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Simultaneous lidar measurements of the mesospheric sodium layer were made at the Air Force Geophysics Laboratory (AFGL) and University of Illinois at Urbana-Champaign (UIUC) on the nights of August 28, October 9 and October 16, 1985. On these nights the layer centroid height was 1 to 3 km lower at AFGL. In October the altitude of the layer bottomside was near 80 km at AFGL compared to 85 km at UIUC. Gravity wave activity was present in the layer at both sites on all 3 nights. In October, the wave amplitudes were significantly larger at AFGL. The sodium profiles were compared with similar measurements obtained at the Goddard Space Flight Center in October 1981 and at the White Sands Missile Range in October 1984. The data from all four sites indicate that there is a significant longitudinal variation in the layer structure between 70°W and 90°W. It is suggested that these structural differences may be due to dynamics. The most promising mechanism capable of producing the large 1 to 3 km differences in the layer centroid heights between UIUC and AFGL is a small difference in the mean vertical wind velocity. Because the typical residence time for a sodium atom in the layer is approximately 5.8 days, a 0.4 cm s^{-1} difference in the mean vertical wind velocities at the two sites is capable of inducing a 2-km difference in the centroid height of the sodium layer.

INTRODUCTION

For more than 15 years lidar systems have been used to study the chemistry and dynamics of the mesospheric sodium layer. Longterm measurements at Winkfield, England [*Gibson and Sanford*, 1971], Haute Provence, France [*Megie and Blamont*, 1977], São Paulo, Brazil [*Simonich et al.*, 1979] and Urbana, Illinois [*Gardner et al.*, 1986] have established the general seasonal, diurnal and geographical variations of the vertical structure of the layer. Meteoric ablation is generally regarded as the dominant source of all the alkali metal layers including sodium [*Jegou et al.*, 1985*a*]. Although the sodium chemistry is complex and is still not completely understood, the dominant sink mechanisms appear to be the formation of cluster ions [*Richter and Sechrist*, 1979] and the reaction of Na with O_2 and a third body to form NaO_2 [*Swider*, 1985]. These two reactions are particularly interesting because the temperature dependence of their rate coefficients may explain the seasonal and geographical variations in sodium abundance [*Jegou et al.*, 1985*b*; *Swider*, 1985].

In addition to chemical activity, the dynamic effects of tides, gravity waves, turbulence and the mean wind fields have a significant influence on the sodium layer structure [*Gardner and Shelton*, 1985; *Batista et al.*, 1985; *Jegou et al.*, 1985*a*]. Steerable lidar systems were first used by *Thomas et al.* [1977] at Winkfield, England to study the horizontal variations of the layer. Similar measurements have been reported by *Clemesha et al.* [1981] at São Paulo, Brazil and by *Gardner et al.* [1982] at the Goddard Space Flight Center in Greenbelt, Maryland. Unfortunately, practical operating considerations limit ground-based measurements of this type to horizontal baselines of about 100 km or less. Gravity waves and tidal winds at mesospheric heights typically have horizontal wavelengths of a few hundred km or longer. To study the sodium layer over longer baselines the first airborne lidar measurements were made by the University of Illinois (UIUC) group in March 1983 on a single roundtrip flight from the NASA Wallops Flight Facility to Albany, New York [*Segal et al.*, 1984]. These experiments demonstrated the feasibility of airborne measurements and did reveal evidence of wave induced horizontal structure over the 650 km flight path.

In July 1985 the first lidar measurements of sodium were made at the Air Force Geophysics Laboratory (AFGL) in Bedford, Massachusetts. Subsequently, the AFGL and UIUC systems were used to make simultaneous measurements on the nights of August 28, October 9, and October 16, 1985. The results, presented in this paper, reveal substantial differences in the sodium layer at the two sites. These measurements are compared with data obtained by the UIUC group in 1981 at the Goddard Space Flight Center, Maryland and in 1984 at the White Sands Missile Range, New Mexico.

EXPERIMENTAL RESULTS

The system parameters of the AFGL and UIUC sodium lidars used for the simultaneous measurements are summarized in Table 1. During the experiments, photocount data were collected at roughly 5-min intervals. Because scattered clouds were present at both sites during each of the 3 nights, there were a few short 10–15 min intervals when measurements were impossible at one or both sites. In these cases, the data from each site were interpolated to fill in the gaps. Both the UIUC and AFGL lidar data were processed using the UIUC analysis software. The average sodium profiles measured at AFGL and UIUC in August and October are plotted for comparison in Figure 1. The profiles have been normalized by the total abundance so that their areas are equal. The data were low-pass spatially filtered with a cutoff frequency of 0.5 km^{-1}. The measurement accuracy is directly related to the sodium and background photocounts. For the normalized profiles plotted in Figure 1, the measurement accuracy of the

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TABLE 1. Sodium Lidar System Parameters

	AFGL	UIUC
Location	42°27′N, 71°16′W	40°10′N, 88°10′W
Altitude	85 m MSL	225 m MSL
Dye laser pump	Nd:YAG at 532 nm	Flashlamp
Wavelength	589 nm	589 nm
Energy	30 mJ/pulse	50 mJ/pulse
Pulse rate	10 pps	5 pps
Linewidth	7 pm FWHM	10.1 pm FWHM
Pulse width	10 ns FWHM	2 μs FWHM
Beam divergence	0.5 mrad FW at e^{-2}	1 mrad FW at e^{-2}
Telescope	Dall-Kircham	Celestron 14
Area	0.6 m^2	0.1 m^2
Field of view	3 mrad	3 mrad
Bandwidth	20 Å FWHM	5 Å FWHM
Range bin length	150 m	150 m

relative sodium density near the peak of the layer is usually better than 1%.

On August 28, three hours of data were collected at both sites starting at 2300 EST (EST = UT − 5 hours). At AFGL the layer had a much steeper bottomside with a peak density at 89.5 km. At UIUC the peak density is near 92 km and there is substantial sodium at the higher altitudes above 95 km. The general characteristics of the layer can be described in terms of the column abundance, centroid height and rms width [*Gardner and Shelton*, 1985]. These parameters are listed in Table 2 for comparison. The accuracies of the centroid and width measurements are each better than 50 m at both sites. The accuracy of the UIUC abundance measurements is about 20%. Uncertainties in the laser tuning limited the accuracy of the AFGL abundance measurements to about 50%. The abundance and width measurements for August 28 are comparable at both sites but the layer centroid height is 1.2 km lower at AFGL.

On October 9 marginal weather permitted only one hour of simultaneous measurements starting at 2115 EST. Again the AFGL layer is much lower (almost 3 km) and wider and the abundance is higher. The bottomside extends below 80 km and the centroid height is 89.5 km compared to 92.2 km at UIUC. The AFGL layer is also considerably lower on October 16. The centroid height is 89.3 km compared to 92.1 km at UIUC. Although the abundance values are comparable at both sites, the rms width is roughly 35% larger at AFGL.

Gravity wave activity was present in the layer at both sites on all 3 nights but was most prominent in October. The wave parameters can be determined by analyzing the spatial power spectra of the profiles and by using the gravity wave dispersion relations [*Gardner and Voelz*, 1985]. On October 9 a wave with vertical wavelength of between 6.5 and 7 km was propagating through the layer at both sites. At an altitude of 90 km, the amplitude of the atmospheric density perturbations due to this wave was approximately 11% at AFGL compared to 3.5% at UIUC. On October 16 a wave with an amplitude of 5.1% (at 90 km) and a vertical wavelength of 5.7 km appeared in the UIUC profiles starting at about 2300 EST. Also starting at about 2300 EST, a wave with an amplitude of 6.8% (at 90 km) and a vertical wavelength of 6.4 km appeared in the AFGL profiles. The measured phase velocity at both sites for this wave was about 1.15 m s^{-1} which implies that the observed wave period was approximately 90 min. By using the gravity wave dispersion equations the horizontal wavelength was calculated to be 105 km.

In 1981, the UIUC group made sodium lidar measurements at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland (39°01′N, 76°50′W) using the NASA 1.22 m diameter satellite tracking telescope. The average layer profiles measured on the nights of October 16, 19 and 21, 1981 are plotted in Figure 2*a*. The layer parameters are summarized in Table 2. The GSFC profiles are similar to the data obtained at AFGL. The bottomsides of the profiles begin near 80 km and the layer centroid heights are 90 km or less on all 3 nights. On October 19 and 22, 1984, sodium lidar measurements were also made by the UIUC group from Alamo Peak (32°55′N, 106°50′W) near the White Sands Missile Range (WSMR), N. M. These profiles are plotted in Figure 2*b*. The layer parameters are listed in Table 2. The WSMR profiles are very similar to those measured at UIUC. The layer centroids are 91.2 and 92.0 km and the bottomside begins near 85 km. Also in agreement with the UIUC data the WSMR profiles are roughly symmetric with the peak densities on both nights occuring near 91 km. In contrast, the October AFGL and GSFC profiles are asymmetric and contain a significant amount of sodium at the lower altitudes between 80 and 85 km.

Also in October 1984, sodium lidar measurements were made by J. P. Jegou and his colleagues at the Haute Provence Observatory (OHP) in southern France (44°N, 6°E). The measurements were made nearly simultaneously with the WSMR observations obtained by the Illinois group. The column abundance, centroid height, and rms width values measured at OHP during the early mornings of October 21 and 22, 1984, are listed in Table 2. The centroid heights are similar to the WSMR (and UIUC) values while the column abundance at OHP is considerably lower. Because of the long 9091-km baseline between WSMR and OHP, chemical effects

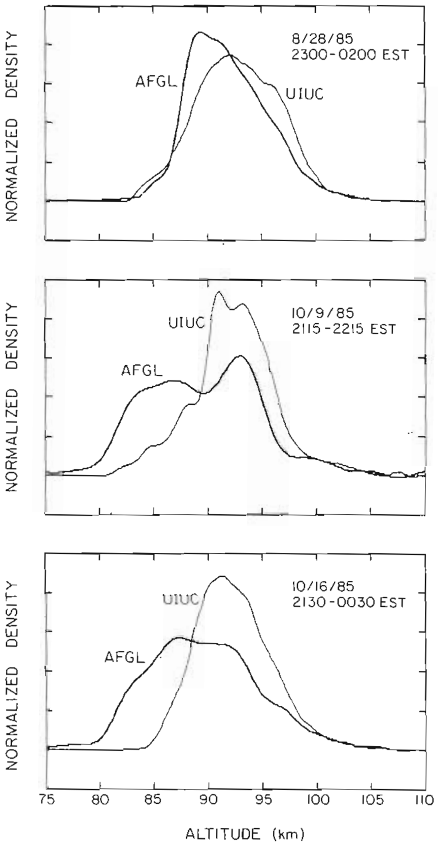

Fig. 1. Normalized sodium layer profiles measured simultaneously at AFGL and UIUC in August and October 1985. Note: EST = UT − 5 hours.

and meteoric influx could be substantially different at the two sites, which may explain the large difference in sodium abundance. Thus the data listed in Table 2 from the five sites suggest that the sodium layer centroid in October is near 91 km at WSMR, UIUC, and OHP and near 89 km at GSFC and AFGL.

Discussion

The data from the four North American sites suggest that there may be a significant longitudinal variation in the layer structure, particularly between 70°W and 90°W. The layer is substantially lower at GSFC and AFGL compared to UIUC and WSMR. The average centroid heights for all the measurement periods are plotted versus longitude in Figure 3. The lines connect the data points measured simultaneously at AFGL and UIUC. Except for the WSMR data point on October 22, 1984 and the simultaneous AFGL-UIUC data points on October 9, 1985, the remaining centroid values were computed by averaging 2 or more hours of observations at each site. The layer centroids measured at GSFC are a bit higher than those measured at AFGL in October but are still considerably lower than the UIUC values. October data points at UIUC, GSFC and AFGL suggest a general increase in the layer centroid height with increasing longitude between 70° and 90°W. Although this longitudinal variation could merely be a short-term phenomenon (on the order of a few hours) produced by a variety of processes such as gravity waves and tides, it is argued here that the observed centroid variation may be steady-state condition that persists at least during the fall when the measurements were made.

Longterm sodium layer measurements at UIUC show that the average centroid height for the year is about 92 km. The lowest value was 90.25 km measured on November 12, 1984 and December 13, 1980 and the highest value was 94.25 km measured on April 12, 1985. It is significant that for roughly 30 hours of October observations at UIUC since 1983, the lowest centroid measurement for any 10-min interval was 91 km. These long-term UIUC observations suggest that the much lower centroids at GSFC and AFGL in October may be a persistent characteristic of the sodium layer at those sites. In general, the seasonal variation of the centroid height at UIUC is not completely clear, however, there is an apparent decrease in average value to about 90.5 km in November and December when abundance is maximum [*Gardner et al.*, 1986]. These results are consistent with other northern hemisphere lidar observations. *Gibson and Sanford* [1971] did not measure the centroid but did find that the altitude of the layer peak decreased substantially from about 92 km in summer to about 87.5 km in winter at Winkfield, England (51°N, 1°W). The lowering of the peak was associated with a significant increase in sodium on the bottomside of the layer. *Megie and Blamont* [1977] also found a decrease of the layer peak from approximately 91 km in summer to about 89 km in late winter at Haute Provence, France (44°N, 6°E). In the southern hemisphere at São Paulo, Brazil (23°S, 46°W), *Simonich et al.* [1979] did not find any significant seasonal variation in the altitude of the layer peak which was typically between 91 and 93 km.

For the data reported in this paper, the separation distances between the four North American sites are rather insignificant on a global scale. The greatest separation distance is about 3280 km between WSMR and AFGL. The baseline between the UIUC and AFGL sites is only 1430 km. Also, the 4 sites

TABLE 2. Sodium Layer Parameters

Date	Site	Abundance, $\times 10^9$ cm^{-2}	Centroid, km	RMS Width, km
Aug. 28, 1985	AFGL	5.7	91.5	4.0
	UIUC	6.5	92.7	3.9
Oct. 9, 1985	AFGL	8.9	89.5	5.3
	UIUC	5.1	92.2	3.90
Oct. 16, 1985	AFGL	6.7	89.3	4.9
	UIUC	7.1	92.1	3.65
Oct. 19, 1984	WSMR	7.1	91.2	3.9
Oct. 22, 1984	WSMR	7.1	92.0	4.3
Oct. 21, 1984	OHP	2.2	90.8	4.9
Oct. 22, 1984	OHP	2.5	91.2	5.0
Oct. 16, 1981	GSFC		90.2	3.9
Oct. 19, 1981	GSFC		89.0	4.5
Oct. 21, 1981	GSFC		89.5	4.0

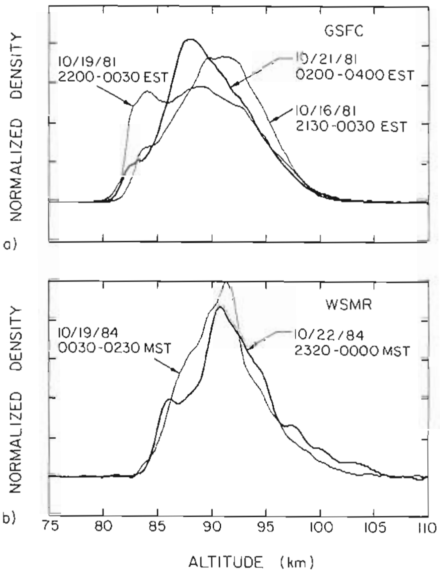

Fig. 2. Normalized sodium layer profiles measured (*a*) at GSFC in October 1981 and (*b*) at WSMR in October 1984. Note: MST = UT − 7 hours.

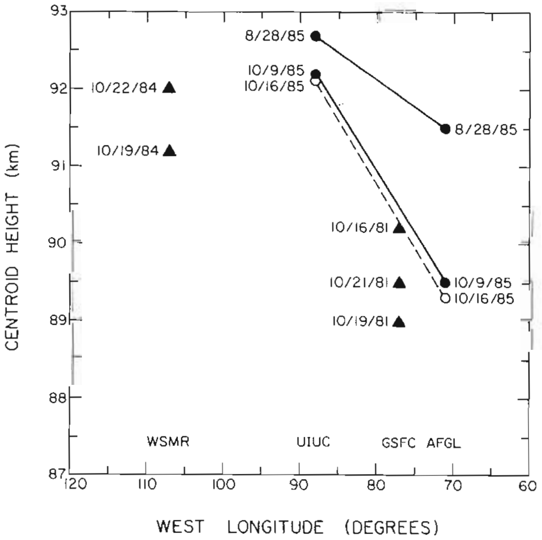

Fig. 3. Variation of the sodium layer centroid height versus longitude.

are all located at mid-latitudes (32°–42°N). As a consequence, the chemical processes governing the basic structure of the sodium layer should be homogeneous over these relatively small distances. Similarly, there is no reason to expect the meteoric source of the layer to vary appreciably among the sites. Therefore, the observed differences in the centroid heights at the UIUC and AFGL sites are most likely the result of differing dynamic activity.

Gravity waves and tidal winds can significantly influence the layer height and structure. Centroid variations on the order of 1–2 km within a few hours have been observed by *Gardner et al.* [1986] and have been attributed to large amplitude gravity waves with large vertical wavelengths (>20 km). However, the present theory suggests that typical gravity waves in the mesosphere should cause centroid perturbations of less than 1 km [*Gardner and Shelton*, 1985]. In any case, it seems unlikely that particular gravity wave events could induce the consistently lower centroids observed near 70°W as these events are generally thought to occur sporadically.

Observations by *Batista et al.* [1985] and recent observations at UIUC [*Gardner et al.*, 1986] suggest that tidal winds on the average cause a 1–2 km variation in the layer centroid height with a predominantly semidiurnal period. At UIUC centroid variations of up to 3 km have been measured and attributed to the semidiurnal tide [*Kwon et al.*, 1986]. Recent tidal models predict vertical velocity amplitudes on the order of 20 cm s^{-1} for the semidiurnal tide at mid-latitudes near the mesopause [*Forbes*, 1982]. Velocities as large as 30 cm s^{-1} with vertical wavelengths on the order of 50 km have been measured using the UIUC sodium lidar [*Gardner et al.*, 1986]. These values are consistent with the meteor radar measurements obtained at Urbana and Atlanta [*Ahmed and Roper*, 1983]. Because of the large vertical wavelength, the tidal winds essentially displace the whole layer downward as the night progresses. Since the UIUC and AFGL are separated by about 17° longitude, the tidal phase difference between these two sites is expected to be about 1 hour. This tidal effect is most evident in the data collected on October 16, 1985. At UIUC the layer centroid decreased steadily from about 93 km at 2130 EST to 91 km at 0040 EST. This displacement is equivalent to a downward vertical velocity of 17.5 cm s^{-1}. At AFGL the layer centroid decreased from 90 km at 2150 EST to about 88 km at 2340 EST. In this case, the downward vertical velocity was 26 cm s^{-1}. Thus the tidal winds can have a significant influence on the height of the layer. However, for a 3-km variation in centroid height with a dominant semidiurnal period, the resultant centroid difference between UIUC and AFGL would only be about 500 m with AFGL leading UIUC by an hour in phase. Thus, tidal winds and gravity wave events do not appear to be capable of inducing the large centroid differences reported here.

A more promising mechanism which is capable of producing the observed centroid height differences is a small difference in continuous mean vertical wind motions between UIUC and AFGL. The required vertical velocity difference between the two sites is the velocity which in effect could move a sodium atom from the height of the layer centroid at UIUC to the centroid height of the AFGL layer within the residence time of the sodium atom in the layer. The atom residence time is typically defined as the total abundance in the layer divided by the source input flux. Using the average sodium abundance value at UIUC of about 5×10^9 cm^{-2} [*Gardner et al.*, 1986] and a typical estimated meteoric flux value of about 1×10^4 cm^{-2} s^{-1} [*Kirchhoff et al.*, 1981], a residence time of 5.8 days is calculated. Thus, an average vertical velocity difference of about 0.4 cm s^{-1} between UIUC and AFGL is required to produce a 2 km centroid height difference between the two sites. Because of the density and temperature structure of the atmosphere near the mesopause, a small continuous difference in background vertical velocities may modify Na layer chemistry and diffusion which in turn may produce changes in abundance values, and therefore different residence times at each site. It is probable that layer widths would also differ. However, because the height differences are less than half the atmospheric scale height for the region, the effects on abundance and width may not be particularly significant and accordingly difficult to isolate in the short data set reported here.

Bjorn et al. [1985], in discussing some recent measurements of heavy mesospheric ions at high latitudes, concluded that the ions may have been influenced by an upwelling of air in the mesosphere with a velocity on the order of 5 cm s^{-1}. It was postulated that the upwelling was related to the meridional mesospheric circulation system. This system is characterized by an upward motion of air over the high latitudes of the summer hemisphere coupled with a downward motion over the high latitudes of the winter hemisphere. Models of this system have actually predicted high-latitude vertical motions on the order of 1 cm s^{-1} [e.g., *Dunkerton*, 1978]. There is some evidence in lidar data that this type of motion affects the sodium layer peak altitude and centroid. As mentioned previously, *Simonich et al.* [1979] observing in lower latitude regions (23°S) found no significant seasonal variation in the altitude of the sodium layer peak. This observation might reflect the fact that the meridional mesospheric circulation is primarily horizontal at low latitudes. The mid-latitude stations at UIUC (40°N), Haute Provence (44°N), and Winkfield (51°N) show some lowering of the layer peak (layer centroid at UIUC) during winter months which perhaps is a response due in part to slight downward motions present over the mid-latitude winter hemisphere. Some high-latitude sodium lidar measurements recorded during winter at Heyss Island (80°N, 50°E), Franz Joseph Land, USSR [*Juramy et al.*, 1981] show layer peak altitudes ranging between 84 km and 90 km which imply an average peak altitude near 87 km. This low peak altitude value could be in part the result of a stronger downward motion expected at high-latitudes during winter, although, from the previous discussion of the sodium atom residence time, the implication is that the downward motion is less than the 5 cm s^{-1} estimated by *Bjorn et al.* [1985] and is more of the order of the 1 cm s^{-1} value predicted by model calculations.

It should also be mentioned here that the seasonal and latitudinal variation of sodium are also thought to be significantly influenced by variations in temperature and possibly eddy diffusion. Chemical modeling attempts to explain the seasonal abundance variation [e.g., *Swider*, 1985; *Fiocco and Visconti*, 1973] have generally produced results that show abundance increases on the bottomside of the layer in winter which have been observed at some lidar sites [e.g., *Gibson and Sandford*, 1971]. An increase in abundance on the bottomside of the layer would also tend to lower centroid values. However, it is not clear that these chemistry studies alone predict the accompanying lower layer peak observed in the lidar data.

In reference to the UIUC and AFGL measurements, it appears that differing mean vertical motions at the sites can account for the differing centroid height measurements. However, because of a lack of knowledge regarding the longitudinal variation of the vertical winds in the mesosphere, it is difficult to isolate a definitive source capable of inducing the effects cited in this paper. It may be significant that the lower centroid heights were observed near the U.S. eastern coast line whereas the high centroid heights were observed near mid-continent.

Recent modeling results of *Jegou et al.* [1985*a*, *b*] suggest a second mechanism which may influence the height of the layer centroid. Their model assumes that ionic species, such as Na^+ and $Na^+ \cdot H_2O$, are of considerable importance in the chemical scheme associated with the neutral sodium layer. Vertical velocities of the ions in the model were found to be proportional to magnetic field and wind values with the mean zonal wind effects dominant in the region. As the ions are swept across magnetic field lines by the winds, a Lorentz force is established and the ions acquire a vertical velocity component. In general, a westward wind induces a downward velocity in the northern hemisphere while an upward velocity results from an eastward wind. *Jegou et al.* [1985*a*] have calculated vertical velocities of about 7 cm s^{-1} for the Na^+ and $Na^+ \cdot H_2O$ ions assuming a 20 m s^{-1} zonal wind at 90 km. Their model calculations demonstrate that for small wind amplitudes (5 m s^{-1}) and gradients, the peak neutral sodium density remains near the peak of the source input (90–91 km). Larger wind amplitudes and divergences tend to alter the altitude of the ionic layers, and also the altitude of the neutral layer depending on temperature conditions affecting the ion-neutral chemistry. In fact, sudden seasonal changes in the zonal wind pattern used in the model result in as much as a 4 km change in the altitude of the layer peak. The implication for the UIUC and AFGL data is that differences in the zonal winds above these sites may cause differences in the layer centroid heights.

Stronger eastward wind components in and above the layer region at UIUC or a larger negative gradient with altitude of the eastward wind at UIUC compared with AFGL would result in a higher centroid height for the sodium layer at UIUC. Radar measurements of the mean mesospheric wind fields at Durham, New Hampshire (43°N, 71°W), Atlanta, Georgia (34°N, 84°W) and Saskatoon (52°N, 107°W) show substantial differences in the zonal wind climatology [*Manson et al.*, 1985]. October wind measurements at Durham in the east and Saskatoon in the west both show eastward winds below 110 km with amplitudes of 10–15 cm s^{-1} at 90 km. However, a larger negative gradient at 90 km is seen in the Saskatoon wind data as compared with Durham (about -1.0 cm s^{-1} km^{-1} versus -0.3 cm s^{-1} km^{-1}) which may be of some significance because this gradient difference would tend to elevate the sodium layer at Saskatoon compared to Durham. It is difficult to further relate the radar data to the lidar data reported here because the differences in latitude between stations (particularly between UIUC and Saskatoon) are significant. It should also be emphasized that the effectiveness of the mean zonal wind mechanism is dependent on the ion-neutral chemistry of the region, which is not well understood.

CONCLUSIONS

These initial simultaneous measurements at AFGL and UIUC clearly show substantial differences in the sodium layer structure at the two sites in August and October. The most striking feature of the measurements are layer centroid heights at AFGL which are 1–3 km lower than those at UIUC. It is argued that the centroid height difference may be a persistent feature at least in the fall and may be caused by differences in background vertical wind velocities at the two sites or possibly by differing zonal winds affecting an ion-neutral chemistry. Because the typical residence time for a sodium atom in the layer is approximately 5.8 days, a 0.4 cm s^{-1} difference in the mean vertical wind velocities between UIUC and AFGL is capable of producing a 2-km difference in the centroid height of the sodium layer. Gravity wave and tidal winds do not appear to be of sufficient strength to cause the observed differences in the layer structure while chemical processes and meteoric influx should be homogeneous over the short 1430 km baseline between the two sites. More extensive measurements over longer observation periods throughout the year should help to clarify the differences in the sodium layer at the two sites and should help identify their causes.

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