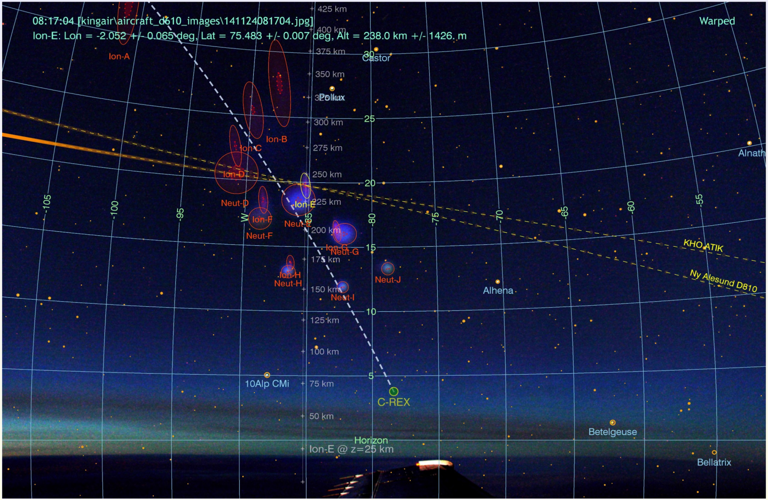
Do Transient Electrodynamic Processes Support Enhanced Neutral Mass Densities in Earth's Cusp-Region Thermosphere via Divergent Upward Winds?



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Scientific Problem: A Thermospheric Density Anomaly

Science Question: *Where are the signatures of processes supporting the observed enhancements of thermospheric neutral mass density at around 400 km altitude near the geomagnetic cusps?*

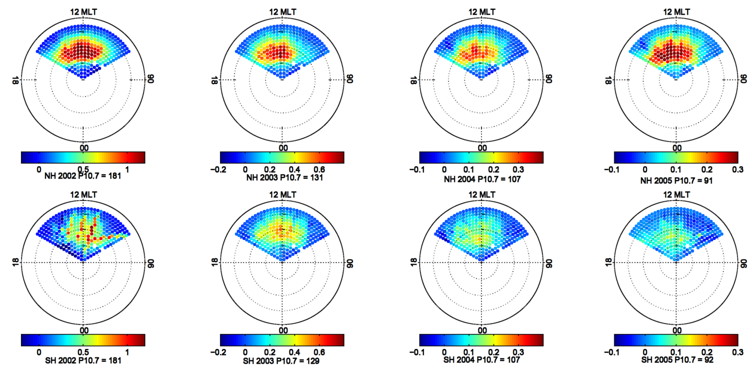


Figure: Neutral mass density measurements from the CHAMP satellite for years 2002 to 2005. The top row is for the northern hemisphere, whereas the bottom row is for the southern hemisphere. **The density anomaly corresponds to the red regions.**

Hydrostatic Equilibrium

- Regardless of how the extra mass gets into this region, once there *it must be supported against gravity*.

- By far the largest terms in the atmosphere's equation of momentum conservation are those due to gravity $\vec{\mathbf{g}}$ and the vertical component of the pressure gradient ∇p.

- Despite being large, these two terms have little impact on dynamics because they exist in balance and *cancel each other out*, in a condition known as "*hydrostatic equilibrium*."

- If we denote the pressure and density in the "background" geographic region surrounding the density anomaly as p_0 and ρ_0 respectively, then hydrostatic equilibrium requires that the vertical component of the pressure gradient ∇p_0 must satisfy

$$\frac{\partial p_0}{\partial z} = -\rho_0 g$$

How is the Density Enhancement Supported?

- Within the anomaly region mass density is enhanced by some increment, ε say, so that the density there is $(1+\varepsilon)\rho_0$.

- *If no other terms in the momentum equation were changed*, vertical forces would be unbalanced, and *the enhanced mass would experience a downward acceleration of εg*. It would fall.

- Clearly this does not happen, which means the density enhancement must be accompanied by corresponding local *changes to one or more of the other terms* in the momentum equation:

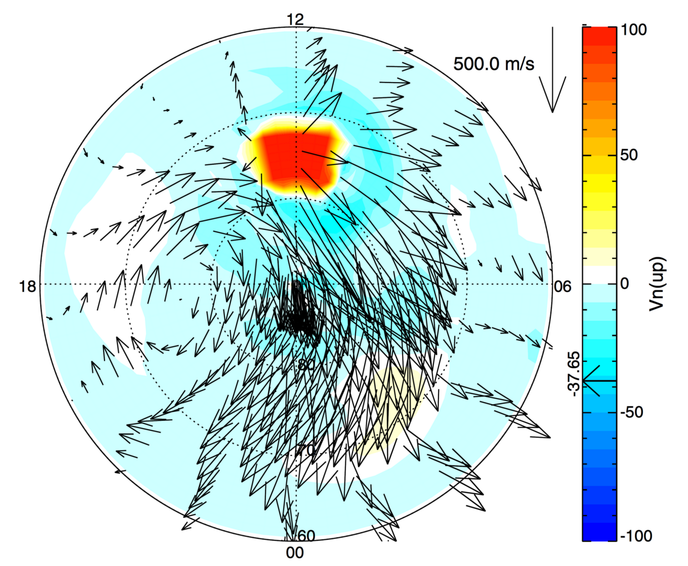
$$\frac{\partial \overrightarrow{\mathbf{u}}}{\partial t} = -\left(\overrightarrow{\mathbf{u}} \cdot \nabla\right) \overrightarrow{\mathbf{u}} - \frac{1}{\rho}\nabla p + \overrightarrow{\mathbf{g}} + \frac{\mu}{\rho}\nabla^2 \overrightarrow{\mathbf{u}} + \overline{v}_{ni}\left(\overrightarrow{\mathbf{v}}_i - \overrightarrow{\mathbf{u}}\right) - 2\overrightarrow{\Omega} \times \overrightarrow{\mathbf{u}} + \Omega^2 \overrightarrow{\mathbf{R}}$$

- Examination of this equation and its consequences shows that *balancing the weight of the enhanced mass requires local perturbations in either the winds or in vertical ion-drag.* The required amplitudes of the perturbations would make them easily observable.

- The purpose of this talk is to examine several sources of observational data to search for signatures of these effects.

Modeling Studies

Various plausible support mechanisms have been studied using models.



- Published models verify the expectation of large vertical winds and strongly divergent horizontal winds near the density anomaly.
- For example, these signatures are easily seen in this figure from a study by *Deng et al.* [2013].

Perturbations in FAC, Ion Drifts and Electron Temperature

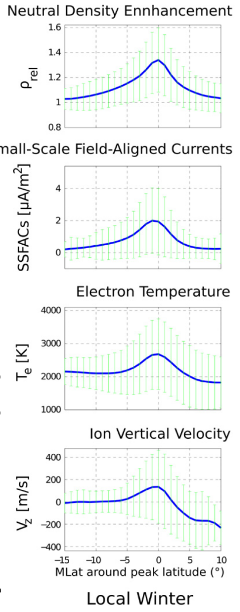


Fig 6 from Kervalishvili & Luhr [2013]

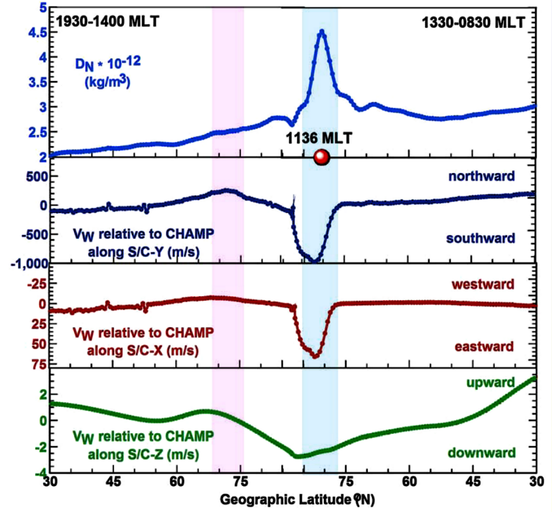
- *Kervalishvili and Lühr* [2013] showed enhancements in climatological averages of CHAMP small-scale FAC, CHAMP electron temperatures, and DMSP upward ion drifts[a] that all correlated with the density enhancements sufficiently well for causal links to be plausible. But the magnitudes of these enhancements are too small (by an order of magnitude) to provide support for the enhanced mass.
- *Kervalishvili and Lühr* [2014] also found perturbations in zonal wind and large-scale field-aligned currents that occur in the vicinity of the density anomalies. But their climatological dependence on IMF B_y did not match that of the density anomalies, suggesting a limited role for these quantities in supporting the enhanced mass density.

[a] Enhanced upward ion drifts reported by *Kervalishvili and Lühr* were broadly similar to the results that we show here, based on DE2 data.

Wind Effects?

Very recently, Horvath & Lovell [2017] presented CHAMP neutral density spikes coincident with *very large spikes* in along-track winds calculated from triaxial accelerometer data.

Figure 7b from Horvath & Lovell JGR Space Physics, 122:4600–4616, 2017



- But *calculating along-track winds this way is subject to large uncertainty.* Unless these meridional wind perturbations can be validated by other independent means, it seems unlikely that they are realistic.
- Plausible ion upflows of around $500\,\mathrm{m\,s^{-1}}$ were also seen by DMSP satellites near the anomalies. However, these are insufficient (by a factor of ~ 4) to support the mass.

Data Sources Used Here

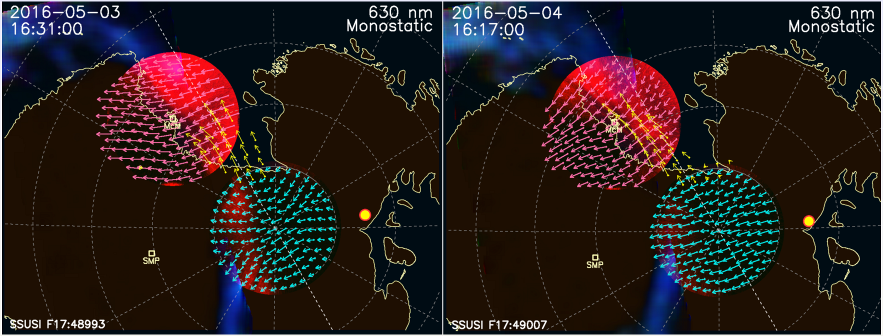
So CHAMP and DMSP data *hint* at other perturbations that may be signatures of mechanisms supporting the density anomalies. But they do not yet show anything large enough to balance the extra mass.

To further this search for signatures of the support mechanisms, we have looked at three additional sources of observational data available to us:

1. Cusp region wind and temperature measurements from two new all-sky Fabry-Perot spectrometers operating at McMurdo & South Pole stations in Antarctica. These instruments are located at site where the thermospheric footprint of the southern geomagnetic cusp passes through their fields of view each day.
2. In-situ thermospheric data from the 1981-1983 DE-2 satellite mission.
3. Wind and ion drift results from the 2014 C-REX-1 rocket mission.

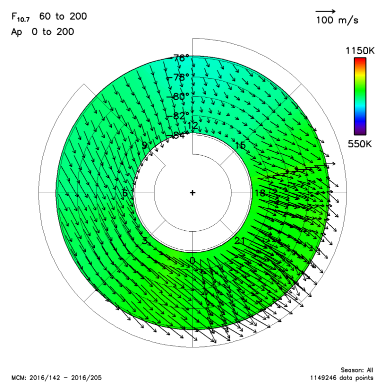
We start by looking at data from the Fabry-Perot instruments, which are indicative of conditions at $\sim$240 km altitude, or roughly two scale heights *below* where the density anomaly is commonly seen.

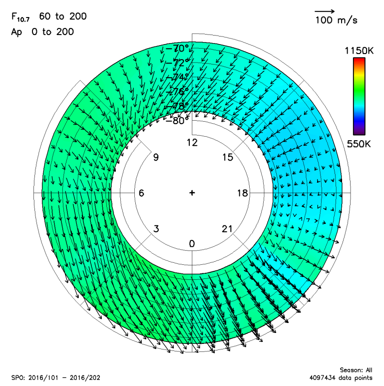
Start from Below



- These panels show red-line FPI winds observed from McMurdo (red) and South Pole (blue.) Two successive days are shown, for local magnetic times when the cusp was passing over South Pole.
- The auroral oval is apparent in a mosaic of FPI and SSUSI F17 image data.
- Yellow arrows depict ion convection velocities measured by SuperDARN.
- *Note the lack of large divergences or other local wind perturbations.*

Climatological Averages of FPI Winds and Temperatures





- The previous figure showed examples of two instantaneous wind field measurements at times when the cusp was passing over South Pole.
- We can also look at climatologically averaged FPI wind and temperature fields for our observing height of 240 km.
- As before, the climatological averages show *no indication of cusp-related local perturbations at 240 km altitude.*

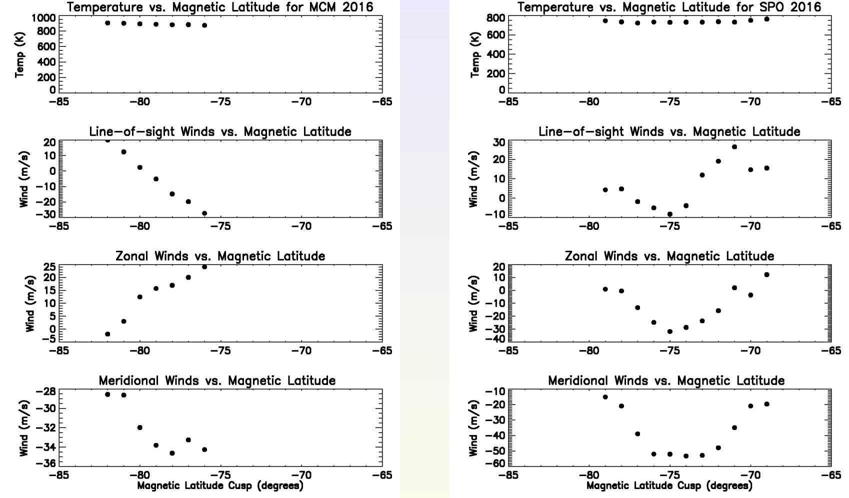
Meridional Cuts Through the FPI Cusp Data

- The climatological averages were based on *automated computer filtering* to eliminate effects of cloud or poor instrumental performance.

- In order to search more carefully and quantitatively for cusp-related wind or temperature signatures, undergraduate research assistant Riley Troyer performed a far more careful and thorough analysis in which he:

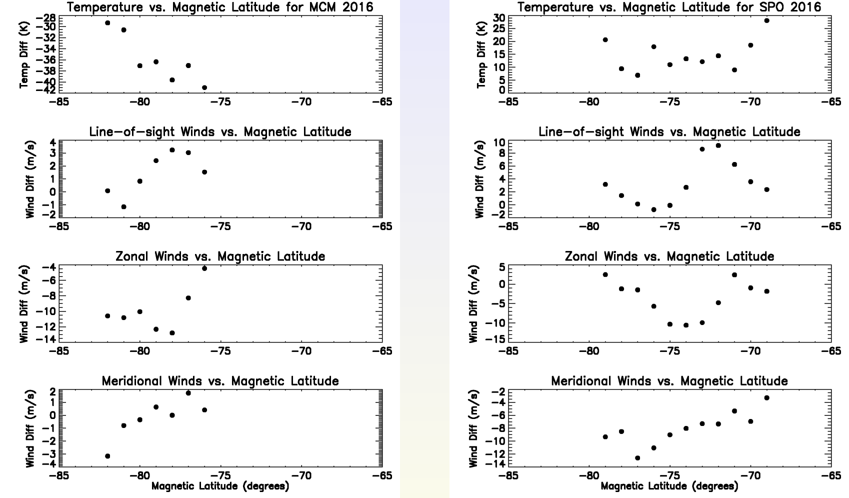
  - Manually inspected all available days of data to select periods of clear skies, good signal levels, and stable instrumental performance.
  - Compiled climatological averages of these selected data.
  - Plotted meridional cuts through the data (similar to those shown earlier from *Kervalishvili and Lühr* [2014]).
  - These profiles were generated both as simple cuts through the cusp latitude region at noon local time, and also as cuts through these data differenced with corresponding measurements from before and after local noon.

Simple Meridional Cuts Through the FPI Cusp Data



These plots show simple cuts through averaged cusp-time wind and temperature data from McMurdo (left) and South Pole (right) for manually selected good data from the 2016 austral winter observing season.

Meridional Difference Cuts Through the FPI Cusp Data

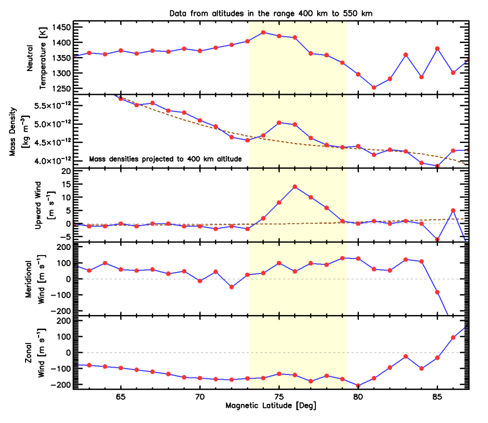


These plots show cuts through wind and temperature difference between cusp times and two hours either side of then, for data from McMurdo (left) and South Pole (right) during the 2016 austral winter observing season. Overall, *there is no evidence of large cusp-region perturbations in any of these quantities at 240 km altitude.*

Dynamics Explorer-2 Data

- No signature of the density anomalies was discernible at 240 km altitude.
- To search for signatures of the required support mechanisms at higher altitudes, undergraduate research assistant Dillon Gillespie used the entire "unified abstract" database of Dynamics-2 measurements to assemble climatological averages of winds, temperatures, densities, and ion drifts measured in situ by the spacecraft.
- These data were compiled at 16-second cadence and so do not represent the highest sample rate available from all instruments. Nevertheless, this rate is adequate and convenient for climatological averaging.
- The spacecraft orbit was not circular; it spanned a range of heights. Results shown here are for data taken from between 400 km and 550 km altitude.
- Even so, atmospheric densities vary substantially over this height range. Mass densities shown here were projected by Dillon to 400 km altitude using a scale height calculated for each measurement from the observed temperature, together with number densities of O and N_2.
- DE2 data were taken between 1981 and 1983, and are heavily biased toward solar maximum conditions.

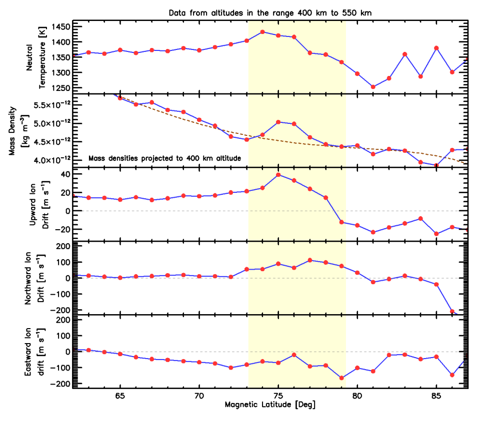
Dynamics Explorer-2 Wind Data



- These data show meridional cuts through climatologically averaged data from between 10.4 and 13.6 hours magnetic local time. Yellow shading indicates latitudes where the density anomaly is seen.
- Parameters shown are, from top to bottom: neutral temperature, projected mass density, zero-mean upward neutral wind, meridional neutral wind, and zonal neutral wind.
- Dashed brown curves show notional background profiles for upward wind and mass density.

- The second panel shows that, like CHAMP, *DE-2 did see a cusp-region density enhancement*, albeit less pronounced than in the CHAMP data.
- There was also *an associated enhancement in vertical wind*, and (weakly) in temperature. There were no obvious signatures in horizontal winds.

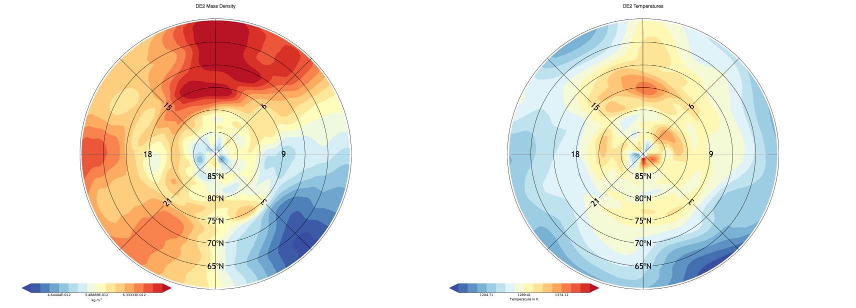
Dynamics Explorer-2 Ion Drift Data



- These data are in the same format as the previous figure, but now the bottom three panels show vertical, meridional, and zonal ion drift data respectively.
- A weak cusp signature appears in the upward ion drift data.
- There is no obvious cusp signature in the horizontal ion drifts.

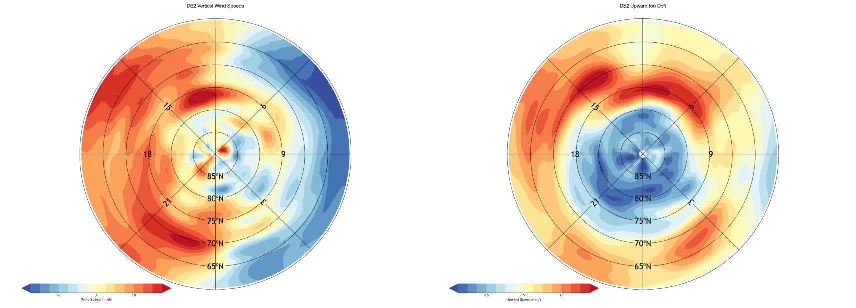
- *Data from altitudes below 400 km did not show these cusp-related signatures*, which is consistent with the FPI data shown here and also with previous studies using different spacecraft [e.g. Streak data shown by *Clemmons et al.* [2009].)

Dynamics Explorer-2 Mapped Data



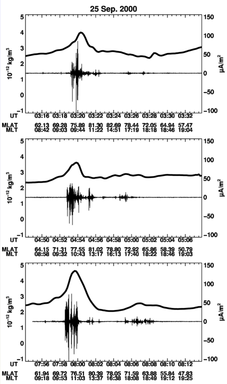
- These data show the northern hemisphere DE-2 data from 400 km to 550 km altitude compiled from throughout the whole mission, binned by magnetic latitude and magnetic local time.
- *DE-2 data confirm the enhancement of mass density near the cusp* (left panel), albeit less strongly than the enhancement seen by CHAMP.
- The right panel shows that this was accompanied by a small increase in neutral temperature.

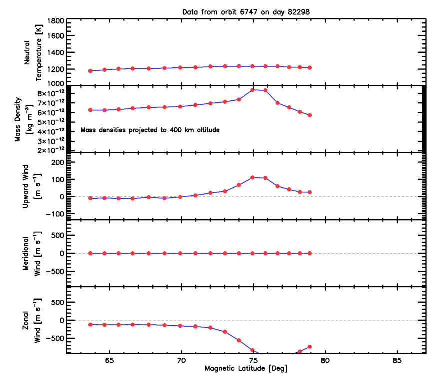
Dynamics Explorer-2 Mapped Data



- These two panels show DE-2 data for upward wind (left) and upward ion drift (right), again for data from 400km to 550 km altitude.
- *Both fields show upwelling near the cusp.*
- However "back of the envelope" calculations suggest neither perturbation is strong enough to fully support the mass density enhancement seen by CHAMP. (The density enhancement seen by DE-2 was only about $\frac{1}{3}$ as strong as that seen by CHAMP. The features seen here might come within a factor of ~ 2 of explaining the DE-2 enhancement.)

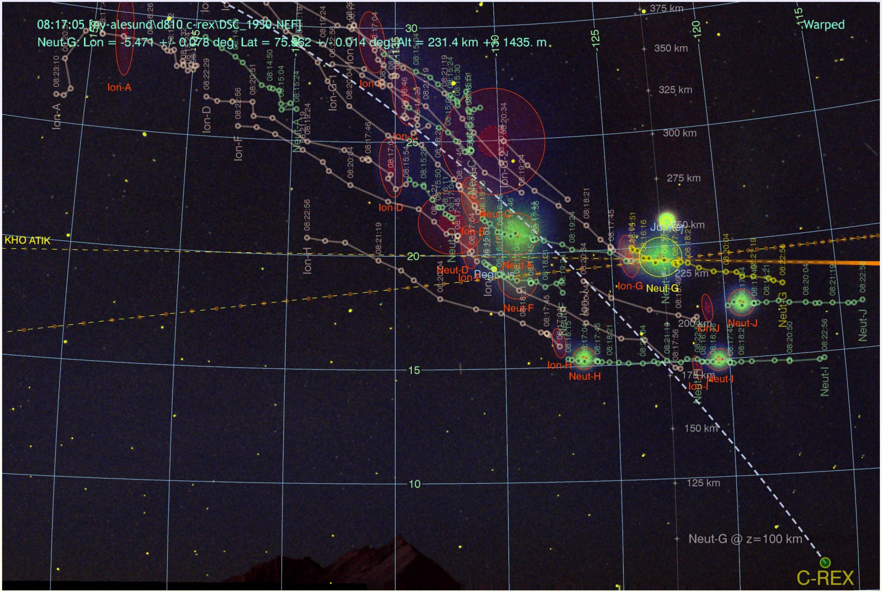
Individual Dynamics Explorer-2 Orbits





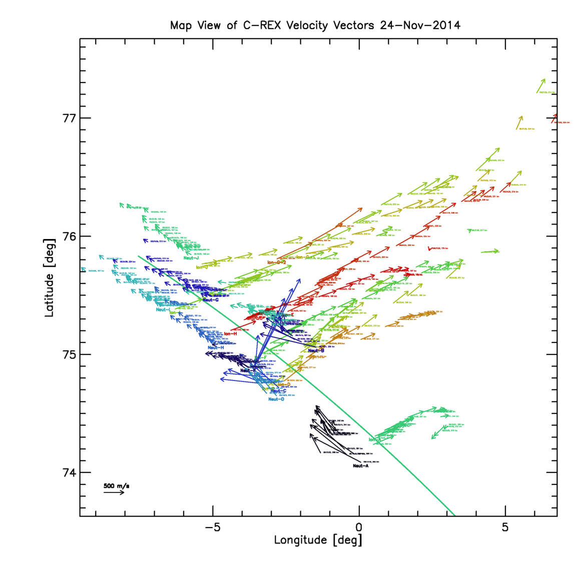
- An obvious possibility is that intense ion & neutral upwelling does occur, but only in *highly localized sheets or filaments* that are washed out by climatological averaging.
- This possibility is strongly suggested by observations (e.g. *Luhr et al.* [2014]) that show density enhancements are often colocated with intense but highly structured regions of small-scale FAC (left panel above).
- Unfortunately the spatial resolution of 16-second DE-2 unified abstract data is too coarse to test this hypothesis (right panel.)

Tracking Ion & Neutral Tracer Cloud Drifts: C-REX



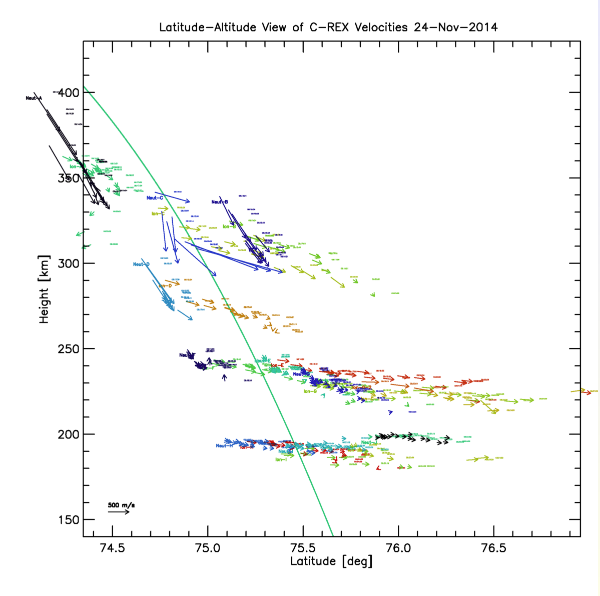
Computed Tracer Drift Velocities – Map View

This map shows observed horizontal drift velocities of ion (warm colors) and neutral (cool colors) tracer clouds.



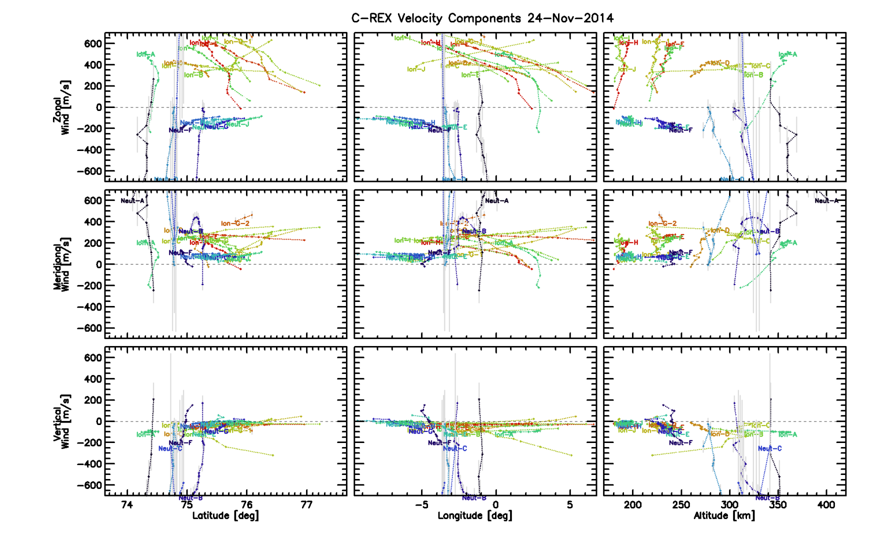
- *The neutrals are drifting north-west, whereas the ions are drifting north-east.*
- No other technique can give these direct in-situ measurements – they show important spatial and temporal detail that is unavailable any other way – especially for the neutral flows.
- Horizontal ion motion was complex. But neutral motion was simple and unlikely to indicate any localized support mechanism.

Drift Velocities Versus Altitude



- This is a side elevation view of the calculated cloud velocities.
- *There is no indication of any upwelling – either neutral or ion.*
- The molecular mass of the tracer species exceeds that of the ambient atmosphere, so diffusive sedimentation that occurs. Predicted downward drift speeds are ∼40 m/s – which is roughly comparable to the vertical drifts observed, suggesting no other vertical flows were occurring.

Drift Velocity Components



Again... *note the absence of any significant upward flows!*

Summary

- *Ground-based FPI data show no obvious cusp-related signatures at ~ 240 km altitude.* Whatever mechanism supports density anomalies, it operates above this altitude.
- C-REX-1 saw *no substantial vertical flows in either neutrals or ions in the height range 250 km to 400 km.*
- However, by combining the rocket data, the UCL "SCANDI" FPI data from Longyearbyen, and EISCAT electron densities, we estimate that significant Joule heating was occurring in this height range, with a specific power density of around $500\,\mathrm{W\,kg^{-1}}$ – adequate to drive a $\partial T/\partial t$ of around $20\,\mathrm{K\,min^{-1}}$.
- *DE-2 satellite data confirm the existence of an upper thermospheric mass density enhancement* near the cusp, albeit with smaller amplitude.
- DE-2 climatological averages for $400\,\mathrm{km} < z < 550\,\mathrm{km}$ show the enhancement is colocated with similar regions of enhanced *temperature*, *upward neutral wind*, and *upward ion drift*. Consistent with the FPI results, these perturbations were not seen at lower heights.
- However *none of the perturbations seen in climatological averages are large enough to adequately explain how the enhanced mass is supported* against gravity.

Taken together, these data suggest the support mechanism operates via intense but highly localized filments or curtains of upwelling, that become smeared out in climatological averages.