HIGH-LATITUDE CONVECTION: COMPARISON OF A SIMPLE MODEL
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Abstract. We have compared a simple model of plasma convection at high latitudes with data obtained from simultaneous measurements made by the incoherent scatter facilities at Chatanika, Alaska and Millstone Hill, Massachusetts in June 1978 during moderately disturbed conditions. The measured horizontal plasma drift velocities were averaged for four days to emphasize gross features of the convection pattern and reduce the effects of substorms. The convection model includes the offset of 11.5° between the geographic and geomagnetic poles, the tendency of plasma to corotate about the geographic pole, and a constant dawn/dusk magnetospheric electric field mapped to a circle about a center offset by 5° in the anti-sunward direction from the magnetic pole. The radius of the circle corresponds to 17° of latitude and the electric potentials are aligned parallel to the noon/midnight meridian within the circle. Equatorward of the circle the potential diminishes radially and varies inversely as the fourth power of sine magnetic co-latitude. A consequence of these two offsets and the sunward alignment of the magnetospheric electric field is that our model predicts different diurnal convection patterns when viewed at different longitudes in the geographic frame. The concurrently observed diurnal distributions of horizontal plasma convection velocities are different for Chatanika and Millstone Hill even though the measurements cover approximately the same range of magnetic latitudes. We find there is good agreement between our simple model and the gross features of these two diurnal patterns.

1. Introduction

In an earlier paper [Sojka et al., 1979] we presented a simple model for the dawn/dusk magnetospheric electric field mapped to the ionosphere, and we discussed the resulting effect on the flow velocities of ionospheric plasma at high latitudes. We found that the displacement between the geographic and geomagnetic poles significantly affected the competition between the corotation flow of the plasma and the convective flow due to the magnetospheric electric field. In a magnetic quasi-inertial frame with the z axis parallel to the dipole axis and the sun lying in the x - z plane the flow was shown to be universal time (UT) independent for a constant magnetospheric electric field. However, the flow pattern becomes UT dependent when viewed in a geographic inertial frame of reference because of the rotation of the geomagnetic pole about the geographic pole.

In this study we have endeavored to improve and substantiate our model by comparing model

predictions of plasma flow patterns with observations by the incoherent scatter radar technique. Of particular interest are differences of plasma flow predicted by the model at different longitudes but otherwise at the same invariant latitude and local time. Experimental data employed were obtained by the Chatanika, Alaska, and Millstone Hill, Massachusetts, incoherent radar facilities during concurrent operations over 4 days in June 1978.

2. Experiment Description

Both incoherent scatter radars were operated extensively during the same 4-day period to measure the ion drift velocity vector in the F region over the range of invariant latitudes 55° to 76° along their respective geomagnetic meridians. Chatanika, located near Fairbanks, Alaska, has a magnetic meridian pointing 29° east of geographic north and sampled the region 56° to 74° invariant latitude (55° to 73° geographic). Millstone Hill radar has a magnetic meridian pointing 3° west of geographic north and sampled the region 55° to 72° invariant latitude (44° - 58° geographic). Five hours of local time separate the stations.

Both experiments utilized their very narrow beam antennas to sample the ionosphere at a succession of paired positions near their magnetic meridians. Many observations were obtained in each position by sampling at different ranges. The new 45-m steerable antenna [Evans et al., 1978] was used at Millstone Hill with excellent effect.

The local time separation between the individual samples entering into a velocity vector calculation was less than 1 hour for Chatanika and 2 hours for Millstone Hill. Maximum separation naturally occurs at the most extreme ranges and was minimized consistent with maintaining low overall statistical uncertainty of the predominant east-west flow velocity.

A set of velocity vectors could be obtained with a pair of antenna positions in about 5 minutes or less, and the same region was sampled again at about 30 minute intervals. Both Chatanika and Millstone Hill radar data were analyzed at USU (Utah State University) by using essentially the same methods. It is clearly impractical here to present error bars on the velocity vectors, but perhaps the ensemble of vectors shown will suffice. Unacceptable data were discarded by statistical signal criteria before the vectors were computed, but noisy data are evident at the extreme ranges (to the far north and south for Chatanika, and just to the far north for Millstone Hill).

The upper panels of Figures 1 and 2 show the ion drift velocities obtained from Chatanika and Millstone Hill, respectively, for 4 days of

Fig. 1. Distribution of horizontal plasma drift velocities observed from Chatanika (upper panel) and the predictions for this location of our convection model (lower panel).

experiments. For the purposes of this paper the detailed measurements have been sorted into half-hour UT bins and have also been averaged over the set of 4 days. Further, although the data are shown in geographic coordinates to facilitate comparison with the models, each station's measurements covered nearly the same invariant latitudes. A vector is plotted as a dot at the central point of observation with a line indicating strength and direction.

Although the temptation is strong to consider these data as a 'snapshot' of the entire auroral convection pattern, they are really scans over the same invariant latitudes accumulated over a 24-hour period. The overall patterns

nevertheless are those commonly encountered in many similar experiments. Substorms occurred which produced strong reorientations of the flow lasting for 30 minutes to over an hour and are impossible to remove from the data set simply by averaging.

3. Comparison of Model Predictions With Observations

Development of the Convection Model

The initial objective of this study was to compare the simple plasma flow model of Sojka et al. [1979] with experimental plasma flow

observations. The model assumes that the ionospheric plasma tends to corotate about the geographic pole and that the magnetospheric electric field maps into the ionosphere about the geomagnetic pole. This electric field is represented by a uniform dawn-dusk electric field within a circle bounded by 75° geomagnetic latitude. The magnetic field model used is that of a dipole field. Equatorward of this circle the electric potential diminishes meridionally and inversely as the fourth power of the sine of magnetic colatitude. The consequence of an offset between the geographic and geomagnetic poles is to introduce very marked universal time variations which are apparent when observing the plasma flow in the geographic frame at different

longitudes yet at the same local time and magnetic latitude.

The predicted plasma flow pattern for Chatanika is shown in Figure 3 for this simple convection model. The display format was chosen to match that of the data (Figure 1, upper panel). This model reproduces only the gross characteristics of the observed ion drift pattern; namely, the westward and eastward flow directions in the local evening and morning sectors (the zonal flow-pattern) and the west-south-east reversal around midnight. The most obvious feature of the experimental data is the movement of the convection field to low latitudes at night and its retreat to high latitudes in the day, a feature which is absent

Fig. 2. Distribution of horizontal plasma drift velocities observed from Millstone Hill (upper panel) and the predictions for this location of our convection model (lower panel).

Fig. 3. Distribution of horizontal plasma drift velocities predicted for Chatanika by our convection model but with magnetospheric convection mapped symmetrically about the geomagnetic pole.

from the model predictions shown in Figure 3. Also the model predictions are much more symmetric in local time than are the observations. In particular, the Chatanika data show a region of nonzonal flow moving to a lowest latitude of 68° near local midnight and poleward out of the range of the radar near local noon. This region is not predicted by the model calculations shown in Figure 3. This last feature is indicative of a boundary in the drift pattern moving toward Chatanika around 10 UT and away again around 18 UT.

In order to include such a feature in the model the center of the circle defining the magnetospheric electric field boundary was shifted antisunward along the magnetic midnight meridian by 5° . Motivation for this offset can be found by looking at the nearly circular quiet time inner boundary of the Feldstein oval [Feldstein, 1963], DMSP (Defense Meteorological Satellite Program) low light observations [Meng et al., 1977] and particle observations [Meng, 1979]. A second, minor, adjustment is that the radius of the electric field circle is increased from the 15° of the initial model to 17° .

For comparison with the radar data of Figure 1 a cross tail potential of 90 kV was selected so that the model predictions and observations would agree with regard to the magnitude of the drift velocity vectors in the afternoon sector. This potential corresponds to moderately active conditions and is consistent with the activity at the time the measurements were made.

Comparison With Observations

By using the improved model described in the previous subsection the ion drift patterns for both the Chatanika and Millstone Hill sites have been calculated; these are shown in Figures 1 and 2 (lower panels), respectively. The predictions of the improved model are seen to be in good qualitative agreement with the observations.

At Chatanika (Figure 1), features of the predicted and observed regions of zonal flow now match more closely. The 5° antisunward offset of the center of the model convection electric field results in the zonal flow pattern moving out of the field of view of the radar near local noon. Near local midnight the zonal flow is closest to Chatanika, an invariant latitude of 65° . Poleward of this zonal flow is a region which contains both a discernable antisunward flow component before midnight and a reversed zonal flow in the early morning. The latitudinal extent of the zonal flow pattern and its magnitude as well as the flow characteristics poleward of this zonal flow are well represented by the model predictions. The effects of substorms are not included in the model, thus resulting in its smooth overall appearance when compared to the observed data.

The predictions for the Millstone Hill site also show good general agreement with the data (Figure 2). However, the model predictions for Millstone Hill primarily show the main region of zonal flow; only around local midnight is there any evidence of antisunward flow. The magnitude and direction of the predicted and observed flows compare favorably, which is noteworthy since the convection pattern predicted for Millstone Hill is significantly different from that predicted for Chatanika.

Having shown the general agreement between the observations and predictions, it is necessary to point out a number of regions of discrepancy between the model and data. The afternoon westward flow is observed at Chatanika between 22 and 09 UT, whereas this flow is not seen in the predictions until 03 UT. The occurrence of a well-defined westward flow region in the early afternoon is a common but not universal feature of Chatanika data.

The west-south-east flow reversal near local midnight occurs in the vicinity of the Harang discontinuity in the ionospheric current pattern.

Modeling of the Harang discontinuity requires very localized asymmetric potential distributions [Kamide and Matsushita, 1979], and even then agreement is only obtained in restricted regions. The model used here does not attempt to include the detailed physics associated with the Harang discontinuity. Thus the general comparison of the observations and predictions in this local time sector is good even though a precise account of the fine structure is not to be expected.

At both Chatanika and Millstone Hill the predicted flow reversal near midnight appears between 1 and 3 hours later than observed, and at Chatanika the noon sector pattern is predicted to occur several hours later than seen in the data. There appears to be a systematic time slippage between the predictions of the model and the data.

The model contains a magnetospheric electric field that is symmetric about the noon-midnight meridian. It is mainly this symmetry which determines the local times at which the speed reversal regions are predicted. There are a number of different ways in which the model magnetospheric electric field can be modified to better fit the observed data. Heppner [1977] introduces asymmetries in the two cells, that is, having an enhanced dawn or dusk cell but still maintaining a noon-midnight alignment. Yasuhara et al. [1975] introduce an alignment along a meridian offset by a few hours from the noon-midnight meridian, the direction of the offset on the dayside being a few hours before midday.

We have examined the relative merits of these two empirical methods of distorting the mapped cross-tail magnetospheric electric field. Adjusting the alignment of the mapped equipotentials so that they are parallel to the 10-22 LT direction produced a significant improvement in the agreement between the predicted distribution of the plasma flow vectors

and those observed at Chatanika, whereas the other method failed to improve the agreement. Figure 4 shows the predictions of a model identical to that used earlier, except for a skewing of the magnetospheric electric field to give equipotentials parallel to the 10-22 LT direction. Better agreement between this model and the Chatanika measurements is seen in the postnoon region. Also the timing of the flow reversals near local noon and midnight is in better agreement with the measurements. This figure is presented as an indication of how empirical adjustments can be used to provide a better match to the data. We are reluctant to recommend the use of this empirical feature at this stage because of the limited data base used in the comparison, and we revert back to the earlier improved model for the following section.

Latitudinal Gradient of Speed Distribution

A second goal of this study was to estimate the latitudinal variation of the flow speed at a given local time. Both Chatanika and Millstone are located such that they see little of the polar cap, but they do provide excellent latitude coverage in the region where the model predicts a latitude gradient in plasma drift speed. The two data sets were averaged over 1-hour intervals and plotted to show latitudinal gradient of the plasma drift speed. In the model the gradient is the result of a meridionally diminishing potential which varies inversely as the fourth power of sine colatitude in the magnetic frame [Volland, 1978]. The model was also run for an inverse 'second power' potential gradient representative of more slowly diminishing potentials, and the calculated speed gradients were compared directly with the plotted data. Figure 5 shows four of these latitude gradients derived by plotting the logarithm of speed versus geographic latitude. The observations shown are

Fig. 4. Distribution of horizontal plasma drift velocities predicted for Chatanika by our convection model modified to include an empirical skew to the mapped magnetospheric electric field resulting in equipotentials aligned parallel to the 10-22 LT direction.

Fig. 5. Variation of plasma drift speeds with geographic latitude for four local time periods as observed at Chatanika (data points). The data were collected over a time period of 1 hour immediately prior to the time shown. The solid lines are the model predictions for the indicated local times. The dashed line corresponds to the variation in drift speed for an inverse second power decay in the magnetospheric electric potential (see text).

all from Chatanika, the data being represented by points and the 'fourth power' model gradient being represented by the solid lines. In the first panel of Figure 5 a dashed line is included; this represents a 'second power' model gradient.

It is apparent that the 'fourth power' model gradient clearly produces better agreement with the measurements than the 'second power' gradient. The four local times shown in Figure 5 were chosen for display because a smooth gradient in the speed distribution was clearly evident in the data at these times. A similar comparison between model predictions and observations at other local times indicated that the fourth power produced a better agreement than the second power for most of the day. However, there were periods during the day when the falloff of the magnetospheric potential could not be determined unambiguously. For example, in the midnight sector the boundary between the zonal and the polar cap flows and the velocity changes across the west-south-east flow reversal region fall within the 72° to 60° region of comparison, and a meaningful determination of the slope was not possible.

The comparison of model and observation for Chatanika and Millstone Hill suggests that the magnetospheric electric potential in the falloff region outside the polar cap is better represented by an 'inverse fourth' power than an 'inverse second' power. In contrast, Heppner [1977] suggested that the magnetospheric electric potential diminishes more slowly than the fourth power. However, we caution the reader that our conclusion is based on a limited data set. Data taken at other seasons or under other geophysical conditions could produce different results.

4. Summary

The gross features of the diurnal variation of horizontal plasma drift velocities measured

concurrently by the incoherent scatter radar installations at Chatanika and Millstone Hill in June 1978 have been compared with the predictions of a simple model of ionospheric convection. The model used is based on that of Sojka et al. [1979] and refined by offsetting the mapped magnetospheric electric potential 5° from the magnetic pole in the antisunward direction. We have shown that the differences in the convection pattern observed at the two sites are consistent with the predictions of this simple model. We are encouraged by the agreement between the model and the data and feel that further comparisons would be fruitful in refining the model. The comparison we have made in this study underlines the importance of taking universal time into consideration when analyzing high-latitude convection measurements.

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