Localized Neutral Temperature Responses to Magnetosphere-Ionosphere-Thermosphere Coupling — A Mechanism Study of Temperature Inversion Layer

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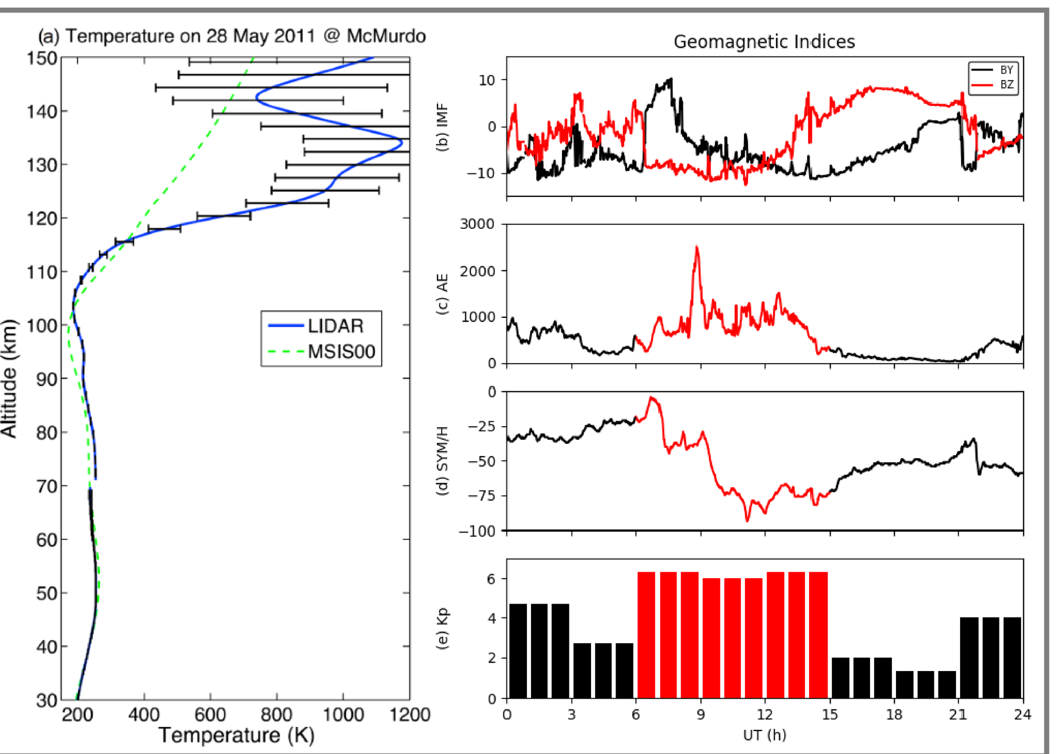
Abstract A large neutral temperature enhancement (~500 K) and neutral temperature inversion layer (NTIL) around 130 km are observed by the Fe Boltzmann lidar at McMurdo (78° S, 166° E), Antarctica, on 28 May 2011. The NTIL has a highly-structured vertical variation and the peak temperature exceeds 1000 K, which suggests strong localized energy deposition. None of empirical models and default physics models capture such observations, and the formation mechanism is unknown. We use TIEGCM driven by AMIE and constrained by various kinds of observations to explore the physical processes leading to NTIL and the underlying MIT coupling processes. The aurora precipitation maps observed by DMSP/SSUSI are incorporated since the empirical auroral model in TIEGCM tends to underestimate both energy flux and mean energy. The electric field variabilities, commonly seen in a parameterized way in TIEGCM, are reconsidered and implemented in a more self-consistent way. Using more realistic auroral maps together with enhanced electric field variabilities, TIEGCM succeeds in reproducing NTIL near 150 km. In particular, the introduction of electric field variabilities significantly enhances localized Joule heating, which results in strong upward motion of the atmosphere. The resultant cooling effect from work is stronger at higher altitude, leading to significant temperature decrease at ~200 km compared with ~150 km, where Joule heating dominates. The analysis of the thermodynamics equation shows that such differential cooling effect is crucial to the formation of the NTIL, while strong Joule heating is the trigger. Our work demonstrates that the variability of electric field could cause significant increase of energy deposition locally with magnetospheric origin that dramatically changes neutral dynamics in the lower thermosphere. The sensitivity of our results to model resolution and gravity waves propagating from the lower atmosphere will be our future work.

1. Motivation

- NTIL is discovered by Chu et al. [2011] during storm time (Kp≈6). Temperature profile shows significant elevation and inversion.
- What is the mechanism generating NTIL and what does it imply in MIT coupling?
- Can general circulation models resolve localized phenomena like NTIL?

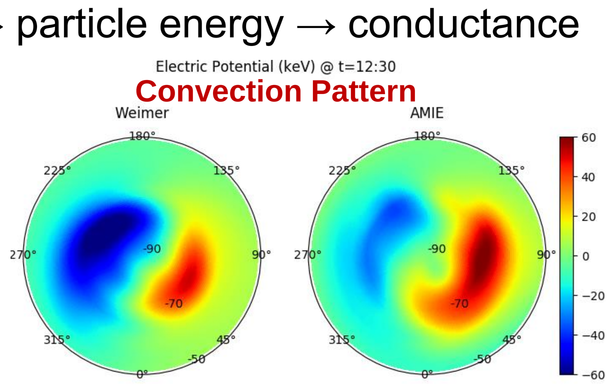


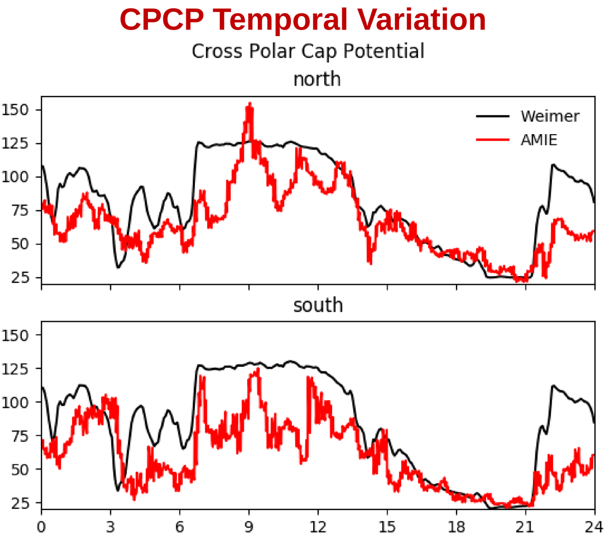
2. Data and Methodology

2.1 TIEGCM (2.5° × 2.5°) with AMIE as High-Latitude Driver

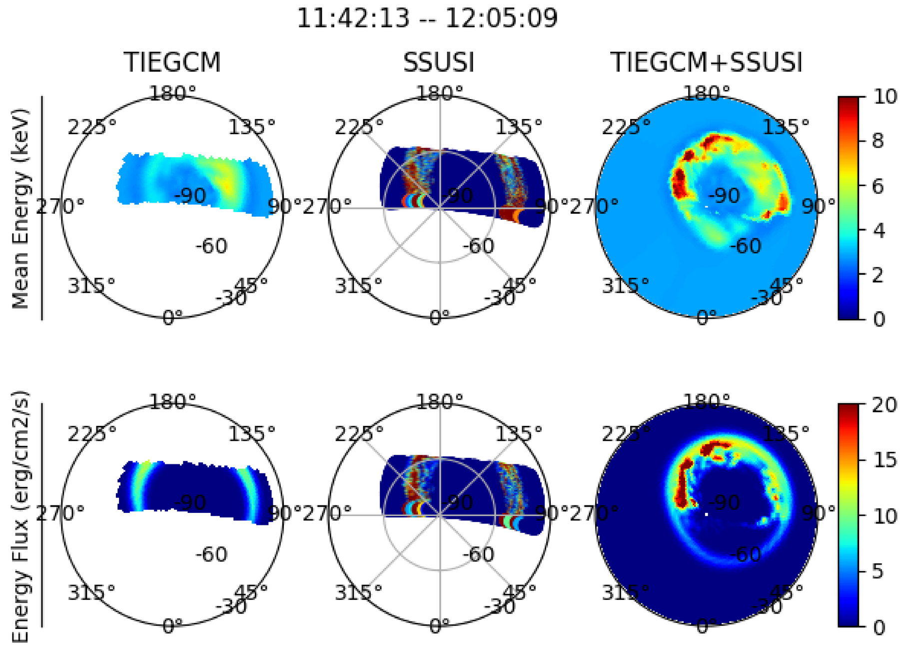
Data Used in AMIE
- SuperMAG → magnetic perturbation
- SuperDARN → ion drift → electric field
- DMSP/SSJ → particle energy → conductance

AMIE shows stronger electric field variabilities temporally and spatially than Weimer.



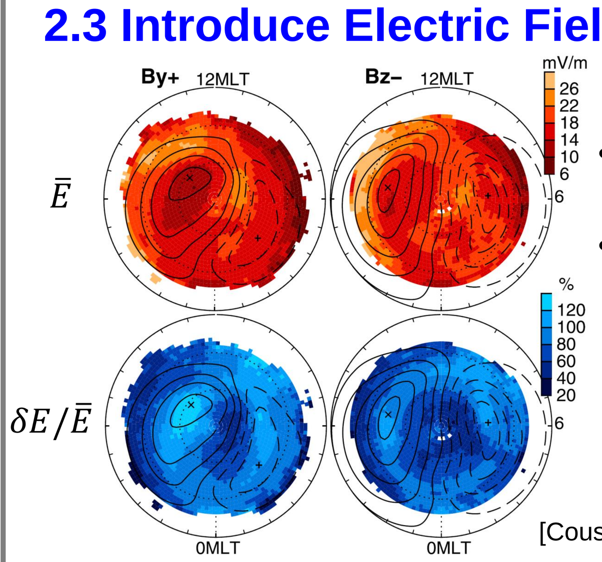


2.2 Incorporate Aurora Observations into TIEGCM



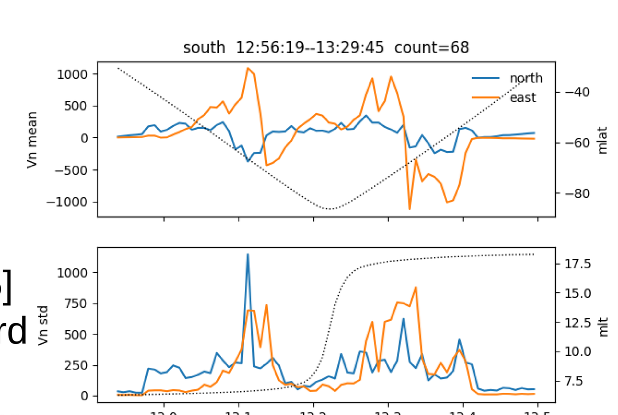
- TIEGCM underestimates aurora precipitation compared to DMSP/SSUSI observations.
- We interpolate SSUSI auroral EDR data in mlat × mlt grids.
- The aurora in TIEGCM is replaced by SSUSI measurements. In case there is no observation, the model aurora is used.
- The modified auroral maps in TIEGCM better capture SSUSI observations.

2.3 Introduce Electric Field Variabilities



- First raised by Codrescu et al. [1995]
- Cousins and Shepherd [2012] shows strong electric variabilities are common at aurora latitudes.

[Cousins and Shepherd, 2012]

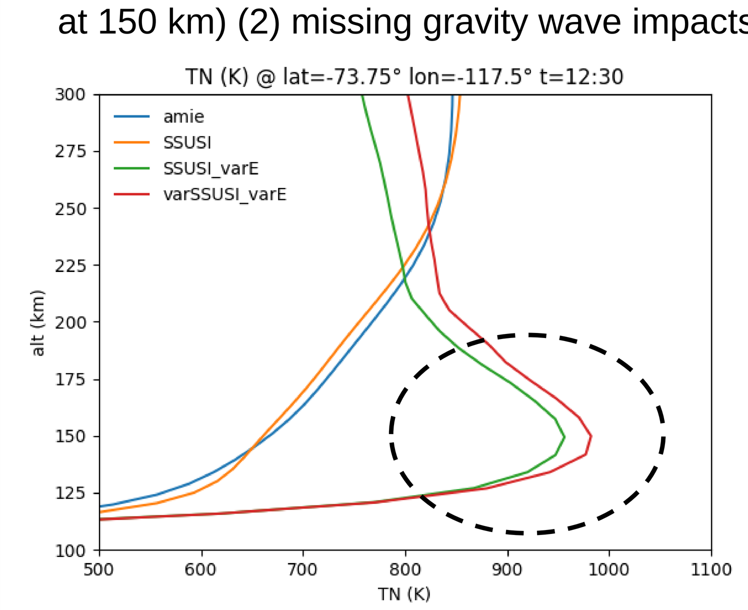


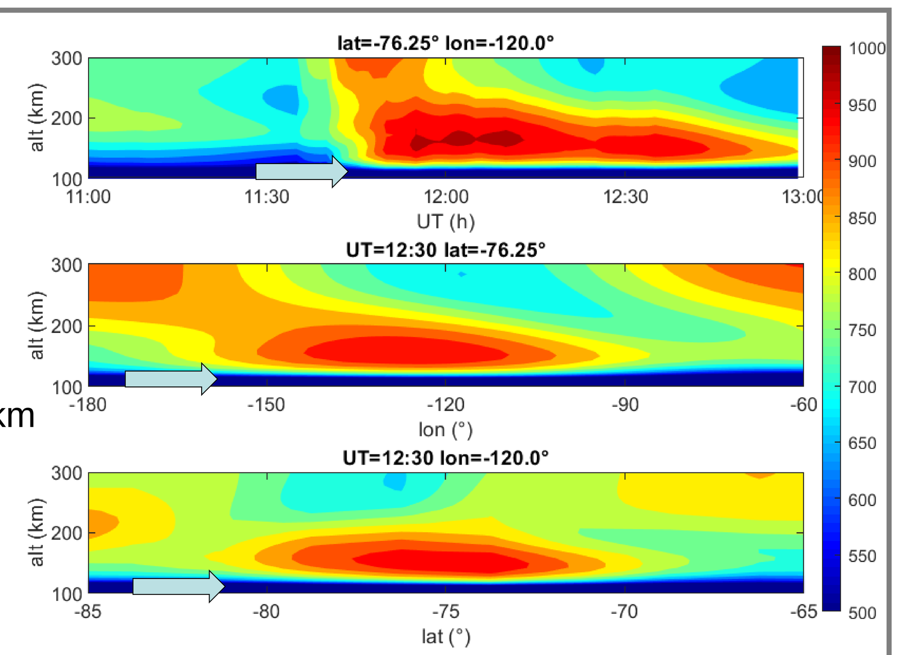
- DMSP/SSIES ion drift measurements also show that electric field is more variable at aurora latitudes.

3. Model Simulations

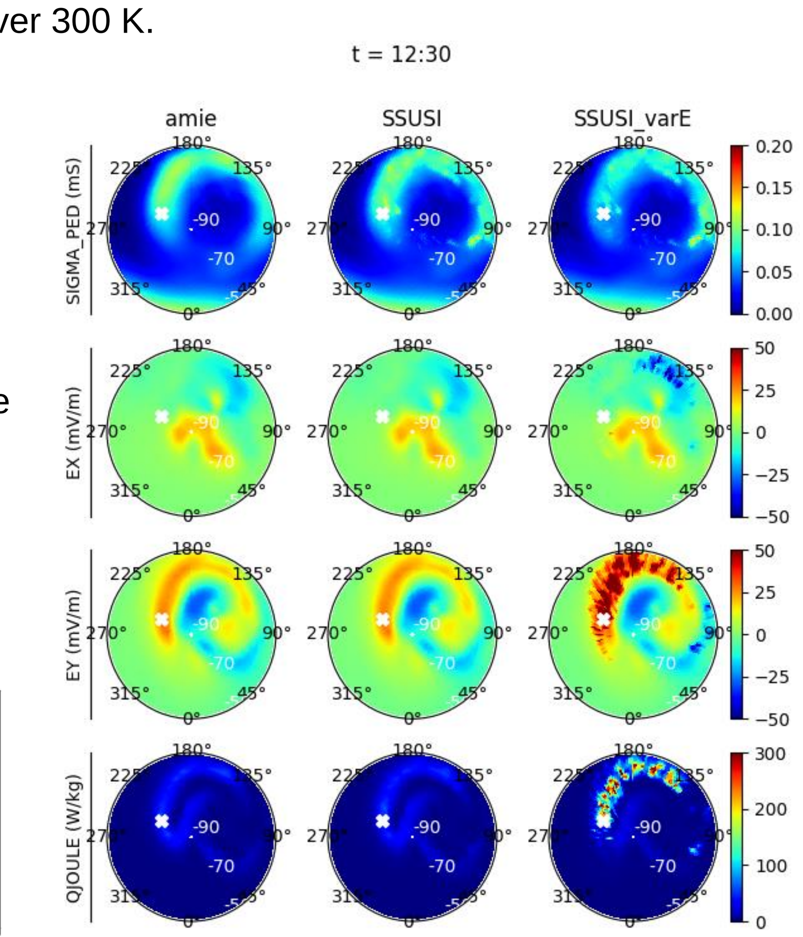
3.1 NTIL in TIEGCM

- Modeled NTIL lasts ~1h. Its spatial span is ~60° in longitude and ~10° in latitude.
- NTIL happens at an altitude range between 140 km and 200 km.
- Possible reasons for the inconsistency: (1) model vertical resolution is too coarse (~10 km at 150 km) (2) missing gravity wave impacts



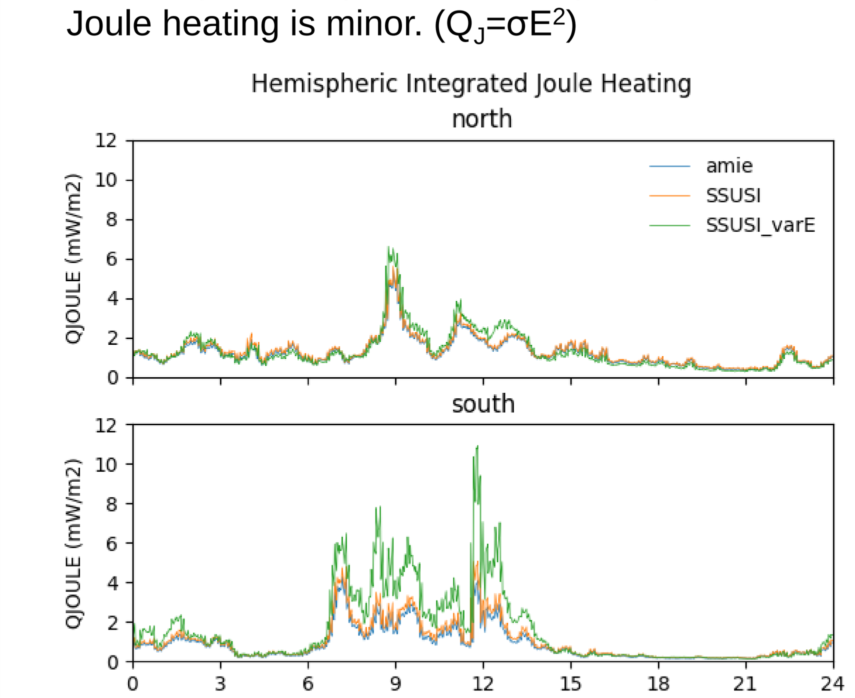


- For TIEGCM-AMIE runs with only modified aurora maps, no NTIL is seen.
- Runs with enhanced E-field variabilities show NTIL and the temperature enhancement at 150 km is over 300 K.



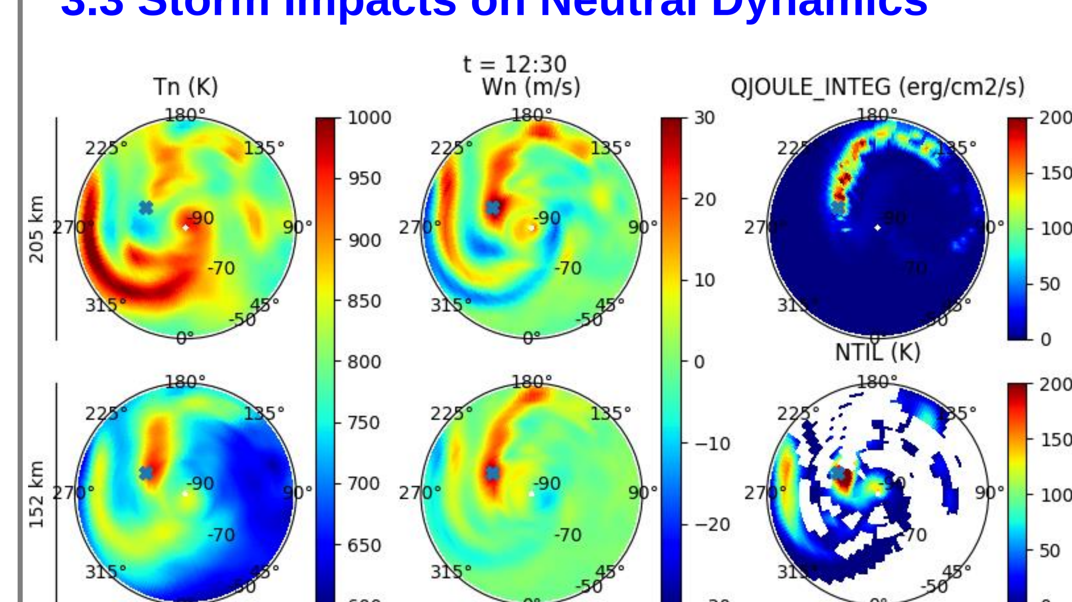
3.2 Energy Budget

- Enhancements in aurora precipitation result in increase of conductivities.
- Electric field is squarely related to Joule heating, so the inclusion of variabilities contribute to Joule heating (JH).
- Joule heating is mostly influenced by E-field variability. The impact of aurora precipitation on Joule heating is minor. ($Q_J = \sigma E^2$)



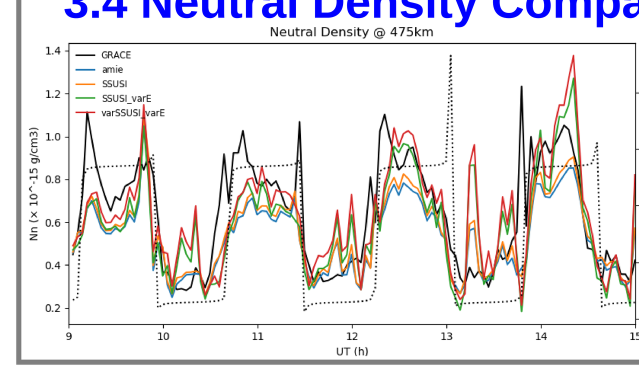
- E-field variability is a major cause in boosting up hemispheric integrated JH budgets.
- Joule heating enhancements are more significant in SH, in agreement with the observational evidence that winter hemisphere shows more E-field variabilities.

3.3 Storm Impacts on Neutral Dynamics



- NTIL is seen when intense Joule heating happens.
- Upward wind is seen at all altitudes below 200 km.
- Temperature response is different at different altitudes. (decrease at 200 km, increase at 150km), which generates NTIL.
- Wave-like horizontal structures suggest gravity wave generation.
- The secondary NTIL might be caused by wave propagation from the primary NTIL.

3.4 Neutral Density Comparison with GRACE



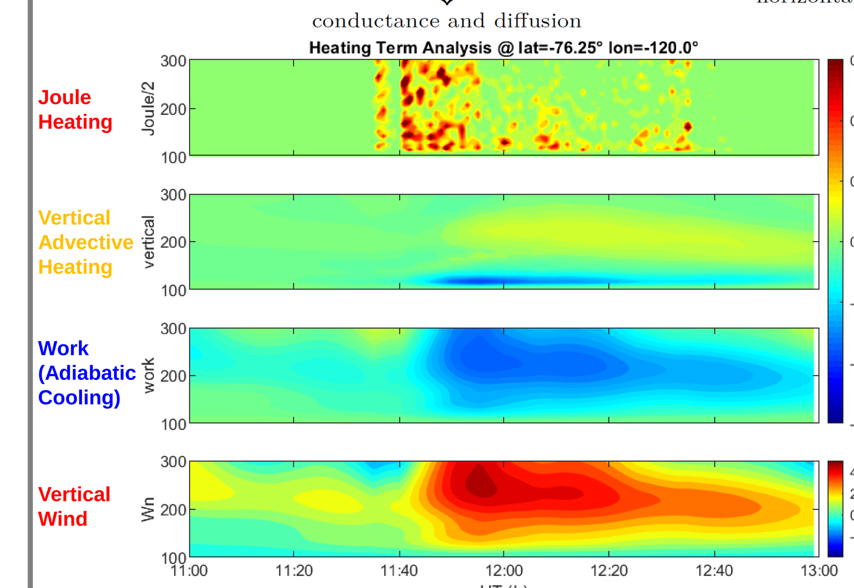
- Different runs generally replicate GRACE neutral density measurements. Runs with enhanced electric variabilities agree better during daytime. However, slightly overestimation can be seen during nighttime.

TIEGCM runs with the observed auroral maps and enhanced electric variabilities reproduce reasonable physics and have an overall good match with observations.

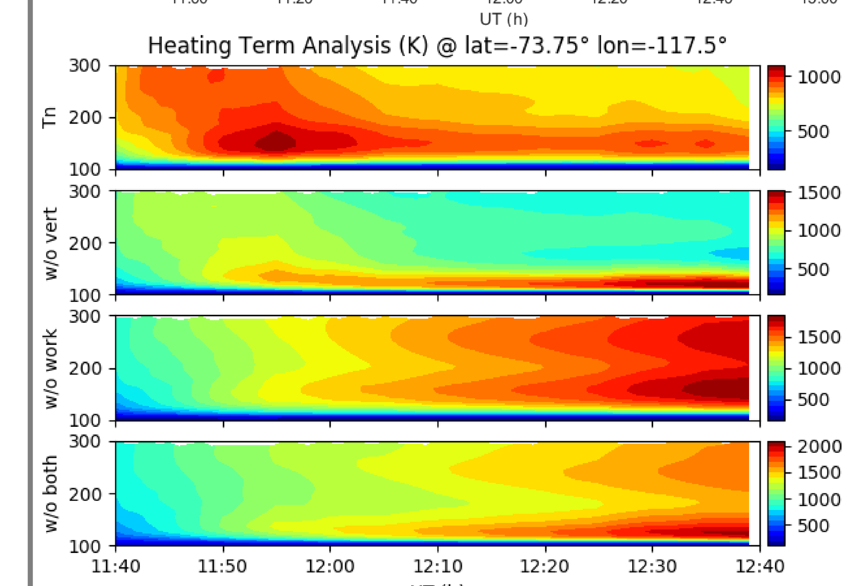
4. Mechanism Study

$$\frac{\partial T_n}{\partial t} = \underbrace{\frac{g e^z}{p_0 c_p}\frac{\partial}{\partial z}\left[\frac{K_T}{H}\frac{\partial T_n}{\partial z} + K_E H^2 c_p \rho\left(\frac{g}{c_p} + \frac{1}{H}\frac{\partial T_n}{\partial z}\right)\right]}_{\text{conductance and diffusion}} \underbrace{- \mathbf{v}_n \cdot \nabla T_n}_{\text{horizontal advection}} \underbrace{- W\left(\frac{\partial T_n}{\partial z} + \frac{R^* T_n}{c_p \bar{m}}\right)}_{\text{adiabatic}} + \underbrace{\frac{Q^{\exp} - e^z L^{\exp}}{c_p} - L^{\exp} T_n}_{\text{diabatic}}$$

Vertical advective heating
work

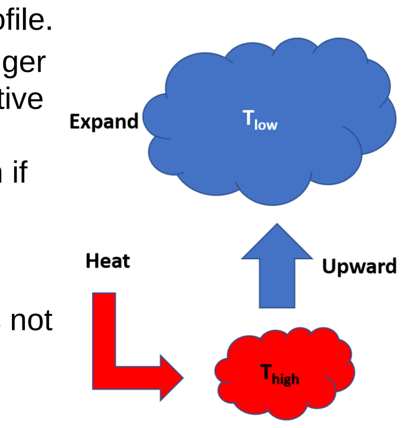


- Vertical profiles of Joule heating, vertical advective heating and work (adiabatic cooling) are much larger than the rest terms.
- Joule heating is intense and doesn't show too much vertical structure.
- Vertical advective heating acts as a cooling term at ~120 km and a minor heating term above 200 km.
- Large vertical wind is seen when NTIL happens, resulting in strong negative work.
- Work shows significant vertical structures from 150 to 300 km and peaks at ~250 km. The strong cooling effect results in temperature decrease at ~200 km.



The effects of individual heating terms are demonstrated by subtracting their time evolutions from the temperature profile.

- NTIL becomes stronger when vertical advective heating is absent.
- NTIL cannot happen if there is no work.
- Joule heating alone (without advective heating and work) is not enough to produce NTIL.



Conclusions

- The enhanced E-field variability results in strong localized Joule heating in the lower E-region, which induces significant upwelling motion and work (adiabatic cooling).
- The adiabatic cooling effects are larger at higher altitudes, while Joule heating effects are more uniform across different altitudes. Their combined effects lead to heating at ~150 km while cooling above. The net result is generating the NTIL.
- The vertical advective heating also plays a nonnegligible role in the heating budget, but it tends to weaken the NTIL.
- The secondary NTIL at lower latitude could be caused by wave propagating outward from the regional heating around the primary NTIL region.
- The remaining underestimation of the sharpness associated with NTIL will be studied using a higher vertical resolution TIEGCM and incorporating gravity waves.

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