Annual Variations of Pre-Dawn Thermosphere-Ionosphere Na (TINa) Layers Observed by Lidar over Boulder and their Relationship to Sunrise and Tidal Winds

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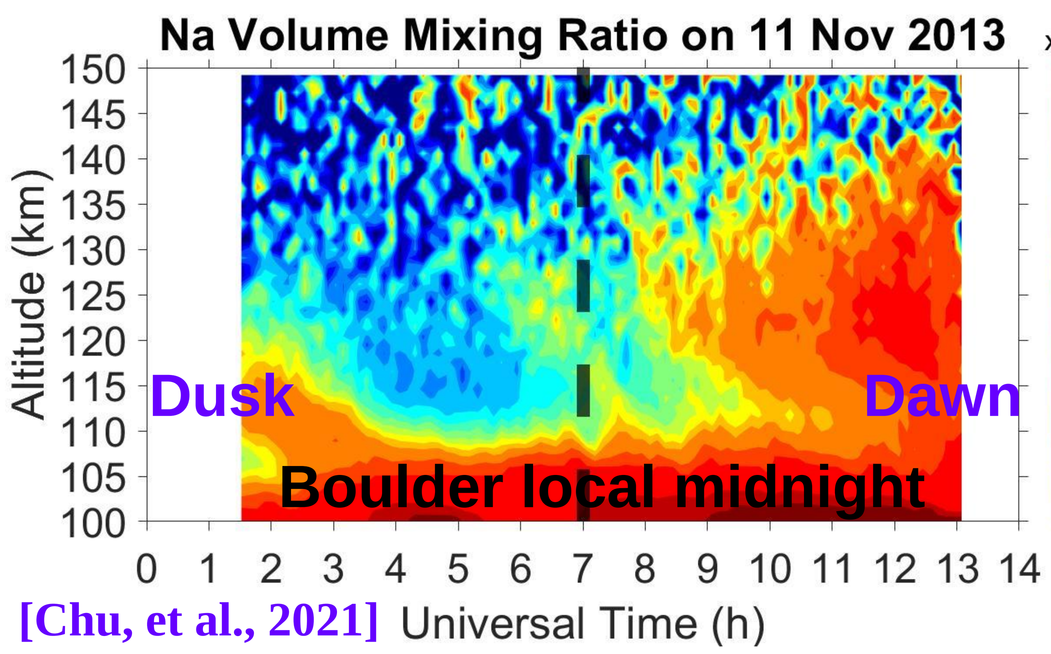
Introduction & Motivations



1. **TINa** (thermosphere-ionosphere Na) **layers:**
   - ❑ **Regular occurrence** is reported in 2021.
   - ❑ TINa occurs after dusk and before dawn.
   - ❑ Formation Mechanism: **Neutralization** of **converged** TINa$^+$ ions via recombination **with electrons** produces neutral TINa ($TINa^+ + e^- \rightarrow \boldsymbol{TINa} + h\nu$).
2. **Importance:**
   - ❑ Tracers to make direct measurements in **"thermospheric gap"** (100–200 km).
   - ❑ Study fundamental processes in the **space-atmosphere interaction** region.
3. **Motivation:**
   - ❑ Investigate relationship between predawn **TINa, sunrise and thermal tides** to better study TINa formation mechanism.

Data & Methodology

1. **Data:**

❖ **Na Lidar Observations** (STAR Lidar)
- ❑ Table Mountain Obs. (40.13°N, 105.24°W)
- ❑ Time range: From 2011 to 2017
- ❑ Laser tuned to Na absorption line at 589 nm

❖ **CTMT** (Climatological Tidal Model of the Thermosphere) [Oberheide et al., 2011]
- ❑ HME (Hough Mode Extensions) modeling using a physics-based empirical model
- ❑ 6 diurnal and 8 semidiurnal tidal components
- ❑ Components in-situ generated not included

❖ **ICON** (Ionospheric Connection Explorer) **HME** data [Cullens et al., 2020]
- ❑ HME fit to MIGHTI data from 90 to ~109 km
- ❑ Latitudinal range: 10°S–42°N
- ❑ Diurnal and semidiurnal tides (no terdiurnal)

2. **Calculation of vertical drift velocity of Na$^+$**

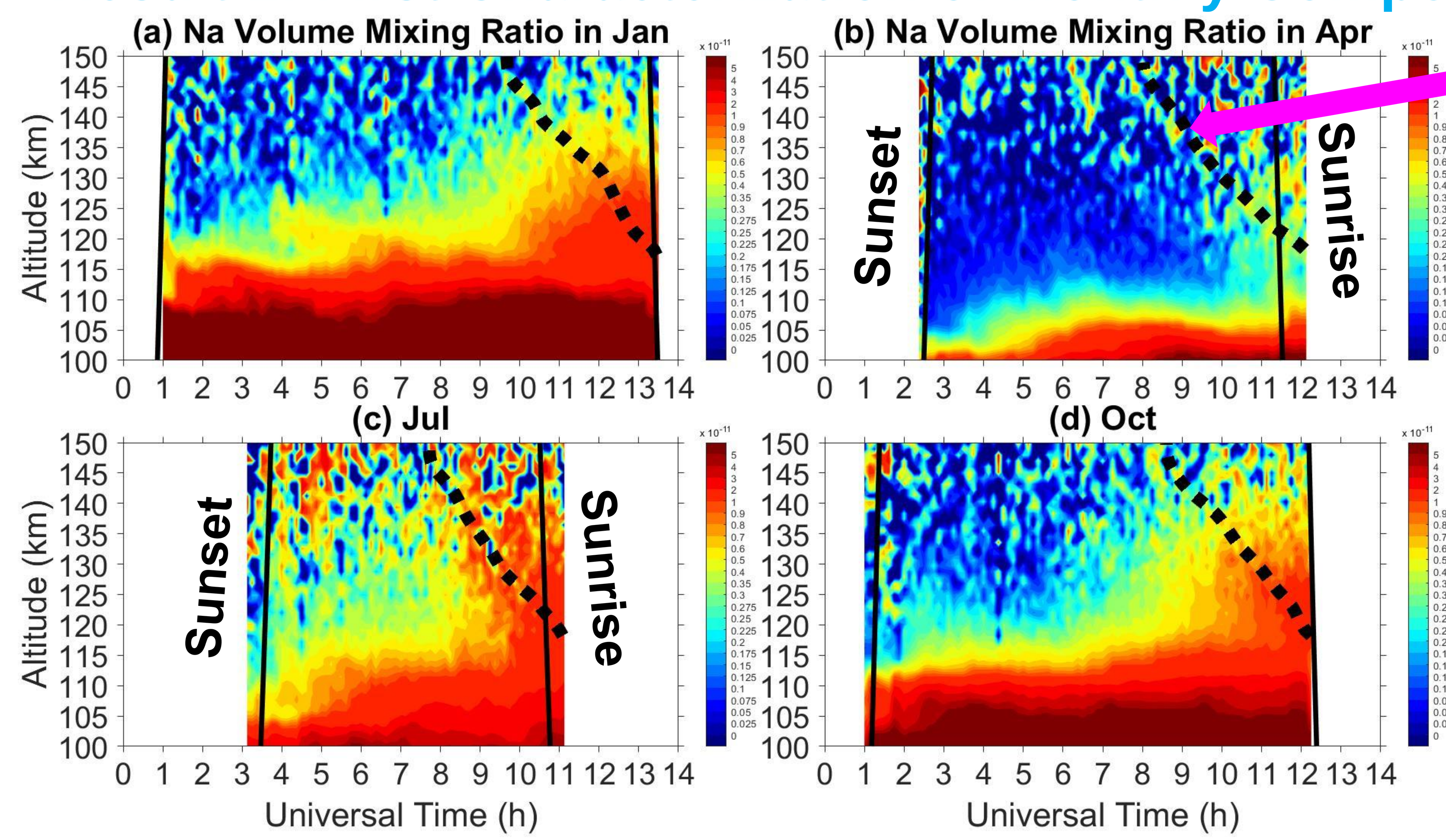
V_{izw} induced by tidal neutral winds in zonal ($V_{n,x}$), meridional ($V_{n,y}$), and vertical ($V_{n,z}$) directions.

$$V_{izw} = \frac{\xi \cos\theta_D}{1+\xi^2} V_{n,x} - \frac{\sin(2\theta_D)}{2(1+\xi^2)} V_{n,y} + \left(1 - \frac{\cos^2\theta_D}{1+\xi^2}\right) V_{n,z}$$

ξ: ion-neutral collision frequency to the gyro frequency of Na$^+$; $\theta_D = 66.55°$: Boulder dip angle

→ **Vertical shears** of horizontal winds converge TINa$^+$ ions explained in wind shear mechanisms.

Result 1: First Characterization of Monthly Composites of TINa



Monthly Composite Methodology:
- Na mixing ratios averaged from **138 nights**
- Bin in the same local time at the same altitude
- Data resolution: **7.5 min; 0.96 km**

Figure 1. Monthly composite contours of Na volume mixing ratios of pre-dawn TINa layers from 100 to 150 km for January, April, July and October over Boulder (40.13°N, 105.24°W), Colorado.

Key Points:
- ❑ Elevated Na mixing ratios exhibit continuous downward phase progression from the top altitudes (roughly 135–150 km) to ~110 km in each month (**pre-dawn TINa layers**).
- ❑ Occurrence time of pre-dawn TINa layers apparently shifts with seasons, related to sunrise.

Result 3: Correlation of Pre-Dawn TINa Layers to Tidal Winds

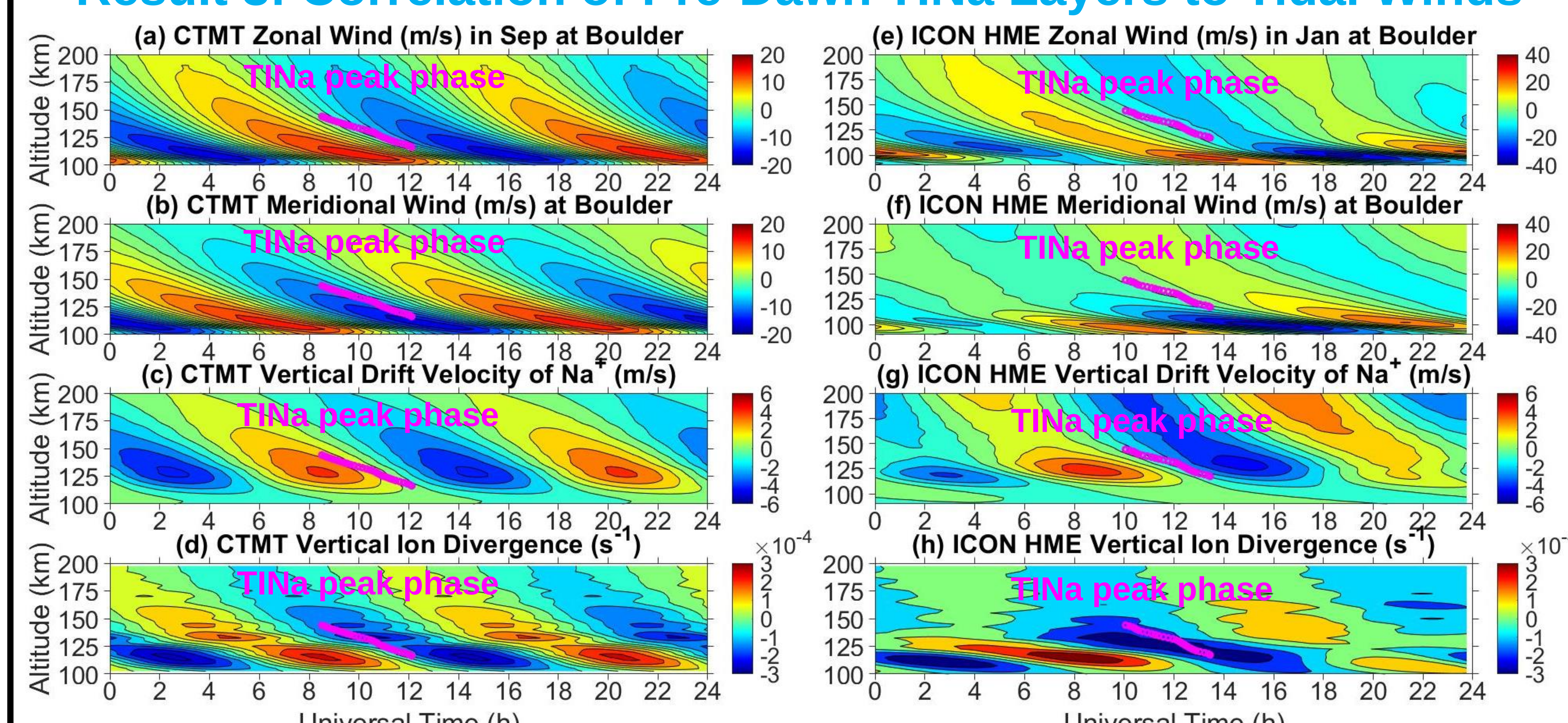


Figure 3. Neutral horizontal (zonal and meridional) winds provided by CTMT in September (left column) and ICON HME in January (right column) tidal winds (SW2 + DW1). The bottom two rows show Vertical ion drift velocity (V_{izw}) of TINa$^+$ ions and Vertical ion divergence ($\partial V_{izw}/\partial z$) calculated using the winds in top two rows.

Top 2 Rows:
- ❑ Pre-dawn TINa peak phases **descend along** wind phase lines and lie closely to the **vertical shears** of zonal, meridional winds in both CTMT and ICON HME.
- ❑ Because eastward and southward (westward and northward) winds transport ions upward (downward), these shears of horizontal winds **cause ions to converge**.

Bottom 2 Rows:
- ❑ Occurrence region of pre-dawn TINa layer corresponds where vertical ion divergence is negative ($\frac{\partial V_{izw}}{\partial z} < 0$), i.e., the region where TINa$^+$ ions converge to increase concentrations.

Key point: Similarity between descent rates of TINa and modeled ion convergence regions supports the formation mechanism, i.e., neutralization of converged TINa$^+$ ions forming TINa.

Result 2: TINa Phase Annual Variations

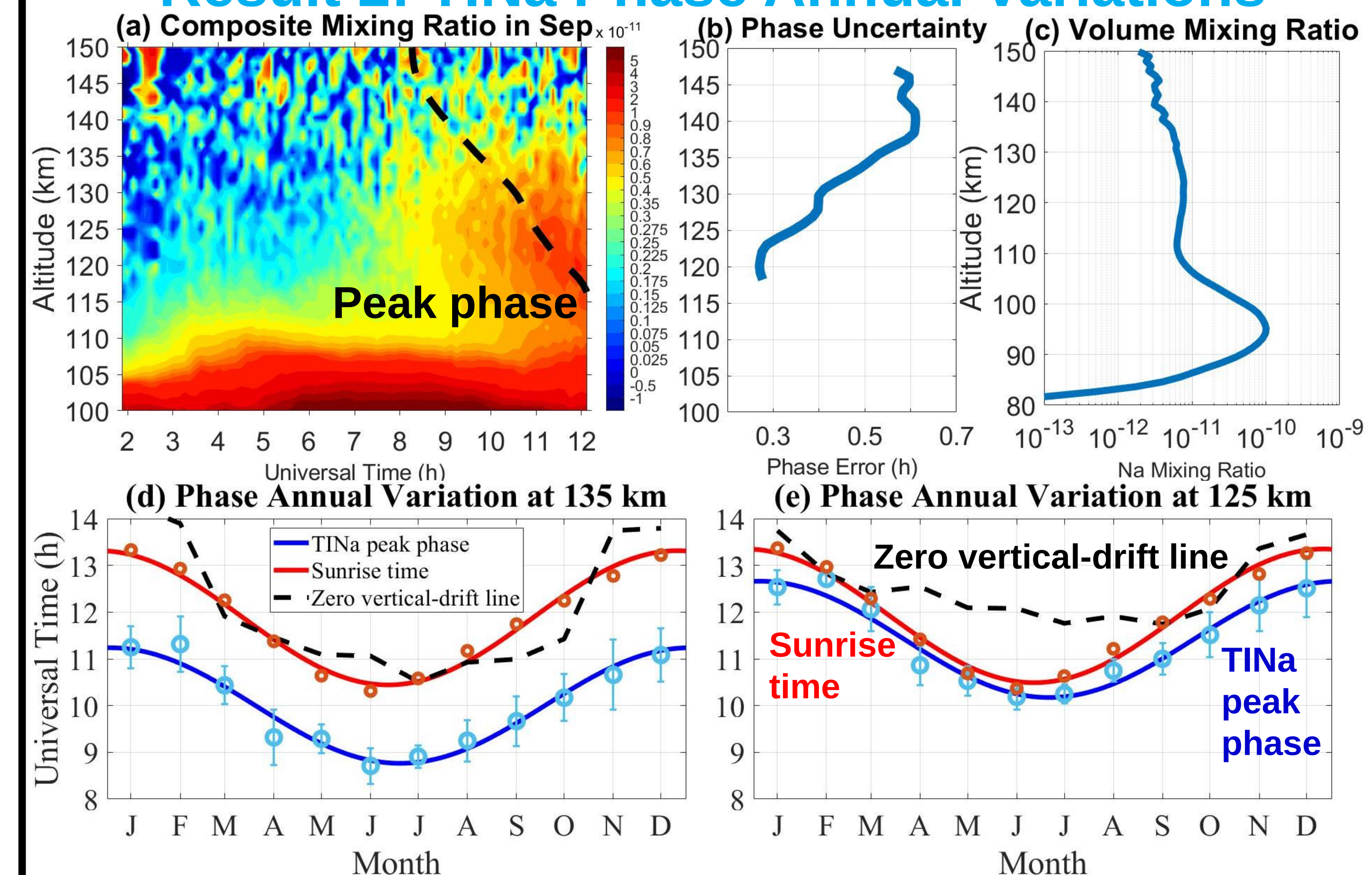


Figure 2. (a) Peak phase tracking of pre-dawn TINa in Sep. (b) Uncertainty. (c) The altitude profile of pre-dawn TINa mixing ratio in monthly composite. (d-e) Vertical ion convergence line overplotted on the pre-dawn TINa peak phase and sunrise time.

Pre-dawn TINa Peak Phase Determination:
- ❑ 2D Hamming smoothing windows with full widths of **0.5 hr and 5 km** for minimizing noise to better determine peak mixing ratios.
- ❑ **Phase uncertainty**: Standard deviation of various nights' phases.

Key Points:
- ❑ Annual variations of TINa peak phase and sunrise time are strikingly similar—**earliest in summer and latest in winter**.
- ❑ CTMT phases of semidiurnal westward-propagating tidal winds (SW2) undergo **similar annual variations** as sunrise and TINa.
- ➢ Phases of **migrating tidal winds** in lower thermosphere have annual variations, which in turn drive TINa phase variations.

Conclusions and Outlook

In this study, after utilizing seven years of Boulder Na lidar data
1. We statistically characterized **monthly composites** of TINa.
2. We discovered the pre-dawn TINa layer phase undergoes clear **annual variations**, which are closely correlated to the annual phase variations of **both sunrise and migrating tidal winds**.
3. We found the pre-dawn TINa neutral layers **descend at similar rates** as, and in the **vertical ion convergence** regions, modeled with the migrating tidal winds data.
4. These results suggest migrating tidal winds play the major role in TINa$^+$ ion convergence thus strongly influencing the phase annual variations of pre-dawn TINa layers.

Future Work:
1. Monthly-composite TINa layers exhibit **annual variations in the TINa volume mixing ratios**, which deserve future investigation.
2. Develop model to integrate factors like **ionospheric electric fields, mean background winds, and in-situ generated tides** together and quantitatively study TINa formation mechanism.

COMING SOON Chen and Chu (2023). Phase Annual Variations and Correlation with Sunrise and Tidal Winds. *Geophysical Research Letters*, in revision.

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