

Eastward transients in the dayside ionosphere. II. A parallel-plate capacitorlike effect

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During the 23 April 2023 geospace storm, we observed chorus-wave-driven, energetic particle precipitation on closed magnetic field lines in the dayside magnetosphere. Simultaneously and in the ionosphere's bottom side, we observed signatures of impact ionization and strong enhancements in the ionospheric electric field, via radar detection of meter-scale turbulence, and with temporal characteristics matching those of the magnetospheric observations. We detail this in another work [M. F. Ivarsen *et al.*, *Phys. Rev. E* **112**, 045204 (2025)]. In the present article we place those observations into context with the dayside ionosphere and describe a remarkably similar event that took place during the May 2024 geospace superstorm. In both cases, fast, eastward-moving electric field structures were excited equatorward of the ionospheric cusp, on closed magnetic field lines, observations that challenge existing modes of explanation for electrodynamics in the cusp region, where most such observations are interpreted in the context of poleward-moving auroral forms. Instead, primarily eastward-moving electric field structures were associated with turbulent Hall currents that are perhaps characteristically excited during geospace storms by wave-particle interactions near the magnetospheric equator or by proton precipitation characteristics in the cusp, forming a parallel-plate capacitorlike effect. We propose that transient eastward electrodynamic bursts in the dayside ionosphere might be a common, albeit previously unresolved, feature of geomagnetic storms.

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I. INTRODUCTION

The solar wind, a stream of plasma at various densities, pushes against Earth's magnetosphere, driving large-scale

electrical currents and plasma convection in Earth's ionosphere [1]. Large energy transfers are brought about through magnetic reconnection, the interface between the terrestrial and solar magnetic fields, a process that transfers magnetic flux from the dayside to the nightside [2]. On the Sun-facing side of the magnetosphere, closed field lines open up to the solar wind, forming the magnetospheric cleft, or cusp region [3], which plays host to plasma outflow and particle precipitation [4,5].

Poleward-moving auroral forms are frequently sighted in the ionospheric cusp and they are manifestations of dayside magnetic reconnection. They consist mostly of red auroral arcs that drift poleward along with the reconnected field lines from the cusp and into the polar cap in pulses [6–8], as is illustrated in Fig. 1(a). The pulsations reflect the temporal evolution in flux transfer events, meaning that a study of the dynamics in one system is applicable to the other [9,10]. For this reason, the systematic study of poleward-moving auroral forms have yielded crucial physical insight into the

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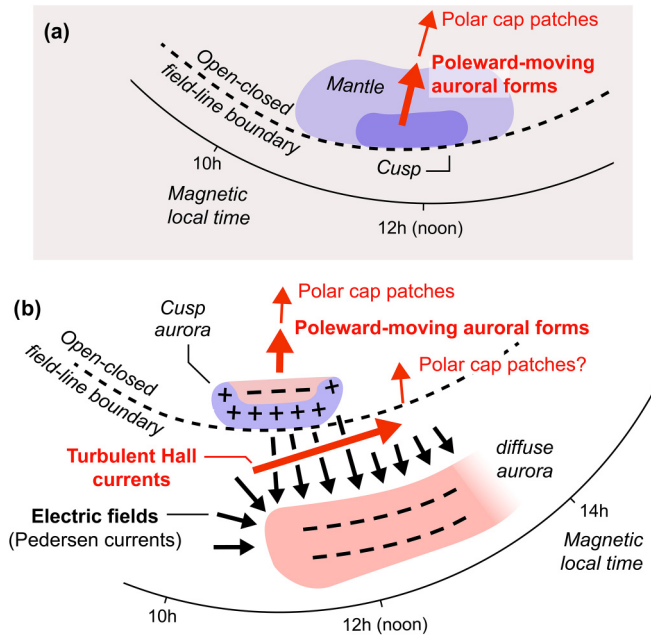


FIG. 1. (a) Schematic drawing of the cusp, its extended mantle, and the motion of traditional poleward-moving aurora forms, as well as their expected seeding of polar cap patches. (b) Schematic drawing of the greater cusp region, showing a mix of low-energy electrons (pink shaded area, minus signs) and protons (light blue shaded area, plus signs), with the most intense proton aurora on its equatorward edge. A region of high-energy diffuse aurora lies somewhere to the southeast of the cusp, and the two regions are separated by the open-closed field-line boundary. A strong equatorward electric field forms between the regions, driving turbulent electrojets, currents whose laminar form is broken up and developing the condition. The action of the turbulent Hall drifts (red arrows) may push islands of structured ionization into the polar cap, if aided by dayside reconnection.

magnetosphere. Relevant for the study at hand, such aurorae are invariably accompanied by fast plasma flow channels in the topside ionosphere [11,12], with typical reported speeds ranging from 500 m/s to 2 km/s [13].

There are however observations of poleward-moving forms that move faster than the magnetospheric convection would imply [14], in counterintuitive directions [15], and some that occur on closed magnetic field lines [16], observations that challenge the accepted notion of magnetic flux being peeled off from the magnetopause into the polar cap [17]. In an attempt at reconciling the field, Ref. [18] proposed that hot electrons from a dayside plasma sheet [19] may precipitate in numbers sufficient to produce a perturbation electric field (aligned with the Pedersen currents that close the field-aligned currents), thereby powering fast drifts, a situation that we illustrate in Fig. 1(b).

Indeed, high-energy diffuse aurorae are a staple of the day-side ionosphere [20–22], where the mechanisms responsible originate with plasma waves near the magnetospheric equator; these interact with orbiting electrons, causing pitch-angle scattering of those electrons into the loss cone and subsequent precipitation into Earth’s atmosphere [23,24]. Having high kinetic energy, dayside diffuse aurorae will ionize the *E* region, the bottomside ionosphere [25], at altitudes even

lower than the extant extreme ultraviolet radiation from the Sun would imply [26]. Thereby, diffuse aurorae drive field-aligned currents, an action whose reaction comes in the form of local, strong, perpendicular electric fields, conforming to expectations from the conservation of current vorticity, fields that efficiently move ions in the direction of negative charge deposition (see, e.g., Fig. 5 in Ref. [27]).

The above paragraphs describe the energy source for the mechanism suggested by Ref. [18], and the resulting fast motions are found in Ref. [28], reporting recent radar measurements of fast-moving electric field structures in the *E*-region ionosphere. Figure 1(b) presents a schematic of the process and thereby summarizes the results of Ref. [28] and the present article: Equatorward of the cusp and poleward of diffuse aurorae, a series of superfast turbulent Hall flow channels briefly appeared during two major geomagnetic storms. Given the proximity to the ion precipitation inside the cusp, an experiment that superficially resembles a parallel-plate capacitor emerges. Aided by increased plasma convection caused by dayside reconnection, the action may in the end transport plasma into the polar cap, thereby seeding polar cap patches eastward of the cusp.

Since dynamic and active aurorae dissipate energy, partially through turbulence, the question of what powers them strikes at the heart of the ionosphere-magnetosphere coupling: the greater energy flow from the solar wind down to Earth’s dense resistor of an ionosphere. Whereas traditional poleward-moving auroral forms are powered directly by the coupling that takes place in the cusp region, that of the ionosphere and the solar wind, we here evoke a mechanism involving oscillatory magnetic energy and the particle populations near the magnetospheric equator. In particular, whistler-mode chorus waves are the ultimate source of free energy in the system under study (a bold claim that is substantiated in a related paper [28]).

The core dataset used in the present article consists of coherent radar echoes from the unstable *E* region, also called the radar aurora [29]. In Ref. [28] we present in detail observations of dynamic radar aurorae that would seem to drift poleward but mostly eastward, at a location equatorward of the cusp and on closed magnetic field lines, which we measured using the ICEBEAR radar. ICEBEAR is a coherent-scatter radar [30] whose signal reflects off small-scale (3-m) Farley-Buneman waves, unstable structures excited by the relative motion between electrons and ions [31,32]. The small-scale turbulence dissipates fast, giving the radar aurora an ephemeral quality [33,34]. Reference [35] exploits this quality to identify and track moving clusters of echoes, the apparent motion of which act as a measure of the ionospheric electric field [36].

Based on such electric field observations through two 2-h intervals, occurring during the 23 April 2023 and 10 May 2024 geomagnetic storms, the present article substantiates the observations of a series of transient, turbulent Hall currents that formed equatorward of the cusp, and for the 23 April 2023 storm, we demonstrate in a related paper that those motions were observed on the poleward side of dayside diffuse aurorae, and that the radar observations were strongly correlated with chorus-wave-driven particle precipitation observed near the equatorial magnetopause [28].

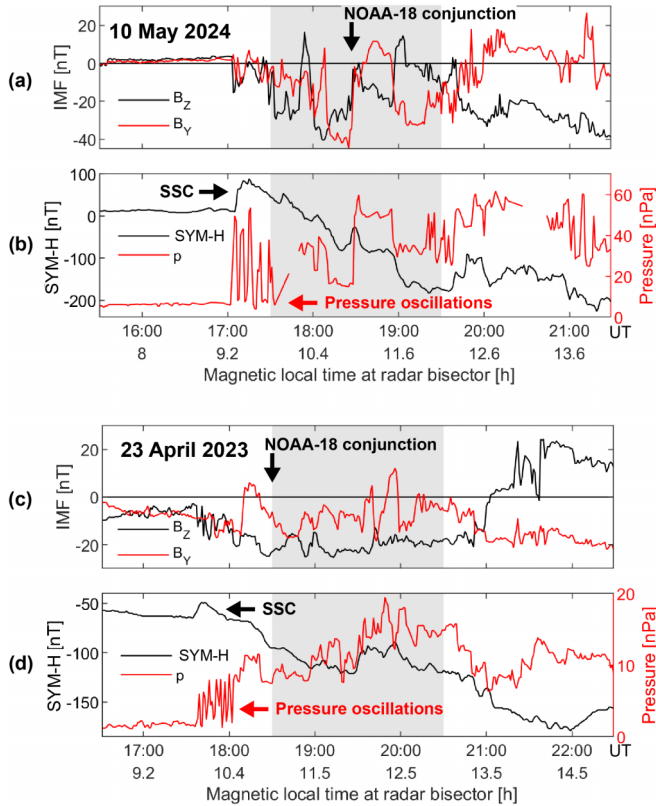


FIG. 2. Solar wind parameters and geomagnetic activity index values for the period leading up to two major geomagnetic storms, occurring on (a) and (b) 10 May 2024 and (c) and (d) 23 April 2023. The shaded gray area denotes the duration of the two events under study. (a) and (c) Interplanetary magnetic field B_Z (black) and B_Y (red) components time shifted to the bow shock [37]. (b) and (d) Sym-H geomagnetic storm index (black, left axis) and solar wind dynamic pressure (red, right axis). Various features are annotated with arrows (SSC stands for sudden storm commencement).

II. RESULTS

Figure 2 elucidates the state of the solar wind prior to the 23 April 2023 [Figs. 2(a) and 2(b)] and 10 May 2024 [Figs. 2(c) and 2(d)] storms. In both cases, our observations occurred during geomagnetic noon in Western Canada, in full daylight, coinciding with the two storms' main phases. Furthermore, the two events share several key characteristics: A clear sudden storm commencement coincided with intense pressure oscillations, indicative of nonlinear processes near the magnetosheath, possibly triggering bow shock ripples and high-speed jets [41], sources of free energy for the dayside ionosphere on closed field lines [42]. In both events, the pressure oscillations are followed by a severe southward turn of the interplanetary magnetic field, down to $B_Z < -25$ nT and $B_Z < -40$ nT, respectively. In both cases, the southward shift in the B_Z components was severe enough that the open-closed field-line boundary and the dayside auroral region migrated equatorward into the field of view of ICEBEAR and the Saskatoon SuperDARN radar.

The similarities between the two events under study do not end there. Figure 3 presents two fortuitous space-ground conjunctions of the U.S. National Oceanic and Atmospheric Administration polar orbiting climate satellite, revealing the

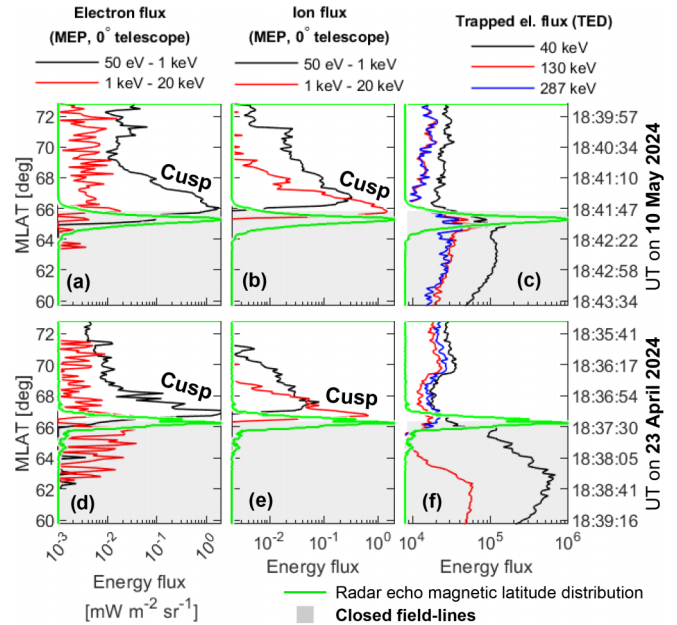


FIG. 3. Observations made by the NOAA-18 spacecraft [38] of precipitating (a) and (d) electrons and (b) and (e) ions, using the TED 0° telescope, and (c) and (f) trapped electrons, using a medium-energy proton and electron detector 30° telescope [39], during two space-ground conjunctions: (a)–(c) one occurring on 10 May 2024 and (d)–(f) one occurring on 23 April 2023. Magnetic latitude (calculating using AACGM [40]) is shown on the left y axis, while time in UT is shown on the right y axis. In (a), (b), (d), and (e), black and red lines indicate low- and high-energy particle fluxes, respectively, while (c) and (f) show three distinct high-energy fluxes. In all panels, the latitudinal distribution of ICEBEAR echoes (with locations traced along Earth's magnetic field lines) are shown with a green line. A gray shaded region indicates where Earth's magnetic field lines are inferred to be closed.

exact locations of the ionospheric cusp and the open-closed field-line boundary, which are compared to the distribution of observed radar echoes, for both events under study. The satellite is in a polar orbit (98.74° inclination) and is equipped with rudimentary particle detectors that allow for an estimate of the precipitating flux of low- and high-energy electrons and ions, as well as the trapped particle population in the topside F region. In both events under analysis, we observe a sharp increase in the low-energy electron energy flux [black line in Figs. 3(a) and 3(d)], coincident with a localized, strong ion energy flux [Figs. 3(b) and 3(e)], a characteristic signature of the ionospheric cusp [43,44]. We here note a tendency for the most energetic and numerous protons usually being located on the equatorward edge of the cusp in our data, conforming to expectations for a southward interplanetary magnetic field configuration [compare, say, Figs. 3(b) and 3(e) with Fig. 2 in Ref. [45]].

Equatorward of this position, the abrupt change in the trapped electron flux [Figs 3(c) and 3(f)] is a signature of the open-closed field-line boundary [46]. In all panels of Fig. 3, the latitudinal distribution of ICEBEAR echoes (green line) confirms that the radar echoes originate just equatorward of the cusp, on or near the open-closed field-line boundary.

Figure 4 summarizes the various velocities measured during the two events, with poleward velocities shown in Figs. 4(a), 4(b), 4(e), and 4(f) and eastward velocities shown in Figs. 4(c), 4(d), 4(g), and 4(h). Measurements from SuperDARN are plotted in red and blue, utilizing (F -region) data both from the local radar and inferred from the global convection model, respectively. Green circle data points show the ICEBEAR velocities, which are the motions of E -region radar aurorae, as they appear and disappear inside the radar's field of view. The panels in the right column show histograms of the various velocities posted in the left column.

It is important to note that the bulk motion of irregular structures in the E region has long been poorly understood. Individual turbulent structures generally do not move faster than the local ion sound speed, that is, the zero-growth condition for the Farley-Buneman instability [47,48]. A value of around 300–600 m/s is favored. A recent paper [36] interprets the much faster apparent motion of radar aurorae as being caused by the ephemeral nature of small-scale plasma turbulence: When the instability drivers (electric field enhancements) move, new turbulent waves are continuously excited along their paths, with each turbulent wave quickly saturating and dissipating. We reiterate that the apparent radar motions, or echo bulk velocities, act as proxy measurements of the ionospheric electric field [35,36].

In Figs. 4(a), 4(b), 4(e), and 4(f) the poleward component of the various measured and estimated velocities, the distribution of ICEBEAR velocities, matches that of the local SuperDARN radar, though there is a much greater spread in the former, and the weighted mean echo velocity (weighted by the number of echoes per tracked cluster) equals the average SuperDARN convection speed inside ICEBEAR's field of view [the blue line in Figs. 4(a) and 4(b)]. However, this agreement is not the case for the eastward motions. Here ICEBEAR consistently see much faster velocities, with individually tracked clusters measuring almost 5000 m/s, in a region where the SuperDARN global data assimilation model predicts a low or even negative (westward) convection velocity.

The implication of Refs. [35,36] is that the disproportionately fast ICEBEAR velocities that we see in Fig. 4 are caused by highly localized electric field structures (see, in particular, Fig. 5 in Ref. [35] and Figs. 3 and 4 in Ref. [36]), capable of saturating the Farley-Buneman instability, that are ostensibly missed by the model-based estimation by SuperDARN.

Figure 5 shows the situation in spatial terms, with arrows representing velocities in geomagnetic coordinates. The SuperDARN-estimated convection pattern is represented by thin blue arrows, while the ICEBEAR cluster velocities are represented by red arrows (magnitude shown with a color scale), for the interval between 18:20 UT and 19:00 UT on 10 May 2024 (for a similar plot pertaining to 23 April 2023, see Fig. 5 in Ref. [28]). Figure 5 shows very clearly that the ICEBEAR-derived velocities in the E region are heavily skewed eastward, considerably faster than the convection would imply.

A. Description of geospace

We are in a position to present a sufficiently lucid description of two very similar but also very surprising datasets.

As is shown in Fig. 2, sudden storm commencement events coincided with the onset of rapid high-amplitude fluctuations in the solar wind dynamic pressure, consistent with the trigger of high-speed jets in the magnetosheath [42,49], which are known to cause aurorae in the noon sector [50], as well as a cascade in wave-energy of the various unstable modes. In both events, the solar wind dynamic pressure thereafter went through a manifold increase, causing Earth's dayside magnetosphere to compress, while the interplanetary magnetic field turned severely southward. Dayside compression events modulate wave activity [41], leading to a magnetohydrodynamic energy cascade and eventually to the formation of aurorae [51], an outcome also expected from the severely southward interplanetary magnetic field, by which time ICEBEAR observed profuse radar aurorae in the E region on closed magnetic field lines. The related paper [28] demonstrates that the above expectations were largely all brought to fruition during the 23 April 2023 event, where we establish a clear link between the radar observations and the observed energy flux of precipitating particles as well as chorus wave activity.

B. Turbulent electrodynamics on closed field lines

Figure 3 substantiates the claim that the radar observations, in both events under study, were made on closed magnetic field lines, on or very close to the open-closed field-line boundary. Furthermore, Fig. 4 makes it very clear that the tracked radar velocities were strongly skewed in the eastward direction and much faster than expected based on the modeled, global F -region convection pattern (displayed in Fig. 5).

These observations do not adhere to expectations for fast motions in and around the cusp (referring to both the proper motion of field lines and the F region $\mathbf{E} \times \mathbf{B}$ drift). Here traditional poleward-moving auroral forms are excited in the cusp, on open magnetic field lines, after which they drift poleward with the F -region convection into the polar cap (see, e.g., Fig. 8 in Ref. [6]). Instead, our observations are consistent with the mechanism evoked by Ref. [18], where the motion of auroral forms in the noon sector are powered by the polarization electric field produced by high-energy aurorae on closed magnetic field lines.

The relative positions of the ICEBEAR motions with respect to the cusp, as well as the peculiar cusp precipitation (Fig. 3), are important. As has been shown in the past [45], the most numerous and energetic protons here create an equatorward edge consisting of protons. In our observations, on the cusps immediate equatorward edge, we find the ICEBEAR echo distributions. Together with regions of dayside diffuse aurorae, which deposit negative charges, strong electric fields form individually: one pointing away from the ongoing positive charge deposition and one pointing towards the ongoing negative charge deposition. A situation superficially akin to a parallel-plate capacitor momentarily forms, with strong electric fields distributing charges equatorward in the Pedersen direction, the very currents that close the induced current systems.

It is important here to point out that the electric fields we infer are the very fields that drive the Pedersen currents that are necessitated by magnetohydrodynamic considerations, a perpendicular current of ions moved by strong electric fields.

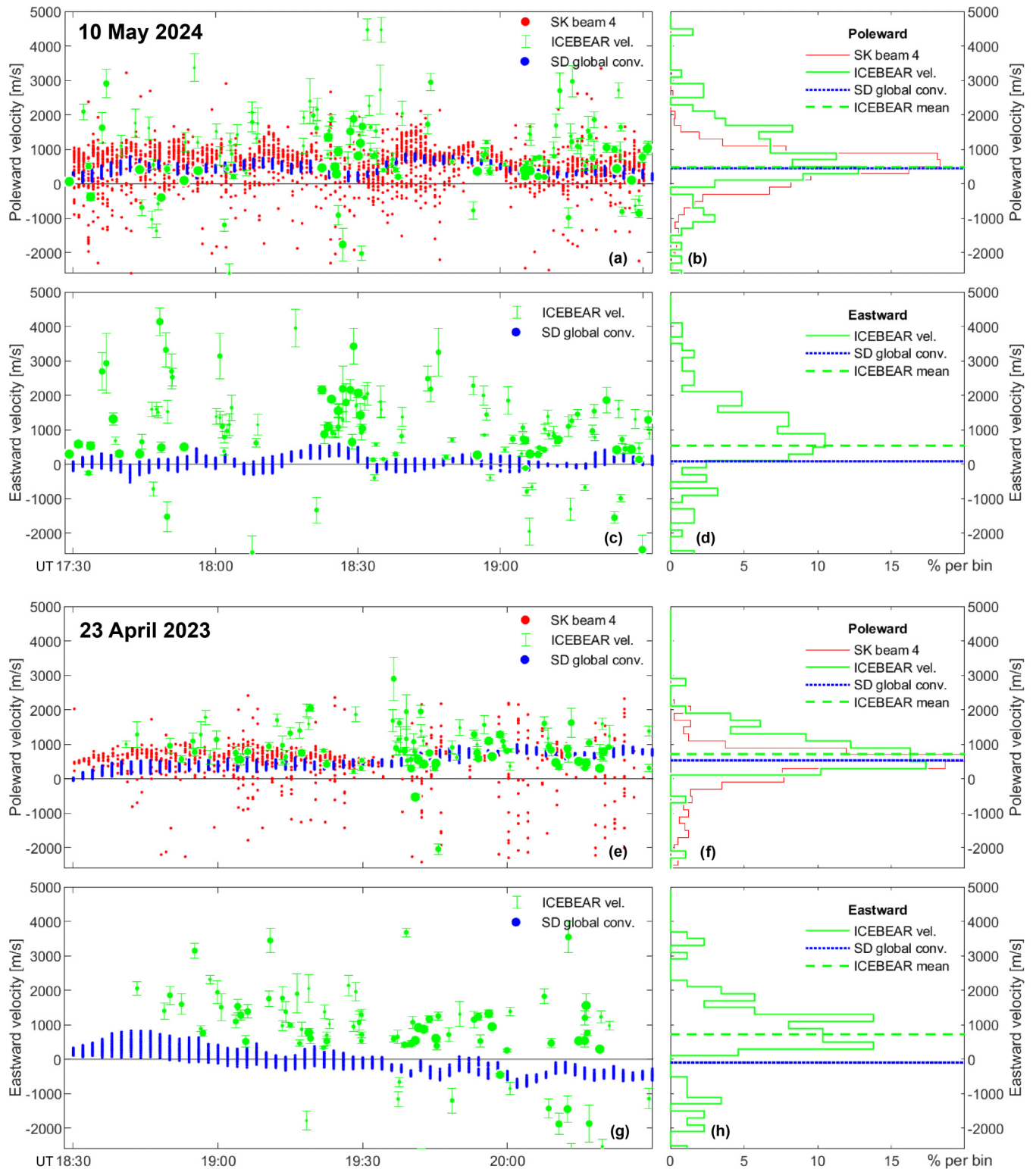


FIG. 4. ICEBEAR cluster motions (green) compared to *F*-region velocities from Super DARN, both observations (red) and model derived (blue). The left column shows the temporal development in velocities while the right column shows histograms; the four top panels show the 10 May 2024 event, while the bottom four panels show the 23 April 2023 event. Tracked ICEBEAR echo clusters were selected for containing a minimum of 300 echoes, a minimum duration of 6 s, and variability (68% confidence intervals of the linear fits of the echo cluster motion measurements) that did not exceed 2/3 of the cluster speed itself (variability is shown by green error bars). (a), (b), (e), and (f) For poleward motions, Doppler shifts measured by the Saskatoon SuperDARN radar are shown in red (using beam 4, which is pointing in the direction of the geomagnetic north pole).

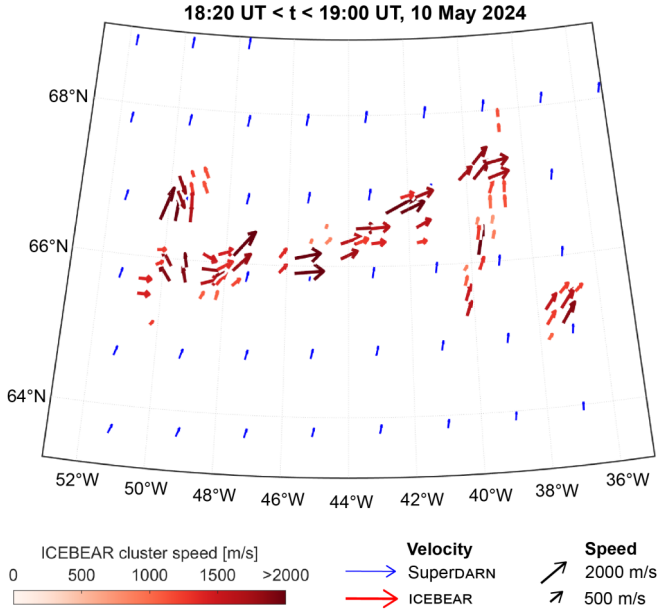


FIG. 5. ICEBEAR echo velocities in geospace are shown as red arrows (speed indicated with a color scale) and SuperDARN global convection velocity are shown as blue arrows, for a 40-min interval on 10 May 2024. See Figs. 4(a)–4(d) for a detailed description of the directions and magnitudes of the measured and estimated velocities.

The same electric fields trigger the Farley-Buneman instability inside the perpendicular current region, in the Hall direction (perpendicular to both the field lines and the Pedersen direction). Turbulent electrojets then form between the two regions in geospace, as illustrated in Fig. 1(b). This is the $\mathbf{E} \times \mathbf{B}$ drift direction, and so the effect would cause field lines equatorward of the cusp to move eastward, in addition to the poleward component associated with the global convection pattern.

III. DISCUSSION

In the present article we have shown that fast eastward motions can be observed equatorward of the cusp, in the E region, and on closed magnetic field lines. Moreover, these motions are ostensibly much faster than the simultaneously observed F -region drifts. Naively, this appears diametrically opposite to the expectations of the interplay of the E and F regions. For example, Fig. 2 in Ref. [48] shows observations of E -region Doppler speeds that were limited to the local ion sound speed (400–600 m/s), while the authors simultaneously observed that the F -region drifts were twice faster. How can we account for this seeming contradiction? The answer is relatively simple. The radar aurora motions seen by ICEBEAR track moving electric field source regions, a motion that is naturally unaffected by collisions, and is “frozen into” the geomagnetic field [35,36].

If the moving electric field structures are frozen into the geomagnetic field, SuperDARN should, during severe storms in geospace, routinely observe these eastward motions. However, compared to SuperDARN, ICEBEAR operates with 30 and 60 times higher spatial and temporal resolution, respectively. This extreme improvement in spatiotemporal resolution is

likely to have caused SuperDARN to have missed the highly transient spikes in the electric field. Such transient or spiky appearances are unsurprising. The perturbed electric fields of the auroral region are in general highly localized and dynamic [52–55] and a considerable Poynting flux lies “hidden,” as it were, in small-scale electric field enhancements [56].

Increased conductivities in the sunlit ionosphere should amplify (and be amplified by) the number flux of precipitating electrons [57], thereby further enhancing the perpendicular electric field at their emission altitude. The elevated conductivities also facilitate the formation of Pedersen currents, which in fact counteract the electric field enhancements, by virtue of neutralizing extant charges. However, the observed particle precipitation (Fig. 5 in Ref. [28]) should drastically increase the ratio of Hall to Pedersen conductance [58,59]. Since the Pedersen currents cancel the source of the Hall currents, a very high ratio speaks to the probability of there being extant, observable electrojets. In this work the Hall drifts that we observe in Fig. 4 may have appeared as the poleward portion of the auroral convection vortices, such as in predictions by Hosokawa *et al.* [59,60].

Although a strong equatorward electric field is expected poleward of diffuse aurorae [61], this is not among the established expectations for the region equatorward of the cusp. However, inspecting Fig. 3, we do note that peak proton precipitation occurred on the equatorward side during the two events, and such a configuration is indeed established in the literature for southward interplanetary magnetic field configurations [45]. The results can therefore be taken into account for further proof in support of a distinct equatorward proton edge in the cusp, one that is shifted sufficiently equatorward to be noticeable by the electric field record in its equatorward vicinity.

The observations in the present paper, illustrated in Fig. 1(b), are essentially what superficially resemble poleward-moving auroral forms, but, instead of moving with the magnetospheric convection on open field lines from the cusp and into the polar cap, transient excursions away from equilibrium, observed equatorward of the cusp, came in the form of fast eastward motions. While these motions were triggered by bursts of wave-particle activity on closed magnetic field-lines in Ref. [28], bursts of proton precipitation in the cusp may in principle likewise control the temporal evolution of the signal.

IV. CONCLUSION

Traditional poleward-moving auroral forms move on open field lines [3,11] and their effects are felt in the F -region ionosphere [8,12,14]. In a similar fashion albeit in different ways, transient, turbulent electrojets can be excited equatorward of the cusp ionosphere during disturbed conditions, powered in part by high-energy diffuse aurorae, a staple phenomenon in the dayside ionosphere during geospace disturbances [21,22,62]. (In the Appendix we elucidate the routine expectations of having dayside, high-energy diffuse particle precipitation equatorward of the cusp.) The observed mechanism (and the theory developed in Ref. [18]) can potentially be woven into a substantial part of the body

of knowledge concerning dynamic dayside aurorae and the magnetosphere-ionosphere coupling.

Our study is based on an analysis of two case studies that occurred during two recent, major geospace storms. Similar observations may have eluded previous efforts in part due to the difficulty of observing the *E*-region ionosphere, which has led to a scarcity in reliable data [63]. Exacerbating this, ICEBEAR is located at auroral latitudes and is not likely to observe the cusp on a regular basis. Further studies of the phenomenon are needed, and in this regard the rich dataset analyzed in the present study may yield additional insights through modeling efforts [64]; especially pertinent will be the changes to Joule heating rates brought on by the introduction of intense Farley-Buneman turbulence [65,66].

In closing, we have observed a dynamic phenomenon near the ionospheric cusp, pertinent to flux of protons through the cusp itself, as well as the transient energy exchanges between the magnetosheath and the dayside ionosphere on closed magnetic field lines. The fast motions that we have observed share some key characteristics with poleward-moving auroral forms, but the two phenomena have starkly different causes. Naturally, they are not mutually exclusive, but can both be taken to account for observations of strong electric field modulations near the ionospheric cusp.

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DATA AVAILABILITY

The data that support the findings of this article are openly available: the ICEBEAR 3D echo data are available from [30,67,68], the supermag data are available from [69], and the solar wind data from NASA's OMNI service are available from [70]; NOAA-18 data are available from [71]; SuperDARN Canada data are available from [72]; embargo periods may apply.

APPENDIX

To provide additional evidence for our explanation beyond the two case studies already covered, we introduce a statistical representation of the particle precipitation landscape near the cusp region during disturbed conditions. For this purpose, we turn to the U.S. Defense Meteorological Satellite Program (DMSP), a long-lasting mission to study the causes of space weather in the topside ionosphere, whose instru-

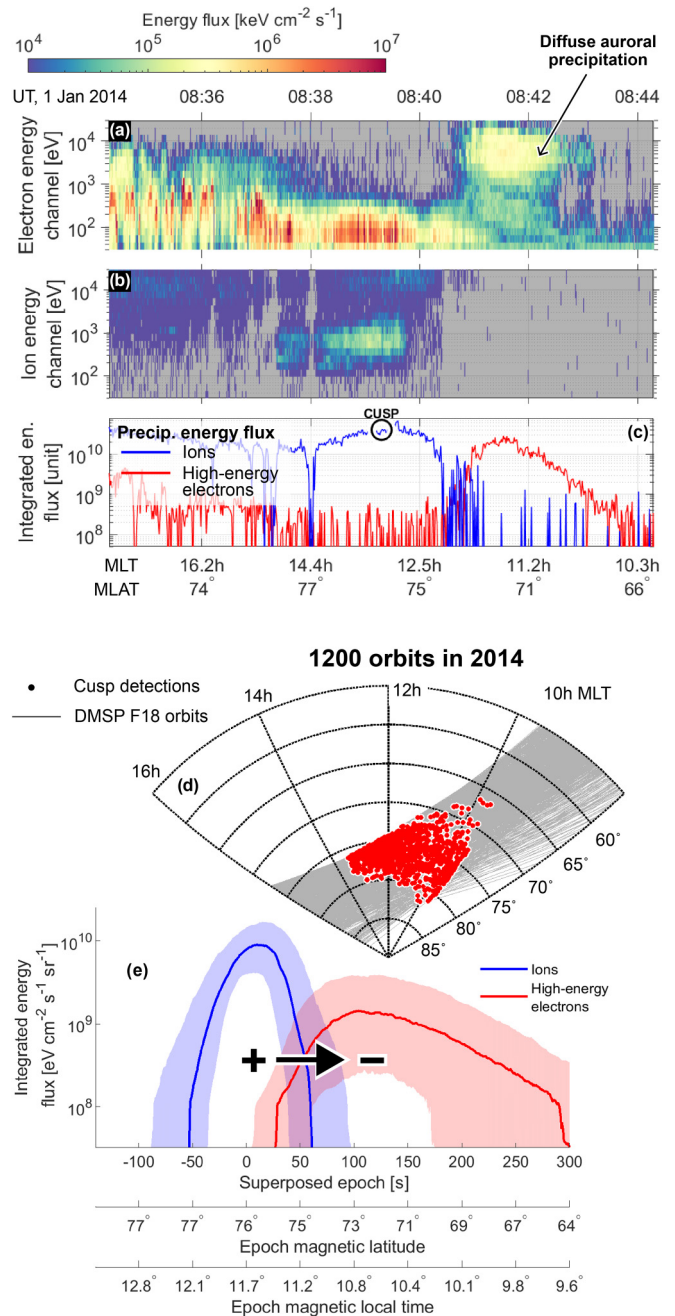


FIG. 6. Precipitating (a) electron and (b) ion energy fluxes during an orbital pass by the DMSP F18 satellite on 1 January 2014, with particle energy along the *y* axes. (c) Integrated ion (blue) and high-energy electron (red) fluxes, with the location of the cusp indicated. (d) All 1200 orbits made during disturbed conditions (SuperMAG auroral electrojet index greater than 192 nT) in 2014, during which the cusp was identified (red circle points, geomagnetic noon is upward and dawn is to the left). (e) All 1200 passes through the cusp in a superposed epoch analysis, with the integrated ion and hard electron fluxes as blue and red lines (shaded regions indicate upper and lower quartile distributions).

mentation offers precise measurements of the precipitating particle fluxes.

The DMSP satellites operated with heliosynchronous dawn-dusk polar orbits at an altitude of around 840 km,

covering most of the northern hemisphere, dayside high-latitude ionosphere. The Special Sensor J instrument consisted of particle detectors that measured the number of energy fluxes of precipitating electrons and ions through 19 energy channels, sensitive to energies between 30 eV and 30 keV, and the instrument operated with a measurement frequency of 1 s [73]. We characterize the high-energy electron precipitation by integrating over energy channels between 2 and 30 keV, following the method outlined in [73]. Furthermore, we classify each precipitating particle as having been directly sampled in the cusp, following Refs. [44], [43]. Here a cusp data point is defined as having an average precipitating electron energy lower than 220 eV, an average precipitating ion energy higher than 300 eV and lower than 3000 eV, a precipitating electron energy flux through channels 2 and 5 keV being lower than 10^7 keV cm⁻² s⁻¹ sr⁻¹, and a total integrated ion energy flux that should exceed 2×10^9 keV cm⁻² s⁻¹ sr⁻¹.

After many decades of operation, the DMSP mission is winding down, and there is very limited coverage during the years of our case studies, and so we have analyzed data from 2014, an active year. Figures 6(a)–6(c) show a pass through the ionospheric cusp by the DMSP F18 satellite on 1 January 2014. The orbit brought the satellite directly through the cusp,

after which it traversed a region of characteristic dayside diffuse aurorae [indicated with a black arrow in Fig. 6(a)]. The two regions are separated in space, with the latter appearing directly equatorward of the former.

Next we analyze the 1200 orbits that occurred during disturbed conditions and during which the cusp was successfully identified in the data [Fig. 6(d)]. Figure 6(e) shows a superposed epoch analysis of all these orbits, centered on the cusp ($t = 0$ s), with blue and red lines showing the integrated ion flux and the integrated flux of high-energy (greater than 2 keV) electrons, respectively. This view of the cusp region is not new and is reflected in climatological studies of particle precipitation [44,74].

If we discount the intense, soft electron flux inside the cusp (which will be stopped by Earth's atmosphere far above the *E* region [25,75]), the two fluxes in Fig. 6(e) will produce transient space-charge fields that are entirely consistent with the particle precipitation landscape that we are immersed in. While it is highly unlikely that this situation is sufficient to produce measurable electric fields in all 1200 orbits, the superposed epoch analysis in Fig. 6 presents unequivocal evidence that the conditions necessary for the observations are a routine feature of the noon-sector ionosphere.

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