Subionospheric VLF measurements of the effects of geomagnetic storms on the mid-latitude D-region

W. B. Peter, M. Chevalier, and U. S. Inan
Stanford University, 350 Serra Mall, Stanford, CA 94305

Abstract

We examine the effects on the mid-latitude *D*-region of two geomagnetic storms, the "Halloween storm" of late October 2003 and the 07 April 2000 storm, by means of the associated perturbations of several subionospheric VLF/LF signals propagating in both the northern and southern hemispheres. We use VLF/LF nighttime data from the Holographic Array for Ionospheric/Lightning Research (HAIL), located in the United States ($L = 2-3$), as well as data from Palmer Station, Antarctica ($L = 2.4$). On 07 April 2000, a ~ 5 dB depression in VLF amplitudes was recorded at multiple HAIL stations, with a depression onset that occurred later for VLF/LF signal paths at lower latitudes. On both 07 April 2000 and 31 Oct 2003, fluctuations in the amplitude of the VLF signals were first observed in the premidnight sector and persisted through the end of the data-recording period (dawn). The frequency content of the fluctuations was predominantly in the 0.01 to 0.02 Hz range, but extended up to ~ 0.03 Hz. Increases in the energetic electron flux in the loss cone as measured by the NOAA-POES satellites were observed on both 07 April 2000 and 31 October 2003. We suggest that both the signal depressions and subsequent fluctuations were associated with variations in the precipitation flux of energetic electrons onto the upper atmosphere. We provide evidence that the fluctuations and the signal depression coincide with the equatorward edge of the auroral oval extending over the perturbed VLF/LF Great Circle Paths. Quantitative modeling of subionospheric VLF wave propagation incorporating energetic electron flux measurements (and the associated altitude profiles of secondary ionization produced) yield results consistent with the variations in the VLF signal amplitude observed. The occurrence rate of lightning-induced electron precipitation (LEP) events, as recorded on several VLF/LF signals, was seen to be highly variable with geomagnetic activity. Comparison of LEP event occurrence rates with measurements of energetic electron flux levels from the NOAA-POES satellite supports the notion that this variability is largely due to geomagnetic storm-associated increases in the energetic electron population in the slot region.

Introduction

VLF waves are guided within the spherical waveguide formed between the earth and the ionosphere. The amplitude and phase of the subionospherically propagating VLF signals depend sensitively on the electrical conductivity of the lower ionosphere as well as that of the ground. The amplitude and phase of VLF transmitter signals observed at any point can be used to probe ionospheric processes that occur near ~85 km, the inferred nighttime upper reflection height of the waves. In this paper, we examine mid-latitude ionospheric *D*-region perturbations as detected by VLF signal variations associated with two geomagnetic storms, the 07 April 2000 storm and the "Halloween storm" of late October 2003.

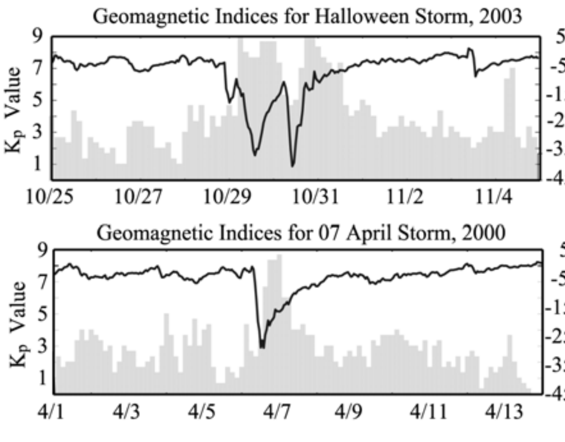

Figure 1: Geomagnetic indices for the Halloween storm of late October 2003 and the 07 April 2000 geomagnetic storm.

Figure 1 shows D_{st} and K_p indices for the two periods. For the 07 April 2000 storm, increased geomagnetic activity began in the morning (Mountain Standard Time) of the 7th and persisted through the night. For the Halloween storm, increased activity began on the night of 29 October, with high levels of activity persisting through the night of 31 October. Moderate geomagnetic activity continued for several days afterwards.

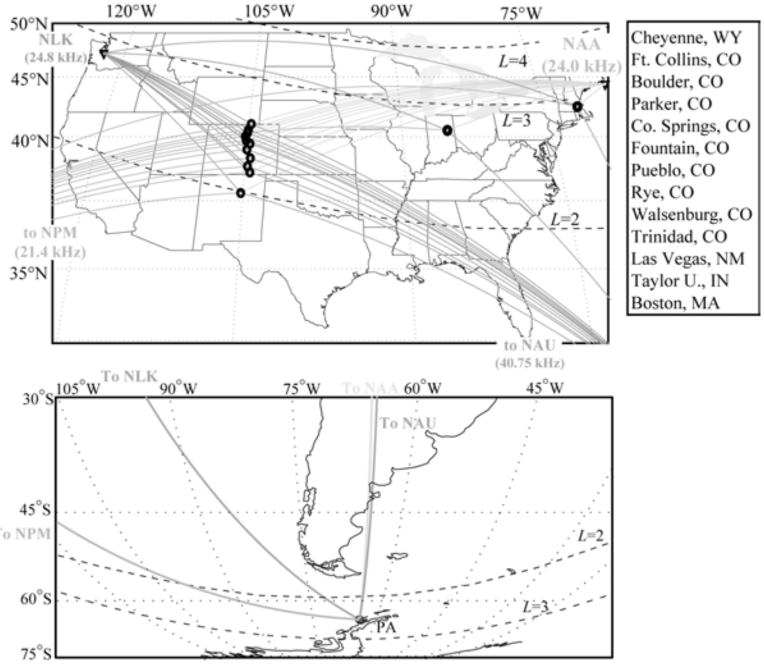

Figure 2: Map of the HAIL array and Palmer Station, Antarctica. The Great Circle Paths (GCPs) of the subionospherically propagating VLF signals are shown as solid lines. The names of the receiver stations are shown to the right.

We utilize subionospheric VLF signal data from the Holographic Array for Ionospheric/Lightning research (HAIL) and Palmer Station, Antarctica. Figure 2 shows the Great Circle Paths (GCPs) of subionospherically propagating VLF signals recorded at the HAIL array (top panel) and Palmer station (bottom panel). The receivers continuously monitor the amplitude and phase of coherent and subionospherically propagating VLF transmitter signals operated by the United States Navy in Washington (NLK at 24.8 kHz), Maine (NAA at 24.0 kHz), Hawaii (NPM at 21.4 kHz) and Puerto Rico (NAU at 40.75 kHz).

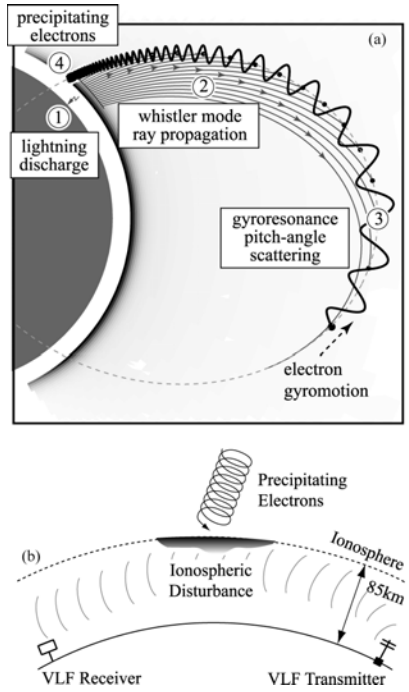

Figure 3: Cartoon of Lightning Induced Electron Precipitation (LEP) events. Adapted from *Lauben et al.,* [2001].

Lightning-induced electron precipitation (LEP) events are produced by the fraction of the VLF energy radiated by lightning discharges that escapes into the magnetosphere and propagates as a whistler-mode wave (Figure 3a). The whistler-mode wave interacts with trapped radiation belt electrons through cyclotron resonant pitch angle scattering, causing some of those close to the loss cone to precipitate and produce secondary ionization. The precipitating energetic electrons (~50 to 500 keV) cause secondary ionization via impact with atmospheric constituents, altering the conductivity of the *D*-region of the ionosphere (Figure 3b). This ionospheric disturbance in turn changes the amplitude and/or phase of VLF/LF transmitter signals propagating in the earth-ionosphere waveguide on GCPs that pass through or near the localized disturbances [*Poulsen et al.,* 1993].

In general, the occurrence rates of LEP events as monitored by the HAIL array have been seen to be highly variable. Figure 4 shows HAIL amplitude data from two days in March 2001, with pronounced LEP event activity on the 28th, but not on the 9th, despite similar thunderstorm activity on the two days. The LEP events were induced by nonducted obliquely propagating whistler waves, as determined by the temporal and spatial characteristics of the VLF perturbations. As was the case for these two nights, LEP event occurrence rates have been shown to exhibit a dependence on geomagnetic activity [*Peter and Inan* 2004]. When compared to electron flux data from the NOAA-POES satellite, the data suggests a correlation between the occurrence rates of lightning-induced electron precipitation events measured on the HAIL array and the energetic electron flux levels in the radiation belts ($2 < L < 3$). However, long-term studies correlating lightning flashes with LEP event occurrence have yet to conclusively determine the relationships between geomagnetic activity, flash intensity, flash locations, and the loss of electrons by LEP.

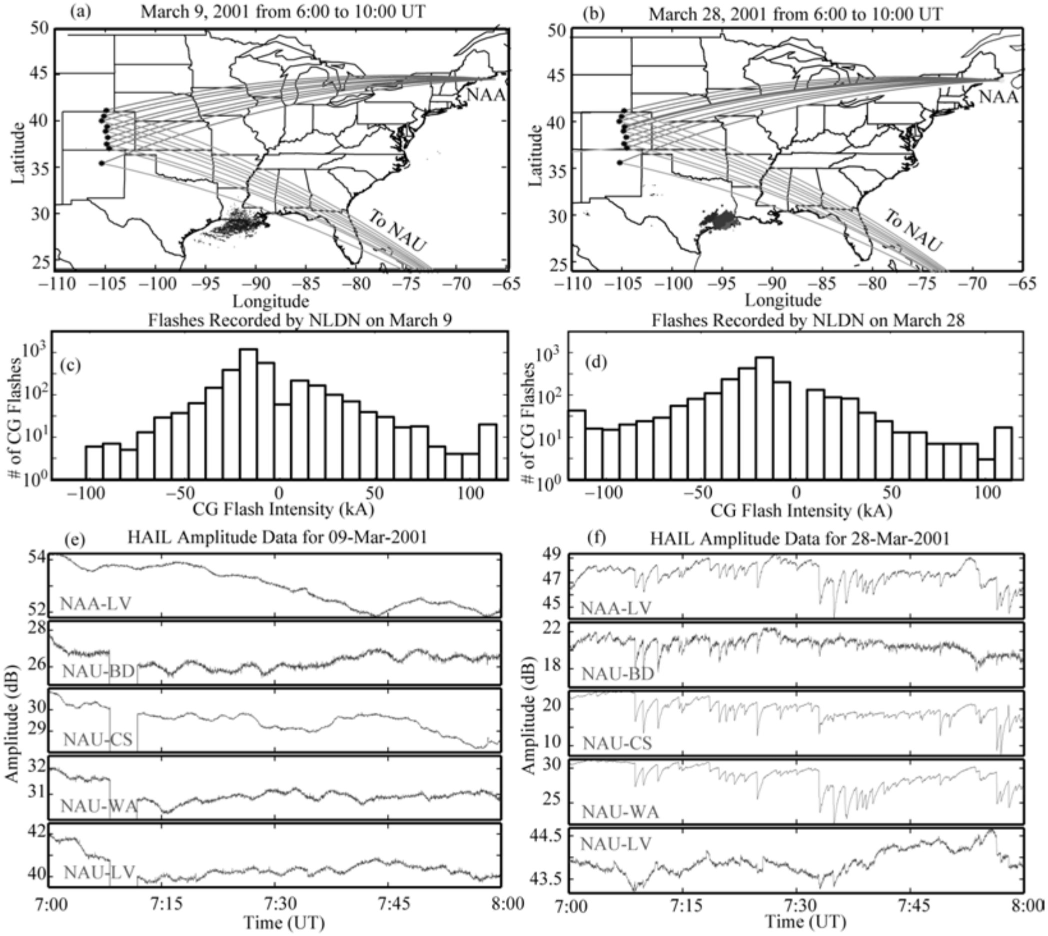

Figure 4: LEP event occurrence for two thunderstorms. (Top) Maps showing the location of two storms of similar locations during March 2001. (Middle) Histogram of all CG flashes as recorded by the NLDN network from 6:00 to 10:00 UT, binned according to flash intensity. (Bottom) HAIL amplitude data from 7:00 to 8:00 UT showing pronounced LEP event activity on the 28th, but not on the 9th.

Halloween Storm

Figure 5 shows four-hour panels of NLK amplitude data recorded at Palmer (PA) for each night from 27 October to 05 November 2003. Fluctuations in the signal are an indication of varying disturbances of the *D*-region ionosphere along the GCP. During times of quiet geomagnetic conditions (26-29 October), the signal amplitude did not fluctuate significantly, indicating that the state of the *D*-region (i.e., the altitude profile of secondary ionization) was relatively stable. Beginning on 30 October, fluctuations were evident, with the maximum activity occurring on the night of 31 October. The increase in fluctuations on the 31st was observed on all the NLK and NAA signals received at the different HAIL stations, as well as several different signals received at Palmer. By 01-05 November, the signal amplitude had returned to its “quiet” conditions exhibited before the Halloween geomagnetic storm. In comparison with NOAA-POES satellite auroral activity patterns, the fluctuations of the VLF signal amplitudes enhanced on nights when the auroral oval had extended equatorward over the HAIL paths (and presumably the Palmer GCPs). This correlation supports the idea that the fluctuations were caused by variations in auroral precipitation of energetic electrons that dominated the state of the *D*-region during these disturbed times.

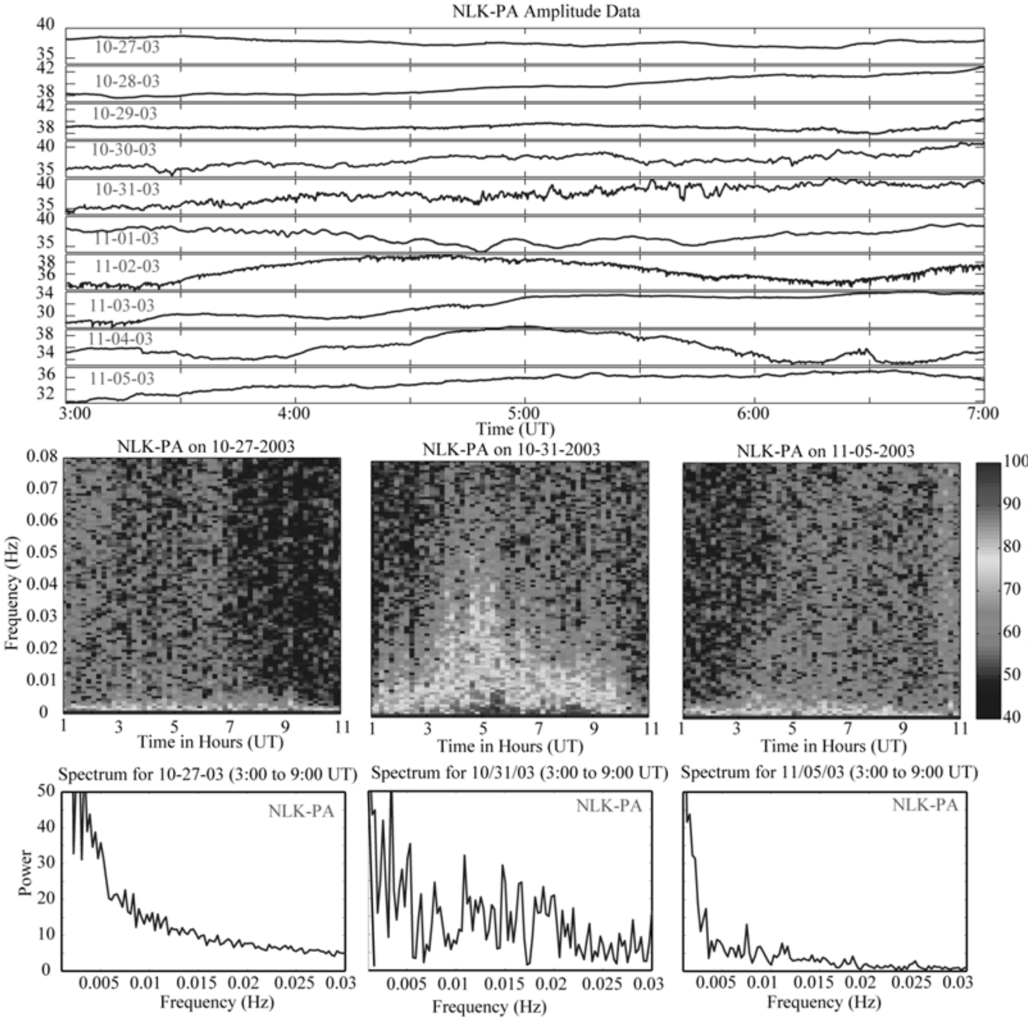

Figure 5: Halloween Storm VLF fluctuations in Southern Hemisphere. (Top) Four-hour panels of the received NLK signal amplitude from 03:00 to 07:00 UT for each day from 27 October to 05 November recorded at Palmer (PA). (Middle) Spectrograms of the narrowband NLK-PA amplitude signal for 27 October, 31 October, and 05 November. (Bottom) Fourier Transform of the amplitude signal for the same three days.

In order to examine the frequency content of these fluctuations, we display the modulations of the VLF signal in the form of spectrograms (middle panels of Figure 5) produced by Fourier transformation of the time series of the narrowband amplitude data. The spectrogram content represents amplitude modulation of the received NLK transmitter signal at Palmer. A pronounced increase in spectral content, extending up to ~0.03 Hz, can be seen from 03:00 to 09:00 UT (21:00 to 03:00 MLT) on 31 October. The spectral content displayed in Figure 5 is typical of the fluctuations observed in NLK and NAA amplitude data recorded at the HAIL receivers, as well as multiple VLF signals recorded at Palmer station.

The bottom panels of Figure 5 show Fourier Transforms of the amplitude of the NLK-PA signals. The transform is taken of data from 03:00 to 09:00 UT, giving a frequency resolution of ~5×10^{-5} Hz. An increase in frequency content of the fluctuations is evident on 31 October 2003. There is no indication of a single discrete frequency component. The modulations of the VLF signals for the cases examined here contain the most structure in the 0.01 to 0.02 Hz range, corresponding to periodicities in the 50-100 s range. The lack of a single discrete frequency of modulation may indicate that the electron precipitation responsible for the ionospheric disturbances occurred at several discrete patches along or near the GCP, each with different and/or variable frequencies of modulated precipitation. In this context, it may be noteworthy that the chemical recovery times for secondary ionization in the nighttime *D*-region are typically in the 10-100 s range [*Pasko and Inan*, 1994].

Several days after the onset of geomagnetic activity, an unusually high number of large (>0.5 dB) LEP events were detected on the HAIL and Palmer VLF signals. Figure 6 shows NPM signal amplitude data from 6:45 to 7:00 UT for each day from 31 October to 05 November recorded at Palmer Station. An increase in the number of events was detected on both the northern and southern hemisphere sites from 2-4 November (Figure 6b). Figure 6c shows 16-second averaged 100-300 keV electron flux data from the NOAA-POES satellite, with the detector nearly perpendicular (with a window of 30 degrees) to the magnetic field. All satellite passes occurred between 3:00 and 9:00 UT over the Southern Hemisphere, between 40 and 110 degrees west geographic longitude.

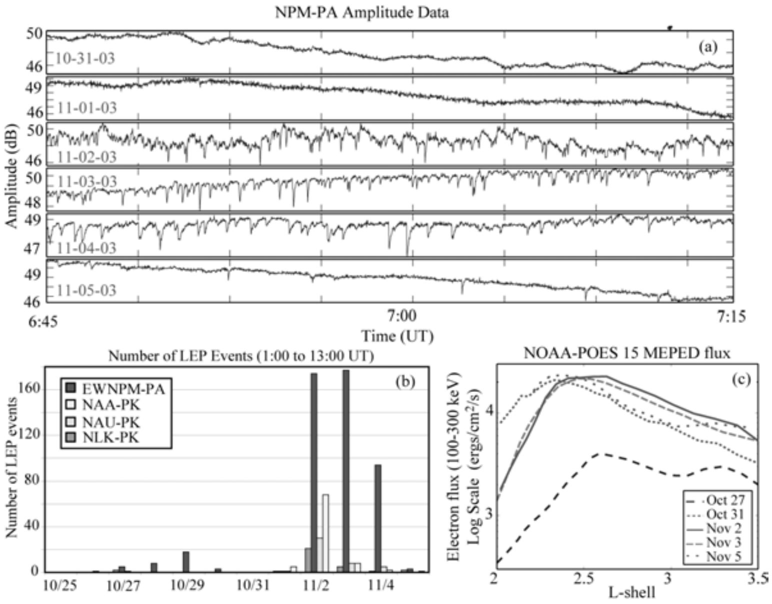

Figure 6: (a) Half-hour panels of the received NPM signal amplitude from 6:45 to 7:00 UT for each day from 31 October to 05 November recorded at Palmer. (b) The number of LEP events observed each night from 25 October 2003 to 5 November 2003. (c) Data from the Space Environment Monitor's (SEM-2) Medium Energy Proton and Electron Detector (MEPED) aboard the NOAA-15 POES satellite.

Prior to the onset of geomagnetic activity, when the occurrence rates of detected LEP events were low, the detected energetic electron flux levels were also lower (Figure 6c). However, on 31 October, a sharp increase in flux levels was observed. This increase suggests that the energetic electron population in the slot region (L = 2 to 3) was enhanced by at least an order of magnitude above levels typically observed during quiet geomagnetic conditions. The high levels of flux continued through 5 November, including the nights of increased LEP event activity (2-4 November). This occurrence supports the notion that the increase in the number of LEP events detected was largely due to the energetic electron population in the slot region increasing with the advent of geomagnetic activity [*Friedel et al.,* 1995], thus increasing the population of energetic electrons available for scattering into the loss cone by lightning induced whistlers. On the nights of elevated energetic electron flux levels in the slot region that did not exhibit an increased number of LEP events (i.e., 31 October), there were few lightning flashes, as recorded by the National Lightning Detection Network, in the regions typically associated with inducing precipitation on HAIL and Palmer station VLF signals [*Peter and Inan,* 2004].

07 April 2000 Storm

Figure 7 shows nine-hour panels of NLK (left) and NAA (right) signal amplitude data recorded at six HAIL VLF receivers. The NLK signal exhibits a ~4 dB decrease in amplitude, starting at ~04:00 UT on the more northern paths (i.e., NLK-BO) and ~05:30 on the southernmost path (NLK-WA). Following this depression, the NLK signal amplitude exhibits fluctuations similar to those observed on 31 October 2003 during the Halloween geomagnetic storm. The signal amplitude remains depressed throughout the night, and at 11:00 UT the day-night terminator moves across the GCPs. The onset of the signal depression roughly corresponds to the rotation of the auroral oval through the GCPs of the HAIL array, as determined by inspection of NOAA-POES auroral activity patterns (not shown). The auroral oval likely overlayed the more southern GCPs (i.e., NLK-WA) at a later time as it rotated westward. By 07:49 UT, all of the NLK GCPs were overlaid by the auroral oval and exhibited depressed signal levels with quasiperiodic fluctuations.

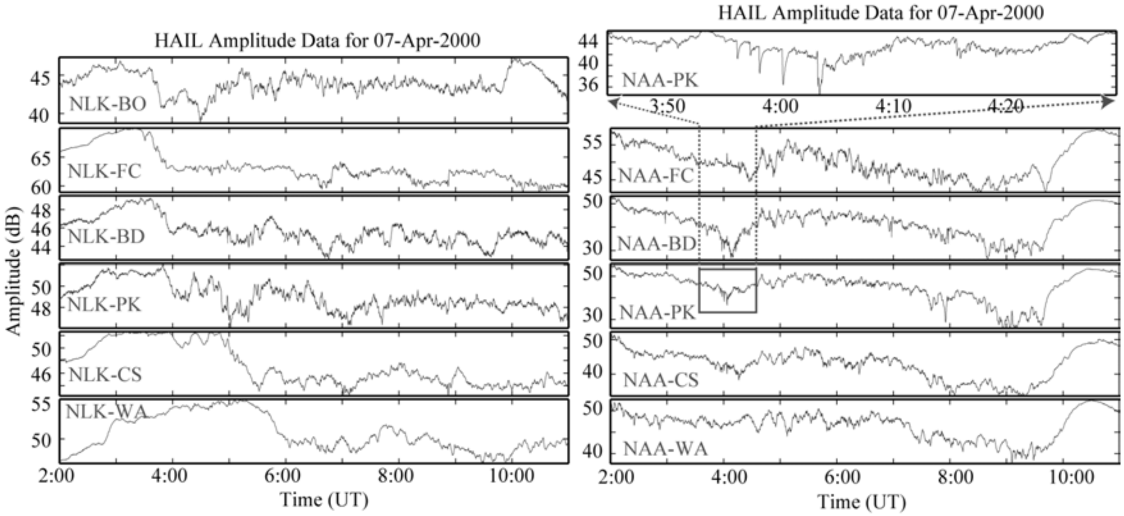

Figure 7: VLF Signal Amplitude on 07 April 2000. (Left) Nine-hour panels of the NLK signal amplitude recorded at six HAIL VLF receivers. All panels show the signal amplitude on an 8-dB scale, with top to bottom corresponding to North to South GCPs. (Right) Nine-hour panels of the NAA signal amplitude recorded at HAIL VLF receivers. The panels show the signal amplitude on different scales. A 45-minute zoom-in of the NAA-PK signal shows the occurrence of several large (>5 dB) LEP events.

Nine-hour panels of the NAA signal amplitude recorded at the HAIL receivers are shown on the right side of Figure 7. Fluctuations in the amplitude of the signal are evident at the beginning of the data acquisition (01:00 UT) and persisted until 09:00 UT when the day-night terminator moved over the eastern GCPs. As the NAA transmitter is located in the northeastern United States, the auroral oval was already overlaying the NAA GCPs at the start of the data acquisition (01:00 UT). The occurrence of auroral precipitation throughout the night over the NAA GCPs explains the presence of fluctuations in signal amplitude throughout the night. The top right panel is a 45-minute zoom-in of the NAA-PK signal, showing the occurrence of several large (>5 dB) LEP events, possibly indicating an increase in trapped energetic electron (100-300 keV) flux levels in the radiation belts [*Peter and Inan* 2004].

In order to estimate the significance of the amplitude depression and subsequent fluctuations in terms of electron precipitation, we use a quantitative model of VLF subionospheric wave propagation together with precipitating flux measurements from four satellite passes. The middle panel of Figure 8 shows electron flux measurements from the NOAA-16 POES satellite, of the same format as Figure 6, except that the detector is now oriented nearly parallel to the magnetic field. The data shown is assumed to be representative of the energetic electron precipitation flux as a function of L-shell over the region. Data from four satellite passes are shown. The first (A) occurred at 02:54 UT on 06 April, prior to the advent of geomagnetic activity. The second (B) occurred at 04:37 UT, also before the onset of geomagnetic activity, with a similar flux profile to that measured at time A. The third pass (C) occurred after the onset of geomagnetic activity, at 02:37 on 07 April 2000. A sharp increase in precipitation flux is observed. Note the L-shell variability in flux levels, especially the peak in flux between L=2.5 and L=2.7. The fourth pass (D) occurred shortly after the third pass, at 04:14 on 07 April. The elevated flux levels are still observed, although the peak in flux between

L=2.5 and *L*=2.7 is no longer observed. In our modeling, we use the measured flux profiles to ascertain whether they are consistent with the disturbances in the VLF amplitude data, and to assess the sensitivity of VLF signal amplitude to changes in the precipitation flux.

We use the four different flux profiles as recorded by the NOAA-POES satellite to generate ionospheric electron density profiles as a function of *L*-shell. The fluxes from the satellites are used as inputs into a Monte-Carlo simulation of the penetration of energetic electrons into the ionosphere [*Lehtinen et al.,* 1999] to determine the amount of secondary ionization produced by energetic electron precipitation as a function of altitude. The secondary ionization rates, as well as the ambient ionization rate (i.e. the ionization rate without precipitation), are used in an ionospheric chemistry model [*Glukhov et al.,* 1992; *Pasko and Inan*, 1994] to obtain electron density profiles for each of ten segments along the NLK-PK GCP, assuming the electron density varies only in *L*-shell. Finally, for each of the four satellite passes, the NLK signal propagation and resultant amplitude and phase measurements at a HAIL site located in Parker, Colorado are determined using the Long Wave Propagation Capability (LWPC) code [*Ferguson and Snyder,* 1987; *Poulsen et al.,* 1993] with the ten segments of previously calculated ionospheric electron density profiles along the NLK-PK GCP as input.

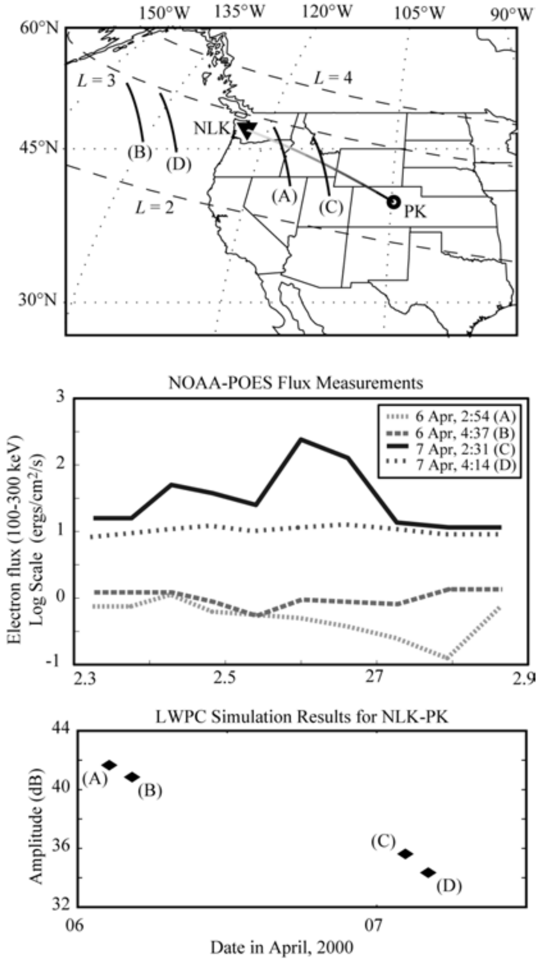

Figure 8: Model calculations for 07 April 2000 Storm. (Top) A map shows the corresponding tracks of the satellite passes with relation to the NLK-PK GCP, projected down to 120 km altitude along the field line passing through the satellites. (Middle) Data from NOAA-16 POES satellite, of the same format as Figure 6. (Bottom) The results of LWPC modeling of the NLK subionospherically propagating signal amplitude as recorded at Parker for the four case times and flux profiles.

The results of the model calculations are shown in the bottom panel of Figure 8. Using precipitation flux data from satellite pass A, the calculated NLK-PK amplitude is assumed representative of “quiet” conditions. Using data from satellite pass B, the model calculations yield a similar amplitude for NLK-PK as that from pass A, with a change of less than 0.5 dB. The similar results for cases A and B are consistent with the NLK-PK amplitude data on 06 April, which varies little over the course of the night. Calculations for pass C give a signal amplitude level significantly depressed (~5 dB) from those of passes A and B. This result indicates that the changes in precipitation flux as measured by the NOAA-POES satellite between pass C and passes A and B could result in the depression of the NLK signal amplitude observed on 07 April 2000. There is a difference of ~1 dB in the NLK-PK amplitude between passes C and D. This difference is consistent with the scale of the fluctuations observed on the NLK-PK signal subsequent to the signal depression. In summary, the LWPC model calculations incorporating NOAA-POES satellite measurements yield results consistent with the variations in the amplitude of the NLK-PK signal observed on 6-7 April 2000.

Concluding Remarks

The depression and variation of the NLK-PK signal amplitude are shown to be consistent with measured variations in the energetic electron precipitation flux as recorded by the NOAA-POES satellite. The satellite recorded variations in precipitation flux in the energy range 100-300 keV, those energies thought to be most effective in altering the *D*-region conductivity [*Lev-Tov et al.,* 1995]. VLF propagation model calculations performed in *Cummer et al.,* [1997] showed that observed VLF amplitude decreases were consistent with propagation under conditions of enhanced *D*-region ionosphere electron densities caused by auroral electron precipitation, and suggested that electrons with energies greater than 100 keV were responsible for the VLF amplitude depressions observed. Increases in electron precipitation flux with energies greater than 100 keV could explain the behavior of the VLF signals observed during the two storms considered.

The occurrence rate of LEP events is also found to be highly dependent on geomagnetic activity. The data in Figure 6 is consistent with the previously noted *Leyser et al.,* [1984] relations between geomagnetic activity and the conditions conducive to the occurrence of detectable LEP events. However, a significantly longer time epoch of analysis is necessary to accurately quantify the degree of this correlation, especially since the variable occurrence of lightning activity is a necessary prerequisite for LEP events to occur. Furthermore, daily variations in the percentage of CG flashes that induce detected LEP events (Figure 4) is likely a result of different magnetospheric conditions and variations in the flux of trapped electrons, since precipitation induced by discrete waves is proportional to the available trapped flux. Thus, the LEP activity as measured on the HAIL array may be a rudimentary indicator of magnetospheric conditions, or the trapped radiation flux levels, especially in the slot region.

We have demonstrated that subionospheric VLF signals can be used as a diagnostic of both auroral precipitation and LEP events. The ability to locate and characterize the extension of auroral precipitation to lower latitudes can increase our understanding of the mechanisms and ionospheric effects of these geomagnetic storms.

Acknowledgements

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