Lidar Discovery of AO and SAO of TINa Layers from the First Na Climatology of 75–150 km: Connections to Metallic Ions, Wave and Eddy Transport, and Meteoric Influx

MLTL-4

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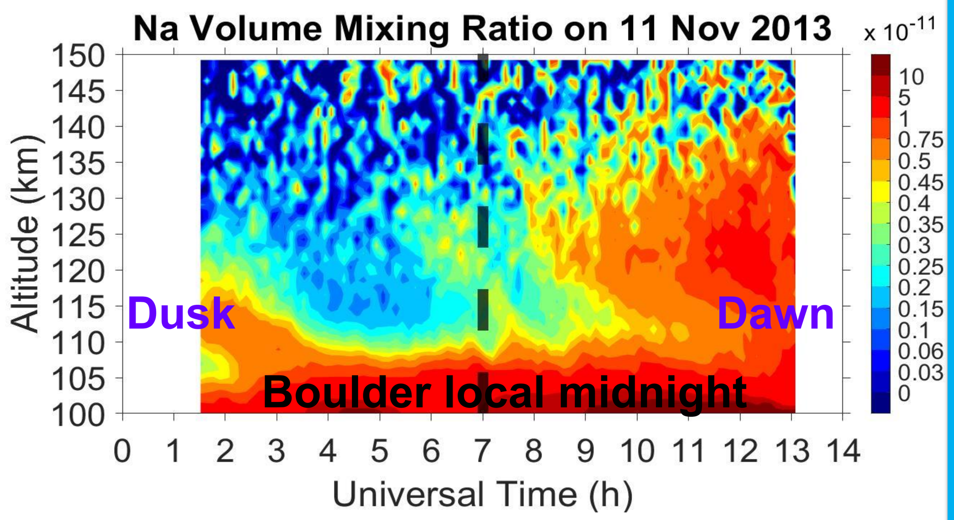
Abstract: First characterization of year-round thermosphere-ionosphere Na (TINa) layers (~105-150 km) is enabled with 7 years (2011–2017) of lidar observations over Boulder. Clear **annual and semiannual oscillations (AO and SAO)** are discovered in the nightly-mean TINa number density and volume mixing ratio (VMR) with the maximum in summer but minimum around spring equinox (Mar/Apr). The results are in stark contrast to the summer minimum and Nov maximum in the main Na layers (~75–105 km), supporting the theory of TINa formed via TINa⁺ ion neutralization. SAO in TINa VMR/density is linked to the thermospheric density SAO and the minimal wave/eddy transport around midlatitude equinoxes which hinders TINa⁺ ion production and upward transport via reduced diffusion of the main Na layer. Stronger TINa in autumn than in spring equinox is explained by the maximal and minimal meteoric input fluxes (MIF) occurring in Sep and Apr, respectively.

Highlights of Science Discoveries from Boulder TINa Layers

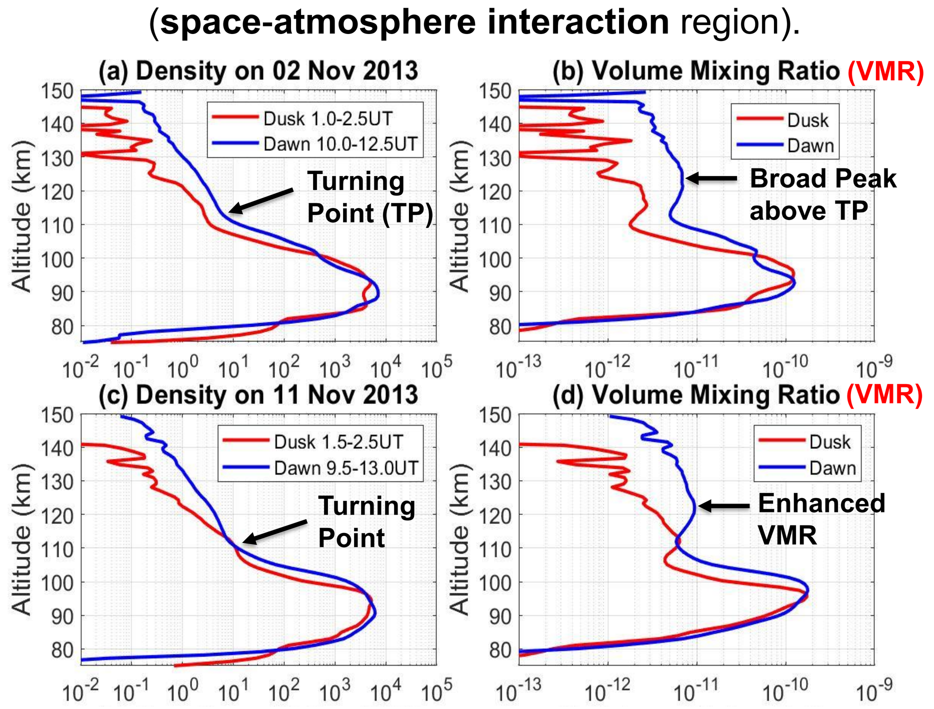


TINa (thermosphere-ionosphere Na) layers:
Occur above the main Na layers **(~75–105 km)**, extending to much higher altitude **(~110 to ~150 km).**

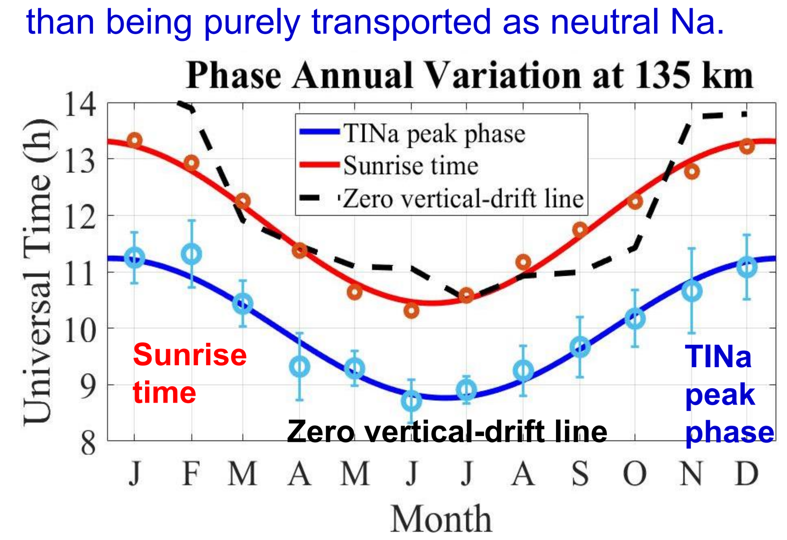
- **First regular occurrence** is reported in 2021.
- TINa occurs **after dusk** and **before dawn**.

Importance and **Motivations:**

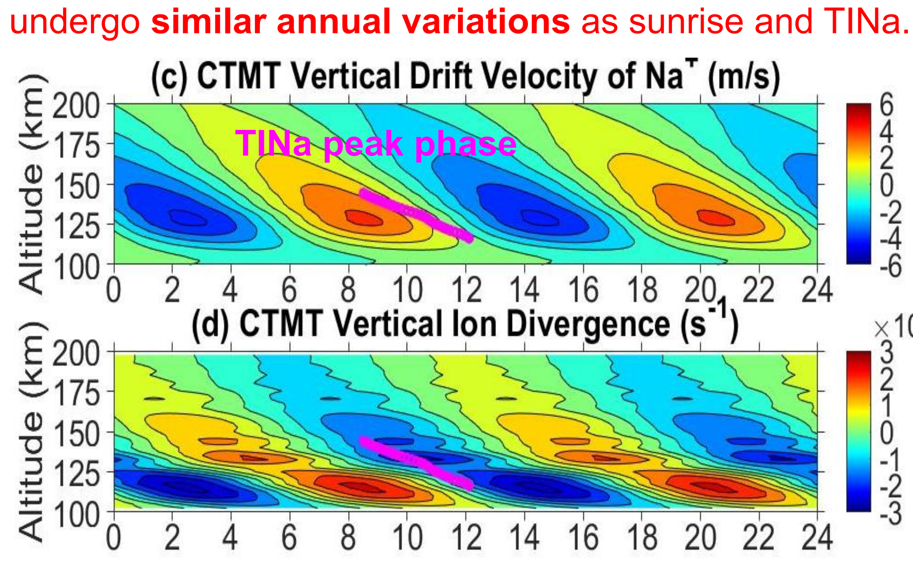
- Tracers to make direct measurements in the **"thermospheric gap"** region (100–200 km).
- Study fundamental processes in the **SAIR** (**space-atmosphere interaction** region).



TINa **Turning Point (TP) ~110 km** and the broad peak **(enhanced VMR)** above TP suggest TINa layers are formed through **in-situ production**, rather than being purely transported as neutral Na.



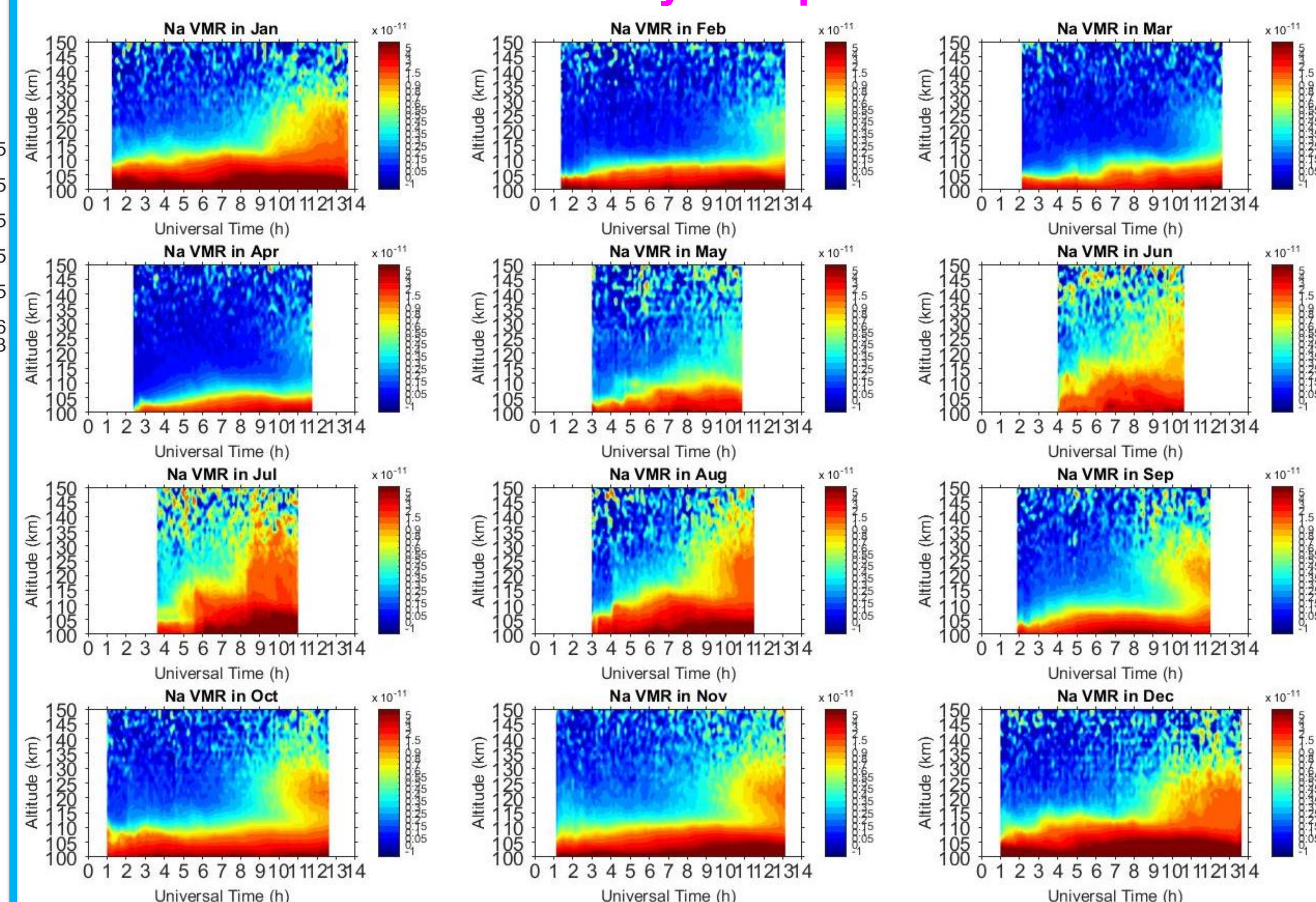
Annual variations of predawn TINa peak and sunrise time are similar—**earliest in summer and latest in winter**.
CTMT phases of semidiurnal migrating tidal winds (SW2) undergo **similar annual variations** as sunrise and TINa.



→ **Vertical shears** of horizontal winds converge TINa⁺
→ Occurrence region of TINa corresponds where vertical ion divergence is negative, i.e., the region where TINa⁺ converge to increase concentrations

- Formation Mechanism: **Neutralization** of **converged** TINa⁺ ions via recombination **with electrons** produces neutral TINa ($TINa^+ + e^- \rightarrow TINa + h\nu$).

Characterization of Monthly Composites of Boulder TINa: Annual Variations



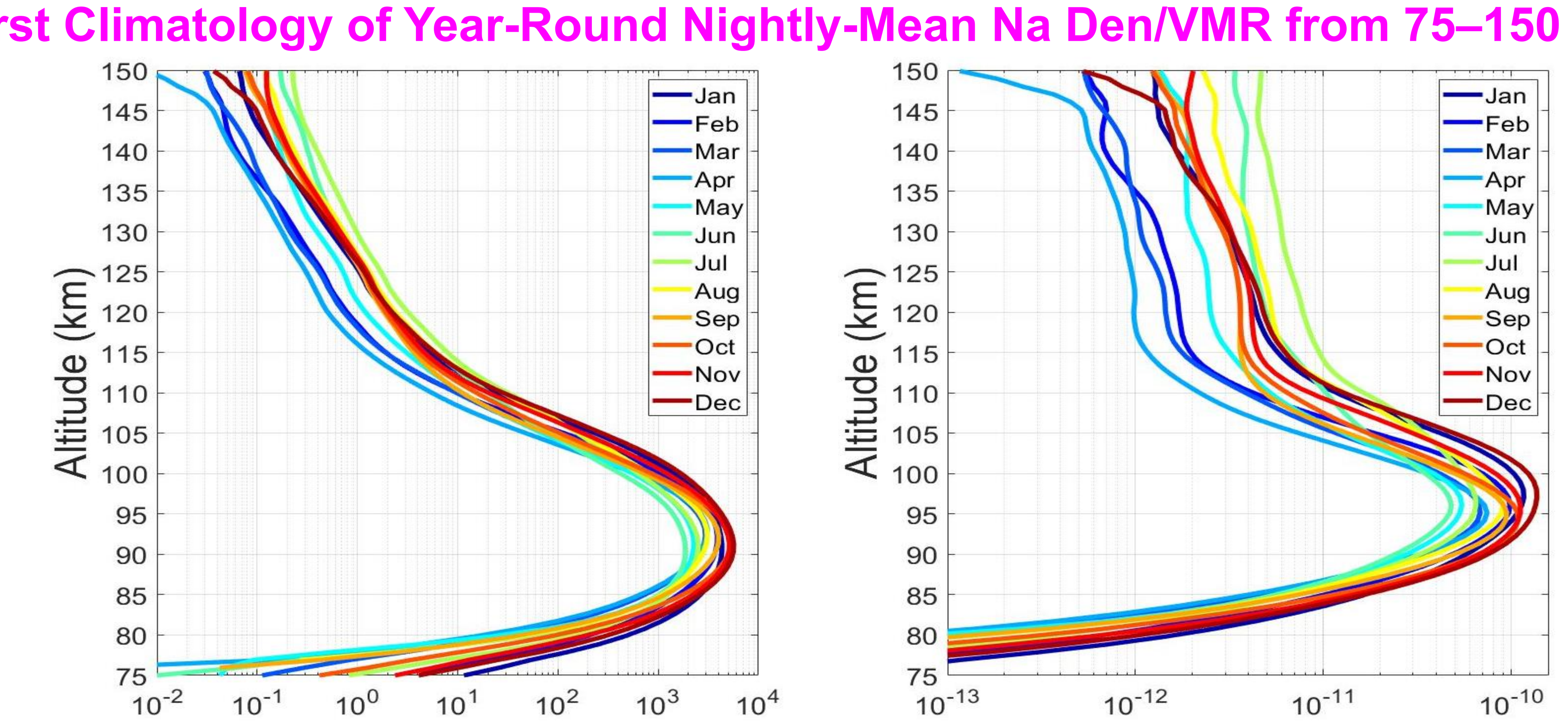
Monthly Composite Methodology:

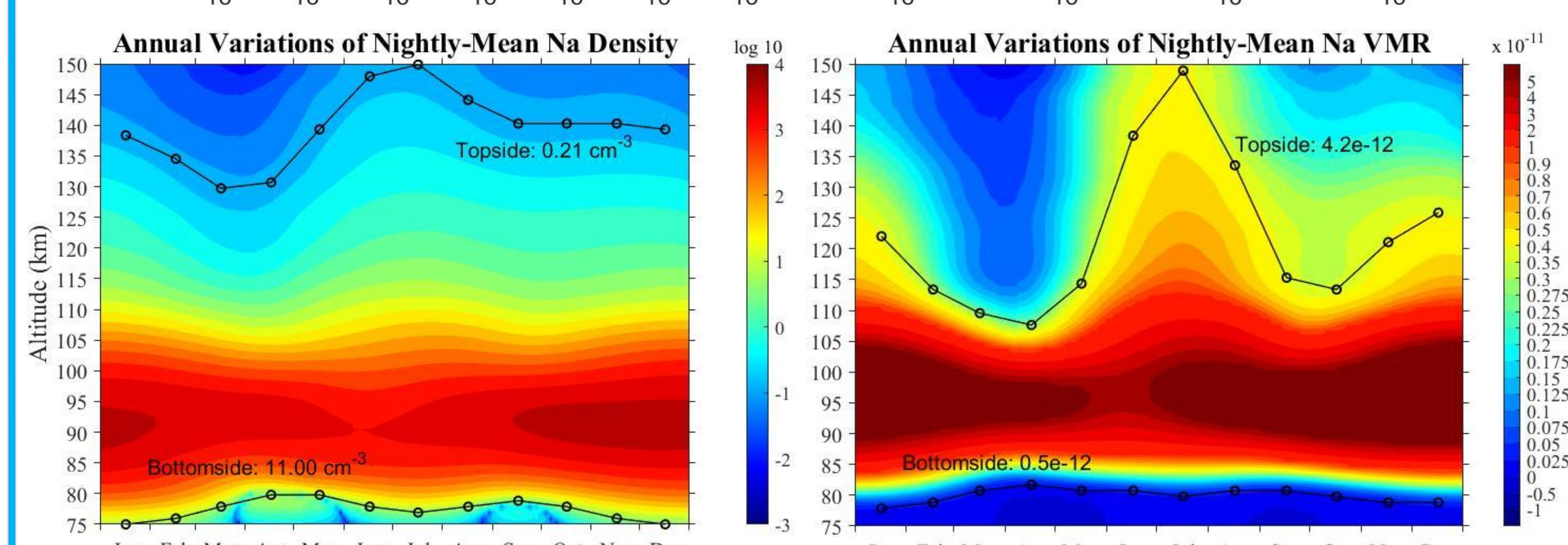
- Na VMR averaged from **7 years (2011 to 2017)**
- Bin in the same local time at the same altitude
- **Δt = 7.5 min**
- **Δz = 0.96 km**

Elevated Na VMR exhibit **continuous downward phase** progression from ~135–150 to ~110 km in each month.

Besides TINa Annual Phase Variations, ? Annual TINa Den/VMR Variations
→ First Climatology of Year-Round TINa

First Climatology of Year-Round Nightly-Mean Na Den/VMR from 75–150 km





Top: 12 monthly profiles of (a) nightly mean Na density and (b) Na VMR from January through December.
Bottom: Climatology of year-round nightly-mean (c) Na density and (d) VMR from 75–150 km over Boulder.

Harmonic fitting consisting of an annual mean (A_0), annual oscillation (AO), and semiannual oscillation (SAO)

$$Na\ Density\ or\ VMR = A_0 + A_{12}\cos\left[\frac{2\pi}{365}(day - P_{12})\right] + A_6\cos\left[\frac{2\pi}{\frac{365}{2}}(day - P_6)\right]$$

Key Findings:

Stark contrast between SAO of TINa (105–150 km) and AO of the main Na layers (75–105 km)

- SAO signatures in TINa density and VMR: **Two minima** occur around the spring (Mar-Apr) and autumn (Sep-Oct) equinoxes with spring being the primary minimum, and **two maxima** occur in summer and winter with summer being the primary maximum.
- The results are in stark contrast to the summer minimum and Nov maximum in the main Na layers (~75–105 km), supporting theory of TINa formed via TINa⁺ neutralization **($TINa^+ + e^- \rightarrow TINa + h\nu$)**.

Acknowledgement

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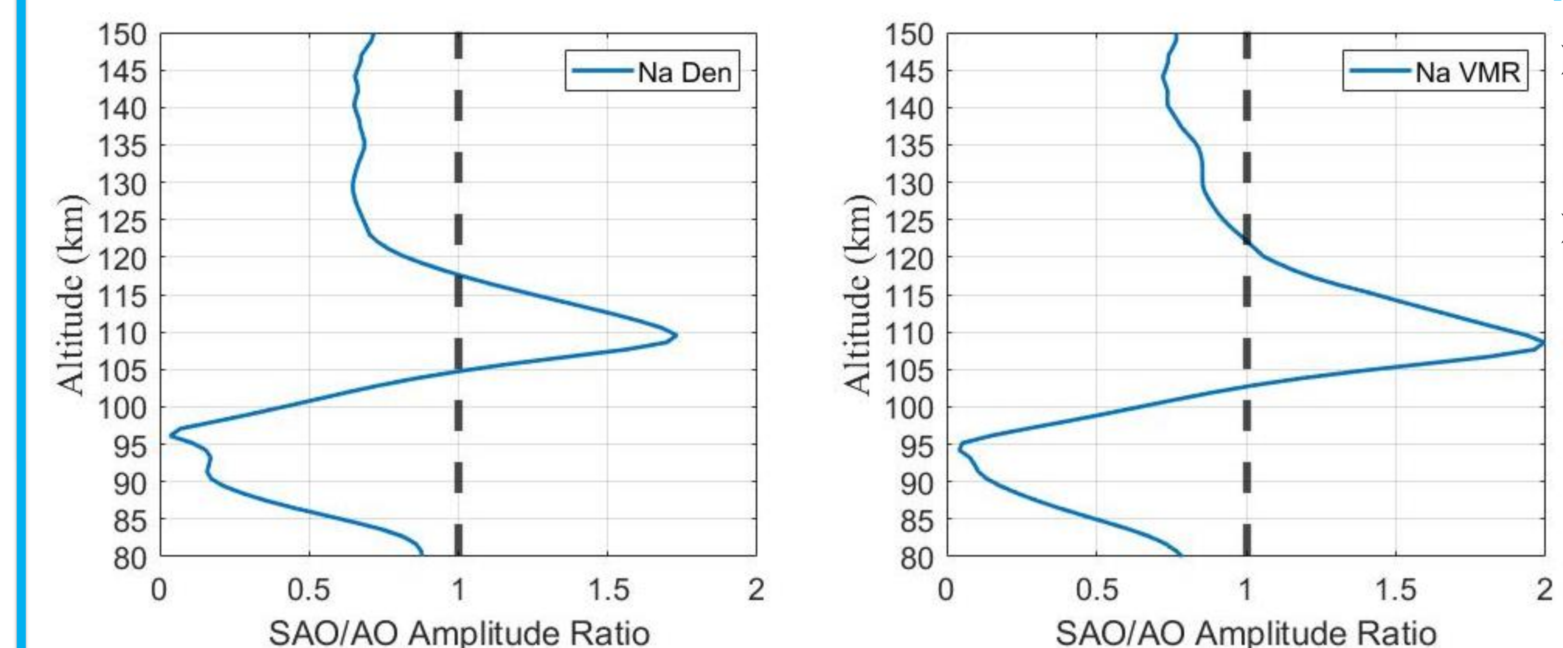
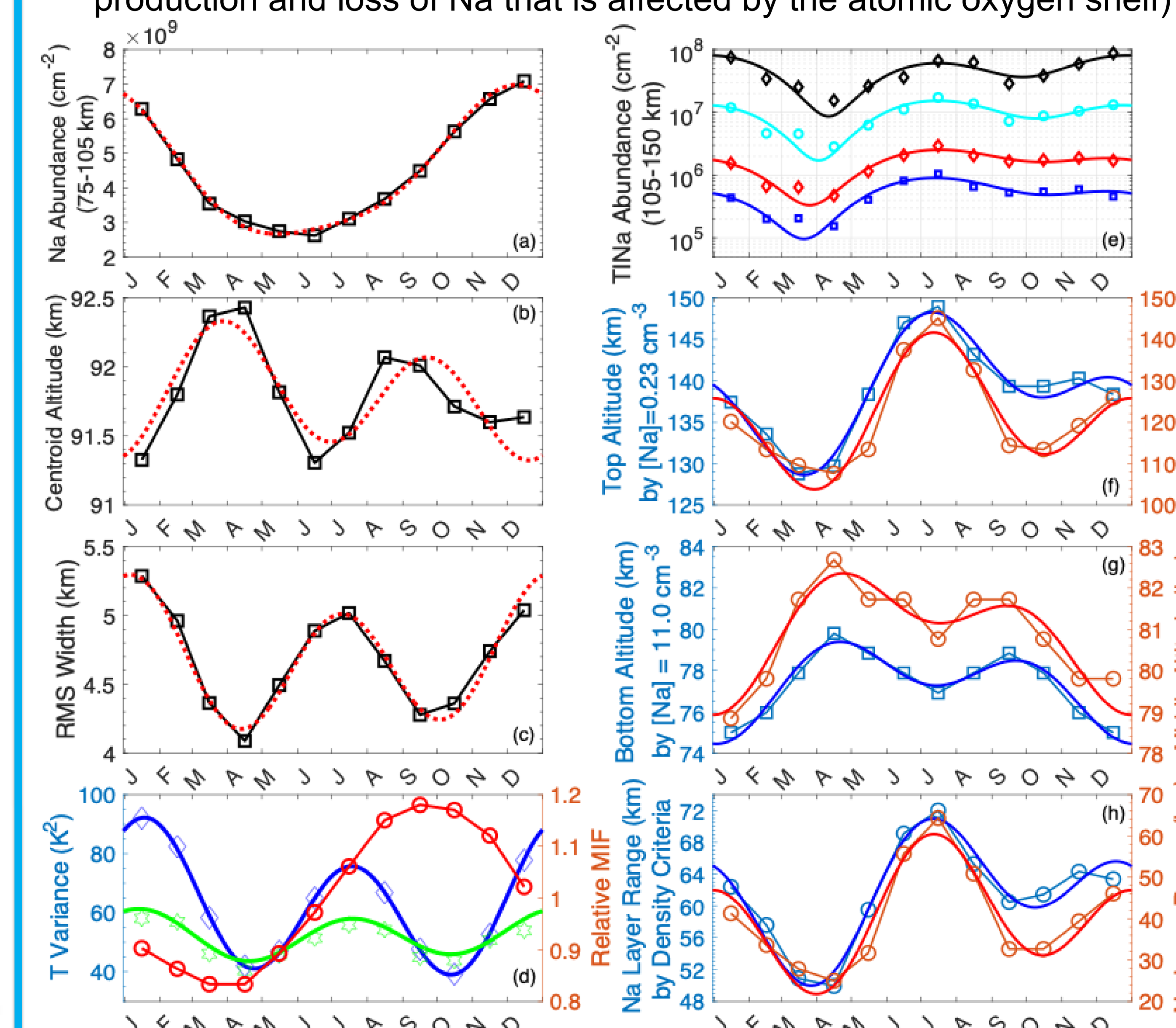
Characterization of SAO and AO and Connections to Transport, Metallic Ions, MIF



- SAO to AO Amp ratio is computed from the harmonic fitting Amplitude.
- The **significant changes of the SAO/AO ratio** along altitude are stunning, from **the minimum ratio** of ~0.03–0.07 at 95–96 km to the **maximum** of ~1.8 at ~109 km for Na density and ~2.0 at ~108 km for VMR.

1) AO dominates the main Na layer in **~87–99 km (neutral chemical reactions)** dependent on **temperature**.
2) Dominant SAO signatures in **gravity wave activity** cause increase of SAO/AO ratio from **~100 to 110 km**.
3) **From ~109 to ~120 km**, decrease of SAO/AO ratio suggests **production of TINa** from neutralization of TINa⁺ ions starts to take more important roles than that of **wave and eddy transport**.
4) Direct neutral transport of Na by wave and eddy cease functioning but the production of TINa dominates TINa density, thus the SAO/AO ratio turns to be stable **from 123 to 150 km**.
5) **Below ~87 km**, balance between the dynamical transport (wave and eddy) and chemical transport (chemical production and loss of Na that is affected by the atomic oxygen shelf) likely leads to a SAO/AO ratio of ~0.8.



Wave and Eddy Transport

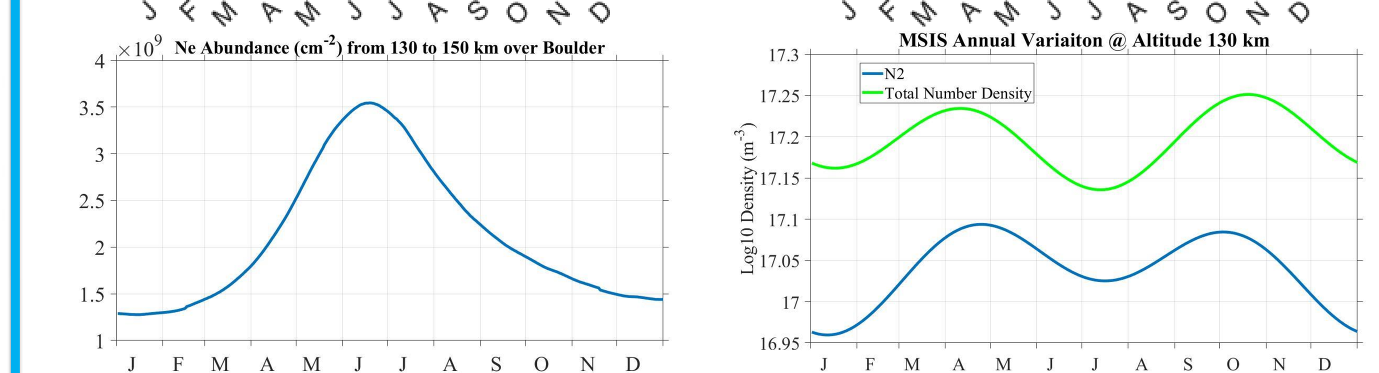
- The lidar-measured **temperature variance** $Var(T')$ at SOR (used to represent wave-induced K_E) is minimum at two equinoxes but at maxima during summer and winter
- Suggesting that the thermospheric density SAO is mainly induced by the lower atmosphere SAO.

Two minima at Two equinoxes:

- The minimal wave-induced and eddy transport causes the main Na layer to have **narrower width**, resulting in **weaker upward transport** of Na⁺ due to the **increased ion-neutral collisions**.
- **Meteoric influx** is minimized around **spring equinox** while maximized around autumn equinox, leading to overall column abundance of Na and Na⁺ being minimal around spring equinox.

Two maxima in Summer and Winter:

- Strong wave-induced transport and eddy diffusion helps **extend the main layer's topside**, not only leading to the wider width of main layer but also enabling production of **more Na⁺ via charge transfer** with NO⁺ and O2⁺ ~100-110 km.
- More photoionization due to longer sunlit time **in summer** also helps keep higher concentrations of ions and electrons than other seasons.



- **The total number density** reaches two minima in summer and winter while two maxima in Apr and Oct.
- Such **thermospheric density SAO** helps enhance two summer and winter maxima and two equinox minima of TINa VMR.

Conclusions

1. First characterization of year-round Na layers from 75–150 km **discovers AO & SAO** in Boulder TINa (~105–150 km) —the summer maximum and spring minimum (March/April).
2. The results are in **stark contrast** of the maximum TINa to the minimum main Na layer in summer, supporting TINa origin being neutralization of converged TINa⁺ ($TINa^+ + e^- \rightarrow TINa + h\nu$).
3. SAO in TINa is likely linked to **thermospheric density SAO** and to the **minimal wave/eddy transport** at equinoxes when TINa⁺ ion production and upward transport is hindered by less diffusion of main Na layers.
4. TINa being stronger around autumn equinox than spring equinox is likely explained by the maximal and **minimal meteoric input fluxes (MIF)** occurring in Sep and April, respectively.
5. This study is the first of its kind for characterizing entire Na layers **from 75 to 150 km**. Such studies offer a unique opportunity to explore the fundamental processes and coupling mechanisms in "thermospheric gap".