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

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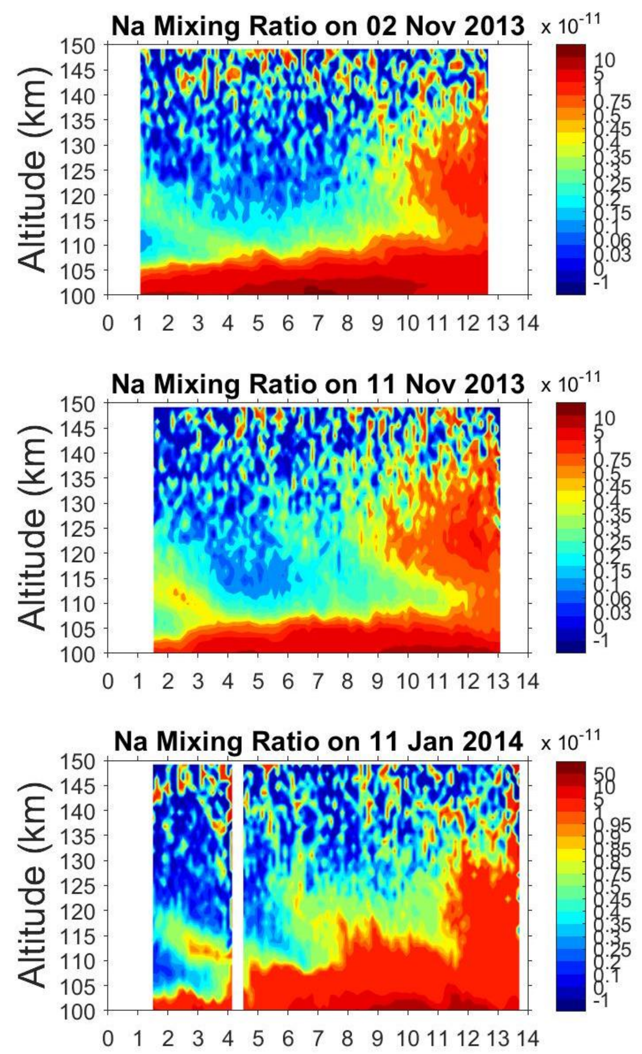
First Discovery: TINa Regular Occurrence

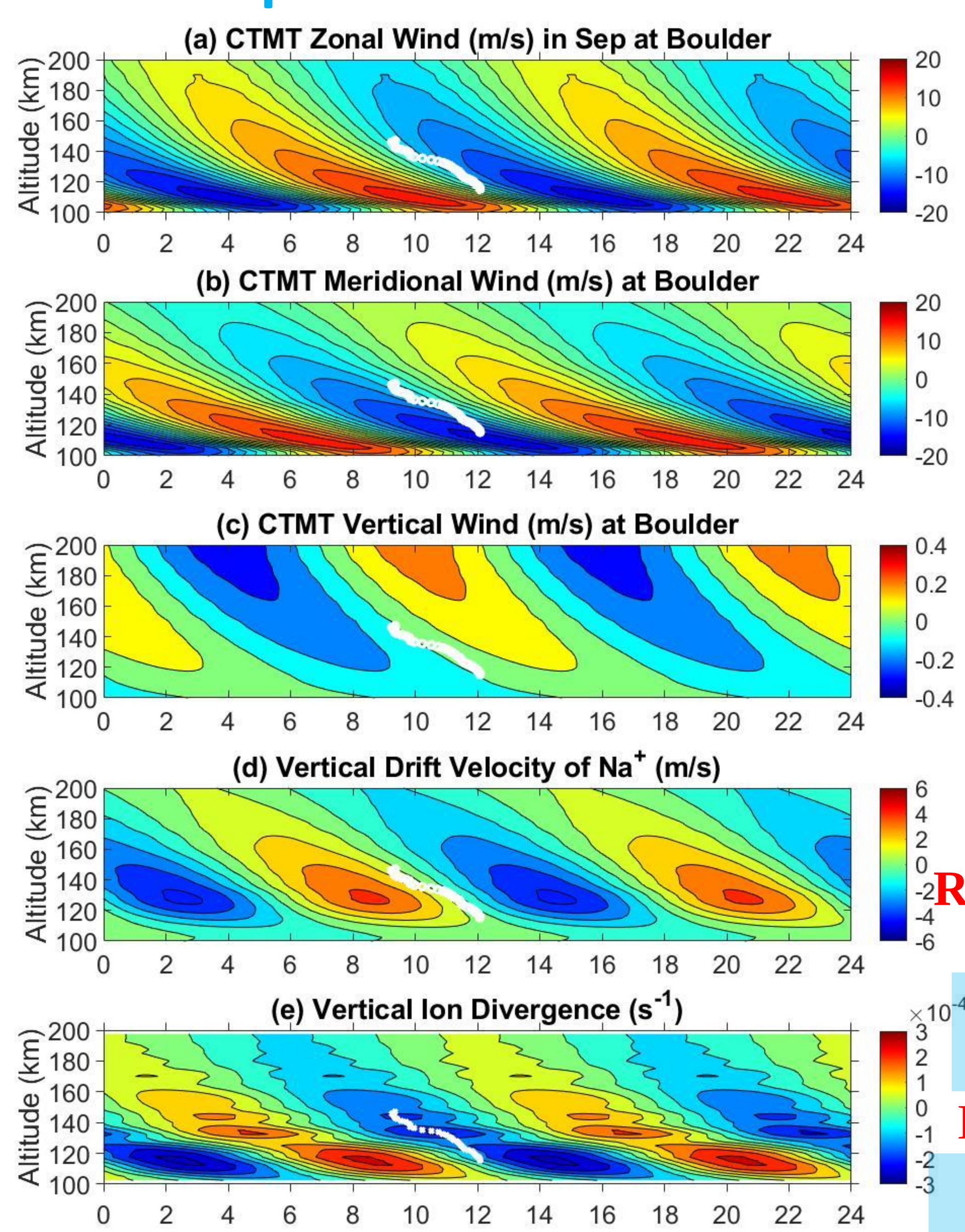


Thermosphere-ionosphere metal (TIMt) layers provide tracers to study fundamental processes in the space-atmosphere interaction region, especially in the E–F regions where measurements of neutrals are scarce but plasma-neutral interactions are rich (Chu et al., 2020).

Nearly 50 years of lidar observations showed only irregular occurrence of TINa layers from a few locations. Then in 2021, the first discovery of regularly occurring mid-latitude TINa layers was made over Boulder, enabled by the combination of **high detection sensitivity** of lidars and creative data processing techniques (**volume mixing ratio** calculations). Boulder TINa layers are studied further in this report.

[Chu, Chen, et al., GRL, 2021]

Proposed Formation Mechanism



ξ: ratio of ion-neutral collision freq. to gyro freq. of Na^+

θ_D: dip angle

$$f_U = \frac{\xi \cos\theta_D}{1+\xi^2}$$

$$f_V = -\frac{\sin(2\theta_D)}{2(1+\xi^2)}$$

$$f_W = 1-\frac{\cos^2\theta_D}{1+\xi^2}$$

Recombination

Direct

$$Na^+ + e^- \rightarrow Na + hv$$

Dissociative

$$Na^+ \cdot X + e^- \rightarrow Na + X$$
$$(X = O, N_2, CO_2)$$

The vertical ion divergence (∂Vizw/∂z), which is defined as the vertical gradient of the vertical ion drift velocity. Figures show **convergent phases** of the horizontal winds but **divergent phase** of the vertical wind near TINa. Pre-dawn TINa layer occurs in the region where vertical ion divergence is strongly negative, i.e., the region where accumulation of $TINa^+$ ions is expected.

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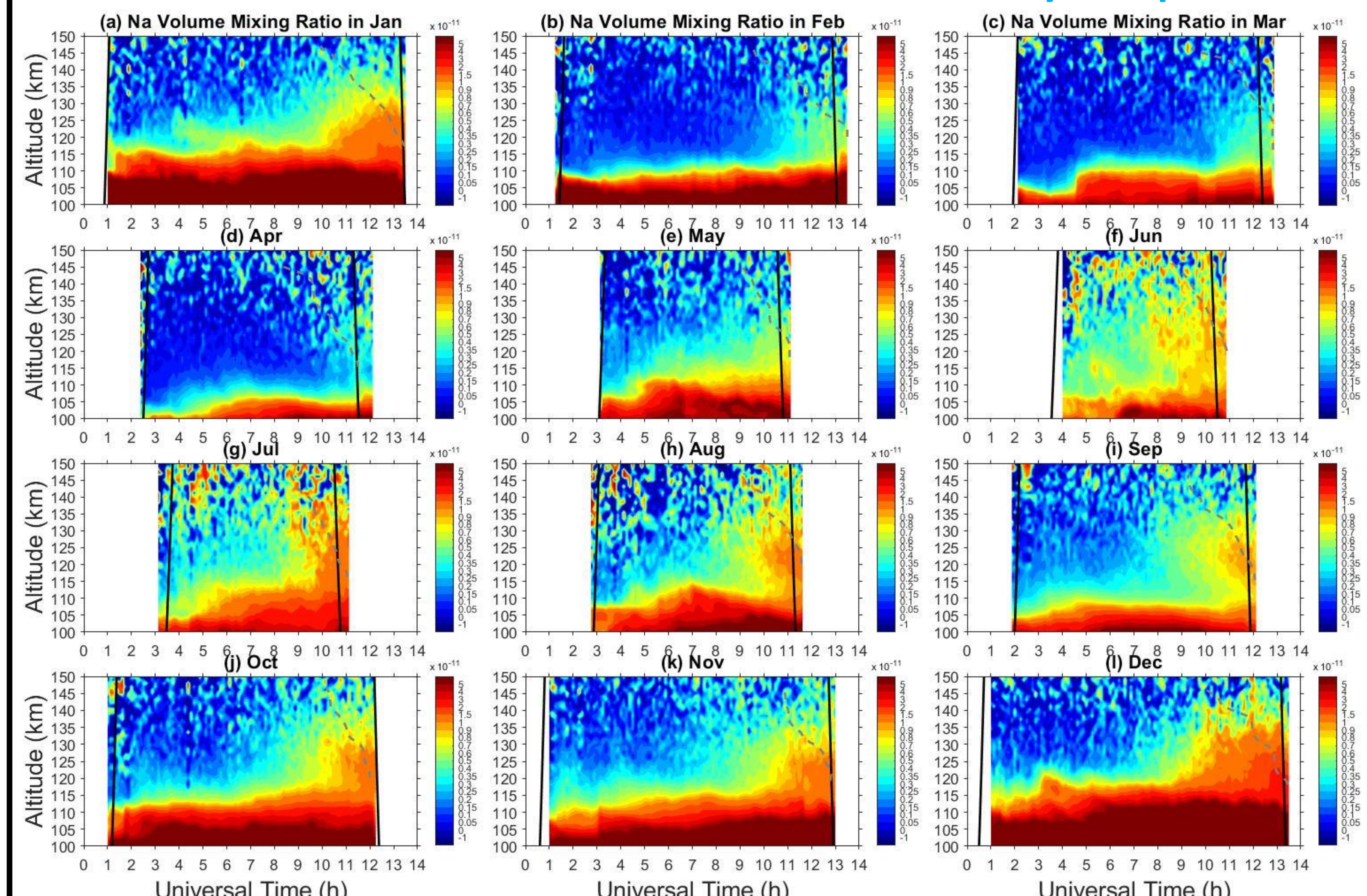
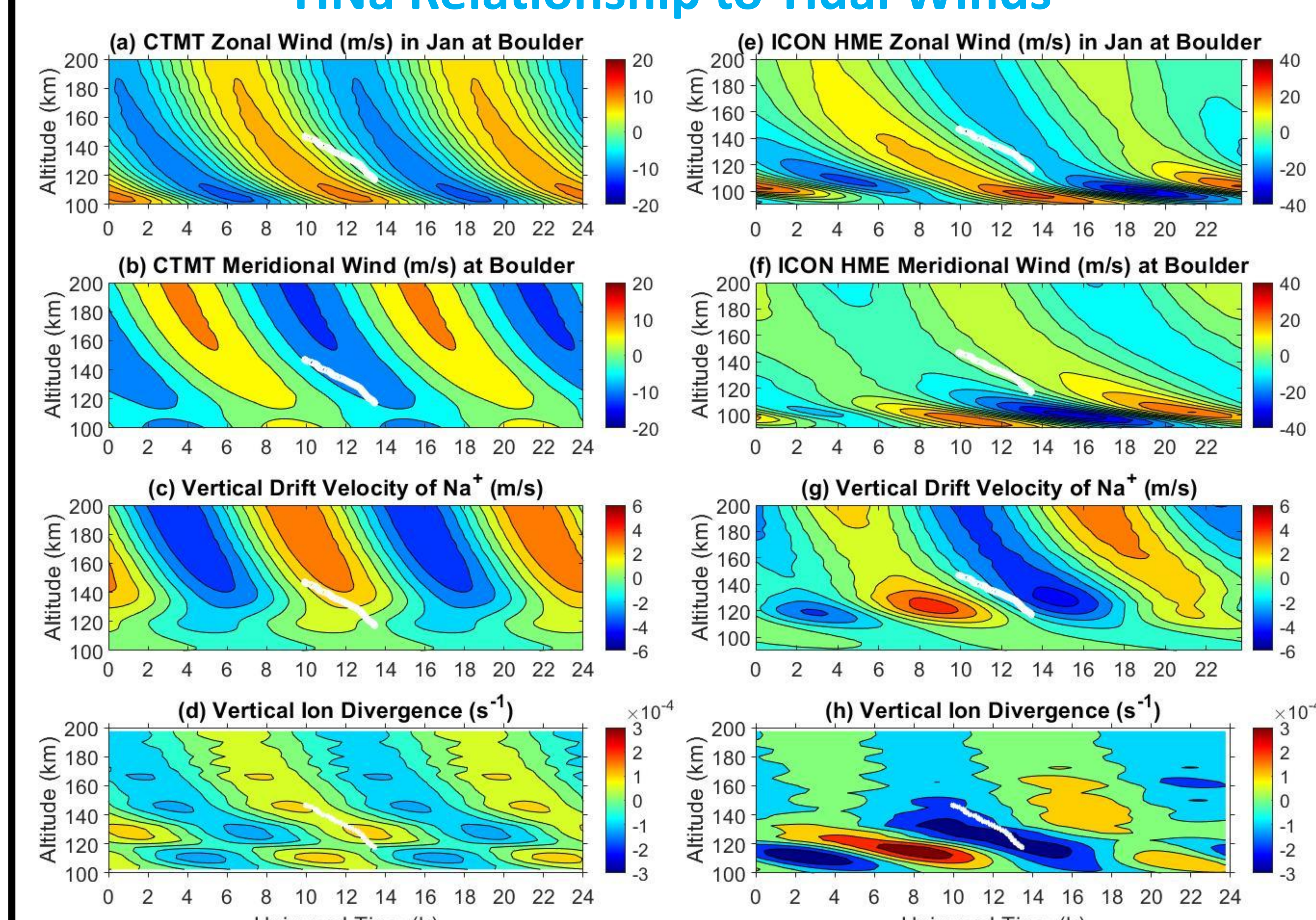
Abstract: We have discovered that the peak phase of pre-dawn TINa layers undergoes clear annual variations with the earliest occurrence in summer and latest in winter over Boulder, which are closely correlated to annual variations of sunrise and tidal winds. Such discoveries were enabled by the first characterization of 12 monthly composites of TINa layers from January through December using 7 years of lidar observations (2011–2017). These TINa layers occur where vertical ion convergence, computed using CTMT tidal winds, is strong but tidal vertical wind causes neutrals to diverge. These results support the formation mechanism proposed previously and suggest migrating tidal winds experience phase annual variations.

First Characterization of 12 Monthly Composites of Pre-Dawn TINa Layers



- With the nearly 100% occurrence rate (160 out of 164 nights of observations), the regular occurrence of pre-dawn TINa layers can be decisively confirmed at mid-latitudes.
- Based on the regularly occurring Boulder TINa dawn layers, the TINa mixing ratio composite contours are calculated in 12 different months from 7 years of lidar data.
- That is, averaging Na mixing ratio in the same local time (LT) and at the same altitude bin within the same month.
- **Downward phase progression** (grey dashed line) can be seen clearly each month before dawn, descending from ~150 km to 110 km. An implication of the results is that the driving factors of the pre-dawn TINa layers must have excellent *"year-to-year repeatability"*.
- **Such coherent phase features** indicate that the phase of the main causative agent, likely the semidiurnal tides, is not random but relatively steady from day to day at Boulder within each of the 12 months from Jan through Dec. We term this phenomenon as the *"day-to-day phase coherence"*.
- Such pre-dawn TINa layers appear to be **positively correlated with sunrise time**. Black solid lines in those plots are the sunlit altitudes at sunrise.

TINa Relationship to Tidal Winds



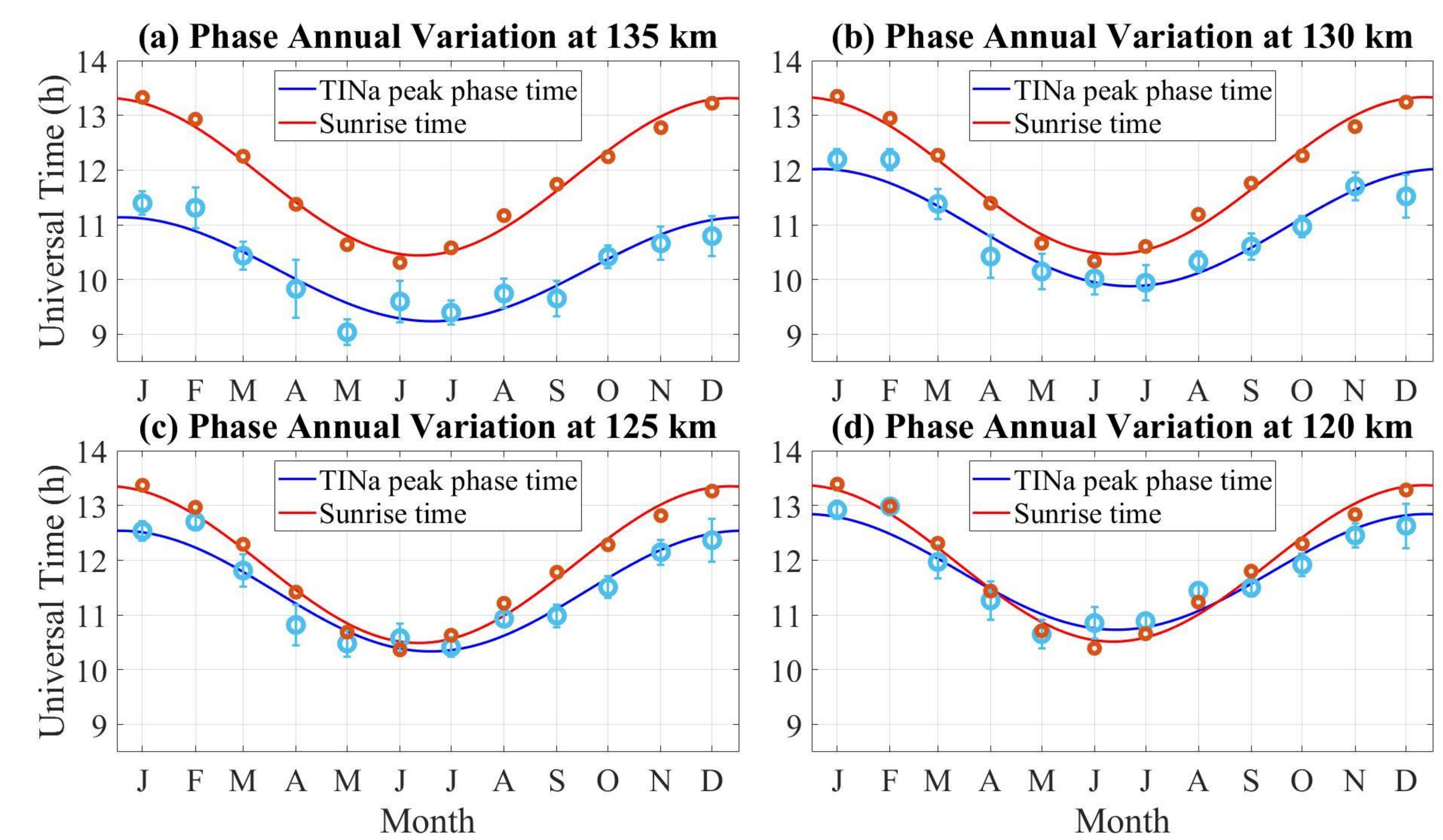
[Chu, Chen, et al., GRL, 2021]

White circles plotted are the TINa peak phase.

Vertical drift velocity calculated with ICON HME tidal winds shows **convergent flow phases** aligned well with Boulder TINa.

- CTMT tidal winds in Jan do not provide consistent phases with the pre-dawn TINa layers; however, the ICON HME tidal winds in Jan are closely lined up with the observed TINa.
- To reconcile these discrepancies, it is necessary to consider other factors like mean horizontal winds, ionospheric electric fields and meteor input fluxes in future model study.

TINa Relationship to Sunrise Time



Conclusions

1. Boulder pre-dawn TINa layers occur in earlier hours in summer than in winter. Such phase annual variations are correlated with sunrise and solar-driven tidal winds. TINa peak phase follows convergent wind shears for ions but divergent shear for neutrals.
2. These TIMt layers are of great scientific interest as they provide unique tracers for making direct measurements in the least understood but crucially important "thermospheric gap" region of 100–200 km.