The Tropical Semiannual Oscillations in Temperature and Ozone as Observed by the MLS

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ABSTRACT

The first two years of MLS temperature and ozone data are used to examine the tropical upper-stratospheric SAO. Time series analysis revealed that the strongest amplitudes of the SAO occurred near the equator at 2 mb for temperature and 5 mb for ozone, consistent with previous observations. The first cycle of each calendar year was observed to have a much higher amplitude than the second cycle except for the warm phase in late 1991. Interannual variability in the strength of the SAO, such as the much stronger warm phase of late 1991 as compared to late 1992, was significant and could be partly attributed to the QBO in zonal wind.

1. Introduction

The tropical semiannual oscillation (SAO) was first discovered in radiosonde and rocketsonde measurements of zonal wind and temperature by Reed (1962, 1966). Subsequent studies (Hirota 1980) utilized more extensive radio/rocketsonde measurements, and more recently satellite measurements (Maeda 1984; Hitchman and Leovy 1986; Delisi and Dunkerton 1988; Sun and Leovy 1990), to further detail the observed characteristics of the tropical SAO.

The SAO has gained so much attention over the past three decades mostly because it is the strongest mode of variability in the Tropics above 30 km. It was discovered by Hirota (1978) that two distinct SAOs exist in the Tropics: one at the level of the stratopause, and the other at the level of the mesopause. The stratopause SAO is characterized by the occurrence of easterly winds during the solstice seasons and westerly winds during the equinoxes, each phase having an amplitude of about 30 ms^{-1}. The first cycle of the calendar year typically has a stronger amplitude than the second cycle. The easterly phase is observed to appear almost simultaneously from the lower mesosphere to the middle stratosphere, while the westerly phase appears first above 60 km and descends slowly, taking up to 2 months to reach the middle stratosphere.

Several sources of zonal momentum that are thought to contribute to the zonal wind SAO have been identified. High-speed Kelvin wave and gravity wave propagation into the upper stratosphere and the resultant deposition of eddy zonal momentum is thought to be the most significant forcing of the westerly acceleration (Holton 1975; Hirota 1978; Dunkerton 1979; Hitchman and Leovy 1988; Hamilton and Mahlman 1988). Easterly accelerations, on the other hand, appear to be forced meridionally by planetary waves and meridional advection. The most prominent sources of easterly momentum flux are believed to be mean advection of summer easterlies across the equator (Holton and Wehrbein 1980) and lateral momentum transfer by planetary waves in the winter hemisphere (Hamilton and Mahlman 1988; Andrews et al. 1987). The asymmetry in the two SAO cycles each calender year is thought to be due to the fact that the equatorward Eliassen–Palm flux due to planetary Rossby waves is stronger in the Northern Hemisphere winter than in the Southern Hemisphere winter (Delisi and Dunkerton 1988). This would cause a stronger easterly phase near the northern winter solstice, allowing greater momentum deposition from Kelvin and/or gravity waves, subsequently resulting in a stronger westerly acceleration.

Due to the dynamical and photochemical balance in the tropical middle atmosphere, the SAO in zonal wind is associated with SAOs in other geophysical fields. To maintain thermal wind balance, an SAO in temperature follows that in zonal wind. The temperature SAO is sustained against radiative damping by a secondary mean meridional circulation, which has descent (ascent) and warming (cooling) over the equator in westerly (easterly) zonal wind shear (Andrews et al. 1987).

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The temperature SAO has been observed to have maximum amplitudes of 2–4 K over the equator at about 2–3 mb (Angell and Korshover 1970; Nastrom and Belmont 1975; Crane 1979; Gao et al. 1987). The cold phase descends with the easterly shear zone around the solstice seasons, and the warm phase descends with the westerly shear zone in the equinox seasons.

Ozone has a short photochemical lifetime in the tropical upper stratosphere (several hours to several days); this lifetime depends inversely on the local temperature (Froidevaux et al. 1989; Perliski et al. 1989). Thus, ozone responds quickly and in the opposite sense to any change in temperature, which suggests that a significant SAO in ozone should exist in the tropical stratosphere. The ozone SAO has been observed to have maximum amplitudes of 0.3–0.55 ppmv over the equator between 3 and 6 mb (Maeda 1984; Belmont 1985; Perliski and London 1989). It descends a half-cycle out of phase with temperature from the stratopause to about 10 mb. Below this level the photochemical lifetime of ozone becomes long enough that dynamical changes become important and the ozone SAO loses its close out of phase relationship with the temperature SAO.

2. Data

The Microwave Limb Sounder (MLS) on the *Upper Atmosphere Research Satellite (UARS)* measures atmospheric microwave thermal emission, which is inverted to obtain profiles of temperature, O_3, and several other trace molecules (Waters 1993). MLS measurements cover from 80° in one hemisphere to 34° in the opposite hemisphere. The satellite performs a yaw maneuver to keep some of the instruments protected from the sun's radiation, every 36 days or so, which allows high-latitude coverage to switch between north and south with this period.

The MLS data used in this study is from the period 1 October 1991–30 September 1993 (*UARS* days 20–750) and latitudes equatorward of 34°, since this region is measured nearly continuously. MLS Version 3/level 3AL data, which is linearly interpolated with respect to latitude along the measurement tangent-point track onto a regular 4 deg latitude grid, were used to make zonal mean time series. For this data version, the vertical range of most reliable MLS temperature measurements is from 22 to 0.46 mb, with values below 22 mb obtained by linearly interpolating National Meteorological Center (NMC) daily analysis onto the MLS retrieval grid, or when NMC analysis is not available, a climatology developed by the *UARS* science team is used. The MLS 205-GHz channel ozone measurements used in this study are most reliable between 46 and 0.46 mb. The vertical resolution of the MLS measurements is approximately 5 km, although vertically interpolated MLS data is included at the standard *UARS* levels (2.5-km resolution) in between the MLS measurements. A complete overview of the first 2 years of MLS zonal mean results is given by Froidevaux et al. (1994).

3. Observed SAO

A Fourier analysis of the 2-year time series of zonal mean temperature and ozone was performed to isolate the semiannual harmonic. Time gaps were filled by linear interpolation,[1] and the data were smoothed in time using a 13-point low-pass filter. The Fourier analysis revealed the semiannual amplitude of temperature (Fig. 1a) to have a maximum of 4.5 K centered over the equator at 2 mb with a latitudinal half-width of 15°, which is consistent with previous studies. The first positive maximum at 2 mb occurred on approximately 15 April (Fig. 1c). The semiannual amplitude of ozone (Fig. 1b) had a region of maxima (>0.55 ppmv) centered over the equator between 4 and 5 mb, with a latitudinal half-width of 20°. The first positive maximum at 2 mb occurred on approximately 15 April (Fig. 1c). The semiannual amplitude of ozone (Fig. 1b) had a region of maxima (>0.55 ppmv) centered over the equator between 4 and 5 mb, with a latitudinal half-width of 20°. The first positive maximum of ozone in this region occurred on approximately 15 February (Fig. 1d). The ozone SAO was almost exactly half a cycle out of phase with temperature in the upper stratosphere, consistent with ozone photochemistry. At 5 mb over the equator the first positive maximum of ozone occurred on 15 February, less than 2 weeks from the time of the first SAO temperature minimum at this level.

Two regions of secondary ozone SAO amplitude maxima are seen at 10 mb, 15°S, and 25°N, each of which had a positive maximum during the first week of April. The ozone SAO in each of these regions was only about a month out of phase with the temperature SAO, despite the fact that the photochemical lifetime of ozone in these regions is only 1–2 weeks, which would suggest a close half-cycle (or 3 month) out of phase relation with temperature. At 10 mb, ozone destruction is known to be dominated by the NO_x chemical family (Perliski et al. 1989). In their study of Solar Backscatter Ultraviolet (SBUV) and Limb Infrared Monitor of the Stratosphere (LIMS) data, Sun and Leovy (1990) found an ozone SAO maximum at 10 mb over the equator that they attributed to an SAO in the NO_x species concentration, which was believed to be mostly caused by an SAO in the residual mean circulation. Since NO_x species are controlled by a combination of dynamics and photochemistry in this region, if the vertical component of the residual mean circulation were positive, NO_x would decrease due to

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[1] The longest time gap occurred from 29 May to 7 June 1992 (*UARS* days 261–271).

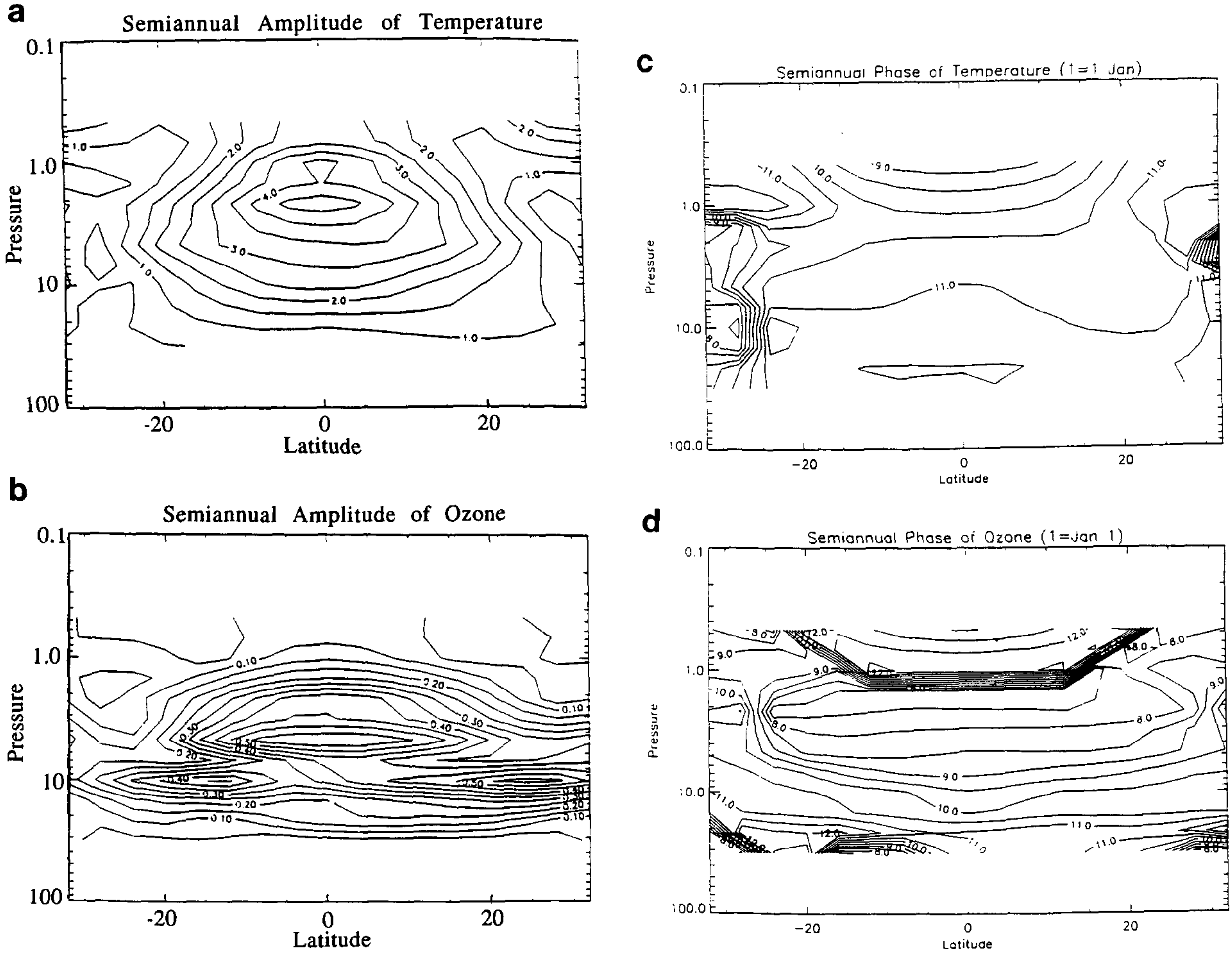

FIG. 1. The semiannual amplitudes and phases of temperature (a,c) and ozone (b,d) from a Fourier analysis of 2 years (Oct 1991–Sep 1993) of MLS data. Amplitude contour intervals are 0.5 K and 0.05 ppmv, and the phase contour interval is 0.5 months with a value of 1.0 representing maxima on 1 Jan and 1 Jul.

its mean upward gradient and ozone would subsequently increase, and vice versa.

Residual mean circulation vertical velocities from 1992–93 produced from a radiative model that used species and temperature data from several *UARS* instruments (Rosenlof 1994, personal communication) contained an SAO with small amplitudes near the 10-mb level decreasing away from the equator. The SAO in the residual vertical velocity had positive maxima approximately 2 months out of phase with ozone and 3 months out of phase with temperature in the 10-mb region. The out of phase relationship between temperature and residual mean vertical velocity is expected due to adiabatic cooling associated with ascent and adiabatic heating associated with descent. But if vertical advection of NO_x species were controlling the ozone SAO at 10 mb, the residual mean vertical velocity and ozone SAOs should be closely in phase. So the SAO in vertical advection in the Tropics does not seem to explain the latitudinal structure of the ozone SAO at 10 mb seen in the MLS data.

The ozone SAO maximum over the equator at 4 mb had amplitudes larger than in most previous studies, especially compared with the SAO amplitude maximum in the 9 years (October 1978–September 1987) of SBUV ozone, which was about 0.3 ppmv between 3 and 6 mb as computed by Perliski and London (1989). At 10 mb a small region of SAO amplitude maxima is seen at 20°–25°N and 10°–15°S in Perliski and London's (1989) study, but these maxima regions are much less noticeable compared to those in the MLS data. The finer vertical resolution of MLS, compared to SBUV, may explain much of the amplitude difference in ozone SAO between the two datasets, as well as the greater detail in the shallow 10-mb amplitude features seen in MLS data.

Time–height cross sections of the MLS temperature and ozone deviations from their respective 2-year means over the equator are shown in Figs. 2a,b. The time series reveal the SAO as the dominant pattern of variability, with the largest negative temperature and positive ozone deviations (≈10 K and 1.2 ppmv) occurring in the upper stratosphere, around the stratopause for temperature and at 3 mb for ozone. The negative temperature and positive ozone deviations occur almost simultaneously over a large depth, extending down into the middle stratosphere during the solstice seasons. The positive temperature (8–10 K) and neg-

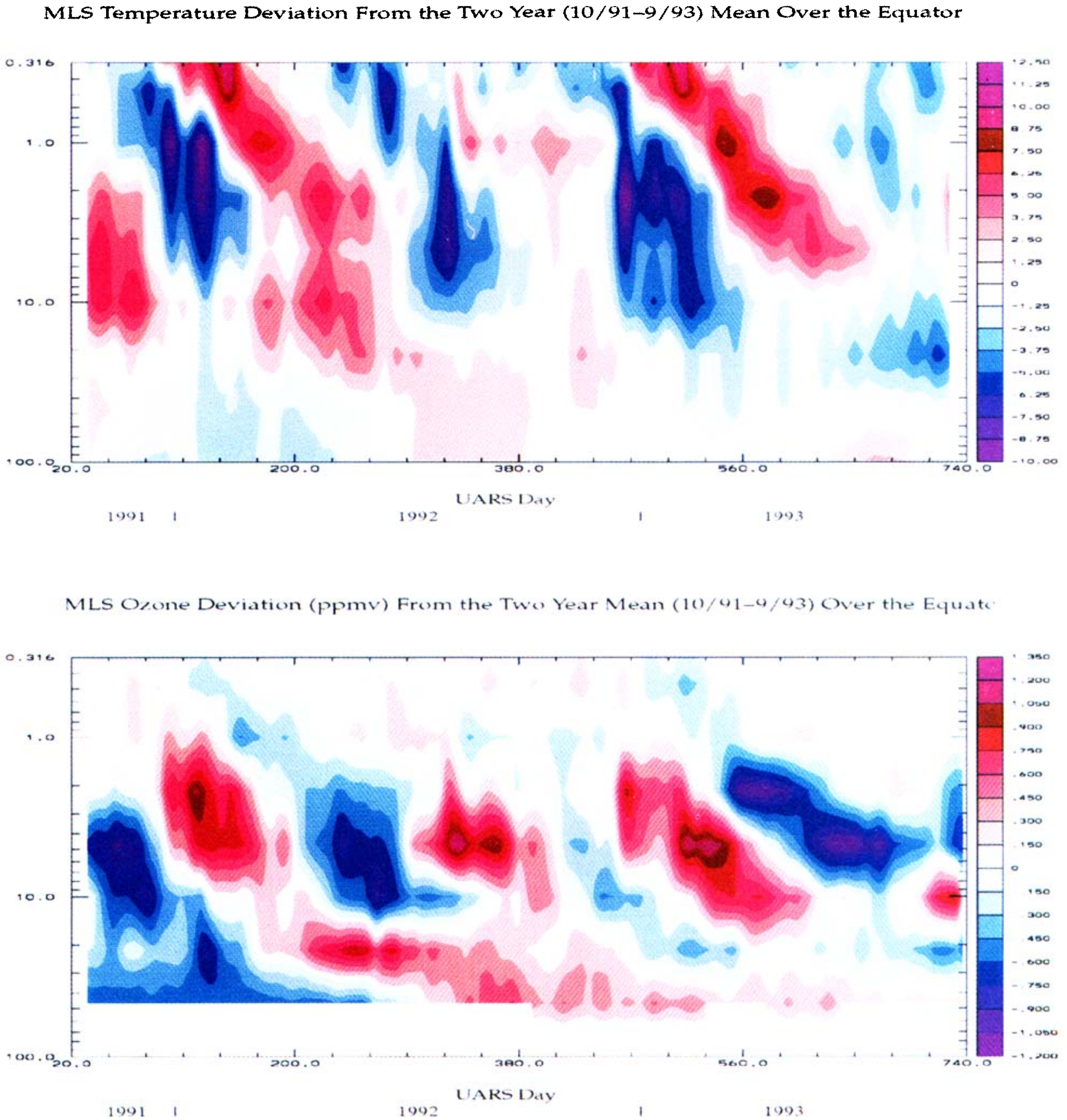

FIG. 2. Time–height cross section of MLS (a) temperature (K) and (b) ozone (ppmv) deviations from the 2-year (Oct 1991–Sep 1993) mean over the equator. *UARS* day 20: 1 Oct 1991, *UARS* day 200: 29 Mar 1992, *UARS* day 380: 25 Sep 1992, *UARS* day 560: 24 Mar 1993, and *UARS* day 740: 20 Sep 1993.

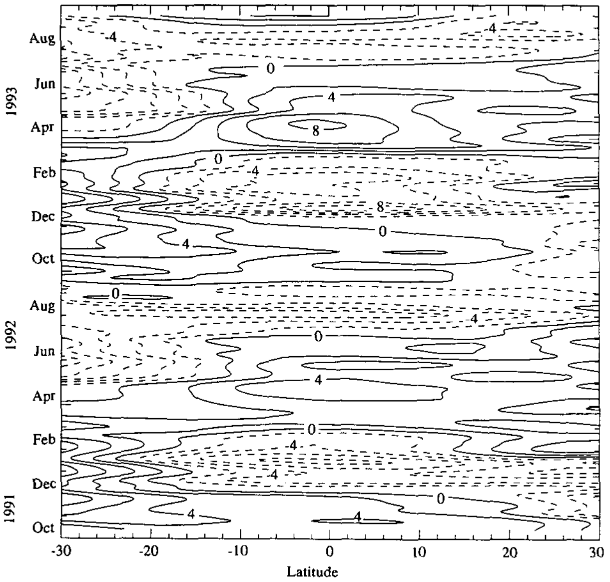

FIG. 3a. Time–latitude cross section of MLS temperature deviations from the 2-year mean at 2.1 mb. Contour interval is 2 K.

ative ozone (−1 ppmv) deviations originate near the stratopause and descend more gradually to the middle stratosphere over a period of about 2 months during the equinox seasons.

In the upper stratosphere, temperature and ozone deviations are a half-cycle out of phase, as expected from the inversely temperature-dependent photochemical control of ozone in this region. As the deviations descend below 10 mb the two fields become out of phase by only several weeks or less due to the transition of ozone from photochemical to dynamical control and the vertical gradient of ozone becoming positive (as for temperature) in this region.

Pulses of low temperatures of duration 1–2 weeks are noticeable in the first three cold phases of the SAO. These pulses coincide with high-latitude winter stratospheric warming events, which are compensated for in the Tropics by means of a global-scale meridional circulation (Fritz and Soules 1972; Hitchman and Leovy 1986; Delisi and Dunkerton 1988; Randel 1993). This circulation has rising motion and adiabatic cooling in the Tropics, which enhances the negative SAO deviations in temperature, associated with the easterly shear zone during this period.

The first SAO cycle of each calendar year generally had a larger amplitude during the two-year period than the second cycle. In the first cold phases of 1992 and 1993, deviations at 2 mb exceeded 9 K, while during the second cold phases the deviations at 2 mb reached 7 and 3 K during 1992 and 1993, respectively. The warm phases had a similar relation with deviations at 2 mb reaching 6 and 8 K during early 1992 and 1993, respectively, while deviations reached only 2 K in late 1992. The warm phase of late 1991 had deviations of 5 K at 2 mb and 6 K from 10 to 3 mb, which were larger deviations than during any of the subsequent warm phases below 3 mb. This suggests a significant interannual variability in the strength of the SAO.

Small oscillations with a period of approximately 35 days (which corresponds with the yaw frequency of the satellite) noticeable in both the temperature and ozone time series (Fig. 2) are an artifact of the current MLS data processing. This oscillation has been decreased in more recent versions of the MLS data but has not been completely resolved (E.F. Fishbein and L. Froidevaux 1994, personal communication).

Time–latitude cross sections of temperature deviations at 2 mb (Fig. 3a) and ozone deviations at 4.6 mb (Fig. 3b) reveal the latitudinal structure of the two fields at the levels of maximum SAO amplitudes. The temperature deviations at 2 mb show the broad region of SAO variability around the equator with a transition to annual variability poleward of 20°. Ozone deviations at 4.6 mb also show strongest SAO variability near the equator, with annual variability poleward of 20°. The latitudinal structure of the ozone variability is characterized by maximum deviations occurring about 10° north or south of the equator, in contrast to the temperature deviation pattern that has local maxima centered on the equator. This displacement of ozone deviations off the equator is explained by the latitudinal displacement of the ozone maximum values, which approximately follow the latitude of the lowest solar zenith angle, moving to about 10° in the summer hemisphere around the time of the summer solstice (Fig. 3c).

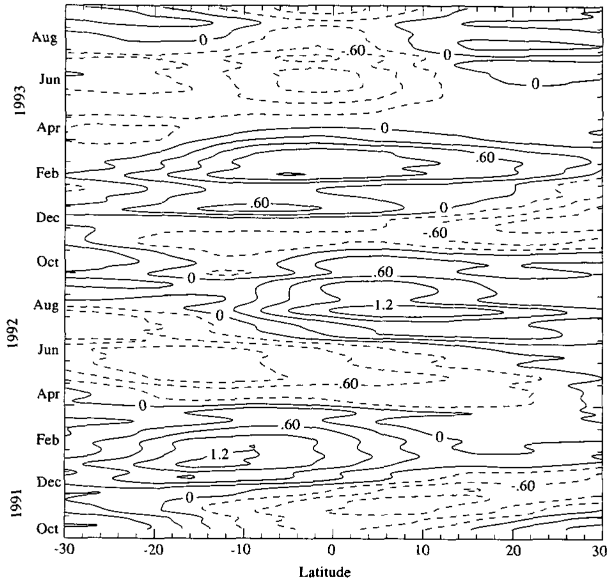

FIG. 3b. Time–latitude cross section of MLS ozone deviations from the two-year mean at 4.6 mb. Contour interval is 0.15 ppmv.

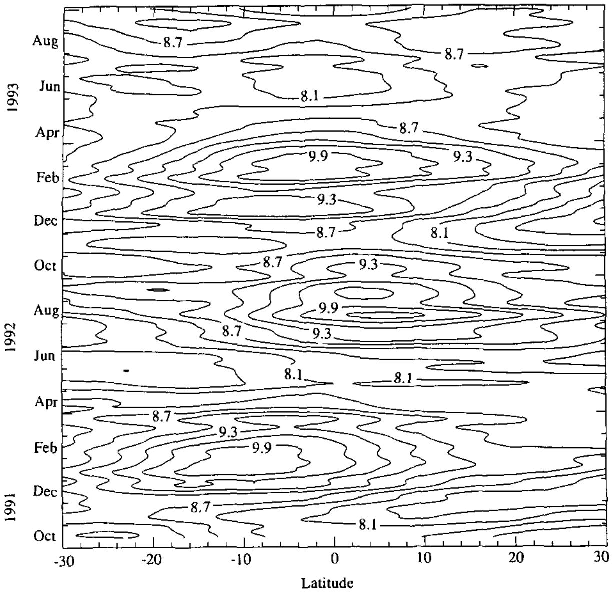

FIG. 3c. Time–latitude cross section of absolute values of MLS ozone at 4.6 mb. Contour interval is 0.2 ppmv.

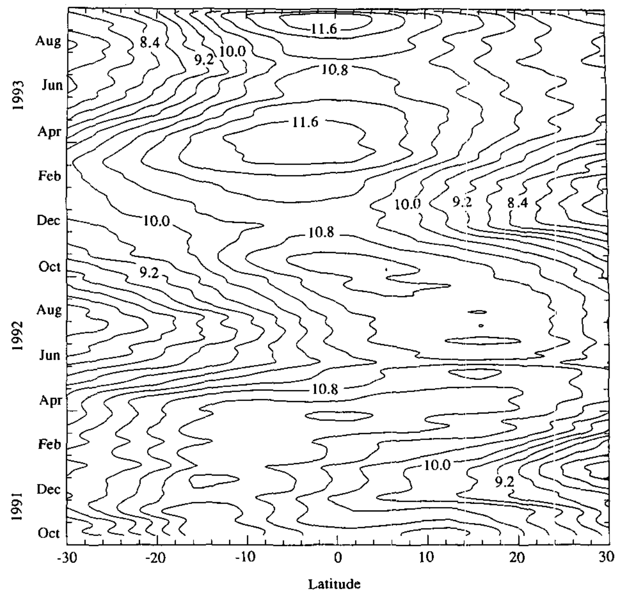

FIG. 3d. Same as Fig. 3c except at 10 mb. Contour interval is 0.25 ppmv.

At 10 mb, the time–latitude plot of ozone (Fig. 3d) reveals a similar, but more pronounced, shift of maximum mixing ratios into the summer hemisphere in comparison to that at the 4.6-mb level. The summer hemisphere at the 10-mb level is also characterized by relatively small temporal changes, while late fall and early winter are marked by a rapid decrease in ozone mixing ratios followed by a rapid increase in late winter and early spring. This rapid winter decrease in ozone could be due to more effective horizontal transport of high NO_x air into the subtropical and tropical region due to increased wave activity in the winter. Future studies of NO_x measurements from the Cryogenic Limb Array Etalon Spectrometer (CLAES) instrument aboard *UARS* may help to determine the cause of ozone variability in this region.

Interannual variability

Much of the interannual variability in the strength of the SAO, as mentioned in the previous section, can be accounted for by the quasi-biennial oscillation (QBO) in zonal wind. A time–height cross section of U.K. Meteorological Office (UKMO) zonal wind over the equator is shown in Fig. 4. The UKMO winds are produced by a special version of the UKMO data assimilation system, designed for use by the *UARS* project. The system assimilates measurements from radio/rocketsondes and NOAA polar orbiter satellites (Lorenc et al. 1991). The QBO pattern is prominent below 10 mb, with easterlies from late 1991 to late 1992 and westerlies from late 1992 to late 1993. Above 10 mb the variability changes to an SAO pattern.

The QBO in zonal wind affects the upper-stratospheric SAO in two ways. The first is the temperature perturbation due to the zonal wind shear and subsequent mean meridional circulation required to maintain thermal wind balance at the levels, typically between 5 and 20 mb, where QBO winds change to SAO winds (Andrews et al. 1987). When the SAO phase is op-

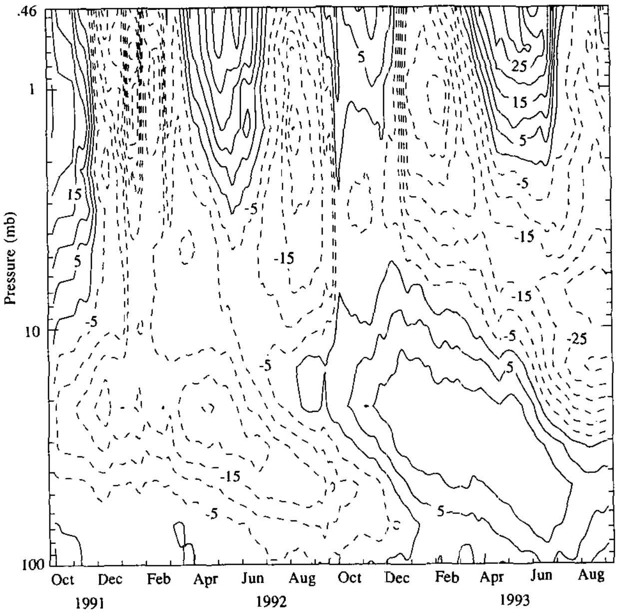

FIG. 4. Time–height cross section of zonal mean UKMO zonal wind over the equator from Oct 1991 to Sep 1993. Contour interval is 5 m^{-1}.

posite to that of the QBO, a strong shear zone results that produces a large perturbation in temperature, whereas when the SAO and QBO are in phase, the shear is weak and the temperature perturbation is relatively small. The second effect of the zonal wind QBO on the strength of the zonal wind SAO is due to the different transmissivity of the lower stratosphere to vertically propagating waves during the different phases of the QBO (Dunkerton 1979). The presence of QBO easterlies is conducive to higher propagation of Kelvin waves and westerly gravity waves, which enhance the westerly SAO phase. The presence of QBO westerlies is only conducive to the propagation of easterly gravity waves that would enhance the easterly SAO phase and diminish the westerly SAO phase. Conflicting results were obtained from two observational studies of Kelvin wave propagation to the stratopause region and its effect on the SAO. Randel and Gille (1991) determined that Kelvin waves were not a deciding factor in the interannual variability of the SAO at the stratopause level, while Hirota et al. (1991) found high Kelvin wave amplitudes to be closely related to westerly acceleration of the zonal wind SAO at the stratopause level and also found a QBO modulation of the stratopause SAO.

The MLS and UKMO data generally confirm the theory of Dunkerton (1979) and the observational evidence of Hirota et al. (1991). A strong SAO westerly phase overlays QBO easterlies in late 1991 and the strong westerly shear between 20 and 2 mb corresponded to a strong warm phase in temperature (Fig. 2a). The QBO westerlies at their onset in August and September 1992 underlay a strong easterly SAO phase, which coincided with a strong low temperature SAO phase. The weak warm and cold phases of late 1992 and 1993, respectively, coincided with periods of negligible zonal wind shear between 20 and 2 mb. The warmer SAO phase of early 1993 as compared to early 1992 coincided with strong westerly shear between 1 and 3 mb. This high correlation between MLS temperature deviations and UKMO zonal wind shear zones also seems to imply a consistency between the MLS data and analyzed data from operational satellites.

4. Summary and conclusions

Analysis of 2 years of zonal mean tropical temperature and ozone data has revealed a significant semiannual oscillation in the middle and upper stratosphere. Fourier analysis revealed SAO amplitudes of temperature greater than 4 K over the equator at 2 mb and SAO amplitudes of ozone greater than 0.5 ppmv over the equator between 4 and 5 mb and at 20°–30°N, 10 mb, and amplitudes greater than 0.4 ppmv at 10°–20°S, 10 mb. The regions of SAO maxima in the upper stratosphere were expected from dynamical and photochemical theory and have been found in previous observational studies. The SAO maximum in ozone at 10 mb has been noticed previously (Sun and Leovy 1990), but the latitudinal structure found in the ozone SAO in this study was not expected, and the mechanism(s) responsible for the SAO in this region could not be identified easily.

Time–height cross sections of the 2 years of data show some of the details of the SAO, such as the more gradual descent of the warm, negative ozone deviations during the equinox seasons as compared to the sudden cold, positive ozone deviations during the solstice seasons. Also, 1–2-week pulses of cold temperatures during the first three cold phases are prominent and are well correlated with high-latitude stratospheric warmings.

Interannual variability in the strength of the SAO signal, particularly in the second cycles of each calendar year, is shown to correlate well with the QBO in zonal wind. The zonal wind shear at the levels where QBO winds change to SAO winds creates temperature deviations that vary in strength depending on the strength of the shear zone. Strong easterly shear zones are seen to coincide with strong cold SAO phases and strong westerly shear zones with strong warm SAO phases. The high correlation between MLS temperature deviations and UKMO zonal wind shear zones seems to imply a dynamical consistency between the MLS data and analyzed data from operational satellites.

Further study of *UARS* data, including more recent MLS ozone and temperature measurements, as well as revised versions of CLAES ozone and NO_x species, would surely reveal more details of the dominant SAO in the tropical upper stratosphere. CLAES data may also help to determine the cause of the SAO in ozone at 10 mb, which would allow a greater understanding of the interaction of dynamics and photochemistry in this region.

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