation in the entry value of water vapor mixing ratio is larger in the real world than the scenario used in this paper, the influence of the QBO in the tropical CPT can reach higher altitudes than what is shown here. Note also that the QBO variation in H_2O+2CH_4 exists throughout the stratosphere, which is in agreement with what was seen in the HALOE observations.

b. ENSO variations

Zhou et al. (2001b) have also found ENSO modulations of tropical CPT temperatures; however, the ENSO variations are much more zonally asymmetric than are the QBO variations. This leads to much greater uncertainty in estimating the ENSO modulation of the entry point water vapor mixing ratio entering the stratosphere. This, in turn, arises from the uncertainty of exactly where the dehydration of air entering the stratosphere takes place. For instance, Dessler (1998) has argued, by examination of tropical radiosonde soundings, that air need not enter the stratosphere through the ''stratospheric fountain'' as was suggested by Newell and Gould-Stewart (1981). On the other hand, Zhou et al. (2001a) have suggested that a cooling trend has occurred in tropical tropopause temperatures over the past few decades and that this implies that the air entering the stratosphere must have experienced dehydration in the stratospheric fountain region.

Figure 7 shows the results of a simulation in which the annual and QBO variations in transport are included and both QBO and ENSO modulations in entry point water vapor mixing ratio are included. For this calculation, we have assumed that the dehydration signal in entry point water vapor mixing ratio is determined by conditions in the Tropics between 90°E and 180°. This gives a QBO modulation of about 0.25 ppmv and an ENSO variation of about 0.8 ppmv (see Fig. 2). Thus,

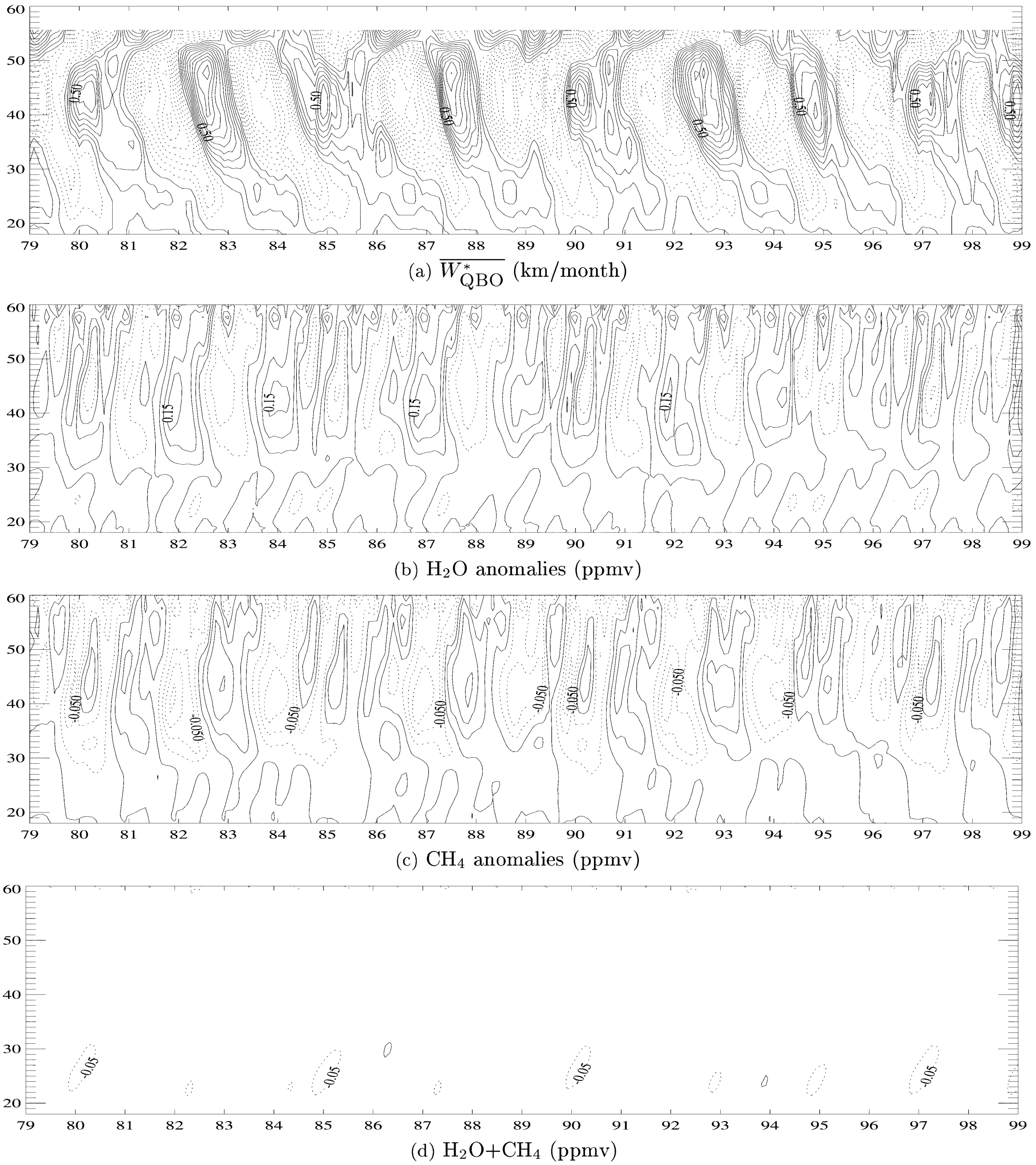

FIG. 5. (a) QBO-induced upwelling anomalies over 2.5°N and its induced (b) water vapor, (c) methane, and (d) H_2O+CH_4 anomalies over 2.5°N. Anomalies are the difference of monthly outputs between the current experiment and the standard run. The contour interval for $\overline{W^*_{\mathrm{QBO}}}$ is 0.1 km month^{-1}, 0.05 ppmv for H_2O and H_2O+CH_4 anomalies, and 0.025 for CH_4 anomalies. The zero contours in (d) were suppressed on purpose.

the results of this simulation show much more interannual variability than is seen in Fig. 6. QBO variability is seen in the stratospheric water vapor anomalies, but the ENSO effect produces a great level of variability in the variations from one QBO cycle to another. In this sense, the results of Fig. 7 are similar to what was seen in Fig. 1. This simulation should also ideally include the effects of ENSO variations in stratospheric transport, but these are not known by either observations or theory, so they are not included.

5. Discussion and conclusions

a. Discussion

This paper has stressed that because of QBO and ENSO variations in the tropical tropopause, there exist

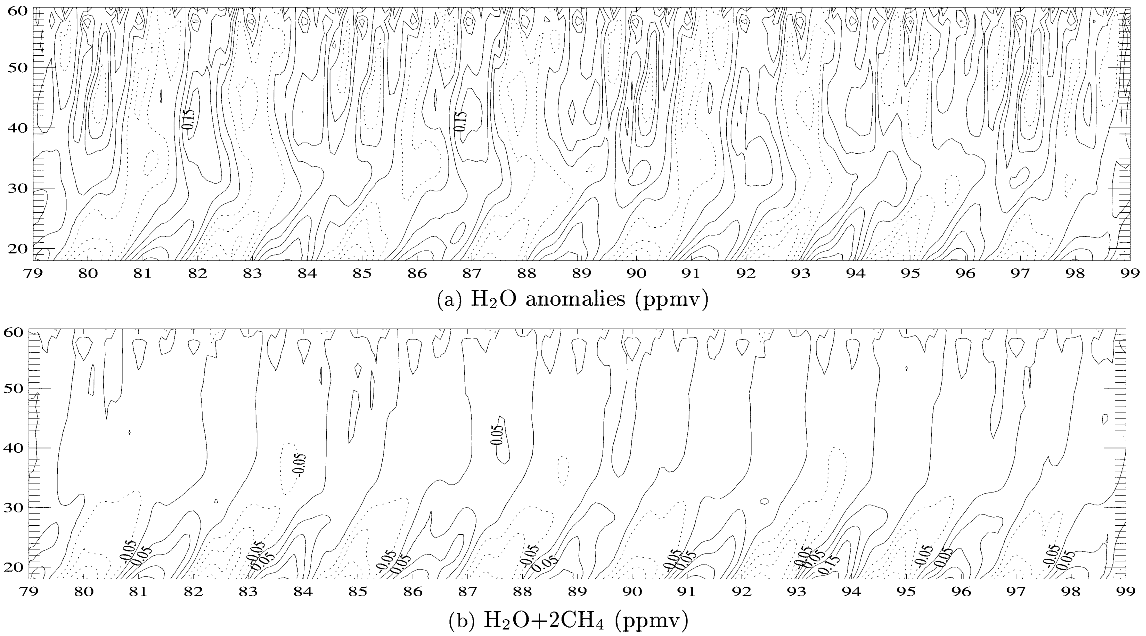

FIG. 6. Altitude–time sections of the (a) H_2O and (b) H_2O+2CH_4 anomalies over 2.5°N for the experiment in which both the QBO signature in tropical cold point tropopause temperatures and the QBO-induced circulation were considered. Anomalies are the difference of monthly outputs between the current experiment and the standard run. The contour interval is 0.05 ppmv.

low frequency QBO and ENSO ''tape recorders'' in addition to the well known annual tape recorder that was documented by Mote et al. (1996). These results are very consistent with the results from Giorgetta and Bengtsson (1999) even though our modeling approaches are very different. Both our modeling works predict the existence of low frequency tape recorders that are associated with QBO and ENSO modulation of tropical CPT temperatures. We have presented strong observational evidence for the existence of the QBO tape recorder, but at the present time there is insufficient evidence to verify the existence of the ENSO tape recorder. Clearly then, there is evidence for interannual variations in stratospheric trace species that arise from dynamical redistribution (e.g., the CH_4 and N_2O results in OD97 and R98), but in the special case of H_2O, there is also interannual variation caused by changes in dehydration conditions.

Some uncertainty in the magnitude of water vapor variations in these various tape recorders exists so long as there exist corresponding uncertainties in when and where air enters the stratosphere from the troposphere (e.g., Dessler 1998; Zhou et al. 2001a). There is also some uncertainty in the physical processes that determine the degree of saturation in that air (e.g., Danielsen 1982; Sherwood and Dessler 2000).

For simplicity, in this paper the SMRs at the tropical CPT derived from ECMWF reanalyses were used to specify the entry value of water vapor mixing ratio at the tropical CPT. The observational record on this point is anything but clear, however. A few observations showing that air parcels at the tropical CPT are saturated during strong convective events can be found in Teitelbaum et al. (2000). However, there are some observations indicating that air parcels at the tropical CPT may be unsaturated or oversaturated (Vömel et al. 1995;

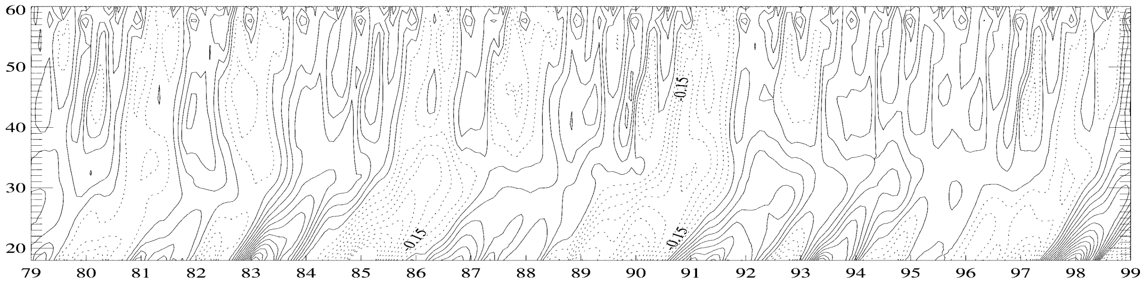

FIG. 7. Altitude–time section of the H_2O anomalies over 2.5°N for the experiment in which the QBO and ENSO signatures in tropical cold point tropopause temperatures and the QBO-induced circulation were considered. Anomalies are the difference of monthly outputs between the current experiment and the standard run. The contour interval is 0.05 ppmv.

Vömel and Oltmans 1999). Specifying the entry value of water vapor mixing ratio across the tropical tropopause according to tropical CPT SMRs assumes that temperature is the major factor that determines large-scale and/or long-time (with respect to convective events) features of the entry value of water vapor. This assumption is probably true, and is implied by the ''annual tape recorder,'' which is related to the annual cycle of tropical tropopause temperatures (Mote et al. 1996).

When discussing Fig. 1, it was pointed out that more upward propagation was evident in the HALOE total hydrogen interannual anomalies shown in the bottom panel than was evident in the H_2O interannual anomalies shown in the middle panel. The reason for this lies in the fact that the H_2O anomalies were seen to have been produced by dynamical redistribution above about 30–35 km, whereas the anomalies below this altitude were seen to be due to the QBO tape recorder signature of the QBO variations in the tropical tropopause. In the case of the H_2O+2CH_4 anomalies, of course, dynamical redistribution produces a smaller signature due to its smaller spatial gradients. In the case of ENSO variations due to ENSO modulation of the tropical tropopause (Zhou et al. 2001b), again a pure tape recorder signal was seen in H_2O since, in the absence of information, no ENSO changes were taken to be present in the stratosphere. Thus, in this case we expect pure tape recorder signals to be seen throughout the entire stratosphere due to the relative isolation of stratospheric tropical air from midlatitude air. On the other hand, when the tape recorder signal competes with dynamical redistribution (e.g., the annual and QBO cycles in H_2O), we expect an upward propagation signature to give way to a redistribution signature above about 30 km.

b. Conclusions

There are both specific and general conclusions to be drawn from the results in this paper. Some of the specific conclusions are as follows.

1) The SUNY-SPb 2D model is able to simulate most features of the annual cycle of stratospheric water vapor and methane.
2) Water vapor anomalies due to the QBO circulation show large values in the middle stratosphere, consistent with the vertical structure of observations (R98). However, they are too small to explain the observed interannual anomalies of water vapor in the tropical lower stratosphere.
3) Water vapor (H_2O) anomalies associated with the QBO circulation are approximately canceled by methane (CH_4) anomalies in the simulation. The observed upward propagation of H_2O+2CH_4 anomalies must be due to low-frequency modulation in the water vapor entry value at the tropical CPT.
4) The influences of low-frequency thermal effects in CPT temperatures associated with the stratospheric QBO and the tropospheric ENSO produce low frequency tape recorder signals.

In a more general sense, interannual variations in stratospheric water vapor have two general causes—the interannual variability of stratospheric dynamics and the interannual variability in the entry value of the water vapor mixing ratio. Of course, these two processes are not completely independent. For instance, changes in tropical upwelling will give rise to changes in the tropical tropopause, and it is also part of the entire transport circulation. Some insight may be gained into these processes by comparing the variations of conserved chemical tracers, such as CH_4 and N_2O, with water vapor. In the case of CH_4 and N_2O, no analogy to water vapor dehydration exists, so only transport effects exist.

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