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Possible connection of polar cap flows to pre- and post-substorm onset PBIs and streamers

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[1] Recent analysis of a short period of observations has led to the hypothesis that enhanced meso-scale flows from well within the region of open polar cap field lines may cross the nightside polar cap boundary into the closed field line region and contribute to the triggering of equatorward (earthward) meso-scale flows across the ionospheric (equatorial) portion of plasma sheet fields lines and lead to PBIs and streamers. This includes the streamers that have been postulated to bring new plasma equatorward (earthward) and lead to substorm onset. Meso-scale structure of flow within the polar cap, often studied near the dayside polar cap boundary, has not previously been generally recognized as significant within the nightside polar cap. Here we have taken advantage of new capabilities to measure polar cap convection by the Resolute Bay incoherent scatter radar and the Rankin Inlet PolarDARN radar, coordinated with THEMIS all-sky imager observations, to study flow measurements from well within the polar cap to near the polar cap boundary. We present evidence that flow structures moving from the polar cap toward the nightside polar cap boundary may be important for triggering the flows that lead to substorm onset streamers. The new observations also have given evidence that the flow structures come from deep within the polar cap, and have given unexpected evidence that a continuation of flow structures moving from the polar cap toward the nightside polar cap boundary after substorm onset may be important in controlling the poleward expansion and duration of post-onset auroral activity.

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1. Introduction

[2] *Nishimura et al.* [2010b] used observations from the all-sky imager (ASI) array [*Mende et al.*, 2008] of the THEMIS program [*Angelopoulos*, 2008] to suggest a possible resolution to the long-standing problem of determining the sequence of events leading to substorm onset. Figure 1, based on the schematic summary by *Nishimura et al.* [2010b], illustrates this sequence within the ionosphere, numbers 1–4 indicating the time ordering of pre-onset phenomena discussed in here. A repeatable auroral sequence was often observed, starting with formation of a poleward boundary intensification (PBI) (at time 2 in Figure 1) near the auroral poleward boundary, which lies approximately along the boundary between open and closed magnetic field lines, or magnetic separatrix. A roughly north–south oriented (NS) auroral streamer then extends equatorward from the PBI toward the equatorward portion of the aurora oval. Substorm auroral onset occurs either near the location where the streamer first reaches a growth phase arc located near the equatorward boundary of the auroral oval or after an enhanced auroral luminosity region moves azimuthally (generally westward) along the growth phase arc to the onset location. The average time between PBI intensification and substorm onset was found to be 5.5 min. It is well known that inner plasma sheet conditions must be appropriate for a substorm onset to be possible, and many streamers do not lead to onsets [*Henderson et al.*, 2002; *Nakamura et al.*, 2001; *Sergeev et al.*, 2000]. However, it has been found that pre-onset streamers that do not lead to onset may be important for setting up inner plasma sheet conditions that are favorable for an ensuing streamer to lead to onset [*Nishimura et al.*, 2010c].

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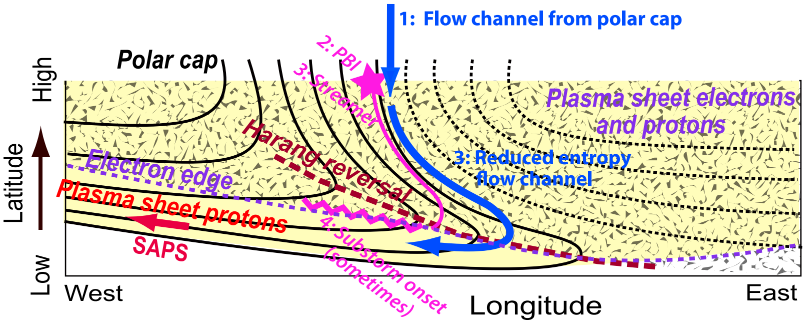

Figure 1. Schematic illustration of motion of pre-onset auroral forms and their relation to nightside ionospheric convection and flow channels based on *Nishimura et al.* [2010b]. The pink star, NS oriented pink line, and azimuthally extended wavy lines indicate a PBI, an auroral steamer, and an onset arc, respectively. Blue arrows illustrate the plasma flow pattern inferred by Nishimura et al. and from the polar cap flow observations considered here. Numbers 1–4 show the time sequence of pre-onset phenomena discussed in this paper. Yellow and mottled shading, respectively, correspond to the regions of proton and electron precipitation, SAPS refers to the region of sub-auroral polarization streams that lies equatorward of the inner edge of plasma sheet electron precipitation, and black curves represent the large-scale background convection flow pattern.

[3] Auroral PBIs and streamers are known to be associated with the converging electric fields that lie along the westward edge of longitudinally localized, equatorward-directed ionospheric flow channels, which map along magnetic field lines to earthward flow channels within the plasma sheet [*de la Beaujardière et al.*, 1994; *Henderson et al.*, 1998; *Liang et al.*, 2004; *Lyons et al.*, 1999; *Nakamura et al.*, 2001; *Pitkänen et al.*, 2011; *Sergeev et al.*, 1999; *Zesta et al.*, 2002, 2000]. Based on this association, *Nishimura et al.* [2010b] suggested that new plasma crosses the polar cap boundary into the plasma sheet over a longitudinally localized region and then intrudes to the equatorward portion of the plasma sheet precipitation region (near-Earth region of the plasma sheet), leading to onset. Evidence for enhanced flows crossing the separatrix into the plasma sheet prior to substorm onset has been seen in the ionosphere with the Sondrestrom radar [*Lyons et al.*, 2010a] and with THEMIS spacecraft near the outer boundary of the plasma sheet [*Angelopoulos et al.*, 2008, 2009; *Lyons et al.*, 2010b]. Additionally, evidence of the flows propagating within the central plasma sheet toward the inner plasma sheet in association with streamers leading to onset has been seen by the THEMIS spacecraft [*Xing et al.*, 2010] and in the ionosphere by the Poker Flat Incoherent Scatter Radar [*Lyons et al.*, 2010a].

[4] Potentially important for understanding the source of the channels of enhanced flow leading to streamers and proposed to lead to substorm onset is the observation that flow enhancements leading to PBIs can cross into the plasma sheet from the high latitude, polar-cap region [*de la Beaujardière et al.*, 1994; *Lyons et al.*, 2010a, 2010b]. *Nishimura et al.* [2010c] found several narrow flow bursts within the nightside ionosphere moving from far within the nightside polar cap toward the polar cap boundary and leading to PBIs that are followed by streamers, including one that led to a near-Earth substorm onset. This association led *Nishimura et al.* [2010c] to hypothesize that enhanced meso-scale flows from well within the region of along open polar cap field lines may contribute to the triggering of the meso-scale earthward flows along plasma sheet field lines that lead to PBIs, streamers, and substorm onset. This hypothesis is illustrated in Figure 1 by the flow channel from the polar cap, which would occur at a time (time 1 in the figure) preceding the flow entry into the closed field line region, which would be the time of PBI formation. Meso-scale flow structures, while often studied and recognized as important within the plasma sheet, have not previously been considered significantly within the nightside polar cap. Additionally, a direct connection between flow structure within the polar cap and disturbances along plasma sheet field lines has not previously received attention within the community. If this structuring and its connections to plasma sheet flows and disturbances are found to indeed be important, it could be of substantial importance to our understanding on causes of plasma sheet disturbances.

[5] The PolarDARN radar program was designed to study flow structures within the polar cap, and the first PolarDARN HF radar began operating in 2005 at Rankin Inlet (RANK, magnetic latitude Λ = 73.1°N) [*Koustov et al.*, 2009]. Also the incoherent scale AMISR radar RISR-N at Resolute Bay (Λ = 83.9°N) [*Bahcivan et al.*, 2010] has recently begun operations. Both of these new radars make measurements poleward of the THEMIS ASI located at RANK. Here we focus on substorms and take advantage of these new capabilities to make an initial study of ionospheric flow measurements from well within the polar cap to near the polar cap boundary to determine whether we find evidence that flow structures moving from the polar cap toward the nightside polar cap boundary lead to onsets. We also look for evidence that these flows lead to the streamers that have been postulated to bring new plasma earthward and lead to substorm onset, and we discuss unexpected evidence that a continuation of flow structures moving from the polar cap toward the nightside polar cap boundary after onset may be important in controlling the poleward expansion and duration of post-onset auroral activity.

2. Observations

[6] Figure 2 shows the field-of-views (FOVs) of the PolarDARN and RISR-N radars, and the locations of the

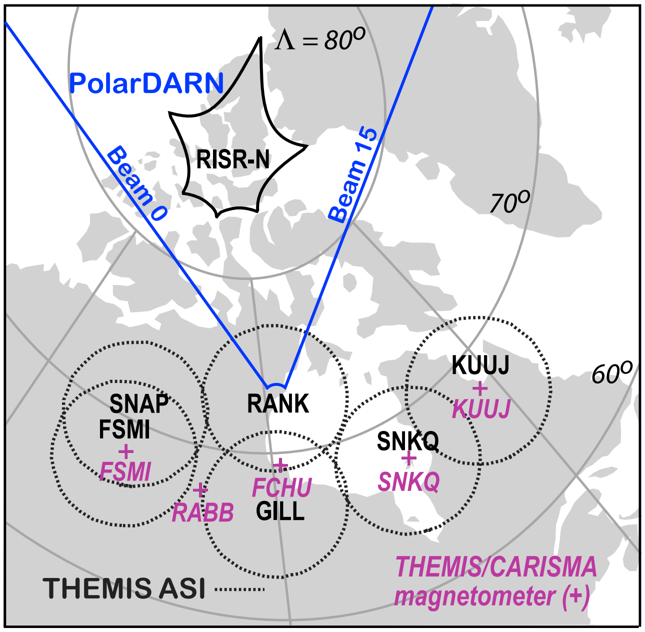

Figure 2. Field-of-views (FOVs) of the PolarDARN and RISR-N radars, and the locations of the ground magnetometers and ASIs used in this study. Dashed circles give approximate FOVs of the ASIs and longitude lines are spaced 3 h in MLT apart.

ground magnetometers and ASIs used in this study. Dashed circles give approximate FOVs of the ASIs. It can be seen that the PolarDARN and RISR-N have excellent views of polar cap flows poleward of comprehensive auroral zone ASI and magnetometer coverage. RANK lies near the typical Λ of the poleward boundary of the auroral oval [*Lyons et al.*, 1999], and is at an ideal longitude for the RANK ASI to detect PBIs and streamers that might be related to incoming polar cap flow structures detected by PolarDARN and RISR-N. The other ASIs in Figure 2 give thorough coverage of the main portion of the auroral oval and allow for detection of substorm features within $\sim$1 h of MLT of the RANK meridian.

[7] After RISR-N became fully operational during August 2009, there were 15 nights of observations in the mode designed for measuring large-scale convection from Aug 26 to Nov. 9. Winter ionospheric densities during the extreme solar minimum became too low for larger-scale convection monitoring after Nov. 9. We found that three of these nights satisfied the criteria that there was good echo coverage from PolarDARN, that auroral viewing conditions were sufficient for identifying activity by one or more of the ASIs in Figure 2, and that at least one auroral substorm onset could be identified with the ASIs during $\sim$0430 to 0730 UT, when RANK is at $\sim$22–01 MLT.

2.1. 21 September 2009, 0626:30 UT Onset

[8] Figure 3 shows an overview of conditions from 04 to 09 UT on 21 September 2009. From top to bottom are shown the IMF B_z and B_y time shifted to just upstream of the magnetopause nose by the Weimer technique [*Weimer et al.*, 2002], the flow magnitude versus Λ obtained from the multibeam line-of-sight (LOS) velocities measured by RISR-N assuming longitudinal uniformity across the radar FOV [*Heinselman and Nicolls*, 2008], keograms of white-light auroral intensities from the SNKQ and FSMI ASIs along the ASI magnetic meridian from the most equatorward (pixel 0) to the most poleward image pixels, and ground magnetic observations from the same two stations. Solid vertical gray lines give the onsets of four auroral substorms, which were identified by brightenings near the equatorward portion of the auroral oval and subsequent poleward expansion in the two-dimensional ASI auroral images (discussed later). Onset times are identified to the nearest 30 s using the images, which are available with 3 s time resolution. These onsets can be seen in Figure 3 as intensifications in the auroral keograms and ground magnetic perturbations at one or both of stations shown. The auroral and magnetic activity starting near 0750 UT (dotted vertical line) is seen in the ASI images to be PBIs and streamers initiating near the poleward boundary of the auroral oval, and is not discussed further.

[9] The RISR flow magnitudes in Figure 3 show flow speed enhancements initiating $\sim$10–15 min prior to each of the substorm onsets. Figure 4 displays an overview of the RISR-N and PolarDARN observations for this period. The RISR-N data are shown as both flow magnitude and flow vectors versus latitude. The PolarDARN observations are shown as LOS flow speeds (positive toward the radar) as a function of Λ along 2 of the 16 radar beams. The LOS flows are displayed using two velocity scales, one for $\Lambda > 78°$ that is appropriate for echoes from the *F* region, where the ion flow velocity equals the electric field drift velocity, and the other for $\Lambda < 80°$ that mainly reflects the lower speeds that occur within the *E* region, where the ion flow velocity is reduced in magnitude and deflected toward the direction of the electric field by collisions.

[10] Flow speed enhancements can be seen $\sim$10–15 min prior to each of the substorm onsets in the PolarDARN observations as well as the RISR-N observations, clear flow enhancements being identified by solid magenta ellipses and less-clear possible enhancements by dashed magenta ellipses. Enhancement can be seen in the PolarDARN flows from the higher latitudes that are also covered by RISR-N (for 3 of the onsets) to close to the lowest observable latitude of 74° (for 3, and possibly all 4, of the onsets). Note that there is no clear evidence of a propagation of the flow enhancements from higher to lower latitudes. This could be a result of longitudinal motion of flow enhancements that are narrow in longitude or it could indicate that flow changes initiate across the polar cap more rapidly than expected from simple flow propagation. Such a more rapid response has been seen for large-scale ionospheric convection [*Ridley et al.*, 1998; *Ruohoniemi and Greenwald*, 1998; *Senior et al.*, 2002] as well as for magnetospheric convection [*Nishimura et al.*, 2010a] and has been related to the effect of ionospheric incompressibility and to energy transmission in the ground-ionosphere waveguide [*Kikuchi*, 2005], both of which would cause a displacement within a localized region to give rise to drifts over a much larger area [*Lockwood and Cowley*, 1999; *Ruohoniemi et al.*, 2002].

[11] To examine the relationship between the measured radars flows and the simultaneous auroral activity, we overlay the LOS flow vectors from each radar beam over a merging of the auroral images from the ASIs in Figure 2 that give the best coverage of the auroral activity for each onset.

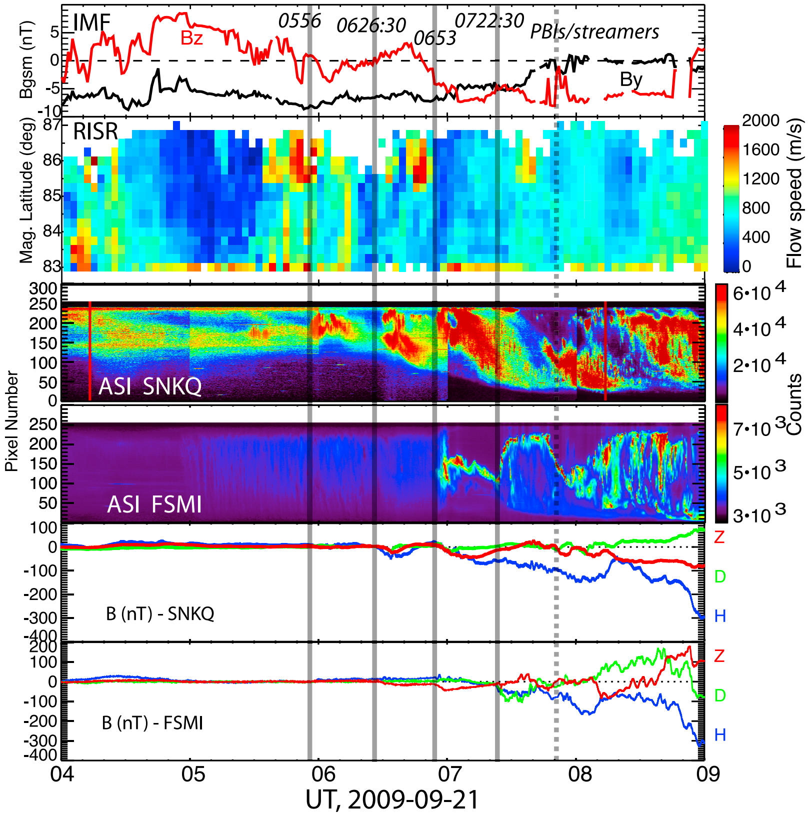

Figure 3. Overview of conditions from 04 to 09 UT on 21 September 2009. From top to bottom are shown the IMF B_z and B_y time shifted to just upstream of the magnetopause nose, RISR-N flow magnitude versus Λ, keograms of white-light auroral intensities form the SNKQ and FSMI ASIs along the ASI magnetic meridian (pixel 0 is the most equatorward), and ground magnetic observations from SNKQ and FSMI. Solid vertical gray lines give the onsets of four auroral substorms, and a dashed vertical gray line identifies the approximate beginning of period with enhanced PBIs and streamers. The two red vertical lines in the SNKQ keograms are from light contamination.

The most ideal combination of auroral and radar coverage occurred for the 0626:30 UT onset on 21 September 2009, an event with moderate auroral expansion though relatively weak detected ground magnetic perturbation. A time sequence of selected flow-image overlays for the period of this onset is given in Figure 5. A file of overlays for every 30 s from 0530 to 0810 UT, covering all the onsets in Figures 3 and 4, is given in Figure S1 in the auxiliary material (images are viewable individually or can be played as a movie with a PDF viewer).[1] The RISR and PolarDARN flows, available with 3 min and 1 min resolution, respectively, that are overlaid in each panel are from the measurement interval with center time nearest the image time.

[12] For this ideal event, a flow enhancement is first seen in the westward and poleward looking beams of RISR (0612 UT), as indicated by the orange arrow. These flows are directed southeastward, based on the RISR flow vectors in Figure 4. Then, as indicated in Figure 5, an equatorward directed LOS flow enhancement is seen in the highest latitude echoes of the eastern PolarDARN beams starting at 0616 UT. A longitudinally limited band of equatorward flows are then soon seen (starting at 0617 UT) centered slightly to the east of the center of the PolarDARN FOV from Λ = 74° to 79°, and this channel of enhanced flow appears to be directly connected to an auroral streamer that is seen extended from Λ ~ 72° toward the diffuse auroral band lying near the equatorward boundary of the auroral oval. The enhanced flow channel then moves westward within the PolarDARN FOV, and the streamer moves westward along with the flow channel. Westward motion continues until ~0622 UT, and the auroral substorm onset is clearly seen at 0627 UT very near the longitude of the flow enhancement and the streamer just after the streamer extended equatorward and contacted the pre-existing azimuthally aligned aurora near the auroral equatorward boundary. The flow enhancement gradually decreases and is no longer seen by 0634 UT, and the aurora expands modestly to Λ ~ 71°.

[13] The flow channel that appears to lead to the substorm onset is narrow in longitudinal extent, much narrower than expected for large-scale convection, and is seen persistently for the 10 min period prior to onset from Λ ~ 78° to the most equatorward PolarDARN range gate at Λ = 74°. It is tempting to connect this flow channel to the flow enhancements seen earlier at higher latitudes by PolarDARN and RISR-N, suggesting that the enhanced flow propagated from well within the polar cap, although it is not possible to

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011JA016850.

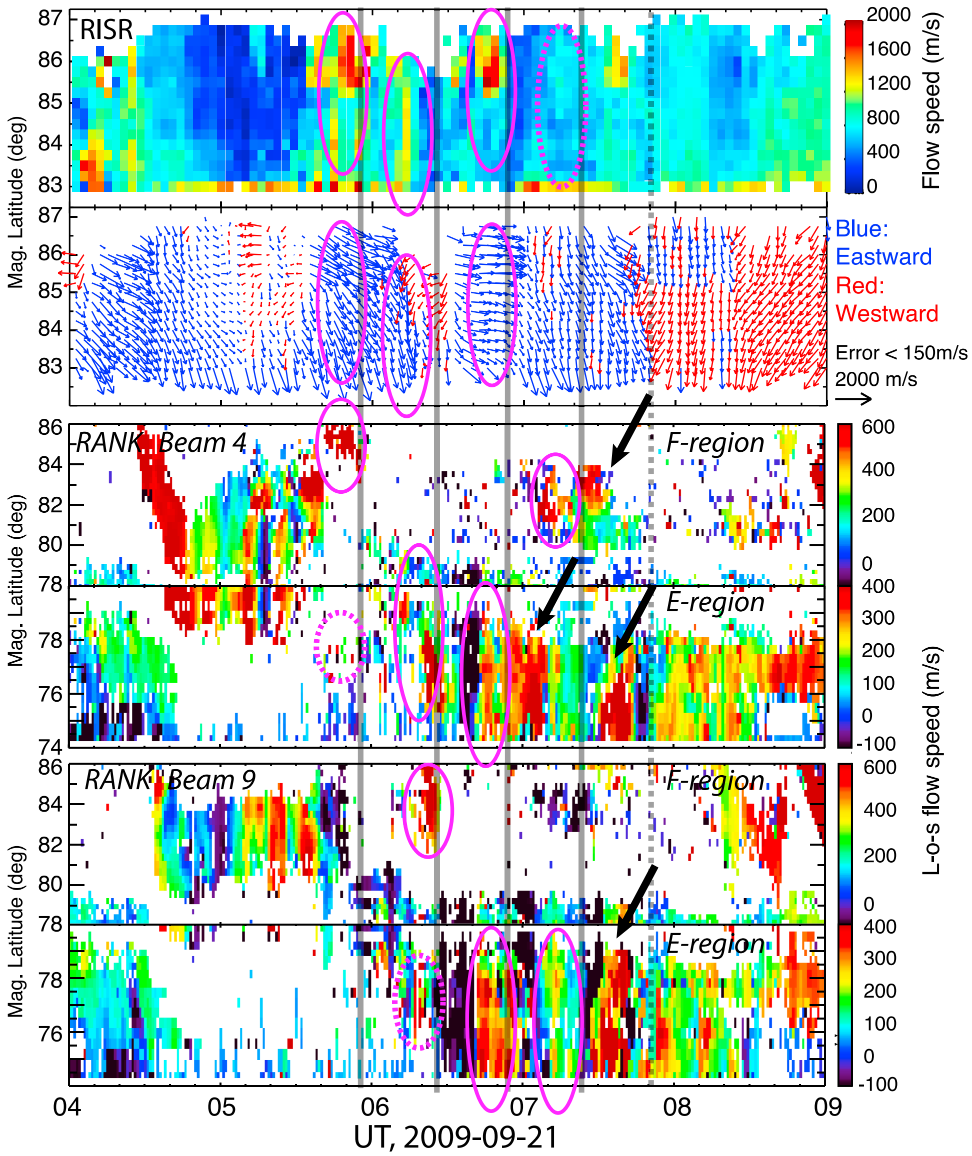

Figure 4. Overview of the RISR-N and PolarDARN observations for 04–09 UT on 21 September 2009. The RISR-N data are shown as both flow magnitude and flow vectors versus latitude. The PolarDARN observations are shown as LOS flow speeds (positive toward the radar) as a function of Λ along 2 of the 16 radar beams, increasing beam numbers identifying increasingly eastward beams as illustrated in Figure 2. Clear flow enhancements preceding an onset are identified by solid magenta ellipses and less-clear possible enhancements before an onset by dashed magenta ellipses. Heavy black arrows along the LOS velocities identify prolonged periods of post-onset flow enhancements.

reliably determine if there was such a connection using the available LOS flow measurements. The connection of this flow channel to the streamer and the ensuing onset seems quite clear. However, this is only one event, and it is quite fortuitous to find an event with a flow channel and a streamer appearing to lead to onset within the narrow longitude sector of the most equatorward PolarDARN range gate and to remain within that longitude range while moving azimuthally. None of the rest of the events we have identified are this ideal.

[14] It is also interesting to note that the flow enhancements poleward of the post-onset auroral activity continue until 0634 UT, and poleward expansion of the aurora ceases and auroral activity begins to decrease at about that time. Below we examine the extent to which the pre-onset polar-cap flow signatures seen in the above ideal example are seen in our other examples, and we explore the possible connection between the polar-cap flows and post-onset auroral expansion and activity.

2.2. 21 September 2009, Other Onsets

[15] Figure 6 shows time sequences of selected flow-image overlays for the other three identified onsets on 21 September 2009, and Figure S1 includes overlays for every 30 s for these events. Prior to the 0556 UT onset, a substantial increase in flow was seen in the western beams of

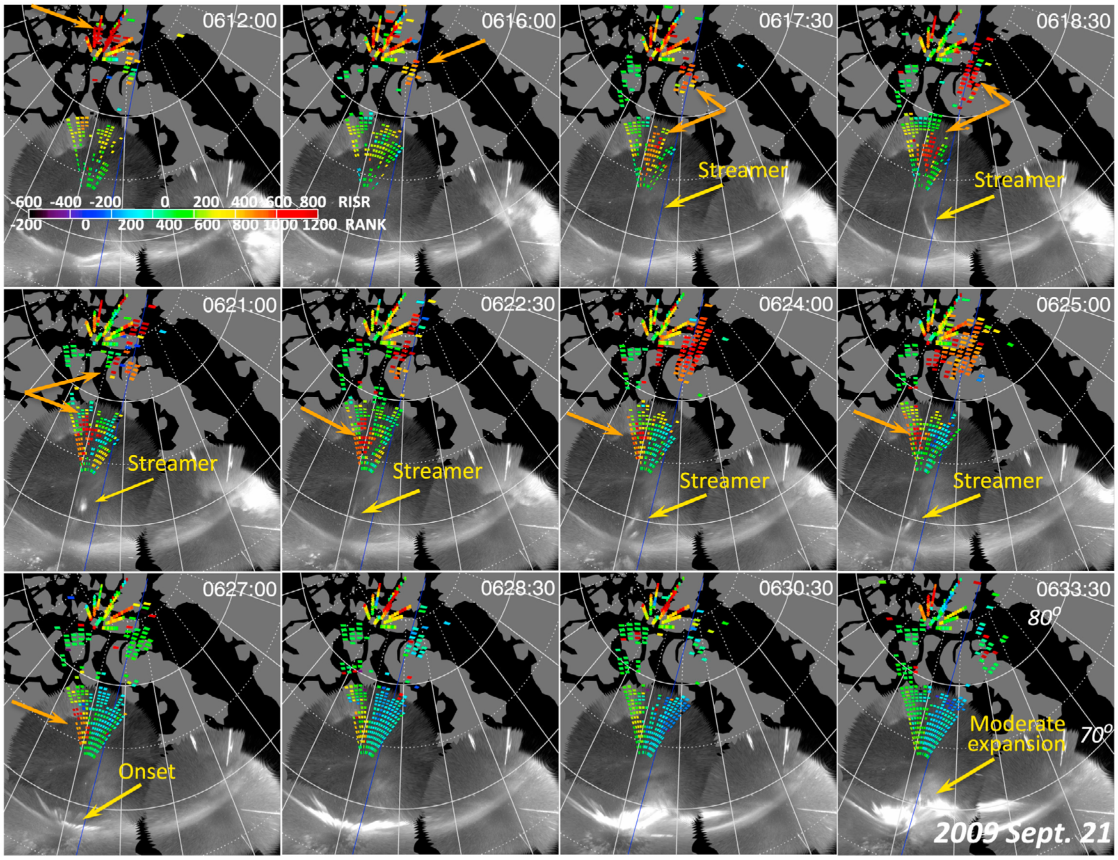

Figure 5. Selected overlays of all LOS flow vectors from each radar beam over a merging of the auroral images from the ASIs in Figure 2 that give the best coverage of the auroral activity for each onset. The time sequence is for the 0626:30 UT onset on 21 September 2009. Yellow arrows identify aurora features discussed in the text, and orange arrows identify equator directed LOS flow channels. To clearly show the onset, the image with the onset auroral brightening identified is for a time slightly (~1 min) after the image with the first auroral signature of onset. The blue line marks magnetic midnight. And longitude lines are spaced 1 h apart.

RISR-N at 0544 UT. As can be seen from the flow vectors in Figure 4, the enhanced flow was directed southeastward. Enhanced flows then were seen in the eastern PolarDARN beams at $\Lambda > 80°$, as indicated by the arrow in the 0550:00 UT panel of Figure 6. Some weak enhancement in equatorward flow was also seen at lower Λ in the easternmost PolarDARN echoes at 0550 and 0556 UT, and, while there was some interference by clouds passing through the FOV of the GILL ASI, there is some evidence for a weak streamer at 0556 UT, just prior to the first auroral signature of onset (at 0556:12 UT, based on the every 3 s ASI images). This possible streamer was a little to the east of the lowest latitude portion of the PolarDARN FOV, so that main part of any incoming polar cap flow channel that might have been responsible for the streamer would be expected to be located east of the radar FOV. Poleward auroral extension was very limited after this onset, only reaching $\Lambda \sim 69°$, and expansion phase auroral activity quickly ceased and became no longer discernible by 0612 UT. It is interesting that, despite the auroral onset occurring near the central PolarDARN magnetic meridian, substantially enhanced equatorward flow channels were not persistently observed after the onset at $\Lambda < 80°$ by PolarDARN for this event that had limited auroral poleward expansion and limited activity after the onset.

[16] After activity from the 0626 UT onset died down, enhanced flows were detected by the western beams of RISR and at $\Lambda < 80°$ by PolarDARN at ~0645 UT. A strong, equatorward directed flow channel then appeared in the eastern PolarDARN beams at 0649 UT. This flow channel appears to have then connected to an auroral streamer seen at 0651:30 UT and then to the substorm auroral onset seen at 0653 UT near the equatorward edge of the FOV of the RANK ASI (clouds interfered with the ASI observations at the more equatorward GILL ASI during this event). This pattern of an equatorward directed flow channel appearing to directly lead to a streamer and then to substorm onset is the same as for the 0626 UT onset, though pre-onset azimuthal motion was not seen for this event. One major difference between this event and the previous two events is that post-onset active aurora expanded substantially further poleward (to $\Lambda \sim 72.5°$) and substantial PBI/streamer activity persisted to after 0710 UT. Also, unlike for the previous two events, PolarDARN persistently observed strong flow channel activity until 0710 UT directed toward the region of

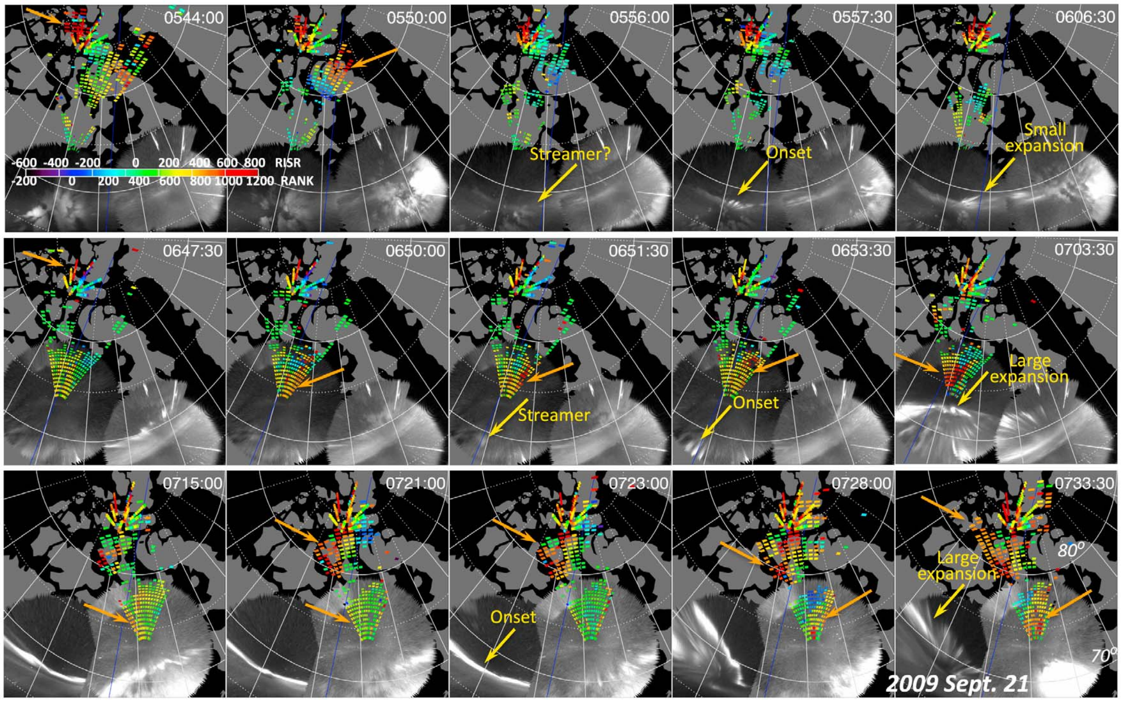

Figure 6. Same as Figure 5, except for the other onsets on 21 September 2009.

the persistent auroral activity. These flows are seen from Λ = 74 to 78°. They are identified in the PolarDARN observations in the 0703 UT overlay in Figure 6, with a heavy black arrow along the beam 4 LOS velocities in Figure 4, and can be clearly seen in Figure S1.

[17] The 0722:30 UT onset occurred slightly to the west of the PolarDARN FOV. This onset was to the west of remnant activity from the previous onset, and, as can be seen from the 30 s images in Figure S1, was not connected to that activity. Equatorward directed flows can be seen in the westernmost PolarDARN beams starting at 0713 UT extending from Λ > 80° to the lowest latitude of observations. This flow channel is identified in the 0715 and 0721 UT overlays in Figure 6, and it continued to be seen until about 1 min before the auroral onset. While some PBI activity can be seen within the FOV of the RANK ASI just prior to onset, it is not possible to identify a specific streamer that led to the onset. This could be a result of viewing conditions at RANK becoming limited by scattering of light from the own of Rankin Inlet clouds. As with the previous event, post-onset active aurora expanded substantially poleward (to Λ ~ 72.5°) and persisted for a prolonged period of time after onset (to ~0747 UT), and strong equatorward-directed flow channel activity persisted during this post-onset period within the PolarDARN FOV (until ~0745 UT). The auroral activity was detected primarily by the FSMI ASI, scattered light limiting the viewing of activity within the RANK ASI FOV.

2.3. 26 and 27 August 2009 Onsets

[18] Figures 7 and 8 show, respectively, overviews of conditions from 0230 to 0730 UT on 26 and 27 August 2009 in the same format as Figure 3. Two auroral onsets occurring relatively close together in time were identified on both nights using the images with 3 s time resolution. The auroral activity and ground magnetic signatures were larger for the second of the two onsets on each night. The RISR flow magnitudes in Figures 7 and 8 show a modest flow speed enhancement initiating ~10 min prior to the first onset on 26 August and a stronger enhancement ~20 min prior to the first onset on 27 August.

[19] Figures 9 and 10 display an overview of the RISR-N and PolarDARN observations for 2 h periods that include the two onsets on each of these nights. The format is the same as for Figure 4. Equatorward LOS flow speed enhancements can be seen in the *E* region PolarDARN flows starting just before each of the onsets on 26 August. Enhanced flows at higher latitudes are seen in the *F* region before the second onset, but there were no radar echoes prior to the time these flows were first observed so that it is not possible to determine when these flows actually began. Enhanced equatorward flows in the PolarDARN observations are seen prior to the first onset on 27 August at Λ > 78° starting near the same time as seen by RISR-N; however enhanced flows were not seen at the lowest PolarDARN latitudes until a few minutes prior to the onset. Enhanced equatorward flows can also be seen starting ~5 min prior to the second onset on 27 August.

[20] Figure 11 shows time sequences of selected flow-image overlays for the time periods including both onsets on 26 August (Figure 11, top) and 27 August (Figure 11, bottom). The display is the same as in Figures 5 and 6, except that different flow scales are applied to the lower latitude PolarDARN *E* region echoes than for the RISR and the higher latitude PolarDARN *F* region echoes. A curved white line in each overlay separates the regions where each scale was used for the PolarDARN flows. File of overlays for every 30 s from 0530 to 0730 UT on 26 August and from 0300 to

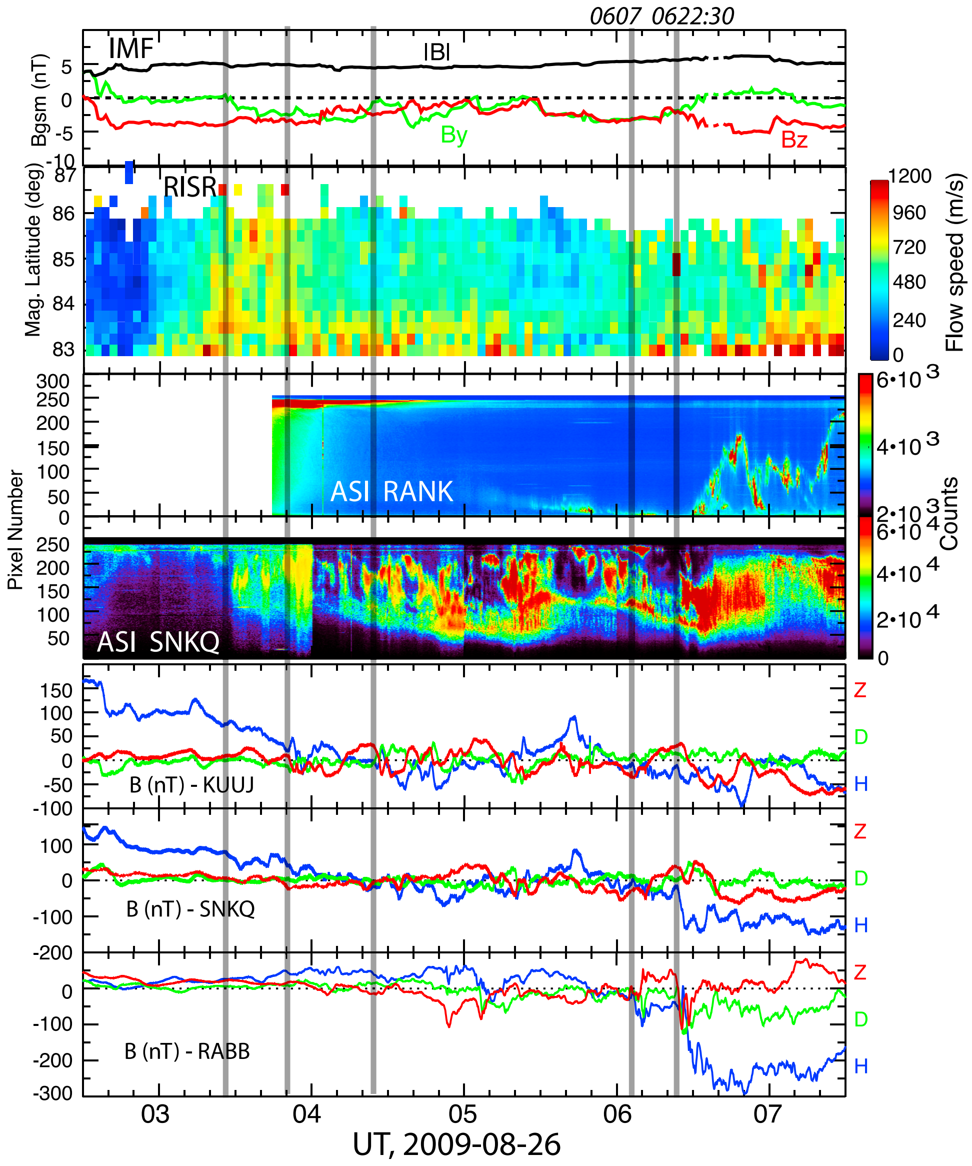

Figure 7. Overview of conditions from 0230 to 0730 UT on 26 August 2009 in the same format as Figure 3.

0500 UT on 27 August are given in Figures S2 and S3, respectively.

[21] Enhancement of flows before the first onset on 26 August is first seen at RISR and the highest latitudes of PolarDARN at ~0556 UT. Channels of enhanced equatorward flow were seen earlier in the *E* region PolarDARN echoes starting at 0550 UT and were associated with considerable PBI activity seen in the RANK ASI near Λ = 70°. The strongest equatorward flow channel was observed in the western beams starting at 0605 UT and is identified in the 0606 UT overlay in Figure 11, just prior to the 0607 UT onset. Since the onset was very near the equatorward boundary of the FOV of the RANK ASI (it was cloudy at GILL), and the PBIs were also well equatorward of the center of the FOV and there were multiple PBIs, it is not possible to clearly distinguish PBIs from streamers or to associate any particular such intensification with the substorm onset. Despite this limitation, it is clear that the strongest equatorward directed flow channel headed toward the region of PBIs and possible streamers at a time and location appropriate for this polar cap flow channel to have led to a streamer that led to onset.

[22] After the 0607 UT onset, flow channels continued and the aurora expanded moderately to Λ = 69°. Flows and the auroral activity decreased starting at ~0615 UT, but enhanced equatorward flows then soon appeared in the high latitude PolarDARN data as indicated in the 0616:30 UT overlay in Figure 11. A channel of enhanced equatorward flow was then seen in the western (0618 UT) *E* region beams. That channel then moved toward the center of the *E* region FOV and appears to have connected with a streamer at 0622:30 UT, leading to the onset, which was first seen in the 3 s images at 0622:42 UT. This onset was followed by large poleward expansion (to Λ ~ 74°) and auroral activity continued for over an hour. Strong flow channel activity was observed by PolarDARN during the large

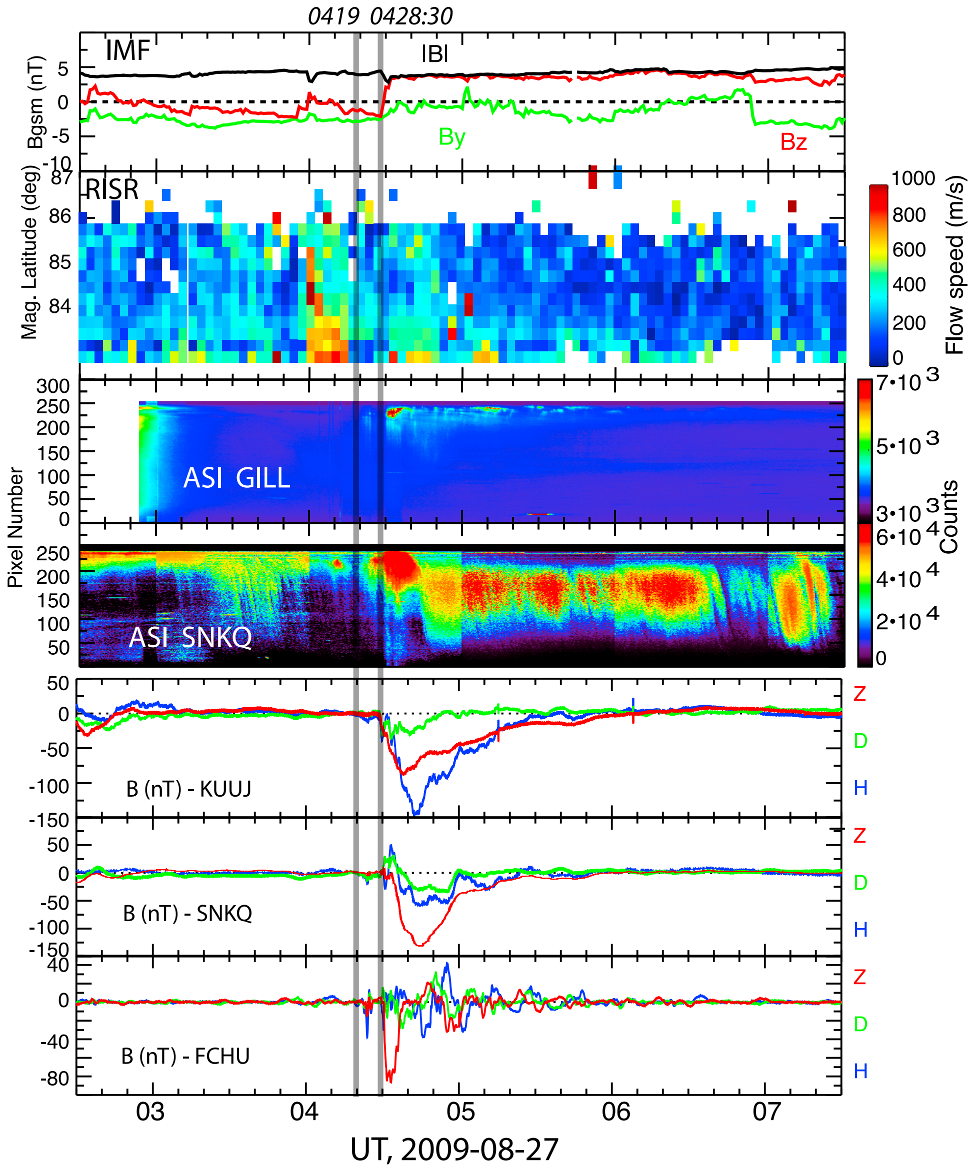

Figure 8. Overviews of conditions from 0230 to 0730 UT on 27 August 2009 in the same format as Figure 3.

poleward expansion and continued during the very prolonged period of auroral activity after the onset. This flow channel activity is identified in Figure 9, though it comes in and out of the 2 beams shown in that figure, and the prolonged continuation of this activity is identified in the 0642:30 and 0716 UT overlays in Figure 11 and is clearly seen in Figure S2. That a prolonged period of channels of flow directed toward the polar cap boundary from the polar cap was associated with prolonged period of PBI and streamer activity after the onset is consistent with what was seen for the later two onsets on 21 September.

[23] Similar to the previous events, the events on 27 August had equatorward flow enhancements prior to the onsets, as identified in Figures 10 and 11. Pre-onset streamers cannot be identified for these events. (RANK ASI images are not included here because of light contamination, though they show some evidence for a streamer just prior to the 0419 onset. For the second onset, the poleward auroral boundary seems to move equatorward and nearly contacted the auroral equatorward boundary. This type of onset is referred to as a "contact event" by *Nishimura et al.* [2011], indicating that the plasma sheet has become thin and the nightside magnetic separatrix is located closer to quite close to the onset latitude. Also, the pair of onsets on this night are another example where weak poleward expansion and auroral activity were observed after the onset (0419 UT) without prolonged post-onset strong flow channel activity, and strong auroral poleward expansion and prolonged activity were observed after the onset (0428:30 UT) that was followed by prolonged post-onset strong flow channel activity.

3. Summary and Conclusions

[24] This work was motivated by the study of 1 h of simultaneous PolarDARN and RANK ASI observation on 15 February 2008 [*Nishimura et al.*, 2010c]. These observations

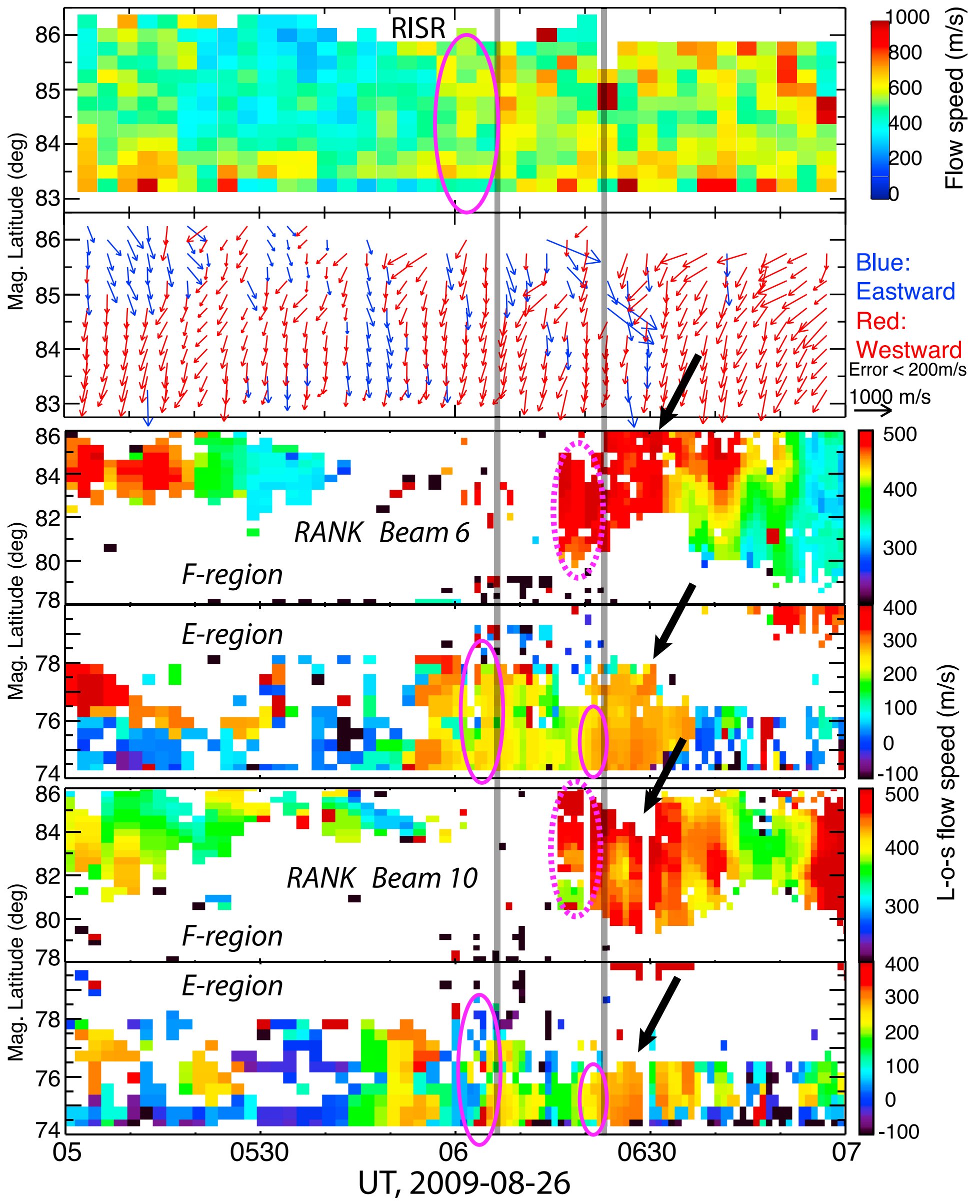

Figure 9. Overview of the RISR-N and PolarDARN observations for 05–07 UT on 26 August 2009 in the same format as Figure 4.

showed several narrow flow bursts that came from far within the nightside polar cap and appeared to have led to PBIs that were followed by streamers, including one that led to a near-Earth substorm onset, leading to the hypothesized sequence of flow and auroral signatures schematically illustrated in Figure 1. We have focused on substorms, and we found three nights having good observing conditions simultaneously from RISR-N, PolarDARN, and the ASIs in Figure 2, and during which substorm onsets occurred near the longitudes covered by the FOV of the RANK PolarDARN radar. Eight onsets were identified during these nights while RANK was at ~22–01 MLT, and equatorward-directed flow channels, appearing to be smaller in longitudinal width than the PolarDARN FOV where observed before all eight onsets. The flows could be seen within the relative narrow longitude range of the most equatorward PolarDARN observations for all but the two of these onsets that occurred east of the most equatorward PolarDARN observations. This is as expected for the flow channels leading to onset, since onsets have been observed to typically occur near or west of the location the pre-onset streamers reach the equatorward portion of the auroral oval [*Nishimura et al.*, 2010b]. For four of the onsets (and possibly a fifth), evidence was also found for auroral streamers at longitudes appropriate for connection to the pre-onset, polar-cap flow channels, and the streamers appeared to lead to the substorm as found by *Nishimura et al.* [2010b]. Furthermore, the flow observations presented here lead to the inference that the enhanced flow channels leading to onset may propagate from deep within the polar cap, although it is not possible to determine this precisely with the limited available LOS flow measurements.

[25] The measurements presented here support the hypothesis that enhanced meso-scale flows from deep within

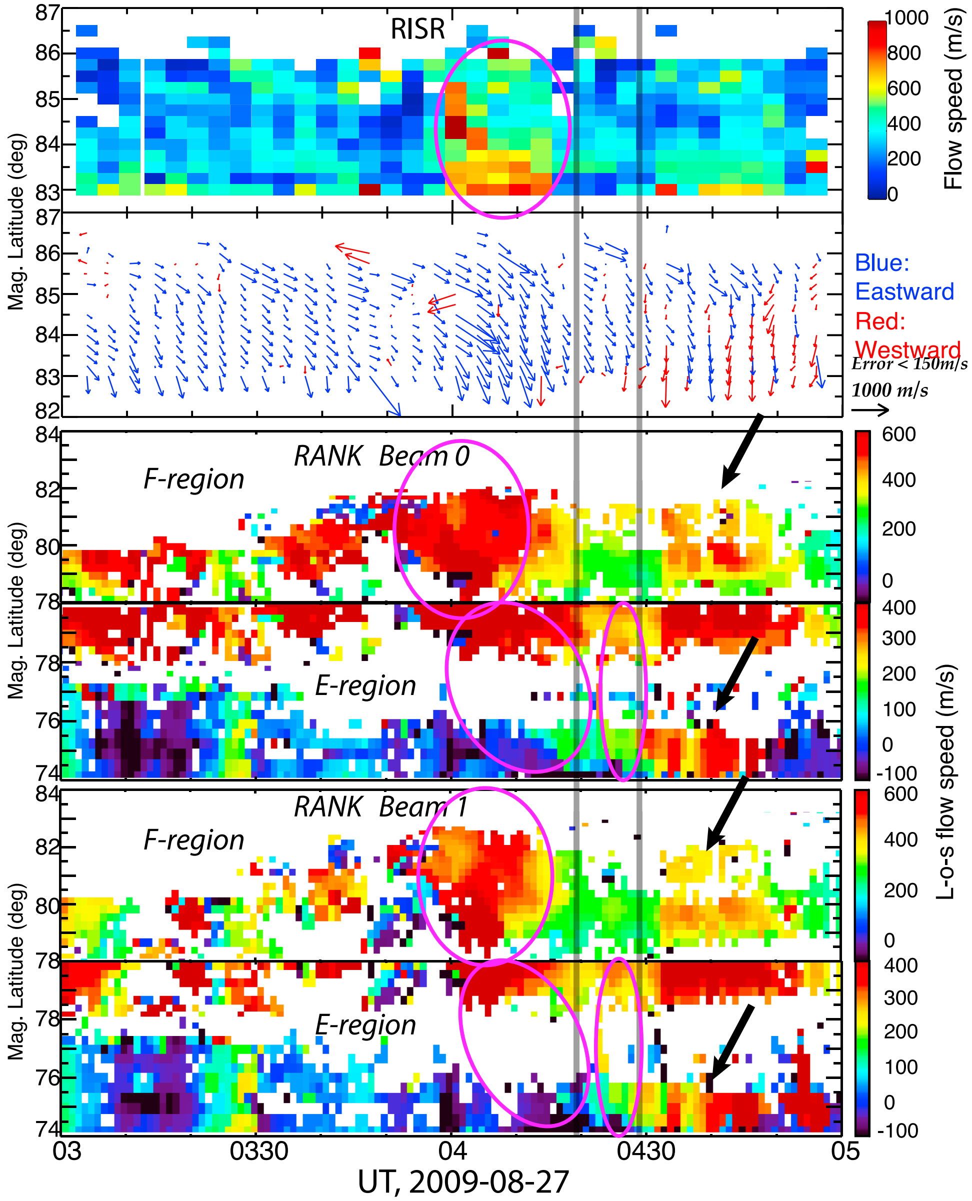

Figure 10. Overview of the RISR-N and PolarDARN observations for 05–07 UT on 27 August 2009 in the same format as Figure 4.

the polar cap and impinging on the nightside polar-cap boundary may contribute to the triggering of the meso-scale earthward flows that lead to PBIs, streamers, and substorm onset. However, the connections between a particular polar cap flow channel, the ensuing streamer, and the substorm onset are most clear for only the one ideal onset at 0626:30 UT on 21 September. For the other three events the signature of the pre-onset streamer was less ideal due primarily to the streamer being located further from the center of the FOV of an ASI. For three of the events where a pre-onset streamer was not identified, viewing conditions limited streamer identification of a possible streamer, and the other event was a contact event, where the closeness of the auroral poleward and equatorward boundaries near the longitude region of onset inhibits identification of any streamer between the two boundaries and where it is possible that the poleward boundary may have nearly contacted the auroral equatorward boundary.

[26] The hypothesis that PBIs can be triggered by flow channels from deep within the polar cap is further supported by observations of drifting 630.0 nm airglow patches in the polar ionospheric F-layer measured by the meridian scanning photometers (MSP) at Λ = 75.3° near Longyearbyen, Svalbard [*Lorentzen et al.*, 2004; *Moen et al.*, 2007]. Such patches were often observed within the nightside polar cap drifting from the poleward boundary of the MSP FOV, which is above Λ ~ 85°, toward the polar cap boundary with meridional drift speeds from 350 to 1000 m/s. When the poleward boundary of the auroral oval (the open/closed field line boundary) was within the MSP FOV, all patches were observed to drift into that boundary with subsequent brightenings of PBIs [*Lorentzen et al.*, 2004]. Since these

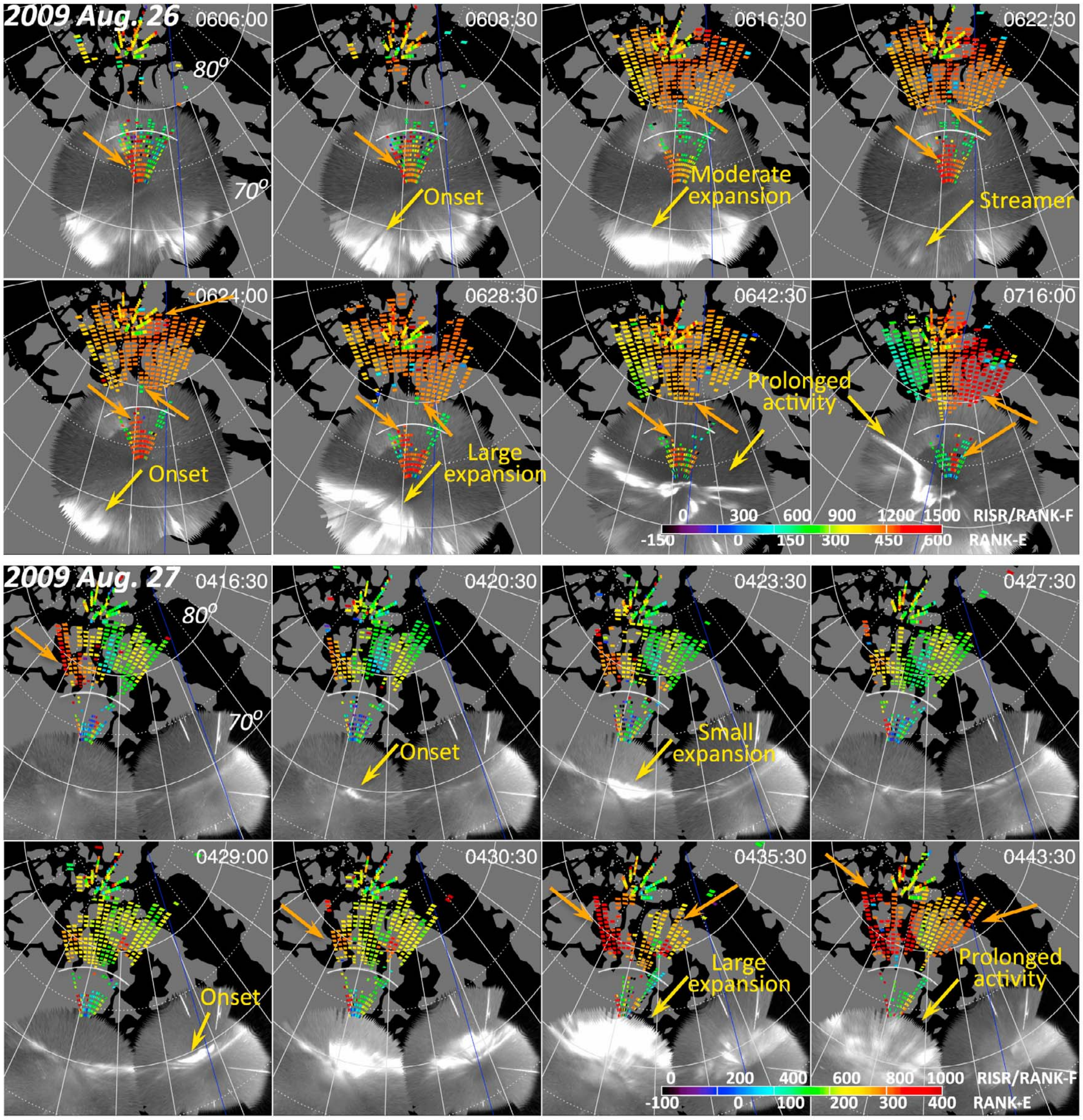

Figure 11. Same as Figure 5, except for (top) the two onsets on 26 August 2009 and (bottom) the two onsets on 27 August 2009.

patches are known to drift with the *F* region plasma drift speed [e.g., *Doolittle et al.*, 1990; *Hosokawa et al.*, 2010], these brightenings were taken as a unique signature of tail reconnection bursts, which carry plasma from open polar cap field lines into the plasma sheet as illustrated by the flow channel from the polar cap in Figure 1. The authors did not address whether the drifting patches were associated with localized flow channels within the polar cap, however the meridional drift speeds, which are only a component of the total drift speed, exceed those seen in our observations during periods between flow channels, suggesting that the patches move across the polar cap within the flow channels. As discussed by *Lorentzen et al.* [2004], polar cap patches are believed to originate near the dayside polar boundary. This indicates a possibility that the polar cap flow channels that we have observed within the nightside polar cap could have their origin on the dayside; however this speculation is beyond the scope of the present paper.

[27] Our analysis of these eight events has also yielded an unexpected suggestion, which, if true, could shed light on why some auroral onsets are followed by limited poleward expansion and others by much larger poleward expansion, and why some onsets are followed by prolonged auroral activity, which appears to consist mostly of PBIs and streamers, and some are not. In particular, four of our onsets where followed by prolonged periods of channels of flow directed toward the polar cap boundary from the polar cap, and these onsets were followed by large auroral poleward expansion and by a prolonged period of PBI and streamer activity that continued during the period of the equatorward directed flow channels. The other four onsets were not followed by such prolonged polar-cap flow channel activity

and had more limited poleward auroral expansion and much shorter periods of activity after the onset.

[28] Our results are consistent with the possibility that enhanced meso-scale flows, formed within the polar cap and heading toward the nightside polar cap boundary before substorm onset, contribute to the triggering of PBIs and streamers, and in particular to those that lead to substorm onset. In addition, the results suggest the possibility that such flow channels occurring after substorm onset play an important role in post-onset auroral poleward expansion and in the duration of post-onset auroral activity. The above possibilities, if true, would have important implications for our understanding of plasma sheet and substorm dynamics, and we believe that they warrant much more in depth analysis than presented in this initial study. Studies using the RANK PolarDARN radar and the THEMIS ASIs, even without RISR, could be important, as could studies with other Super Dual Auroral Radar Network (SuperDARN) radars (see http://sd-software.ece.vt.edu/tiki/tiki-index.php?page=Radar+Overview for radar locations). Two upcoming radars will also provide important observations for future study of the above possibilities. The first is RISR-S radar, which is being located to look south toward the RANK ASI from the same location as RISR-N, and the second is a PolarDARN radar looking roughly westward from Clyde River on Baffin Island, with FOV spanning the latitudinal range of RISR-S and part of RISR-N.

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