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Can High-Sensitivity Doppler Lidar Measurements of TIMt Turning Points Contribute to the Studies of Turbopause?

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Abstract: The turbopause represents the transition from strong turbulent mixing in the middle atmosphere to molecular diffusion dominating in the upper atmosphere. Despite extensive studies of the turbopause with a variety of techniques, there had not been a single contribution from lidar techniques due to challenges in making measurements at such high altitudes (~105 km and above). Development of high-sensitivity resonance-fluorescence lidar technologies has enabled the routine measurements of thermosphere-ionosphere metal (TIMt) layers at such high altitudes over Boulder, Colorado and at McMurdo, Antarctica. These unique data reveal clear turning points in the metal density and mixing ratio profiles of TIMt layers at both locations representing the midlatitudes and polar regions. These TIMt turning points locate right around 105–110 km, basically overlapping the turbopause altitudes. Furthermore, we report for the first time in this paper that the turning point altitudes exhibit annual variations with the winter turning points located ~5 km higher than the other seasons. Such variations resemble the turbopause annual variations nicely, inspiring us to ask whether lidar measurements of TIMt layers can help the studies of turbopause on Earth and Mars. This paper explores this question after characterizing the turning points over Boulder.

1. Introduction

Thermosphere-ionosphere metal (TIMt) layers occurring above the main layers are a recent discovery made with lidar observations [1]. Ablated cosmic dust [2] forms the main metal layers in the upper atmosphere from ~75 to ~105 km, which have been studied for about a century [3]. However, it was not until 2011 when the TIMt layers above 105 km were first discovered by Chu and co-workers with an Fe Boltzmann lidar at McMurdo, Antarctica [1]. Following this, TIMt layers have been reported for low, mid, and high latitudes. The discovery of TIMt layers has significantly increased the vertical extent of metal atom lidar observations up to ~200 km for neutrals and ~300 km for metal ions (e.g., Ca^+) [4], and opened a new window to uncover new phenomena/processes and challenge existing understandings [5–8].

Among all the reports of TIMt layers around the world, the only regular occurrence case of TIMt layers was reported for Na species (TINa) in 2021 over Boulder [7]. Through studying the formation mechanisms behind such regularly occurring TINa, several science discoveries have been made in Chu, Chen et al. (2021) [7] and Chen & Chu (2023) [8]. An interesting one was the turning points of Na density and mixing ratio profiles (Fig. 1), above and below which the log-scale Na densities and mixing ratios exhibit different slopes. Similar turning points at ~110 km (see Fig. 1) was first reported for both Fe and Na layers in Antarctica in 2020 [6].

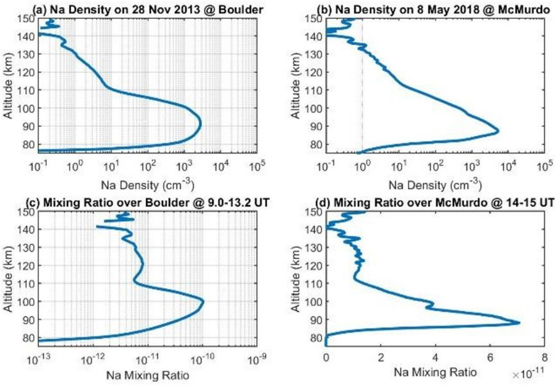

Figure 1. Vertical profiles of Na density and volume mixing ratio for Boulder (left column) and McMurdo (right column). The Na detection limit is better than 0.1 cm^{-3}.

Except the similar turning point altitudes noted in [7], there were no further studies of these turning points until this report. Different slopes above and below the turning point likely indicate quite different formation mechanisms between the main layers (~75–105 km) and TINa layers (~105–150 km). The similarities in turning points between Boulder (midlatitude 40ºN) and McMurdo (polar region 78ºS) suggest something in common globally. Notice that the turning point altitudes basically overlap the altitudes of turbopause (~105–110 km) [9]. Naturally we want to know if the TINa turning points are related to the turbopause and what the turning points mean to the metal chemistry & the middle and upper atmosphere dynamics. To answer such questions, we must characterize the turning points and variations systematically, which is the major goal of this paper. The possibilities and challenges of using the turning points of Tempt layers to study the turbopause are discussed at the end.

2. Comparing TINa layers between Boulder and McMurdo

The Na density turning point was first noted in Chu et al. (2020) [6] from McMurdo TINa and TIFe layers in Antarctica, and Na and Fe mixing ratios were calculated for the first time to better characterize the tenuous TINa and TIFe layers. The Na density profiles in log-scales (Fig. 1b) exhibit one trend from ~90 to ~110 km and then a different trend above the turning point at ~110 km where TIMt layers emerge [6]. Interestingly, this feature is also found from Boulder TINa observations [7, 8] (Fig. 1a). Another similar feature between Boulder and McMurdo TINa related to the turning point is that the Na mixing ratios exhibit a broad peak above 110 km (Fig. 1c and 1d), providing strong evidence for *in situ* production of neutral Na atoms [6, 7].

Despite the similarities of TINa between two locations, there are many differences in TINa between mid and high latitudes. Compared to the regular occurrence every night in Boulder, TINa layers in Antarctica exist in extremely long hours during nighttime showing diffusive patterns as shown in Fig. 2 and Fig. 3. Detailed comparison of TINa between midlatitudes and polar regions will likely lead to new findings and understandings for the middle and upper atmospheric research but that is beyond the scope of this paper. Nevertheless, the TINa layer differences between two locations make the similar turning points even more stunning. Studying the TINa turning points will aid to understand the atmospheric dynamics because these metal species are transported by various forcings from various energy sources.

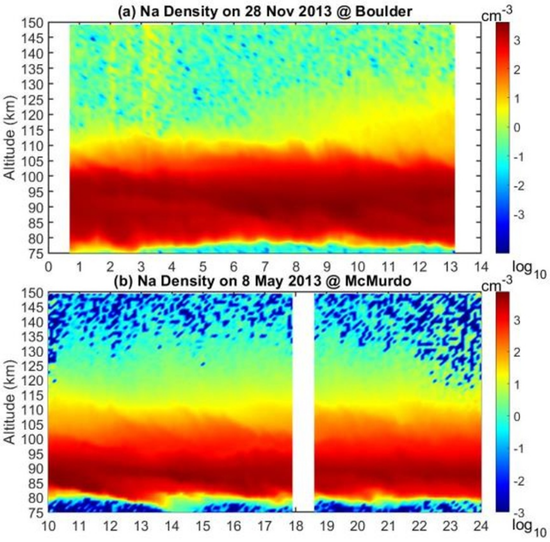

Figure 2. Na Doppler lidar observations of TINa layers over Boulder (top) and McMurdo (bottom). Na number density in log-10 scale.

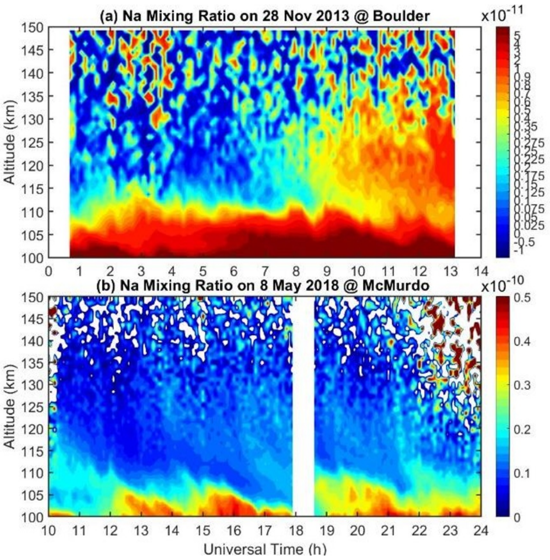

Figure 3. Same as Fig. 2 for Na mixing ratio.

3. Annual Variations of Turning Point Altitudes over Boulder

Through seven years of high-sensitivity lidar observations (2011–2017), totally 140 nights of data were chosen for the predawn TINa turning point determination over Boulder. July has the least but still four cases, sufficient for turning point calculations, while maximum 24 nights of data were used in November. A criterion to determine the turning point is that there must be significant slope differences above and below the turning point. Within certain altitude range, a linear fitting is applied to the log-scale Na density to obtain the slope baseline. Then after subtracting the slope baseline, the remaining slopes above and below the turning point must have a sign change (i.e., the change between positive and negative slopes). Applying this method, the turning point altitude is calculated for the predawn TINa layers [8] of individual nights first, and then averaged in the same month to obtain the monthly mean turning point altitudes.

The results are illustrated in Fig. 4 for all 12 months along with the standard errors as error bars. Interestingly, the turning point altitudes vary with seasons. The winter months (Oct, Nov, Dec, and Jan) have the turning point located above 110 km, obviously higher than the other seasons. Checking the 140 individual nights, the minimum altitude ~104 km occurs in April and in summer, while the maximum altitude ~118 km occurs in winter.

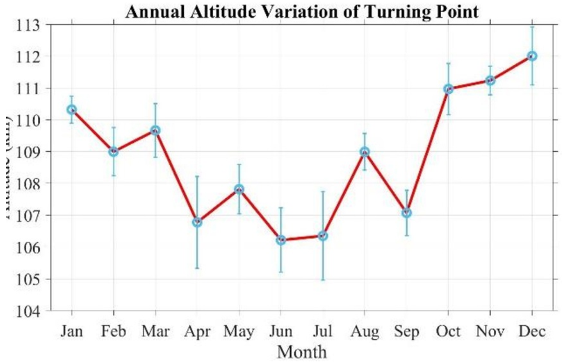

Figure 4. Annual variations of turning point altitudes for 12 months using 7 years of lidar observations over Boulder.

To further characterize this annual trend, a harmonic fitting is applied to the TINa turning point altitudes:

$$z(DOY) = z_0 + A_{12} cos\left[\frac{2\pi}{365}(DOY - \varphi_{12})\right]$$
$$+ A_6 cos\left[\frac{2\pi}{365/2}(DOY - \varphi_6)\right]$$

where DOY is the day of year, z_0 is the annual mean of turning point altitude, A_{12} and A_6 are the amplitudes of annual oscillation (AO) and semi-annual oscillation (SAO), and φ_{12} and φ_6 are the corresponding phases of AO and SAO. The fitting results are shown in Figure 5. The obtained amplitudes of AO and SAO are ~2.4 and ~0.4 km, while AO and SAO phases are ~346 and 285 DOY.

This annual trend of turning point altitude is quite like the annual variations of turbopause altitude, which is also lower in summer and higher in winter [9–13].

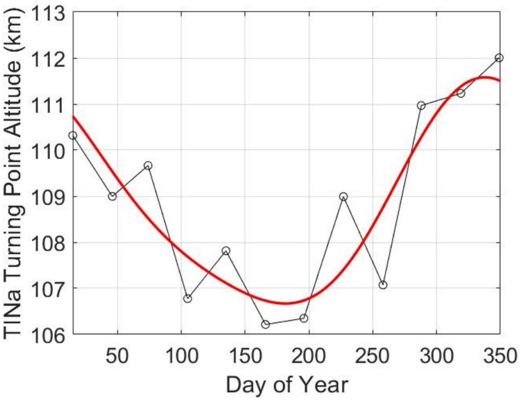

Figure 5. A harmonic fit (red curve) consisting of mean, AO, and SAO is applied to the 12 months of TINa turning-point altitudes.

4. Discussion and Conclusions

Variations in turbopause altitudes mean the changes in vertical transport of energy, mass, and momentum and their deposition at different altitudes, which affect the thermal, chemical, and dynamical states of the middle and upper atmosphere. Such motivations not only attract efforts to study the Earth's turbopause, but also inspire the turbopause studies on Mars [11]. Three concepts have been developed—the turbopause, homopause (or mixing turbopause), and wave turbopause. They are inter-connected but each emphasizing the different aspects of the transition from the turbulence-dominated regions to the molecular diffusion dominated upper atmosphere [11–14]. Generally speaking, turbopause is located between 90 and 110 km altitude with spatial and temporal variations. According to some literatures, wave dissipation dominates below the wave turbopause, causing lower stability in the region, while above the turbopause, less wave dissipation makes the upper atmosphere more stable [11,12]. There are still many unknowns about turbopause despite extensive efforts studying it.

In the upper atmosphere above the turbopause, besides the molecular diffusion overpowers the turbulent mixing, ion concentrations increase quickly with altitude. Consequently, ion drag and plasma-neutral coupling play more and more important roles. Indeed, the leading theory of the formation mechanisms of neutral TIMt layers above 110 km is the neutralization of metallic ions via direct recombination with electrons [1,5–8]: $TIMt^+ + e^- \rightarrow TIMt + hv$.

Through studying TIMt formation mechanisms, the transport of minor species will be better investigated and understood.

Tidal winds were invoked to explain the annual phase (occurrence time) variations of predawn TINa layers observed by lidar over Boulder [8]. That is, $TINa^+$ ions are accumulated in the convergent phase of tidal wind shear, and then neutralized to form the neutral TINa layers. Because the tidal winds experience an annual phase variation likely induced by the sunrise annual variation, the predawn TINa layers experience earlier occurrence in summer but ~2.5 hr later in winter [8]. To explain the newly discovered annual variations of TINa turning point altitude, we hypothesize that some tidal modes may break at different altitudes in different seasons, causing the turbopause and the TINa turning point to have annual variations in altitudes. If this is the case, then the variations of TINa turning point altitude may reflect the turbopause variations, thus a possibility to study the turbopause using lidar observations of metal layers in the mesosphere and thermosphere.

The discovery of annual variations of the turning point altitudes raises new questions, e.g., what causes the turning point in TIMt density and mixing ratio profiles? How is it related to the turbopause variations? How does the transition region affect the TIMt layer formation? What roles do turbulence and molecular diffusion play in the thermal, chemical, and dynamical states of the middle and upper atmosphere? Considering single species like Na may not be sufficient to address turbopause, we propose to make simultaneous lidar observations of Fe and Na layers. Because Fe and Na have mass numbers of ~56 and ~23, respectively, it is an analogy to the usage of Argon/N_2 ratios (~40 over ~28) to determine the turbopause altitudes [11, 14]. Studying of the TIMt turning points and their relation to the turbopause may provide insight to the transport and dynamics in the upper atmosphere.

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