GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 14, PAGES 2783-2786, JULY 15, 2001

# Quantification of High Latitude Electric Field Variability

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**Abstract.** Variability in the high latitude electric field has been identified as a major contributor to global Joule heating. Electric field patterns from the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure are used to characterize the E-field temporal variability over the course of 18 hours. The standard deviation of the E-field magnitude on May 4, 1998 often exceeds the average value of the E-field magnitude. A significant fraction of this variability arises from oscillations with period less than one hour. This confirms that Joule heating calculations based on time-averaged E-fields may significantly under-predict the heating.

## Introduction

The electric field is one of the most important electrodynamic quantities that determine the coupled behavior of the high latitude ionosphere and thermosphere (I-T). Knowledge of the electric field is required to specify ionospheric transport, the ion-drag force on the neutral gas, and frictional heating of the ion and neutral gases. The ion drag force leads to the momentum forcing of the neutral gas and the setting up of global wind patterns. The frictional heating (Joule heating) drives horizontal and vertical winds, and leads to changes in the global temperature and compositional structure of the thermosphere, with resulting changes in ionospheric electron density [*Crowley*, 1991; *Immel et al.*, 2000].

Historically, the effect of the magnetosphere on the I-T system, and of the I-T system on the magnetosphere has been taken into account by the use of electric field climatologies constructed from an ensemble of many days of observations [e.g. *Foster et al.*, 1986; *Weimer*, 1996]. However, these simple boundary conditions are now restricting our understanding, and we need to better understand the ITM coupling. One of the critical factors involved in understanding the coupling is to determine the temporal and spatial scales over which the ionospheric electric field varies.

At the largest spatial scale sizes (200 - 2000 km), the ionospheric convection pattern is controlled mainly by the IMF. The existence of 2, 3 and 4-cell patterns under various IMF conditions is well established [*Crowley et al.*, 1992; *Greenwald et al.*, 1995]. However, the IMF is extremely variable, and the corresponding temporal and spatial changes of the large-scale patterns are not well characterized. Temporal variability could be responsible for a large fraction of the Joule heating experienced by the atmosphere [*Codrescu et al.*, (1995)], and this heating is not captured by GCMs when driven by climatological E-field models. [*Codrescu et al.*, [1997] demonstrated the effect by arbitrarily adding variability to the E-field specification in their global model.

*Foster et al.*, [1986] constructed a climatological E-field model using Millstone Hill radar data. Recently, *Codrescu et al.*, [2000] re-analyzed the Millstone Hill data obtained from 1979-1986 between 48° and 78° North magnetic latitude to obtain an estimate of the corresponding standard deviations. The line-of- sight measurements were binned as a function of magnetic local time (1-hr), magnetic latitude (2°), auroral activity (Hp Index) and season. The standard deviation generally increased from lower to higher latitudes, reaching a maximum near the sunward-to-antisunward flow reversal, before decreasing into the polar cap. For quiet conditions, standard deviations exceeded 400 m/s in a 10° latitude band in the midnight sector, reducing to a 5° band on the dayside. For active conditions, the convection pattern expanded, and a significant fraction of the high latitude region experienced more than 200 m/s standard deviations. Assuming a Gaussian distribution of variability around the mean E-field, they showed that the mean E-field and standard deviation have equal weights in Joule heating generation. Thus, they assert the mean square E-field magnitude is roughly double the square of the mean E-field magnitude. This argument provides a justification of the *ad-hoc* doubling or tripling of Joule heating applied in many GCM's.

The *Codrescu et al.*, [2000] study represents a major step forward in quantifying the variability of the electric field. However, the uniqueness of the variability obtained from that work, and the manner in which it should be applied are unclear. For example, the *Codrescu et al.*, [2000] study was limited to line of sight drift measurements from one location gathered over a period of many years. The ensemble standard deviation they compute is thus not necessarily representative of the standard deviation that would be observed over a period of one day or one hour. The present paper introduces a new technique for obtaining statistical information on the electric field. It explores whether the ensemble standard deviation is an appropriate number, and what the standard deviation over an interval of about 1-day would be if one could continuously measure the E-field at each location. It also examines what percentage of the variation comes from high and low frequencies.

## Method

Our lack of knowledge about the temporal and spatial variability of the electric field and conductance is partly due to the difficulty of measuring these parameters everywhere simultaneously. Ideally, all of the electrodynamic parameters would be routinely measured at high resolution throughout the high latitude region. In reality, what is available is a

Paper number 2000GL012624.
0094-8276/01/2000GL012624$05.00

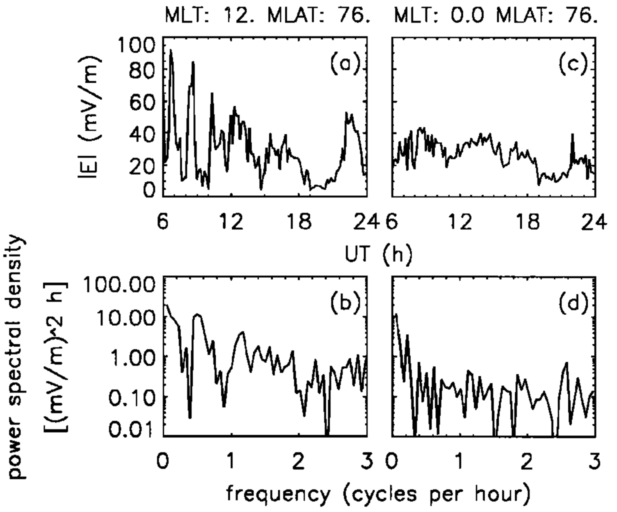

**Figure 1.** Time history and power spectrum of AMIE electric field magnitude at two grid locations for May 4, 1998.

sparse collection of single-point measurements irregularly located in time and space. The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure is an inversion technique that can ingest data from a wide range of sources to produce a realistic representation of the high latitude electrodynamic state for a given time [*Richmond,* 1992]. The data inputs typically include electric fields derived from ion velocities measured by radars, satellites, and digital ionosondes, together with magnetic perturbations from ground and space based instruments. Particle precipitation data from satellites and auroral images have also been used to provide ionospheric conductance inputs for AMIE [e.g. *Crowley et al.*, 2001]. Using these data, the distribution of various electrodynamic parameters, including the electric field, can be derived through the electrodynamic equations.

This paper demonstrates how the AMIE output fields provide a basis for quantifying the temporal and spatial variability in the E-field for all MLT and magnetic latitude bins simultaneously and continuously. The present study was undertaken to evaluate the temporal variability of the electric field and conductance in the AMIE fields for a single day. The spatial variability will be the subject of a later paper. The AMIE electric fields used for this study were taken from work by *Crowley et al.,* [2001], which discusses the sensitivity of the AMIE procedure to various input data sets. The investigation was based on the 4th May (Day 124) 1998 storm. The present paper is restricted to the 0600-2400 UT period after the main phase of the storm because POLAR UVI conductance data are only available from 0830 – 1830 UT. The AMIE run also continuously ingested other data, including magnetic field data from 80 magnetometers, and E-fields and conductances derived from 3 DMSP satellites. The SuperDARN radar E-field data from this period were very sparse, and were not included in the run.

# Results

AMIE provided electric field values at 10-minute time intervals, with a spatial resolution of 2° magnetic latitude and 1-hr MLT. The temporal variability of the electric field was characterized by computing the mean values and variances from the mean at every grid point. This temporal variability was further characterized by taking the Fourier transform in time of the electric field magnitude at each spatial location. On this particular day, the electric field was most active on the day side, and Figure 1a shows the time history of the E-field magnitude for 12 MLT and 76° MLAT, along with the corresponding power spectrum in Figure 1b. The nightside values and variability were relatively small, as characterized by Figures 1c and 1d for 00 MLT and 76° MLAT. Figure 2 shows a sample of the large dayside highlatitude E-fields, and demonstrates the good agreement between the absolute value of AMIE generated E-fields and the corresponding values measured along the DMSP satellite orbit.

Through processing of the power spectrum, the total variance was divided into a high frequency part (periods less than one hour), and a low frequency part (periods more than one hour). Figure 3a depicts the average E-field magnitude as a function of MLT and magnetic latitude. (The outer latitude circle is at 50° ). Figure 3b shows the RMS E-field distribution, and figure 3c illustrates the standard deviation. These quantities are related by $< E^2 > = < E >^2 + \sigma^2$, and *Codrescu et al.,* [1995] argue that $< E^2 >$ is the proper term to use in Joule heating calculations. Here, brackets <> denote average over time.

Figure 3 confirms that $E_{RMS}$ is often significantly larger than the mean E-field, and that the use of the mean E-field in global models will lead to an underestimate of thermospheric Joule heating. However, unlike the *Codrescu et al.,* [2000] study, which found them to be of equal importance, we find that the standard deviation can also be smaller than the mean field. Figure 3d depicts the standard deviation as a percentage of the mean E-field, and the standard deviation poleward of 70°N is generally less than 80% (and frequently only 30%) of the mean E-field. On the dayside, equatorward of 70°, where the mean E-fields are smaller, the percentage increase contributed by variability ranges from 80% to 140%. Figures 3e and 3f are derived from the Fourier transform in time of the E-field, and show the standard deviation contributed by periods greater than 1-hour and less than 1-hour, respectively. The contribution from the longer period variations (1e) is about half that from the shorter period (1f) variations for this day.

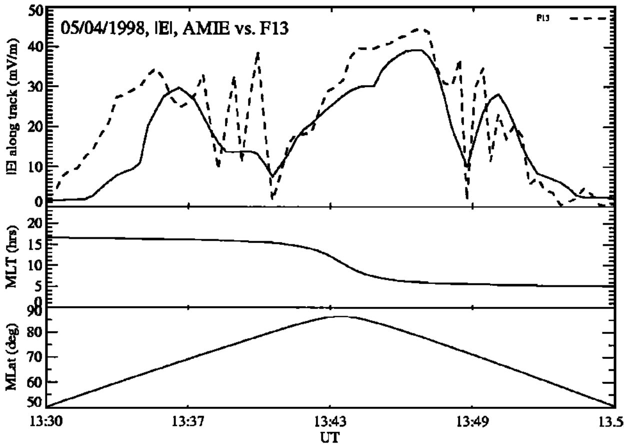

**Figure 2.** Comparison of absolute values of along-track E-field from AMIE (solid line) versus DMSP-F13 measurements (dashed line).

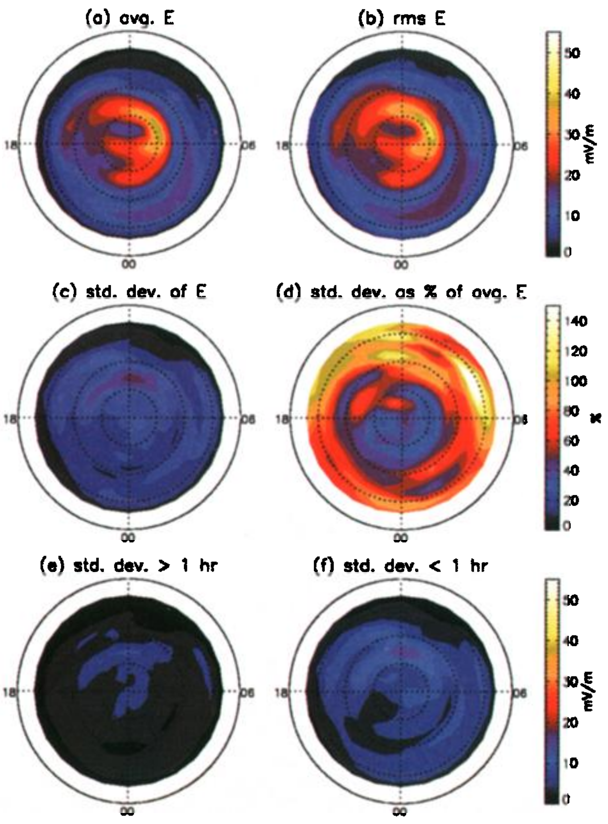

**Figure 3.** Statistical analysis of fields driven by all available data for May 4, 1998. (a) average E-field magnitude, $< E >$; (b) rms E-field magnitude, $< E^2 >^{1/2}$; (c) standard deviation of the E-field magnitude; (d) total standard deviation as a percentage of the local E-field magnitude; (e) component of standard deviation with period of variation less than one hour; (f) component of standard deviation with period greater than one hour.

The way to interpret Figure 3 is that Figure 3a shows the result of using a fixed mean electric field model. Figure 3e indicates the variability that would be added if the electric field were changed with a cadence of about an hour. Figure 3f indicates the additional variability from changing the E-field with a 10- minute cadence. On this particular day the high frequency (< 1 hour) part of the variance contributes up to 80% of the overall variability of the E-field in the polar cap. The gentle slope of the spectrum in Figure 1b indicates that there may also be significant variations at higher frequencies that are not captured by the 10-minute cadence.

The quality of the AMIE patterns depends on the amount and quality of the data used to feed the assimilation. If the AMIE input data covered the entire high latitude region, then the fitted coefficients and corresponding mapped functions such as the electric potential would be constrained in all locations. On the other hand, if there are no data in large regions of the high latitude ionosphere, the fitted coefficients are not constrained (in those regions), and the mapped function may contain large uncertainties. In the data inversion, a model is generally used to provide background information at particular locations. The background models are statistical in nature and help to specify the inversion in regions of the ionosphere where there is little or no input data. For example, 80 magnetometers contributed to the present study, but the density of magnetometer stations is much greater in the European and North American/Canadian sectors than in the Russian and North Pacific sectors. The lack of data in certain sectors for ingestion into AMIE presents a perennial problem for obtaining realistic high latitude fields, and in those sectors AMIE is generally forced to rely on statistical models. For the present case, the problem is mitigated by the inclusion of conductances and E-fields from the three DMSP satellites, and conductances derived from the POLAR/UVI instrument. Ideally, more data would be available, including E-field measurements from the SuperDARN and Sondrestrom radars, but the present data set illustrates the technique.

It is also important to note that the background patterns were not static, but were themselves driven by external data. In this study, the background patterns were *Weimer* [1996] patterns driven by ACE measurements of the IMF with a 10-minute cadence. To ensure that the analysis presented in Figure 3 is not simply providing an estimate of the variability in the *Weimer* model, we applied the same Fourier analysis to the *Weimer* background patterns driven only by the IMF (i.e. no magnetometer, or other data ingested by AMIE). The results are shown in Figure 4, and reveal that the mean E-field distribution (Fig 4a) is somewhat different from that shown in Figure 3a. Similarly, the variability as revealed by the distribution of the standard deviation (Fig 4c) is also different from that obtained using the AMIE patterns in Figure 3c. Comparison of Figures 4e and 4f indicates that

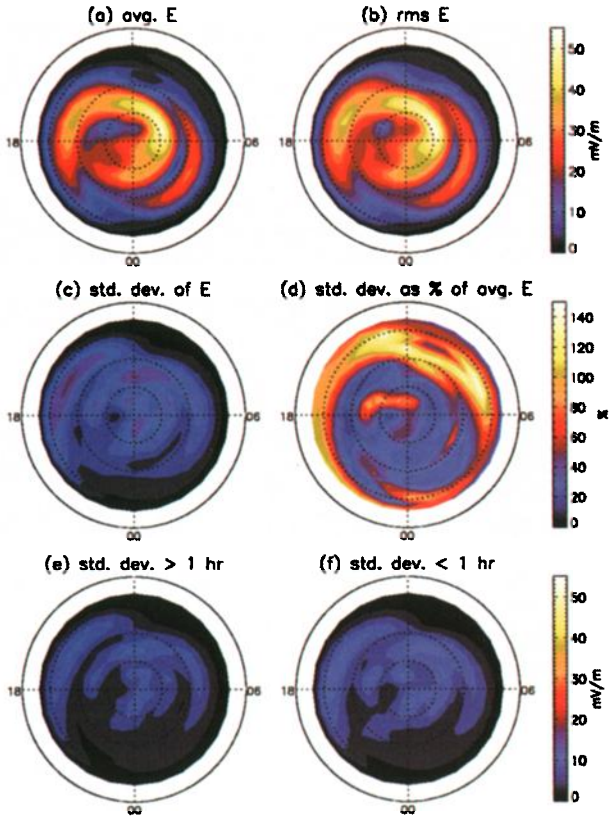

**Figure 4.** Same as Figure 3, but for background model driven only by IMF data.

the variability in the background patterns is similar on time scales of greater than 1-hour and less than 1-hour. The variability in the short period component increases when data are ingested into AMIE. This control study using only the *Weimer* patterns suggests the variability found in Figure 3 is probably a real geophysical effect, although the variability might be underestimated.

## Conclusions

We have demonstrated the potential for using the time-resolved electric fields from AMIE to characterize the high-latitude E-field temporal variability. For a particular 18-hour interval, the standard deviation was comparable with the mean value of the high latitude E-field. Therefore, Joule heating calculations based on time-averaged E-fields will significantly under-predict the heating. There are significant differences between these AMIE results and the ensemble standard deviation of the *Codrescu et al.* [2000] results. *Codrescu et al.* were unable to examine the polar cap in detail, but suggested that the greatest variability occurs in an annulus corresponding to the auroral oval. In contrast, the AMIE results (Figure 3c) show peak variability in the cusp and polar cap, with standard deviations reaching 20 mV/m (equivalent to 400 m/s ion velocity) which are comparable with the auroral standard deviations obtained by *Codrescu et al.* [2000]. The data set used by *Codrescu et al.* [2000] did not permit an examination of temporal variability in different frequency ranges. Most of the variability in our data-driven AMIE patterns arose from variations with periods of less than one hour. In spite of gaps in the spatial coverage of the AMIE input data-sets, we showed in a control-experiment that the observed E-field variability is a function of actual measurements and not simply the background *Weimer* [1996] pattern driven by the IMF.

This work has demonstrated the principle of using AMIE to study temporal E-field variability, but it generates more questions than it answers. Since this data is from a period following the main phase of a storm, the results may not be typical, and in future a much larger statistical study involving other intervals will be performed. The present study contained a relatively small amount of E-field data, and it will be particularly interesting to investigate intervals for which there are large quantities of radar E-field measurements. Because of the AMIE data-fitting procedure, the AMIE results will always be less variable than the data, and will lead to an underestimate of the temporal and spatial variability of the E-field. This smoothing effect is visible in Figure 2. In a future investigation, the variability spectrum for a faster cadence, such as every 1-minute, will be examined. Since the AMIE technique also produces global conductance patterns, this technique will be extended to analyze the conductance and Joule heating variability directly. The AMIE fields will also permit investigation of the spatial variability.

In principle, studies of this kind provide a factor with which to correct the average E-field models and Joule heating when they are used in global I-T models. However, the variability is not uniformly distributed around the high latitude regions, and therefore uniformly applying a correction factor is inappropriate. For most applications, including space weather, the variability of the electric field and its effect on Joule heating in the numerical I-T models would be better specified by using realistic convection patterns (such as those from AMIE) instead of fixed average convection models.

**Acknowledgments.** This work was supported by NSF grant ATM-9806600 and NASA grant NAG5-10059.

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(Received November 10, 2000; revised February 9, 2001; accepted February 26, 2001.)