

Large amplitude perturbations in mesospheric OH Meinel and 87-km Na lidar temperatures around the autumnal equinox

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Abstract. Two high-precision CEDAR instruments, an OH Mesospheric Temperature Mapper (MTM) and a Na Temperature Lidar, have been used to investigate seasonal variability in the mid-latitude temperature at ~87 km altitude over the western USA. Here we report the observation of a large perturbation in mesospheric temperature that occurs shortly after the autumnal equinox in close association with the penetration of planetary-wave energy from the troposphere into the mesosphere. This perturbation has been observed on three occasions and exhibits a departure of up to ~25-30 K from the nominal seasonal trend during a disturbed period of ~2 weeks. Such behavior represents a dramatic transient departure from the seasonal trend expected on the basis of current empirical models. These novel results coupled with a recent TIME-GCM modeling study [Liu et al., 2000] provide important insight into the role of planetary waves in mesospheric variability during the equinox periods.

Introduction

Early investigations of the thermal structure of the upper mesosphere and lower thermosphere (MLT) region using in situ probes, radar soundings, and airglow observations were based on relatively infrequent soundings that provided only a coarse picture of the variability. More recently, Rayleigh and resonance lidar systems have been developed to probe this important atmospheric region in detail [e.g. Leblanc et al., 1998]. These studies utilize only a few nightly (or diurnal) soundings per month (smoothed with an ~1-month window function), for constructing monthly/seasonal MLT climatology. Such sampling schemes are unlikely to reveal rapid change in the MLT dynamics expected around the equinoxes.

Recently, Shepherd et al. [1999] have combined data from the Wind Imaging Interferometer (WINDII) aboard the Upper Atmospheric Research Satellite (UARS) with ground-based airglow observations from three well-separated sites in the northern hemisphere to help characterize what they term "a springtime transition in atomic oxygen". Their data revealed large perturbations in the springtime oxygen airglow emission rates that were planetary-scale in nature, possibly associated with the seasonal reversal of the zonal wind field. Limited data on the OH and O₂ rotational temperatures also indicated a high degree of correlation with the emission rate changes.

In this letter, we report the first observations of an autumnal perturbation in MLT temperatures possibly complementary to the springtime observations of Shepherd et al. [1999]. Our results indicate that a large departure from the ~87-km climatological seasonal temperature can occur shortly after the fall equinox. This perturbation appears to be related to the penetration of planetary-wave energy into the MLT region during this transition period. A full description of the planetary-wave development using the TIME-GCM model is given in an accompanying paper by Liu et al. [this issue].

Mesospheric Temperature Measurements

The data were obtained using the Colorado State University Na Temperature Lidar system and a recently-developed Mesospheric Temperature Mapper (MTM). Details of these instruments are given in She and Lowe [1998] and Pendleton et al., [2000]. Joint measurements were made at Ft. Collins, CO (41°N, 105°W), June 1997 to June 1998. MTM measurements were continued from the Starfire Optical Range, NM (35°N, 107°W) from November 1998 to December 2000 alongside the University of Illinois Wind-Temperature Lidar system. The MTM has a 75° field of view (128 x 128 superpixels), but for this study, only the central 5 x 5 superpixels were used to determine the zenith temperature variability at the OH emission height ~87 km (averaged over the layer width of ~8 km). These data were later averaged together to determine a mean value, and its RMS variability, for each night of operations (~20 nights/month centered on the new moon). In comparison the CSU lidar system was operated for typically 4 nights/month irrespective of the moon's phase.

Seasonal Observations

A total of 114 nights of MTM data and 48 nights of lidar data were obtained during the 12-month campaign at Ft. Collins. Figure 1 compares the nightly mean OH temperatures for the period June-December, 1997 with the lidar-derived temperatures for the 87-km level smoothed over 3.7 km in height. To minimize the effects of tides and gravity waves on the nightly mean values, only data sets > 4-hr in length are plotted. A measure of the nocturnal geophysical variability is given by the vertical bars as the precision of the nightly means is <1 K for each instrument. An unoptimized comparison of the MTM and lidar temperatures for 12 nights of overlapping data during this period (average data length ~7.5 hr) yielded a correlation coefficient (*r*) of 0.96 and a mean nightly difference of only 0.6 K (excluding 3 Nov., see below). However, variations on a night-by-night basis indicate that our nightly means, referenced to the 87-km lidar-derived temperatures, are compatible to about ± 5 K. This result is supported by the solid curve which shows the expected annual variation in temperature at the 87-km level

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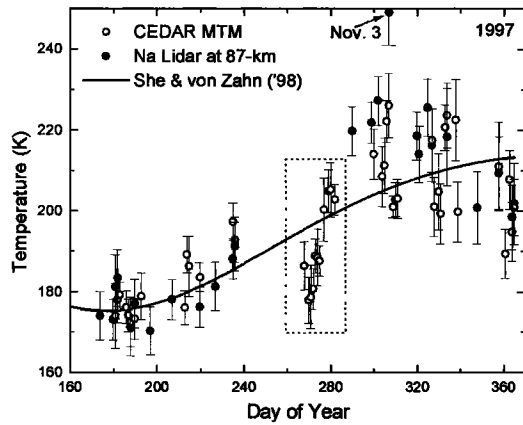


Figure 1. Comparison of MTM nocturnal mean temperatures and 87-km lidar temperature for Ft. Collins, CO, from Jun-Dec. 1997.

based on a harmonic analysis of Na lidar measurements for the previous year at Ft. Collins [She and von Zahn, 1998]. Both data sets show the expected ~ 35 K winter-summer difference at $\sim 41^\circ\text{N}$ and both reveal similar nocturnal trends (not shown) on nights of coincident data reinforcing the argument that under normal conditions the OH temperatures may be used as a proxy for atmospheric temperature at ~ 87 km [She and Lowe, 1998]. This said, there is a significant difference between the summer and winter data sets. During the summer months the lidar and MTM data are closely clustered about the 87-km mean and exhibit modest variability; however, during the winter months both data sets reveal substantial short-term (\sim a few days) variations in the average nocturnal temperature and enhanced nocturnal activity.

This change in mesospheric temperature variability appears to occur shortly after the fall equinox, when the MTM data reveal the existence of a large perturbation (highlighted by the dotted box). Unfortunately there are no lidar data for this period. However, the magnitude (≈ 23 K) and duration (~ 2 weeks) of this disturbance are quite remarkable. A second unusual feature in the late fall data is the exceptionally high mean nocturnal temperature (249 K at 87 km) that was determined by the lidar on 3 November 1997. The MTM also yielded an enhanced mean temperature (226 K) on this occasion but considerably less than that determined by the lidar. This event is currently being modeled (S. Melo, private communication) and will not be discussed further here.

Autumnal Perturbation Characteristics

Figure 2a shows an enlargement of Figure 1 centered on the temperature perturbation that was observed by the MTM during a 17-day period (UT days 268-284, 1997). For reference the dashed lines depict the $\pm 2\sigma$ band around the expected seasonal temperature variation at the 87-km level (central curve) over a 120 day period as determined from the Ft. Collins Na lidar measurements during 1996/97 [She and von Zahn, 1998]. MTM data sets obtained prior to and after the fall equinox, averaged over several days (crossed bars), lie within the confidence limits established by She and von Zahn. In contrast, at its extreme, the temperature perturbation departs markedly from the expected seasonal value (~ 201 K) reaching temperatures as low as ≈ 178 K, which are more akin to annual minimum summertime levels. Indeed, during this

period the total observed temperature change (≈ 30 K) approached that expected for the entire summer-to-winter annual variation (~ 38 K) (dashed horizontal lines). Although our MTM data do not capture this event completely, measurements were obtained 2 nights prior to the minimum and for 14 nights afterwards helping to characterize its shape. Of particular interest is the steep, quasi-monotonic rise of ≈ 3.2 K/day (mean value) back to normal seasonal levels that occurred over a several day period following the minimum. (Note: The largest day-to-day change was ≈ 16 K.) This feature represents a major disturbance in the 1997 fall seasonal trend that has not been previously reported.

Figure 2b shows the corresponding relative intensity changes. The seasonal variability in OH M (6,2) emission at Ft. Collins has yet to be fully characterized, and, for reference, data from Haute Provence (OHP), France (44°N) is shown [Wiens and Weill, 1973]. The data have been normalized to unity for the August nocturnal mean since this is typically the minimum monthly level of the annual cycle. A high degree of correlation ($r \approx 0.88$) between the intensity and temperature perturbations is evident indicating that both were characterized by a major decrease followed by a rapid return to nominal conditions. The magnitude of the relative intensity change is large (~ 1.9) and spans the full climatological range of annual variability in an interval of a few days. In addition, nocturnal-mean [OI] $\lambda 558$ -nm zenith intensity data obtained at Bear Lake Observatory, Utah (41.6°N , 111.6°W) during this event (not shown) also indicate a strong correlation ($r \approx 0.94$) with the OH intensity data at Ft. Collins. As these two sites are separated by about 550 km, and as the emission layers have a typical vertical separation of ≈ 10 km, the perturbation must have been relatively large-scale since there was no apparent phase shift between these two data sets.

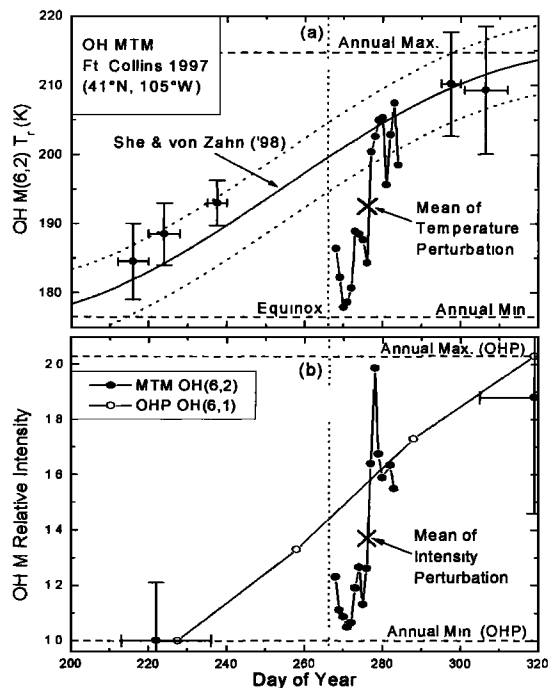


Figure 2. Comparison of (a) OH temperature and (b) corresponding zenith intensity perturbation characteristics for the 1997 fall event of Figure 1. The intensity data are plotted against an OH (6,1) climatology from Haute Provence (OHP), France (44°N).

To investigate this phenomenon further, we have analyzed two additional temperature data sets that encompass the same near-equinoctial period. Figure 3a shows data extracted from the 1996 Na lidar measurements at Ft. Collins reported by She and von Zahn [1998]. As expected, the averaged lidar values prior to and after the fall equinox (large crossed bars representing small-sample standard deviations), lie almost centrally on the seasonal trend. However, 5 nights of lidar data during a 7-day period (UT days 279-285) again show a major departure from this trend. The data are available at 1 km height resolution and are plotted for 87 km (solid circles) and 86 km (crosses) to illustrate height variability of the temperature perturbation. The main characteristics of this disturbance are its large magnitude, ~ 36 K, and the steep recovery rate. However, in this case the lidar data suggest an "overshoot" in temperature above the seasonal trend following the minimum. Unfortunately, the lidar was limited in its operation, but a subsequent 7-day average (centered on UT day 335) suggests a return to normal seasonal levels. This behavior is very similar to the MTM data of Figure 2a.

Figure 3b shows the most recent MTM data obtained during the fall 1999 from the Starfire Optical Range, NM which is $\sim 6^\circ$ lower in latitude than Ft. Collins. In this case, we have used the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) to define the expected 87-km temperature trend (solid curve) at this site. The accompanying dotted lines indicate temperature range for ± 0.5 scale heights. The range of summer-winter variability at this latitude is significantly less at ~ 30 K. MTM data during the period again indicate a large temperature perturbation with a corresponding intensity variation (not shown) of similar magnitude and temporal characteristics to those described earlier. In this case, the temperature change exceeded the estimated summer-winter annual range, and the minimum was ~ 10 K cooler than the model-based summer-

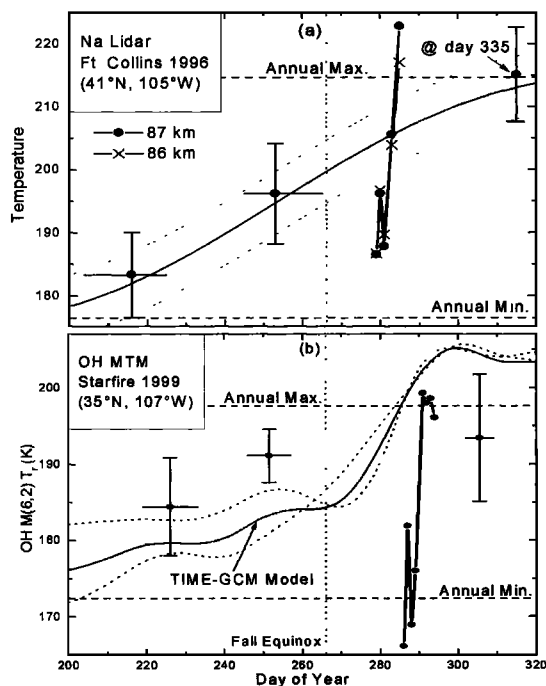


Figure 3. Autumnal temperature perturbations observed at (a) Ft. Collins, CO, 1996 (Na lidar), and (b) Starfire, NM, 1999 (MTM).

Table 1. Summary of temperature results (in K) for Figures 2 and 3.

Site/Instrument	UT Days	T_{\min}	T_{\max}	ΔT	MRR
Ft. Collins, 1997 (41°N, 105°W) MTM	268-284	178	207	23	3.3
Ft. Collins, 1996 (41°N, 105°W) Lidar	279-285	186	223	18	4.8
Starfire, 1999 (35°N, 107°W) MTM	286-294	166	199	32	6.6
Model, 1997 (42.5°N, 105°W)	260-285	192 (179)	203 (211)	9 (22)	1.3 (4.0)

Notes: ΔT = maximum departure from seasonal norm; MRR = Mean Recovery Rate (K/day); parentheses = adjusted model values.

time values. For comparison, averaged MTM temperatures for data windows prior to and after this period (crossed bars) show fair accord with the TIME-GCM model predictions. Table 1 summarizes the main properties of these three events.

Discussion

These data, obtained over a 4 year interval, strongly suggest the development of a major perturbation in mesospheric temperature and airglow intensity shortly after the fall equinox that has not previously been reported. The perturbations are almost certainly related to the large-scale variations observed in the OH M and O₂(0,1) airglow emission intensities associated with changes in atomic oxygen around the spring equinox [Shepherd et al., 1999]. In particular, the geographically dispersed observations of Shepherd et al. indicated a "pulse-like" enhancement in the OH zenith intensity (factor 2-3 times) and temperature (~ 30 K) over a period of a few days said to be consistent with the transition of a large planetary-scale feature. In comparison, our autumnal data, recorded from two sites of similar longitude over the western USA, were characterized by a marked decrease in OH temperature and intensity followed by a steady return to normal conditions of duration about 2 weeks. These results are compatible with the idea that the enhancement (decrease) is due to an adiabatic compression (expansion) associated with strong vertical displacement of the OH layer. Of key importance to both of these studies is the finding that the perturbations are transient in nature and geographically extensive supporting a planetary-wave-type perturbation.

Recent quasi-global studies of MLT winds [e.g. Smith, 1997] and 87-km temperatures [Drob et al., 2000] provide

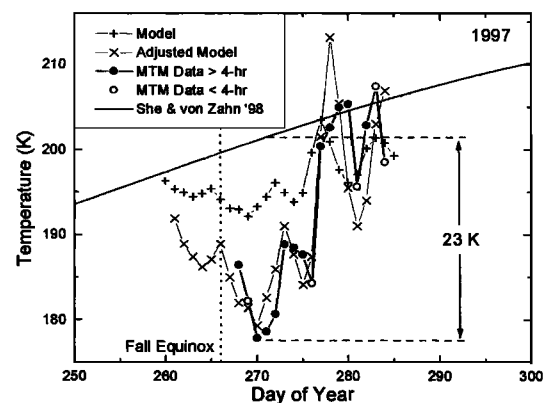


Figure 4. Comparison of TIME GCM model results of SPW transience effects at 87-km level with MTM data for the 1997 autumnal event. The adjusted model agrees well with the data.

strong evidence for the importance of stationary planetary waves (SPW) to the energetics, dynamics, and annual variability of this region. However, very little is known about changes in the SPW field around the equinoxes resulting from the seasonal reversal of the stratospheric wind field. Liu et al. [this issue] have suggested that the development of SPW activity in the northern-hemisphere MLT region during the fall equinox transition period may have been the source of the temperature (and intensity) perturbations documented here.

To test this hypothesis, the impact of the seasonal SPW transition on the MLT temperature and wind fields was studied using the NCAR TIME-GCM model. The 1997 event (Figure 2a) was selected for investigation since its evolution was the most fully documented. Realistic forcing of the SPW at the lower boundary of the model (~30 km) was provided by temperature and geopotential height variations at the 10-mb level specified by the daily National Centers for Environmental Prediction (NCEP) analysis. Full details of the model simulation are given in a companion letter [Liu et al., 2001].

Figure 4 shows the MTM mean temperatures from Ft. Collins for the 17-day period (UT days 268–284) compared with predictions of 87-km nocturnal mean temperatures based on the TIME-GCM results. The observing conditions were very good during this period and 12 of the data sets were > 4 hrs duration (range: 4.3–9.1 hr; mean ~7.0 hr), the remaining 5 data sets were between 1–4 hr in duration. The predicted perturbation pattern agrees well in shape with the MTM data, but the observed magnitude exceeds the predictions by a large factor. A linear correlation analysis of these two plots yields a coefficient $r \cong 0.73$ with an optimum correlation ($r \cong 0.86$) obtained by advancing the model results by one day, suggesting a high degree of temporal correlation. The disparity in magnitude is indicated by the fractional RMS perturbations of $\cong 1.7\%$ and $\cong 5.1\%$ for the model and the data, respectively. This may result, in part, from the model causing some damping of the SPW due to its relatively coarse resolution (5° grid size), and/or to the NCEP analysis underestimating the 10-mbar perturbation amplitudes. Such a disparity is not without precedent. Shepherd et al. [1998] concluded that their ground-based O_2 temperature data agreed well in shape with the TIME-GCM model but differed in amplitude for the tidally-induced variations by a similar factor of ~3, with the observations also exceeding predictions.

To account for the disparity in our comparison, the model was adjusted to have the same mean (192.5 K) and standard deviation (9.9 K) as the data, and then shifted forward by one day for maximum correlation. The adjusted model results bear a remarkable similarity to the MTM data suggesting that a rapid phase shift of a quasi-stationary planetary wave 1 caused the large mesospheric temperature perturbation observed around the 1997 fall equinox [Liu et al., 2001]. However, due to the limited data and data-model comparisons, these initial results are promising but not definitive.

In summary, this study provides new evidence for the development of SPW activity near the mesopause around the fall equinox period. The signature of the transition period from summer conditions (exhibiting relatively low rms variability) to winter-time conditions where large, short-term (~ a few days) variations in the average nocturnal temperature are predominant has yet to be fully documented. The key properties of this autumnal transition perturbation as measured over the western USA are: (1) a significant departure from the climatological trend of magnitude ~25–30 K; (2)

transient duration ~2 weeks; and (3) recovery rate of typically 3–7 K/day. The perturbation has been observed 3 times during the past 4 years, occurring shortly after the autumnal equinox. However, on-going modeling studies indicate that its magnitude, pattern and duration at a given location may vary significantly depending on competing factors such as SPW forcing in the lower atmosphere and gravity-wave forcing of the mean flow in the MLT region. What is clear is that we can expect to see increasing variability around the fall equinox associated with the onset of upper mesospheric planetary wave activity. The OH temperature and intensity changes are highly correlated during this time and coherent over a large geographic area ($>7^\circ$ in longitude), consistent with the growth of planetary waves and associated wave transience in the MLT region. Additional geographically distributed measurements and data-model comparisons are needed to unequivocally establish the growth of SPWs in the MLT region as the primary source of the observed perturbations. Such measurements, performed in conjunction with the NASA TIMED satellite mission, would be invaluable.

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