The Tropical Semiannual Oscillation (SAO) in Temperature and Ozone as Observed by the Microwave Limb Sounder (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 the strongest amplitudes of the SAO to occur near the equator at 2 mb for temperature and 5 mb for ozone, consistent with previous observations. The first cycle of each calender 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 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 SAO's 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 m/s. The first cycle of the calender year typically has a stronger amplitude than the second cycle, The easterly phase is observed to appear over a large depth, from the lower mesosphere to the middle stratosphere, almost simultaneously; the westerly phase appears first above 60 km and descends slowly, taking up to two 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

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Due to the dynamical and photochemical balance in the tropical middle atmosphere, the SAO in zonal wind is associated with SAO's 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). The temperature SAO has been observed to have maximum amplitudes of 2°K-4°K over the equator at about 2-3mb (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 a significant SAO in ozone should exist in the tropical stratosphere. The ozone SA() 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 microwave thermal emission from the atmosphere, 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 other during a single orbit. 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 October 1, 1991-September 30, 1993 (UARS days 20-750) and latitudes equatorward of 34°, since this region is measured nearly continuously. MLS Version 3 and level 3al data, which is latitudinally binned at four degree intervals, was used to make zonal mean time series. The vertical range of MLS temperature measurements is from 22- 0.46 rnb, with values below 22 mb consisting primarily of NMC measurements, while MLS ozone measurements extend from 46-0.04 mb.

3. Observed SAO

A Fourier analysis of the two year time series of zonal mean temperature and ozone was performed to isolate the semiannual harmonic. This analysis revealed the semiannual amplitude of temperature (Fig. la) 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 occured on April 15. The semiannual amplitude of ozone (Fig. lb) 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 occured on February 15. 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 occured on February 15, less than two 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 rnb, 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 one to two weeks, which would suggest a close half cycle (or three 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 SBUV and LIMS data, Sun and Leovy (1990) found an ozone SAO maximum at 10 mb over the equator which 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 its mean upward gradient and ozone WOUI d subsequent y increase, and vice versa.

Residual mean circulation vertical velocities from 1992-93 produced from a radiative model which used species and temperature data from several UARS instruments (Rosenlof, 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 two months out of phase with ozone and three 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 diabatic 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 SAO's 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 had amplitudes larger than in most previous studies, especially compared with the SAO maximum in the nine years (10/78-9/87) of SBUV ozone, which was about 3 ppmv as computed by Perliski and London (1989). The difference could be partly attributed to interannual variability in the strength of the SAO.

Time-height cross sections of the MLS temperature and ozone deviations from their respective two year means over the equator are shown in Figures 2a and 2b. Time gaps were filled by linear interpolation and the data was smoothed in time using a 13-point low-pass filter. The time series reveal the SAO as the dominant pattern of variability with the largest cold temperature and positive ozone deviations (1 0°K and 1.2 ppmv) occuring in the upper stratosphere, around the stratopause for temperature and at 3 mb for ozone. The onset of the cold temperature and positive ozone deviations occur almost simultaneously over a large depth, extending down into the middle stratosphere, during the solstice seasons. The warm temperature (8-10°K) and negative ozone (-1 ppmv) deviations originate near the stratopause and descend more gradually to the middle stratosphere over a period of about two 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, the same as temperature in this region.

Pulses of cold temperatures of duration one to two weeks are noticeable in the first three cold phases of the SAO. These pulses coincide with high

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

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, Randel, 1993). This circulation has rising motion and adiabatic cooling in the tropics which enhances the cold SAO deviations associated with the easterly shear zone during this period.

The first SAO cycle of each calender 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°K and 3°K during 1992 and 1993 respectively. The warm phases had a similar relation with deviations at 2 mb reaching 6°K and 8°K during early 1992 and 1993 respectively, while deviations only reached 2°K in late 1992. The warm phase of late 1991 had deviations of 5°K at 2 mb and 6°K from 10-3 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.

Time-latitude cross sections of temperature deviations at 2 mb (Fig. 3a) and ozone deviations at 6.8 mb (Fig. 3b) reveal the latitudinal structure of the two fields at the levels of maximum SAO amplitudes. The temperature deviations show the broad region of SAO variability around the equator with a transition to annual variability poleward of 20°. Ozone deviations show SAO variability near the equator, with annual variability poleward of 15°. The latitudinal structure of the ozone variability is characterized by maximum deviations occuring about 10° north or south of the equator, giving the appearance of a high latitude deviation which extended across the equator for a couple of months. This is in contrast to the temperature deviation pattern which has local maxima centered on the equator.

3.1 Interannual Variability

The variability in the strength of the SAO signal during the two-year time series of MLS ozone and temperature suggests a significant interannual component of variability. The largest interannual variability at the levels of maximum SAO amplitude were noticeable during the second cycles of each calender year. The first cycles of each calender year were similar in strength and period, with the most notable difference being the warmer (lower ozone) phase of early 1993 compared to early 1992. The second warm (low ozone) phase in 1991 and the second cold (high ozone) phase in 1992 were two to three times as large as the warm and cold phases in late 1992 and 1993 respectively.

Much of this interannual variability can be accounted for by the quasi-biennial oscillation (QBO) in zonal wind. A time-height cross section of UK Meteorological Office (UKMO) zonal wind over the equator is shown in Figure 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 (Swinbank and O'Neill, 1993). 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.

When the SAO phase is opposite to that of the QBO, a strong shear zone results which, similar to the shear zones between SAO phases, produces a perturbation in temperature by means of a meridional circulation to maintain thermal wind balance (Fig. 5). A strong SAO westerly phase overlays QBO easterlies in late 1991 and the strong westerly shear between 20 and 2 mb is also noticeable as a strong warm phase in temperature (Fig. 2a). The onset of QBO westerlies in August and September 1992 underlie a strong easterly SAO phase which coincides with a strong cold 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.

4. Summary and Conclusions

Analysis of two 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 to occur 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 20°-30°N, 10mb, and amplitudes greater than 0.4 ppmv at 10°-200S, 10 rnb. The regions of SAO maxima in the upper stratosphere were expected from dynamical and photochemical theory, and have been found in previous observational studies. However, the two regions of SAO maxima in ozone at 10 mb are unexpected and cannot be easily traced to a specific cause.

Time-height cross sections of the two 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, one to two 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 calender 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 which 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 presence of QBO easterlies is also 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 which would enhance the easterly SAO phase and diminish the westerly SAO phase. The 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

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FIGURE CAPTIONS

Figure 1: The semiannual amplitudes of (a) temperature and (b) ozone from a Fourier analysis of two years (10/91-9/93) of MLS data. Contour intervals are 0.5°K and 0.05ppmv.

Figure 2:· Time-height cross section of MLS (a) temperature ("K) and (b) ozone (ppmv) deviations from the two year (1 O / 91-9 /93) mean over the equator. UARS day 20 = 1 Ott 1991, UARS day 200 = 29 March 1992, UARS day 380 =25 Sp 1992, UARS day 560 = 24 March 1993, UARS day 740 = 20 Sep 1993.

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

Figure 3b: Time-latitude cross section of MLS ozone deviations (ppmv) from the two year mean at 6 mb. Contour interval is 0.15 ppmv.

Figure 4: Time-height cross section of zonal mean UKMO zonal wind over the equator from 10/91 -9/93. Contour interval is 5 m/s.

Figure 5: Schematic latitude-height sections showing the mean meridional circulation associated with the equatorial temperature anomaly of the QBO. (a) Westerly shear zone, (b) easterly shear zone. (Plumb and Bell, 1982)

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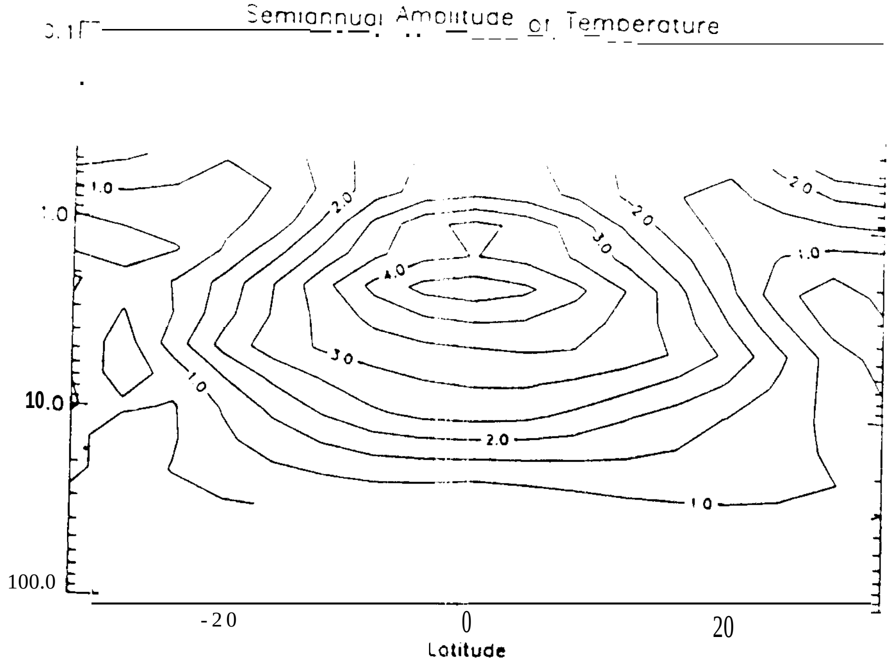
(a)



(b)

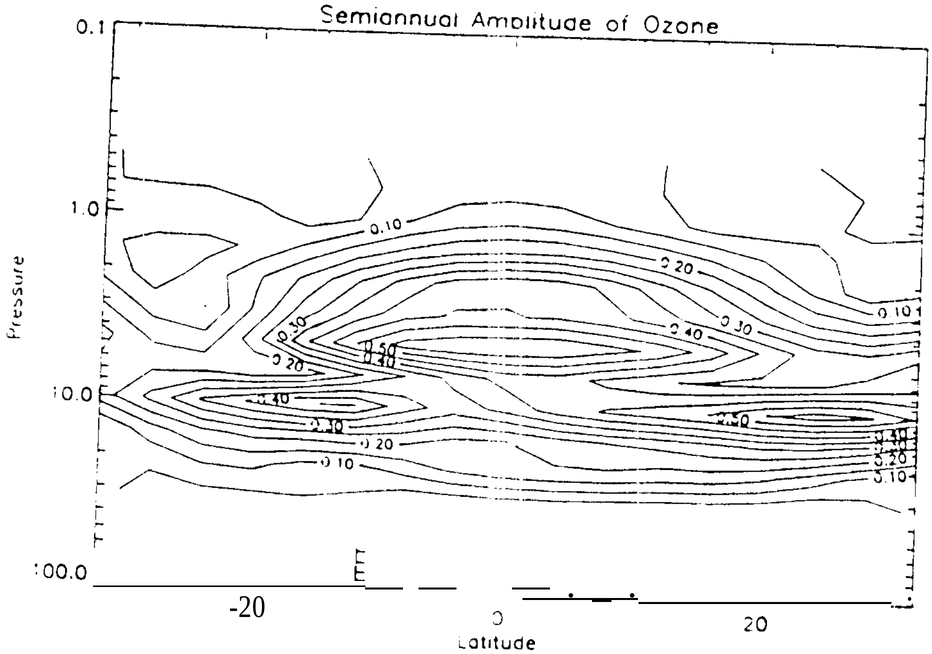
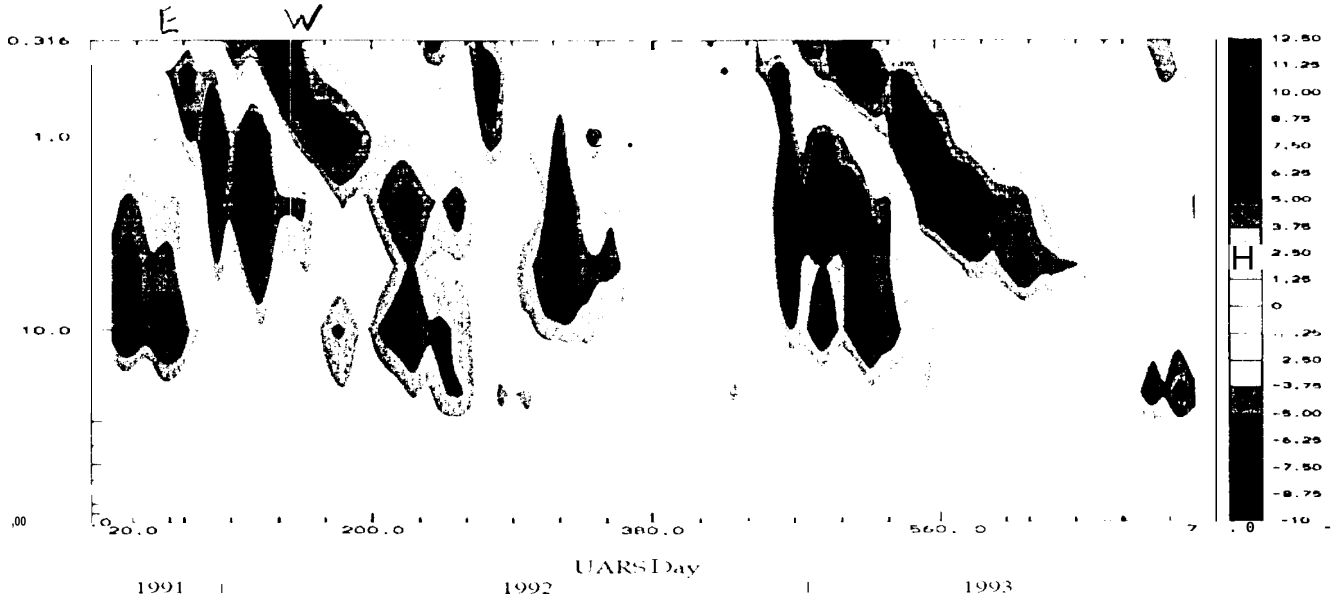
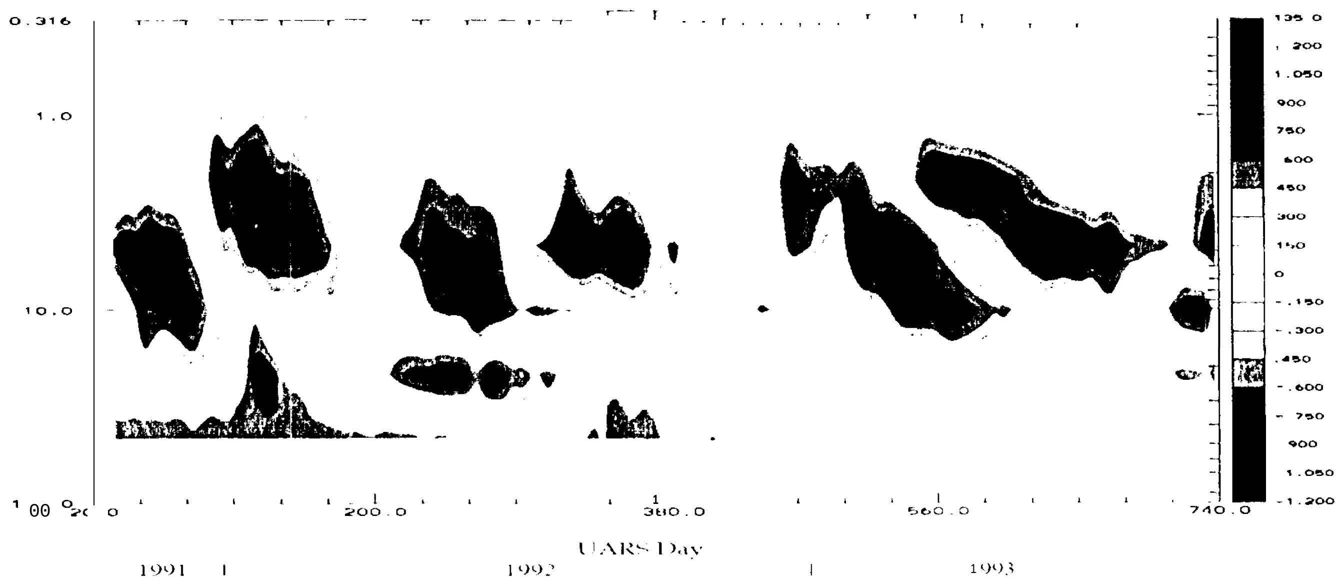


Figure 1 The semiannual amplitudes of (a) temperature and (b) ozone from a Fourier analysis of two years (10/91-9/93) of MLS data. Contour intervals are 0.5°K and 0.05 ppmv.

MLS Temperature Deviation From the Two Year (10/91-9/93) Mean Over the Equator



MLS Ozone Deviation (ppmv) From the Two Year Mean (10/91-9/93) Over the Equator



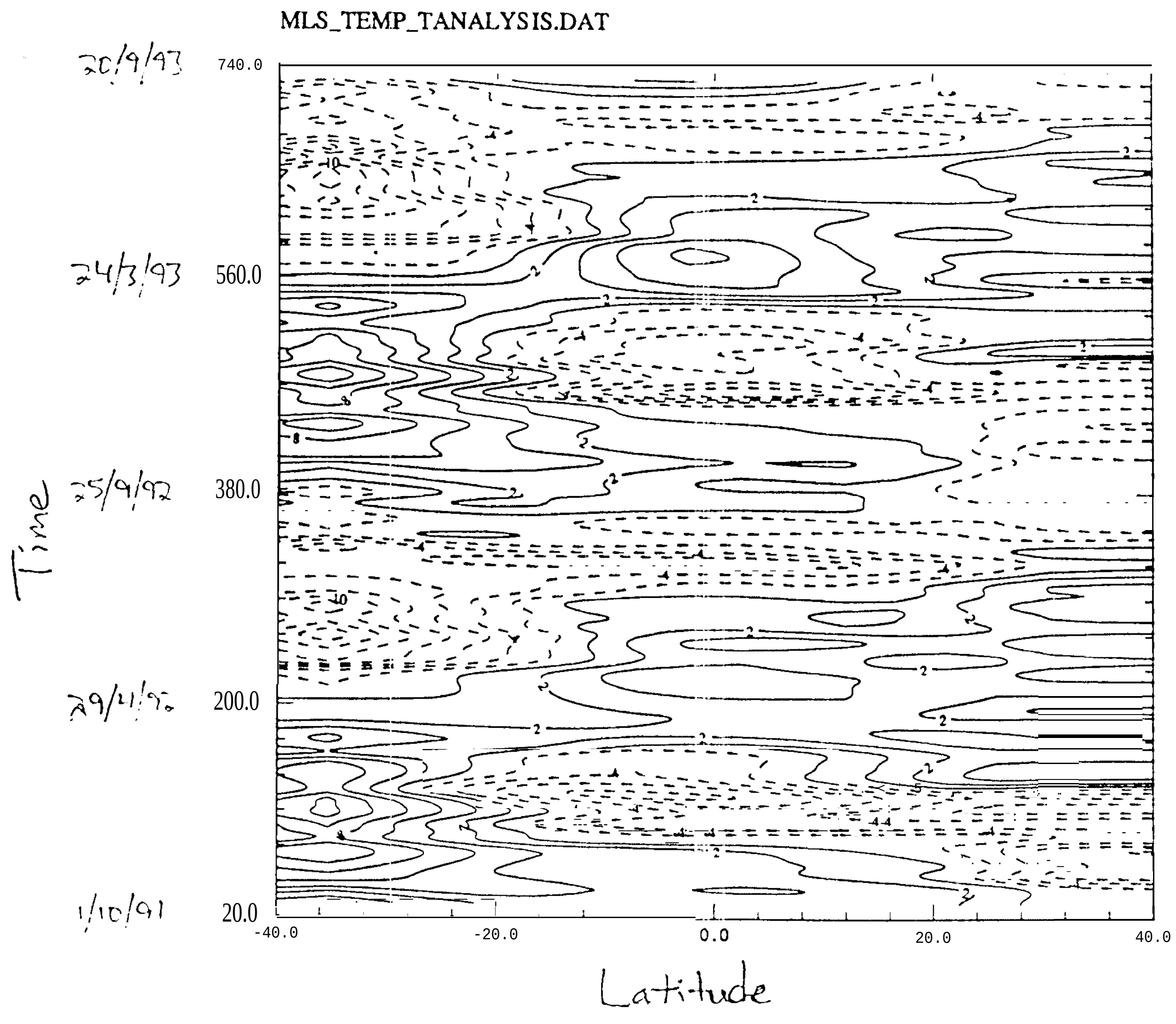


Figure 3a Time-latitude cross section of MLS temperature deviations from the two year mean at 2.1 mb. Contour interval is 2“K.

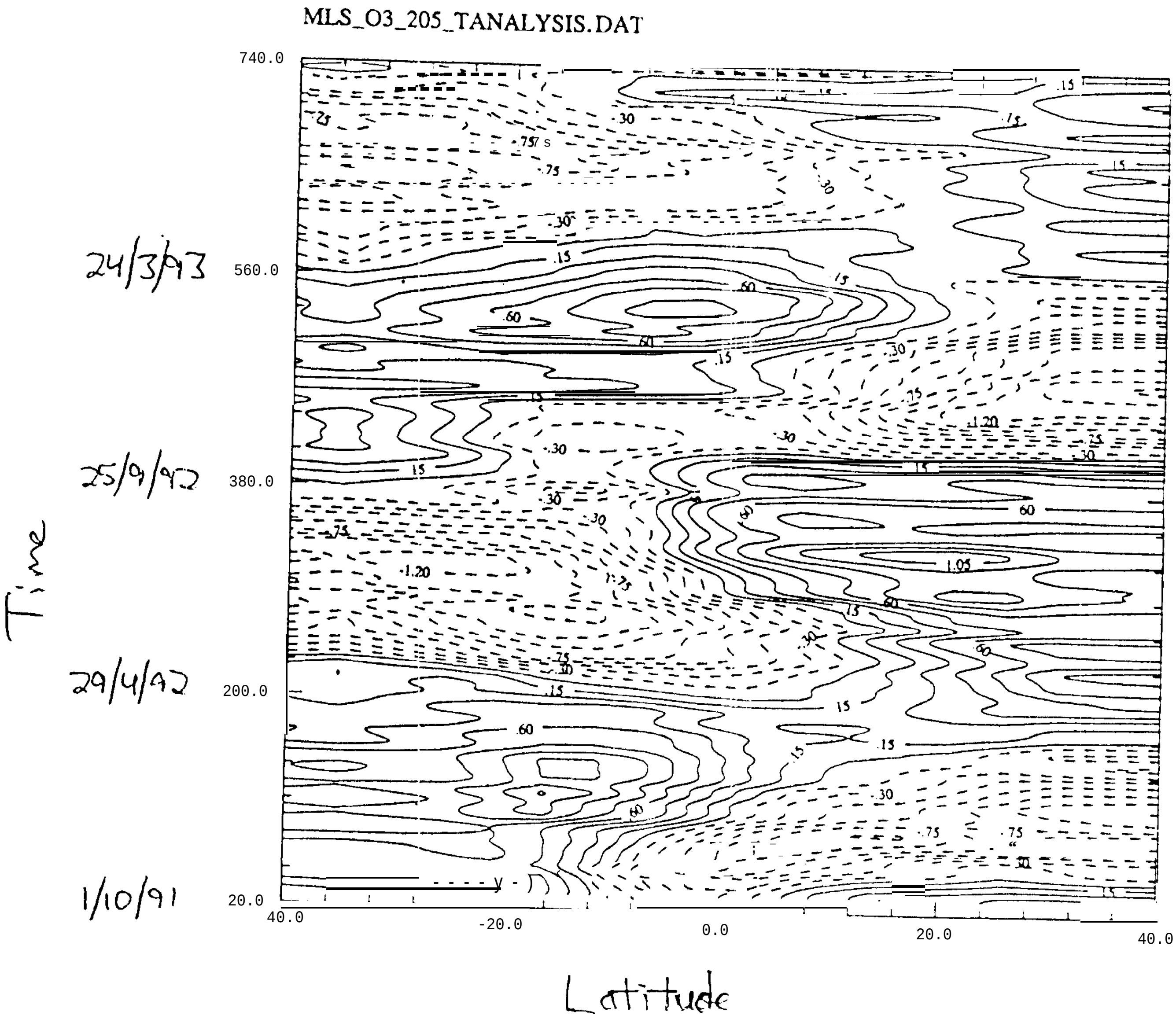


Figure 3b Time-latitude cross section of MLS ozone deviations (ppmv) from the two year mean at 6 mb. Contour interval is 0.15 ppmv.

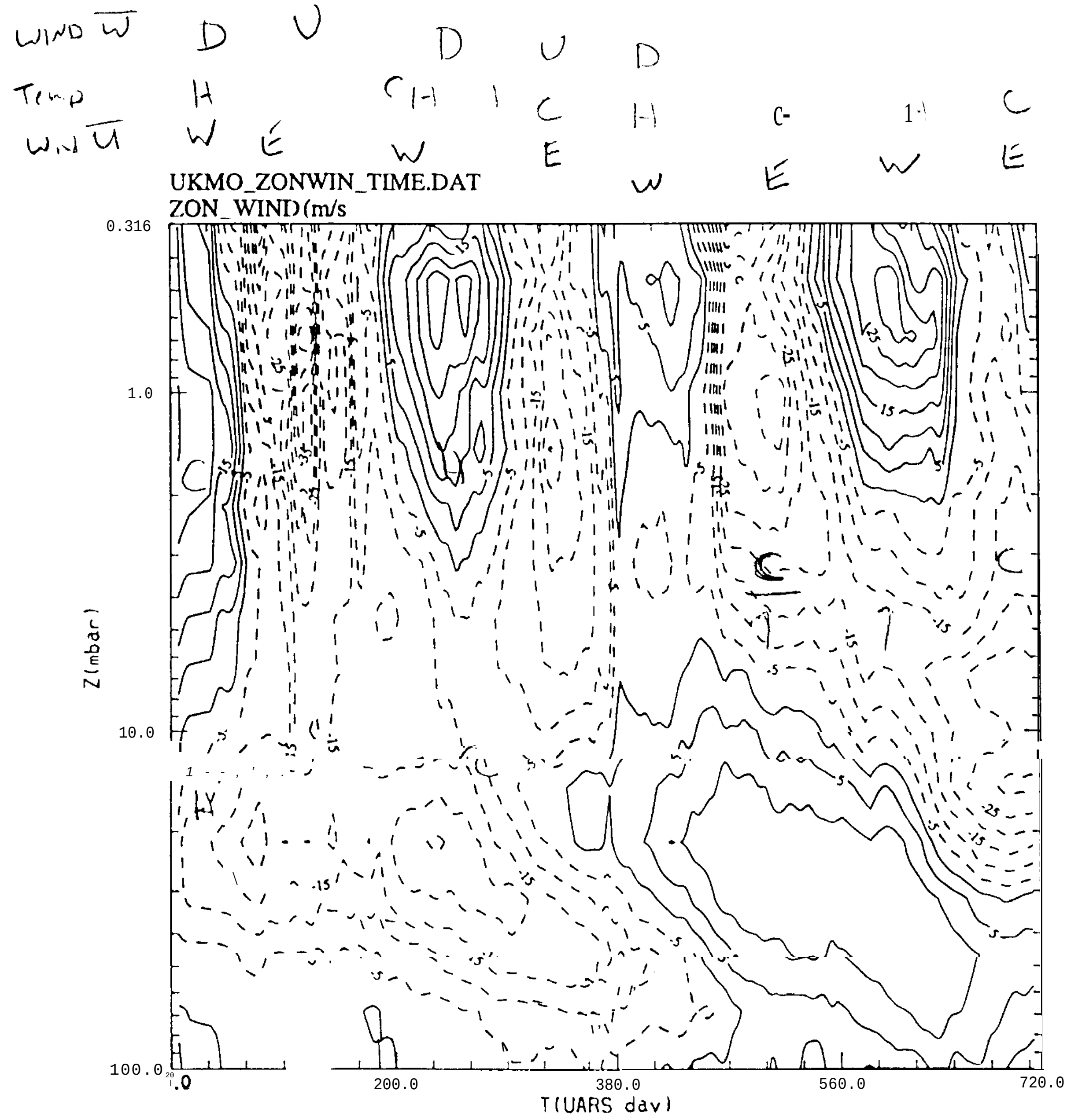


Figure 4 Time-height cross section of zonal mean UKMO zonal wind over the equator from 10/91-9/93. Contour interval is 5 m/s.

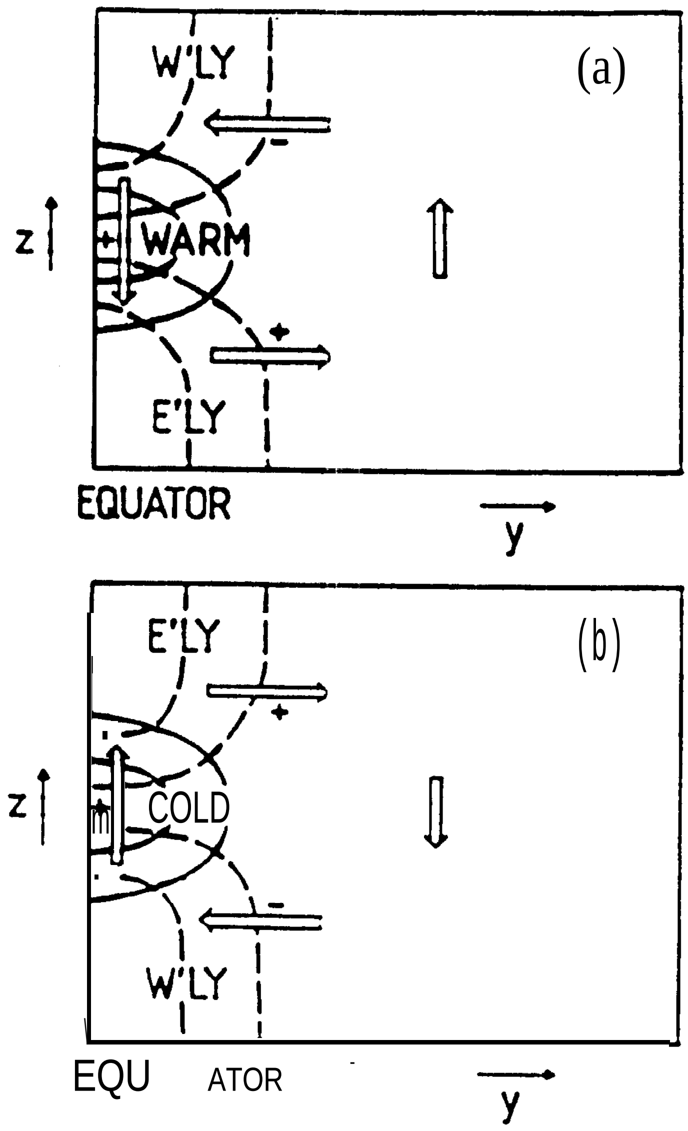


Figure 5: Schematic latitude-height sections showing the mean meridional circulation associated with the equatorial temperature anomaly of the QBO. (a) Westerly shear zone, (b) easterly shear zone. (Plumb and Bell, 1982)