JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. A11, PAGES 26,349–26,358, NOVEMBER 1, 1998

Global analysis of three traveling vortex events during the November 1993 storm using the assimilative mapping of ionospheric electrodynamics technique

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Abstract. We have studied three traveling vortex events during the November 3-11, 1993, storm period using the assimilative mapping of ionospheric electrodynamics technique to help interpret the ground magnetic response from a global set of stations. When the AMIE potential patterns are high-pass filtered, clear vortex structures are observed. The AMIE output compares reasonably well with the ground magnetic data, although AMIE has a tendency to smooth out the structures. Single vortices are observed to form near 1000 MLT and propagate to 1400 MLT, over the Greenland magnetometers and across noon. The velocity of the vortices is approximately 4-8 km/s (0.2° - $0.3^\circ s^{-1}$ between 70° and 75°) eastward along a line of invariant latitude. The number of vortices, as well as the motion of the vortices, differs from the classical picture of a traveling convection vortex. We therefore suggest that these vortex events might have a different generation mechanism or occur under a different state of the magnetosphere, and thus that they should be considered a separate class of events. The AMIE technique offers the possibility to relate the vortices to the large-scale convection patterns. We note how the vortices can be interpreted as small scale, rapid changes in the large-scale convection pattern, although these changes show many differences to previous studies of changing large-scale convection patterns. We speculate that this particular class of traveling vortex event may be generated by a perturbation in the separatric on the dayside magnetopause, caused by an enhancement or depreciation of the magnetic merging.

1. Introduction

By determining the driving mechanisms behind small-scale electrodynamic processes observed in the high-latitude ionosphere, one may gain insight to the large-scale coupling between the solar wind and the magnetosphere. One such process is the so-called traveling convection vortex (or TCV). TCVs were first described by *Friis-Christensen et al.* [1988] using a chain of magnetometers. They show that some magnetic impulse events (MIEs) exhibit a longitudinal phase velocity. They further show that these events can be interpreted as steady ionospheric convection vortex structures passing overhead along constant magnetic latitudes. These phenomena have been the focus of many studies [*Glassmeier et al.*, 1989; *Lanzerotti et al.*, 1991; *Glassmeier and Heppner*, 1992; *Lühr et al.*, 1993; *Lühr and Blawert*, 1994; *Lysak et al.*, 1994; *Lühr et al.*, 1996].

On the basis of these studies a picture of a classical TCV event has developed. TCVs are the manifestation of field-aligned currents (FACs), which originate on the dayside around 70° invariant latitude. Some TCVs have been shown to form near 1200 MLT and to bifurcate away from 1200 MLT along the same invariant latitude, traveling both toward dawn and dusk simultaneously with speeds of 1-20 km/s. TCVs often travel in pairs, so an observatory (a chain of magnetometers or a radar, etc.) in the morning region would observe a twin-vortex structure propagating westward. In the afternoon region, an eastward propagating twin-vortex structure would be observed. This type of a event is what we call a classical TCV event. The mechanism for generating TCVs is still under debate, although the most commonly believed driving mechanism is the variation of the solar wind pressure which causes a perturbation at the magnetopause.

Paper number 97JA03433.
0148-0227/98/97JA-03433$09.00

Perturbations give rise to FACs which flow between the magnetosphere and the ionosphere because of the required divergence of the Chapman-Ferraro currents on the magnetopause. These perturbations on the magnetopause move along the flanks of the magnetosphere with the solar wind, which causes the FACs to travel antisunward with the solar wind. This theory is described in more detail by *Glassmeier and Heppner* [1992]. We note, however, that TCV events have also been associated with interplanetary magnetic field orientation changes [*Friis-Christensen et al.*, 1988].

It should also be noted that very few TCV event studies have been global in nature. Most of the studies described above focus on single chains of magnetometers which only encompass a few hours in magnetic local time (MLT). Therefore many of the global aspects of the classical TCV have been verified with simultaneous measurements in only a few instances [e.g., *Moretto et al.*, 1997].

Most TCV events have been observed during quiet geomagnetic conditions. It is not clear whether the lack of TCV events observed during active time periods is due to a true natural phenomenon or whether the TCVs are too small to be distinguished from other geomagnetic disturbances. Even though TCV events may not be common during storm conditions, TCV-like signatures have been observed by the Greenland magnetometers during the November 1993 storm period, and we wish to investigate these further here.

This storm event has become the focus of the space physics community. A large number of data sets have been gathered to try to create a global picture of the magnetosphere-ionosphere system during this time period. This storm period therefore offers a unique opportunity to study traveling convection vortices because the coverage of the magnetometer stations is much larger than any other earlier study of TCVs. It also offers an opportunity to answer some of the outstanding questions discussed above. We have computed ionospheric convection maps using the assimilative mapping of ionospheric electrodynamics (AMIE) technique to study the vortex events and their relationship to the large-scale convection configuration.

The main objectives of the study presented here are (1) to show that the traveling vortex events, though different in some ways from classical TCV events (as described above), can also be identified during very active storm conditions such as during the storm period of November 3-11, 1993; (2) to determine if the AMIE technique can be used to resolve such small-scale structures, and at the same time, to verify the conclusions made on the basis of raw magnetometer data; (3) to use AMIE to relate the vortices to the large-scale convection pattern as well as changes therein; and (4) to examine possible generation mechanisms for the events.

2. Event Presentation and Analysis

Figure 1 shows the ground magnetometer coverage for the northern hemisphere above 50° for November 7, 1993, at 1400 UT. The west coast Greenland magnetometer stations are centered directly at 1200 MLT. We use this meridional chain of magnetometers to identify the events presented here.

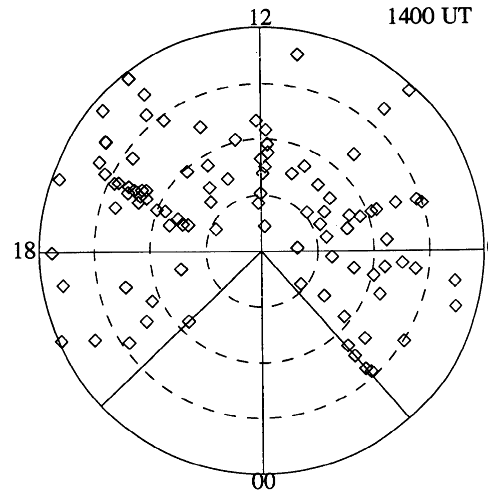

Figure 1. The locations of the ground magnetometers used in this study at 1400 UT on November 7, 1993.

During the initial storm onset the magnetic measurements are too disturbed to identify any distinct TCV-like signatures in the data. During the recovery phase, from November 5 to 9, however, the activity drops to a level where impulsive type of events can be identified, even with the presence of a significant amount of background activity.

Ten TCV-like signatures have been identified in the Greenland data during the storm recovery phase. We shall present three of these events, for which the vortex structure and propagation are particularly clear. The times of these events are 1400 UT on November 5, 1445 UT on November 6, and 1400 UT on November 7.

In order to avoid lengthiness, we will discuss only one event in detail and make comments about the similarities and differences for the other two events. The event that best relays all of the important features is the event on November 7, 1993.

2.1. November 7, 1993 Event

Figure 2 shows the filtered magnetic traces of the Greenland magnetometer chain for an hour time period surrounding the event. The filter used passes signals with periods shorter than 30 min. Much wave activity is observed during this time period. Nevertheless, a few pulsations do stand out in amplitude in all three of the components over the background activity. The pulsations which we have identified as signatures of possible TCVs have a vertical line through them.

To verify our interpretation of the impulses as being traveling events, a cross correlation is done between longitudinally spaced stations ATU and MCE (separated by about 850 km). A time lag of 2.67 min is derived, implying that the pulsations are traveling with a propagation velocity of 5.2 km/s eastward. The measured value of the cross correlation (0.63) is low, but it is typical of traveling events [e.g., *Clauer and Ridley*, 1995]. This value is explained as the vortices changing shape and magnitude during the propagation. Also, any conductivity changes between the stations would account for different signatures.

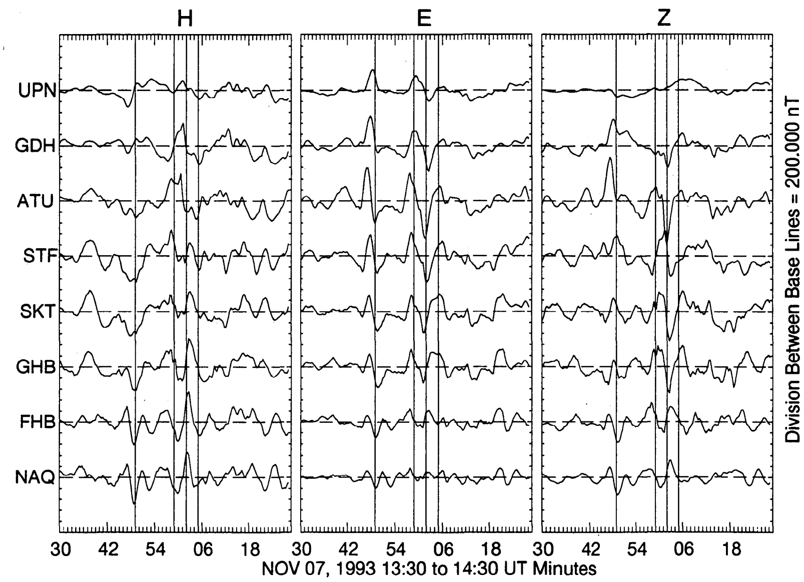

Figure 2. The west coast of Greenland magnetometer traces for the TCV event on November 7, 1993. Positive H is magnetic north, positive E is magnetic east and positive Z is downward.

We next plot the magnetometer data as a time series of equivalent convection vectors, as shown in Figure 3. This is done by rotating the horizontal component of the magnetic perturbation by 90° counterclockwise. This method assumes that the magnetic signature results from the Hall current only and has been used in many previous studies [e.g. *Friis-Christensen et al.*, 1988; *Glassmeier et al.*, 1989]. Since the structures which we observe are propagating eastward, this is similar to scanning the structures from right to left (assuming that the structures do not change during the propagation). We therefore let time run from right to left in this plot.

In this event there are four vortices observed to propagate over Greenland, centered at 1350, 1358, 1402, and 1405 UT. The direction of the corresponding field-aligned currents are indicated at the vortex centers. The circles with arrows are drawn to indicate convection flow, and are not meant to give an indication of the relative size of the vortices. All four vortex centers are located around 75° invariant latitude, although the 1402 UT vortex may be a little lower in latitude. The approximate location of the center of each vortex is determined by eye. For example, the 1358 UT vortex contains eastward flow above the center and westward flow below; in addition, there is poleward flow to the east and (roughly) equatorward flow to the west, while at the (displayed) vortex center there is little flow. This pattern is indicative of a clockwise flowing vortex, with the center located in the marked position. The opposite pattern is observed in the 1350 UT vortex. The location of the centers of the 1402 and 1405 UT vortex centers are slightly less obvious, because of the ATU magnetometer. If this magnetometer is ignored, then the vortex centers are clearly between STF (73.5°) and GDH (76°). We have placed the centers halfway between. The ATU signature may be caused by fine scale structure within the overhead field-aligned current.

The vortex structures described above are consistent with the interpretation that these are typical TCVs, similar to those described by *Friis-Christensen et al.* [1988], *Glassmeier et al.* [1989], and *Glassmeier and Heppner* [1992].

We next present the potential patterns derived by the

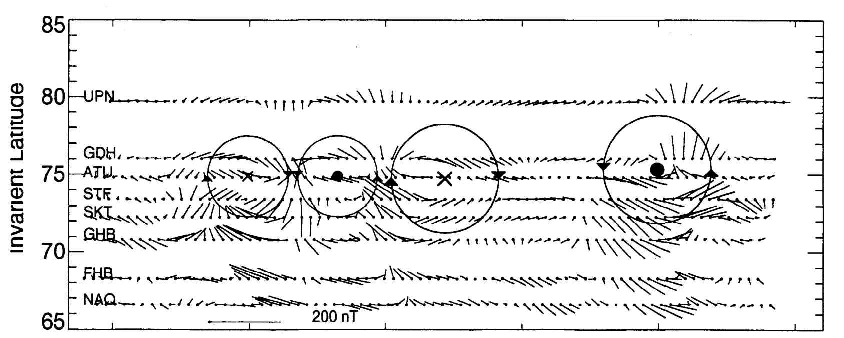

Figure 3. The west coast of Greenland magnetometer horizontal perturbations rotated by 90° counterclockwise to show the equivalent convection for the time period 1345 - 1410 UT on November 7, 1993.

AMIE technique for the same time period, to attempt to examine the global nature of the traveling vortex events. Since we are mainly focused on the dayside convection during the vortex events, we display in Figure 4 only the dayside part of the pattern. Though no interplanetary magnetic field (IMF) data are available, it is clear that the dayside convection is consistent with a negative B_z condition (i.e., strong antisunward flow over the pole) [*Heppner and Maynard*, 1987; *Papitashvili et al.*, 1994]. During the 21 minutes the convection throat region moves repeatedly back and forth between 1000 and 1200 MLT. Such a motion is normally, at least if seen on a larger timescale, taken as an indication of an oscillating IMF B_y [*Ridley et al.*, 1998].

Figure 5 shows the AMIE derived potential patterns with a 30 min running average removed. The 1-min potential patterns from 15 min before and after the specific time are averaged together and subtracted from the plot. This is equivalent to high-pass filtering the patterns with a 30-min frequency cutoff and is the same filtering technique that has been applied to the magnetometer data in Figures 2 and 3. Since the magnetometer data and potential patterns are filtered in the same way, the results can be directly compared.

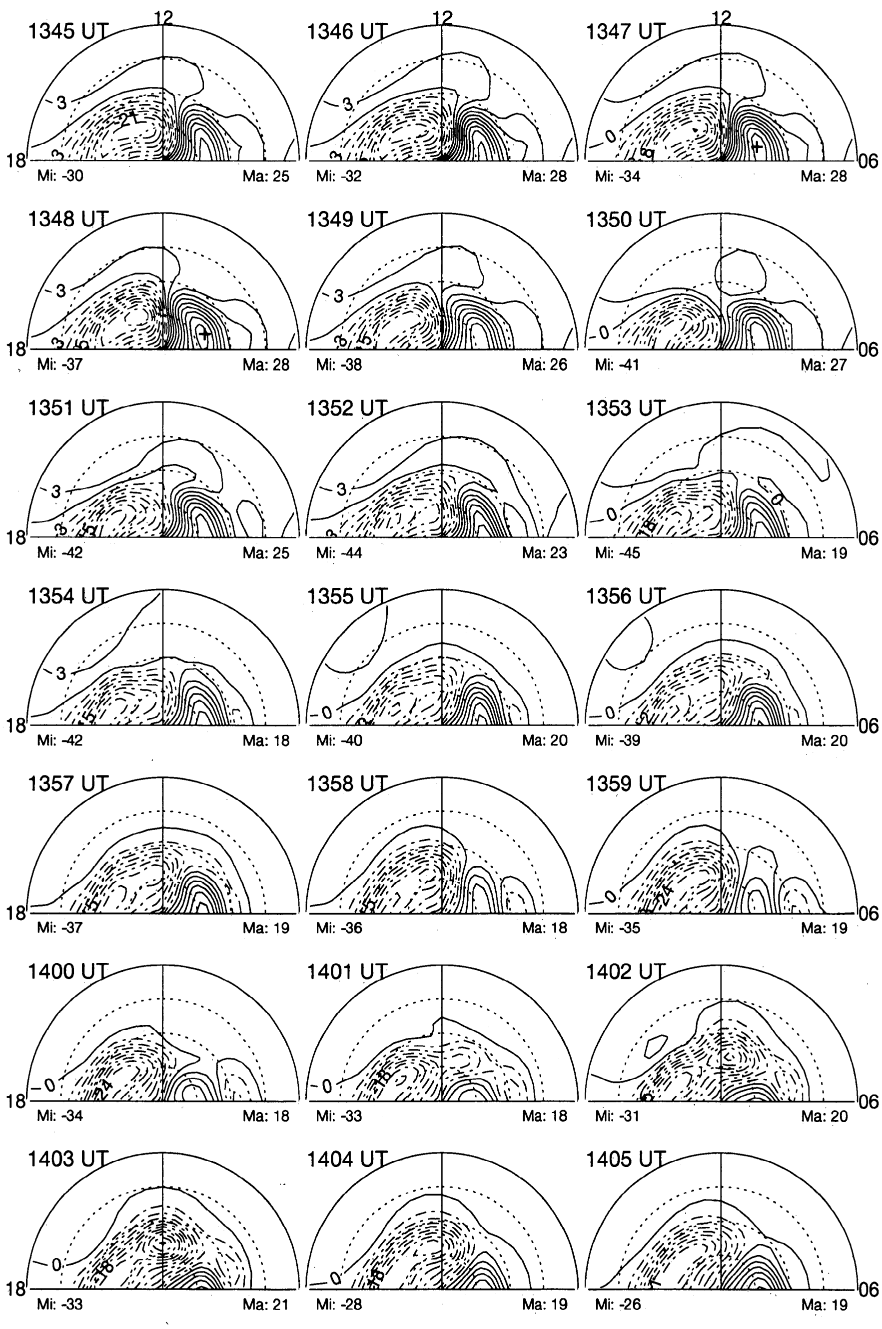

Figure 4. The dayside potential is derived using the AMIE technique. The top of each half circle is noon, with the right side being dawn. The outer circle is 50° invariant latitude. The solid (dashed) contours represent positive (negative) potential. The contour intervals are 3 kV. The maximum and minimum potential values are displayed under the half circle.

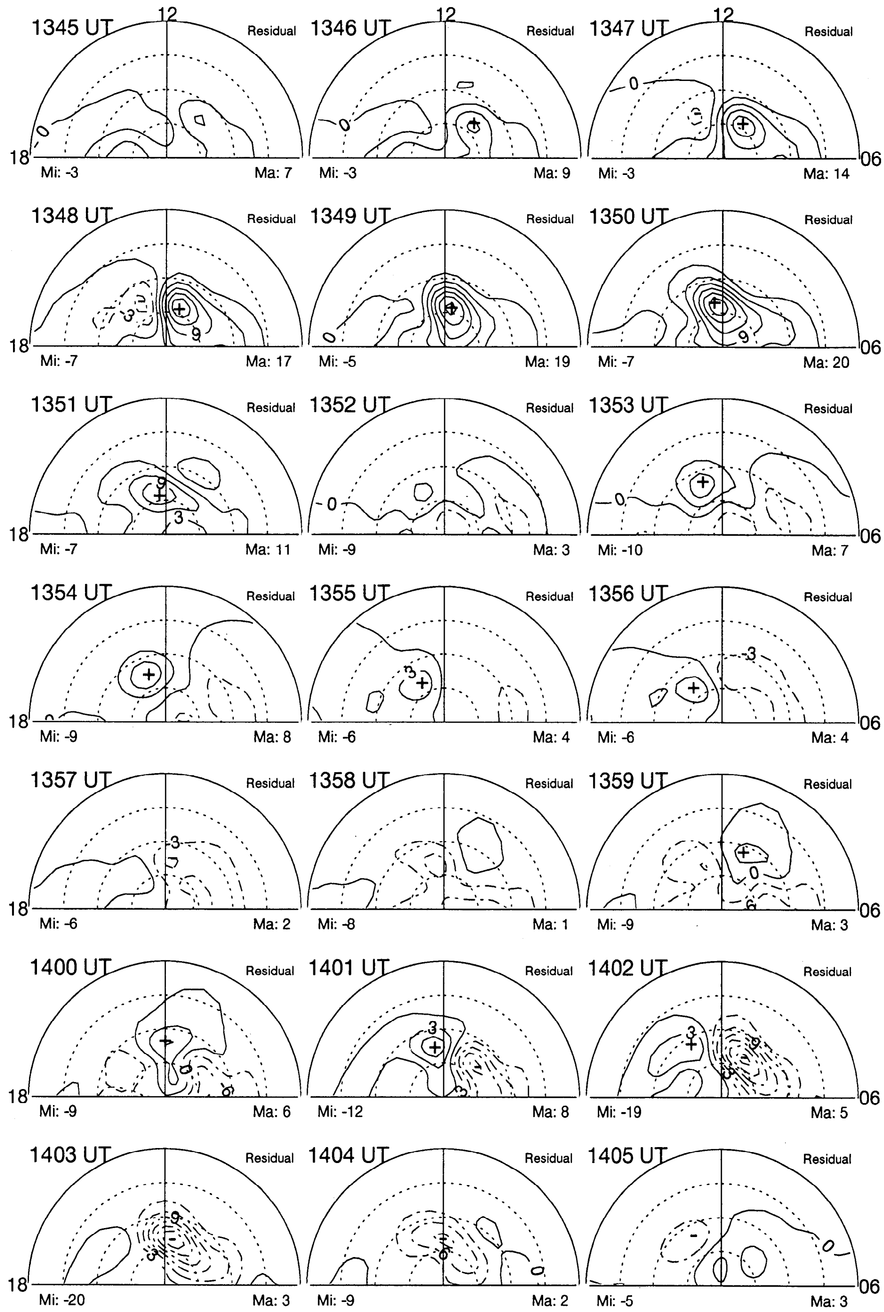

Figure 5. The dayside residual potential patterns. These patterns are derived by subtracting a 30-min running average of the AMIE derived potential patterns, centered at the time of the plot. The top of each half circle is noon, with the right side being dawn. The outer circle is 50° invariant latitude. The solid (dashed) contours represent positive (negative) residual potential. The contour intervals are 3 kV. The maximum and minimum residual potential values are displayed under the half circle.

The main features of the residual potential patterns can be summarized as the following (note that the west coast of Greenland is located at 1200 MLT during this time period):

1. At 1345 UT a positive cell starts to develop west of Greenland.

2. Between 1345 and 1351 UT the positive cell grows in intensity and moves eastward (over the chain of magnetometers). The center is at 78° invariant latitude. The vortex appears to retain its general shape, although the equatorward portion may be moving a little faster than the center. The average velocity of the vortex center is $0.17°s^{-1}$, corresponding to approximately 4.2 km/s.

3. From 1350 to 1351 UT the equatorward portion of the vortex is moving faster than the center. The vortex potential is decreasing in magnitude.

4. At 1352 UT the positive cell almost disappears.

5. From 1352 to 1356 UT the positive cell reappears and disappears once again but does not propagate.

6. At 1356 UT a negative cell begins to form west of Greenland at 1100 MLT. This cell is much weaker than the positive cell.

7. From 1356 to 1400 UT the negative cell propagates east over the chain of magnetometers. The southern portion of the vortex is moving faster than the center, which I located at approximately 75°. This motion gives the vortex a semielongated shape. The average velocity of the vortex center is $0.25° s^{-1}$ (or 7.2 km/s), almost twice as fast as the previous vortex.

8. At 1358 UT a positive cell forms west of Greenland at 1000 MLT. Also this vortex is weaker than the existing one.

9. At 1359 UT the negative cell begins to fade while the positive cell intensifies.

10. From 1358 to 1403 UT the positive cell propagates eastward with its center located between 72° and 75°. The average velocity of the vortex center is $0.25° s^{-1}$ (or approximately 7.2-8.6 km/s.)

11. At 1400 UT a negative cell begins to develop west of Greenland at 0800 MLT, and later on becomes as strong as the existing positive vortex.

12. At 1402 UT the positive cell begins to fade and by 1404 UT it is completely gone.

13. From 1400 to 1405 UT the negative cell propagates eastward, over the chain of magnetometers. The vortex center is at 75°. The average velocity of the vortex center is $0.25° s^{-1}$ (or 7.3 km/s.)

14. From 1404 to 1406 UT the negative potential cell reduces in magnitude and disappears.

To compare the magnetometer data with the AMIE output, we determine the electric field along the meridian at noon MLT and then rotate 90° counterclockwise into the direction of convection. A time series of the vectors between 65° and 85° invariant latitude is displayed in Figure 6, for direct comparison with the time series of equivalent convection derived from the magnetometers, shown in Figure 3. The convection matches in general shape. For example, the strong poleward convection at 1348 UT and the strong equatorward flow at 1402 UT are observed in both. The AMIE patterns look smoother than the magnetometer data because of spatial smoothing in AMIE.

The same four vortices are observed in the AMIE meridional convection plot as in the magnetometer equivalent convection plot. The centers of the vortices are once again determined by eye, as was done in Figure 3. Although this method may not be as rigorous as using a model, or calculating the vorticity, we are simply interested in examining and comparing the gross features. The first and last vortex centers are easily determined (as described previously), while the central vortices are more ambiguous, with a possible latitudinal error of a few degrees. Keeping this in mind, we note that the 1350 UT AMIE vortex is located at a similar latitude as the magnetometer vortex. However, the last three vortices are generally a few degrees lower in latitude in the AMIE output.

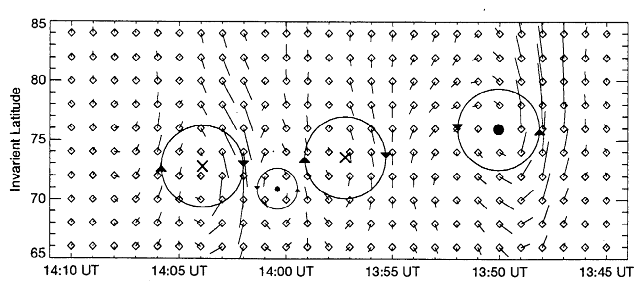

Figure 6. Horizontal electric fields calculated from the electric potential patterns, rotated into the direction of convection. This plot shows the equivalent convection from the noon meridian for the same time as Figure 3.

2.2. November 5, 1993 Event

Figure 7 shows the structure of the traveling vortex event on November 5, 1993, which is very similar to the November 7 event. In this case there are four vortices which propagate eastward over the Greenland chain of magnetometers (at 1358, 1401, 1405, and 1410 UT). A new vortex forms as the existing vortex is fading, as in the previous example. The intensity, speed, and lifetime of the vortex structures are similar to the middle two vortices in the first example.

2.3. November 6, 1993 Event

The residual potential patterns for the November 6, 1993, TCV event are displayed in Figure 8. The first two vortices on this day differ from many of the previously discussed TCVs. The first difference lies in the formation of the first two vortices: they form simultaneously, one east of Greenland and one west of Greenland (at 1439 UT). Both vortices then propagate eastward with the same speed. The second difference occurs when the western vortex reaches Greenland (at 1442 UT). The vortex stops and remains in a fixed location for approximately 5 min (while the positive cell fades quickly during this time period). This is similar to the positive vortex observed at 1353 UT on November 7, but it is different from all the others. The negative cell then starts propagating eastward again at 1446 UT and fades as all of the other events have. As this vortex is fading, a third vortex forms west of Greenland, similar to the previous examples.

3. Summary and Discussion

3.1. Classes of TCVs

The events which we present here differ from the classical TCV events (as defined in the Introduction) in a number of ways: they form in the morning region but propagate eastward, across noon; all but one of the events travel as a single vortex; and there are no westward propagating vortices to match the eastward propagating vortices as would be otherwise expected in the classical TCV. In addition, the events are observed during active time periods. The structures are thus not classical TCV events, although they clearly are propagating vortex structures.

Some earlier studies have also described events differing from the classic picture of a TCV. For example, *McHenry et al.* [1990], *Clauer et al.* [1990], *Clauer and Ridley* [1995],

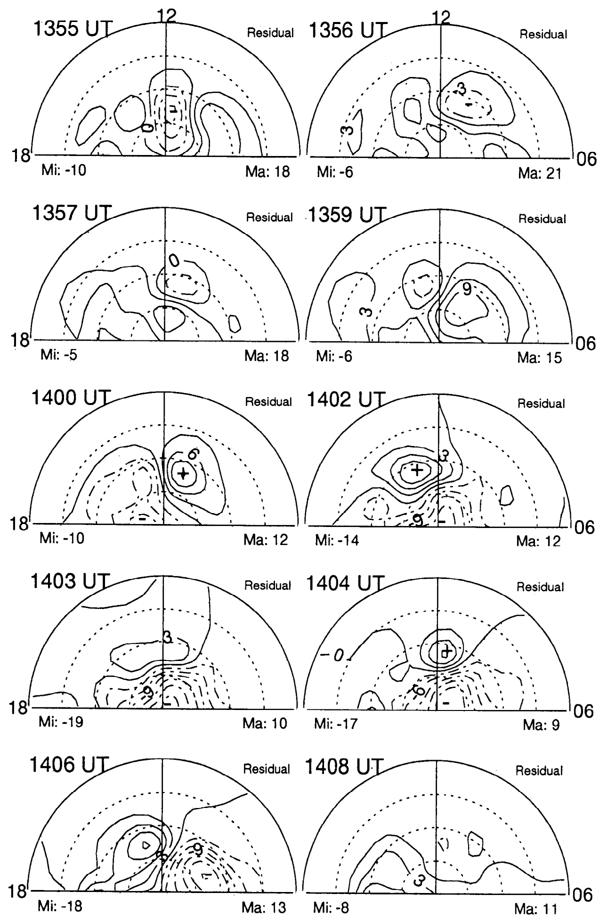

Figure 7. The dayside residual potential patterns, similar to those shown in Figure 5, on November 5, 1995.

and *Ridley and Clauer* [1996] describe a class of traveling vortices which come in trains. The generation mechanism for this type of structure has been attributed to the Kelvin-Helmholtz instability at the convection reversal boundary. This is a very different type of generation mechanism as compared to those proposed for classical TCVs.

The term traveling convection vortex (if taken literally) thus covers a broad spectrum of phenomenalogically different events. An important step in the study of traveling vortices will be to classify the events in a way that can guide us in an understanding of the phenomena and in the search for generation mechanisms. It is also important to note that vortices generated with the same mechanism during different magnetospheric conditions (e.g., B_z south compared to B_z north conditions) may also show completely different behaviors.

We further note that the classification of vortex events will require incorporating more than a single chain of magnetometers. We show examples of events that can not be distinguished from classical TCVs when observed only with the Greenland chain of magnetometers. Until recently [e.g., *Moretto et al.*, 1997], this has been the way to determine whether an event is a TCV or not. When some events are examined on a global scale, however, they show many features which do not fit into the classical picture of a TCV. Global analysis is therefore needed to determine the class of the vortex event.

Moretto et al. [1997] reaches a similar conclusion based on a study using a global distribution of magnetometers. They describe one vortex event which is similar to the classical TCV and another one which is similar to the events presented here.

We conclude that each magnetic perturbation event should be examined using a global data set. This would allow an observation of where the event originates, how many cells originate with it, what the magnitudes of the cells are, the speed and direction of their motion, how far they travel, and how the background activity relates to the event. Once these observations have been made, one can begin to classify the events into different categories. For example, most of the vortices which we present form in the prenoon sector, travel across noon and fade in the postnoon sector. These events are in a completely different category from those type of events which form at noon with four vortices and propagate antisunward (i.e., the classical TCV). Separating the events into different categories may infact elucidate the understanding of the broad class of traveling vortex events.

3.2. Accuracy of AMIE Technique

For all three of the time periods which we have studied, the equivalent convection plots produced with the magne-

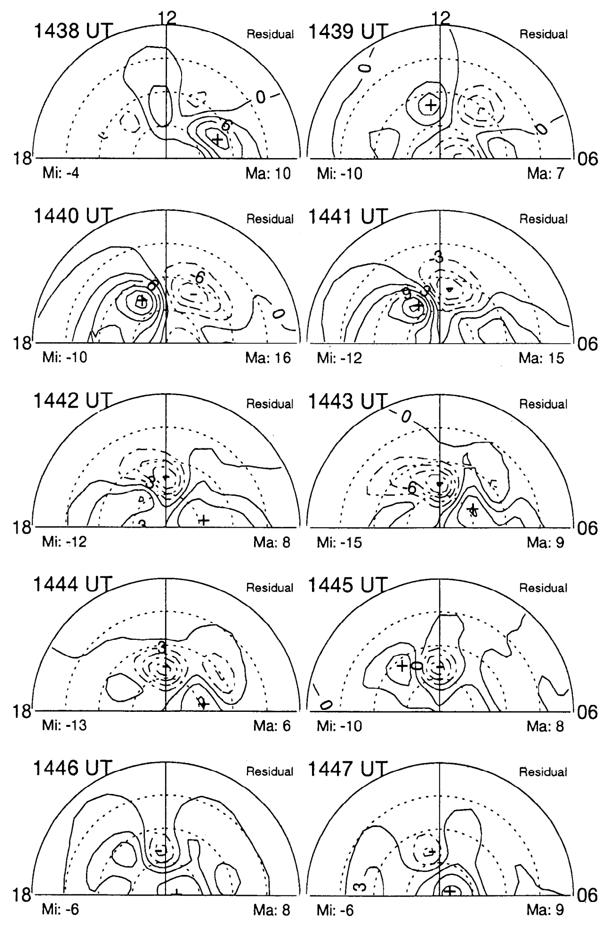

Figure 8. The dayside residual potential patterns, similar to those shown in Figure 5, on November 6, 1995.

tometer data and the meridional cut of the AMIE electric fields are consistent. One would expect that these plots would be very similar, since AMIE is a data inversion technique, and the only data which we have used during this study is the magnetometer data. On the other hand, the resolution of AMIE is approximately 2° in latitude, and the structures which we are examining are only a few times larger than that. In addition, the magnitude of the vortices is much smaller than the background convection, so one may not expect the vortices to show up as clearly as they do after the high-pass filtering is performed. Furthermore, we have selected a single stationary meridional cut, while the Greenland magnetometers are spread out in MLT and are moving under the pattern. This may cause some of the discrepancies shown in the comparison. There is also some smoothing of the data in the AMIE plot since AMIE uses an orthogonal polynomial fit to produce the patterns.

What is unknown, however, is whether the cells are indeed accurately represented in spatial size and magnitude. The size of cells may be misrepresented when the cell is over a sparse-data-coverage zone. Therefore the change in shape observed (i.e., spreading) may sometimes be artifacts of uneven magnetometer coverage. Also, a high-intensity peak may not show up in areas where there is sparse data. Therefore we may have missed some features which did not show up in either the AMIE produced potential patterns or the magnetometers.

We conclude that the AMIE technique, when there is a dense coverage of magnetometers, can reasonably recapture the gross features of the relatively small-scale phenomena, like traveling vortices. This technique is useful in deriving a global view which is necessary to understand this type of phenomena. The AMIE technique will likely smooth out the fine-scale structures, but the general flow patterns will be similar.

3.3. Relation to Large-Scale Convection Changes

We next examine how traveling vortex events relate to the large-scale ionospheric convection. For two of the three events presented above, the vortex events occur at a similar latitude as the convection reversal boundary in the afternoon cell. For the third event, the vortices originate a few degrees lower in latitude. For all of the events, the vortices originate near the throat region or on the morning side and propagate into the afternoon side. When the large-scale convection patterns are examined, the vortex events appear as oscillations in the location of the throat region, often taken to indicate small changes in the IMF Y component. We therefore compare the vortex events to past studies of large-scale convection changes which have not focused on traveling vortices:

3.3.1. Location. The changes in convection have been shown to start at the ionospheric projection of the cusp [*Saunders et al.*, 1992; *Etemadi et al.*, 1988; *Stauning et al.*, 1995], which is also the approximate location where the vortices start to evolve in this study. *Ridley et al.* [1997, 1998] show that the ionospheric convection change is located near the cusp associated with IMF B_y changes.

3.3.2. Propagation. *Saunders et al.* [1992] and *Etemadi et al.* [1988] have shown that the change in convection propagates away from the cusp region, similar to the events shown here; however, they also show in their study a symmetric westward propagation in the morning sector, which is not observed here. *Stauning et al.* [1995] and *Clauer et al.* [1995] have shown the propagation of the changes in convection associated with changes in B_y to be poleward. *Ridley et al.* [1997, 1998] have shown that the ionospheric convection changes are fixed in location.

3.3.3. Timescales. The vortex structures seems to grow much more rapidly than in prior observations of ionospheric convection changes. The vortex structure in the events presented here seem to evolve on a timescale of few minutes, while prior observations have shown the large-scale ionospheric convection changes to evolve over an 8-20 min period [*Clauer and Friis-Christensen*, 1988; *Saunders et al.*, 1992; *Hairston and Heelis*, 1995; *Ridley et al.*, 1998].

3.3.4. Spatial Scales. The vortices are more localized than some prior observations of large-scale convection changes. *Ridley et al.* [1997] show that the change in the large-scale ionospheric convection is global when the IMF B_z changes. However, when B_y changes, they note that the change in the large-scale ionospheric convection is localized. *Etemadi et al.* [1988]; *Saunders et al.* [1992] show the changes in the large-scale convection reaching back toward the dawn-dusk meridian, although they mainly focus on changes in the IMF B_z. *Stauning et al.* [1995] and *Clauer et al.* [1995] observe very spatially isolated changes in the large-scale convection in response to IMF B_y changes.

By comparing traveling vortex events to the changes in the large-scale convection, we may be able to better understand the generation mechanisms for the different classes of traveling vortex events. For example, if some class of vortices are caused by IMF orientation changes, their ionospheric signatures may be similar to the large scale convection changes. We find that the vortices which are examined here are similar in some regards to prior observations of changes in the large-scale convection change, but they are different in many other ways.

3.4. Generation Mechanism

In the previous sections, we state that the events which are described in this paper are not traveling convection vortices in the classical sense. This implies that they may have a different generation mechanism. We discuss above the possibility that the events may be associated with large-scale convection changes, but the results seem to indicate that they are significantly different. We therefore attempt to determine a generation mechanism for this class of convection vortices.

The vortex events appear to form and fade relatively close to noon and relatively close to the convection throat (where the dayside convection makes the turn from sunward to antisunward directed). The separatrix (the line separating open and closed field lines) has been shown to be related to the position of the throat region [e.g., *Lu et al.*, 1995]. The vortex events appear to be associated with the separatrix. The latitude and width of traveling region are similar to separatrix locations and longitudinal widths.

We suggest that these vortex events may be generated by enhanced or depreciated reconnection events which generate a perturbation in the separatrix. These perturbations may expand (or travel) along the magnetopause in the direction of the flow of the newly merged field lines, causing an enhancement in the cusp currents. In this case, the ionospheric convection flow over the pole is antisunward and eastward (as shown in Figure 4). It would therefore be consistent that the perturbation in the separatrix would expand eastward, along the magnetopause boundary, but in the general direction of the flow.

The perturbation in the separatrix may cause field-aligned currents to flow in the cusp region. The events described here seem to imply the currents may be similar to B_y driven cusp currents, which are observed as single potential cells developing near the cusp region [*Ridley et al.*, 1997]. This type of current system would explain the solitary nature of the cells.

4. Conclusions

We have studied three traveling vortex events during the November 3-11, 1993 storm period using the assimilative mapping of ionospheric electrodynamics technique. The events were selected based on data from the Greenland chain of magnetometers showing vortex structures in equivalent convection plots.

When the AMIE convection patterns are high-pass filtered by removing a 30-min running average, the same filter used on the magnetometer data, the resulting potential patterns show clear small-cell structures. These cells are observed to propagate eastward from around 1000 MLT, where they are generated, to 1400 MLT. Speeds of approximately 4-8 km/s (0.2 - 0.3 $^\circ s^{-1}$) are estimated, as was indicated in the cross-correlatio done on the Greenland magnetometer data.

The AMIE patterns are consistent with the magnetometer generated equivalent convection plots in terms of the general flow patterns. One of the vortex centers is located in the same place in each, while the other three vortices have a tendency to be slightly lower in latitude in the AMIE patterns. This is most likely caused by the uneven magnetometer coverage, the smoothed fitting of the data and the spatial resolution of the AMIE technique.

The AMIE derived residual patterns show that the traveling vortices which we observe differ in several respects from classical TCVs described in prior studies [e.g., *Lühr et al.*, 1996, and references therein]. The events we observe show single vortices propagating eastward across noon. They are short-lived and do not propagate all the way back to the nightside. No westward propagating vortices are observed in the morning sector, and thus there is no morning - afternoon symmetry.

The events studied here resemble the December 18, 1993, event studied by *Moretto et al.* [1997]. Like that study, we conclude that the term TCV is too broad to unambiguously differentiate the different types of convection vortices observed in the ionosphere. Further studies are required to categorize and eventually to determine generation mechanisms for different types of traveling vortex events. For such studies a semiglobal analysis, like the one presented here, is required to determine where the vortices form, how they propagate, and where they decay. This information is essential in the classification of the different events.

The changes in the large-scale convection pattern associated with these events suggest an interpretation in terms of IMF B_y changes. It is important, however, to note that these changes in the large-scale convection pattern are much more rapid than in the studies of *Stauning et al.* [1995], *Etemadi et al.* [1988], *Saunders et al.* [1992], and *Ridley et al.* [1997, 1998] relating changes in the large-scale convection with changes in the IMF. Furthermore, none of these studies observe the morning - afternoon asymmetric eastward propagation of the convection changes seen here. It is therefore concluded that the vortex events described here are not related to large-scale changes in the ionospheric convection.

The vortices described here appear to be associated with the separatrix. We therefore speculate that these events may be caused by a perturbation in the separatrix, possibly caused by enhanced or depreciation merging, spreading across the dayside magnetosphere. This perturbation would cause an increase in the cusp currents, which would propagate with the perturbation. The eastward propagation of the perturbation is most likely caused by the eastward motion of the newly merged field lines (observed as eastward flow over the polar cap).

Acknowledgments. We are deeply indebted to all of those who have contributed data for the November 3-11, storm time campaign. The magnetometer data used to produce the AMIE potential patterns were supplied by the following people: The 210 E longitude chain provided by K. Yumoto and K. Shiokawa; Arctic and Antarctic Research Institute (AARI) provided by O. Troshichev; Bell Laboratories provided by L. Lanzerotti and C. Maclennan; University of Maryland, T. Rosenburg and D. Detrik; British Antarctic Survey provided by J. Dudeney and A. Rodger; CANOPUS array provided by T. Hughes and G. Rostoker; Danish Meteorological Institute provided by E. Friis-Christensen and C.R. Clauer and R. Sitar; Institute of Cosmophysical Research and Aeronomy provided by S. I. Solovyev; IMAGE array provided by H. Luehr; ING provide by L. Cafarella; INTERMAGNET data provided by A. Green; IZMIRAN data provided by A. Zaitzev; MACCS array provided by M. Engebretson and G. Hughes; National Geophysical Data Center (NGDC) data provided by L. Morris; RGON data provided by J. Olson; Sub Auroral Magnetometer Network (SAMNET) array provided by D. Milling; SIBIZMIR array provided by V.M. Mishin. This work has been supported by National Science Foundation grant ATM-9501380 at the University of Michigan. One of the authors (A.J.R.) was supported by a Newkirk Fellowship at the High Altitude Observatory, while a student at the University of Michigan.
The Editor thanks K.-H. Glassmeier and another referee for their assistance in evaluating this paper.

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(Received May 5, 1997; revised November 19, 1997; accepted November 20, 1997.)