

## Electron precipitation events driven by lightning in hurricanes

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[1] In mid-September of 2003, Hurricane Isabel passed through the Great Circle Path (GCP) of a subionospherically propagating LF signal between the NAU transmitter in Puerto Rico and a receiver located outside Boston. Cloud-to-ground lightning flashes detected by the Long-Range Lightning Detection Network (LRLDN) and located in the outer rainbands of the hurricane were associated with perturbations in the received LF signal consistent with lightning-induced electron precipitation (LEP) events. The number of perturbations, detected on the LF signal, exhibiting the known characteristics (rapid onset followed by slow recovery) of LEP events tended to increase with the occurrence of hurricane-associated lightning near the GCP. The majority (>65%) of causative lightning flashes (those flashes recorded in the LRLDN data that were time-correlated with spherics associated with LEP events in the VLF/LF data) occurred within 500 km of the GCP; and those flashes associated with Isabel typically occurred in the outer rainbands of the hurricane. While lightning generally occurs more frequently in the outer rainbands of hurricanes than in other tropical oceanic storms, there is no indication that the hurricane-associated lightning is more likely to induce electron precipitation events than lightning associated with other storm systems. Hurricane Floyd (in September of 1999) and Hurricane Fabian (in August/September of 2003) also passed near the GCP of subionospherically propagating VLF/LF signals, and the received signals exhibited similar perturbation patterns.

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### 1. Introduction

[2] Extensive experimental evidence associates individual lightning flashes with precipitation of energetic electrons [e.g., *Voss et al.*, 1998, and references therein], and these lightning-induced electron precipitation (LEP) events are a well-established contributor to the loss of trapped radiation belt electrons at mid-to-low latitudes. Perturbations in subionospheric VLF/LF signals have long been used to study LEP events [e.g., *Peter and Inan*, 2004, and references therein]. This paper examines the occurrence of LEP events associated with hurricane activity in the Atlantic Ocean off the eastern coast of the United States.

[3] Recently, there has been significant effort in studying the frequency and distribution of lightning in hurricanes. *Molinari et al.* [1999] examined cloud-to-ground flash locations for nine Atlantic basin hurricanes using data from the National Lightning Detection Network (NLDN). The lightning flash rates associated with hurricanes in the Atlantic basin were found to be highly variable from hurricane to hurricane, ranging from nearly zero to more than 5700 detected flashes per day, with no obvious correlation to hurricane intensity. *Cecil et al.* [2002b]

examined 261 overpasses of 45 different hurricanes of various global locations by the Tropical Rainfall Mission (TRMM) satellite to document total lightning (cloud-to-ground and intracloud) associated with hurricanes. They found that the outer rainbands of hurricanes produced about four times as much lightning (per unit area of rainfall) as other tropical oceanic precipitation systems, even when other remote sensing signatures (radar reflectivity and passive microwave brightness temperature) suggested that the two precipitation systems should be equal. However, it was found that the hurricane samples still produced less than one-tenth the lightning (per unit area of rainfall) than tropical continental samples. Because of the episodic nature of lightning flashes near the core of hurricanes and their documented increase in occurrence rates during times of change in the intensity of hurricanes [*Molinari et al.*, 1999; *Lyons and Keen*, 1994], it has been suggested that knowledge of “ground flashes in mature tropical cyclones might prove to be useful for intensity prediction of such storms” [*Molinari et al.*, 1999].

[4] Despite this recent effort to examine lightning in hurricanes, little is known about the interaction of hurricane-associated lightning with the ionosphere. *Burke et al.* [1992] reported a direct satellite detection of the ionospheric effects of a lightning flash from Hurricane Debbie in the

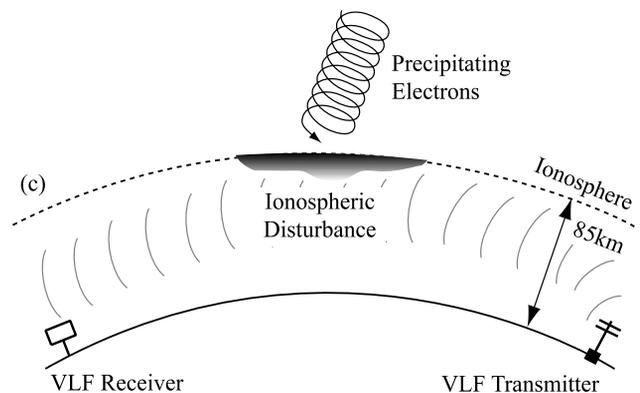
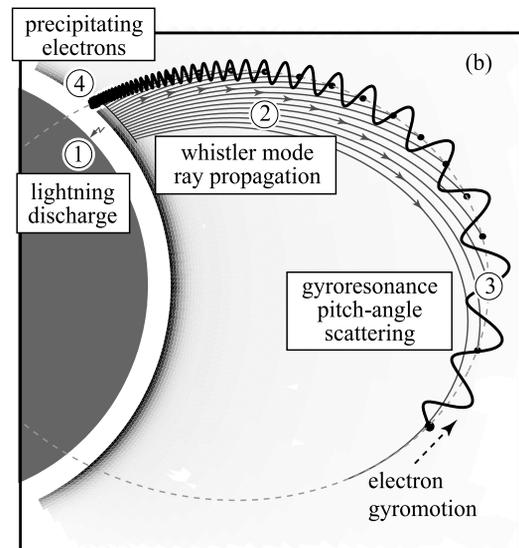
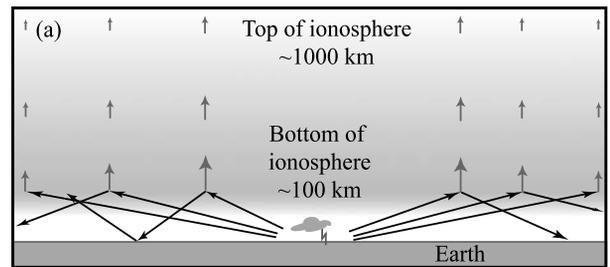
Atlantic Ocean. They suggested that the discharge resulted in “runaway” electrons, accelerated by an  $E_{\parallel}$  pulse, which propagated to the nighttime  $E$ -region. They also detected a single energetic electron precipitation event consistent with prior descriptions of LEP events. While satellites typically pass over hurricanes in a matter of minutes, and therefore have a small chance of detecting a transient LEP burst, VLF/LF remote sensing can be used to continuously monitor possible effects of hurricane-associated lightning on the  $D$ -region. This paper thus constitutes the first extensive examination of the occurrence of multiple LEP events associated with hurricanes in the Atlantic Ocean.

## 2. Lightning-Induced Electron Precipitation (LEP) Events

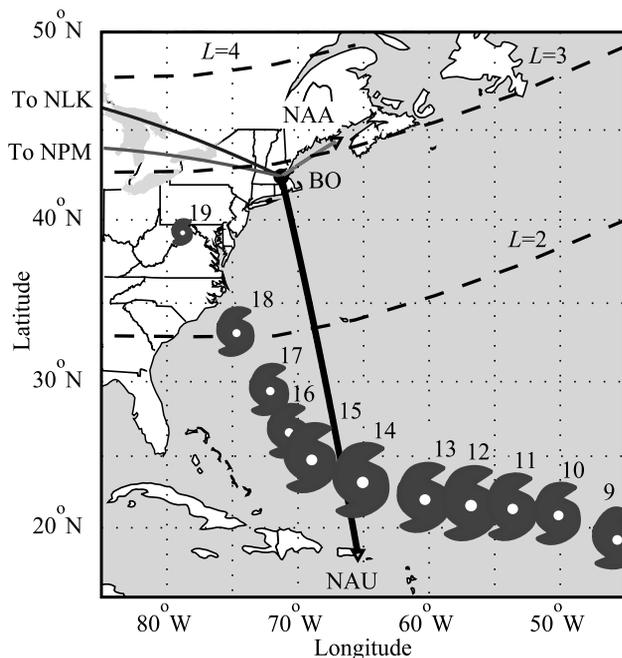
[5] VLF/LF waves are effectively guided within the spherical waveguide formed between the Earth and the ionosphere. The amplitude and phase of the subionospherically propagating VLF/LF signals depend sensitively on the electrical conductivity of the lower ionosphere as well as that of the ground. The amplitude and phase of VLF/LF transmitter signals observed at any point can thus be used to detect disturbances in the lower ionosphere that overlie or are near the great circle paths (GCPs) between the transmitter and receiver.

[6] Lightning discharges indirectly produce localized ionospheric disturbances as a result of lightning-induced bursts of precipitation of energetic radiation belt electrons. 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 1). 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. Past work has distinguished two types of perturbation signatures associated with electron precipitation induced by “ducted” and “nonducted” whistler waves. In the presence of field-aligned ducts of enhanced ionization in the magnetosphere, “ducted” whistler waves propagate along the enhanced duct [Burgess and Inan, 1993]. Precipitation of energetic electrons can also be caused by obliquely propagating “nonducted” whistlers [Johnson *et al.*, 1999]. As the present study analyzes perturbations on only one LF signal, there is insufficient data to determine whether observed LEP events are due to “ducted” or “nonducted” whistler waves, even though LEP events produced by nonducted whistler waves are believed to be more common, as their occurrence does not require any special conditions, such as the presence of field-aligned density enhancements (i.e., ducts). In any case, all events studied in this paper are simply referred to as LEP events.

[7] Whether scattered by “ducted” or “nonducted” whistler waves, the precipitating energetic electrons ( $\sim 50$  to  $500$  keV) cause secondary ionization via impact with atmospheric constituents, altering the conductivity of the  $D$ -region of the ionosphere. 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



**Figure 1.** Lightning induced electron precipitation (LEP) events. (a) Illustration of a lightning discharge radiating VLF wave energy, a portion of which is coupled into the magnetosphere and propagates therein as a whistler wave. (b) Illustration of the wave-particle interaction process: 1, lightning discharge occurs; 2, propagation of the whistler wave in the magnetosphere; 3, wave-particle interaction near the equatorial plane scatters the pitch angle of a fraction of the trapped energetic radiation belt electrons into the loss cone; 4, electrons precipitate into the dense upper atmosphere. (c) Precipitating electrons produce secondary ionization, which in turn changes the electrical conductivity of the upper boundary of the Earth-ionosphere waveguide and perturbs the VLF/LF wave propagating underneath. (Adapted from Lauben *et al.* [2001].)



**Figure 2.** Track of Hurricane Isabel. Daily positions (at 06:00 UT) of Hurricane Isabel according to the National Weather Service's Tropical Cyclone Report are represented by cartoon symbols, scaled according to the maximum sustained wind speeds exhibited during that day. The Great Circle Paths (GCPs) between four VLF/LF transmitters (NAU, NAA, NLK, and NPM) and one receiver located at Boston (BO) are shown. Footprints of the  $L = 2$ ,  $L = 3$ , and  $L = 4$  field lines are shown for reference. Satellite images of hurricane Isabel are shown in Figures 7–11.

disturbances [Poulsen *et al.*, 1993a]. The fact that resulting ionospheric disturbances decay away (via recombination and/or attachment) over 10–100 seconds allows ample time to detect LEP events by means of the associated VLF/LF signal perturbations.

### 3. Description of Experiment

[8] A VLF/LF receiver at the Hanscom Air Force Base outside Boston, Massachusetts, continuously monitors the amplitude and phase of coherent and subionospherically propagating VLF/LF 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). This study focuses on the recorded amplitude of the NAU transmitter signal.

[9] Data are typically acquired nightly from 01:00 to 13:00 UT, when the GCP between the NAU transmitter and the Boston (BO) receiver is partially or wholly in the nighttime sector. A  $1.7 \times 1.7$  m<sup>2</sup> magnetic loop antenna connected to a preamplifier is used to detect the VLF/LF signals. The broadband VLF/LF signal is bandpass filtered to a range of 9 to 45 kHz and is then digitized at a rate of 100 kHz with 16-bit resolution, with triggers provided by GPS timing. The receiver digitally down-converts the VLF/LF signal and records the demodulated amplitude and phase with 20 ms resolution. Only amplitude data are included in

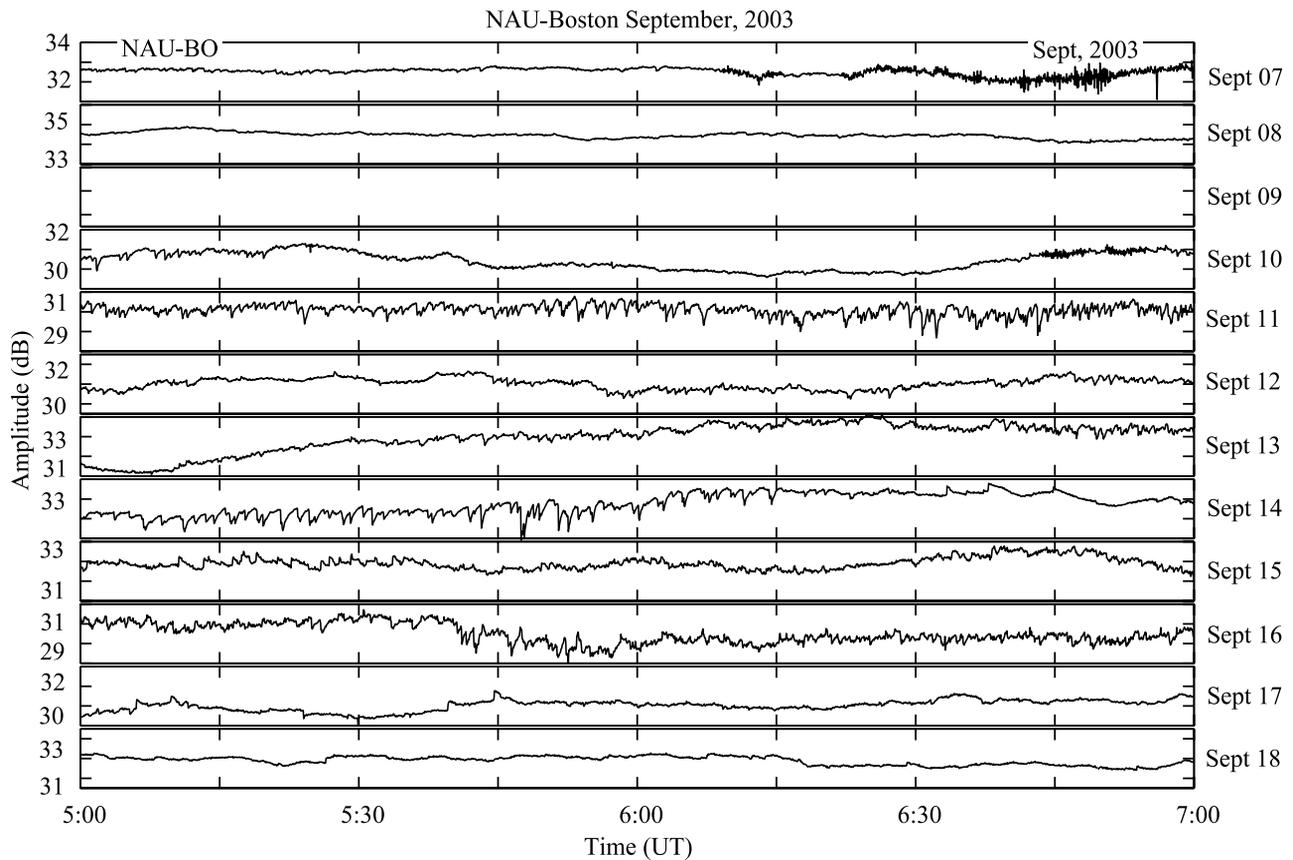
this study, both because spheric noise typically requires a longer averaging period for phase measurements and because our conclusions are sufficiently drawn from the examination of the relative magnitudes of VLF/LF signal changes.

### 4. Hurricane Isabel

[10] Hurricane season in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico runs from 1 June to 30 November. In 2003, Hurricane Isabel, a long-lived hurricane that briefly reached Category 5 status on the Saffor-Simpson Hurricane Scale, passed through the mid-Atlantic Ocean and later made landfall on the coast of North Carolina during mid-September (at which point it had weakened to a Category 2 hurricane). According to the Tropical Cyclone Report (TCR) issued for Hurricane Isabel by the National Hurricane Center, "Isabel is considered to be one of the most significant tropical cyclones to affect portions of northeastern North Carolina and east-central Virginia since Hurricane Hazel in 1954 and the Chesapeake-Potomac Hurricane of 1933". It was directly responsible for 16 deaths, indirectly responsible for 34 others, and is estimated to have caused a total damage of around \$3.37 billion [Beven and Cobb, 2003].

[11] The path of Hurricane Isabel is shown in Figure 2, with the GCP (represented by a thick solid line) between the NAU transmitter and a VLF/LF receiver located at the Hanscom Air Force Base near Boston, Massachusetts (denoted BO) shown for reference. Tropical Storm Isabel formed on 6 September 2003 from a tropical wave that moved westward from the coast of Africa. On 7 September, Isabel intensified into a hurricane and continued strengthening as it moved westward over the next six days. Isabel, as a Category 4 hurricane, moved directly through the GCP between the NAU transmitter and the VLF/LF receiver around 14 September 2003, with a sustained wind speed of 130–140 mph and a minimum pressure of 933 mb during that time. Afterwards, Isabel turned northward and gradually weakened after 15 September. Isabel made landfall near Drum Inlet North Carolina near 17:00 UT on 18 September as a Category 2 hurricane, and then further weakened as it moved inland, eventually losing tropical characteristics on 19 September [Beven and Cobb, 2003].

[12] During September of 2003, sizable perturbations ( $>0.5$  dB) were observed on the NAU signal recorded at the Boston VLF/LF receiver. Figure 3 shows two-hour panels of the NAU signal amplitude recorded at Boston from 5:00 to 7:00 UT each night from 7 September to 18 September 2003. Data are missing for 9 September due to hardware problems. All panels show the signal amplitude on a 3-dB scale. The ambient signal amplitude exhibits day-to-day variations typical of subionospherically propagating VLF signals. While it has been shown that the perturbation magnitude of events is influenced by the location of the receiver near a null in the propagating VLF signal [Poulsen *et al.*, 1993b], it is assumed in this work that the relatively small day-to-day variations ( $<4$  dB) in the ambient amplitude are indicative of the fact that there are no significant nulls near the receiver location. We assume that measurements of perturbations in dB magnitude are indicative of the occurrence rates of LEP event activity, regardless of



**Figure 3.** Daily plots of VLF data. Two-hour panels of the received NAU signal amplitude from 05:00 to 07:00 UT for each day from 7 September 2003 to 18 September 2003 recorded at the Boston receiver (BO). All panels show the signal amplitude on a 3-dB scale. Data for 9 September 2003 are missing due to hardware difficulties.

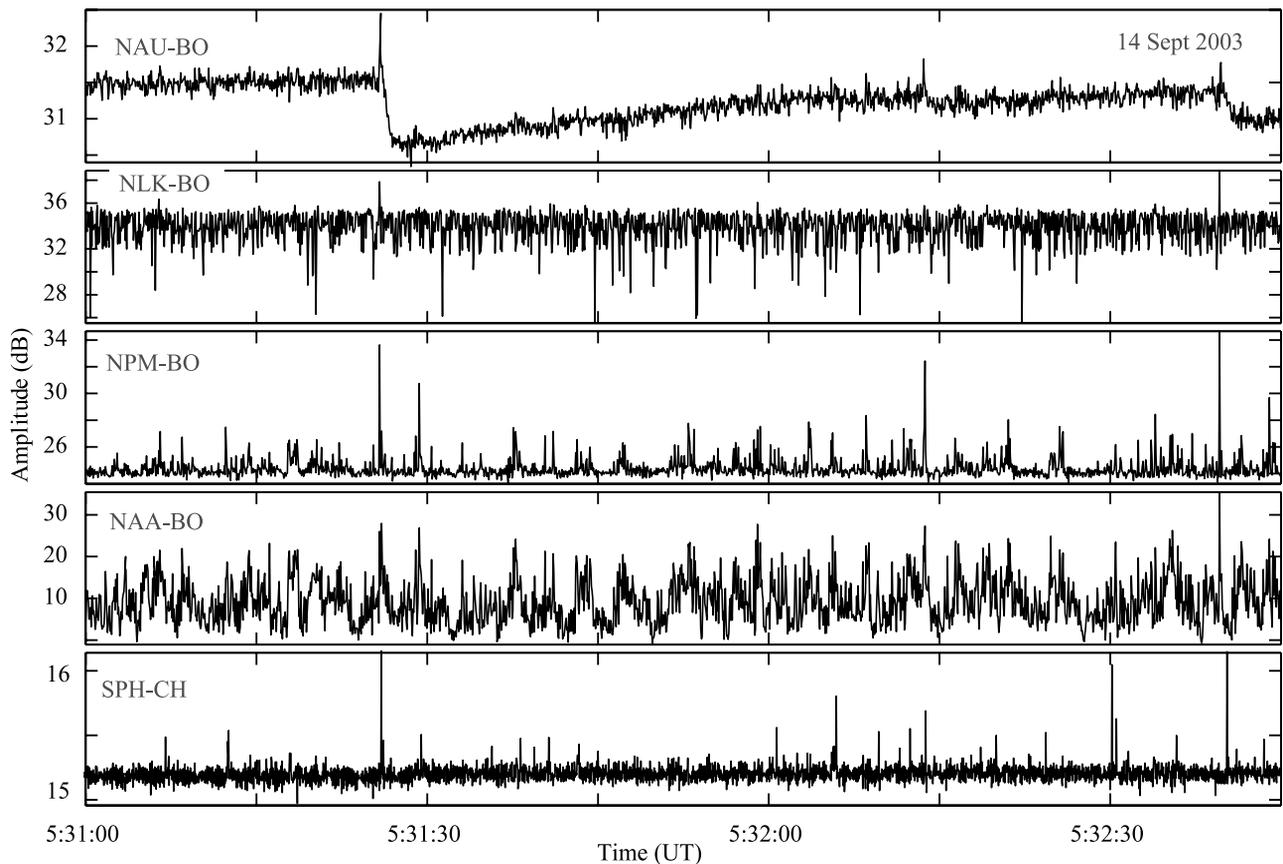
ambient signal levels. The daily variations in the ambient signal amplitude may be indicative of ionospheric and/or meteorological conditions, but such analysis is outside the scope of this work.

[13] Few sizable perturbations ( $>0.5$  dB) are visible on 7, 8, and 10 September. During this time, Isabel was intensifying and moving westward. Starting on 11 September, and continuing until 16 September, an increase in the number of perturbations is visible. During this period, Isabel reached its maximum sustained wind speeds and moved across the NAU to Boston GCP. Finally, on 17 and 18 September, the number of perturbations visible on the NAU-BO signal decreased. By this time, Isabel had weakened to a Category 2 hurricane and reached landfall.

[14] A typical perturbation observed during this period is shown in Figure 4. A 1-minute, 45-second snapshot of the four VLF/LF signals recorded at Boston are shown in the first four panels. A sizable perturbation ( $>0.5$  dB) associated with a LEP event is visible on the NAU-BO signal, while the LEP event is not visible on the NLK-BO, NPM-BO, and NAA-BO signals. The perturbation of only one signal suggests that the LEP event is due to localized precipitation occurring along or near the NAU to Boston GCP, southward of the other GCPs shown. The bottom record shows a measure of the broadband VLF/LF intensity detected at a receiver in Cheyenne, Wyoming, and is used to detect spherics. An impulsive spheric is associated with every

lightning discharge and contains energy over a wide range of frequencies, and is often visible as a sharp peak in the recorded amplitude. In this case, a spheric ( $5:31:25.8 \pm 0.1$  UT) is associated with the LEP event and is visible. The spheric associated with the same causative discharge is also visible as a sharp peak on the NAU-BO, NLK-BO, and NPM-BO signals. The timing of the causative discharge is determined (to within 0.1 s) from the timing of the associated discernible spherics recorded in the VLF/LF signals.

[15] The perturbations of the NAU-BO signal recorded each night from 11 to 16 September 2003 exhibit temporal signatures consistent with previously observed LEP events [Inan *et al.*, 1988]. Figure 5a shows a half-hour snapshot of the amplitude of the received NAU signal, with perturbations exhibiting a relatively sharp change in magnitude followed by a slower recovery back to ambient levels. An expanded record showing a 3.5 second segment of one of the LEP events is shown in Figure 5b. The timing of the labeled causative spheric corresponds to the time of the causative lightning discharge ( $5:31:25.8 \pm 0.1$  UT). Johnson *et al.* [1999] defines LEP VLF/LF events as those perturbations characterized by (1) a characteristic onset delay  $\Delta t$  (a few hundred ms up to 1 s) with respect to the causative spheric due to the magnetospheric travel time of the outgoing whistler wave and the pitch angle scattered particles (Figure 1a); (2) an onset duration,  $t_d$ , (typically 0.5–1.5 s) representing the duration of the precipitation burst,



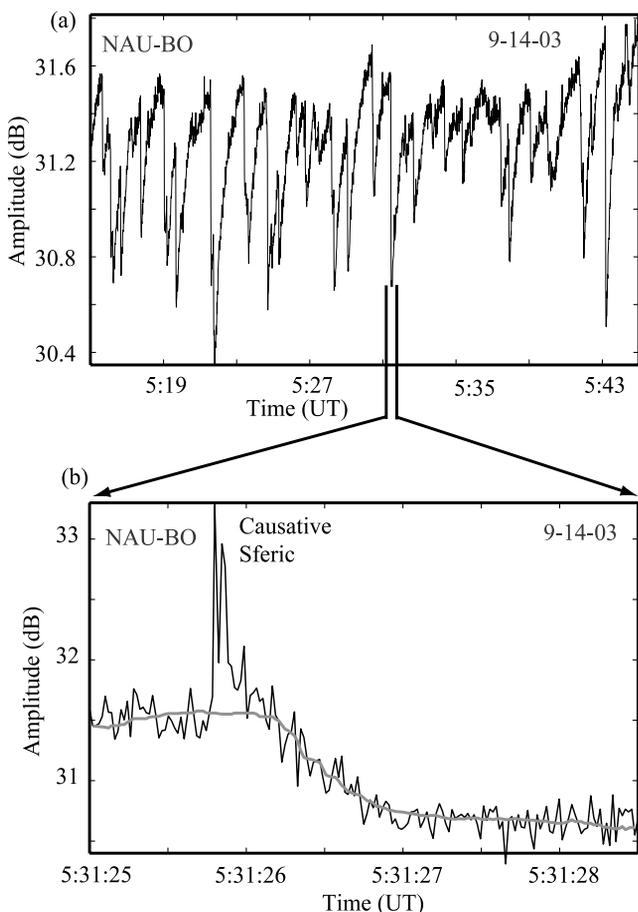
**Figure 4.** An example LEP event (5:31:26). (a) A 1-minute, 45-second snapshot of the four VLF/LF signals recorded at the Boston receiver, as well as a broadband spheric signal recorded at a VLF/LF receiver located in Cheyenne, Wyoming (denoted by SPH-CH). The GCPs between the four VLF/LF transmitters and the Boston receiver are shown in Figure 2.

during which the VLF/LF event magnitude increases due to continuing generation of secondary ionization; and (3) a recovery period of 10–100 s following the termination of the precipitation burst, as the ionization returns from enhanced levels back to preevent levels. In this paper, we also consider the (4) event perturbation magnitude ( $\Delta A$ ) of the VLF/LF signal, referring to the change in amplitude, measured in dB, from the ambient levels prior to the event, to the maximum (or minimum) levels reached during the event. For this paper we only consider events with perturbation magnitudes of at least 0.5 dB, for ease of identification and accuracy of statistics in the presence of other fluctuations in signal amplitude. While our choice of a threshold of 0.5 dB excludes smaller perturbations that may also be a result of lightning-induced electron precipitation, it allows for a more reliable classification of perturbations as LEP events.

[16] Using the criteria set forth above, the recorded NAU-BO signal for each night (01:00 to 13:00 UT) was examined for perturbation signatures of LEP events, with the number of perturbations qualifying as LEP events shown in Figure 6a. A relatively small number of LEP events occurred on earlier days in September, with the number of LEP events detected increasing during mid-September and then returning back to lower numbers of LEP events in late September. From 6 to 8 September, only five perturbations were classified as LEP events. There was no recorded data

for 9 September due to hardware difficulties. Between 27 and 93 perturbations classified as LEP events occurred each night from 10 September to 16 September, with the highest number of events occurring on 11 September (93), 14 September (65), and 16 September (65). A relatively small number of LEP events occurred after 16 September, with no more than 18 perturbations classified as LEP events occurring on any night from 17 September to 20 September.

[17] A frequently used indicator of the strength of a hurricane is the sustained wind speed. Figure 6a shows the number of perturbations classified as LEP events (left axis) compared to the sustained wind speed (right axis) of Isabel from 6 September to 20 September 2003. The sustained wind speed of Isabel roughly corresponds to the number of LEP events detected, although the location of the lightning flashes associated with the hurricane have not yet been considered (see section 4.1., Daily Analysis). The hurricane increased in strength over 8, 9, and 10 September, with the highest number of LEP events occurring during the period when Isabel had reached maximum strength (11 September to 16 September). The hurricane then lost strength after 17 September, and the number of LEP events detected sharply declined. Figure 6b shows a geomagnetic activity ( $K_p$ ) index for the same period. No obvious correlation is evident between the number of LEP events detected and geomagnetic activity as indicated by the  $K_p$  index. The  $K_p$  index is highest from 16 to 20 September, which are the



**Figure 5.** A typical LEP event (14 September 2003). (a) A half-hour snapshot of the received NAU signal on 14 September 2003. (b) A zoom-in of one of the LEP events showing a 3.5-second snapshot, showing the time of the causative spheric ( $5:31:25.8 \pm 0.1$ ). A 10-point median filter of the original data is shown as a thick solid line.

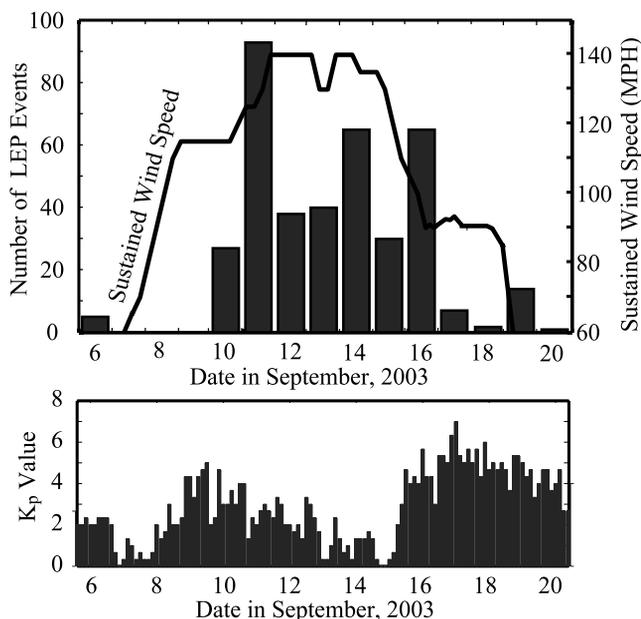
same days when the number of LEP events decreased. Previous work has suggested a correlation between geomagnetic activity [e.g., *Leyser et al.*, 1984; *Peter and Inan*, 2004] and the conditions conducive to the occurrence of detectable LEP events. However, the lack of correlation in this study suggests that factors other than geomagnetic activity are influencing the number of LEP events observed, such as the occurrence rates of lightning discharges.

#### 4.1. Daily Analysis

[18] The variability in the number of LEP events detected suggests that the occurrence rates of lightning flashes associated with Isabel located near the GCP between NAU and Boston may play an important role in determining the amount of observed LEP activity. We examine five separate three-hour periods for the dates of 8, 11, 14, 16, and 18 September to further explore this relationship (Figures 7–11). All figures are of the same format. The specific three-hour periods each night were chosen according to the period during which the highest number of LEP events detected on the NAU-BO signal occurred, therefore supplying the largest data set with which to correlate lightning data. The top panels show example data from

each night, with two successive half-hour amplitude plots of the received NAU signal (the upper panel from 05:00 to 05:30 UT and the lower data panel from 05:30 to 06:00 UT). The middle panels show GOES-12 Infrared images of the Northern Hemisphere, obtained from the National Climatic Data Center (NCDC) website (<http://cdo.ncdc.noaa.gov/GOESBrowser/goesbrowser>). The geostationary GOES-12 satellite measures the temperature of the clouds and the surface of the Earth with an infrared sensor, with white denoting lower temperatures in the images. Clouds are usually colder than the Earth's surface (land or water), and are therefore detected by the infrared sensor. The superimposed dashed line represents the GCP from the NAU transmitter to the VLF/LF receiver located near Boston. The infrared images show the cloud cover over the region of interest and the location of Isabel each night with respect to the GCP. The bottom panels show all cloud-to-ground or ground-to-cloud (referred to as CG in this paper) lightning flashes, denoted by black dots, recorded by the Long-Range Lightning Detection Network over the three-hour period.

[19] The Long Range Lightning Detection Network (LRLDN) provides the timing and location of CG lightning discharges within 2000–4000 km of the United States with one-second time resolution. *Cramer and Cummins* [1999] reported that only larger peak current ( $>30$  kA) flashes are seen by the network, with median location accuracy of approximately 5 km when lightning is located between subsets of sensors. However, the lightning flashes examined here do not occur between subsets of sensors, and the detection efficiency and location accuracy decreases with increasing distance of the lightning flash from the continent. According to estimates given in *Boeck et al.* [2000], the

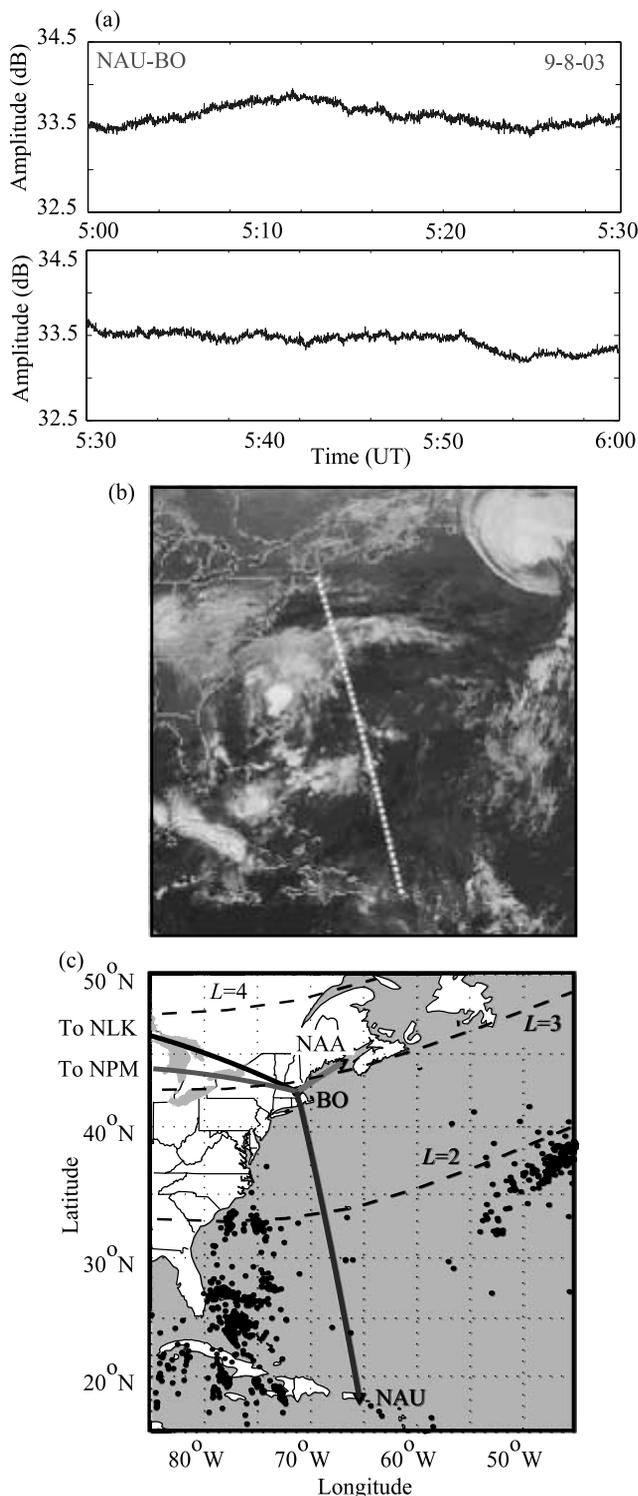


**Figure 6.** Hurricane Isabel LEP events. The number of LEP events during each night from 01:00 to 13:00 UT (left axis) compared to the sustained wind speed (right axis) of Hurricane Isabel from 6 September to 20 September 2003. (b) Geomagnetic activity ( $K_p$ ) index for the month of September 2003.

detection efficiency is  $\sim 10$  percent for CG flashes within 3200 km of the U.S. coast, with a median location accuracy of 32 km. *Peter and Inan* [2004] found that for two thunderstorms located over Texas, more than 95% of the NLDN recorded CG lightning flashes associated with LEP events detected on the HAIL array had a flash intensity of at least 50 kA. Therefore, we can reasonably assume that at most a small percentage of CG flashes with peak currents less than 30 kA and not detected by the LRLDN are likely

to induce precipitation detectable on the NAU-BO GCP, so that these flashes not recorded by LRLDN can be assumed to have minimal impact on our results. By design, the LRLDN network records only CG lightning flashes, though intracloud (IC) lightning is generally more common than CG flashes at these latitudes [*Prentice and Mackeras*, 1971]. Based on the fact that previous work [i.e., *Peter and Inan*, 2004] associated the majority ( $>80\%$ ) of LEP events with CG discharges, we can assume that the IC flashes not recorded by LRLDN do not influence our results. In this context, we note that an adequate number (more than 60) of the detected LEP events in this study were associated with causative CG flashes recorded by the LRLDN network. In this work, we assume that the location and occurrence patterns of CG flashes detected by the LRLDN are consistent with the location and occurrence patterns of all lightning flashes (both CG and IC flashes). Furthermore, the location accuracy of the LRLDN is on the scale of 32 km [*Boeck et al.*, 2000], whereas previous work [*Peter and Inan*, 2004; *Clilverd et al.*, 2002; *Johnson et al.*, 1999] suggests that the extent of the perturbed region in the ionosphere associated with LEP events is on the order of 100's of kilometers. The location accuracy of LRLDN is thus fully adequate for our analysis of lightning locations with respect to the occurrence of LEP events. Finally, the effect of the reduction of the detection efficiency and location accuracy of the LRLDN (with the distance of the lightning flash from the continent (where the network is located) is discussed where relevant.

[20] For each LEP event that occurred during the three-hour period of the five different nights, a spheric (an impulse in the received VLF signal) associated with the causative lightning discharge was measured with 10 ms resolution. The recorded timing of the spheric was then associated with a causative CG discharge in the LRLDN data. Owing to the low (1-second) time resolution of the LRLDN data, the majority of the spherics could not be confidently associated with a CG discharge in the LRLDN data, and so these causative discharges were not included in the analysis. The LRLDN network frequently detected multiple CG flashes within the same second, albeit usually at the same location (within 10 km of each other). Consequently, only causative spherics that could be associated



**Figure 7.** 8 September 2003. (a) The amplitude of the received NAU signal from 05:00 to 05:30 UT (top) and 05:30 to 06:00 UT (bottom) on 8 September, shown on a 2-dB scale. No LEP events fulfilling the defined criteria are visible. (b) The GOES-12 Infrared image for 00:00 UT of the Northern Hemisphere shows the cloud cover over the region of interest. Image was taken from NCDC Historical GOES Browser (<http://cdo.ncdc.noaa.gov/GOESBrowser/goesbrowser>). The superimposed dashed line represents the Great Circle Path from the NAU transmitter to the VLF/LF receiver located at Boston. Hurricane Isabel is not yet visible. (c) Map showing all CG lightning flashes, denoted by black dots, recorded by the Long-Range Lightning Detection Network over the three-hour period from 03:00 to 06:00 UT. The map covers the same area as that of the GOES image shown in Figure 7b. The great circle paths of the received signals are shown for reference.

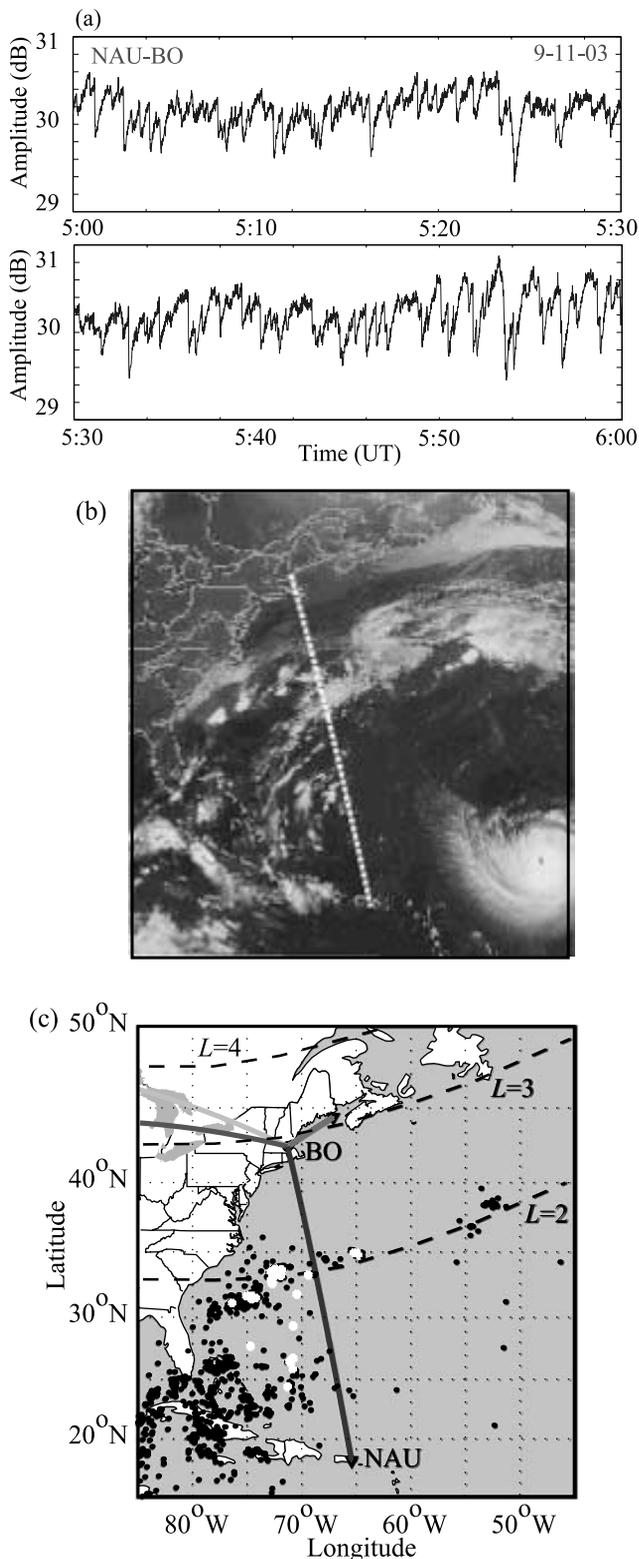
with a single lightning location (including those locations of multiple flashes all occurring within 10 km of each other but within the same second) were considered, excluding any spherics that could be associated with LRLDN recorded flashes of different locations (>10 km).

[21] The frequent occurrence of multiple CG flashes within the time scales considered here (1-second) as well

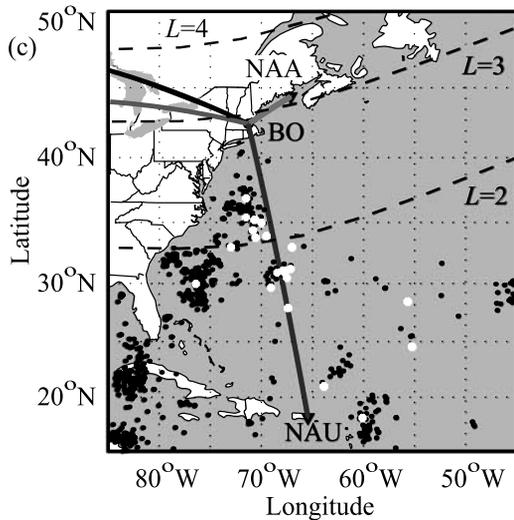
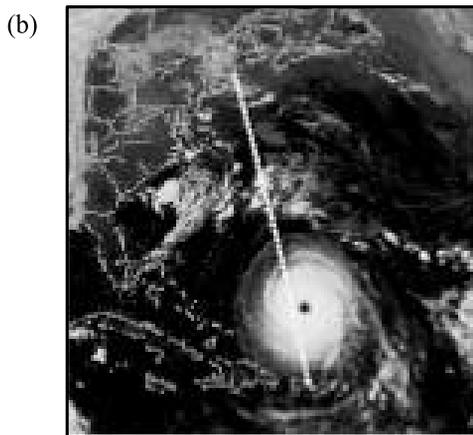
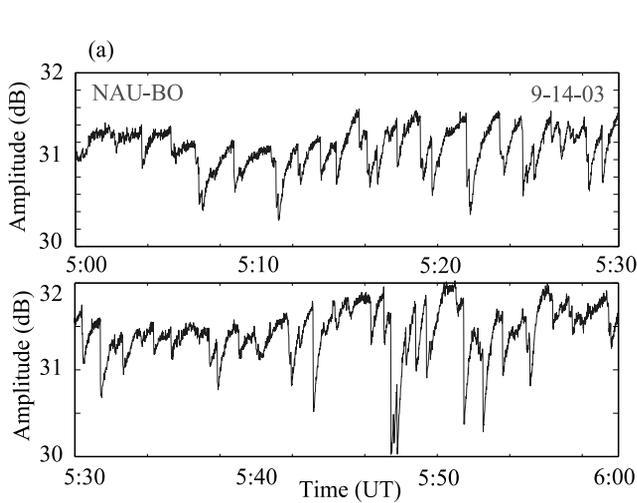
as the limited location accuracy of the LRLDN network necessarily limits our certainty in locating the causative discharges. However, high time-resolution (<1 ms) data was also analyzed to confirm the validity of our correlations of the causative spherics with CG flashes detected by the LRLDN network. The locations of the causative discharges determined from using the higher time-resolution were similar to those obtained from using the low-time resolution (1-second) data, with the only difference being that approximately 50% more causative flashes were successfully correlated with LRLDN data. Since this larger data set of causative flashes confirmed the trends obtained by using the low time resolution data, all subsequent analysis was done with 1-second resolution data. The results obtained can thus be considered to be representative of all causative discharges associated with LEP events. We assume that the causative discharge locations as determined are an accurate representation of the general location of all lightning discharges inducing LEP events considered in this study. These causative CG discharge locations taken from the LRLDN data are denoted as white dots in the bottom panels.

#### 4.1.1. 8 September 2003

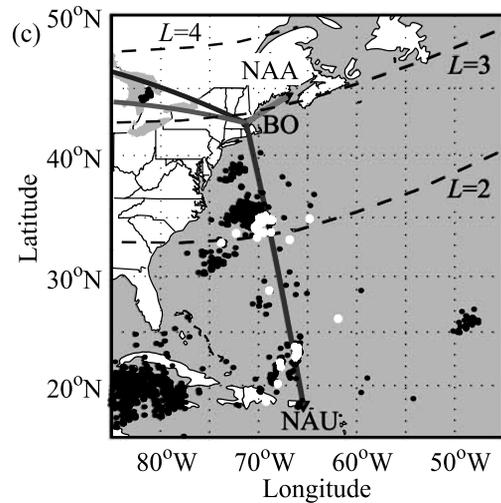
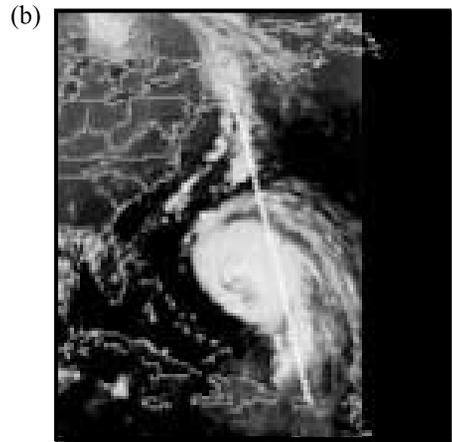
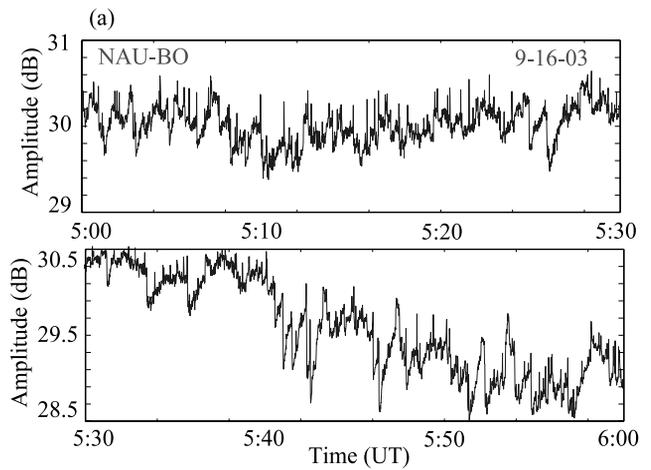
[22] The amplitude of the received NAU signal from 05:00 to 06:00 UT on 8 September is shown in Figure 7a. No LEP events fulfilling the defined criteria are visible during this period. The GOES-12 Infrared image (Figure 7b) shows the cloud cover over the region. At this time, Isabel was a tropical wave (an area of relatively low pressure moving westward through the trade winds) lying east of the region shown. Even though the image shows some cloud cover off the southeastern coast of the United States, there appears to be little significant cloud cover near the GCP between NAU and Boston. Figure 7c shows all CG flashes recorded by the LRLDN over the three-hour period from 03:00 to 06:00 UT. The network detected multiple CG lightning flashes off the eastern coasts of South Carolina and Florida and the northern coast of Cuba. These storm systems were west of the GCP between NAU and Boston by over 500 km. The LRLDN also detected CG flashes eastwards of the GCP, over 1000 km east of the continent. The ability of the LRLDN to detect lightning at this distance from the coast, even if at a low detection efficiency and/or poor location accuracy, suggests that the LRLDN data can correctly locate the general regions of CG flash activity over the length scales of this study. No CG flashes associated with Isabel are visible during this period. Very few (<0.01%) of the CG flashes recorded during this time occurred within 200 km of the GCP between NAU and BO. There were no LEP events detected on the NAU-BO



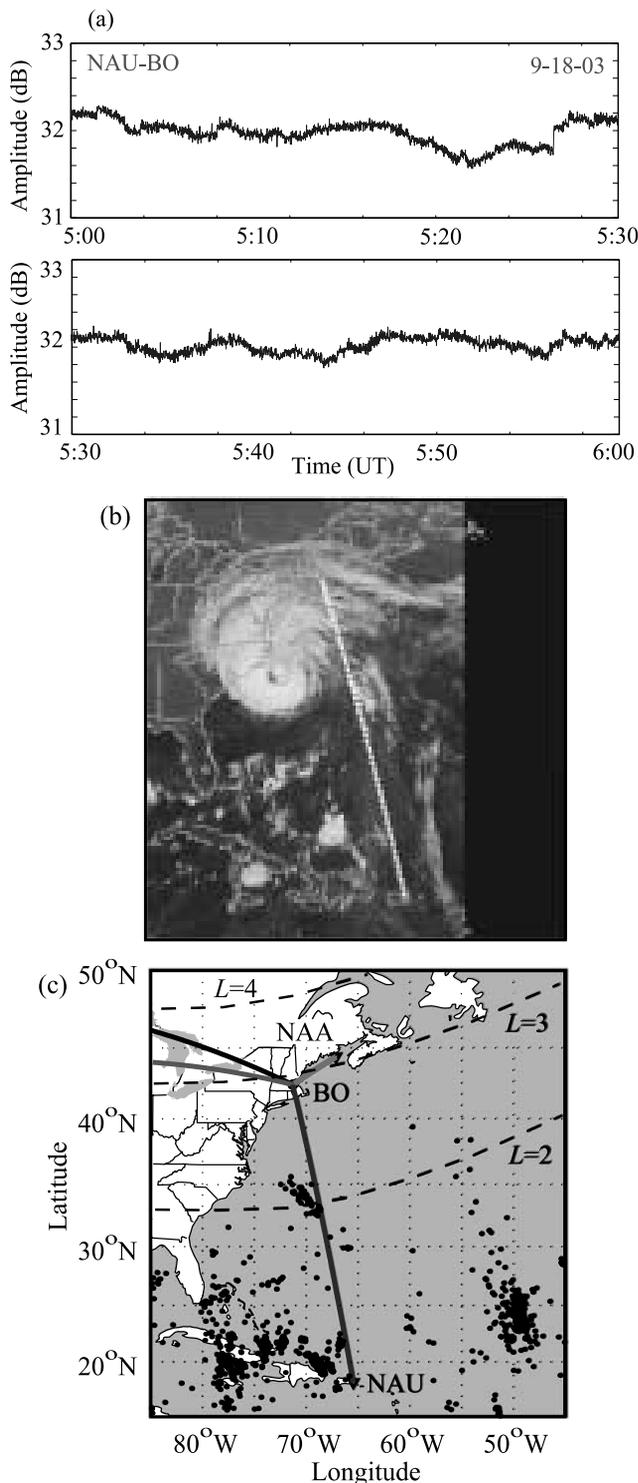
**Figure 8.** 11 September 2003. The same format as that of Figure 7, except that the period examined is now from 03:00 to 06:00 UT on 11 September 2003. (a) The received signal exhibits frequent perturbations consistent with our defined criteria for LEP events. (b) Hurricane Isabel is now visible on the GOES image (taken at 00:00 UT), but is still displaced from the NAU-BO path. (c) The black denotes all CG lightning flashes detected by the LRLDN from 03:00 to 06:00 UT on 11 September. The white dots denote lightning flashes time-correlated with LEP events measured on the received NAU signal over the three-hour period.



**Figure 9.** September 14 2003. The same format as that of Figures 7 and 8, except that the period examined is from 05:00 to 08:00 UT on 14 September 2003. (a) Frequent perturbations consistent with our defined criteria for LEP events are visible on the received signal. (b) GOES-12 infrared image for 12:00 UT on 14 September. Hurricane Isabel is now located along the Boston to NAU great circle path. (c) The causative lightning discharges associated with Hurricane Isabel occur in the northern rainband, along the GCP between Boston and NAU.



**Figure 10.** 16 September 2003. The same format as that of Figures 7, 8, and 9, except that the period examined is from 03:00 to 06:00 UT for 16 September. (a) Frequent perturbations consistent with our defined criteria for LEP events are visible on the received signal. (b) GOES-12 infrared image for 12:00 UT on 16 September. The black section of the image represents the area where no data are available during the period. Hurricane Isabel is still located along the Boston to NAU great circle path. (c) The causative lightning discharges associated with Hurricane Isabel occur in both the southern and northern rainbands, along the GCP between Boston and NAU.



**Figure 11.** 18 September 2003. The same formats as that of Figures 7, 8, 9, and 10, except that the period examined is from 03:00 to 06:00 UT on 18 September. (a) No perturbations consistent with our defined criteria for LEP events are visible. (b) GOES-12 infrared image for 12:00 UT. The black section of the image represents the area where no data are available during the period. Hurricane Isabel has now reached landfall, and is no longer located along the Boston to NAU great circle path. (c) The CG lightning discharges in the region are no longer associated with Hurricane Isabel.

signal during these three hours, and therefore no CG flashes were associated with causative spherics. The likely reason for the lack of LEP event activity here is that the region near the GCP is relatively calm in terms of storm intensity and lightning occurrence for this time of year, with neither Isabel nor any other major thunderstorm system being near the GCP.

#### 4.1.2. 11 September 2003

[23] The first night of increased LEP activity on the NAU-BO signal occurred on 11 September (Figure 8). Forty-eight perturbations classified as LEP events under the criteria of this study were detected from 03:00 to 06:00 UT, with Figure 8a showing the amplitude of the received NAU signal from 05:00 to 06:00 UT. Hurricane Isabel is now visible in Figure 8b; however, it is more than 500 km east of the GCP between NAU and Boston. Instead, the GOES-12 image shows scattered clouds slightly west (<300 km) of the GCP. Figure 8c shows that the LRLDN network detected CG lightning associated with these scattered clouds. Twenty-one of the forty-eight spherics associated with LEP events in the received NAU-BO signal were successfully time-correlated (within one second) with CG flashes recorded by the LRLDN network, these “causative lightning flashes” locations are denoted by white dots on the map. The multiplicity of CG flashes at different locations during the same second prevents the reliable association of many of the causative spherics with CG flashes in the LRLDN data. However, the use of higher time resolution (<1 ms) LRLDN data corroborated our associations of LEP events with causative CG flashes in the 1-second time resolution data, so that the results obtained from the 1-second resolution data can be considered accurate. As a result, our results indicate that lightning flashes associated with the scattered clouds near the GCP induced all of (or at least the majority of) the LEP events, rather than lightning associated with Isabel. In fact, there are few flashes recorded by the LRLDN associated with Isabel, although this result may be due to the low detection efficiency and poor location accuracy of the LRLDN for lightning flashes far removed (>2500 km) from the continent, where Isabel was centered on 11 September [Cramer and Cummins, 1999].

#### 4.1.3. 14 September 2003

[24] By the night of 14 September, Hurricane Isabel had moved westward across the GCP between the NAU transmitter and the VLF/LF receiver located near Boston. Forty-four perturbations classified as LEP events under the criteria of this study were detected from 05:00 to 08:00 UT, with Figure 9a showing the amplitude of the received NAU signal from 05:00 to 06:00 UT. The GOES-12 infrared image (Figure 9b) for 12:00 UT shows that Isabel was then located along the GCP. Figure 9c shows the lightning activity in the region from 05:00 to 08:00 UT, as recorded by the LRLDN network. The majority of the CG flashes detected by the network are not associated with Isabel, rather with thunderstorms over western Cuba and off the coast of Georgia and Virginia. This result may be due to the lower detection efficiency of the network at the location of Isabel than at the location of the thunderstorms. Regardless, the majority of the CG flashes associated with Isabel are near the outskirts of the hurricane, in a region termed the “outer rainbands”.

[25] *Molinari et al.* [1994, 1999] defined three distinct regions of tropical cyclones using radial profiles of lightning flash counts for ten hurricanes located near the United States in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. The three categories are (1) the eyewall region, (2) the inner rainband region, and (3) the outer rainband region, distinguished by their radial distance from the cyclone center. A local maximum in flash density was found at a distance of 20 to 80 km from the center, corresponding to the eyewall region. Eyewall lightning (that occurring within the eyewall region) occurred episodically, with only 7% of the hourly intervals analyzed containing detected flashes. A minimum in flash density extended about 100 km beyond the eyewall region, corresponding to the inner rainband region. The outer rainband region was defined as the region with the greatest flash density, 210–290 km from the cyclone center for the cases analyzed, with a mean maximum flash density at the 250 km radius. The vast majority of the lightning associated with the hurricanes occurred in the outer rainbands. A dramatic azimuthal variation of lightning activity was apparent, with the azimuthal distribution of lightning “likely to vary with the direction of vertical wind shear, the presence of isolated upper-tropospheric phenomena interacting with the hurricane, the distribution of land and ocean, and the variation between the storm motion and the basic current” [*Molinari et al.*, 1999]. While there is no predefined limit on the distance an outer rainband extends from the cyclone center, *Cecil et al.* [2002a] considered a maximum outer rainband radius of  $\sim 1000$  km for the 45 hurricanes of their study, with a mean radii of extent for the outer rainband region of 350 km.

[26] Lightning occurrence data for Hurricane Isabel indicates a picture consistent with past works [i.e., *Molinari et al.*, 1994, 1999; *Cecil et al.*, 2002a]. For the nights of 14 September (Figure 9c) and 16 September (Figure 10c), the LRLDN network detected few flashes within 80 km of the center of the hurricane, with the vast majority of the flashes occurring 200 to 500 km from the cyclone center in the outer rainbands of the hurricane. The outer rainband lightning also exhibited a pronounced azimuthal asymmetry.

[27] The majority of lightning detected by the LRLDN from 05:00 to 08:00 UT on 14 September associated with Hurricane Isabel was located in the outer rainbands. Of the forty-four LEP events recorded on the NAU-BO signal during these three hours, twenty of the causative spherics associated with the LEP events were successfully time-correlated with CG flashes in the LRLDN data. White stars in Figure 9c denote the locations of these causative CG flashes. A little over half (12 out of 20) of these causative CG flashes were located in the outer rainbands of Isabel. The other causative CG flashes were associated with other thunderstorms located off the eastern coast of the United States.

#### 4.1.4. 16 September 2003

[28] Hurricane Isabel was still located along the GCP between the NAU transmitter and the VLF/LF receiver near Boston on the night of 16 September. Figure 10a shows two half-hour panels of the amplitude of the received NAU-BO signal from 05:00 to 05:30 UT and from 05:30 to 06:00 UT. Over the three hour period from 03:00 and 06:00, forty-seven perturbations classified as LEP events under the criteria of this study were detected. The GOES-12 infrared

image for 12:00 UT (Figure 10b) shows that the hurricane center had moved westward of the GCP (by  $\sim 200$  km), with the outer rainbands still crossing the GCP. Twenty-one of the forty-seven causative spherics associated with LEP events detected during these three hours were successfully time-correlated with recorded CG flashes in the LRLDN data. White dots in Figure 10c denote the locations of these causative flashes. As on the night of 14 September, the majority of the lightning associated with Isabel (and detected by the LRLDN) was located in the outer rainbands. While the LRLDN detected CG flashes south of Cuba and off the coast of Maryland and Virginia, few, if any, of these flashes were time-correlated with causative spherics associated with LEP events. Instead, the majority of the causative CG flashes are associated with the northern and southern rainbands of Isabel. While it is difficult to conclusively determine for some of the causative lightning flashes whether they are associated with the rainbands of Isabel or surrounding storm systems (especially those flashes in the northern rainband), it appears that CG flashes associated with the outer rainbands of Isabel induced at least some of the precipitation that perturbed the received NAU-BO signal.

#### 4.1.5. 18 September 2003

[29] Finally, by 18 September Hurricane Isabel had lost strength and reached the eastern coast of the United States, with its center being more than 500 km away from the GCP (Figure 11b). No perturbations consistent with our definitions of LEP events were visible on the NAU signal from 03:00 to 06:00 UT. Figure 11a shows the amplitude of the received NAU signal from 05:00 to 06:00 UT. The signal had returned to its “quiet” conditions exhibited on 8 September, before the storm systems moved near the GCP. The LRLDN recorded a few CG flashes associated with Hurricane Isabel, as well as some scattered flashes over Cuba and further out in the Atlantic. On a night similar to 8 September in terms of the detection of relatively few CG flashes near the GCP, no LEP events on the NAU-BO signal were detected.

## 4.2. Causative CG Flash Locations

[30] On the nights of 11, 14, and 16 September, the causative CG flashes (those flashes detected by the LRLDN network and time-correlated with causative spherics associated with LEP events in the NAU-BO data) were typically located near the GCP, while flashes located further away from the GCP were typically not time-correlated with any causative spherics. For the three-hour period examined on 11 September, two-thirds (14 of 21) of the causative CG flashes occurred within 500 km of the GCP. For the three-hour period on 14 September, 16 out of 20 causative CG flashes occurred within 500 km of the GCP, while on the night of 16 September, 18 out of 21 occurred within 500 km of the GCP. Previous studies have suggested that CG flashes located near a GCP of a propagating VLF/LF signal would be more likely to induce perturbations of that VLF/LF signal. *Inan et al.* [1988] analyzed perturbations of a VLF signal propagating from the NAU transmitter (at which time it was operating at 28.5 kHz) to a VLF/LF receiver operated in Lake Mistissini, Quebec. These LEP events were associated with CG flashes, recorded by the State University of New York (SUNY)–Albany lightning detection network, in the Atlantic Ocean  $\sim 400$  km off the eastern coast of the

United States. The results suggested that the spatial size of the perturbed ionospheric region(s) may have been confined to the vicinity ( $\pm 150$  km) of the causative CG flashes, with amplitude changes in the received VLF/LF signal most sensitive to precipitation occurring within  $\sim 150$  km of the GCP. Our results also suggest that amplitude changes in the NAU-BO signal may be most sensitive to precipitation induced by causative CG flashes occurring near the GCP, although a significant number of causative CG flashes were detected up to 500 km away from the GCP. This result suggests that the disturbed ionospheric region may extend up to 500 km from the causative CG flash for the LEP events considered here.

[31] *Peter and Inan* [2004] presented evidence that over 90% of nonducted whistler-induced precipitation occurs over a region  $\sim 900$  km in latitudinal extent poleward displaced  $\sim 600$  km of the causative CG flash for thunderstorms located in Texas. If the LEP events detected on the NAU-BO signal were associated with nonducted whistler-induced precipitation, the induced precipitation would likely occur over a region of similar extent and displacement (poleward) from their causative discharges, as predicted by *Lauben et al.* [2001] for these latitudes. However, the spatial characteristics of the induced precipitation would likely be strongly influenced by the existence of the South Atlantic magnetic anomaly near the conjugate point of the CG discharge, as discussed in the subsequent section. Conversely, the electron precipitation induced by ducted whistlers would likely be restricted to a region of  $\sim 150$  km [*Inan et al.*, 1988]. Depending on the location of the duct's footprint onto the atmosphere with respect to the CG flash, the precipitation could also be significantly displaced from the causative lightning flash. With the present data set, a conclusive determination of the spatial extent of the disturbed region or whether the driving waves are ducted or nonducted is not feasible.

[32] The prevalence of CG flashes located west of the GCP (Figures 7c–11c) is probably due to a combination of factors, including the greater detection efficiency of the LRLDN network nearer the continent and the higher occurrence rates of lightning flashes over the coast. Flashes southwest of the GCP are predicted to be more likely to induce precipitation on the NAU-BO GCP due to the poleward displacement of precipitation induced by nonducted obliquely-propagating whistler waves.

### 4.3. Electron Precipitation in the Conjugate Region

[33] Lightning flashes generated in the Northern Hemisphere produce south-going whistler waves, causing particles perturbed through the gyroresonance interaction with south-going whistler waves to first precipitate into the Northern Hemisphere. This type of precipitation is referred to as “direct” precipitation [*Inan et al.*, 1988] and is the type we have examined thus far. However, scattered electrons also precipitate in the Southern Hemisphere (“mirrored” precipitation) when perturbed through gyroresonance interaction with south-going whistler waves after first mirroring and/or backscattering in the north [*Inan et al.*, 1988]. For causative lightning flashes located near the conjugate of the South Atlantic magnetic anomaly, mirrored precipitation is believed to be significantly more effective (i.e., higher precipitated flux levels are expected) than direct precipita-

tion [*Inan et al.*, 1988], due to the asymmetry in the bounce loss cones in the two hemispheres.

[34] Figure 12a shows the track of Hurricane Isabel, the same map as that of Figure 2. Also shown is a hypothetical precipitation region based on the location of CG flashes on the night of 16 September and theoretical predictions of *Lauben et al.* [2001] for lightning source locations at a similar latitude. Figure 12b shows a map of the conjugate region in the Southern Hemisphere, where the “mirrored” precipitation is expected to occur. The GCPs between three VLF/LF transmitters (NAU, NST, and NLK) and a VLF/LF receiver located at Palmer (PA) station, Antarctica, are shown. The daily positions of Isabel are mapped to their geomagnetically conjugate location in the Southern Hemisphere and are represented by cartoon symbols. These cartoon symbols represent the approximate locations of the conjugate points to CG flashes associated with Isabel. A hypothetical region of the “mirrored” precipitation is superimposed.

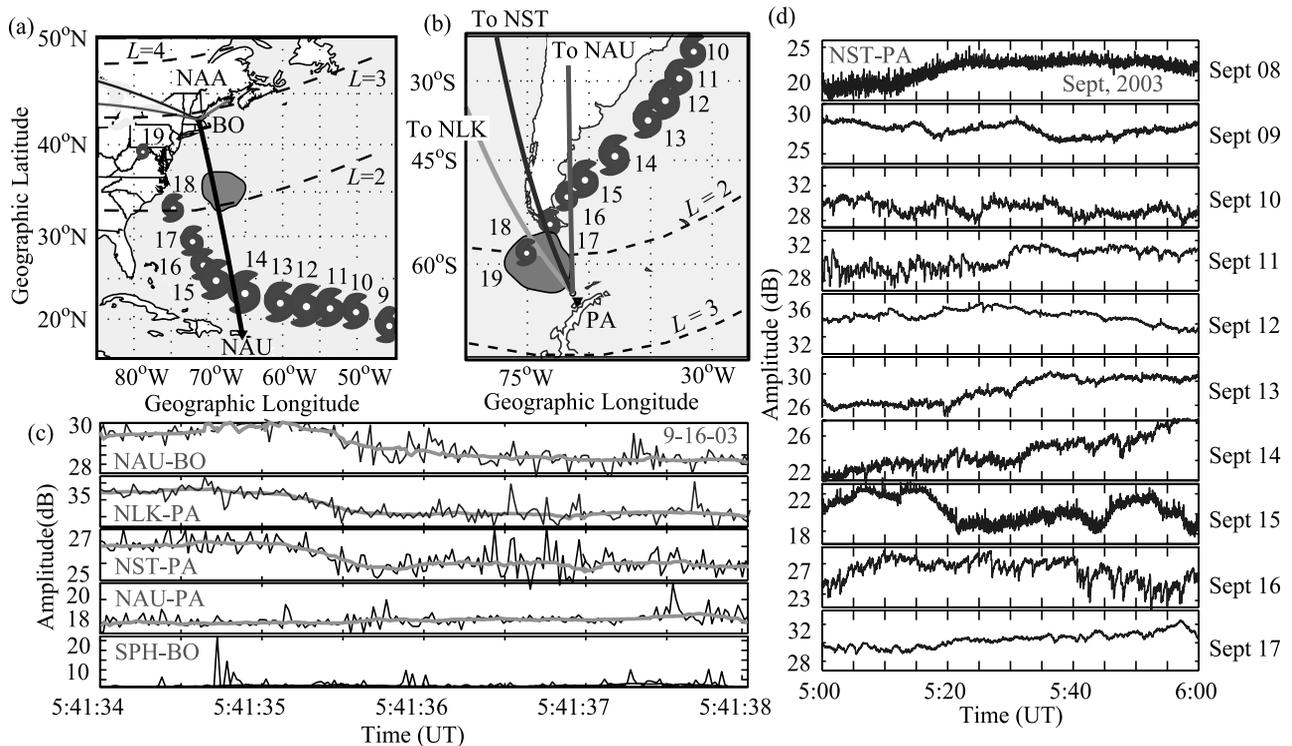
[35] The associated VLF/LF data are shown in a four-second snapshot (Figure 12c). The top signal shows an example LEP event as recorded by the NAU-BO signal on the night of 16 September. The conjugate precipitation perturbs the amplitude of the received signal from the NLK and NST transmitters, but not from the NAU transmitter. The bottom panel shows a broadband spheric signal used to detect the causative spheric. The perturbation of the signals received at Palmer has an onset delay similar to the perturbation of the NAU-BO signal. The majority ( $>60\%$ ) of the LEP events detected on the NAU-BO signal on 16 September were also associated with perturbations of the NLK-PA or NST-PA signal.

[36] Perturbations of the VLF/LF signals received at Palmer associated with causative flashes in the Northern Hemisphere occurred on the other days of September 2003 when LEP events were detected on the NAU-BO signal. Figure 12d shows one-hour panels of the NST signal amplitude recorded at Palmer from 05:00 to 06:00 UT each night from 8 September to 17 September 2003. Sizable perturbations ( $>0.5$  dB) similar to those observed on the NAU-BO signal (Figure 3) are visible. An increase in the number of perturbations is visible on the nights of 11, 14, and 16 September, those days with the highest number of LEP events detected on the NAU-BO signal (Figure 6). The time-coincident perturbations of the NST-PA signal amplitude with those perturbations of the NAU-BO signal is consistent with past observations of conjugate precipitation of electrons caused by single lightning discharges [*Burgess and Inan*, 1990, 1993]. Future studies that seek to quantify the loss of radiation belt electrons due to lightning-induced whistlers must consider the relative amounts of “mirrored” and “direct” precipitation.

## 5. Other Hurricanes

### 5.1. September 2001

[37] In comparison with the NAU-BO signal during September 2003 when Hurricane Isabel was moving through the GCP, the NAU-BO signal during September of 2001 exhibits different daily trends. Figure 13b shows two-hour panels of the received NAU signal amplitude from 05:00 to 07:00 UT for each day from 9 September 2001 to



**Figure 12.** The conjugate region. (a) The same figure as Figure 2, showing the track of Hurricane Isabel. A hypothetical precipitation region is superimposed. (b) A map of the conjugate region in the Southern Hemisphere. The Great Circle Paths (GCPs) between three VLF/LF transmitters (NAU, NST, and NLK) and one receiver located at Palmer (PA) are shown. The daily positions of Hurricane Isabel (see Figure 12a) are mapped to their geomagnetically conjugate locations in the Southern Hemisphere (using the DGRF/IGRF geomagnetic field model) and represented by the cartoon symbols. A hypothetical precipitation region is superimposed. (c) A 4-second snapshot of the NAU signal recorded at the Boston receiver (top panel) and three VLF/LF signals recorded at a VLF/LF receiver located at Palmer Station, Antarctica. The bottom panel shows a broadband spheric signal recorded at Boston (denoted by SPH-BO). A 10-point median filter of the original data is shown as a thick solid line. (d) Daily plots of Palmer VLF/LF data. One-hour panels of the received NST signal amplitude from 05:00 to 06:00 UT for each day from 8 September 2003 to 17 September 2003 recorded at the Palmer receiver. All panels show the signal amplitude on a 6-dB scale.

18 September 2001. While the number of LEP events is of the same order as in 2003, the daily occurrence rates are significantly different from those of September 2003. September is in the midst of hurricane season for the region, and three hurricanes (Gabrielle, Felix, and Erin) were in the region of the GCP between 9 and 18 September (Figure 13a). These tropical cyclone systems might explain the daily variation in the number of LEP events detected. While the number of perturbations meeting the classification of LEP events is fewer in total than in 2003, there are still a significant number of LEP events detected on the NAU-BO signal during hurricane season in the Atlantic basin.

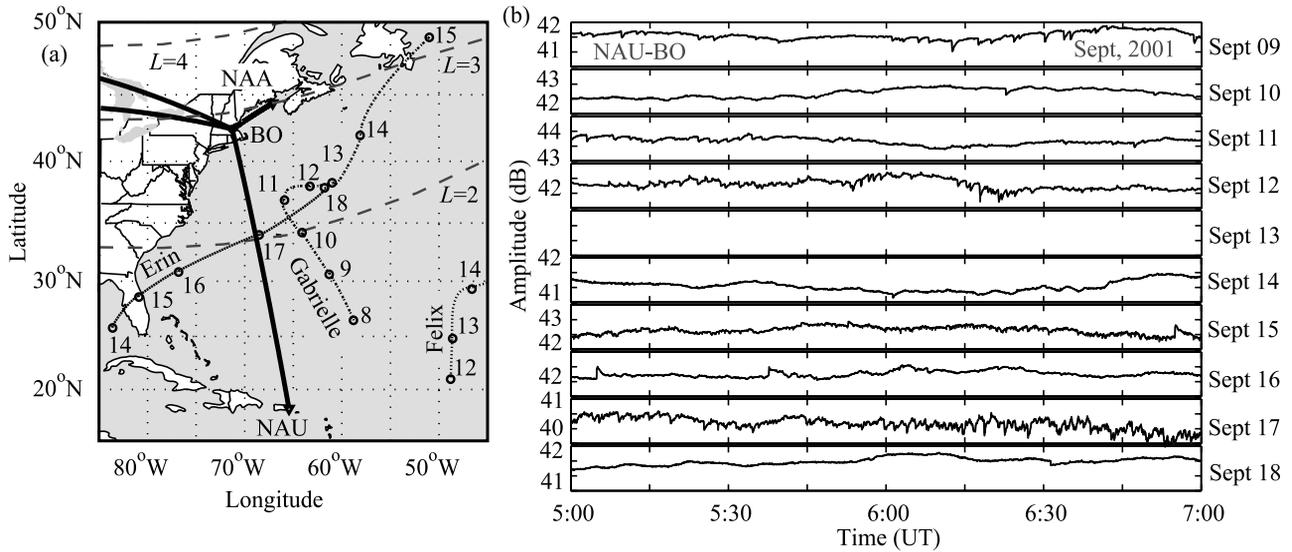
## 5.2. Hurricane Floyd

[38] A VLF/LF receiver, similar to the one set up at the Hanscom Air Force Base, operated near Dartmouth, Nova Scotia during September of 1999. The receiver monitored the NAU LF transmitter, with the GCP between the NAU transmitter and the Dartmouth (DA) receiver shown in Figure 14a. Figure 14a also maps the daily positions of Hurricane Floyd, based on the Tropical Cyclone Report

issued for Hurricane Floyd by the National Hurricane Center. Floyd crossed through the GCP between NAU and Dartmouth between 11 and 12 September. Figure 14b shows two-hour panels from 03:00 to 05:00 UT for each night from 9 to 18 September. The perturbations classified as LEP events are circled. The events occur during the period (13, 14, and 15 September) when the center of Floyd was west of the GCP. The Dartmouth receiver recorded relatively few perturbations compared to the receiver near Boston during Hurricane Isabel. This may be due to differences in the sensitivity of the instrument due to higher ambient noise levels or differences in the mode structure of the propagating LF signal. Regardless, LEP events again occur during a period of hurricane activity near the GCP of a propagating LF signal, although a more detailed analysis of lightning data would be needed to determine if the causative lightning flashes were associated with Floyd or other storm systems in the area.

## 5.3. Hurricane Fabian

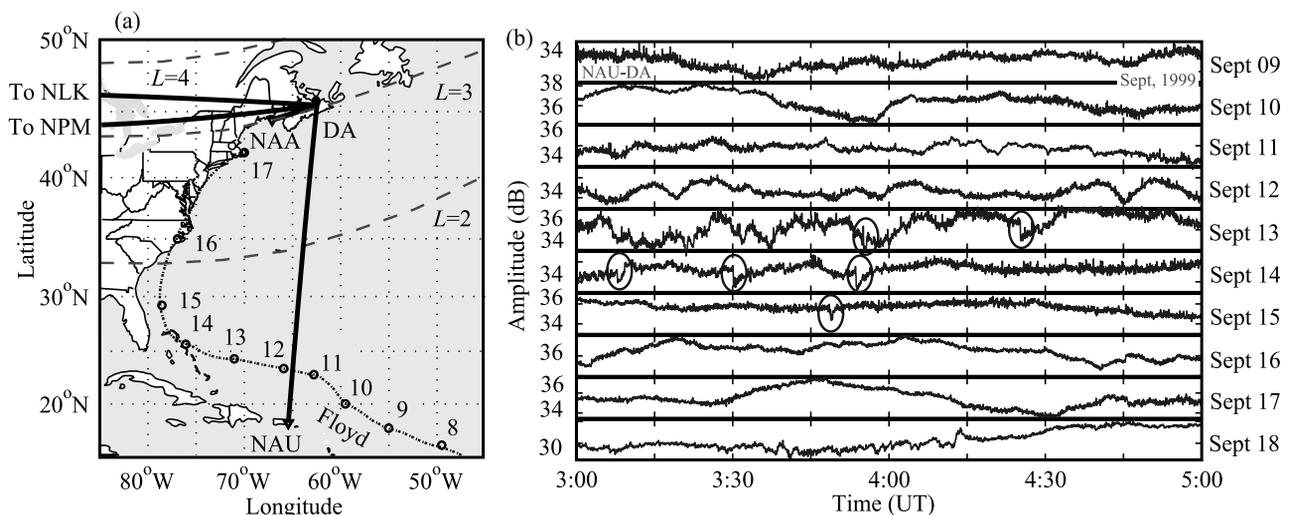
[39] Before Hurricane Isabel crossed the GCP between NAU and Boston, Hurricane Fabian passed near the GCP



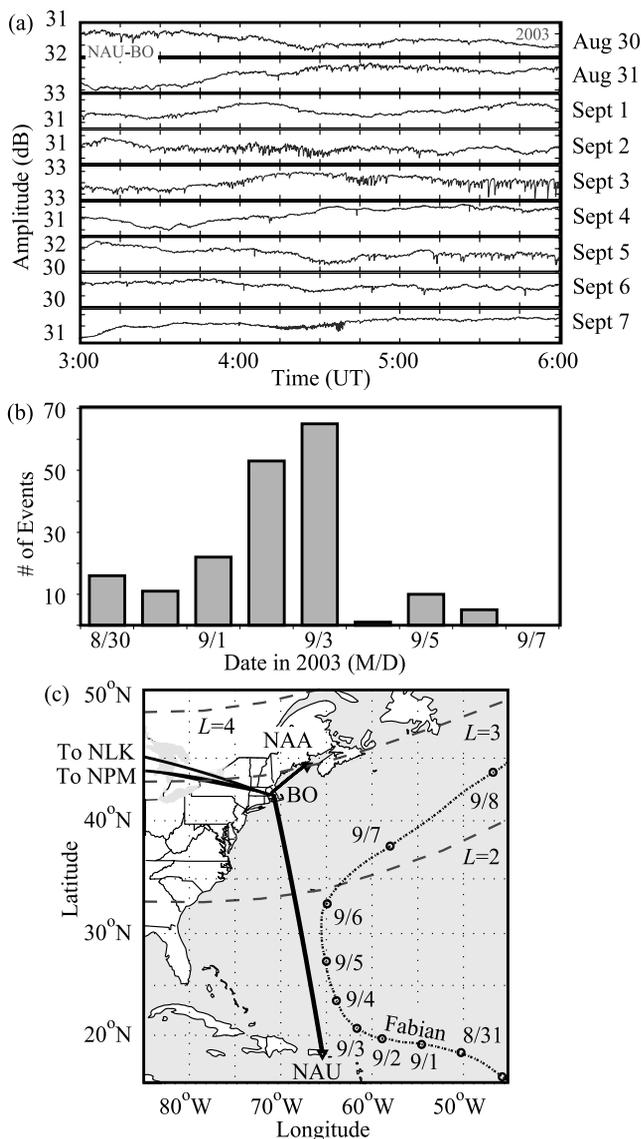
**Figure 13.** VLF data from September 2001. (a) Daily positions (at 06:00 UT) of Hurricanes Erin, Felix, and Gabrielle, according to the National Weather Service’s Tropical Cyclone Reports. All three hurricanes passed close to the Boston-NAU GCP during mid-September, 2001. (b) Two-hour panels of the received NAU signal from 05:00 to 07:00 UT for each day from 9 September 2001 to 18 September 2001 recorded at the Boston receiver. The panels all show the amplitude of the received signal on a 3-dB scale. Data for 13 September 2001 is missing due to equipment malfunction on that day.

during late August and early September of 2003. Figure 15a shows three-hour panels of the received NAU signal from 03:00 to 06:00 UT for each night from 30 August to 7 September. Figure 15b shows the number of LEP events detected each night (from 01:00 to 13:00 UT). On the nights of 30 August and 31 August, small numbers (10 and 15, respectively) of LEP events on the NAU-BO signal were recorded. Thereafter, the number of LEP events increased, with over sixty events recorded on the night of 3 September. The number of LEP events detected decreased

on 4 September, with relatively few events occurring each night through 7 September. Figure 15c shows the path of Hurricane Fabian, with Fabian passing near the GCP from 2 to 6 September 2003. The activity on the NAU-BO signal subsides prior to Hurricane Fabian leaving the region. This decrease in LEP activity may be due to the inconsistent nature in the location and frequency of lightning flashes associated with hurricanes and their rainbands. While the presence of Fabian is concurrent with an increase in the number of LEP events detected, other storm systems may



**Figure 14.** Hurricane Floyd. (a) Daily positions (at 06:00 UT) of Hurricane Floyd which passed through the GCP between NAU and Dartmouth during September 1999. (b) Two-hour panels from 03:00 to 05:00 UT for each day from 9 September 1999 to 18 September 1999. Circles mark those perturbations fulfilling our criteria for LEP events.



**Figure 15.** Hurricane Fabian. (a) Three-hour panels of the received NAU signal from 03:00 to 06:00 UT for each day from 30 August 2003 to 7 September 2003 recorded at Boston. The panels all show the amplitude of the received signal on a 3-dB scale. (b) The number of LEP events, during each night (from 01:00 to 13:00 UT), from 30 August to 7 September 2003. (c) Daily positions (at 06:00 UT) of Hurricane Fabian. The solid line represents the GCP between NAU and Boston.

have played a significant role in the LEP activity recorded on the NAU-BO signal.

## 6. Conclusion

[40] We have presented the first extensive examination of the occurrence of multiple LEP events associated with hurricanes in the Atlantic Ocean. For three hurricanes in the Atlantic Ocean (Isabel, Floyd, and Fabian), the number of LEP events detected on VLF/LF signals tended to increase when the hurricane was near the GCP between

the transmitter and the receiver. Hurricane Isabel, crossing the GCP between the NAU transmitter and a VLF/LF receiver located near Boston, Massachusetts, in mid-September of 2003, contributed to an increase in LEP events detected on the received signal. The majority of the causative CG flashes (those that were time-correlated with LEP events) associated with Isabel occurred in the outer rainbands of the hurricane and within 500 km of the GCP. Our analysis of five separate nights in mid-September of 2003 shows that while many of the causative CG flashes were associated with Hurricane Isabel, many of the LEP events were associated with other storm systems near the GCP. This suggests that hurricane-associated lightning can produce LEP events, but there is no indication that it is more likely to induce precipitation than lightning in other storms of similar location.

[41] The number of LEP events observed from 11 September to 16 September 2003 is relatively high for the NAU-BO path compared to nonhurricane periods. However, an extensive survey of occurrence rates of LEP events on the NAU-BO path has not been performed. Previous counts of LEP event activity over the continental United States, using the same criteria described above, resulted in count rates less than 10 events per day under quiet geomagnetic conditions [Peter and Inan, 2004]. However, the Rodger *et al.* [2003] study considered an average occurrence rate of 0.79 events per minute, based on observations of perturbations recorded at Faraday, Antarctica and using different criteria for defining LEP events. The occurrence rate of LEP events is highly dependent on the meteorological and geomagnetic conditions, the location of the GCP on which the perturbations are detected, and the criteria used to define the events. The fact that the number of events observed on 11 September are comparable to the number of events observed on 16 September, with both being orders of magnitude greater than occurrence rates on 6–9 September, suggests the occurrence rates observed on 11–16 September 2003 are typical of nights with major storm systems near the NAU-BO GCP.

[42] Peter and Inan [2004] suggested that variations in magnetospheric conditions, as well as CG flash rates, might influence the amount of LEP activity observed on VLF/LF signals. Owing to their longevity (on the order of days or even weeks), hurricanes provide excellent case studies of the different factors influencing LEP activity. Previous work [e.g., Bortnik *et al.*, 2003; Abel and Thorne, 1998a, 1998b] has suggested wave energy injected by lightning discharges may be an important contributor to the loss rates of radiation belt particles, especially at lower  $L$ -shells ( $L < 3$ ), demonstrating the need for further studies on the properties of lightning discharges and geomagnetic conditions that influence LEP event activity. Hurricane Isabel provided a source of CG flashes that moved through the GCP of a LF signal over the course of several days. The analysis of the associated perturbations of the LF signal with the movement of Isabel gives an indication of the impact of Hurricane Isabel on the  $D$ -region ionosphere in its vicinity. With the extensive monitoring of hurricane activity driven by the societal impacts of these events, lightning associated with hurricanes should provide well-documented case studies to quantify the processes of lightning-induced electron precipitation in future studies.

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