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Special Section:
The Rocket Experiment for Neutral Upwelling (RENU2): Examination of Cusp Dynamics and Energization during Poleward Moving Auroral Form Events

Key Points:
- RENU2 measured particles and fields within a PMAF-driven neutral upwelling event
- PMAFs consist of multiple thin arcs; poleward motion leads to a quasiperiodic heating process
- Neutral upwelling (driven by soft precipitation) is dynamic and highly structured in space

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Overview of the Rocket Experiment for Neutral Upwelling Sounding Rocket 2 (RENU2)

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Abstract The Rocket Experiment for Neutral Upwelling 2 (RENU2) rocket was launched on 13 December 2015 at 07:34 UT. The payload transited the cusp region during a neutral upwelling event, supported by a comprehensive set of onboard and ground-based instrumentation. RENU2 data highlight two important processes. One is that a proper understanding of neutral upwelling by Poleward Moving Auroral Forms (PMAFs) requires a treatment that mimics the quasiperiodic passage of a sequence of PMAFs. As a PMAF reaches a flux tube, its physical consequences must be determined including the residual history of effects from previous passages, implying that understanding such a process requires an accounting of the system hysteresis. Second, RENU2 observations suggest that neutral density enhancements driven by precipitation and/or Joule heating can be highly structured in altitude and latitude. In addition, timescales involving neutral dynamics suggest that the structuring must be slowly changing, for example, over the course of 10 to tens of minutes.

1. Introduction

Perhaps the earliest observations of neutral density enhancements at high latitudes are those reported by Jacchia and Slowey (1964) and based on measurements of atmospheric drag on the Injun 3 satellite during times of elevated solar activity. These authors suggest that this effect is consistent with Joule heating (e.g., Cole, 1962).

Observations of density enhancements were largely limited to similar (presumably) large-scale features for several decades until Lühr et al. (2004) showed drag measured by the ultrasensitive accelerometer on CHAMP (Challenging Minisatellite Payload). A unique aspect of these data are the narrow peaks in deceleration that indicate small-scale "bumps" observed as the satellite passed over the cusp region. These bumps are "encountered almost every time when crossing the cusp region" and, although the density structures tend to have scale sizes the order of the cusp (350 ± 150 km), Lühr et al. (2004) emphasize that the upwelling is fundamentally associated with *fine-scale* currents, having magnitudes the order of $150 \mu A/m^2$.

1.1. Altitudinal Structuring

Additional modeling constraints have arisen from recent observations, those that show not only density enhancements but also *depletions* at higher altitudes. For example, the Streak satellite observed relative density *depletions* near the southern cusp in the altitude range 123–325 km when averaged over all orbits (Clemmons et al., 2008). These authors explain that traditional Joule heating (i.e., at *E* region altitudes) would be expected to create density enhancements that simply decrease monotonically with altitude, including altitudes above which the Joule heating maximizes. As such, if Joule heating from below 200 km drives a 30% enhancement seen by CHAMP at 400 km, then similar or greater density enhancements should be observed between these two altitudes.

Clemmons et al. (2008) conclude from these observations that the driver of this process must not be Joule heating and propose a mechanism involving heating due to soft precipitation. Energy from soft electron precipitation is deposited at higher altitudes than Joule heating, allowing observational consistency for the two satellites: if neutrals are upwelling from an altitude between the two orbits, CHAMP could see an enhancement that Streak did not.

Evidence for altitude-dependent density perturbations were also shown by Kervalishvili and Lühr (2018), who compared CHAMP observations (at ~400-km altitude) to GRACE (Gravity Recovery and Climate Experiment, at ~500-km altitude). One important result is that relative density perturbations at 500-km altitude are *greater* than at 400 km, especially in winter (i.e., with a dark ionosphere). The implication is that density enhancements must typically exist at altitudes *greater* than 500 km (i.e., above GRACE altitudes), an effect that might be expected based on hydrostatic equilibrium arguments.

An important consideration is whether (and how) high-latitude winds might play a role in the structuring of neutral upwelling. Demars and Schunk (2007) used a high-resolution model of the thermosphere to investigate thermospheric effects of cusp density enhancements. The response, they explain, is the formation of a “fountain” of neutral particles, one that results in diverging winds both poleward and equatorward of the cusp.

Observationally, Wu et al. (2012) showed dayside equatorward winds from Fabrey-Perot Interferometer data on HIWIND, a high-altitude balloon. Fabrey-Perot Interferometer measurements over the course of three days showed consistent equatorward winds on the dayside, which were shown to contradict NCAR's Thermosphere-Ionosphere-Electrodynamics General Circulation Model model predictions. A similar result was obtained by Horvath and Lovell (2017) using wind measurements derived from the CHAMP accelerometer that show divergent flow structures around the cusp. The results from both of these studies are consistent with the neutral “fountain” effect predicted by Demars and Schunk (2007).

1.2. Modeling Efforts

While the original models drove the upwelling with *E* region Joule heating alone, typical implementations of Joule heating in numerical models have not generally been able to account for the small-scale (and quite intense) neutral upwelling observed by CHAMP. A notable exception, however, is presented by Crowley et al. (2010), who *did* succeed in showing that Joule heating can reproduce the small-scale enhancements reasonably well, albeit for a single and unusual event.

Models that seek to explain neutral upwelling in the cusp have been increasingly incorporating effects of soft electron precipitation (Connor et al., 2016; Crowley et al., 2010; Sadler et al., 2012; Zhang et al., 2015). In some models, electron precipitation drives an enhancement of ionization at *F* region altitudes that intensifies Joule heating (and neutral upwelling) at those altitudes. Carlson et al. (2012) demonstrated that soft cusp precipitation, giving rise to enhanced Pedersen conductivity and hence enhanced frictional heating, is a key mechanism that can explain the thermospheric response to magnetopause reconnection events. Clemmons et al. (2008), on the other hand, show that electron precipitation effects operate on smaller scales that involve either heating of the neutral population directly or as a part of the ion outflow mechanism.

Observationally, some researchers have sought to link such processes. Olson (2012) compared data from CHAMP to the Fast Auroral Snapshot Explorer (FAST) and determined that the CHAMP upwelling events are highly-correlated with FAST ion upflows. Kervalishvili and Lühr (2013) carried out a similar study using CHAMP and DMSP satellites and also determined that neutral upwelling events are correlated with ion upflow events. The apparent connection between ion outflow and neutral upwelling begs the question of whether they are driven independently by a common process or whether they are part of a single process.

2. The RENU2 Mission

The objective of Rocket Experiment for Neutral Upwelling 2 (RENU2) has been to determine the extent to which Joule heating and/or soft electron precipitation contribute to neutral upwelling in the cusp

Table 1
RENU2 Instrumentation

Instrument	Institution	Sensor type	Range
Ion gauge	Aerospace	Anelva ion gauge	$\geq 10^{-10}$ T)
Photometers	Aerospace	391.4, 557.7, and 630.0 nm	50 cts/s/R
EPLAS	UNH/Dart.	Tophat Analyzer	5 eV to 14.6 keV
Heeps Ions (3)	Dartmouth	Tophat Analyzers	0.1 eV to 1 keV
ERPA	UNH	Thermal Electron RPA	0.06–3 eV
COWBOY Electric Fields	Cornell	12-m tip-to-tip wire booms	0–20 kHz, 0–1000 Hz
Science magnetometer	Cornell	three-axis fluxgate	±60, 000 nT
UV PMT	UNH	130.4 nm, 12° FOV	—

RENU2 = Rocket Experiment for Neutral Upwelling 2.

region. The sounding rocket was launched northward from the Andøya Rocket Range, with simultaneous downrange observations including the EISCAT Svalbard Radar, all-sky cameras, scanning photometers, magnetometers, and other instruments. This arrangement resulted in the payload transiting the cusp, while instruments on the ground at Longyearbyen and Ny-Ålesund provided supporting data. RENU2 instruments are listed in Table 1 and include electron and ion analyzers, neutral particle instruments, photometers, electric, and magnetic sensors.

2.1. Launch Conditions

For more than 3 hr before launch, solar wind B_z remained weakly negative, with only brief (5–10 min) positive B_z excursions. For nearly an hour before launch, the solar wind speed averaged ~520-km/s with $B_z \sim -1.5$ nT and $B_y \sim 3.5$ nT, resulting in a series of Poleward Moving Auroral Forms (PMAFs), as seen in Figure 1. The top panel in that figure is a meridional keogram showing a quasiperiodic series of 630.0-nm auroral emissions propagating poleward over time (i.e., PMAFs). During the early part of the interval, snow covered the optical dome and obscured the observation. Near 06:45, the snow was cleared, revealing typical PMAF signatures. Dashed lines in that panel mark the time of the RENU2 flight. The poleward speeds of the PMAFs are estimated to be ~1 km/s.

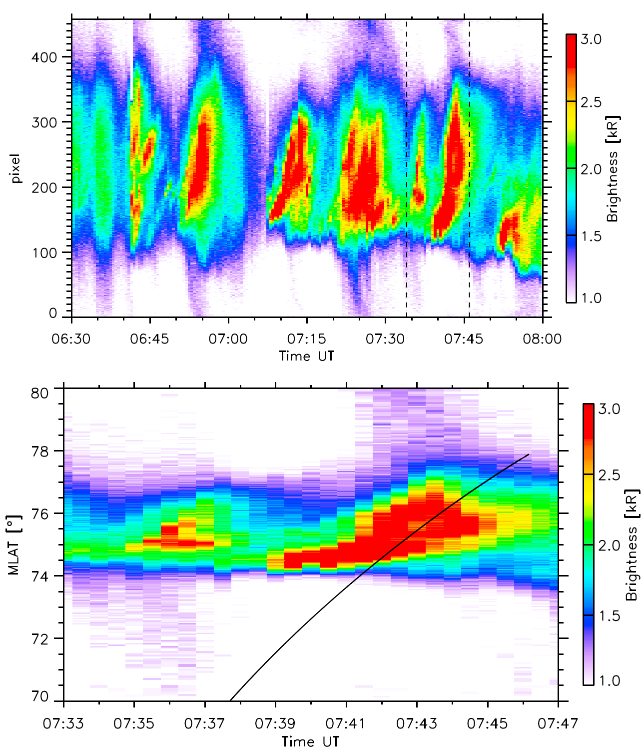

Figure 1. Keograms derived from all-sky cameras at 630.0-nm wavelengths. The black line in the lower panel shows the rocket trajectory projected to the assumed auroral emission altitude (250 km). MLAT = magnetic latitude.

RENU2 was launched at 07:34:00 UT. In the lower panel of Figure 1, the keogram is mapped to magnetic latitude and the payload footprint at 250-km altitude is mapped (using International Geomagnetic Reference Field) to the auroral emission. The launch fortuitously provided observations lasting more than 200 s within a PMAF. The apogee of RENU2 was 447 km, at approximately 408 s after launch.

During the minutes before launch, Collaborative UK Twin Located Auroral Sounding System (CUTLASS) Super Dual Auroral Radar Network (SuperDARN) Radar data (not shown) were intermittent but began to show poleward flows, an indication that the launch range was moving into the cusp region.

EISCAT Svalbard radar data include electron densities and temperatures and ion temperatures and upflowing velocities. Before 07:10 UT there were several transient Joule heating events, where the ion temperature often exceeded two times the ion temperature background (1300 K). After 07:10 UT, the ion temperature for the most part stayed within 10–30% of the background, indicating little or no significant Joule heating. At the same time there was a series of transient electron temperature enhancements that often exceeded 2 times the electron

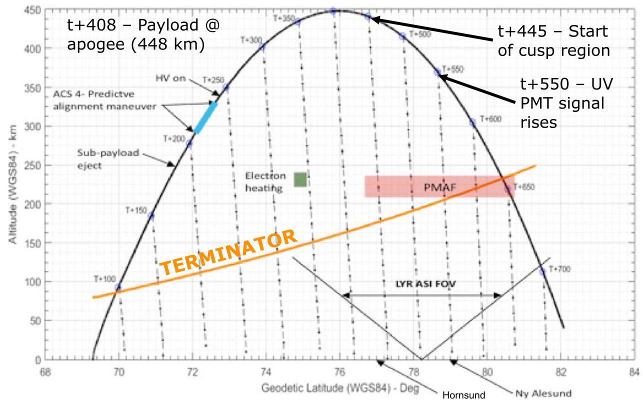

Figure 2. Plot of the Rocket Experiment for Neutral Upwelling 2 trajectory. The mission design was such that the prime observing would take place on the downleg, where the trajectory would have the payload descend (more or less) over Longyearbyen. Dashed lines show the direction of the geomagnetic field (International Geomagnetic Reference Field). PMAF = Poleward Moving Auroral Form.

temperature background (1500 K). Consequently, electron precipitation heating was the dominant process during the RENU2 flight.

3. Results Overview

The mission strategy was to launch poleward from the Andøya Space Center in Andenes, Norway, along a trajectory that would have the payload descend as close as possible to the EISCAT radar beam in Longyearbyen, Svalbard. The goal was to maximize the vertical extent of the measurement in the cusp (i.e., the altitude through which RENU2 would drop while it is in the cusp and as close as possible to EISCAT). EISCAT and the Kjell Henriksen Observatory (KHO), which houses an extensive array of optical and magnetic field instruments, are located at approximately 78° latitude.

Figure 2 shows the final RENU2 altitude profile versus geodetic latitude. Time in seconds-after-launch are noted, for example, as "T+408" in the figure. The orange line represents the sunlight terminator during the flight, showing that the majority of the flight was in sunlight. The "PMAF" label on the plot shows the approximate location of the PMAFs, that is, directly overhead at Longyearbyen and EISCAT. The slanted dashed lines show the International Geomagnetic Reference Field trace for each time stamp marked along the flight trajectory.

On the upleg, RENU2 electron signatures of plasma sheet precipitation are clear. The in situ data show that RENU2 entered the cusp region at approximately T+445 s, or 07:41:20 UT. While in the cusp (specifically passing through the PMAF shown in Figure 1), the electron signatures show a series of small-scale field-aligned electron bursts. Optical signatures also showed a bursty character, with emission lifetimes being the order of 100 ms as PMAF arcs came into the instrument field-of-view (Hecht et al., 2019).

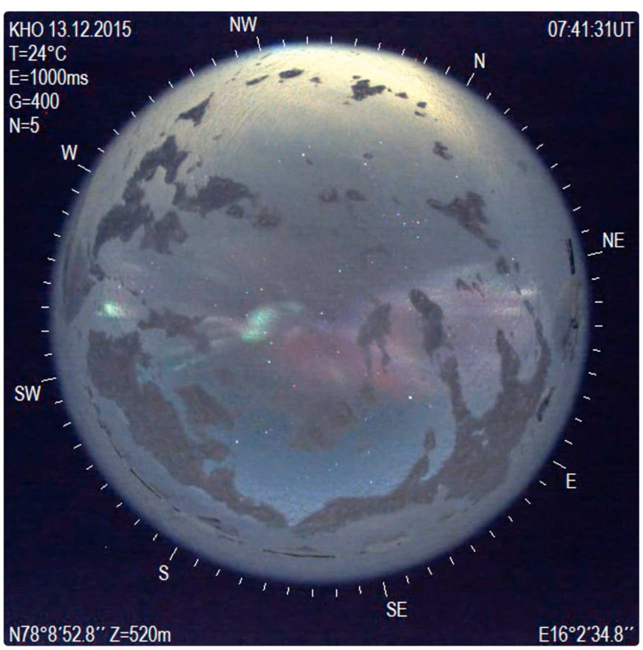

Figure 3. Snapshot of PMAF fine structure, acquired using a ZWO ASI174MC camera. The PMAF itself (the broad region of luminosity) is composed of several thin (subkilometers) dynamic arcs. PMAF = Poleward Moving Auroral Form.

3.1. PMAF Dynamics and Energy Transfer

PMAFs were described by Sandholt et al. (1990), who referred to them as "Midday auroral breakup events" and noted a recurrence time of 3–15 min between events and a duration of 2–10 min. Fasel (1995) followed this work with a statistical study spanning 12 years of data and found an average duration of 5 min and a mean time between successive events of 6 min. Ogawa et al. (2003) related soft precipitation signatures in EISCAT data to upflow in the cusp region and Moen et al. (2004) linked ion upflow to "bursts" of soft electron precipitation specifically associated with PMAFs. These authors suggest that the bursty precipitation signatures resulted from the passage of auroral forms over the radar.

One unexpected but important observation from the RENU2 mission was provided with the use of a KHO ZWO ASI174MC camera, a high-resolution, commercially available color camera. Figure 3 shows a snapshot taken by that camera of the PMAF that RENU2 flew through. Note that not all of the snow/ice had been cleared from the optical dome, which accounts for the dark, patchy regions in the image. While the keograms in Figure 1 seem to show that the PMAFs consist of a broad region of precipitation, the snapshot in Figure 3 shows that the PMAF actually consists of numerous small-scale (thin) arcs. In addition, the original sequence of ZWO ASI174MC images shows that these auroral forms are highly dynamic. A PMAF, in other words, seem to be comprised

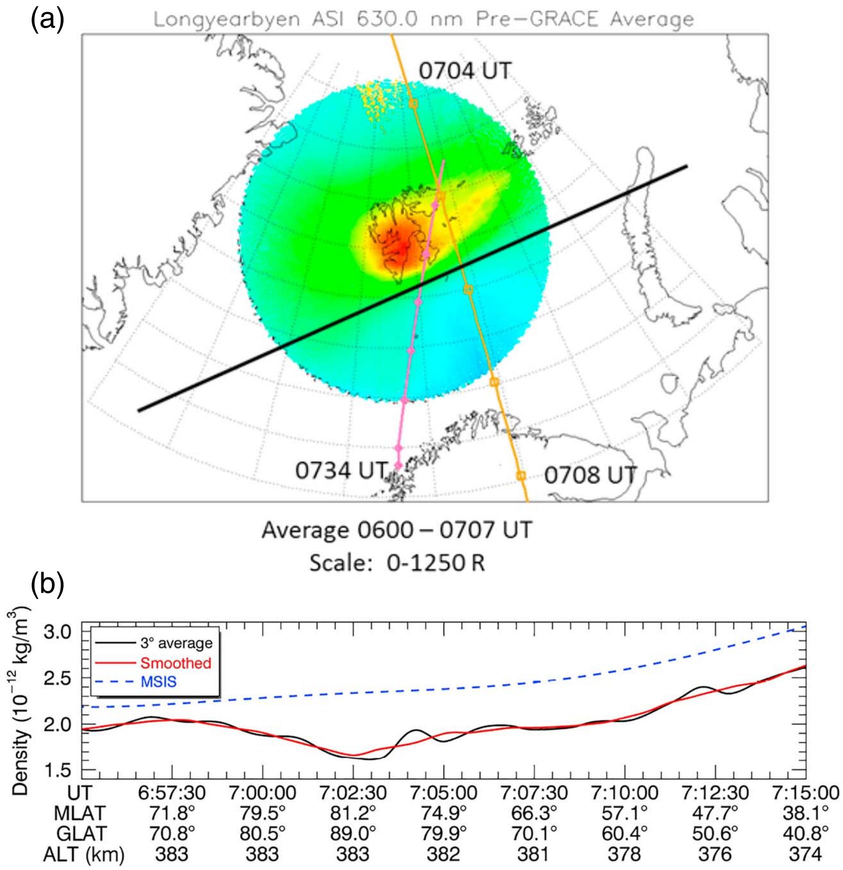

Figure 4. (a) Trajectory and data from the GRACE satellite (GRACE trajectory is in orange; RENU2 is marked by the pink line and the solid black line shows the Poleward Moving Auroral Form orientation; (b) showing a modest neutral density enhancement ~40 min before the RENU2 flight. GRACE = Gravity Recovery and Climate Experiment; RENU2 = Rocket Experiment for Neutral Upwelling 2.

of a group of small-scale arcs that dance back and forth as they drift poleward. This is consistent with the electron precipitation signatures observed in situ.

PMAF motion plays an important role in coupling dynamics, especially when timescales are considered. That is, during times of soft precipitation, ionospheric electron heating begins within a few seconds of the onset of the precipitation and ions respond within tens of seconds, but neutral populations require tens of minutes. For any given fluxtube, heating of the ionospheric and thermospheric populations is accomplished by the quasiperiodic passage of a sequence of PMAFs. As a PMAF reaches any given fluxtube, it encounters initial conditions that retain the history from the passage of the previous PMAF—in other words, the quasiperiodic process needs to account for hysteresis in the system.

Burleigh et al. (2019) examine this process using a two-dimensional model of ion dynamics to study the cumulative effects of the sequential passing of PMAFs. Taking different excitation and relaxation time scales into account (e.g., of electron versus ion dynamics), these authors find that upflow fluxes are the order of half what they would be under steady forcing. A key part of that work is to show how the widely-varying timescales of this process may produce the type of structuring suggested by RENU2.

3.2. Neutral Density Observations

Figure 4a shows the RENU2 trajectory over Svalbard and also shows the trajectory of the GRACE satellite, which provided a fortuitous and important complementary observation of neutral densities. The top panel shows the GRACE trajectory (orange line) relative to that of RENU2 (pink line) and Svalbard. The solid black line shows the PMAF orientation.

GRACE data were acquired roughly 40 min before the RENU2 flight, as GRACE passed over Svalbard, but to the east of Longyearbyen (within perhaps 200 km). The 40-min difference in observing time is significant, although the sequence of PMAFs had been occurring during the GRACE overflight as well. In addition, thermospheric heating (because of the relatively large mass density involved) changes only over the course of several 10s of minutes. The GRACE measurement, we conclude, provides a complementary (and reasonable) estimate of the range of upwelling events during the time leading up to the event that is measured in detail by RENU2.

Figure 4b shows density estimates derived from GRACE satellite accelerometer data. The bottom panel includes the GRACE data averaged over 3 degrees in latitude (black), a reference smoothed plot over 10° in latitude (red), and then the MSIS (Mass-Spectrometer-Incoherent-Scatter) atmospheric density calculated at the spacecraft location (blue). The density enhancement is a modest ∼10% increase, seen near 07:04 UT, and maps fairly well to the RENU2 trajectory.

Measurements of the neutral thermosphere were obtained by RENU2 in situ with the Ion Gauge instrument and show no significant deviation from the MSIS densities during the flight, although these authors do show the presence of strong neutral winds. Using an ultraviolet photometer (UV PMT) to observe atomic oxygen signatures in sunlight (i.e., *above* the payload), Fritz et al. (2019) uses the PMT/GLOW comparison to demonstrate how precipitation-driven emissions in the cusp may be used to infer structural variation in the neutral background.

To summarize, the UV PMT instrument observed a density enhancement *above* the payload beginning near 380-km altitude on the downleg, perhaps providing a measure of horizontal structure based on the sharp dropoff at the highest latitudes (Fritz et al., 2019). On the other hand, the IG instrument provided in situ measurements of the background density and found no significant deviation from the background values (though it may well be the case that a prior density enhancement had moved away from the region). GRACE observed a density enhancement near the same altitude of the UV PMT instrument tens of minutes prior.

The increased density above the payload, taken along with a nominal density *at* the payload and observations of a modest (10%) density increase observed by GRACE 40 min prior, suggest that neutral density enhancements driven by precipitation and/or Joule heating can be highly structured in altitude and latitude. In addition, the timescales involving neutral dynamics suggest that the structuring must be slowly changing, for example, over the course of 10 to tens of minutes.

4. Conclusions

In summary, RENU2 flew into the dayside cusp region with instrumentation to measure magnetospheric energy inputs to the ionosphere and thermosphere. The main objective was to relate these inputs to thermospheric (neutral) upwelling as originally reported by Lühr et al. (2004) and observed by RENU2.

1. Other than a brief period as the payload was entering the cusp (∼20 s), where thermal ions are heated coincident with a local DC electric field increase, the majority of the flight showed that precipitating soft electrons provided the dominant energy input, in the form of Alfvénic aurora during a PMAF. As often seen at rock et altitudes, the dominant field-aligned motion of the thermal ion population was downflowing, with localized regions of upflow. Note that for density enhancement events of ∼100% rather than ∼10% as herein, Joule/ion-frictional-drag heating has been estimated to dominate the soft particle heating (Carlson et al., 2012).
2. High-resolution ground-based images show that the specific PMAF that RENU2 flew through was not a single, broad region of precipitation but that it consisted of a cluster of highly dynamic, small-scale arcs. These images are consistent with the in situ electron measurements, which showed bursts the order of ∼100-m scale sizes.
3. Perhaps most importantly, observations from RENU2 (combined with GRACE) show that the higher-altitude neutral population did not consist of a single region of upwelling but that the neutral density enhancements were quite patchy and extended in altitude and latitude, with strong neutral winds. The topography of the patches can be expected to change over time scales of tens of minutes.
4. The event presented here provides an important example of cross-scale coupling, where the repeated passage of thin (subkilometers) auroral arcs can contribute to neutral upwelling at scale sizes several of tens of kilometers.

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References

Burleigh, M., Zettergren, M., Lynch, K., Lessard, M., Moen, M., Clausen, D., et al. (2019). Transient ionospheric upflow driven by poleward moving auroral forms observed during the Rocket Experiment for Neutral Upwelling 2 (RENU2) campaign. *Geophysical Research Letters*, *46*. https://doi.org/10.1029/2018GL081886

Carlson, H. C., Spain, T., Aruliah, A., Skjæveland, A., & Moen, J. (2012). First-principles physics of cusp/polar cap thermospheric disturbances. *Geophysical Research Letters*, *39*, L19103. https://doi.org/10.1029/2012GL053034

Clemmons, J. H., Hecht, J. H., Salem, D. R., & Strickland, D. J. (2008). Thermospheric density in the Earth's magnetic cusp as observed by the Streak mission. *Geophysical Research Letters*, *35*, L24103. https://doi.org/10.1029/2008GL035972

Cole, K. D. (1962). Joule heating of the upper atmosphere. *Australian Journal of Physics*, *223–235*, 5945–5956.

Connor, H. K., Zesta, E., Fedrizzi, M., Shi, Y., Raeder, J., Codrescu, M. V., & Fuller-Rowell, T. J. (2016). Modeling the ionosphere-thermosphere response to a geomagnetic storm using physics-based magnetospheric energy input: OpenGGCM-CTIM results. *Journal of Space Weather and Space Climate*, *6*(27), A25. https://doi.org/10.1051/swsc/2016019

Crowley, G., Knipp, D. J., Drake, K. A., Lei, J., Sutton, E., & Lühr, H. (2010). Thermospheric density enhancements in the dayside cusp region during strong BY conditions. *Geophysical Research Letters*, *37*, L07110. https://doi.org/10.1029/2009GL042143

Demars, H. G., & Schunk, R. W. (2007). Thermospheric response to ion heating in the dayside cusp. *Journal of Atmospheric and Terrestrial Physics*, *69*, 649–660.

Fasel, G. J. (1995). Dayside poleward moving auroral forms: A statistical study. *Journal of Geophysical Research*, *100*(11), 11,891–11,905. https://doi.org/10.1029/95JA00854

Fritz, B. A., Lessard, M. R., Dymond, K. F., Kenward, D. L., Lynch, K. A., Hecht, J. H., & Clemmons, J. H. (2019). RENU2 UV PMT observations of the cusp. *Geophysical Research Letters*, *46*. https://doi.org/10.1029/2019GL082314

Hecht, J. H., Clemmons, J. H., Lessard, M. R., Kenward, D. L., Sadler, B. F., Fritz, B. A., & Lynch, K. A. (2019). A new technique for estimating the lifetime of bursts of electron precipitation from sounding rocket measurements. *Geophysical Research Letters*, *46*. https://doi.org/10.1029/2019GL082894

Horvath, I., & Lovell, B. C. (2017). Investigating the polar ionosphere during the development of neutral density enhancements on 24–25 September 2000. *Journal of Geophysical Research: Space Physics*, *122*, 4600–4616. https://doi.org/10.1002/2016JA023799

Jacchia, L. G., & Slowey, J. (1964). Atmospheric heating in the auroral zones: A preliminary analysis of the atmospheric drag of the Injun 3 satellite. *Journal of Geophysical Research*, *69*, 905–910.

Kervalishvili, G., & Lühr, H. (2013). The relationship of thermospheric density anomaly with electron temperature, small-scale FAC, and ion upflow in the cusp region, as observed by CHAMP and DMSP satellites. *Annals of Geophysics*, *31*, 541–554. https://doi.org/10.5194/angeo-31-541-2013

Kervalishvili, G. N., & Lühr, H. (2018). Climatology of air upwelling and vertical plasma flow in the terrestrial cusp region: Seasonal and IMF-dependent processes. In H. Lühr, J. Wicht, S. A. Gilder, & M. Holschneider (Eds.), *Magnetic fields in the solar system* (Vol. 448, pp. 293–329). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-64292-5_11

Lühr, H., Rother, M., Köhler, W., Ritter, P., & Grunwaldt, L. (2004). Thermospheric up-welling in the cusp region: Evidence from CHAMP observations. *Geophysical Research Letters*, *31*, L06805. https://doi.org/10.1029/2003GL019314

Moen, J., Oksavik, K., & Carlson, H. C. (2004). On the relationship between ion upflow events and cusp auroral transients. *Geophysical Research Letters*, *31*, L11808. https://doi.org/10.1029/2004GL020129

Ogawa, Y., Fujii, R., Buchert, S. C., Nozawa, S., & Ohtani, S. (2003). Simultaneous EISCAT Svalbard radar and DMSP observations of ion upflow in the dayside polar ionosphere. *Journal of Geophysical Research*, *108*(A3), 1101. https://doi.org/10.1029/2002JA009590

Olson, D. K. (2012). Neutral gas and plasma interactions in the polar cusp (PhD thesis), University of Maryland.

Sadler, F. B., Lessard, M., Lund, E., Otto, A., & Lühr, H. (2012). Auroral precipitation/ion upwelling as a driver of neutral density enhancement in the cusp. *Journal of Atmospheric and Solar-Terrestrial Physics*, *87*, 82–90. https://doi.org/10.1016/j.jastp.2012.03.003

Sandholt, P. E., Lockwood, M., Oguti, T., Cowley, S. W. H., Freeman, K. S. C., Lybekk, B., et al. (1990). Midday auroral breakup events and related energy and momentum transfer from the magnetosheath. *Journal of Geophysical Research*, *95*(A2), 1039–1060. https://doi.org/10.1029/JA095iA02p01039

Wu, Q., Wang, W., Roble, R. G., Häggström, I., & Strømme, A. (2012). First daytime thermospheric wind observation from a balloon-borne Fabry-Perot interferometer over Kiruna (68N). *Geophysical Research Letters*, *39*, L14104. https://doi.org/10.1029/2012GL052533

Zhang, B., Varney, R. H., Lotko, W., Brambles, O. J., Wang, W., Lei, J., et al. (2015). Pathways of *F* region thermospheric mass density enhancement via soft electron precipitation. *Journal of Geophysical Research: Space Physics*, *120*, 5824–5831. https://doi.org/10.1002/2015JA020999