MLTL-1

Climatology of Vertically Stratified Meteoric Na Layers (75–150 km) over Boulder: Lidar Observations and Comparisons with WACCM-X-Na Simulations

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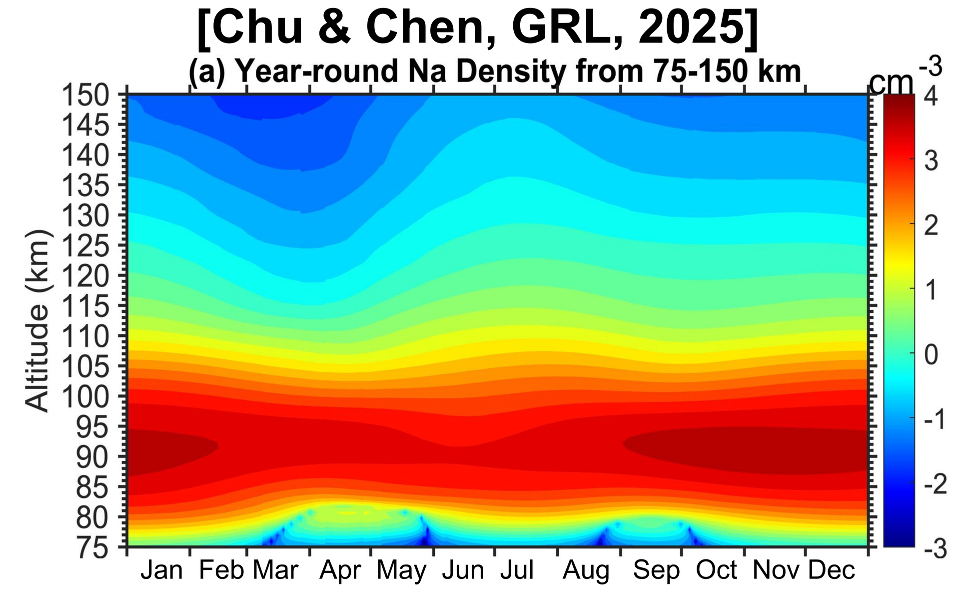
Abstract: Meteoric Na layers provide a natural laboratory for studying the coupled ionosphere–thermosphere–mesosphere (ITM) system but are hard to characterize above the main Na layer. Using 7 years of high-detection-sensitivity Na Doppler lidar observations over Boulder, Colorado (40.13°N, 105.24°W), we establish unified climatologies of Na layers from 75–150 km and compare with WACCM-X-Na simulations. Monthly composites of Na densities, volume mixing ratios, and normalized Na density ratios reveal vertically stratified Na layers consisting of the mesospheric main Na layer (~75–105 km), Na transition layer (~95–120 km), and thermosphere-ionosphere Na (TINa) layer (~110–150 km). WACCM-X-Na largely captures such vertical organization of Boulder Na layers, along with the nocturnal evolution trend and major seasonal behavior. TINa and transition layer phase lines basically align with a tilted tidal-wind-driven structure of alternating ion convergence and divergence. These results suggest that global-scale tidal winds are a major driver of the vertically stratified Na structures via ion-neutral conversion ($Na^+ \rightarrow Na$), demonstrating metal layers as a high-fidelity tracer in the thermospheric gap region.

Introduction: Recent Discoveries from Boulder TINa Layer Studies

1. Full-Altitude Climatology of Na Density/VMR

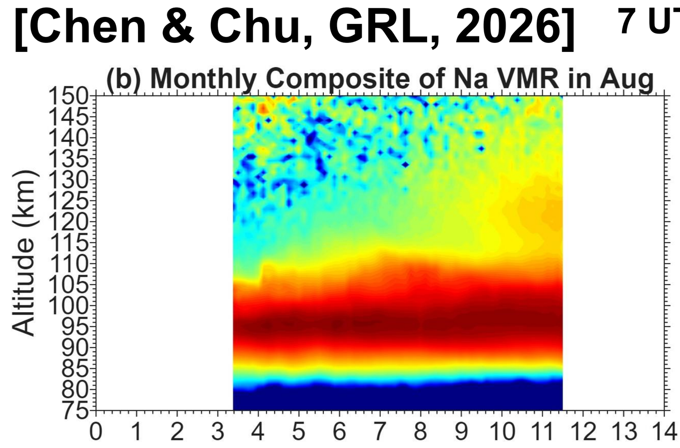
[Chu & Chen, GRL, 2025]



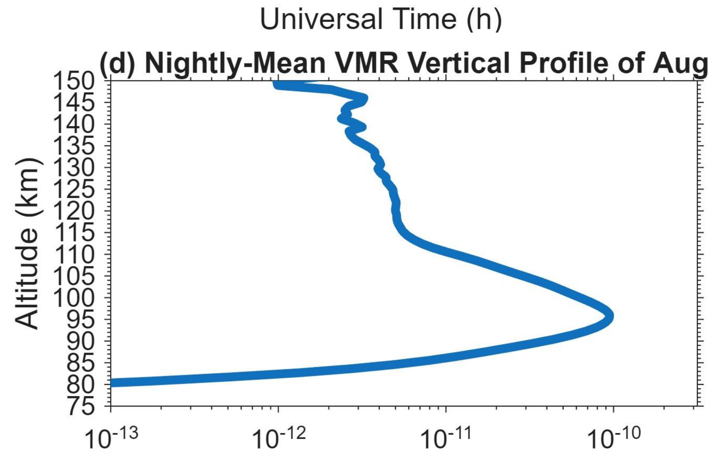
- ❑ **First Na Climatology from 75–150 km:** main Na (75–105 km) and TINa (105–150 km)
- ➢ **Thermosphere-Ionosphere Na (TINa):**
  - First regular occurrence reported in 2021.
  - ✓ **[Chu, Chen et al., GRL, 2021]**
  - TINa occurs after dusk and before dawn.
- ❑ **Stark contrast between** Semiannual Oscillations (SAO) of TINa layers
  Annual Oscillations (AO) of the main Na layers

2. Normalized Na-density-ratio enables discovery of Na transition layer (~120–95 km) linking mesospheric main Na and TINa layers

[Chen & Chu, GRL, 2026] **7 UT → local midnight**



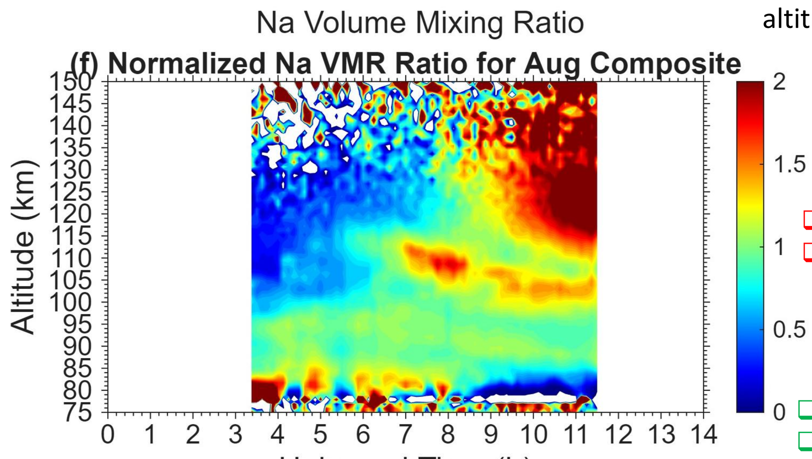
VMR Composite (Volume Mixing Ratio)
- ➢ Predawn TINa
- ➢ Regular Occurrence
- ✓ Phase annual Variation and Correlation to migrating tidal winds
- ✓ **[Chen & Chu, GRL, 2023]**



$$\rho ratio_{Norm\_Na}(z,t) = \frac{\rho_{Na}(z,t)}{\bar{\rho}_{Na}(z)}$$

$\boldsymbol{\rho_{Na}(z,t)}$: Absolute Na density/VMR of monthly composite

$\boldsymbol{\bar{\rho}_{Na}(z)}$: Nightly-mean Na density/VMR averaged at each altitude

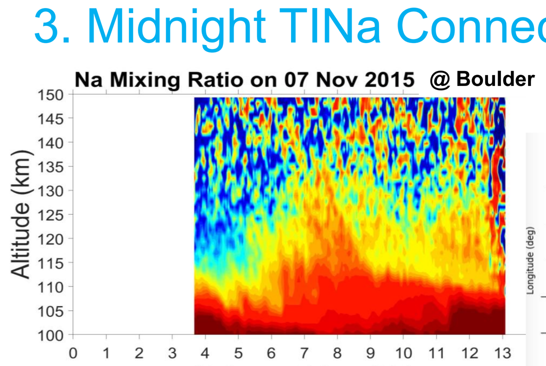


Distinction:

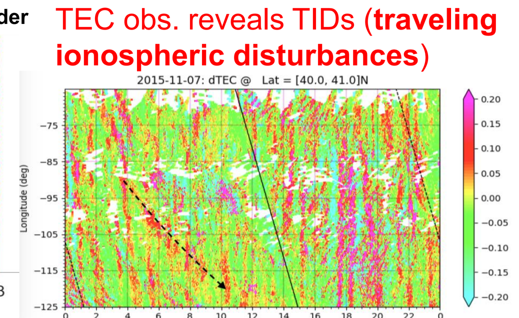
Upper(130km) Predawn TINa
- ❑ Descend faster
- ❑ Wider width

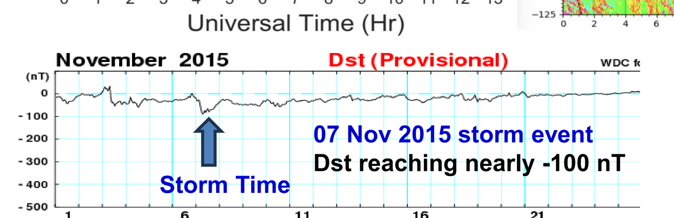
Below(105km) Na transition layer
- ❑ Descend slower
- ❑ Narrower width

3. Midnight TINa Connections to Storm &TIDs



TEC obs. reveals TIDs (**traveling ionospheric disturbances**)





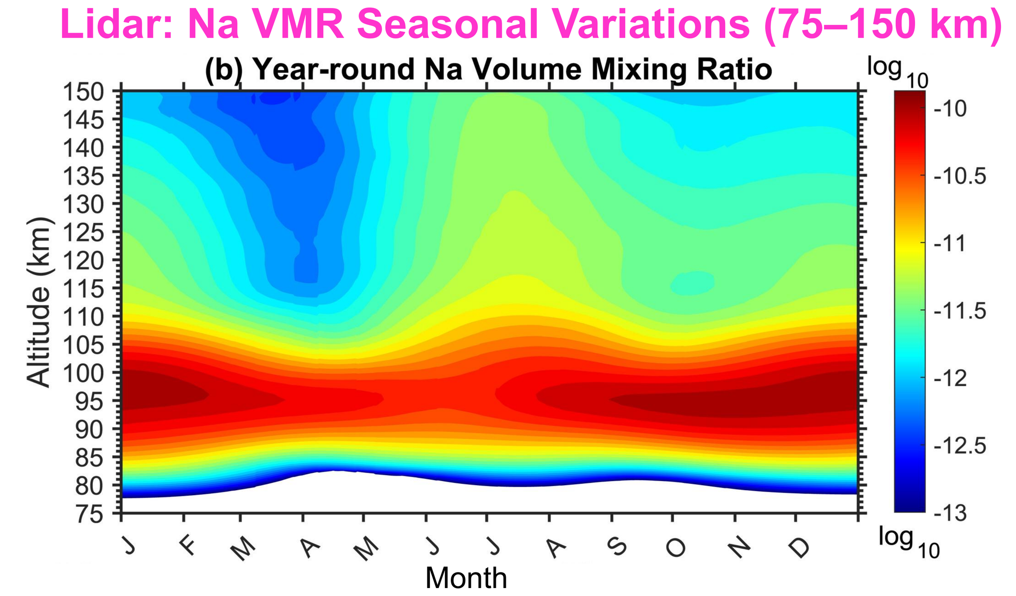
Intermittent Midnight TINa **Formation Mechanisms**? → Prompt penetration electric fields (**PPEF**s) help converge Na+ rapidly?

Comparison of Lidar Observations with WACCM-X-Na Simulations: Seasonal Variations

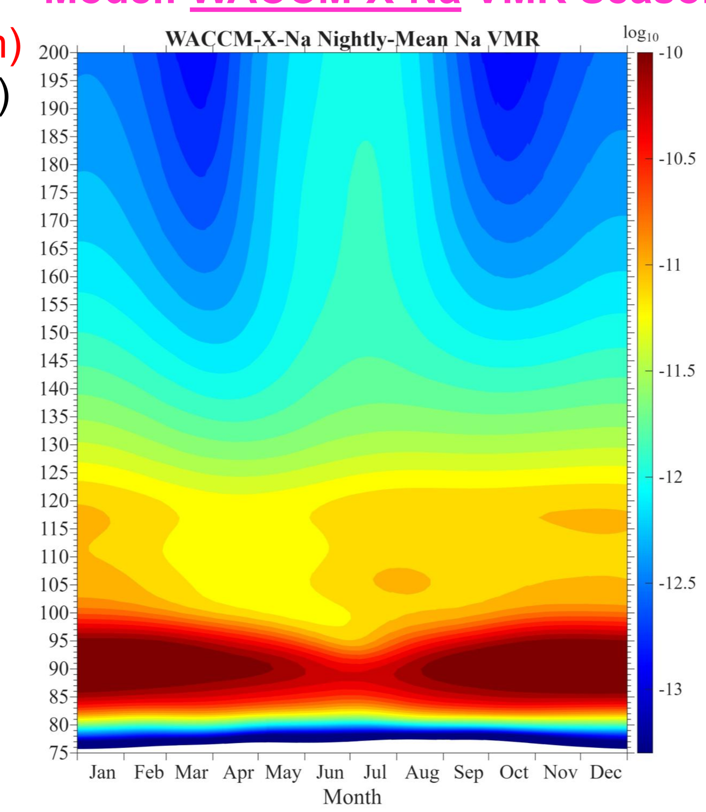
Model captures the broad “seasonal paradox”
- ❑ SAO-feature in thermospheric TINa (above ~105 km)
- ❑ AO-dominated mesospheric main layer (75–105 km)

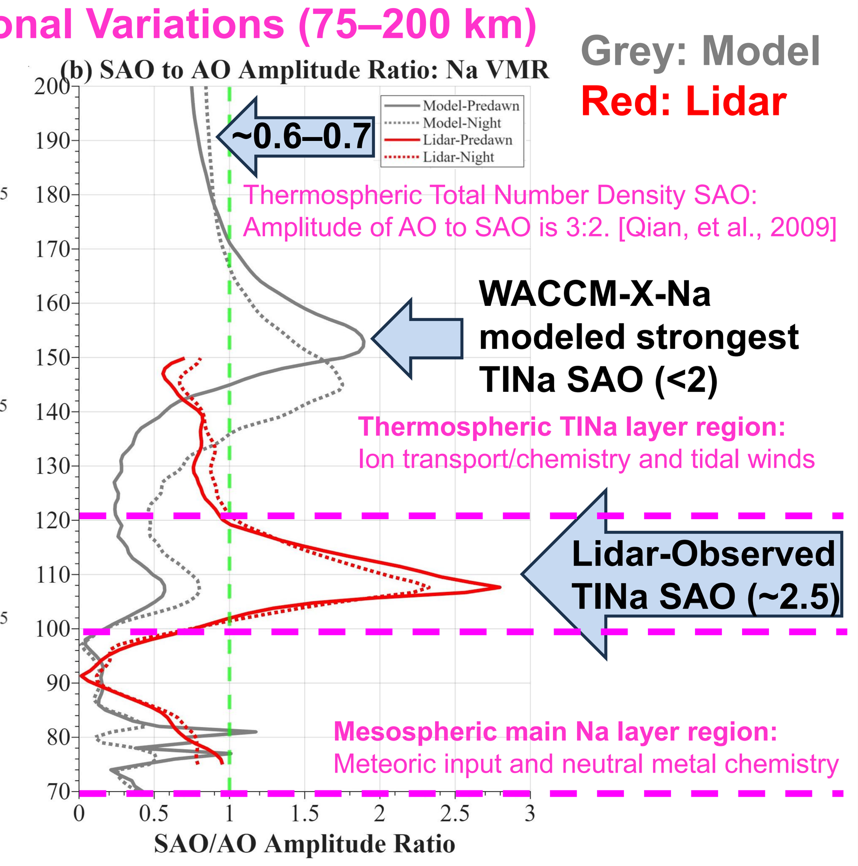
Main WACM-X-Na model bias
- ❑ Strongest SAO too high, mainly above ~140 km.

Lidar: Na VMR Seasonal Variations (75–150 km)

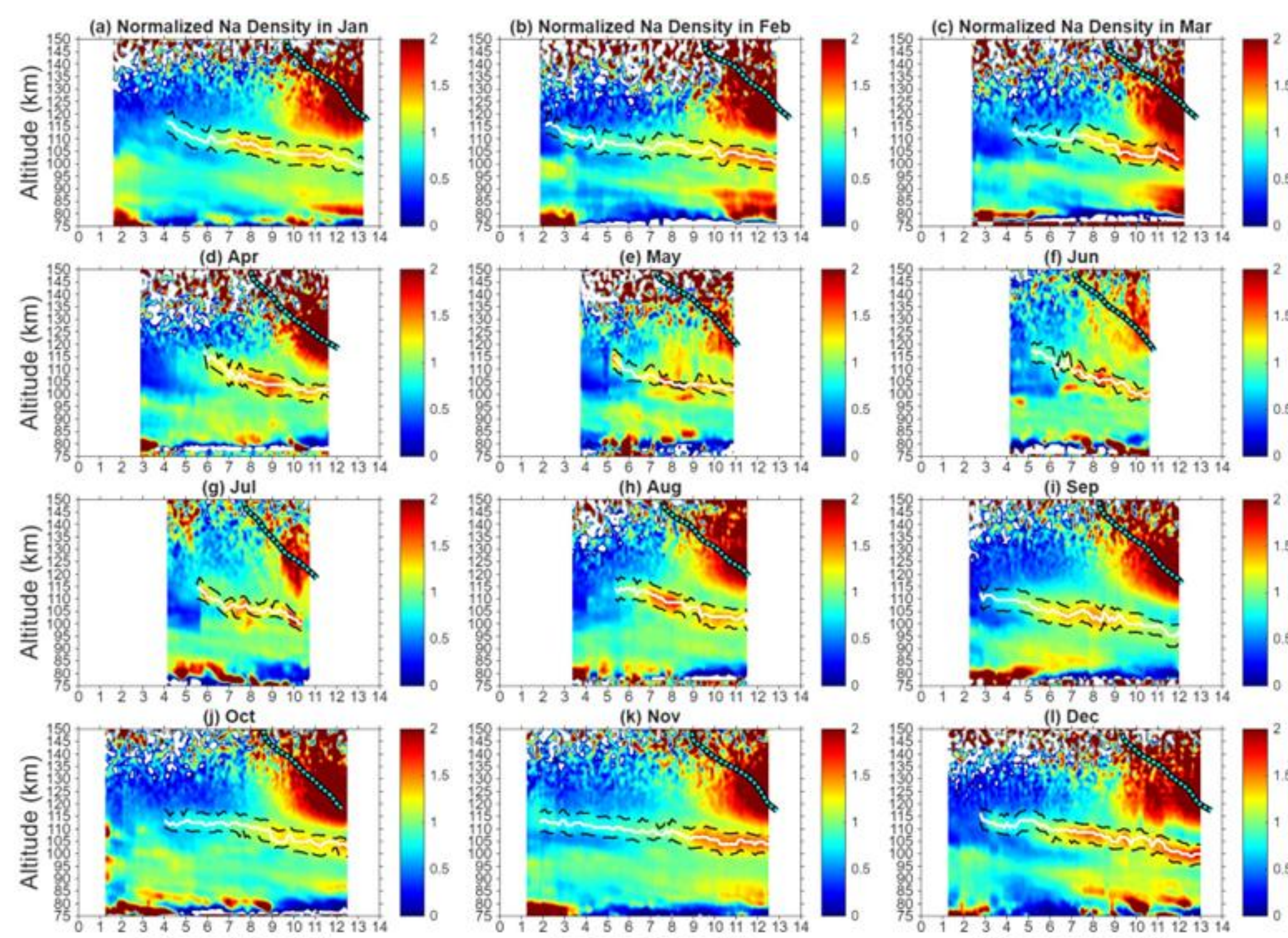


Model: WACCM-X-Na VMR Seasonal Variations (75–200 km)





Lidar Observations of Vertically Stratified Na Layer System Spanning 75–150 km over Boulder

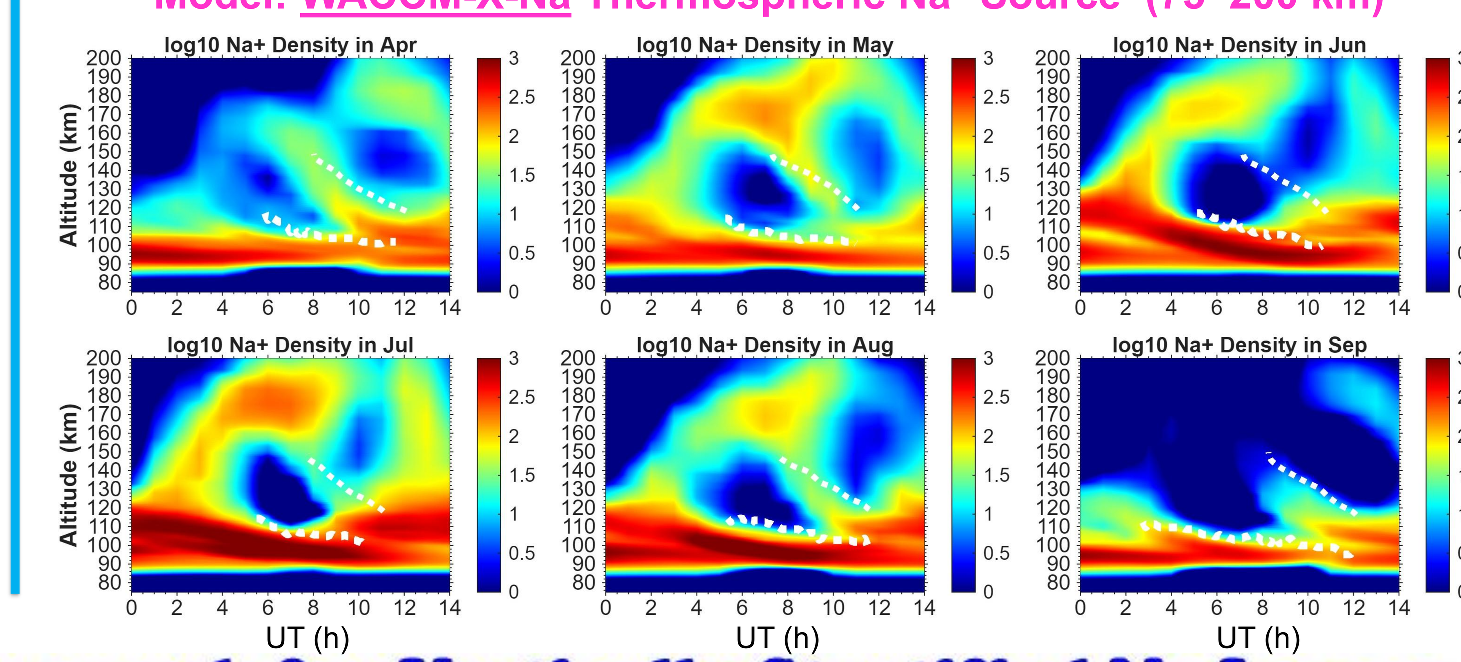


Physical Mechanisms of Vertically Stratified Na Layers

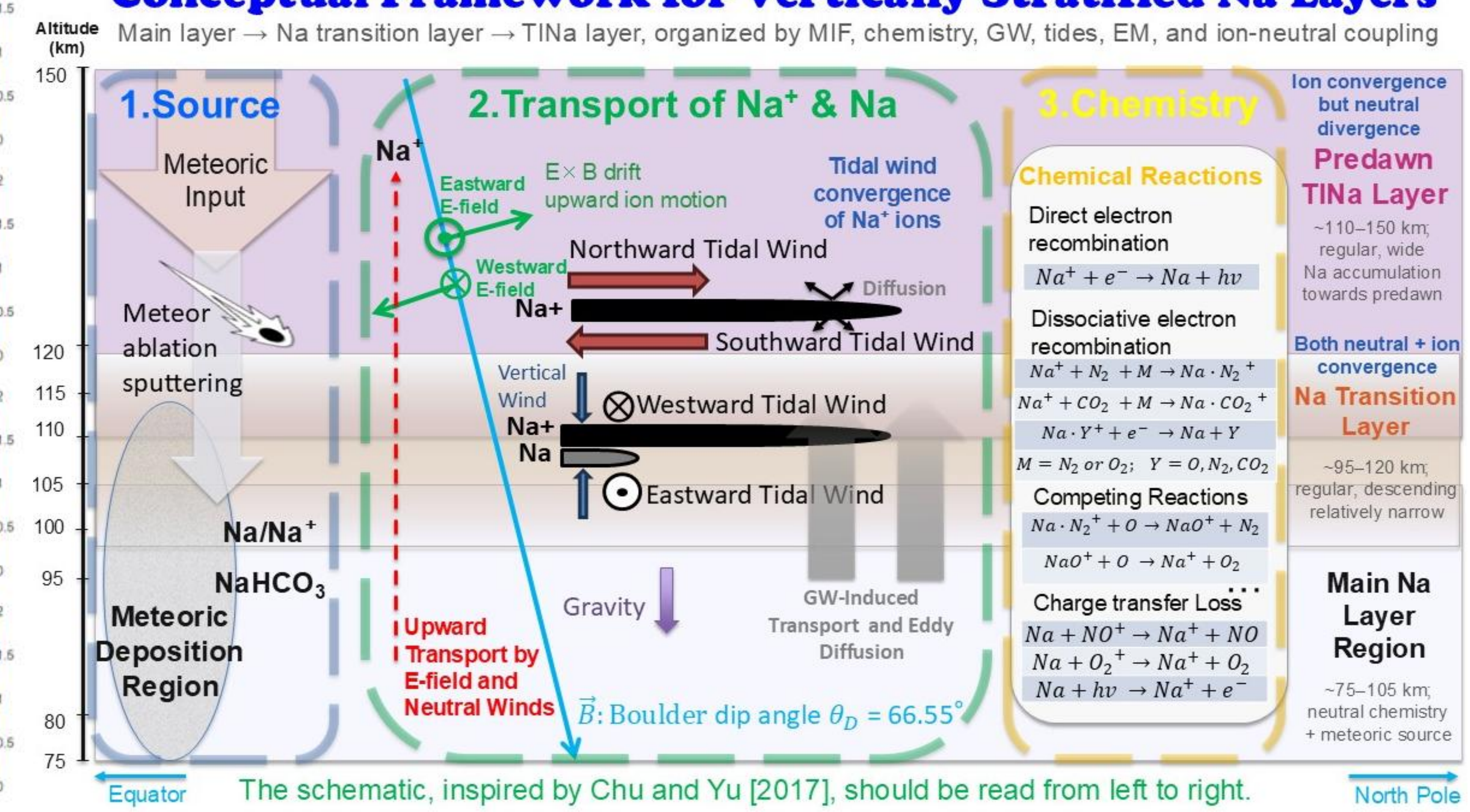
Hypothesis: Three physical conditions are required

1. Sufficient **Na^+ source** above the main layer: Upward transport upward from meteoric deposition region, likely via E×B ion and neutral wind transport.
2. Vertically separated **Na^+ convergence regions**: Na^+ must be concentrated into distinct altitude regions, producing layer-like ion structures.
3. Efficient **ion-neutral conversion**: $Na+ \rightarrow Na$

Model: WACCM-X-Na Thermospheric Na^+ Source (75–200 km)



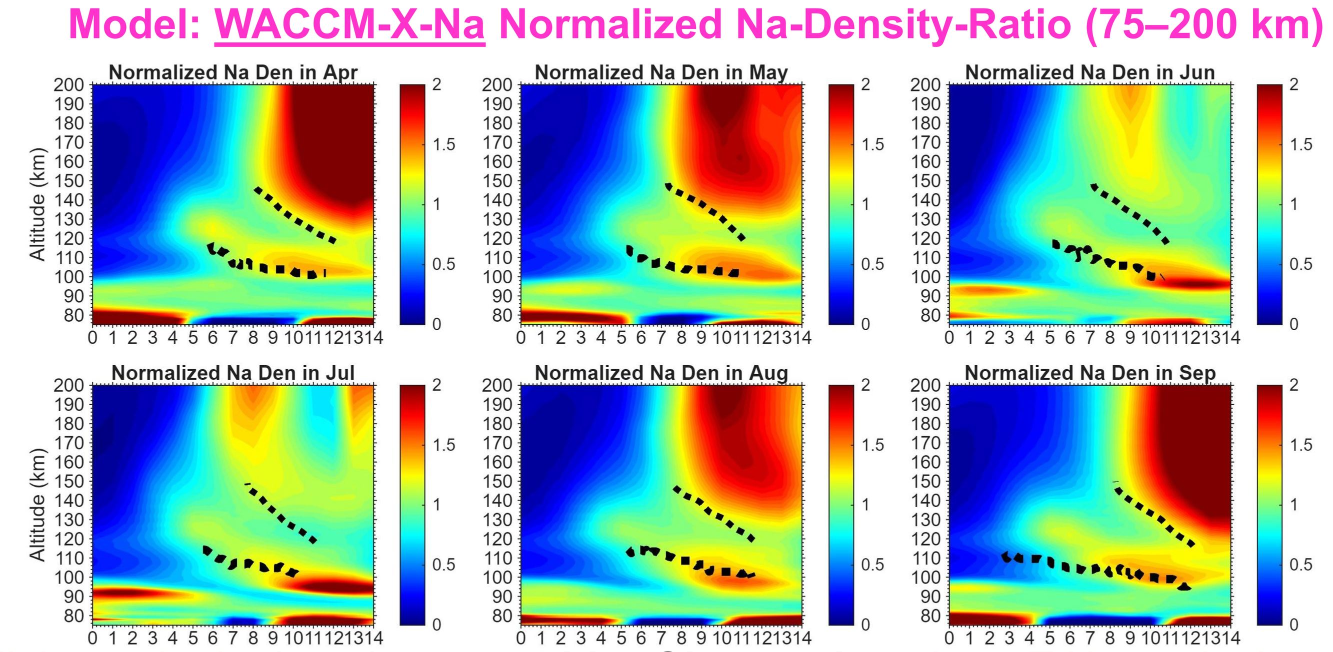
Conceptual Framework for Vertically Stratified Na Layers



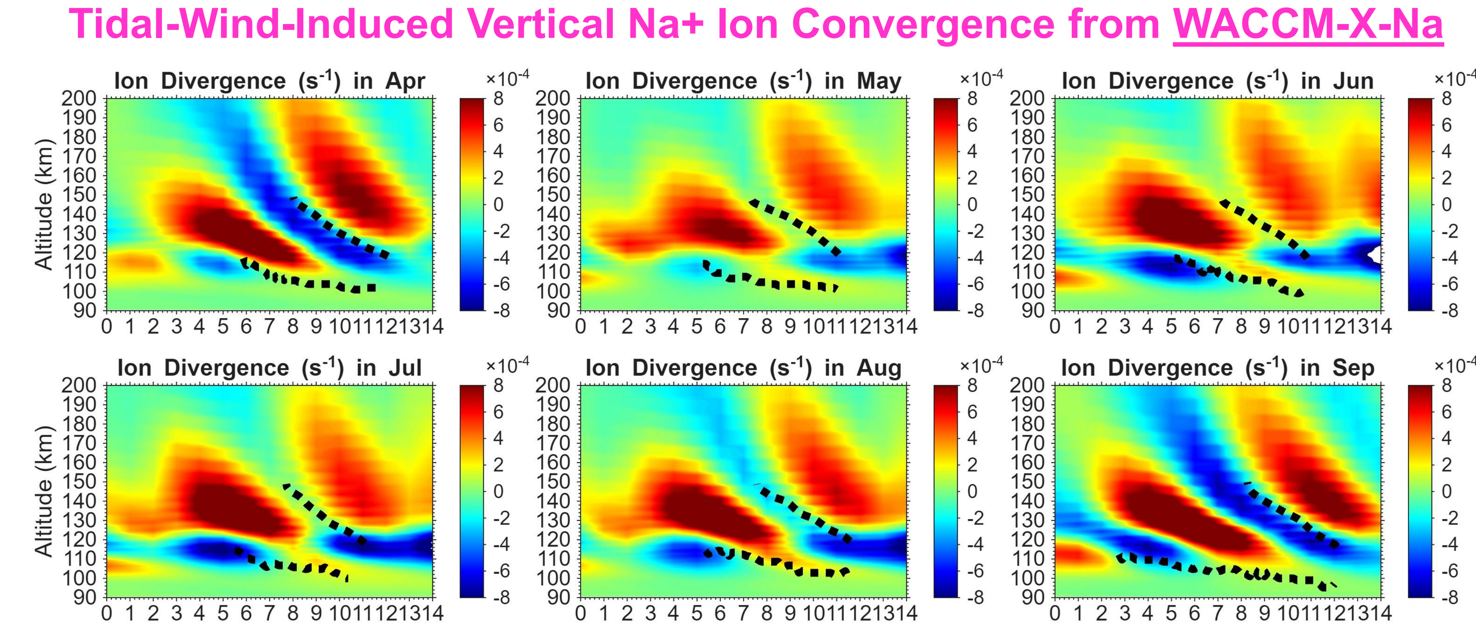
The schematic, inspired by Chu and Yu [2017], should be read from left to right.

WACCM-X-Na largely Captures Lidar-Observed Vertical Stratification of Na Layers and Why?

Model: WACCM-X-Na Normalized Na-Density-Ratio (75–200 km)



Tidal-Wind-Induced Vertical Na+ Ion Convergence from WACCM-X-Na



Higher-altitude dotted curves: **Lidar-Observed** predawn TINa peak phases; Lower-altitude dotted curves: **Lidar-Observed** Na transition layer peak phases

Model Capture key observed behaviors: Reproduce **different morphologies** between transition layer (narrower and slower) and predawn TINa (wider and faster)

Main Discrepancies: 1. Modeled layer's altitude is put **too high**. 2. TINa **too diffuse** and **vertically extended**, **lacking downward phase** progress.

- ❑ **Lidar-Observed** predawn TINa and Na transition layer peak phases occur within strong tidal-wind-driven Na^+ convergence regions (negative ion divergence) **modeled by WACCM-X-Na**.
- ❑ Tidal-wind-driven **convergence** concentrates Na^+ for neutral Na production, while the intervening **divergence** region suppresses Na+ accumulation between the two layers.

Conclusions and Significance

1. Boulder Na atoms form a **vertically stratified Na layer** system from 75–150 km. 7 years of lidar observations reveal three recurring altitude regimes:
   - **Main Na layer (~75–105 km)**
   - **Na transition layer (~95–120 km)**
   - **TINa layer (~110–150 km)**
2. WACCM-X-Na captures the broad structure including observed **vertical stratification** but has systematic biases.
3. Lidar-model comparisons suggest that tidal-wind-driven Na^+ transport and neutralization organize the neutral Na layers through a vertical pattern: **convergence → divergence → convergence**
4. Vertically stratified Na layer system provides a new, high-sensitivity observational window into tide-driven ion-neutral coupling in the thermospheric gap, linking lower-atmospheric wave forcing to thermosphere–ionosphere variability and offering valuable constraints for whole-atmosphere models.

Acknowledgement

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