Simultaneous and Common-Volume Lidar Observations of the Mesospheric Fe and Na Layers at Boulder (40°N, 105°W)

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ABSTRACT

The structures of mesospheric metal layers are produced by complicated chemical and dynamical processes in the mesosphere and lower thermosphere (MLT) region. Current chemical models with parameterized inputs can reproduce some large-scale characteristics but are challenged in simulating small-scale features. Simultaneous and common-volume observations of multiple species are valuable for understanding the processes and validating the models. Such observations of Fe and Na layers are relatively rare. In summer and fall 2010, we made over 12 nights of such observations at Boulder (40°N, 105°W), USA, with two resonance lidars: an Fe Boltzmann temperature lidar and a 3-frequency Na Doppler lidar. The detailed comparisons between Fe and Na layers among their mean characteristics and important features are reported. On 11 August 2010, we also observed several meteor trails of Perseids meteor shower, and found significantly enhanced abundance of both Fe and Na layers. Moreover, the MLT temperatures were obtained simultaneously by the lidars, providing unique and critical information for future modeling effort.

1. INTRODUCTION

The Earth's atmospheric metal layers (Fe, Na, K, Ca, and Li) from 70 to 120 km are believed to originate from meteoric ablation. They have served as excellent tracers for ground-based lidars [1], which provided not only the density distributions but also the more important temperature and wind measurements in the MLT region. Their prominent properties, seasonal variations, and vertical structures have been studies by lidars from many locations [1]. Besides independent measurements, there are relatively rare collaborative observations for multiple metal species simultaneously at the same location [2, 3]. Since the formation and the structures of the atomic metal layer are directly linked to the input of gas-phase metal materials from meteoric ablation, chemical reactions, and dynamic transport, the observations exploring the relationship between various metal layers will help identify the dominant processes in producing any of the layer features and the mechanisms of interactions. This will help refine current models for reproducing the general structures more precisely as well as simulating the challenging small scale features.

In Aug. and Sept. 2010, we made over 12 nights of simultaneous and common-volume lidar observations of Fe and Na at Boulder (40°N, 105°W), Colorado. The MLT temperatures were also obtained by the lidars for future modeling effort.

2. OBSERVATIONS AND DISCUSSIONS

Two resonance fluorescence lidars are used in this research. The Fe Boltzmann temperature lidar was under upgrading and validating at Boulder before its deployment to Arrival Heights, McMurdo in Nov. 2010 [4]. This lidar uses two independent channels probing the 372 and 374 nm absorption lines of neutral Fe atoms, respectively. The temperatures are inferred from the signal ratios between these two channels by employing the Boltzmann technique [1]. Raw data were taken with 48-m and 1-min resolution. The Na lidar is a 3-frequency Doppler lidar probing the Na atoms at D2a transition (589.16 nm) and ±480MHz beside it. One vertical-pointing beam was employed for this study. Ratios are calculated by lidar signals from these three transmitted frequencies to infer the line of sight wind and temperature, which are associated with the Doppler shift and width of the Na resonance [1]. Raw data were collected with 96-m and 0.5-min resolution. The two lidars were 25 meter apart. Although the Fe lidar could cover full-diurnal cycle, the Na lidar was nighttime only. We integrate our data from both lidars to the same 96-m and 5-min resolutions in density calculation in order to increase the signal to noise ratio and make fair comparison. The processed data are truncated to cover

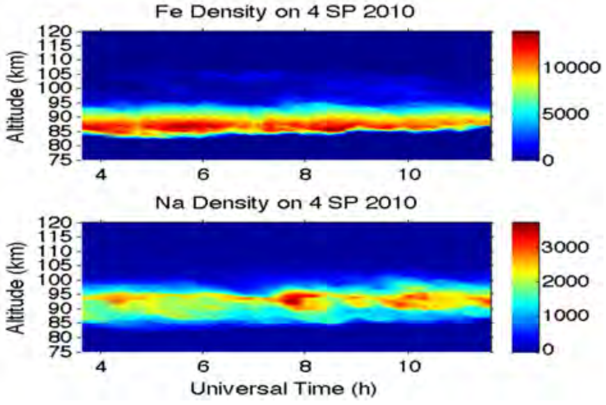

Figure 1. Contours of Fe and Na densities observed simultaneously by two lidars on 4 Sept. 2010 at Boulder.

Fe and Na simultaneously with identical start and end times for each profile. Over 12 nights (59 hours in total, 704 data pairs) of simultaneous measurements were made in August and September 2010. The measured densities on 4 Sept. are shown in Figure 1.

2.1 Mean Characteristics of Fe and Na layer

Fe and Na layers' mean characteristics during our observation period are summarized in Table 1. Comparing to Na layer, the mean density and column abundance of Fe are 3.4 and 3 times higher, respectively; the mean centroid and peak altitudes of Fe layer are 2.4 and 5.2 km lower, respectively; the density slope for Fe at the bottom of main layer is steeper. The Na layer generally extends to higher altitude than Fe; but their RMS widths are comparable. These results are comparable to other observations at mid-latitudes [2, 3]. At Boulder, sporadic Fe and Na layers were very active during our observations, and observed every night.

Table 1. Fe and Na layers characteristics at Boulder.

Mean Characteristics	Fe	Na
Density (10^3cm^{-3})	13.03	3.85
Abundance (10^9cm^{-2})	10.65	3.45
Centroid altitude (km)	89.66	92.04
Peak altitude (km)	86.92	92.08
RMS width (km)	4.38	4.23

A few groups have made some detailed comparisons between the structures of Fe and Na layers at mid-latitudes. Kane and Gardner [2] at 40°N reported the similarity in the temporal variations of Fe and Na layers' parameters attributed to dynamic effects. Yi *et al.* [5] at 30°N reported that the lower boundary of Fe layer is generally slightly higher, about 0.2 km in mean, than that of Na layer, and their altitudes are highly correlated with correlation coefficient of 0.96. They considered this phenomenon as a subtle stratification, and suggested that the correlated altitude variations of their lower boundaries are unlikely caused by gravity waves alone. They also reported the weaker correlation of the upper boundaries because the frequently appearing sporadic layers impair the correct determination of the upper boundary of the normal layer. Considering the differences between two lidars, and the large fluctuations in signals and observed densities, to define the boundaries of the metal layers, we used 2% of the nightly mean peak densities as the limits rather than one fixed detection threshold for two lidars as in [5]. The lower or upper boundary is assigned to be the altitude before the density becomes lower than the limit when moving downward or upward from the peak altitude. Figure 2 shows the calculated boundaries corresponding to the densities in Figure 1.

The correlations between Fe and Na layers for lower and upper boundaries are 99.2% and 72.3%, respectively. After 5 UT, the stronger sporadic layer in Fe, shown in Figure 1, pushed the upper boundary about 8 km higher than normal main layer. It fluctuated and gradually descended to normal height till 11 UT tracing the motion of the sporadic layer.

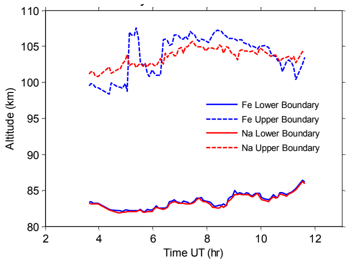

Figure 2. Boundaries of Fe and Na layers on 4 Sept. 2010.

For the total 704 pairs of profiles, the scatterplots in Figure 3 intuitively illustrated the altitude relationship of the boundaries between this two metal layers. The correlation of the lower boundaries is very robust as shown in Figure 2 except for Sept. 14th and 15th, when there are much stronger downward extensions in Fe layer than in Na layer. Mean boundary altitudes and correlations are listed in Table 2. Excluding Sept. 14th and 15th, the mean altitude of Fe lower boundary is 0.16 km higher than that of Na, similar to [5]. But we do think the altitude variations of the lower boundaries are mostly caused by gravity waves or tides propagating through. The variations generally have periods longer than half hour, typical for gravity waves and tides. The so-called stratification is very dependent on how the boundary limit was selected. Moreover, observations at both locations, Wuhan and Boulder, are lack of the temporal and special resolutions to see the complicated

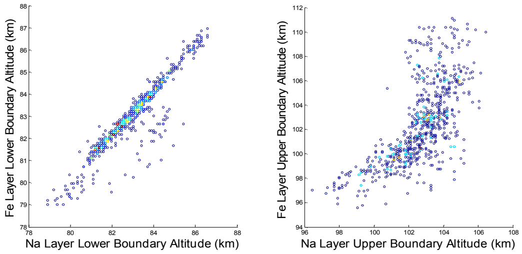

Figure 3. Scatterplots illustrating the relationship between boundaries of Fe and Na layers.

Table 2. Mean values for Fe and Na layers boundaries.

Boundary	Fe	Na	Correlation %
Lower (km)	82.99 (83.17)*	82.97 (83.01)	93.3 (98.5)
Upper (km)	102.38 (102.88)	102.63 (102.93)	67.3 (61.6)

*when September 14th and 15th excluded.

mixing structures produced by the turbulence from breaking gravity waves.

There are very different density scale heights at the bottom part of the two metal layers. The phenomenon, a sharper slope of Fe than of Na, has been reported by Yi *et al.* [5] and other groups. Our explanation is as follows. The lower boundary of a metal layer is mainly determined by the chemical reactions converting lidar-detectable neutral atoms into lidar-undetectable compounds. For the major chemical reactive species, i.e., O_3, O, and H, which convert neutral Fe and Na atoms to compounds or vice versa, there is a sharp transition region around 80 km at night. The one for O is known as "atomic oxygen shelf" [6]. With decreasing altitude around 80 km at night, the mixing ration of O_3, which oxides Fe and Na, varies about 10 times; but the mixing rations of O and H, which covert compounds back to neutral atoms, decrease dramatically ($\sim 10^5$ times). So the neutral atoms would be consumed rapidly below this "shelf". Since the Fe layer peaks at 5.2 km lower than the Na with similar RMS widths of about 4.3 km, near this "shelf", the Fe density drops to zero from a large value near the layer peak forming a sharp slope; on the contrary, the Na density drops to zero near the lower boundary of the layer from a small value. Thus a much smaller density scale height is created at the layer bottom of Fe than of Na.

2.2 Comparison between Density Profiles

As shown in Figure 1, there are many small structures within the main metal layers. The structures change dramatically during our nightly observations. Although some of the models have successfully reproduced some of the primary structures of the normal Fe and Na layers including the averaged layer shape and even some seasonal variations, arbitrary adjustments sometimes have to be made [7]. This indicates that the modelers have grasped major processes controlling the evolving of the metal layers but not all aspects of them. To reproduce the rich small structures in the main layer is very challenging since the model needs to implement all the processes and acquire details of many aspects of the atmospheric environment. Observing multiple metal layers simultaneously would help understand whether a similar feature in multiple metal layers is originated and controlled by one process, and whether the responses in different metals are different and why. Lidar observation is the only method providing continuous monitoring of multiple metal layers with high resolutions, and the available data are still scarce.

The correlation between the density variations in the normal layers of Fe and Na was explored in [8]. There are different methods in investigating the correlation between two metal layers. One would compare sequential density profiles tracing the movements of a prominent feature (e.g. a distinct peak), or correlate the temporal variations at same altitude. Here, we introduce using the relative density perturbations as a new approach of comparison. The averaged density profiles and/or the original profiles at the beginning of each observation normally look very different between Fe and Na. This makes it hard to compare single profile or absolute variations in density with time. As illustrated in Figure 4, the relative density perturbations reveal clearly correlated variations in contrast to the density contours in Figure 1. It is also very sensitive near the edges of the layers where the density is small but the relative perturbation is large.

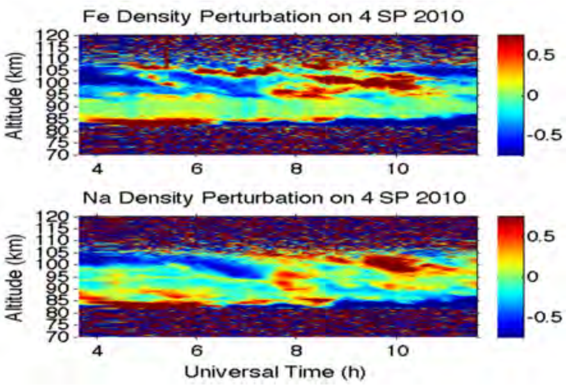

Figure 4. Contours of Fe and Na relative density perturbations on 4 Sept. 2010.

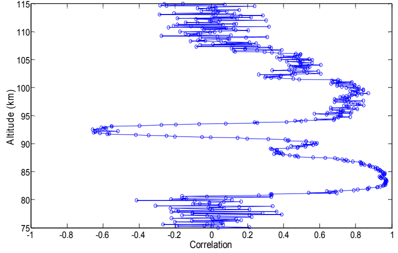

Figure 5. Correlation of Fe and Na density perturbations on 18 Aug. 2010.

The altitude-dependent correlations of the relative density perturbations between Fe and Na layer on Aug. 18th is shown in Figure 5. The figure is almost identical if calculating the correlation using the absolute density variations as in [8]. The highly correlated variations near lower boundary indicate almost identical process responsible for the motion of both Fe and Na, which should be the dynamic transport of propagating waves/tides. The relatively weaker correlation near the upper boundary indicates slightly different processes, maybe the differential ablation of the meteoroid and different ion chemistries for Fe and Na. The correlation decreases dramatically approach the layers peak region, and then significant anti-correlation appears in a narrow region about 2 km around 92 km. The opposite density gradient of Fe and Na at same altitude will introduce opposite density variations through the dynamic transport of propagating waves. We observed significant negative correlation (<-0.3) for all 12 nights, but the coefficients are mostly around -0.5. So waves play a major role, but other chemical and/or dynamic processes are apparently involved. Chen and Yi reported significant negative correlation for only ~63% of their observations [8]. This may indicate weaker impact from gravity waves at their location.

2.3 Perseids Meteor Shower Observed by Lidars

It is still inconclusive whether a meteor shower can noticeably increase the metal layer column abundance. There is few sophisticated observation with enough coverage over the meteor shower period and over different years. The mass input from a meteor shower is generally considered much less than that from the constant micro-meteors to have a significant impact on the metal layers.

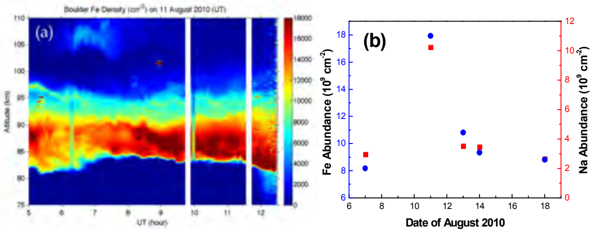

Figure 6. (a) Fe density contour on 11 Aug. 2010; (b) Abundances of Fe and Na in August 2010.

On 11 Aug. 2010, we observed several strong meteor trails in lidar signals, which were rarely observed on other nights. Although Perseids meteor shower is considered a moderate meteor one spreading over July and August without a distinct peak, Figure 6(a) indicates stronger than usual meteor input in this night over the lidar site. We found significant increases in both Fe and Na column abundances comparing to other nights in August, Figure 6(b). The measured MLT temperature is not consistently higher than other nights to produce such an enhancement. Our observations with the Na lidar alone in August 2011 show weaker abundance enhancement (~2 time) on 19th and 20th compared with 2010 on 11th (~3.3 times). We did not find a day with significant increased numbers of meteor trails in 2011. Considering the metal layer abundance is near the lowest in August, our observations do indicate that a localized strong meteor input can significantly enhance metal layers when the background abundance is low in summer.

3. CONCLUSIONS

We made over 12 nights of simultaneous and common-volume lidar observations on mesospheric Fe and Na layers in Aug. and Sept. 2010 at Boulder. It reveals general properties similar to the extensive observations at Wuhan, China. We introduced a new approach of using the relative density perturbation to compare the layer structures. Correlations of the boundaries and relative density variations between two layers indicate that different mechanisms play the major role in modifying the layer structure at different altitudes. The large gradient at the lower boundary of Fe layer is attributed to the chemical “shelf” near 80 km. Localized strong meteor inputs from Perseids meteor shower in 2010 significantly enhanced the metal layers.

ACKNOWLEDGMENTS

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