Geophysical Research Letters

Supporting Information for

Lidar Discovery of Annual and Semiannual Oscillations of Thermosphere-Ionosphere Na (TINa) Layers and the First Na Climatology of 75–150 km: Connections to Metallic Ions, Wave and Eddy Transport, and Meteoric Influx

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Introduction

Na Doppler lidar observations from Boulder, Colorado are used to form the first climatology of Na density and volume mixing ratio (VMR) through the entire altitude range from 75 to 150 km. Annual oscillation (AO) and semiannual oscillation (SAO) signatures are clearly shown in the thermosphere-ionosphere Na (TINa) layers (~105–150 km). The SAO/AO amplitude ratio varies significantly with altitude from 75 to 150 km.

Table S1 provides the statistics of qualified nights in the 7 years of lidar observations (2011–2017), which are used in forming the 12 monthly composites from January through December. Table S2 lists the harmonic fitting parameters to variables shown in Figure 3 and the corresponding SAO/AO amplitude ratios.

Figure S1 shows the 12 monthly-mean raw profiles of Na density and VMR from January through December and compares with the vertically smoothed profiles. Figure S2 plots the TINa top altitude and Na layer's bottom altitude, determined from Na density and VMR, over the climatology of Na density and VRM. Figure S3 compares the temperature variances measured by lidar at SOR from 1998-2000 and at Fort Collins from 1990-2000, 1996-2005, and 2001-2010, with the data taken from Gardner & She

(2022). Also compared are the thermospheric total number density, molecular N_2 number density, and atomic O number density calculated from the MSISE00 empirical model, along with electron column abundance integrated from 130 to 150 km at 10 UT (~3 LT) over Boulder calculated from IRI-2020. Figure 4 in She et al. (2023) is shown as Figure S4 for the convenience of readers, which illustrates the long-term trends of Na layers at Fort Collins and Logan measured by CSU Na Doppler lidar. Figure S5 compares the total number density as well as Na VMR calculated with MSISE00 versus MSIS 2.1.

Table S1. Statistics for Number of Nights Used in the Monthly Composites

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
26	19	16	16	13	8	8	33	28	29	29	14	239

Table S2. Harmonic Fits (Annual Mean + AO + SAO) to the Na Layer Parameters

Parameter	Annual Mean	AO Amplitude	AO Phase (DOY)	SAO Amplitude	SAO Phase (DOY)	SAO/AO Amplitude Ratio
Column Abundance (cm^{-2}) (75–105 km)	4.47×10^9	2.11×10^9	335	2.57×10^8	170	0.12
Centroid Altitude (km)	91.7	0.197	117	0.430	81	2.19
RMS Width (km)	4.46	0.125	359	0.491	189	3.93
TINa Abundance (cm^{-2}) (105–150 km)	3.87×10^7	1.12×10^7	303	1.91×10^7	189	1.70
TINa Abundance (cm^{-2}) (110–150 km)	8.44×10^6	3.03×10^6	64	4.01×10^6	187	1.33
TINa Abundance (cm^{-2}) (120–150 km)	1.45×10^6	7.21×10^5	59	5.36×10^5	185	0.74
TINa Abundance (cm^{-2}) (130–150 km)	4.60×10^5	2.51×10^5	44	1.85×10^5	183	0.74
Top Altitude (km)	139.1	7.10	234	5.81	182	0.82
By VMR (km)	121.3	10.71	210	14.06	190	1.31
Bottom Altitude (km)	78.5	1.55	162	1.55	104	1.00
By VMR (km)	79.3	1.33	171	1.33	100	1.00
Na Layer Range (km)	60.5	6.74	247	7.25	185	1.08
By VMR (km)	42.0	9.69	215	15.38	191	1.59

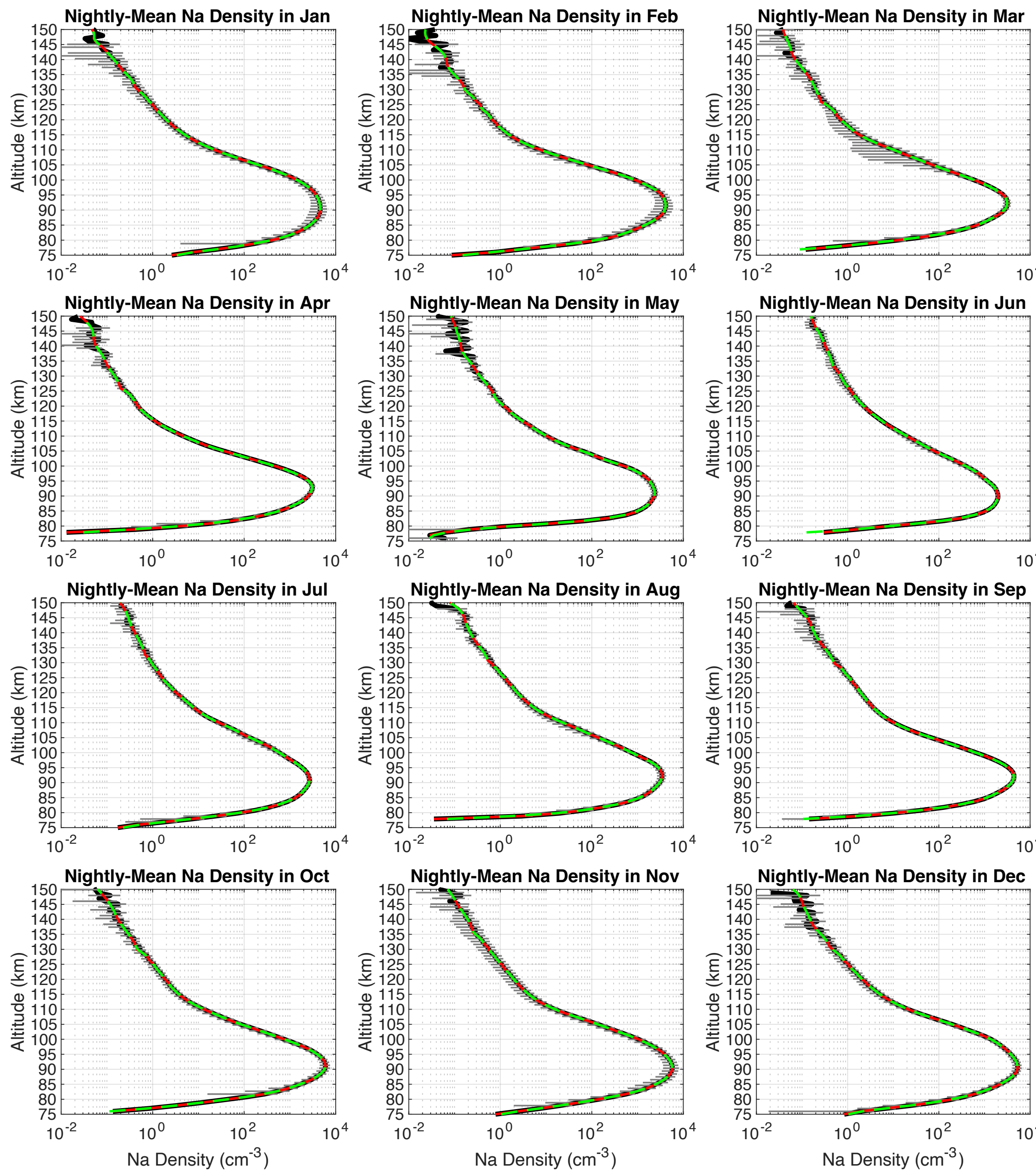

Figure S1A. Monthly Na density profiles (75–150 km) from January through December. Raw profiles (thick black curves) are compared with vertically smoothed profiles (red curves for the results after the 1st vertical smooth and green curves as the final results after the 2nd vertical smooth). Horizontal bars (grey lines) represent standard deviations that are computed from the monthly composites.

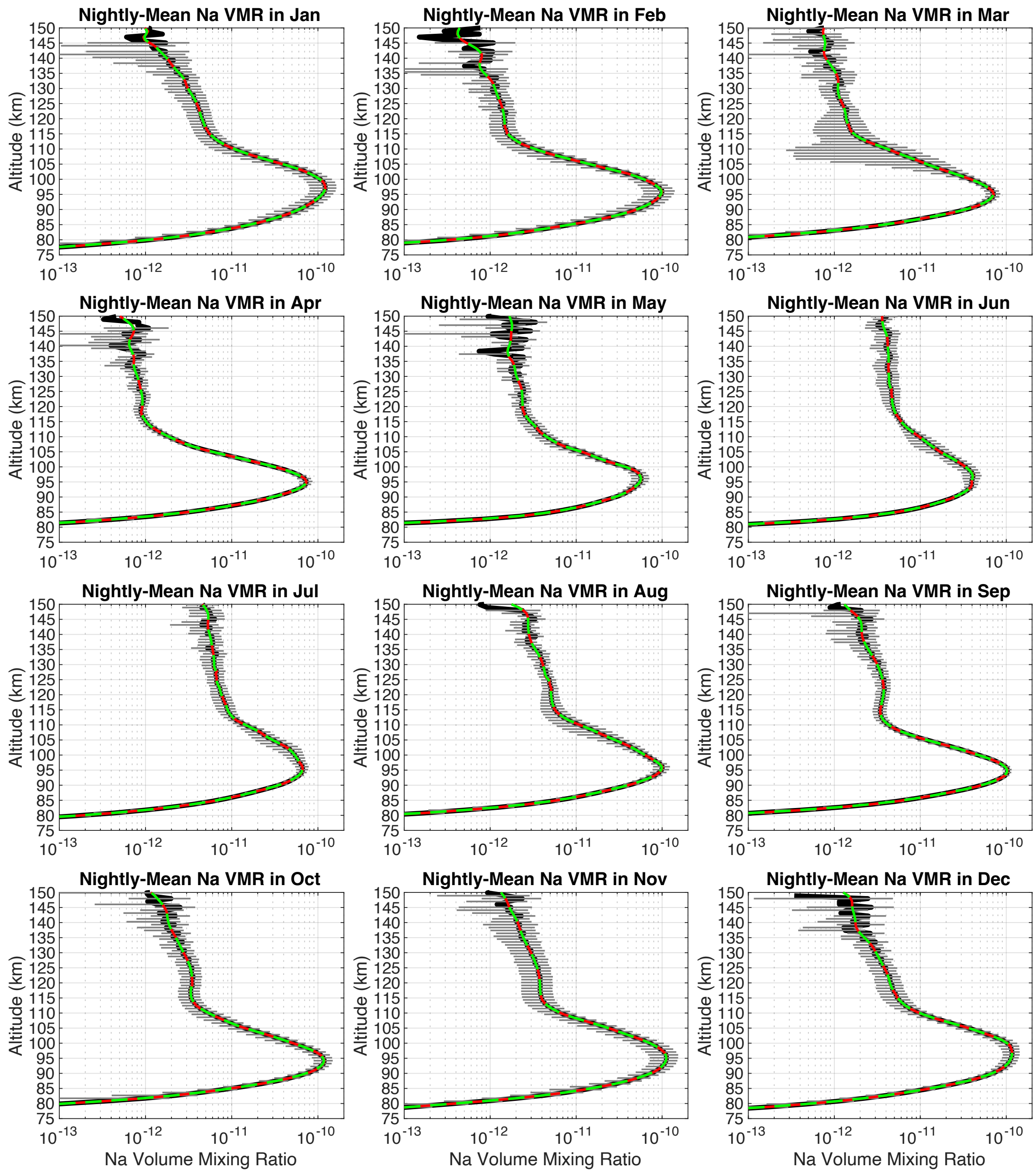

Figure S1B. Monthly Na VMR profiles (75–150 km) from January through December. Raw profiles (thick black curves) are compared with vertically smoothed profiles (red curves for the results after the 1st vertical smooth and green curves as the final results after the 2nd vertical smooth). Horizontal bars (grey lines) represent standard deviations that are computed from the monthly composites.

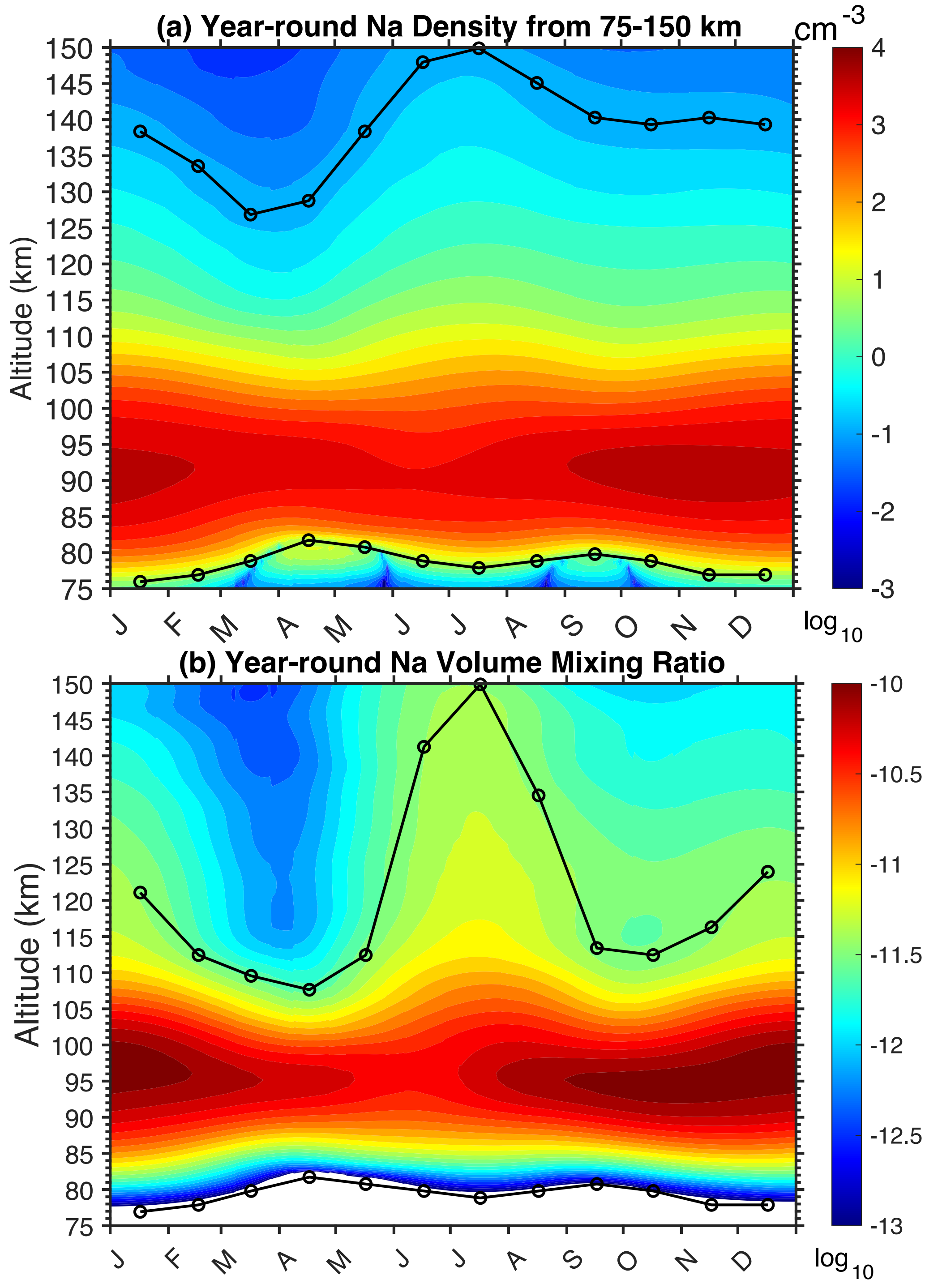

Figure S2. Climatology of year-round nightly-mean (a) Na density and (b) VMR from 75–150 km over Boulder. Overplotted are the topside altitudes defined at $[Na] = 0.20\ cm^{-3}$ and $VMR = 4.20 \times 10^{-12}$ along with the bottom-side altitudes defined at $[Na] = 11.0\ cm^{-3}$ and $VMR = 1 \times 10^{-13}$.

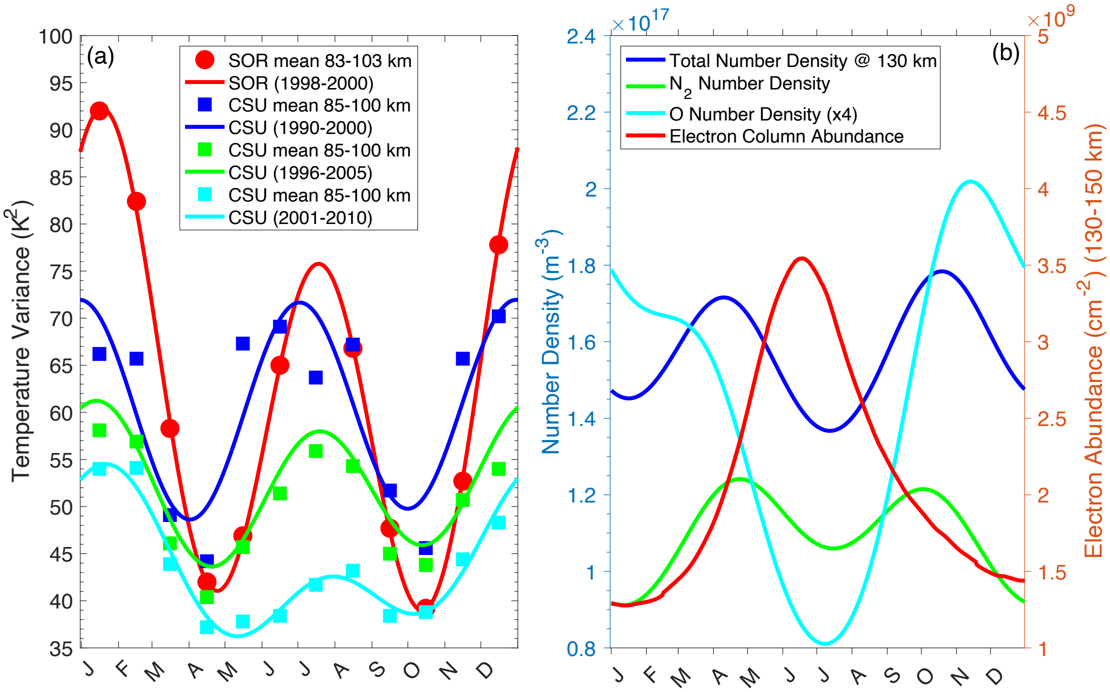

Figure S3. (a) Lidar-measured temperature variance $Var(T')$ at SOR (35ºN, 106.5ºW) and Fort Collins (41ºN, 105ºW) taken from Gardner & She (2022). (b) MSISE00 total number density, molecular N_2, and atomic O number densities at 130 km, where O density has been multiplied by a factor of 4. (c) IRI-2020 electron column abundance from 130 to 150 km at 10 UT (3 LT) over Boulder. Both MSIS and IRI model data were run for year 2013 conditions.

MSISE00 – Mass Spectrometer Incoherent Scatter Radar Empirical model 2000

IRI-2020 – The International Reference Ionosphere 2020

Gardner, C. S., & She, C. Y. (2022). Signature of the Contemporary Southwestern North American Megadrought in Mesopause Region Wave Activity. *Geophysical Research Letters*, *49*(19), 1–8. https://doi.org/10.1029/2022GL100569

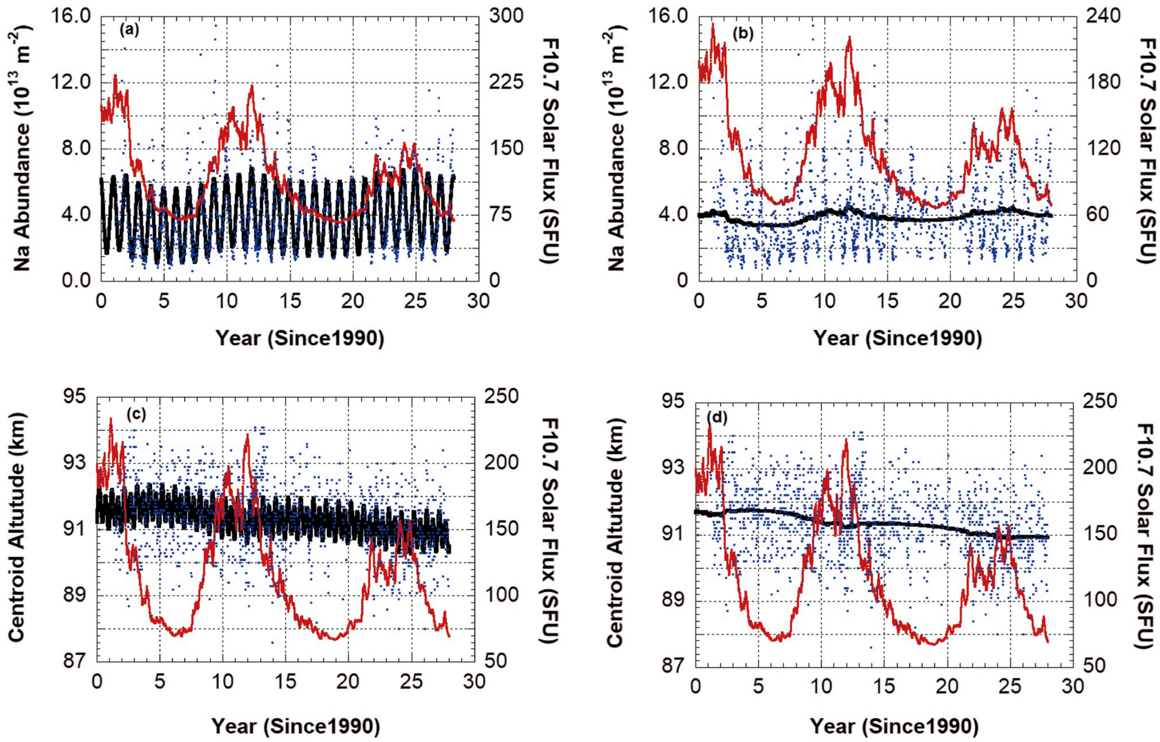

Figure S4. 28 years of Na measurements at Fort Collins and Logan, which show long-term trends of Na column abundance and centroid altitude over decade and solar flux. This figure is taken from Figure 4 in She et al. (2023) with the original caption as below. The fit function (in black curve) is plotted against a 28-year time series of 1,340 nightly mean Na layer characteristic parameters (in blue dots). (a) Column abundance with (_WV) fit. (b) Column abundance with (_NV) fit. (c) Same as (a), except for centroid altitude. Panel (d) same as panel (b), except for centroid altitude. The variation of solar flux during the 28-year span (in red curve) is shown ($1\ SFU = 10^{-22}\ Wm^{-2}Hz^{-1}$) in each panel as a reference.

She, C.-Y., Krueger, D. A., Yan, Z.-A., Yuan, T., & Smith, A. K. (2023). Climatology, long-term trend, and solar response of Na density based on 28 years (1990–2017) of midlatitude mesopause Na lidar observation. Journal of Geophysical Research: Space Physics, 128, e2023JA031652. https://doi.org/10.1029/2023JA031652

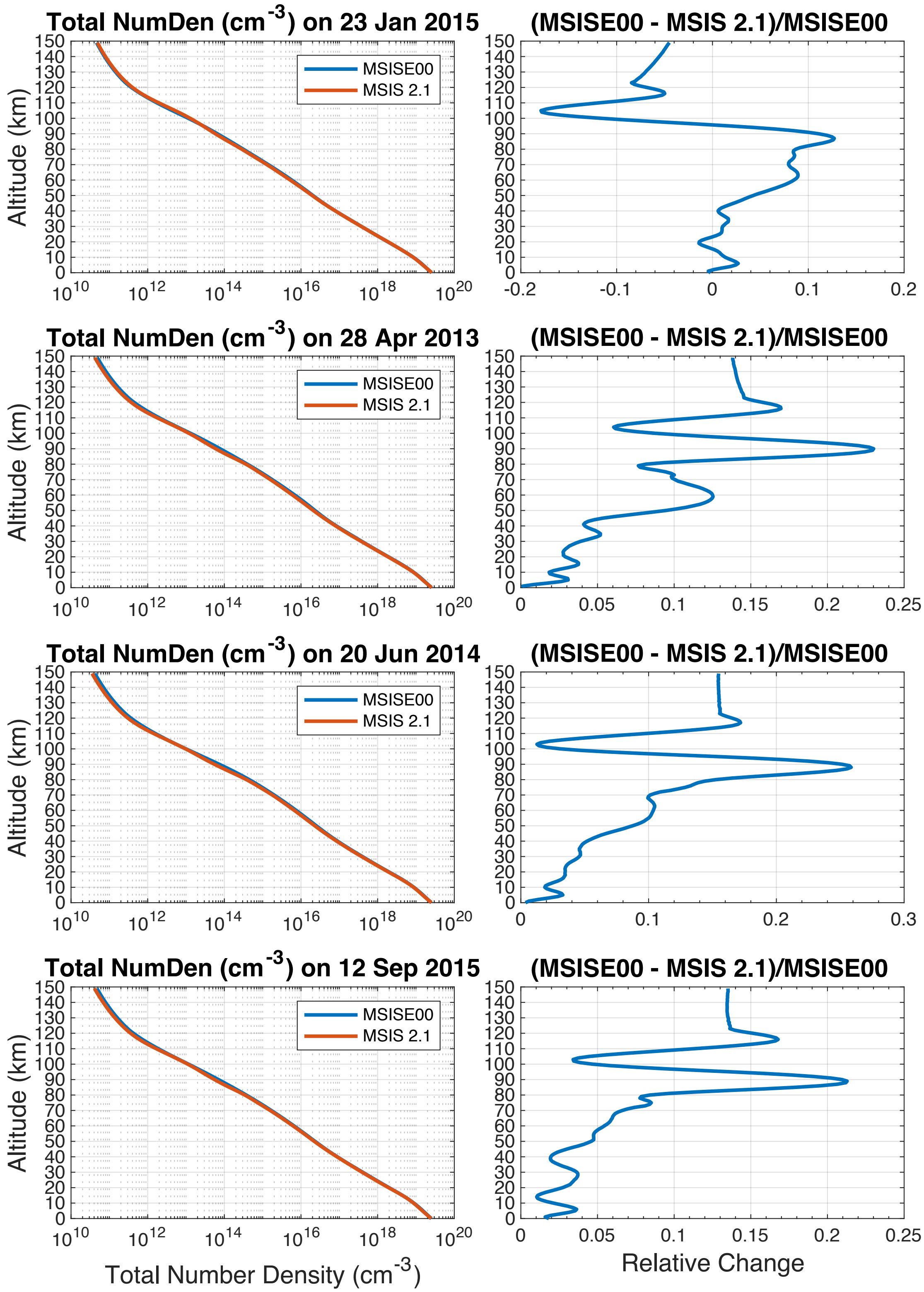

Figure S5A. Comparison of the total number density of atmosphere calculated using MSISE00 and MSIS 2.1, respectively. (Left) Total number density and (b) Percentage of change (MSISE00 – MSIS2.1)/MSISE00.

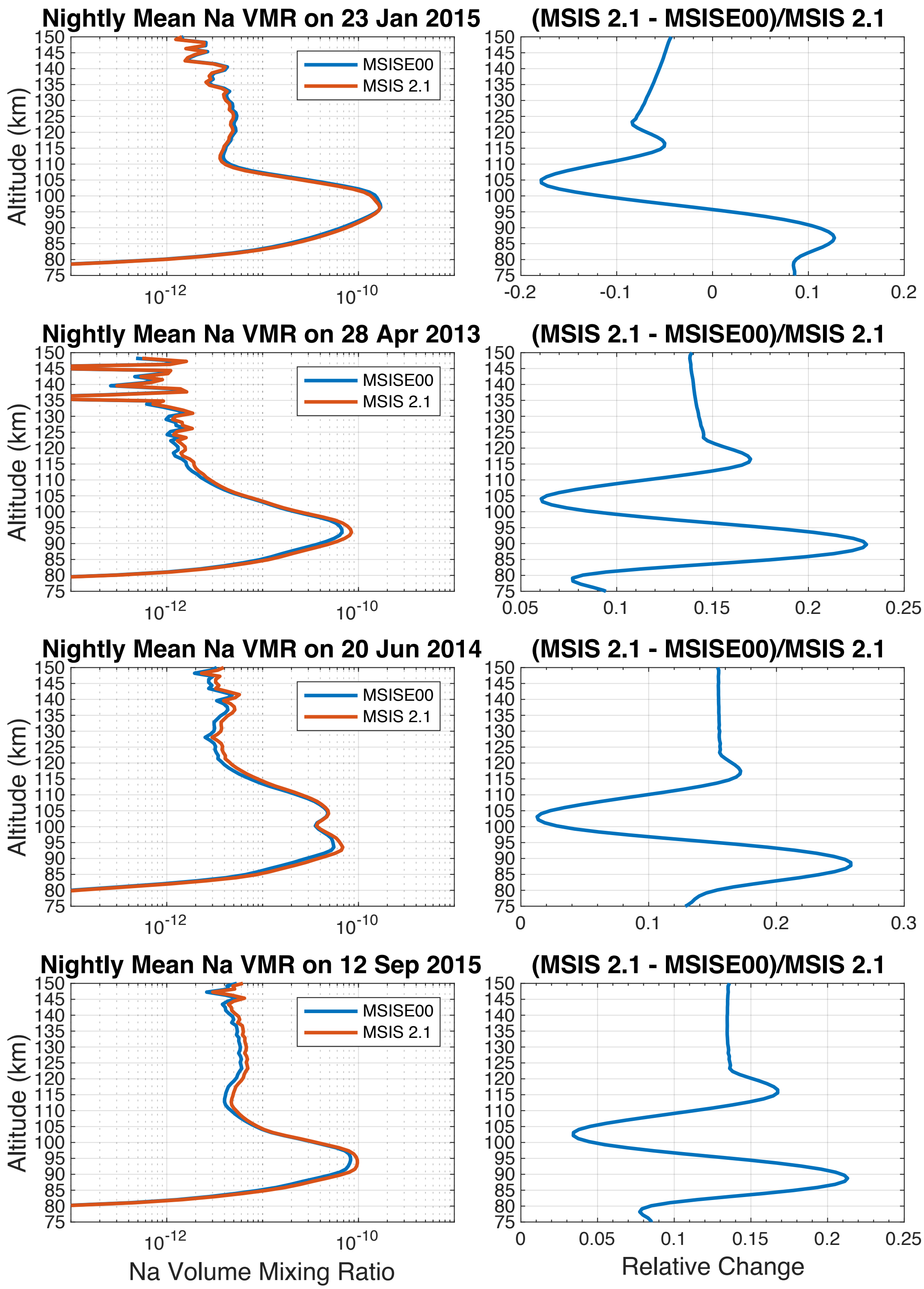

Figure S5B. Comparison of Na volume mixing ratio (VMR) derived using the total number density calculated from MSISE00 and from MSIS 2.1, respectively. Because of the discrepancy in the total number density calculated by different MSIS versions, the accuracy of Na density presented in the manuscript is on the order of 5–10% while the accuracy of Na VMR is on the order of 15–20%.