Elucidating the Role that Diabatic and Adiabatic Effects Play in Anomalous Thermospheric Features

Austin Coleman[1,2], Jeffrey P. Thayer[1,2], Anton Buynovsky[2,3]

[1]CU Boulder/Aerospace Engineering Sciences, [2]CU Boulder/SWxTREC, [3]BAE Systems Space & Mission Systems Inc.

Acknowledgments: Support was provided by CU Boulder. *Corresponding Author:* Austin.Coleman@colorado.edu

Motivation

- Low-Earth Orbit (LEO) is a coveted region of space and coincides with the thermosphere, which even during quiet times is characterized by mass density corrugations.
- The thermosphere is also home to anomalous features which are not properly reproduced in models such as the National Center for Atmospheric Research's Thermosphere, Ionosphere, Electrodynamics General Circulation Model (NCAR-TIEGCM).
- Current efforts focus on diabatic forcing to reproduce anomalies, such as the mass-density cusp enhancement, and fall short; adiabatic effects are often overlooked.
- Rewriting the Continuity Equation and First Law of Thermodynamics provide clear separations of the diabatic and adiabatic effects influencing the mass density and energy of the upper thermosphere.
- This separation of the role that (a)diabatic effects play in the upper thermosphere, and the underlying physics driving the behavior, can give researchers the necessary insight to advance the state of current GCMs.

Theory

- A natural starting place to isolate adiabatic and diabatic effects from one another are "potential" quantities.
  - "Potential" quantities are theoretical quantities that capture the change of a property an air parcel would experience after undergoing an isentropic/adiabatic process.
- Thus, tracking the rate of change of potential quantities enables tracking whether a diabatic process has occurred or not – the starting point is Poisson's equation:

$$C = PV^{\frac{R}{c_P}},$$

where C=constant, P=pressure, V=specific volume, R=specific gas constant, and c_P=specific heat at constant pressure.

- From here both potential density and potential temperature can be derived:

$$\rho_\theta = \rho\left(\frac{P_\theta}{P}\right)^{\frac{c_V}{c_P}} \qquad \theta = T\left(\frac{P_\theta}{P}\right)^{\frac{R}{c_P}},$$

where ρ_θ | θ=potential density | temperature, P_θ=reference pressure, ρ=mass density, T=temperature, c_V=specific heat at constant volume.

- Taking the desired time derivatives, forms of the Continuity Equation and First Law of Thermodynamics are derived that are expressed in terms of potential density and temperature, respectively:

$$\frac{1}{\rho}\frac{D\rho}{Dt} = \frac{1}{\rho_\theta}\frac{D\rho_\theta}{Dt} + \frac{c_V}{RT}\dot{Q}_{adb}\left(= -\nabla\cdot\vec{U}\right) \qquad \frac{DT}{Dt} = \left(\frac{P}{P_\theta}\right)^{\frac{R}{c_P}}\frac{D\theta}{Dt} + \dot{Q}_{adb}.$$

- These forms allow isolating (1) the diabatic forcing contributions, $\frac{D\rho_\theta}{Dt}$ | $\frac{D\theta}{Dt}$, and (2) adiabatic forcing contributions, $\dot{Q}_{adb} = \frac{1}{\rho c_P}\frac{DP}{Dt}$.

Investigating Diabatic and Adiabatic Contributions in the Cusp Area

- The physics of GCMs, such as NCAR-TIEGCM, fall short when it comes to properly reproducing the cusp enhancement (Zhang et al., 2015).
- Direct effects, such as Joule heating or soft electron precipitation do not provide sufficient density change, leaving the models' density magnitude in the cusp region significantly lower than satellite measurements obtained by CHAMP.
- However, NCAR-TIEGCM V3.0 simulations produce a sustained enhancement in mass density during storm time conditions (Kp = 4) relative to quiet time conditions (Kp = 1) within the cusp region.

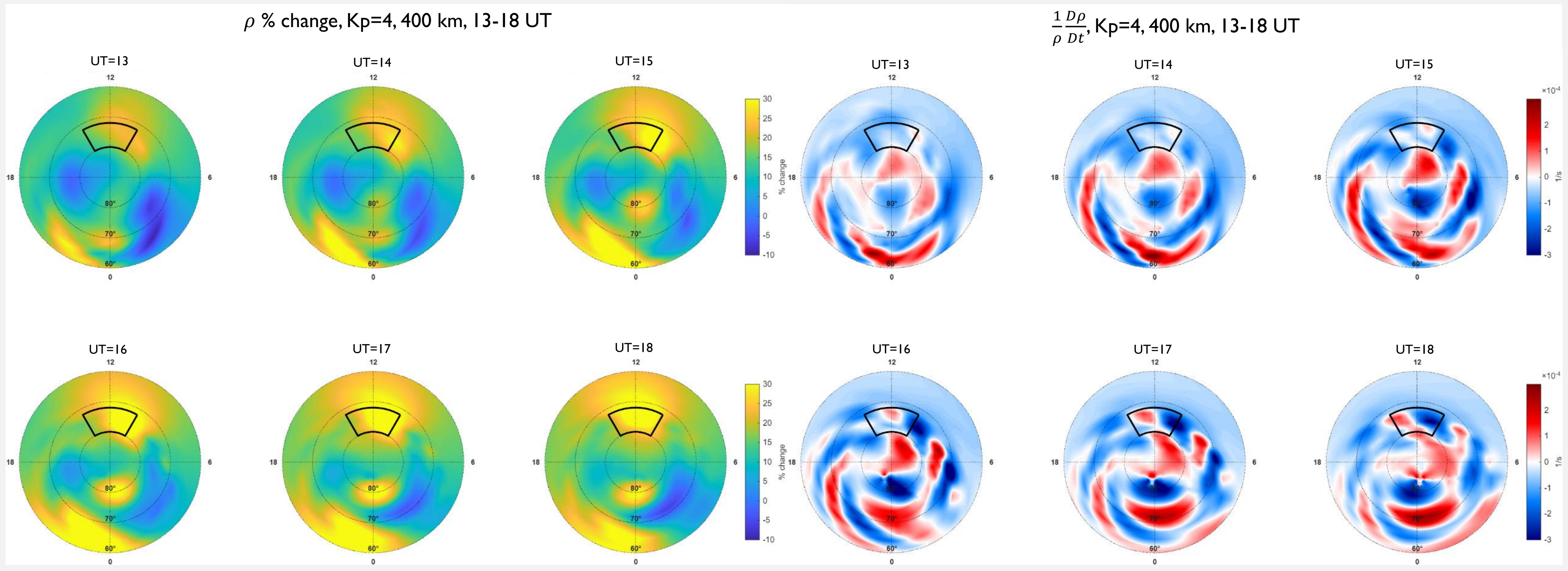

Figure 1. TIEGCM V3.0 simulation results showing the neutral density percent change, relative to quiet time conditions (Kp = 1) during storm conditions (Kp = 4, f10.7=150 sfu start at UT=0) from 13 to 18 UT, at 400 km. The corresponding relative density rate of change plots are included. All plots are in geomagnetic coordinates.

- The density response lags the corresponding rate of change by ~2 hours – a property change is in response to the time integration of a sustained rate of change.
- The rewritten Continuity Equation allows separating the adiabatic and diabatic contributions to elucidate the role that each play in producing the mass density response by TIEGCM.

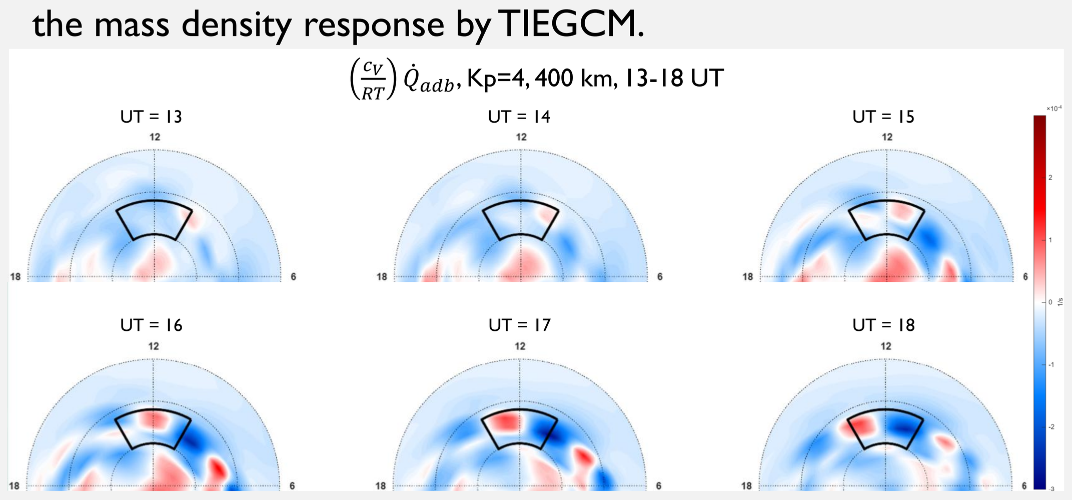

Figure 2. Plots showing the adiabatic contribution to the relative density rate of change from 13 to 18 UT, at 400 km (Kp = 4, f10.7 = 150 sfu). All plots are in geomagnetic coordinates.

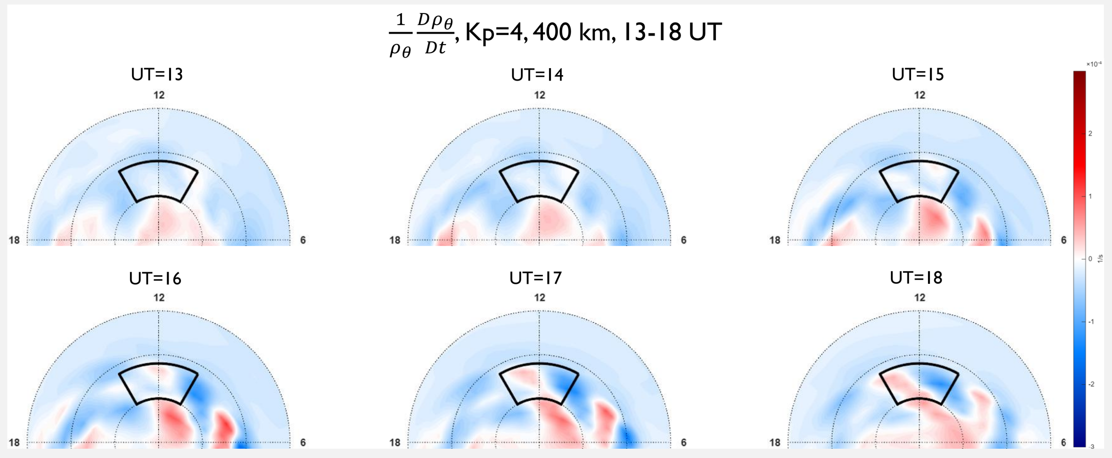

Figure 3. Plots showing the diabatic contribution to the relative density rate of change from 13 to 18 UT, at 400 km (Kp = 4, f10.7 = 150 sfu). All plots are in geomagnetic coordinates.

- Clearly, the structure of the net relative density rate of change in the cusp region is largely determined by adiabatic effects and produces a 30%+ increase in mass density, relative to quiet conditions.
- Thus, this time frame provides a perfect case study for how adiabatic effects can produce a significant response in mass density in the cusp region, and gives insight into the physics responsible for such effects.

Physics Behind Diabatic and Adiabatic Mass Density Effects

- Recalling the definition of adiabatic heating/cooling and utilizing coordinate frame relationships (Thayer and Coleman 2026):

$$\dot{Q}_{adb} = \frac{1}{\rho c_P}\frac{DP}{Dt} = \frac{-g}{c_P}w_D,$$

both adiabatic mass density and energy changes can be directly tied to vertical motions – captured by the terms $\frac{DP}{Dt}$ and w_D.

  - w_D is the "divergent" vertical motion in units of $\frac{m}{s}$, and is the portion of the total wind $w = \frac{Dz}{Dt}\left[\frac{m}{s}\right]$ that crosses pressure surfaces and induces adiabatic expansion/compression.
- As the air parcel travels vertically and traverses pressure surfaces, the parcel equilibrates with its surroundings and expands/compresses as a result of the new pressure environment.
  - The expansion/compression causes the air parcel to cool/heat and the mass density to decrease/increase.
- This vertical motion that crosses pressure surfaces is anti-correlated in sign to the corresponding adiabatic mass density effect: upward/downward vertical motion causes decrease/increase in density.
- To elucidate the underlying physics at play behind the diabatic term, it is separately derived using the ideal gas law:

$$\frac{1}{\rho_\theta}\frac{D\rho_\theta}{Dt} = \frac{P_\theta}{\rho_\theta R^*\theta}\left(\frac{D\overline{m}}{Dt} - \frac{\overline{m}}{\theta}\frac{D\theta}{Dt}\right),$$

where R^*=universal gas constant, and $\overline{m}$=mass mixing ratio.

- Diabatic effects that cause an increase/decrease in mass density are (1) the mass mixing of air parcels and (2) the loss/gain of energy due to heat transfer.
  - Energy loss causes volumetric change, and for a fixed mass, density responds accordingly.

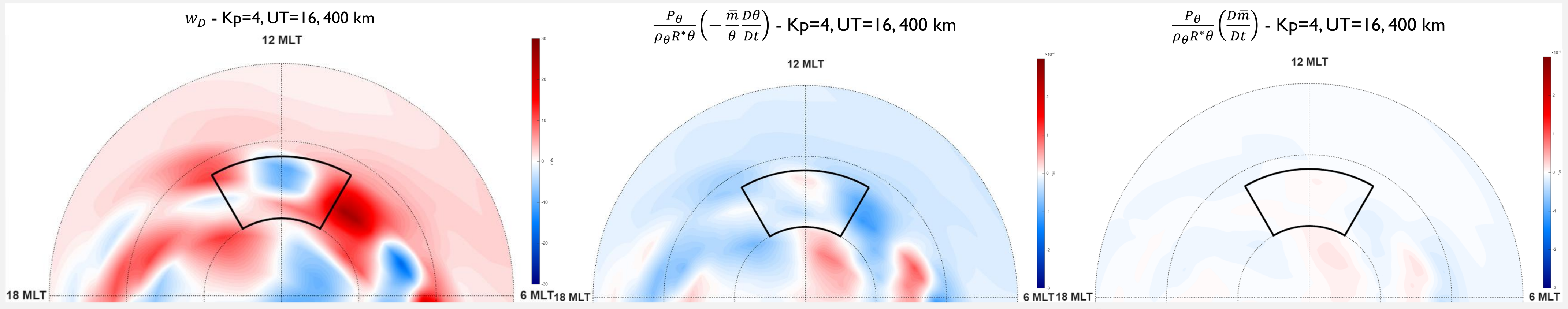

Figure 4. Plots showing w_D, and the energy and mixing contributions of the diabatic mass continuity term at 16 UT (Kp = 4, f10.7 = 150 sfu) @ 400 km. All plots are in geomagnetic coordinates.

- This can be better envisioned by considering an air parcel as either a closed or open control volume.
- Closed systems represent an isobaric, diabatic process taking place; open systems include the physics of an adiabatic process and mass mixing.

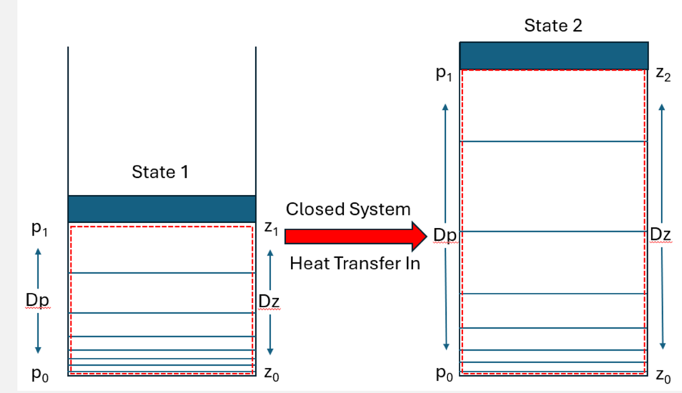

Figure 5. Depiction of a closed system, heat transfer process.

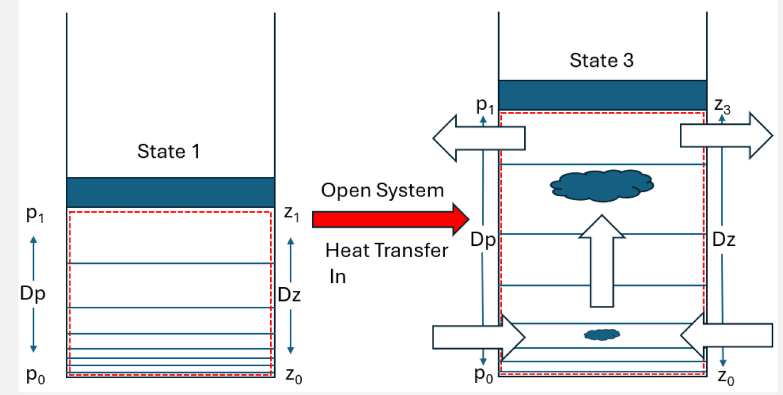

Figure 6. Depiction of an open system undergoing a heat transfer + mass mixing process.

Conclusion/Interpretation/Next Steps

- Potential quantities, specifically potential density and temperature, enable a unique form the of Continuity Equation and First Law to be derived – separating the diabatic and adiabatic effects within those equations.
- Adiabatic processes are shown to dominate in producing a large mass density response in the cusp region, relative to quiet conditions, within the NCAR-TIEGCM.
- This suggests the uncaptured physics within the NCAR-TIEGCM may fall under the regime of mechanical/indirect effects as opposed to direct diabatic effects and should be the focus of future model studies intending to recreate the cusp anomaly within the NCAR-TIEGCM.
- Lastly, future missions such as Geospace Dynamics Constellation (GDC) can provide the observations necessary to validate such studies. Akbari et al., 2024 provides the framework to compute the necessary 4D gradients. However, the degeneration of the constellation during pole crossings poses a potential difficulty in accurately computing the gradients and must be addressed.

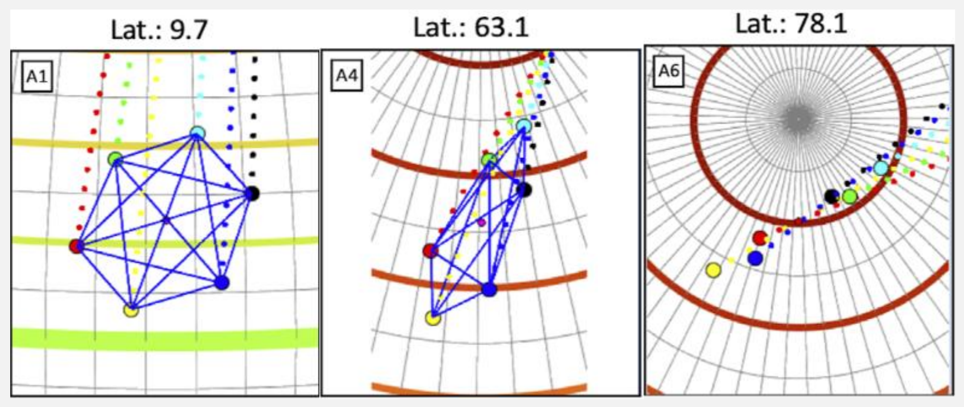

Figure 7: Plots from Akbari et al., 2024 showing satellite configuration degenerate during pole crossings.

References

1. Zhang, B., R. H. Varney, W. Lotko, O. J. Brambles, W. Wang, J. Lei, M. Wiltberger, and J. G. Lyon (2015), Pathways of F region thermospheric mass density enhancement via soft electron precipitation, J. Geophys. Res. Space Physics, 120, 5824–5831, doi:10.1002/2015JA020999.
2. Thayer JP and Coleman A (2026) Resolving thermospheric vertical wind ambiguities and energy processes. Front. Astron. Space Sci. 13:1692425. doi: 10.3389/fspas.2026.1692425
3. Akbari H, Rowland D, Coleman A, Buynovskiy A and Thayer J (2024) Gradient calculation techniques for multi-point ionosphere/thermosphere measurements from GDC. Front. Astron. Space Sci. 11:1231840. doi: 10.3389/fspas.2024.1231840