Geophysical Research Letters

Supporting Information for

Lidar Observations of Predawn Thermosphere-Ionosphere Na (TINa) Layers over Boulder (40.13°N, 105.24°W): Annual Phase Variations and Correlation with Sunrise and Tidal Winds

Yingfei Chen[1] and Xinzhao Chu[1]*

[1]Cooperative Institute of Research in Environmental Sciences & Department of Aerospace Engineering Sciences, University of Colorado Boulder, USA

*Corresponding Author: Xinzhao.Chu@Colorado.edu

Contents of this file

Introduction

Analyses of 7 years of the Student Training and Atmospheric Research (STAR) Na Doppler lidar observations from 2011 to 2017 reveal the regular occurrence and annual phase variations of the predawn thermosphere-ionosphere Na (TINa) layers at Boulder (40.13ºN, 105.24ºW), Colorado. Such phase variations of TINa are correlated to the annual phase variations of sunrise and tidal winds.

Table S1 provides the statistics of qualified predawn TINa layers from 2011 to 2017. Harmonic fitting parameters and their errors are given in Table S2 for annual phase variations. Table S3 lists the correlation coefficients between TINa and sunrise/CTMT tidal winds as well as the corresponding confidence levels.

Figure S1 provides 12 representative individual nights (one per month) of Na mixing ratio contours from 100–150 km for January through December. Figure S2 illustrates 12 monthly composite contours of Na mixing ratios with the TINa peak phase lines overplotted. Figure S3 shows the comparison between CTMT and ICON Hough-Mode-Extension tidal winds in January with the TINa peak phase line overplotted.

Furthermore, the Figures 2 and 3 in Buonsanto & Witasse (1999) that were referenced in the Discussion section are shown as Figures S4 and S5 for the convenience of readers. The Figures S4 and S5 illustrate the statistical mean of F-region ion transport at Millstone Hill measured by an incoherent scatter radar, where geographic and geomagnetic latitudes are similar to those of Boulder.

In response to reviewer comments on “conjugate photoelectrons”, Figures S6 and S7 are added to illustrate the annual variations of Boulder local sunrise and conjugate site sunrise versus the predawn TINa phase variations, and to present the conjugate and local sunrise times from 100 to 1000 km along with the predawn TINa peak phases in January through December. Figures S6 and S7 demonstrate the conjugate photoelectrons being unimportant in the formation of predawn TINa layers over Boulder.

Table S1. Statistics for Pre-Dawn TINa Layers from January through December

	Number of nights for examination	Number of nights of TINa occurrence	Number of nights used for composite	Peak Phase* with error (UT)	Sunrise* Time (UT)
Jan	21	21	18	12.19 ± 0.39	13.35
Feb	11	11	10	12.17 ± 0.30	12.95
Mar	12	12	10	11.39 ± 0.44	12.27
Apr	6	5	5	10.08 ± 0.44	11.40
May	10	9	7	10.07 ± 0.43	10.66
Jun	8	6	4	9.60 ± 0.28	10.34
Jul	5	5	5	9.49 ± 0.35	10.61
Aug	11	11	11	10.17 ± 0.30	11.19
Sep	15	15	11	10.57 ± 0.40	11.76
Oct	23	23	23	10.92 ± 0.45	12.26
Nov	30	30	24	11.69 ± 0.63	12.80
Dec	12	12	10	11.82 ± 0.61	13.24
Total	164	160	138		

* TINa peak phase and sunrise time at the altitude of 130 km

Table S2. Parameters of Harmonic Fittings* to TINa Peak Phase and Sunrise Time

	Mean A_0 (hr)	Annual Oscillation Amplitude A_{12} (hr)	Annual Oscillation Phase φ_{12} (day of year)
TINa @ 135km	10.00 ± 0.06	1.24 ± 0.09**	2.13 ± 4.01**
TINa @ 130km	10.84 ± 0.07	1.29 ± 0.10	1.82 ± 4.46
TINa @ 125km	11.42 ± 0.06	1.24 ± 0.08	3.90 ± 3.76
TINa @ 120km	11.97 ± 0.07	1.16 ± 0.10	6.09 ± 4.77
Sunrise@135km	11.88 ± 0.04	1.44 ± 0.06	359.52 ± 2.33
Sunrise@130km	11.90 ± 0.04	1.43 ± 0.06	359.53 ± 2.32
Sunrise@125km	11.92 ± 0.04	1.43 ± 0.06	359.54 ± 2.31
Sunrise@120km	11.94 ± 0.04	1.43 ± 0.06	359.54 ± 2.31

*The harmonic fitting equation is $y = A_0 + A_{12}\cos\left[\frac{2\pi}{365}(day - \varphi_{12})\right]$.

**The error bars are standard errors whose calculations followed the method outlined in Appendix B in Fong et al. (2014).

Fong, W., Lu, X., Chu, X., Fuller-Rowell, T. J., Yu, Z., Roberts, B. R., et al. (2014). Winter temperature tides from 30 to 110 km at McMurdo (77.8°S, 166.7°E), Antarctica: Lidar observations and comparisons with WAM. Journal of Geophysical Research: Atmospheres, 119(6), 2846–2863. https://doi.org/10.1002/2013JD020

Table S3. Correlation Coefficients between TINa and Sunrise/CTMT Tidal Winds

Alt/km		Sunrise (Scattered points)	Sunrise (Fitted curves)	Zonal Wind	Meridional Wind	Vertical Ion Drift
135	R*	0.975	0.992	0.761	0.940	0.920
	Pr*	100%	100%	99.6%	100%	100%
130	R	0.971	0.992	0.756	0.928	0.879
	Pr	100%	100%	99.6%	100%	100.0%
125	R	0.975	0.987	0.751	0.909	0.813
	Pr	100%	100%	99.5%	100%	99.9%
120	R	0.968	0.980	0.702	0.827	0.679
	Pr	100%	100%	98.9%	99.9%	98.5%

* R is the correlation coefficient and Pr is the corresponding confidence level.

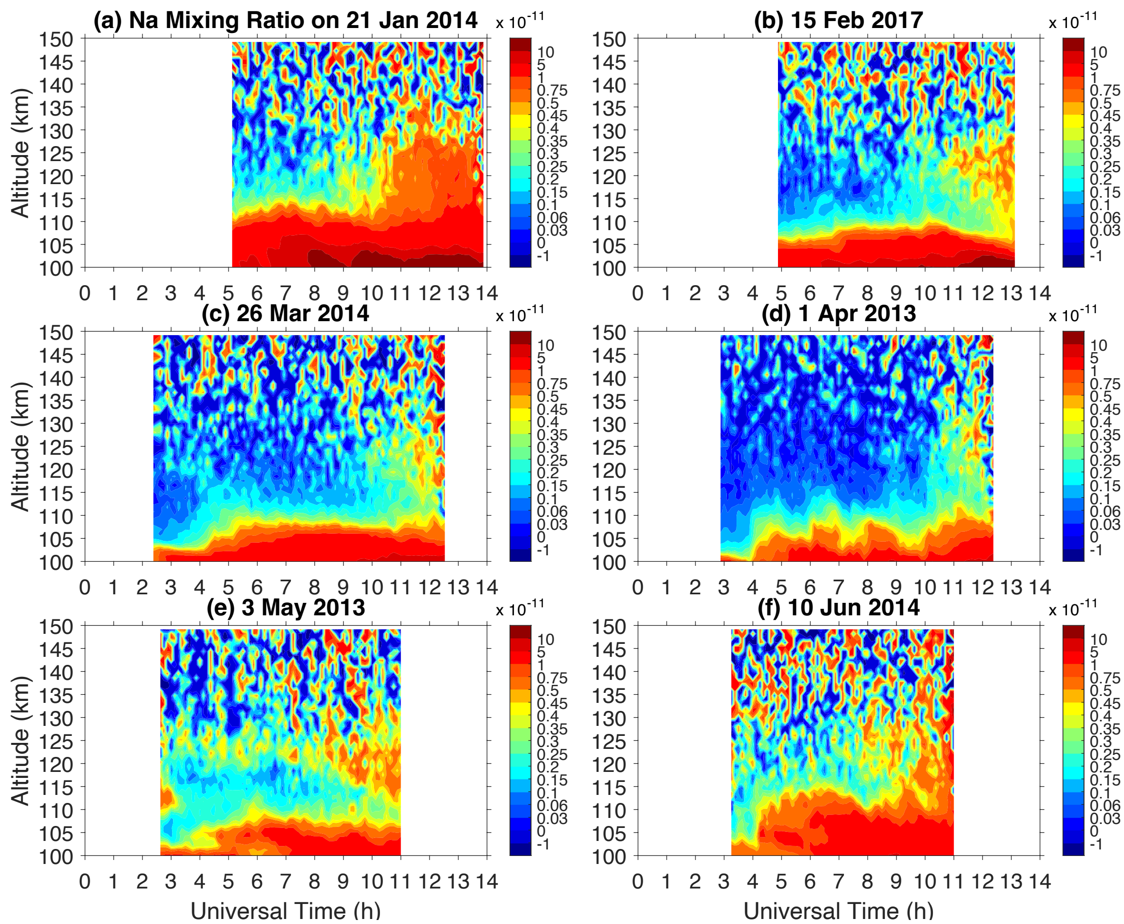

Figure S1A. Contours of Na volume mixing ratios of pre-dawn TINa layers from 100 to 150 km for individual nights in each of the 12 months (January through December) over Boulder (40.13ºN, 105.24ºW), Colorado, observed with a high-sensitivity STAR Na Doppler lidar. The Na densities and mixing ratios were derived at resolutions of 7.5 min and 0.96 km.

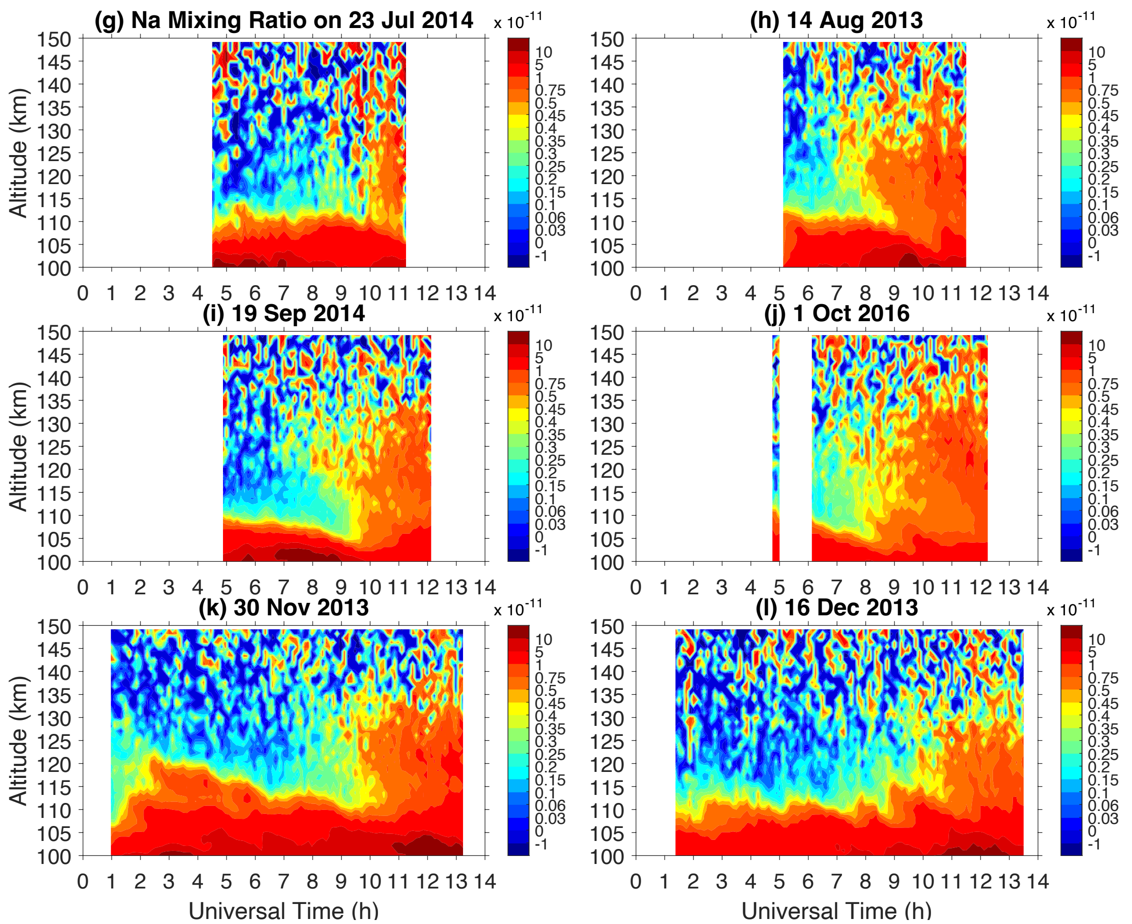

Figure S1B. Contours of Na volume mixing ratios of pre-dawn TINa layers from 100 to 150 km for individual nights in each of the 12 months (January through December) over Boulder (40.13ºN, 105.24ºW), Colorado, observed with a high-sensitivity STAR Na Doppler lidar. The Na densities and mixing ratios were derived at resolutions of 7.5 min and 0.96 km.

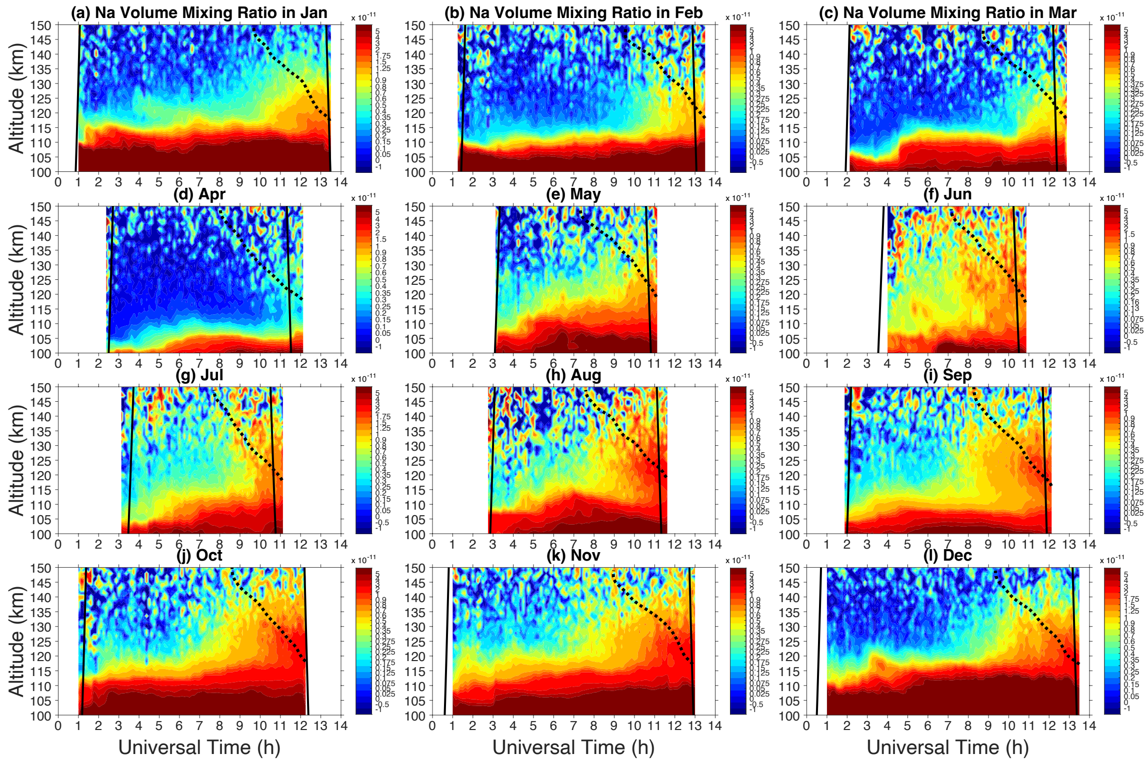

Figure S2. Monthly composite contours of Na volume mixing ratios of pre-dawn TINa layers from 100 to 150 km for 12 months from January through December over Boulder (40.13ºN, 105.24ºW), Colorado. The uneven color bars used in the 12 panels share the same upper and lower limits, but the color scales in between vary with month to show the pre-dawn TINa phases more clearly than using identical uneven color bars. The Na densities and mixing ratios were derived at resolutions of 7.5 min and 0.96 km.

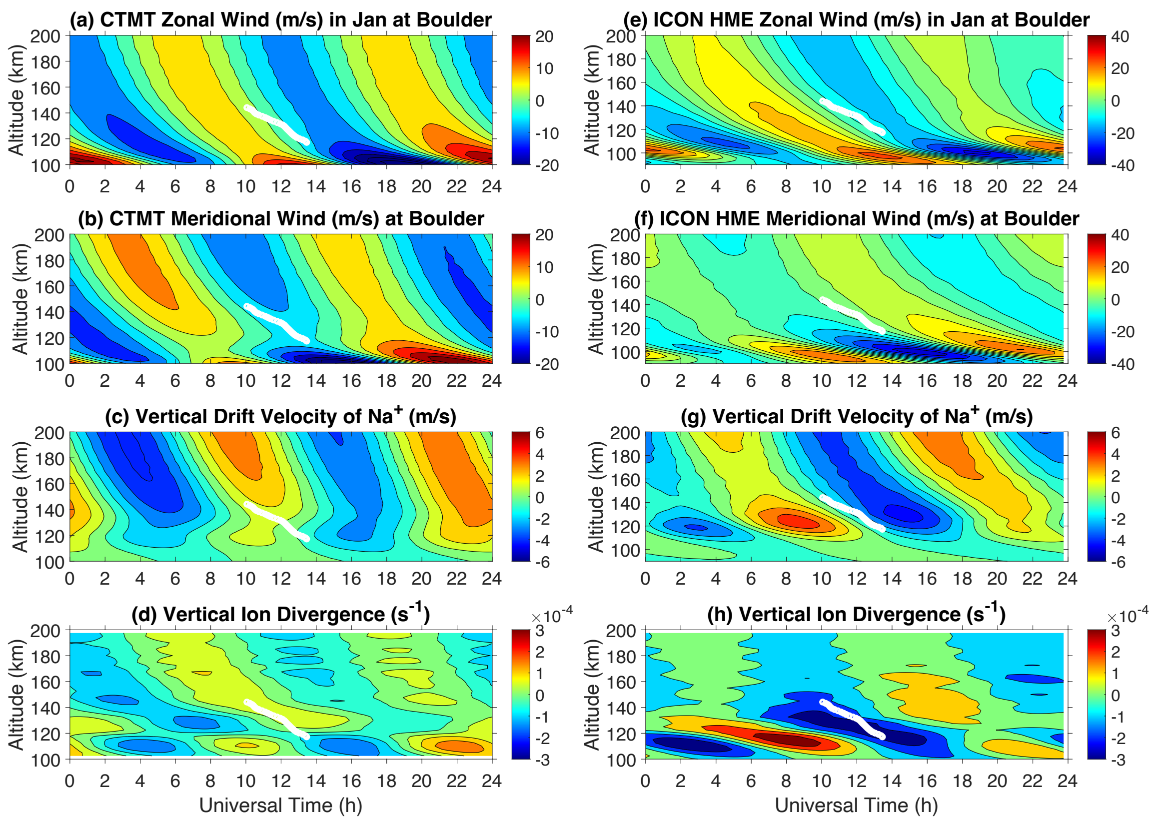

Figure S3. Neutral horizontal (zonal and meridional) winds in January provided by CTMT (left column) and ICON HME (right column) tidal winds (SW2 + DW1) in the top two rows. The bottom two rows show the vertical ion-drift velocity and vertical divergence of $TINa^+$ ions calculated using the winds given in the top two rows. The CTMT data were taken from Oberheide et al. (2011) and the ICON HME data were taken from Chu et al. (2021).

Chu, X., Chen, Y., Cullens, C. Y., Yu, Z., Xu, Z., Zhang, S., Huang, W., Jandreau, J., Immel, T. J., & Richmond, A. D. (2021). Mid-latitude thermosphere-ionosphere Na (TINa) layers observed with high-sensitivity Na Doppler lidar over Boulder (40.13°N, 105.24°W). Geophysical Research Letters, 48(11), 1–10. https://doi.org/10.1029/2021GL093729

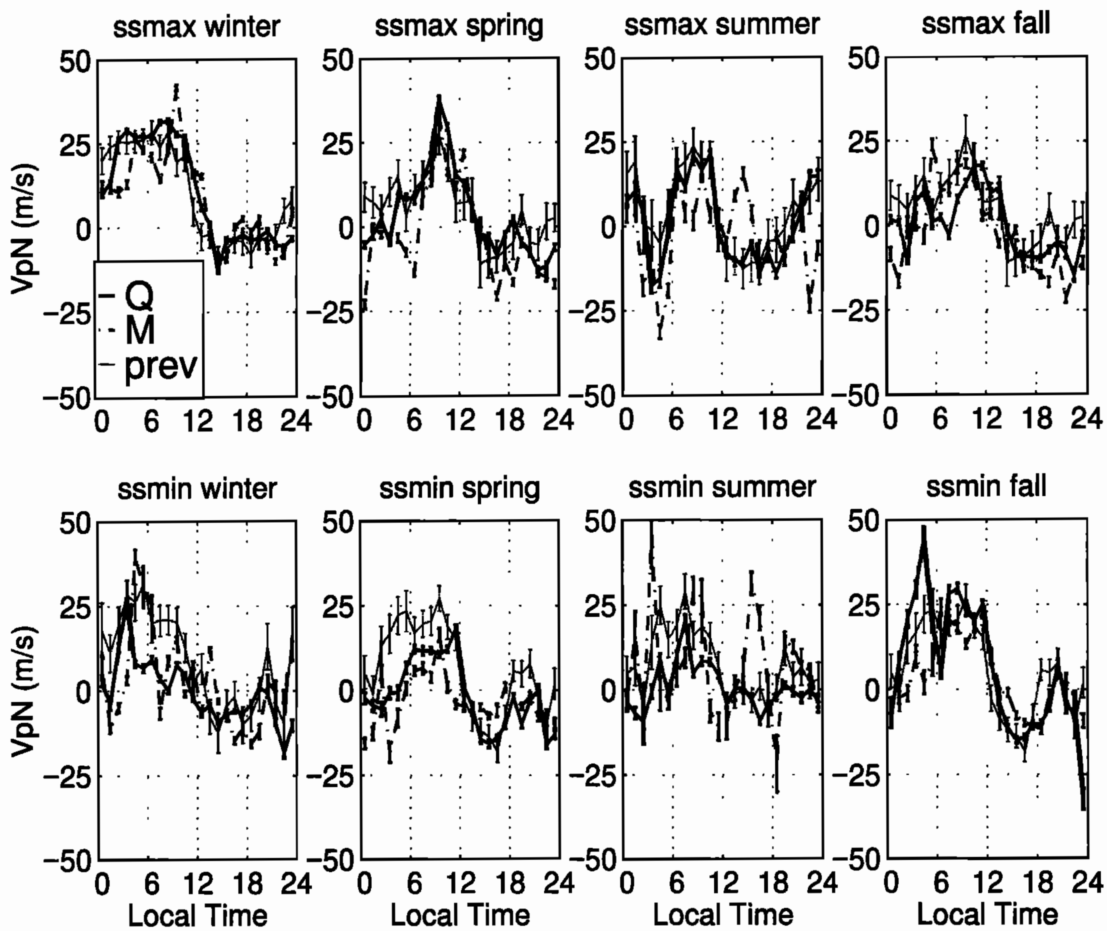

Figure 2. Ion drifts perpendicular to **B** at 300 km altitude above Millstone Hill, positive northward ($V_{\perp N}$). Weighted averages in each local solar time bin are shown for (top) solar maximum and (bottom) solar minimum, for each season. The present results for geomagnetically quiet (Q) and moderately disturbed conditions (M) are compared with previous results (prev) for quiet conditions [*Buonsanto et al.*, 1993].

Figure S4. Millstone Hill Incoherent Scatter Radar (ISR) measurements of ion drifts perpendicular to the magnetic field, where are taken from Buonsanto & Witasse (1999). [Buonsanto, M. J., & Witasse, O. G. (1999). An updated climatology of thermospheric neutral winds and F region ion drifts above Millstone Hill. *Journal of Geophysical Research, 104*, 24,675–24,687. https://doi.org/10.1029/1999JA900345]

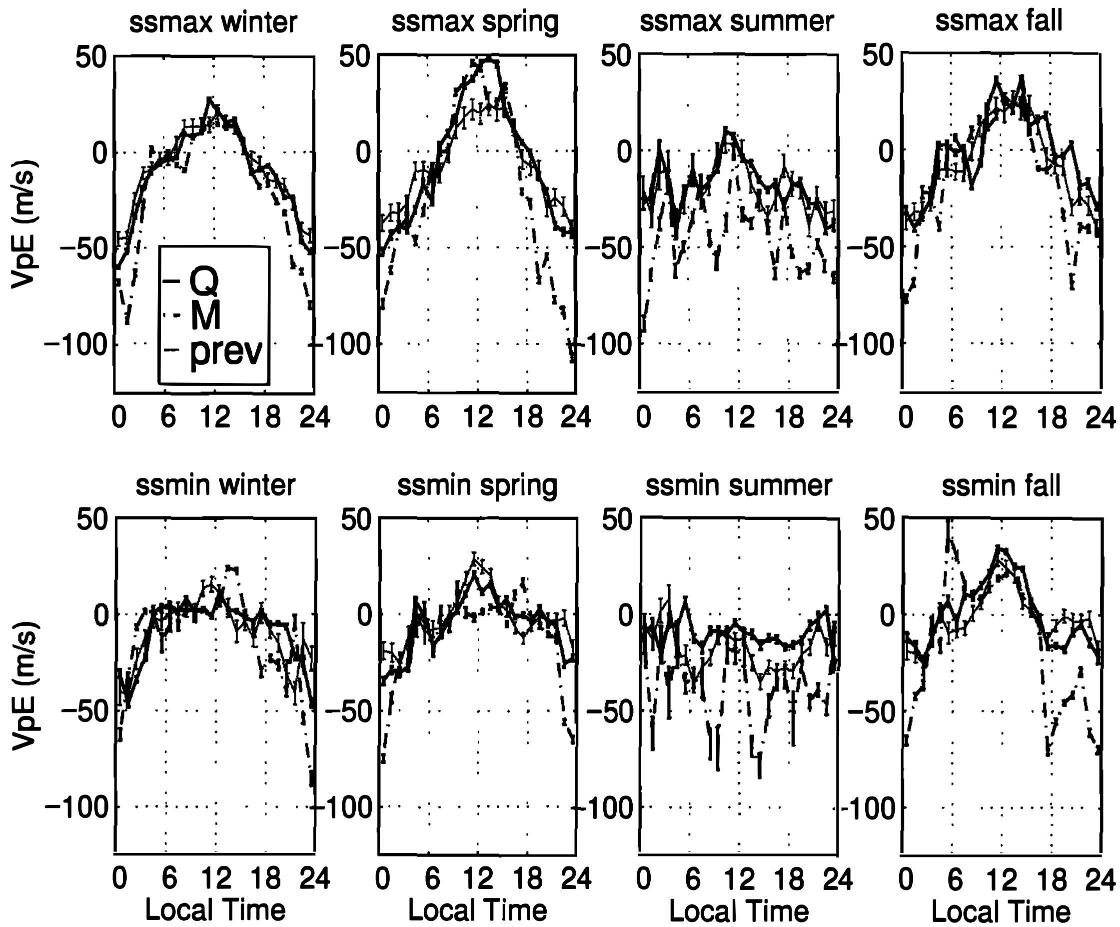

Figure 3. Same as Figure 2, except for ion drifts perpendicular to **B**, positive eastward ($V_{\perp E}$).

Figure S5. Millstone Hill Incoherent Scatter Radar (ISR) measurements of ion drifts perpendicular to the magnetic field, where are taken from Buonsanto & Witasse (1999). [Buonsanto, M. J., & Witasse, O. G. (1999). An updated climatology of thermospheric neutral winds and F region ion drifts above Millstone Hill. *Journal of Geophysical Research, 104*, 24,675–24,687. https://doi.org/10.1029/1999JA900345]

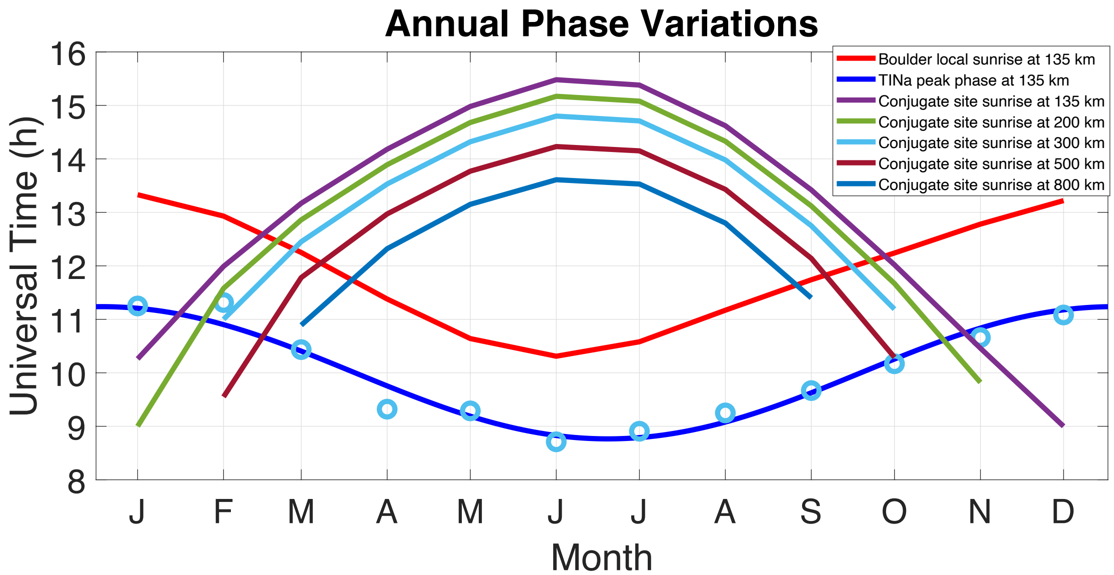

Figure S6. Annual variations of predawn TINa peak phase at 135 km, Boulder local sunrise time at 135 km, and conjugate site sunrise times at 135, 200, 300, 500, and 800 km from January through December. The conjugate site of Boulder varies from (54.8505°S, 128.8075°W) to (54.8553°S, 128.9248°W), staying close to (54.85°S, 128.85°W). The conjugate site of Boulder was calculated using a Python wrapper named ApexPy (https://github.com/aburrell/apexpy). Missing points in Oct to Feb indicate that there is no sunset in these months at high altitudes of the conjugate sites.

The "ApexPy" Python package itself was developed and updated by van der Meeren et al. (2023). The coordinates for the calculations were defined in Richmond (1995) and the algorithm for converting between geodetic, modified apex, and quasi-dipole coordinates was introduced by Emmert et al. (2010).

Emmert, J. T., Richmond, A. D., & Drob, D. P. (2010). A computationally compact representation of magnetic-apex and Quasi-Dipole coordinates with smooth base vectors. Journal of Geophysical Research: Space Physics, 115(8), 1–13. https://doi.org/10.1029/2010JA015326

Richmond, A. D. (1995), Ionospheric electrodynamics using Magnetic Apex Coordinates, Journal of geomagnetism and geoelectricity, 47(2), 191–212. https://doi.org/10.5636/jgg.47.191

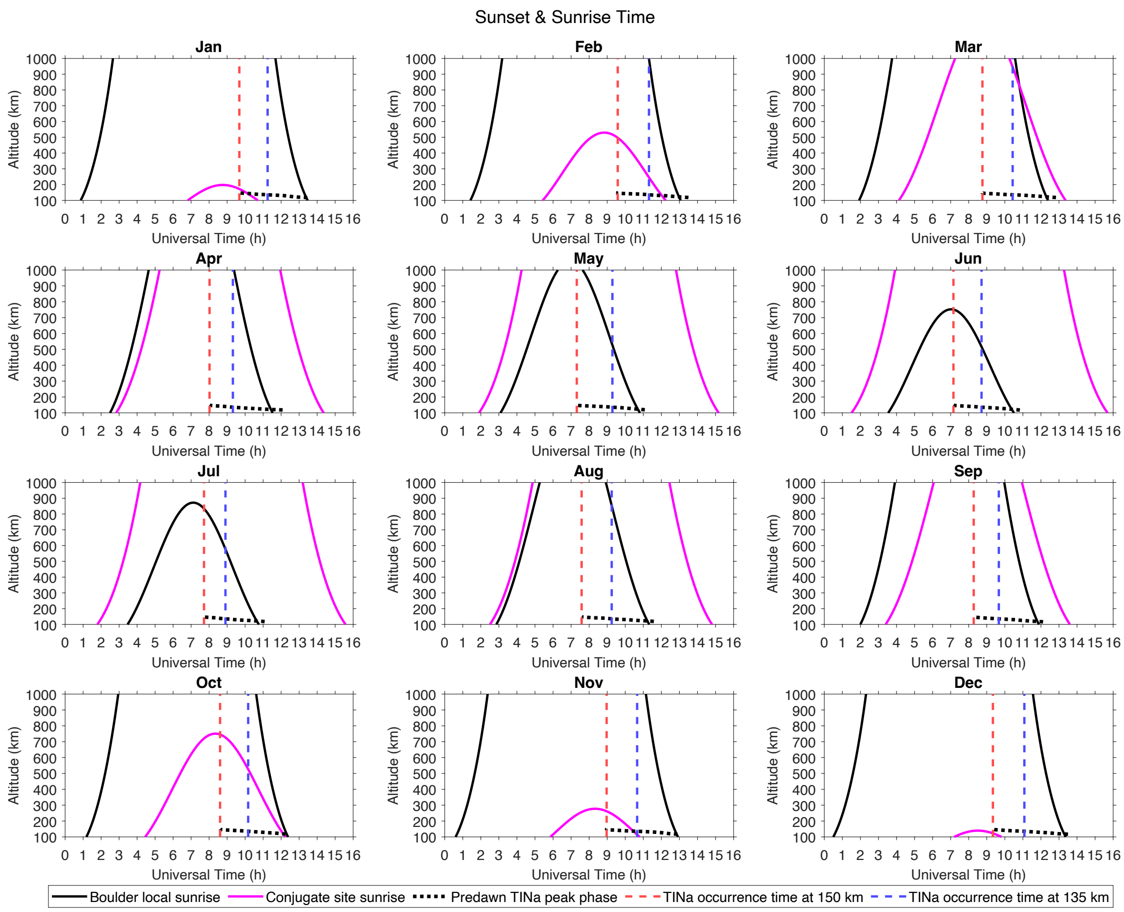

Figure S7. The sunset (on the left side of each panel) and sunrise (on the right side of each panel) times of Boulder and corresponding conjugate sites are plotted against altitude from 100 to 1000 km for the 15th of each month from January to December. The black solid curves are sunset/sunrise time of Boulder while the purple solid lines are those of the conjugate site. The vertical red and blue dashed lines represent the predawn TINa peak phases at 150 and 135 km, respectively, while the black dotted lines show the TINa peak phases in the Boulder predawn conditions.