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Equatorial Kelvin wave variability during 1992 and 1993

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Abstract. Temperature and ozone data from the Microwave Limb Sounder (MLS) instrument on UARS are used to analyze the variability of Kelvin wave activity during the first two years of the UARS mission. The analysis is carried out using the asynoptic mapping technique. Time frequency plots for zonal wavenumbers 1 and 2, at two heights representing the middle stratosphere and the stratopause, respectively, are used to analyze the temporal variability of the waves, and its possible relationship to the equatorial quasi-biennial oscillation (QBO) and semiannual oscillation (SAO). Kelvin wave activity reaches a maximum during the solstice seasons and almost disappears during the equinoxes, in agreement with previous studies. Eastward propagating variance is estimated for wave periods from 4 to 20 days, at all UARS pressure surfaces currently available for MLS. The semiannual modulation of variance is observed to extend down to the lower limits of the height ranges of the temperature and ozone retrievals. Furthermore, a superposed QBO modulation is detected up to the stratopause. Comparison between the variance in eastward propagating waves and the mean zonal wind shows a possible participation of kelvin waves in the forcing of the QBO. At the stratopause the role of Kelvin waves in forcing the SAO appears to be limited, in agreement with previous results. Between the 21-hPa and 4.6-hPa surfaces there appears to be a transition zone where there is no clear relationship between Kelvin wave activity and mean zonal flow acceleration.

1. Introduction

Eastward propagating Kelvin waves are responsible for a considerable fraction of the variance in the middle atmosphere at equatorial latitudes. These equatorially trapped waves have been observed in data obtained through various techniques, including rockets and satellites. Using satellite data, *Salby et al.* [1984, 1990], and *Randel* [1990] found evidence for Kelvin wave activity in temperature and tracer species in the middle atmosphere. Recently, *Canziani et al.* [1994, hereinafter referred to as paper 1], using the temperature and ozone retrievals from the microwave limb sounder (MLS) onboard the Upper Atmosphere Research Satellite (UARS), obtained estimated wave structures that are similar to those measured with the lunar infrared monitor of the stratosphere (LIMS) instrument, onboard Nimbus 7 as well as with other previous observations. Kelvin wave-induced perturbations can be observed in a vertically stratified trace species if the tracer is long-lived with respect to the perturbation and hence is advected, or if the tracer has a temperature dependent photochemistry and sufficiently short photochemical lifetime that it responds photochemically to changes in temperature on a timescale much shorter than that of the wave. Further details on the nature and behavior of Kelvin waves and the development of their study can be found in the above references.

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Kelvin waves are thought to be essential in the westerly acceleration of the semiannual oscillation (SAO) [see *Dunkerton*, 1979] and the quasi-biennial oscillation (QBO) [see *Holton and Lindzen*, 1972]. Satellite data were used by *Coy and Hitchman* [1984], *Hitchman and Leovy* [1988], *Hirota et al.* [1991], and *Randel and Gille* [1991, hereinafter referred to as RG] to study the relationship between Kelvin wave activity and the mean flow, particularly the role of the Kelvin waves in the forcing of the SAO. The results of *Hitchman and Leovy* [1988], based on the LIMS data, showed that Kelvin waves are apparently too weak to fully drive the westerly phase of the SAO. RG, using solar backscatter ultraviolet (SBUV) retrievals, obtained 8-year ensemble mean power spectra of the ozone field at 3 and 0.5 hPa, which are consistent with the LIMS result. *Hamilton and Malhman* [1988] using a general circulation model reached similar conclusions.

Both theoretical [*Holton and Lindzen*, 1972] and experimental [*Wallace and Kousky*, 1968; *Kousky and Wallace*, 1971; *Angell et al.*, 1973] results indicate that Kelvin waves have a dominant role in driving the westerly phase of the QBO. However, *Takahashi and Boville* [1992], using a 3-dimensional high-resolution model of the stratosphere, found that the observed Kelvin wave activity is apparently not sufficient to completely account for the westerly acceleration of the QBO. Furthermore, the difference between the Rossby-gravity waves required to force the easterly phase of the model and the corresponding observed wave activity is even larger. Attempts by RG to link Kelvin wave activity in the upper stratosphere with the QBO observed in the lower stratospheric winds were inconclusive.

Wallace and Kousky [1968], using radiosonde data obtained over Canton Island, reported increased Kelvin wave variance accompanying the descent of the westerly phase of the QBO, with the largest amplitudes occurring in the westerly shear zone. *Hirota* [1978], using 4 years of wind and temperature rocket data over Ascension Island, first reported a strong semiannual modulation of Kelvin wave activity in the middle atmosphere. RG obtained similar results for ozone in the upper stratosphere. Because of limitations in the SBUV retrievals the study of RG was limited to the vicinity of the stratopause.

The aims of the present effort are to report the long-term and seasonal variability of Kelvin waves inferred from the MLS temperature and ozone observations during the first two years of operations of UARS, to compare this variability with the prevailing background mean wind as influenced by the SAO and QBO, and to compare the MLS results with previous Kelvin wave analyses. Despite the relatively short period covered by the present data set, compared to the SBUV sample, the vertical range covered both by the temperature and the ozone retrievals is more extensive and has a better resolution. Admittedly, only one QBO cycle is almost completely covered by this data set. Thus the analysis of the Kelvin wave-QBO relationship should be viewed as a case study. It must be noted that such a study was not possible for LIMS, the previous limb-scanning instrument, because of its short operational life.

The data set and the methods used to analyze it are briefly discussed in section 2. The time evolution of the temperature and ozone power spectra is reported in section 3. Finally, in section 4 the behavior of the temperature spectral power is discussed for a set of levels between 21 and 1 hpa, together with the zonal mean zonal wind. The results are summarized in section 5.

2. Data and Data Analysis Procedure

Temperature and ozone data obtained by MLS are used in this study. The data correspond to level 3AT, version V0003. As explained in paper 1, the 3AT level data is archived along the trajectory of the limb view from the satellite at equal time intervals. The height ranges considered extend from approximately 21 to 0.46 hPa and from 46 to 0.2 hPa for temperature and ozone, respectively. The analyses were performed on the mls independent retrieval surfaces at 46.45, 21.54, 10, 4.6, 2.15, 1, 0.46, and 0.22 hPa, thus including the middle stratosphere and the lower mesosphere. To cover both hemispheres, UARS changes from a north-viewing attitude to a south-viewing one every 26 to 40 days, resulting in samples of varying lengths. The analysis was carried out for the latitude range ±28°, for which there is nearly continuous coverage. But in the results reported below, only the latitude band ±8° about the equator is used. The latitudinal spacing of the grid was 4°. The basic analysis, applied independently to each of the north- and south-viewing intervals, was carried out using the asynoptic mapping technique [*Salby*, 1982a, b], as described in paper 1. Given the characteristics of the UARS orbit, this allows for the reconstruction of twice daily fields in synoptic coordinates. Because of edge effects the asynoptically retrieved maps corresponding to the first and last day of each series have to be discarded. A more detailed description of the MLS retrievals, the alternating north and south viewing of UARS, and the basic analysis procedure can be found in paper 1 and references therein.

The twice daily maps produced by the asynoptic mapping technique were combined to obtain 60-day time series, which were then spectrally analyzed in space and time using the procedure described by *Hayashi* [1971]. Time spectra for waves 1-6 were obtained this way. Since the first and last day of each of the original series had to be discarded, and in many cases if not most it was not possible to use data corresponding to the day of the yaw maneuver needed to invert the satellite, 3-day gaps centered at the yaw days were an unavoidable feature of the longer, reconstructed series. When gaps over 4-5 days occurred, the corresponding 60-day series was discarded unless it was possible to shift the window by a limited extent to avoid them. Missing values were linearly interpolated. Interpolation with higher-order schemes did not yield major improvements and at times actually increased the noise level of the signal. To avoid including an additional gap, the window was sometimes lagged by a few days one way or the other. The resulting power spectra were smoothed in frequency using a Gaussian window with a bandwidth equal to 1/30 d^{-1}. Finally, the power spectra were averaged about the equator between ±8° latitude.

Given the characteristic red nature of the zonal wavenumber spectra of Kelvin waves, we have limited ourselves to waves with zonal wavenumbers 1 and 2. Furthermore, based on the evidence collected in paper 1, where practically all the eastward variance for waves 1 and 2 in the vicinity of the equator corresponded to Kelvin waves, the eastward power found in these averaged spectra was attributed to Kelvin wave activity, unless otherwise stated.

The data set used begins on November 7, 1991 (UARS day 57 or UD57 for short), and ends on September 16, 1993 (UD736). All dates shall be given in UARS days. In subsequent plots of temperature and ozone, two gaps will be observed. The first gap is due to operational problems in UARS during the first half of June 1992 (UD264 to UD276). Though MLS data are present from UD281 to UD303, there is then a 6-day gap before it becomes available again. Given the limitations of the analysis technique, the maps produced for this period could not be included in a 60-day window, resulting in a gap from UD264 to UD310. The other gap corresponds to a 5-day lack of data, starting UD583. This is followed by 4 days of data ending in a yaw maneuver. It is not possible to correctly apply the asynoptic mapping technique for such a short sample, effectively resulting in a 10-day gap. It must be noted that since all power spectra are plotted on the day corresponding to the center of the windowed sample, gaps seem wider than they actually are.

The data base was completed with the zonal wind obtained from the UKMO Meteorological Office (UKMO) data assimilation model [*Swinbank and O'Neill*, 1994]. The winds are provided as correlative data products for the UARS database. The mean zonal wind at the equator was evaluated using a 60-day window displaced 30 days at a time. The results of this averaging for the whole of the period under consideration are shown in Figure 1. Both the SAO and the QBO can be distinctly observed. It must be noted that while a 60-day-long averaging does not appreciably affect the QBO amplitude, it does reduce that of the SAO. However, given that in this study we compare spectra that should be interpreted as a statistical average of the wave activity during the sampled period [*Salby et al.*, 1984], it is logical to use the same averaging for the background wind.

3. Evolution of Kelvin Wave Activity

The temporal evolution of the spectra of temperature and ozone are presented at two levels: 21 hPa and 1 hPa. The QBO

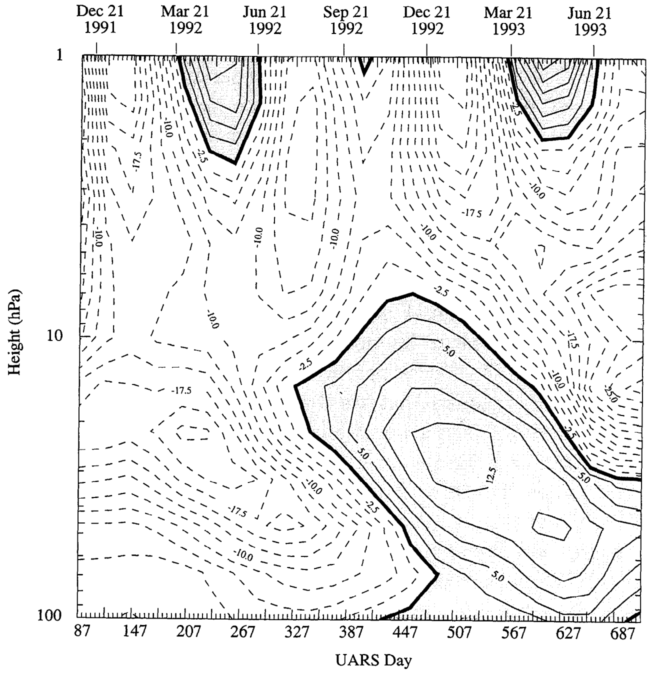

Figure 1. Evolution of the 60-day mean zonal mean United Kingdom Meteorological Office assimilated zonal wind at the equator during the period sampled. Contours are spaced every 2.5 m/s. Gray shade indicates westerly flow.

is the dominant feature of the background state at the first level and the SAO at the other. An overview of Figures 2-5 shows that the semiannual modulation of Kelvin wave activity (power at negative frequencies) is the preeminent feature, as reported by *Hirota* [1978] for the upper stratosphere. Kelvin wave activity generally has its maximum amplitudes at the solstice seasons and minima near the equinoxes. However, spectra for ozone at 21 hPa in both wavenumber 1 and 2 (Figures 2b and 3b) show a maximum in April-May 1992, that is an exception to the dominant semiannual cycle. Latitude-frequency plots of ozone at 21 hPa for this period show a faint structure, similar to that of a Kelvin wave signature but shifted to the north and blending with spectral power penetrating from higher latitudes. Though large spectral amplitudes are not an uncommon occurrence in the winter hemisphere at the higher latitudes of the sampled region, in general the Gaussian-shaped latitudinal structure of a Kelvin wave can be distinctly separated from extratropical influences. There is no evidence of similar behavior in the temperature spectra for zonal wavenumber 1 (Figure 2a), nor in the corresponding latitude-frequency plot for temperature. Thus identification of the April-May 1992 ozone signal with Kelvin waves remains uncertain.

In the case of the zonal wavenumber 2 a secondary maximum can be observed during the April-May 1992 period in the temperature perturbation. However, the associated ozone perturbation has a more prominent maximum at that time than during the solstices. In comparing the temperature and ozone spectra, it should be noted that the ozone perturbation below 10 hPa is primarily dynamical in origin and is caused by vertical parcel displacements in the presence of a background mean vertical gradient in ozone. Thus $\mu' \approx -\zeta' \overline{\mu}_z$, where $\overline{\mu}$ and μ' are the mean and perturbation ozone mixing ratios and ζ' is the vertical parcel displacement owing to the Kelvin wave. Above 10 hPa, ozone is primarily under photochemical control and the Kelvin wave signal is caused by temperature dependent photochemistry. According to RG in this case, it is the normalized mixing ratio r' that should be compared with the temperature perturbation (or vertical parcel displacement):

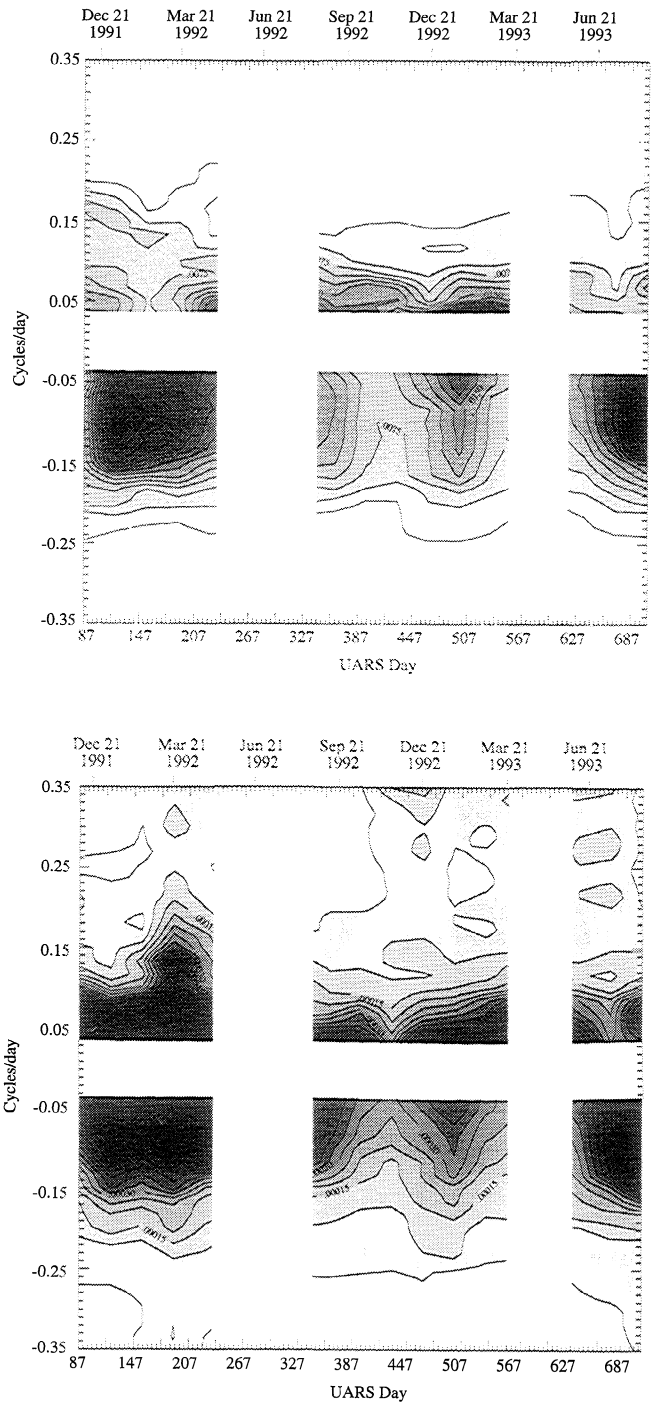

Figure 2. Temporal evolution of the 60-day moving window power spectra for the Microwave Limb Sounder (a) temperature and (b) ozone zonal wavenumber 1 at 21 hPa. The spectra have been averaged between ±8° latitude. Increasing power is highlighted with increasing intensity of the grey scale. Negative frequency corresponds to eastward propagation. The contour spacing is 0.0025 K^2 for temperature and 0.00005 $ppmv^2$ for ozone.

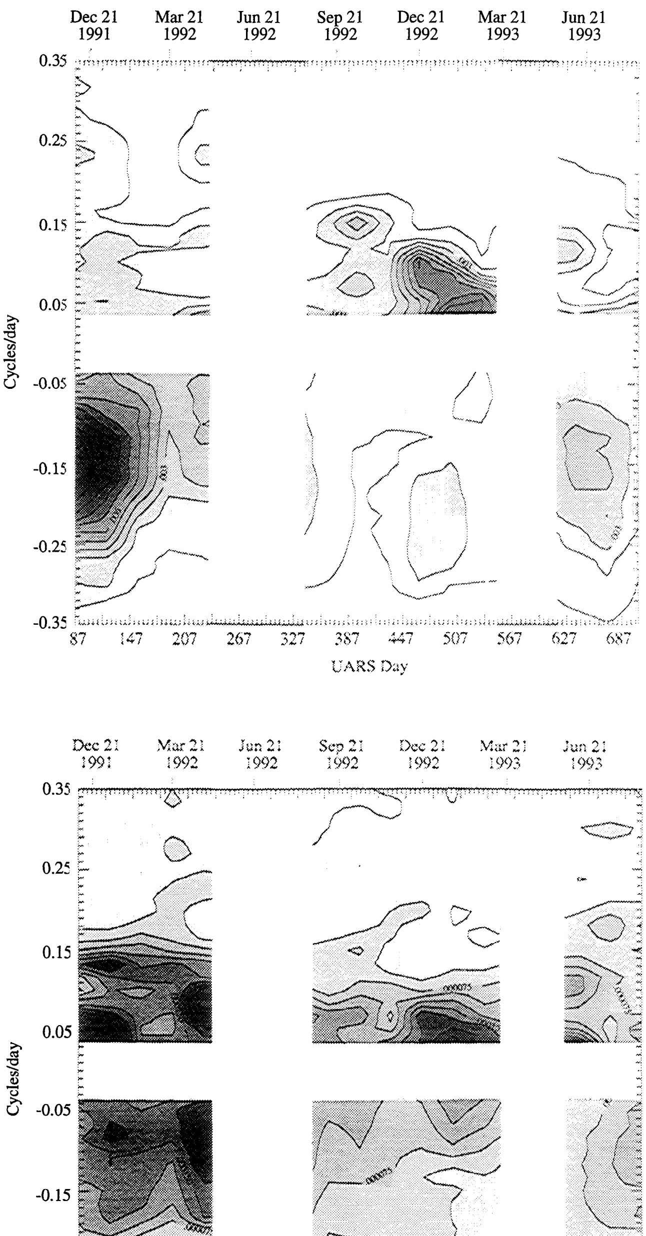

Figure 3. Same as Figure 2 for zonal wavenumber 2, at 21 hPa. The contour spacing is 0.001 K^2 for temperature and 0.000025 $ppmv^2$ for ozone.

$$r' = \frac{\mu'}{\bar{\mu}} \propto \left(\frac{T'}{\bar{T}^2}\right)$$

Except for the difference just mentioned, the temperature and ozone variance, at 21 hPa, are well correlated with each other, particularly for zonal wavenumber 1. The observed variances in this case are coincident both in the time of occurrence and in the frequency range covered as expected for a long-lived vertically stratified tracer. Little variance is obtained for oscillations with periods shorter than 6 days. For zonal wavenumber 2 the relationship between temperature and ozone is not so well defined. The largest variance for ozone, other than during the equinox period previously discussed, can be seen at the beginning and at the end of the sample. Although the temperature spectra also have large amplitudes at these times, there is not a good coincidence in frequency and exact time of occurrence of these maxima. The frequency range for this temperature zonal wave is higher than for wavenumber 1. Though the semiannual modulation is a salient feature, the maxima also appear to be modulated by the QBO. In the case of ozone, even if r' were used in place of μ', the trend would still remain. Notice that for both zonal wavenumbers the highest activity is reached during the easterly phase of the QBO. During strong westerly shears and/or westerly zonal flow the power is less. This is particularly striking in the case of zonal wavenumber 2.

The trends observed at 1 hPa (Figures 4 and 5) are similar to the SBUV results reported in RG, for 3 and 0.5 hPa. For both zonal wavenumbers, temperature and ozone show the strong semiannual modulation, with maximum Kelvin wave activity shortly after the solstices. These maxima in wave activity occur near the times of strong easterly winds at 1 hPa (see Figure 1). It is also possible to observe bursts of low-frequency westward activity at the same time or shortly after Kelvin wave enhancements, as reported by these authors. This is also noticeable for zonal wavenumber 2. As expected, the variance at this height is much larger than at 21 hPa and extends into higher frequencies, particularly for temperature. It must be remembered that higher-frequency modes, with longer vertical wavelengths, tend to become dominant as height increases (compare paper 1 and references therein) [*Boville and Randel*, 1992]. Also notice the doubling in frequency of the maxima of temperature zonal wavenumber 2 with respect to 1. This agrees with *Salby et al.* [1984] and observations in paper 1.

RG concluded, using an annual composite of SBUV data for the 1979-1986 period, that the variance during the January-February maximum is almost twice as large as that of July at 3 hPa and 30% larger at 0.5 hPa. This cannot be distinctly observed in the present sample, due to its relatively short temporal coverage. However, the phase of the QBO wind at lower altitudes does appear to have an impact on the behavior of the Kelvin wave perturbation in ozone near the stratopause. As shown in Figures 4b and 5b, zonal wavenumbers 1 and 2 both have reduced amplitudes in the higher portion of their frequency range during the period from about UD330 to UD560, when mean westerly shears or westerly flow exist in the middle stratosphere. This reduction in power at higher frequencies also occurs even when the Kelvin wave activity is plotted in terms of the normalized ozone mixing ratio, r'.

An analysis of wave phases (not shown) indicates that ozone perturbations are generally 180° out of phase with temperature perturbations at the 1 hPa level. As previously mentioned, ozone in this region is short-lived and the perturbations are photochemically induced. In general, large temperature variance and large ozone variance occur at the same time. However, during the last maximum, for both zonal wavenumbers, the ozone variance lags temperature variance by nearly a month.

To further understand the variability of Kelvin wave activity in this sample, the spectral power was integrated for periods between 4 and 20 days. Previous workers [e.g., *Wallace and*

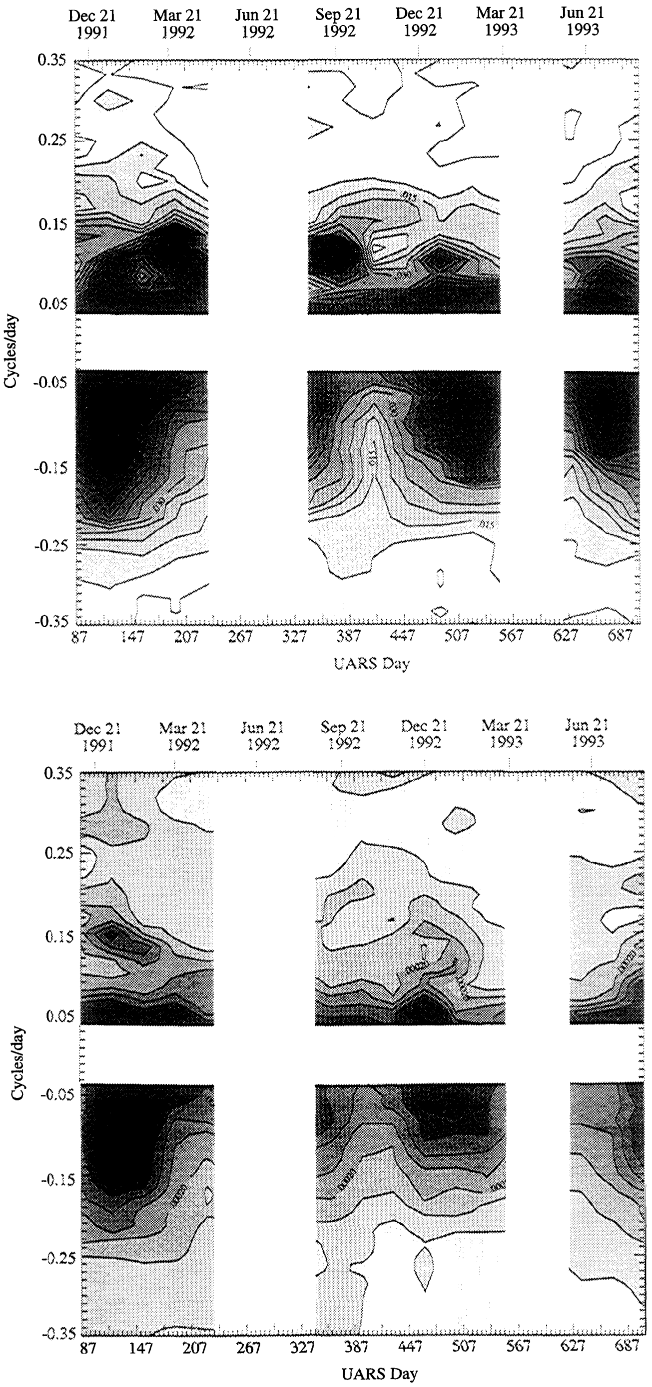

Figure 4. Same as Figure 2, for zonal wavenumber 1, at 1hPa. The contour spacing is 0.005 K^2 for temperature and 0.00005 $ppmv^2$ for ozone.

Kousky, 1968] have noted that Kelvin waves tend to be distributed over a rather broad range of periods. Integration over a broad frequency band thus increases the signal-to-noise ratio in the sample. Figures 6 and 7 present the results, for each zonal wavenumber, respectively, plotted as a function of time and height. The same process was carried out for a number of shorter samples, around the maxima (not shown), so that the data available in June 1992 (UD281-UD303) could be evaluated. The comparison of integrated power with the maxima for this sample showed that during June 1992, Kelvin wave activity was only approximately 10% less than for January 1992. Thus it can be concluded that the usual solstice maximum of Kelvin wave activity occurred during the MLS data gap, even though it was not possible to include that period in the present study.

Figure 6a, showing the temperature zonal wavenumber 1, corresponds to the spectral results for 21 and 1 hPa. Taking into account the observation we have just made on the behavior of the data around UD300, the impact of the QBO is even more evident. The semiannual signature is still present,

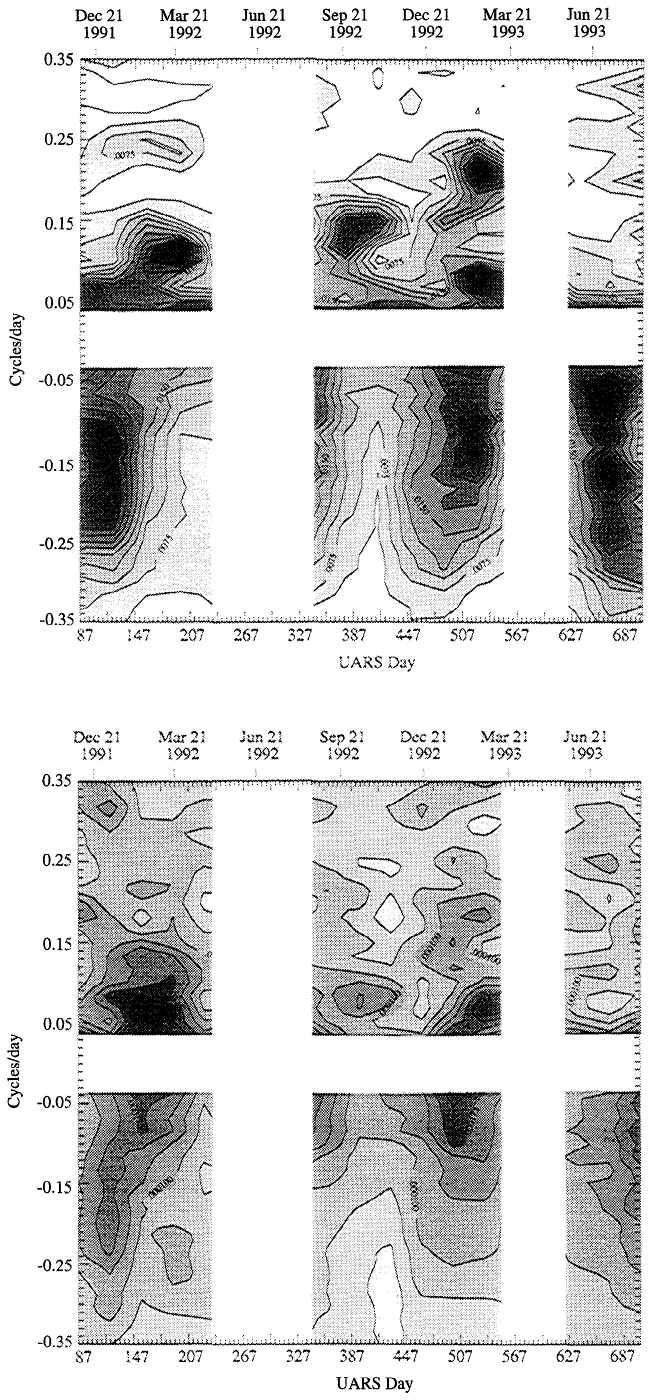

Figure 5. Same as Figure 2, for zonal wavenumber 2, at 1 hPa. The contour spacing is 0.0025 K^2 for temperature and 0.000025 $ppmv^2$ for ozone.

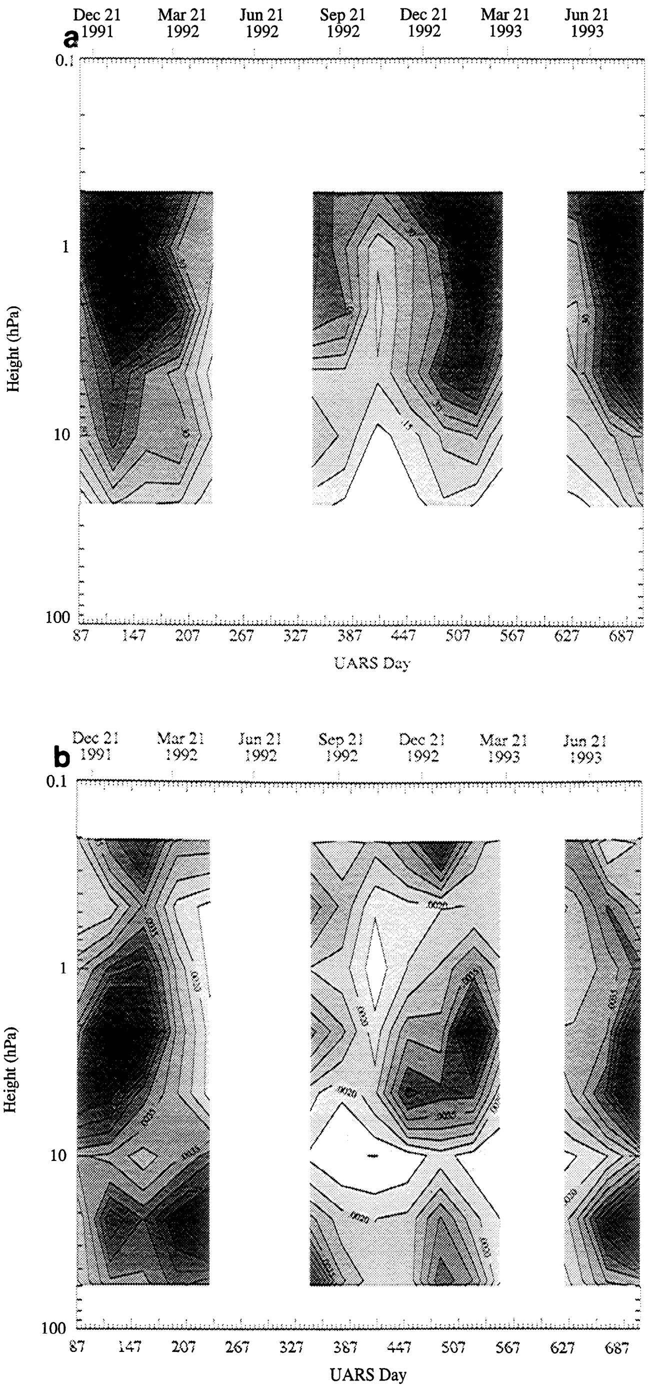

Figure 6. Height-time plots of integrated power for zonal wavenumber 1 eastward oscillations with periods between 4 and 20 days for (a) temperature and (b) ozone. The units are arbitrary. The contour spacing is 0.05 for temperature and 0.0005 for ozone.

but at all heights the amplitude of the wave activity is less following the December 1992 solstice (when the QBO is westerly) than following the December 1991 and June 1993 solstices. The results of *Wallace and Kousky* [1968] and *Kousky and Wallace* [1971] demonstrated that in the lower and middle stratosphere the maxima in Kelvin wave activity appear mostly during the strong westerly shear preceding the change from QBO easterly to westerly flow. Our results in the vicinity of 21-10 hPa appear to disagree with this conclusion. However, the radiosonde observations for 1965 and 1966, combining data from Canton Island and Ascension Island, did show a distinctive semiannual oscillation in the westerly power spectral density of the zonal wind, with maxima shortly after the solstices [*Kousky and Wallace,* 1971, Figure 11]. Yet this does not appear to be a permanent feature at the radiosonde height range since in a 10-year record, starting in 1955 [*Wallace and Kousky*, 1968], there is only evidence for a similar pattern during 1963, albeit a very weak one. It is not possible to confirm the radiosonde results with the current MLS data set, since a longer temporal coverage would be required, covering at least four or five QBOs as well as a

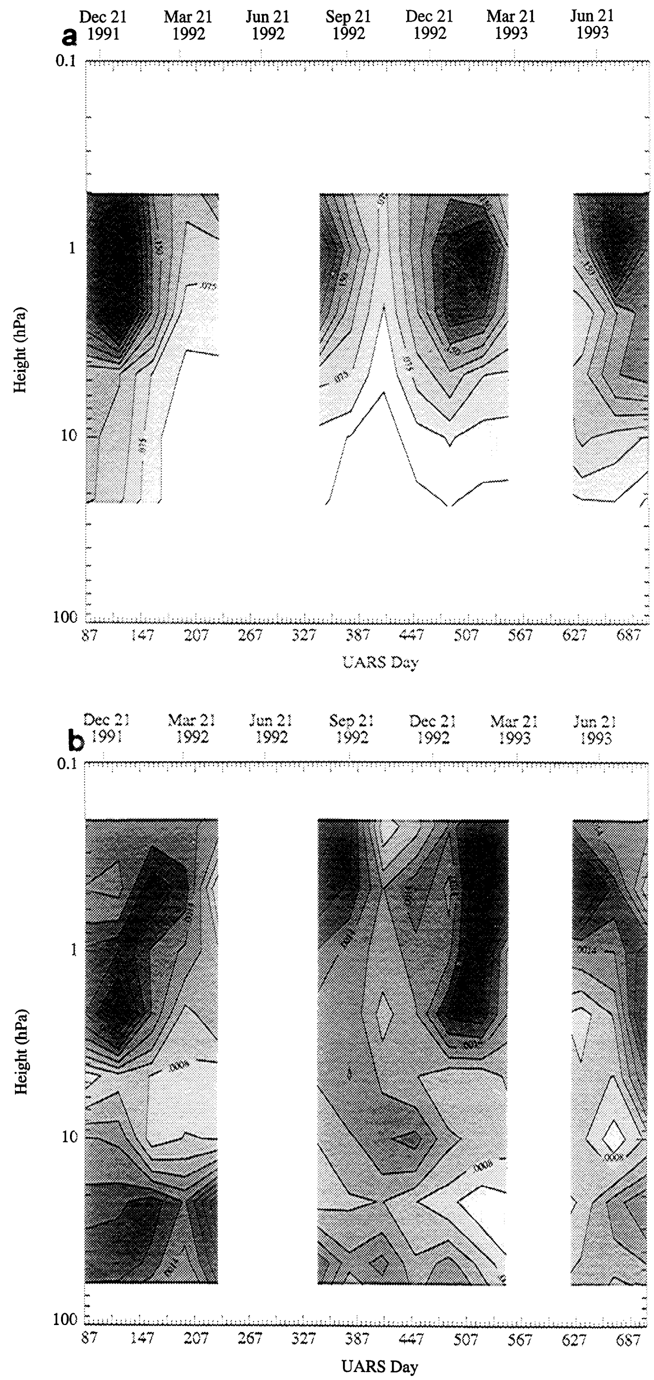

Figure 7. Same as Figure 6, for zonal wavenumber 2. Contour spacing for temperature is 0.025 and 0.0002 for ozone.

downward extension of the vertical range of temperature retrievals.

The ozone zonal wavenumber 1 perturbation (Figure 6b) is consistent with the temperature behavior except for the period UD207-237, as previously discussed. Notice that the vertical structure of the zonal wavenumber 1 ozone perturbation has, throughout the sample, a distinct minimum close to 10 hPa, as discussed in paper 1. This minimum occurs because the perturbation is dependent on the vertical gradient of the background mixing ratio, which at this height nearly vanishes.

The discrepancy referred to above between phases of the temperature and ozone variance during the last maximum of the sample appears to be partially clarified for zonal wavenumber 1 by Figure 6. Figure 6a shows that at most heights in the sample the maximum in T' is reached or is about to be reached at UD705. Only at 1 hPa does the temperature maximum precede that of the rest of the height range. Above 1 hPa the ozone maximum (Figure 6b) descends, starting at UD627 at 0.21 hPa, and is located at 1 hPa by UD705. When wave activity, in terms of r', is integrated as above, this discrepancy disappears; that is, the apparent variations in phase are due to changes in the background ozone mixing ratio.

Temperature zonal wavenumber 2 (Figure 7a) is seen to have appreciable variance only above approximately 5 hPa, with a maximum between 2 and 1 hPa. The semiannual pattern is present again, and the possible QBO signature is only detectable in the lower heights, with a weak amplitude. The behavior of ozone for this wavenumber is not so well defined, though the minimum amplitude near 10 hPa is present throughout most of the sample. There is a certain degree of coincidence with temperature wave activity, but maxima occur at higher altitudes during the westerly phase of the QBO. As was the case of zonal wavenumber 1, there is a discrepancy at 1 hPa between the times of the maxima for temperature and ozone perturbations. Temperature shows a small shift with height in the time of maximum variance, but ozone has a more distinct shift, similar to that of ozone zonal wavenumber 1. As was the case of that wave, the discrepancy disappears when the normalized ozone variable r' is considered.

4. Kelvin Wave Activity, the Quasi-Biennial Oscillation (QBO) and the Semiannual Oscillation (SAO): A Qualitative Look

The results discussed so far have shown that there is an interaction between Kelvin wave activity, the QBO, and the SAO. As discussed above, it is not clear whether Kelvin waves can fully account for the evolution of the westerly phase of the QBO. On the other hand, their role in the SAO is clearer; that is, they participate in the forcing but are not solely responsible for it. The best approach to confirming the SAO results and helping in the clarification of the QBO discrepancies would be to follow the method of *Hitchman and Leovy* [1988], where the actual zonal forcing due to the eastward propagating waves is evaluated. This is a labor intensive procedure. Attempts to obtain forcing estimates directly from the spectra did not meet with success, as was predicted by *Hitchman and Leovy* [1988]. Their method will be applied to the UARS data set in future work. Meanwhile, preliminary qualitative results are presented by comparing time series of Kelvin wave activity, as given by the sum of the integrated wave variance, with periods between 4 and 20 days, of temperature zonal wavenumbers 1 and 2, with the UKMO time mean zonal mean zonal wind and zonal acceleration. The results of this analysis are presented at 21, 10, 4.6, 2.1, and 1 hPa. Figures 8-12 show the 60-day mean zonal mean zonal winds, averaged between 8°N and 8°S, together with the acceleration (in ms^{-1} d^{-1}) and the integrated wave activity (the units are arbitrary, but the relative amplitudes between different heights are preserved), for each level. As mentioned in the previous section, spectral estimates for the second half of June (about UD290) 1992 point to Kelvin wave activity somewhat reduced with respect to the January-February maximum of that year.

At the 21-hPa level (Figure 8), where the QBO is strong, there appear to be periods when the Kelvin wave activity coincides with westerly acceleration, and others where despite the high levels of activity the acceleration is nearly zero or

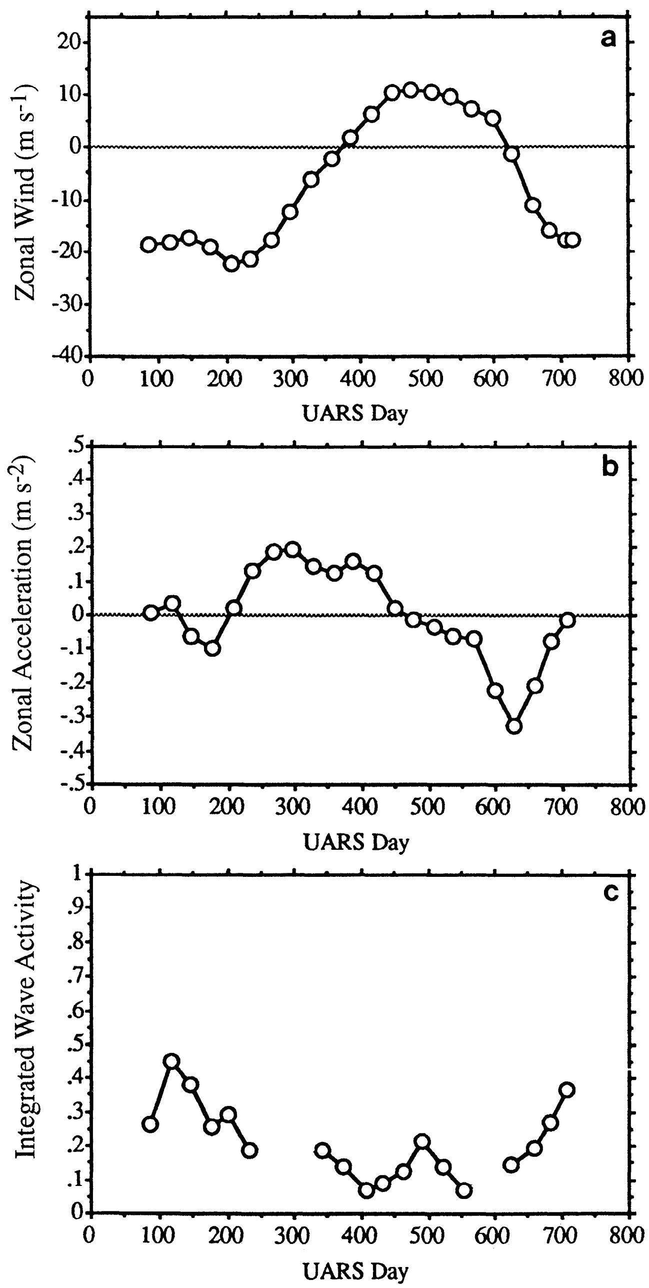

Figure 8. Comparison of the latitudinally averaged (8°N to 8°S) 60-day mean zonal wind (a) with the corresponding acceleration (b) and the 4-20-day period integrated spectral power of temperature (c) at 21 hPa. Integrated power units are arbitrary.

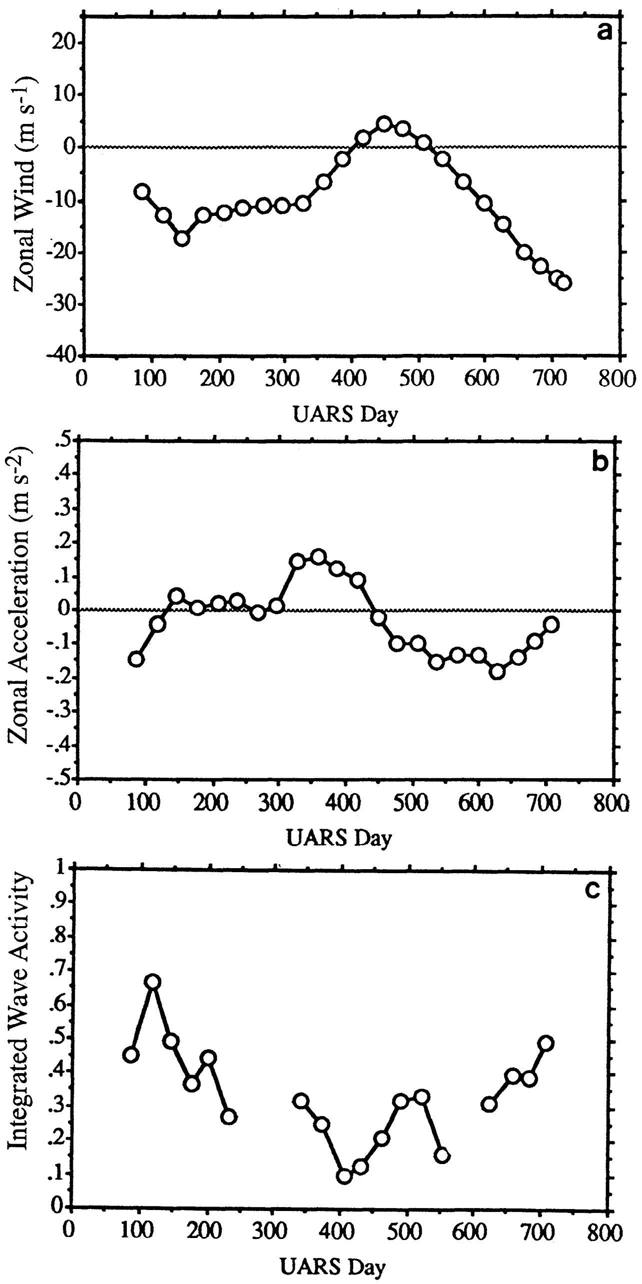

Figure 9. Same as Figure 8, at 10 hPa.

easterly. For example, a weak westerly acceleration occurs for the wave maximum near UD125, but in the period of strong westerly acceleration between about UD250 and UD400 the Kelvin wave activity is generally quite weak. At the time when the westerly flow starts to abate, between UD450 and UD 550, there is a comparatively weak maximum in Kelvin wave activity. The easterly acceleration remains weak at this time, and when the Kelvin waves disappear, the easterly acceleration rapidly increases, as if they were opposing some other mechanism which causes easterly acceleration. According to *Takahashi and Boville* [1992], at lower levels, Rossby-gravity waves can interact with Kelvin waves, resulting in wave breaking, and only small net forcing. During easterly flow, at the beginning and at the end of the sample there does not appear to be a net effect on the acceleration, despite the larger wave activity observed. There are certain events of this kind in the radiosonde results of *Wallace and Kousky*, where relatively weak eastward variance can be observed above 30 hPa during the early stages of the easterly phase of the QBO.

The 10- and 4.6-hPa levels (Figures 9 and 10) appear as transitional, with weak QBO and SAO signatures, respectively. There are no distinct relationships between the Kelvin wave activity and the acceleration. At 2.1 and 1 hPa (Figures 11 and 12) the SAO of the zonal wind is well defined. RG, in comparing the 8-year composites of SBUV westerly variance with monthly mean zonal winds taken from *Belmont et al.* [1974], concluded that at 3 hPa, Kelvin wave activity was in quadrature with the zonal wind acceleration. At 0.5 hPa and only during the northern winter did the correlation between acceleration and wave activity suggest a possible Kelvin wave contribution to the SAO. Furthermore, the SAO of the wind they used had a stronger easterly flow during January than in July, and the Kelvin wave variance was also stronger in January than in July. This asymmetry is more prominent at

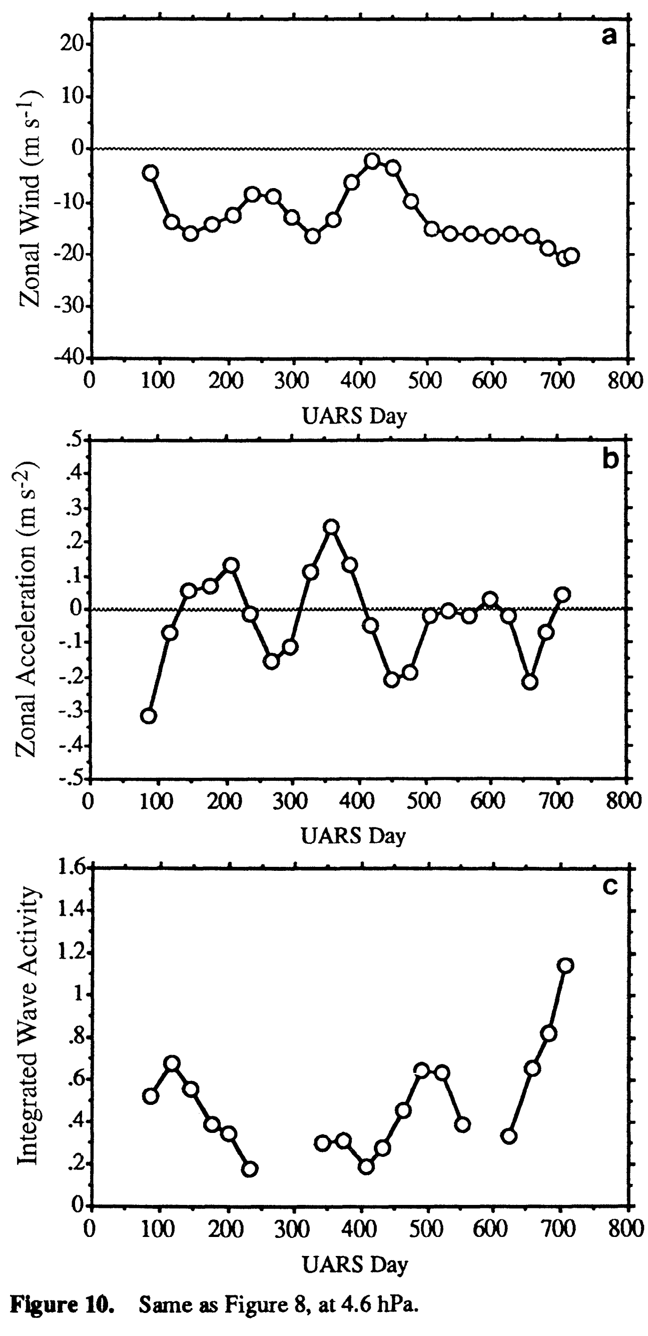

Figure 10. Same as Figure 8, at 4.6 hPa.

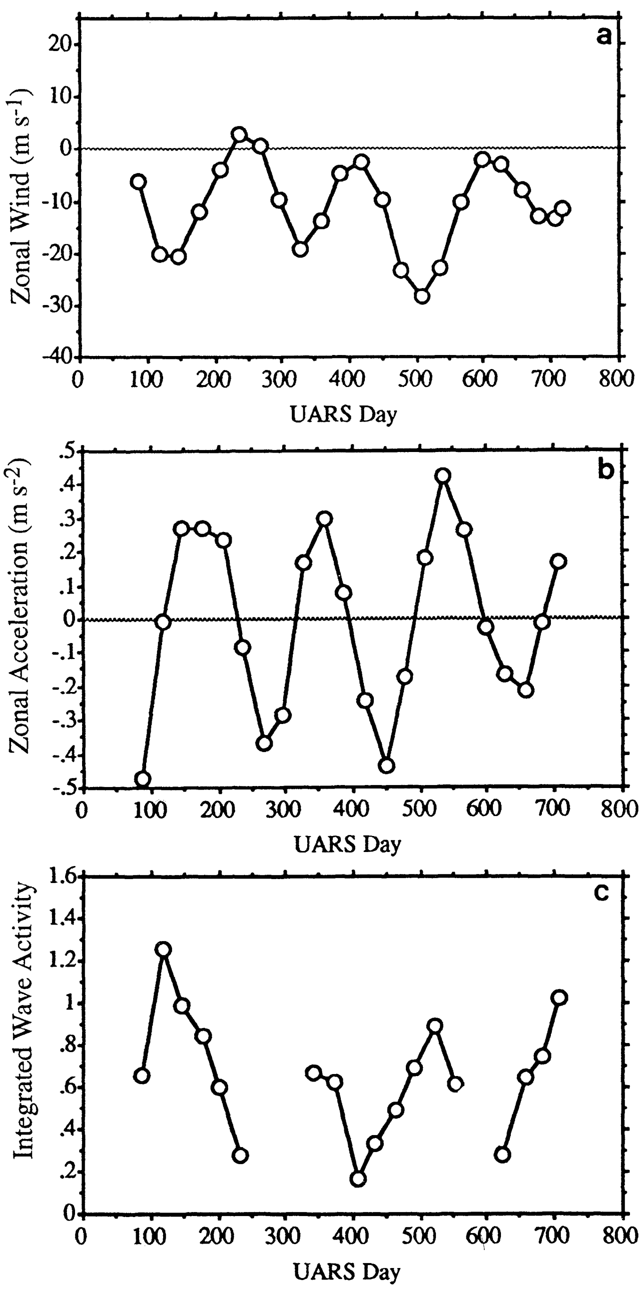

Figure 11. Same as Figure 8, at 2.1 hPa.

3 hPa than at 0.5 hPa. The UKMO zonal wind at 2.1 hPa does have a slight asymmetry between the northern winter and summer seasons, which has been reduced because of the average discussed in section 2. This agrees with RG and references therein. Contrary to their results the seasonal asymmetry for the UKMO zonal wind at 1 hPa is more prominent.

As mentioned before, the largest westerly variance at these heights in the MLS retrievals can be seen near the maxima in the easterly flow. However, the semiannual fluctuations reported by RG, with more important maxima in January than in July, are not obvious from this data set. As mentioned in the previous section, a possible QBO-induced modulation of wave activity reaches to 1 hPa. This is not surprising, since the RG time evolution plots of the SBUV wave activity show years where the January and July variances were at least of the same order of magnitude, for both levels considered. The UKMO acceleration at 2.1 hPa is almost in quadrature with the Kelvin wave variance during the first half of the MLS sample. During the second half the phase difference is less and these waves could be contributing to the SAO acceleration, though they would definitely not be fully responsible for it. At 1 hPa the Kelvin wave variance is not in quadrature during the northern winters (i.e., near UD100 and UD470) but appears to be so during the northern summers (near UD300 and UD700). This last result is closer to the composite comparison of RG. Hence Kelvin waves appear to be collaborating in the forcing of the SAO near the stratopause only during January. As noted in RG, at this height the strongest westerly flows are reached in April rather than in October. At 2.1 hPa there is not an appreciable difference in the westerly flow during those months.

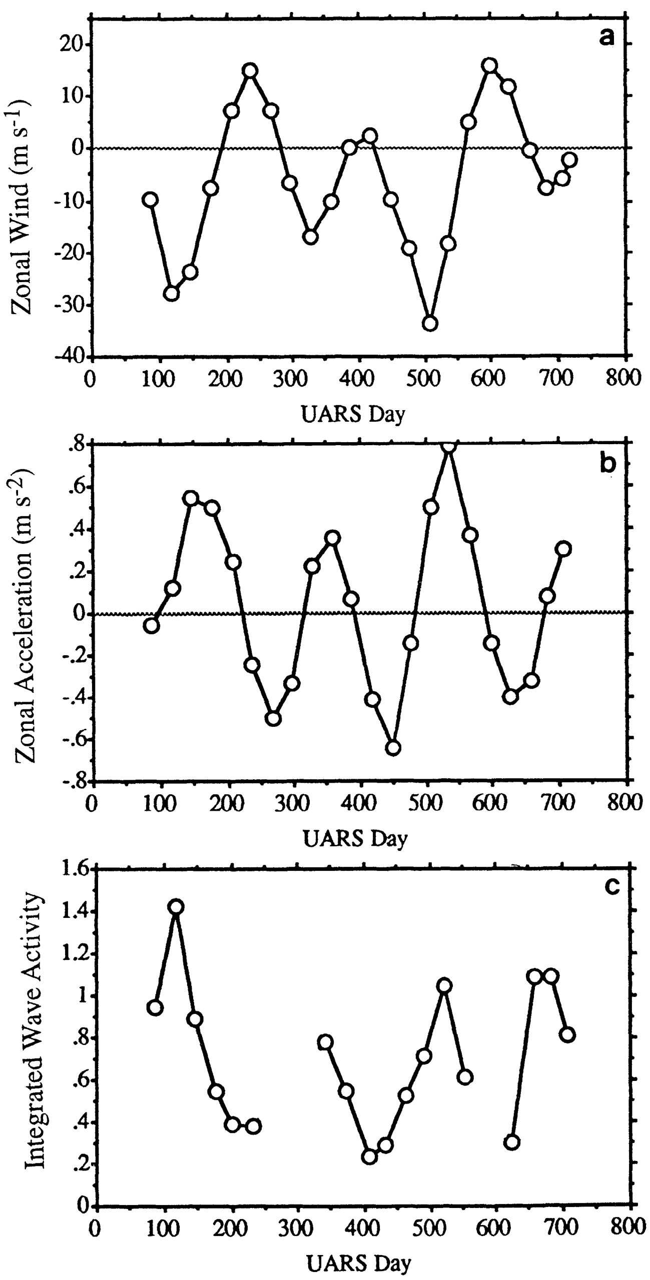

Figure 12. Same as Figure 8, at 1 hPa.

5. Concluding Remarks

The first two years of MLS operations onboard UARS yield results on the variability of Kelvin wave activity in general agreement with previous observations. A well-defined semiannual pattern was obtained throughout most of the height range, for both temperature and ozone. There also were distinct traits of an apparent QBO modulation through most of the height range for zonal wavenumber 1. Apparent discrepancies between the Kelvin wave-induced variations in temperature and ozone were resolved by considering the ozone perturbation ratio r'.

The relationship between the SAO and the Kelvin wave activity agrees with the RG results and further sustains the view, first proposed by *Hitchman and Leovy* [1988], that these waves are not the dominant forcing for the SAO. As to the apparent superimposed QBO modulation, RG did not find in the upper stratosphere a consistent behavior which would identify such a modulation in their 8-year SBUV sample. Given the current length of the MLS data set, it is not clear at this stage whether this is a discrepancy in the observations or just a chance event within a time-limited sample. The region between 10 and 4.6 hPa appears as the transition zone between the SAO and the QBO. It was not possible to observe any relationship between the Kelvin wave activity and the mean zonal flow.

The relationship between the QBO and the wave activity is consistent with observations by radiosondes during a few specific periods [*Wallace and Kousky*, 1968; *Kousky and Wallace*, 1971], when similar behavior was observed. Since this analysis is basically a case study, given the duration of the QBO, the same caveat mentioned in the previous paragraph applies. The radiosonde data do show that large Kelvin wave variances occur only in the easterlies below the leading edge of the westerly phase and in the descending westerly shear zone. At any rate, there is activity close to the leading edge of the westerly phase of the QBO, as suggested by *Wallace and Kousky* [1968], and there is a possibility that the initially slow weakening of the westerly phase could be related to wave breaking, as suggested by *Takahashi and Boville* [1992]. The extent of the latter process still remains to be determined. More definite answers await a longer time series and temperature data at lower altitudes.

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