Solar wind influence on Pc4 and Pc5 ULF wave activity in the inner magnetosphere

W. Liu,[1,2] T. E. Sarris,[1,3] X. Li,[1,2,4] R. Ergun,[1] V. Angelopoulos,[5] J. Bonnell,[6] and K. H. Glassmeier[7]

Received 22 January 2010; revised 19 July 2010; accepted 29 July 2010; published 2 December 2010.

[1] Abundant evidence has shown that ULF wave activity measured at geosynchronous orbit is well correlated with solar wind parameters, such as the solar wind velocity and dynamic pressure. However, many of the past studies were based on magnetic field measurements near the equatorial plane and thus could not unambiguously describe ULF waves, as magnetic field oscillations in the fundamental toroidal mode have a node at the magnetic equator. In this study, we use, for the first time, simultaneous electric and magnetic field measurements by Time History of Events and Macroscale Interactions during Substorms satellites throughout the inner magnetosphere to statistically examine the correlation between ULF wave activity in the inner magnetosphere and the solar wind parameters: velocity, dynamic pressure, and variation in dynamic pressure. On the basis of electric field observations from August 2007 to May 2009, we found that, among the three parameters, the solar wind velocity has the strongest correlation with the daily averaged Pc4 and 5 wave magnitude in 4 ~ 9 R_E. For example, the correlation coefficient of δE_r (the square root of the integrated power spectral density of the radial component of the electric field) in the Pc5 frequency range with the solar wind dynamic pressure is 0.35; with the dynamic pressure variation, it is 0.42; and with the solar wind velocity, it is 0.55. However, using only magnetic field observations, the variation in dynamic pressure is best correlated, with correlation coefficients of δB_r (the square root of the integrated power spectral density of the radial component of the magnetic field) with the dynamic pressure being 0.59, with the dynamic pressure variation being 0.63 and with the solar wind velocity being 0.53. We suggest that this difference arises because toroidal and poloidal mode pulsations are not detected with the same effectiveness in the electric field and the magnetic field near the magnetic equator and/or because of the presence of broadband ULF noise. We further suggest that either directly measured or flow-derived electric field measurements are better suited in the study of the relationship between wave power of fundamental field line resonance (i.e., in Pc5 frequency range) and solar wind conditions.

Citation: Liu, W., T. E. Sarris, X. Li, R. Ergun, V. Angelopoulos, J. Bonnell, and K. H. Glassmeier (2010), Solar wind influence on Pc4 and Pc5 ULF wave activity in the inner magnetosphere, *J. Geophys. Res.*, *115*, A12201, doi:10.1029/2010JA015299.

1. Introduction

[2] Ultralow frequency (ULF) waves are oscillations in the Earth's magnetic field in the frequency band from ~1 mHz to ~1 Hz. There are two primary modes of oscillation [*Southwood and Hughes*, 1983; *Glassmeier et al.*, 1999; *Klimushkin et al.*, 2004]: the toroidal mode, which is a displacement of the magnetic field in the azimuthal direction, creating an azimuthal magnetic perturbation, and the poloidal mode, which is a radial displacement with radial magnetic perturbations. The electric field has the corresponding oscillations in the radial (azimuthal) direction for the toroidal (poloidal) mode. Both theoretical analysis [e.g., *Dungey*, 1954; *Hughes*, 1994] and observations [e.g., *Singer and Kivelson*, 1979; *Liu et al.*, 2009] have shown that fundamental toroidal mode ULF waves have a node (and thus

[1]Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, Boulder, Colorado, USA.
[2]Laboratory for Space Weather, Chinese Academy of Sciences, Beijing, China.
[3]Space Research Laboratory, Democritus University of Thrace, Xanthi, Greece.
[4]Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.
[5]Institute of Geophysics and Planetary Physics, University of California-Los Angeles, Los Angeles, California, USA.
[6]Space Sciences Laboratory, University of California-Berkeley, Berkeley, California, USA.
[7]Institute for Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, and MPS, Katlenburg-Lindau, Germany.

0148-0227/10/2010JA015299

minimum amplitude) at the magnetic equator for the magnetic field and an antinode (maximum amplitude) for the electric field. It is thus suggested that magnetic field observations alone cannot fully characterize all features of the ULF pulsations and that electric field measurements are required to provide an unambiguous picture of ULF activity in the inner magnetosphere at equatorial latitudes [e.g., *Liu et al.*, 2009].

[3] One motivation for studying ULF waves is to analyze their role in the acceleration of energetic (~MeV) electrons in the radiation belt, whose drift period is comparable to the period of Pc4-5 ULF waves. For example, *Rostoker et al.* [1998] observed a strong similarity in the time series of the intensity of Pc5 waves on the ground and the flux of energetic electrons measured at a geosynchronous satellite. Similarly, several other observations [e.g., *Mathie and Mann*, 2000; *Kozyreva et al.*, 2007; *Zong et al.*, 2007] and theoretical analyses [e.g., *Elkington et al.*, 1999; *Fei et al.*, 2006; *Ukhorskiy et al.*, 2005, 2006] confirmed the relation among ULF waves, the solar wind, and energetic electrons.

[4] The solar wind is the main external source of ULF waves in the inner magnetosphere, through either the Kelvin-Helmholtz instability (KHI) [*Southwood*, 1968; *Pu and Kivelson*, 1983] or dynamic pressure variations [*Kepko and Spence*, 2003]. Depending on the excitation mechanism at work, the ULF wave power is expected to correlate better with different solar wind parameters: solar wind velocity in the first case and solar wind dynamic pressure variation in the second case. The relationship between solar wind parameters and ULF wave power has been studied extensively, through both ground magnetometer measurements and in situ observations. Most of the ground-based observations have suggested that the solar wind velocity is a dominant controlling parameter [e.g., *Engebretson et al.*, 1998; *Vennerstrøm*, 1999; *Mathie and Mann*, 2000, 2001; *Baker et al.*, 2003], which is consistent with some of the in situ magnetic field observations [e.g., *Singer et al.*, 1977]. However, based on measurements of the solar wind by ACE and geosynchronous magnetic field by GOES 8, *Takahashi and Ukhorskiy* [2007, 2008] recently concluded that the major driver of geosynchronous Pc5 waves is solar wind dynamic pressure variations rather than the KHI on the magnetopause or the dynamic pressure itself. The different mechanisms generate ULF waves at different locations. Many statistical study [e.g., *Takahashi and Anderson*, 1992; *Cao et al.*, 1994; *Hudson et al.*, 2004; *Liu et al.*, 2009] have focused on the distribution of ULF waves in the magnetosphere.

[5] Most of the past works have been done with magnetic field measurements, whereas electric field observations in the magnetosphere were used less frequently, due to the lack of such instrumentation in many magnetospheric missions and also due to difficulties in measuring electric field with sufficient sensitivity and accuracy with the standard double-probe technique [*Mozer*, 1973]. Some single-case studies that were based on electric field observations include the work by *Singer et al.* [1982], *Glassmeier et al.* [1984], *Rae et al.* [2005], and *Schäfer et al.* [2007]. Furthermore, *Junginger et al.* [1984] and *Junginger and Baumjohann* [1988] have performed statistical studies of the distribution of ULF waves that were based on in situ electric field observations. Of closest relevance to the results presented herein is the work done by *Junginger and Baumjohann* [1988], who studied Pc5 electric field pulsations observed by the electron beam experiment onboard GEOS 2 and compared their spectral power and occurrence rate with interplanetary magnetic field (IMF) and solar wind parameters. To our knowledge, this is the only attempt to address the correlation between electric field ULF wave power in the magnetosphere and solar wind conditions. However, this study was limited to geosynchronous altitudes, due to the orbit of GEOS 2. Finally, *Sakurai et al.* [1999] used Geotail electric and magnetic field data to statistically investigate ULF waves close to the magnetopause.

[6] The Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission [*Angelopoulos*, 2008], which consists of five microsatellites (termed A through E) traversing the magnetosphere near the equatorial plane, provides an ideal tool for characterizing ULF pulsations with both electric and magnetic field measurements. Using the THEMIS electric and magnetic field measurements, *Sarris et al.* [2009a] showed the field line resonances can be present over a wide radial distance in a case study, and *Liu et al.* [2009] provided a statistical analysis of the spatial distribution of ULF waves in the inner magnetosphere. In this paper, we examine the correlation between the power of ULF oscillations and the solar wind parameters using simultaneous electric and magnetic field measurements and comment on the observed differences.

2. Data Set

[7] Measurements of the electric and magnetic field are provided by the electric field instrument [*Bonnell et al.*, 2008] and the fluxgate magnetometer [*Auster et al.*, 2008] onboard THEMIS-D, which has an apogee of ~15 R_E before October 2007 and ~12 R_E afterward and stays within ±10° of the magnetic equator for 85% of the time, providing an excellent opportunity to address the difference in the electric and magnetic field measurements on ULF waves. For our analysis, the components of the electric and magnetic field vectors were projected to a mean-field-aligned coordinate system from the GSE coordinate system, in order to separate the fluctuations in the two perpendicular directions and the parallel direction. In this system, $B_{||}$ is obtained from a 30 min running average of the magnetic field, centered at the data point being processed. The azimuthal direction, $\widehat{\mathbf{e}}_\phi$ is determined by $\widehat{\mathbf{e}}_{||} \times \vec{\mathbf{r}}_\mathrm{e}$, where $\widehat{\mathbf{e}}_{||}$ points along the average background magnetic field direction and $\vec{\mathbf{r}}_\mathrm{e}$ is the radial position vector, positive outward. The third unit vector $\widehat{\mathbf{e}}_\mathrm{r}$, roughly in the radial direction, is defined so that the vectors ($\widehat{\mathbf{e}}_\mathrm{r}$, $\widehat{\mathbf{e}}_\phi$, $\widehat{\mathbf{e}}_{||}$) complete the orthogonal system.

[8] The magnitude of the oscillations in the radial and azimuthal directions of the electric (δE_r and δE_φ, respectively) and in the radial, azimuthal, and parallel directions of the magnetic field (δB_r, δB_φ, and $\delta B_{||}$, respectively) are used in this paper to represent the level of ULF wave activity. These are defined as the square root of the integrated power spectral density of the radial or azimuthal component of the electric field or the magnetic field over a certain frequency range, set

here to the Pc4 (7–22 mHz) and Pc5 (2–7 mHz) frequency ranges,

$$\delta E_{\mathrm{r}} = \sqrt{\int_{f_1}^{f_2} \mathrm{PSD\_}E_{\mathrm{r}}(f)\mathrm{d}f}, \; \delta E_{\phi} = \sqrt{\int_{f_1}^{f_2} \mathrm{PSD\_}E_{\phi}(f)\mathrm{d}f}$$

$$\delta B_{\mathrm{r}} = \sqrt{\int_{f_1}^{f_2} \mathrm{PSD\_}B_{\mathrm{r}}(f)\mathrm{d}f}, \; \delta B_{\phi} = \sqrt{\int_{f_1}^{f_2} \mathrm{PSD\_}B_{\phi}(f)\mathrm{d}f},$$

$$\delta B_{//} = \sqrt{\int_{f_1}^{f_2} \mathrm{PSD\_}B_{//}(f)\mathrm{d}f}.$$

In this paper, we exclude instances of strong broadband intensifications in the wave power spectra, usually associated with magnetopause crossings, during which the magnitude of the electric field often rises to greater than 5 mV/m.

[9] For this analysis, solar wind measurements (velocity and dynamic pressure) are provided by the OMNI 1 min database. The dynamic pressure variation is calculated based on the dynamic pressure data. Various definitions of the solar wind dynamic pressure variation have been used in the past. In this paper, we will first use the definition suggested by *Takahashi and Ukhorskiy* [2008], which is defined as the square root of the integral of the power spectra density over the Pc5 frequency band,

$$\delta P_{\mathrm{sw}} = \sqrt{\int_{f_1}^{f_2} \mathrm{PSD\_}P_{\mathrm{sw}}(f)\mathrm{d}f}.$$

Subsequently, we will examine the difference between the correlation of ULF waves with δP_{sw} and their correlation with another definition suggested by *Li et al.* [2001] and *Posch et al.* [2003], who used the value of $(\Delta(P_{\mathrm{sw}})^2/\Delta t)^2$, referred to as ΔP_{sw} here, to represent the level of dynamic pressure variation. ΔP_{sw} reflects the sudden changes in dynamic pressure, which is also a suggested driver of ULF waves in the magnetosphere [e.g., *Zong et al.*, 2009]. For the definition of δP_{sw}, we focus on wave power in the Pc5 frequency range, which is suggested to be related to the direct driving of ULF waves in the magnetosphere [*Kepko and Spence*, 2003].

3. Statistical Results

[10] In order to analyze the overall response of ULF wave activity in the inner magnetosphere to the solar wind, the daily averaged values of δE_{r} and δE_{φ} over the Pc5 and Pc4 frequency ranges are calculated in the radial distance range of 4 ~ 9 R_E from August 2007 to May 2009, as shown in Figures 1a and 1b, respectively. The daily averaged solar wind velocity, dynamic pressure, and the dynamic pressure variation δP_{sw} are plotted in Figures 1c, 1d, and 1e, respectively. Further to averaging over an entire day, we also investigated averaging the solar wind parameters over only the periods when THEMIS-D made observations between 4 and ~9 R_E. However, the results in these two cases were very similar.

[11] From the comparison between the ULF wave magnitude and solar wind parameters in Figure 1, we can see that during the times when solar wind velocity is higher, the amplitudes of oscillations, δE_{r} and δE_{φ} are also larger. For the dynamic pressure, this relation can only be distinguished during certain times, and the overall correlation is not as obvious as it is with solar wind velocity. The solar wind dynamic pressure variation, δP_{sw}, has a high correlation with the dynamic pressure itself. The correlation coefficient between P_{sw} and δP_{sw} is calculated to be 0.89. The correlation of ULF wave magnitude with δP_{sw} is weaker than its correlation with solar wind velocity, as we can visually distinguish.

[12] From Figure 1, we can also distinguish a local time (LT) dependence of the wave magnitude. The vertical dashed lines in Figure 1 mark the times when the apogee of THEMIS-D was at 0000, 0600, 1200, and 1800 LT, indicating that the spacecraft spent most of the time around the corresponding LT. The differences between the different sectors are visible for both the wave magnitude and its correlation with the solar wind parameters; this is consistent with our previous observations presented in the study by *Liu et al.* [2009]. In Figure 1 we can see that the magnitude of electric field oscillations is stronger in the dayside (July–December 2007 and June–December 2008) than in the nightside (December 2007 to May 2008 and December 2008 to May 2009); the correlation between wave magnitude and solar wind velocity is also stronger in the dayside than in the nightside. In the dusk side (March–June 2008), the wave activity that is observed in both magnetic field and electric field observations might be related to the high M waves generated by the ion drift during magnetic storms [e.g., *Anderson et al.*, 1990; *Takahashi and Anderson*, 1992; *Li et al.*, 1993].

[13] Subsequently, we calculate the correlation coefficients between Pc4 and 5 ULF wave magnitude and the solar wind parameters, as shown in Figure 2. The correlation coefficient measures the strength and the direction of a linear relationship between two variables, whose square value is the ratio of the explained variation to the total variation. For example, a correlation coefficient of 0.7 means that 49% of the total variation in the second variable can be explained by the variance of the first variable under a linear assumption. The calculation of the correlation coefficients confirms that the ULF wave magnitude has a better correlation with the solar wind velocity than with the dynamic pressure and the dynamic pressure variation. For example, the correlation coefficient of δE_{r} with the solar wind velocity is 0.66 (0.55) for Pc4 (Pc5) waves, higher than the correlation coefficient of δE_{r} with the dynamic pressure, which is 0.28 (0.35) for Pc4 (Pc5) waves, and with the dynamic pressure variation, which is 0.42 for Pc5 waves; because of the resolution of the OMNI database (1 minute), the variation of the dynamic pressure in the Pc4 range cannot be calculated. The above correlations are all statistically significant with $P < 0.0001$, where the P value measures how much evidence there is to reject the most common explanation for the data set [*Schervish*, 1996].

[14] The solar wind control of Pc4 and Pc5 waves is expected to be stronger in the dayside region. To investigate this dependence, in Figure 3 only, the data between June

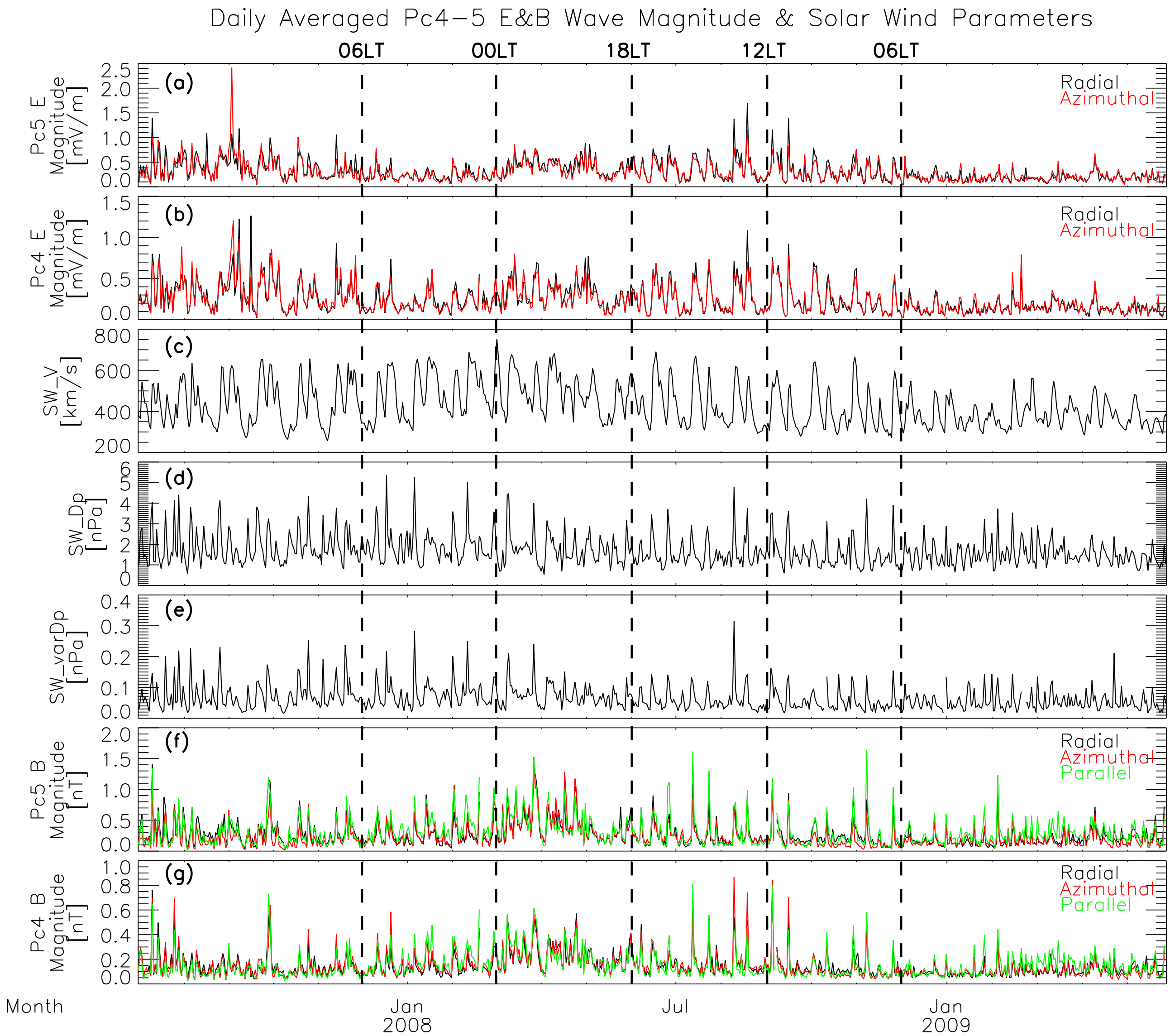

Figure 1. (a) Daily averaged wave magnitude of the electric field in the inner magnetosphere (4–9 R_E) over the Pc5 frequency range in the radial (black) and azimuthal (red) directions from August 2007 to May 2009; (b) same as Figure 1a but over the Pc4 frequency range; (c) daily averaged OMNI solar wind velocity; (d) daily averaged OMNI solar wind dynamic pressure; (e) daily averaged OMNI solar wind dynamic pressure variation; (f) daily averaged wave magnitude of the magnetic field over the Pc5 frequency range in the radial (black), azimuthal (red), and parallel (green) directions; and (g) same as Figure 1e but over Pc4 frequency range. The dash lines mark the time when the apogee of the satellite was at 0000, 0600, 1200, and 1800 LT, respectively.

2008 and December 2008 are plotted, at which time the apogee of the satellite was in the dayside region, between 0600 and 1500 LT. All correlation coefficients calculated during this time period increase compared to the values calculated with the whole data set. For example, the correlation coefficient of δE_r with the solar wind velocity is 0.82 (0.70) for Pc4 (Pc5) waves, which is higher than the correlation coefficient of δE_r with the dynamic pressure, which is 0.37 (0.52) for Pc4 (Pc5) waves, and also higher than the correlation coefficient of δE_r with the dynamic pressure variation, which is 0.60 for Pc5 waves. The statistical significances of these correlations are at a level of $P < 0.0001$.

[15] Similarly, the correlations between solar wind parameters and the magnetic field wave magnitude, δB_r, δB_φ, and $\delta B_\parallel$ are investigated. The time evolution of the Pc5 and Pc4 magnetic field wave magnitude is plotted in Figures 1f and 1g, respectively, and the correlation coefficients are plotted in Figure 4. In Figures 1f, 1g, and 4 we can see that δB_r, δB_φ, and $\delta B_\parallel$ have the highest correlation coefficient with the dynamic pressure variation. For example, the correlation coefficient of δB_r with δP_{sw} is 0.63 for Pc5 waves, higher than the correlation coefficient of δB_r with the velocity, which is 0.44 (0.53) for Pc4 (Pc5) waves, and also higher than the correlation coefficient of δB_r with the dynamic

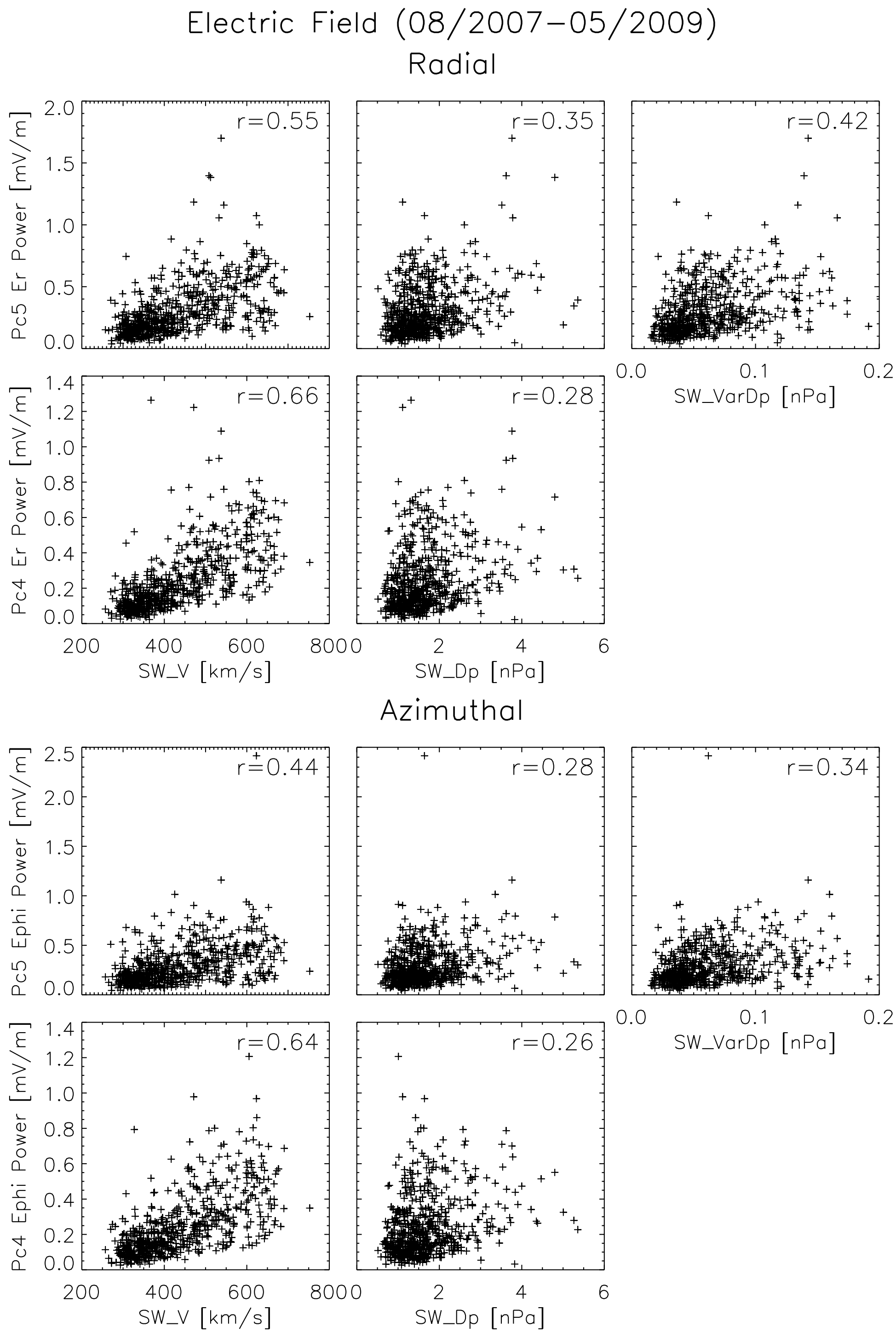

Figure 2. Scatterplots of ULF wave magnitude versus solar wind parameters: The radial and azimuthal wave magnitude in electric field over the Pc4 (bottom) and Pc5 (top) frequency ranges are shown as a function of the solar wind velocity, dynamic pressure, and dynamic pressure variation from August 2007 to May 2009.

pressure, which is 0.54 (0.59) for Pc4 (Pc5) waves. Compared these results with the results from the electric field, we find that the correlation coefficient with the solar wind velocity decreases for the magnetic field, whereas the correlation coefficient with the dynamic pressure variation increases. The statistical significances of these correlations are at a level of $P < 0.0001$.

[16] We also investigated the radial dependence of the correlation coefficients, in order to identify regions in the magnetosphere where the different excitation mechanisms

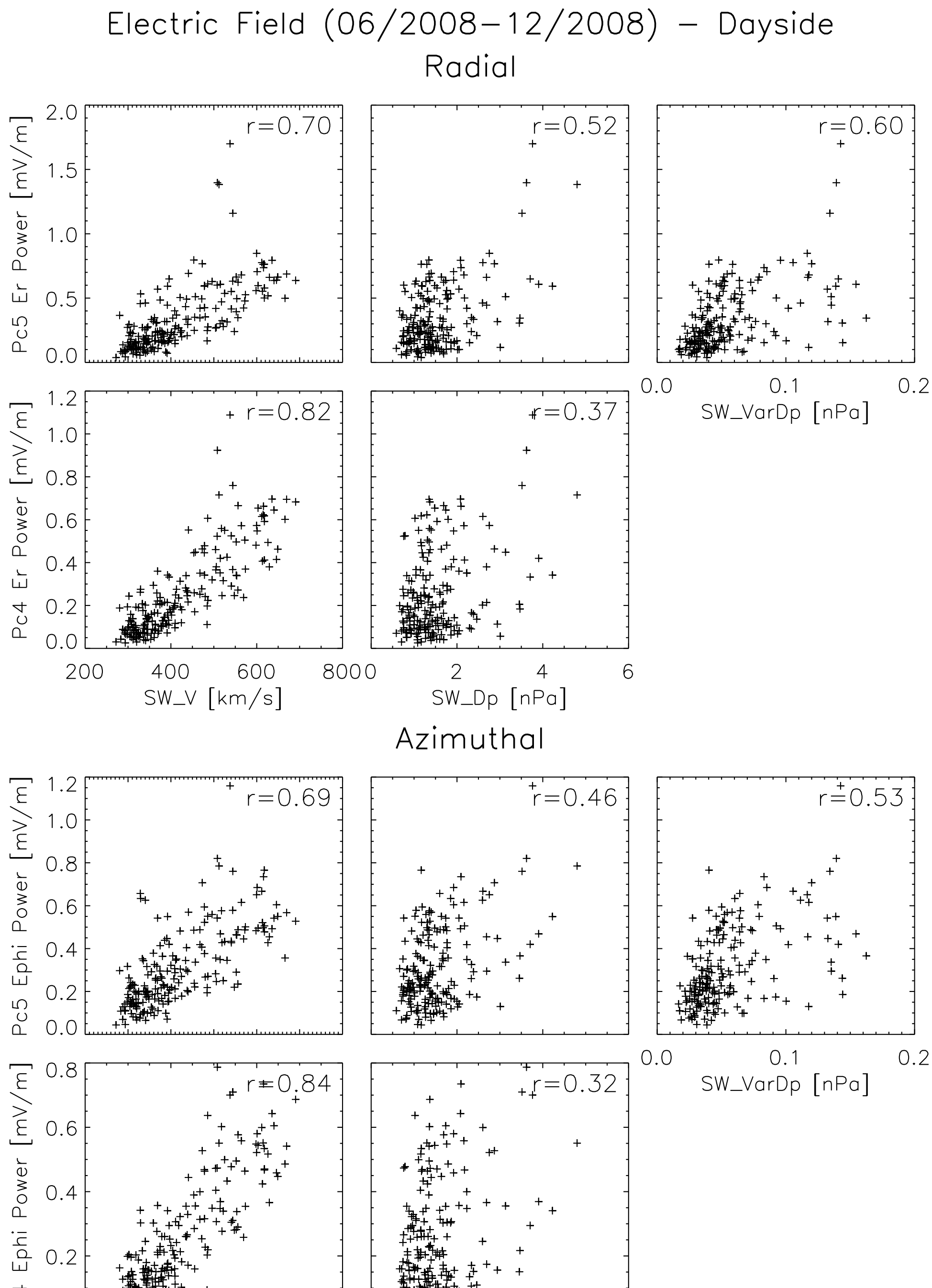

Figure 3. Scatterplots of ULF wave magnitude versus solar wind parameters: The radial and azimuthal wave magnitude in electric field over the (bottom) Pc4 and (top) Pc5 frequency ranges are shown as a function of the solar wind velocity, dynamic pressure, and dynamic pressure variation in the dayside, from June 2008 to December 2008.

may act preferentially. In Figure 5, we plot the correlation coefficients for both the solar wind velocity (solid lines) and the dynamic pressure variation (dashed lines) with the Pc5 wave magnitude in the dayside, binned at different radial distances from 4 R_E to 9 R_E, every 0.5 R_E. Instead of using daily averages of the solar wind parameters, here we use 1 h averages, centered at the corresponding ULF wave observations. It can be seen that in the region between 7 and 8.5 R_E, the correlation coefficients of both the solar wind velocity and the dynamic pressure variation with the Pc5 wave mag-

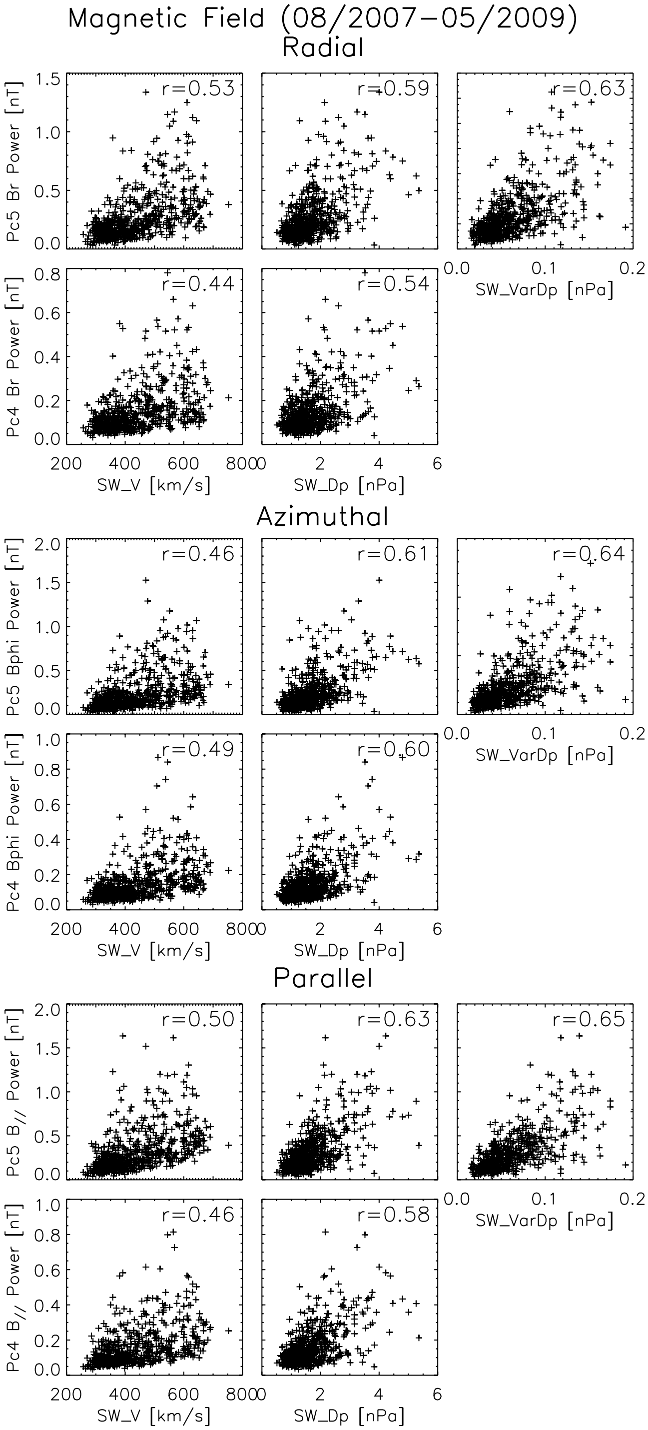

Figure 4. Scatterplots of ULF wave magnitude versus solar wind parameters: The radial, azimuthal, and parallel wave magnitude in magnetic field over the (bottom) Pc4 and (top) Pc5 frequency ranges are shown as a function of the solar wind velocity, dynamic pressure, and dynamic pressure variation from August 2007 to May 2009.

nitude are fairly similar (~0.55). Further in, for the solar wind dynamic pressure variation, the correlation coefficient decreases between 6 and 7 R_E (minimum: ~0.26) and recovers inside of 6 R_E, whereas for the solar wind velocity, the correlation coefficient remains at the same level, until it decreases inside of 5.5 R_E.

4. Discussion

[17] It is well known that the fundamental and other odd harmonics of toroidal ULF waves have a node at the magnetic equator. This makes it difficult for equatorial spacecraft to detect the fundamental toroidal mode of ULF pulsations with only magnetic field measurements [e.g., *Dungey*, 1954; *Hughes*, 1994; *Singer and Kivelson*, 1979]. This was demonstrated by *Sakurai et al.* [1999], who, based on simultaneous electric and magnetic field measurements by Geotail satellite, showed that Pc5 wave activity in the magnetosphere flanks could often be identified only in electric field measurements, whereas there was no indication of activity in the magnetic field. As a clearer demonstration of this effect, in a recent paper by *Liu et al.* [2009], a case study of a field line resonance event was presented, where the signatures of the fundamental mode were more evident in electric field observations throughout an outbound orbit of THEMIS-D from the plasmapause to the magnetopause, mostly in the E_r component, suggesting the presence of waves with a toroidal mode of oscillation; on the other hand, in magnetic field measurements, the fundamental mode was not observed continuously and was not as evident (see Figure 2a in that paper). This was interpreted as an indication that the spacecraft was orbiting close to a node of the magnetic field line. It was thus shown that magnetic field observations alone cannot fully characterize all features of the ULF pulsations and that electric field measurements, either directly measured or flow-derived, are required to provide an unambiguous picture of ULF wave activity in the inner magnetosphere.

[18] In this paper we use both electric and magnetic field measurements to identify correlations with the solar wind parameters, and we compare the corresponding correlation coefficients. The wave magnitude in the electric field is found to be strongly correlated with the solar wind velocity, whereas the wave magnitude in the magnetic field is not as well correlated. We suggest that the difference in these correlations is due to the THEMIS positioning with respect to the magnetic field lines: The orbit of THEMIS-D satellite is close to the magnetic equator and stays within ±10° of the magnetic equator for 85% of the time, which leads to a different efficiency of the two instruments to detect fundamental mode toroidal ULF waves.

[19] Many studies based on both ground magnetometer and in situ observations have shown that the ULF wave power in the inner magnetosphere correlates well with the solar wind (see the references in the introduction session). However, as shown above, there are significant differences in the correlations depending on the use of electric or magnetic field measurements: Our analysis based only on THEMIS magnetic field measurements found that the magnitude of ULF waves has a stronger correlation with the variation in solar wind dynamic pressure δP_{sw} than with the solar wind velocity or the dynamic pressure. However, when including electric field measurements in the analysis, we reach different conclusions, suggesting that the ULF wave magnitude is actually better correlated with solar wind velocity. On the basis of the discussion in the previous paragraphs, we suggest

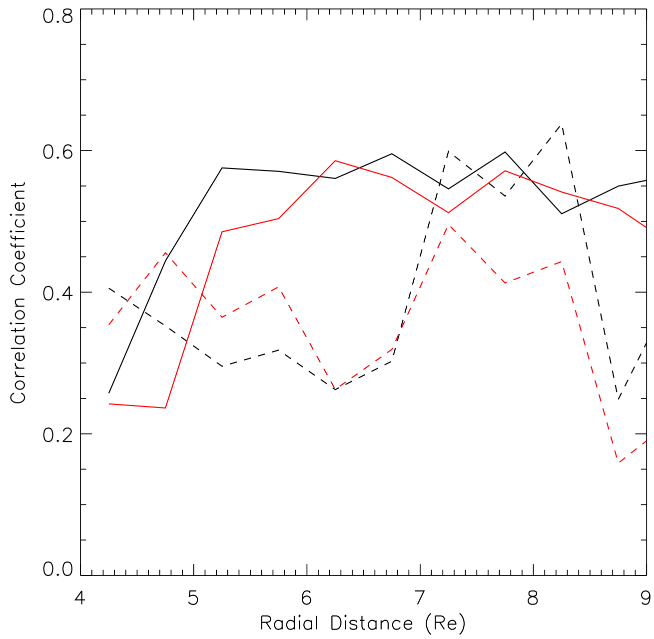

Figure 5. Correlation coefficients between the Pc5 electric field wave magnitude and the solar wind parameters, velocity (solid), and dynamic pressure variation (dashed) as a function of the radial distance from June to December of 2008. The black and red lines are for radial and azimuthal components, respectively. The statistical significances of the correlations in this figure are at a level of $p < 0.0001$.

that the electric field data are better suited in the study of such relationships. *Junginger and Baumjohann* [1988] studied Pc5 electric field pulsations observed by the electron beam experiment onboard GEOS 2 at geosynchronous orbit and compared the measured spectral power and occurrence rate with the IMF and solar wind parameters. They found no clear correlation between the orientation and magnitude of the IMF and pulsation amplitude and occurrence rate. However, they found that significant correlations exist between the spectral power of the pulsations and the solar wind bulk velocity, which is consistent with our study.

[20] A possible additional explanation for the difference between electric and magnetic field observations is the broadband ULF noise: On the basis of Active Magnetospheric Particle Tracer Explorers/CCE magnetic field measurements near the geomagnetic equator, *Anderson and Engebretson* [1995] found that broadband ULF noise is often present in the dayside magnetosphere. Consequently, the signal-to-noise ratio of narrowband fundamental mode ULF wave power could be considerably larger for the electric field than for the magnetic field. It is quite possible that this broadband noise is not causally related to enhanced solar wind velocity but that it is instead related to variations in dynamic pressure. This suggests that, in the dayside magnetosphere and at low latitudes, where magnetic field fluctuations have a node in the fundamental toroidal mode, this broadband noise may dominate the magnetic signal and may cause the correlation to be better with the variability in solar wind dynamic pressure than with solar wind velocity.

[21] By performing an analysis of the radial dependence of these correlations, we found that the correlation coefficient between Pc5 wave magnitude and solar wind dynamic pressure variation is larger beyond 7 R_E, decreases rapidly between 6 and 7 R_E and recovers inside of 6 R_E. This is possibly due to the existence of a turning point for cavity mode pulsations in the plasmatrough region, as discussed in, for example, *Kivelson and Southwood* [1986], *Zhu and Kivelson* [1988], *Waters et al.* [2000], *Klimushkin et al.* [2004], and *Schäfer et al.* [2007]. Fast mode waves are expected to reflect at this turning point, which according to theory is located in the region between 6 and 7 R_E for Pc5 waves [*Waters et al.*, 2000, Figure 3], possibly causing the rapid decrease in the correlation coefficient of ULF wave magnitude with the solar wind dynamic pressure that is observed between 6 and 7 R_E in Figure 5. At the same time, some energy could tunnel through this turning point, possibly causing the recovery of the correlation coefficient inside of 6 R_E.

[22] In the statistical analysis presented above, we performed the same correlations separately for the radial and azimuthal components of the electric and the magnetic field. However, in the statistical results, the difference is not obvious between the two components. This is possibly because, according to simulations [*Rankin et al.*, 2006 and *Kabin et al.*, 2007] and observations [*Sarris et al.*, 2009a], the field line resonances often appear in mixed toroidal and poloidal modes in a compressed magnetic field configuration. It is also possibly because the waves appear to have circular polarization in some cases [*Sarris et al.*, 2009b]. Thus, in the daily averaged value, the differences between the two transverse components diminish.

[23] To address the correlation between ULF wave magnitude and the solar wind dynamic pressure variation, we investigated the difference between two different definitions of dynamic pressure variation, ΔP_{sw} and δP_{sw}. In the analysis performed, ΔP_{sw} was calculated based on the 1 min OMNI solar wind parameters averaged over a 5 min window and was normalized by division by its 2 year averaged value. The tests with different average windows (5 min, half hour, and 1 h) show that, even though the value of ΔP_{sw} depends on the length of the window, its trend is actually independent of the average window and so is the correlation coefficient.

[24] The relations between ULF wave magnitude and ΔP_{sw} as well as δP_{sw} are shown in Table 1. The correlation coefficients of ULF wave magnitude with ΔP_{sw} are found to be lower compared to the correlation coefficients of ULF wave magnitude with δP_{sw}. This suggests that, although sudden impulses in the solar wind dynamic pressure can, in some instances, generate strong ULF waves in the magnetosphere [e.g., *Zong et al.*, 2009], periodic fluctuations in the dynamic pressure are generally more effective in generating ULF waves by continuously supplying the energy for the oscillations [e.g., *Kepko and Spence*, 2003].

Table 1. Correlation Coefficients Between Pc5 Wave Magnitude in Radial and Azimuthal Electric Field Components and the Two Definitions of Solar Wind Dynamic Pressure Variation[a]

	δP_{sw}	ΔP_{sw}
E_r	0.60	0.22
E_φ	0.53	0.16

[a] δP_{sw} and ΔP_{sw} are defined in section 2.

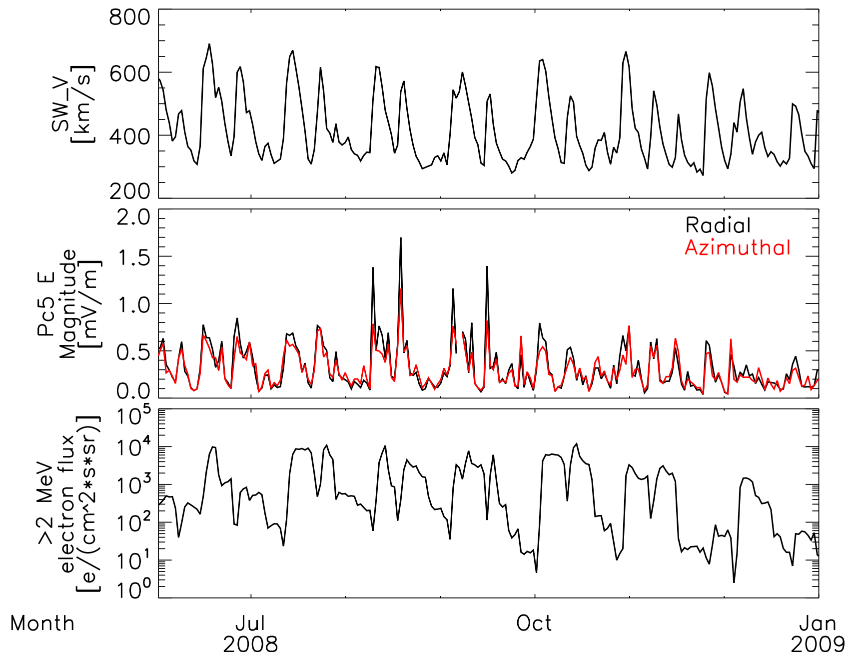

Figure 6. The daily averaged value of the solar wind velocity, the Pc5 wave magnitude in electric field and the >2 MeV electron flux at geosynchronous orbit, from top to bottom.

[25] It has been known that the flux of ~MeV electrons at geosynchronous orbit is highly correlated with the solar wind velocity [e.g., *Paulikas and Blake*, 1976; *Li et al.*, 2001; *Li*, 2004]. One of the explanations for this correlation is that ULF waves driven by the KHI on the magnetopause are responsible for the acceleration of the radiation belt electron [e.g., *Rostoker et al.*, 1998; *Mathie and Mann*, 2000]. In Figure 6 we reinforce this relation with our data set by plotting the daily averaged solar wind velocity, Pc5 wave magnitude, and GOES 11 >2 MeV electron flux from June to December in 2008. It can be seen that most of the increases in the ~MeV electron flux at geostationary orbit are associated with the increases in Pc5 wave magnitude and solar wind velocity, with a delay of 1 ~ 2 days. The database and the results of this paper provide a good baseline for further investigating the relation between ULF waves and energetic electron flux.

5. Conclusions

[26] In this paper we examine the relationship between the intensity of Pc4 and 5 ULF pulsations in the inner magnetosphere and the solar wind parameters, based, for the first time, on simultaneous in situ electric and magnetic field measurements. We find that the Pc4 and 5 wave magnitude of the electric field in the inner magnetosphere is better correlated with the solar wind velocity. In contrast, magnetic field measurements show that the dynamic pressure variation has the strongest correlation with ULF wave magnitude. We attribute this effect to a decreased ability of equatorially orbiting spacecraft to detect toroidal mode waves only with magnetic field instruments, and we suggest that electric field measurements near the magnetic equator are optimal in the investigation of Pc4 and Pc5 ULF waves.

[27] This study provides evidence to support that the solar wind velocity is the dominant factor in the generation of Pc4 and 5 waves in the inner magnetosphere over a range of L shells, including geosynchronous orbit, which agrees with most of the ground-based measurements and with earlier satellite-based electric field measurements. The disagreement between the in situ electric and magnetic field measurements presented in this study and also in previous studies suggests that the observation of Pc4 and 5 waves based on only equatorial magnetic field measurements might be misleading in some cases because of the limited capability of magnetic field instruments in measuring fundamental toroidal mode oscillations. It should be noted here that this limitation only applies to in situ equatorial magnetic field measurements but not to ground magnetometer measurements.

[28] By investigating the radial profile of the correlation coefficient between Pc5 ULF wave magnitude and solar wind parameters, we found that for the solar wind dynamic pressure variation, the correlation coefficient starts to decrease between 6 and ~7 R_E and recovers inside of 6 R_E, whereas for the solar wind velocity, the correlation coefficient remains at the same level beyond 5.5 R_E and decrease inside of 5.5 R_E. This is probably because of the existence of the cavity mode turning point in the plasmatrough region for Pc5 ULF waves.

[29] **Acknowledgments.** This work is supported by NASA grants NNX10AQ48G and NAS5-02099. The work by KHG was financially supported by the German Zentrum für Luft-und Raumfahrt under grant 50QP0402. We acknowledge the OMNI group at NASA/Goddard Space Flight Center and NOAA SEC for making solar wind parameters and GOES electron flux data available. This work was also supported by grants from the National Natural Science Foundation of China (40621003 and 40728005). The work by TES was also supported by ΔΠΘ ETAA-1927.

[30] Robert Lysak thanks Mark Engebretson and another reviewer for their assistance in evaluating this paper.

References

Anderson, B. J., and M. J. Engebretson (1995), Relative intensity of toroidal and compressional Pc 3–4 wave power in the dayside outer magnetosphere, *J. Geophys. Res.*, *100*(A6), 9591–9603, doi:10.1029/95JA00132.

Anderson, B. J., M. J. Engebretson, S. P. Rounds, L. J. Zanetti, and T. A. Potemra (1990), A statistical study of Pc 3–5 pulsations observed by the AmMPTE/CCE magnetic fields experiment: 1. Occurrence distributions, *J. Geophys. Res.*, *95*(A7), 10,495–10,523, doi:10.1029/JA095iA07p10495.

Angelopoulos, V. (2008), The THEMIS Mission, *Space Sci. Rev.*, doi:10.1007/s11214-008-9336-1.

Auster, H. U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, doi:10.1007/s11214-008-9365-9.

Baker, G., E. F. Donovan, and B. J. Jackel (2003), A comprehensive survey of auroral latitude Pc5 pulsation characteristics, *J. Geophys. Res.*, *108* (A10), 1384, doi:10.1029/2002JA009801.

Bonnell, J. W., et al. (2008), The Electric Field Instrument (EFI) for THEMIS, *Space Sci. Rev.*, doi:10.1007/s11214-008-9469-2.

Cao, M., R. McPherron, and C. Russell (1994), Statistical study of ULF wave occurrence in the dayside magnetosphere, *J. Geophys. Res.*, *99*(A5), 8731–8753, doi:10.1029/93JA02905.

Dungey, J. W. (1954), Electrodynamics of the outer atmospheres, *Tech. Rep. 69*, Ions. Res. Lab. Pa. State Univ., University Park.

Elkington, S. R., M. K. Hudson, and A. A. Chan (1999), Acceleration of relativistic electron via drift-resonant interaction with toroidal-mode Pc-5 ULF oscillations, *Geophys. Res. Lett.*, *26*, 3273–3276.

Engebretson, M., et al. (1998), The dependence of high-latitude Pc5 wave power on solar wind velocity and on the phase of high-speed solar wind streams, *J. Geophys. Res.*, *103*(A11), 26,271–26,283, doi:10.1029/97JA03143.

Fei, Y., A. A. Chan, S. R. Elkington, and M. J. Wiltberger (2006), Radial diffusion and MHD particle simulations of relativistic electron transport by ULF waves in the September 1998 storm, *J. Geophys. Res.*, *111*, A12209, doi:10.1029/2005JA011211.

Glassmeier, K. H., et al. (1984), Pc5 pulsations and their possible source mechanisms: A case study, *J. Geophys.*, *55*, 108–119.

Glassmeier, K. H., et al. (1999), Magnetospheric field line resonances: A comparative planetology approach, *Surv. Geophys.*, *20*(1), 61–109.

Hudson, M. K., R. E. Denton, M. R. Lessard, E. G. Miftakhova, and R. R. Anderson (2004), A study of Pc-5 ULF oscillations, *Ann. Geophys.*, *22*, 289–302.

Hughes, W. J. (1994), Magnetospheric ULF waves: A tutorial with a historical perspective, in *Solar Wind Source of Magnetosphere Ultralow Frequency Waves*, *AGU Geophys. Monogr.*, *81*, edited by M. J. Engebretson, K. Takahashi, and M. Scholer, 25–43.

Junginger, H., and W. Baumjohann (1988), Dayside long-period magnetospheric pulsations: Solar wind dependence, *J. Geophys. Res.*, *93*(A2), 877–883, doi:10.1029/JA093iA02p00877.

Junginger, H., et al. (1984), A statistical study of dayside magnetospheric electric field fluctuations with periods between 150 and 600 s, *J. Geophys. Res.*, *89*(A7), 5495–5505, doi:10.1029/JA089iA07p05495.

Kabin, K., et al. (2007), Polarization properties of standing shear Alfve'n waves in nonaxisymmetric background magnetic fields, *Ann. Geophys.*, *25*, 815–822.

Kepko, L., and H. E. Spence (2003), Observations of discrete, global magnetospheric oscillations directly driven by solar wind density variations, *J. Geophys. Res.*, *108*(A6), 1257, doi:10.1029/2002JA009676.

Kivelson, M. G., and D. J. Southwood (1986), Coupling of global magnetospheric MHD eigenmodes to field line resonances, *J. Geophys. Res.*, *91*(A4), 4345–4351, doi:10.1029/JA091iA04p04345.

Klimushkin, D. Y., et al. (2004), Toroidal and poloidal Alfvén waves with arbitrary azimuthal wave numbers in a finite pressure plasma in the Earth's magnetosphere, *Ann. Geophys.*, *22*, 267–287.

Kozyreva, O., V. Pilipenko, M. J. Engebretson, K. Yumoto, J. Watermann, and N. Romanova (2007), In search of a new ULF wave index: Comparison of Pc5 power with dynamics of geostationary relativistic electrons, *Planet. Space Sci.*, *55*, doi:10.1016/j.pss.2006.03.013,755-769.

Li, X. (2004), Variations of 0.7–6.0 MeV electrons at geosynchronous orbit as a function of solar wind, *Space Weather*, *2*, S03006, doi:10.1029/2003SW000017.

Li, X., M. Hudson, A. Chan, and I. Roth (1993), Loss of ring current O^+ ions due to interaction with Pc 5 waves, *J. Geophys. Res.*, *98*(A1), 215–231, doi:10.1029/92JA01540.

Li, X., et al. (2001), Quantitative prediction of radiation belt electrons at geostationary orbit based on solar wind measurements, *Geophys. Res. Lett.*, *28*(9), 1887, doi:10.1029/2000GL012681.

Liu, W. L., et al. (2009), Electric and magnetic field observations of Pc4 and Pc5 pulsations in the inner magnetosphere: A statistical study, *J. Geophys. Res.*, *114*, A12206, doi:10.1029/2009JA014243.

Mathie, R. A., and I. R. Mann (2000), A correlation between extended intervals of ULF wave power and storm-time geosynchronous relativistic electron flux measurements, *Geophys. Res. Lett.*, *27*(20), 3261–3264, doi:10.1029/2000GL003822.

Mathie, R. A., and I. R. Mann (2001), On the solar wind control of Pc5 ULF pulsation power at mid-latitudes: Implications for MeV electron acceleration in the outer radiation belt, *J. Geophys. Res.*, *106*(A12), 29,783–29,796, doi:10.1029/2001JA000002.

Mozer, F. S. (1973), Analyses of techniques for measuring electric fields in the magnetosphere, *Space Sci. Rev.*, *14*, 272.

Paulikas, G. A., and J. B. Blake (1976), Modulation of trapped energetic electrons at 6.6 R_E by the interplanetary magnetic field, *Geophys. Res. Lett.*, *3*(5), 277, doi:10.1029/GL003i005p00277.

Posch, J. L., et al. (2003), Characterizing the long-period ULF response to magnetic storms, *J. Geophys. Res.*, *108*(A1), 1029, doi:10.1029/2002JA009386.

Pu, Z. Y., and M. G. Kivelson (1983), Kelvin-Helmholtz instability at the magnetopause: Solution for compressible plasmas, *J. Geophys. Res.*, *88*(A2), 841–852, doi:10.1029/JA088iA02p00841.

Rae, I. J., et al. (2005), Evolution and characteristics of global Pc5 ULF waves during a high solar wind speed interval, *J. Geophys. Res.*, *110*, A12211, doi:10.1029/2005JA011007.

Rankin, R., K. Kabin, and R. Marchand (2006), Alfve'nic field line resonances in arbitrary magnetic field topology, *Adv. Space Res.*, *38*, 1720–1729.

Rostoker, G., S. Skone, and D. N. Baker (1998), On the origin of relativistic electrons in the magnetosphere associated with some geomagnetic storms, *Geophys. Res. Lett.*, *25*(19), 3701–3704, doi:10.1029/98GL02801.

Sakurai, T., et al. (1999), Dayside magnetopause Pc 3 and Pc 5 ULF waves observed by the GEOTAIL Satellite, *Earth Planets Space*, *51*, 965–978.

Sarris, T. E., et al. (2009a), Characterization of ULF pulsations by THEMIS, *Geophys. Res. Lett.*, *36*, L04104, doi:10.1029/2008GL036732.

Sarris, T. E., A. N. Wright, and X. Li (2009b), Observations and analysis of Alfven wave phase mixing in the Earth's magnetosphere, *J. Geophys. Res.*, *114*, A03218, doi:10.1029/2008JA013606.

Schäfer, S., et al. (2007), Spatial and temporal characteristics of poloidal waves in the terrestrial plasmasphere: A CLUSTER case study, *Ann. Geophys.*, *25*(4), 1011–1024.

Schervish, M. J. (1996), *P* values: What they are and what they are not, *Am. Stat.*, *50*(3), 203–206, doi:10.2307/2684655.

Singer, H. J., and M. G. Kivelson (1979), The latitudinal structure of Pc 5 waves in space: Magnetic and electric field observations, *J. Geophys. Res.*, *84*(A12), 7213–7222, doi:10.1029/JA084iA12p07213.

Singer, H., et al. (1977), Evidence for the control of Pc 3,4 magnetic pulsations by the solar wind velocity, *Geophys. Res. Lett.*, *4*(9), 377–379, doi:10.1029/GL004i009p00377.

Singer, H. J., W. J. Hughes, and C. T. Russell (1982), Standing hydromagnetic waves observed by ISEE 1 and 2: Radial extent and harmonic, *J. Geophys. Res.*, *87*(A5), 3519, doi:10.1029/JA087iA05p03519.

Southwood, D. J. (1968), The hydromagnetic stability of the magnetopause boundary, *Planet. Space Sci.*, *16*, 587–605.

Southwood, D. J., and W. J. Hughes (1983), Theory of hydromagnetic waves in the magnetosphere, *Space Sci. Rev.*, *35*, 301–366.

Takahashi, K., and B. Anderson (1992), Distribution of ULF energy ($f <$ 80 mHz) in the inner magnetosphere: A statistical analysis of AMPTE/CCE magnetic field data, *J. Geophys. Res.*, *97*(A7), 10,751–10,773, doi:10.1029/92JA00328.

Takahashi, K., and A. Y. Ukhorskiy (2007), Solar wind control of Pc5 pulsation power at geosynchronous orbit, *J. Geophys. Res.*, *112*, A11205, doi:10.1029/2007JA012483.

Takahashi, K., and A. Y. Ukhorskiy (2008), Timing analysis of the relationship between solar wind parameters and geosynchronous Pc5 amplitude, *J. Geophys. Res.*, *113*, A12204, doi:10.1029/2008JA013327.

Ukhorskiy, A. Y., K. Takahashi, and B. J. Anderson (2005), Impact of toroidal ULF waves on the outer radiation belt electrons, *J. Geophys. Res.*, *110*, A10202, doi:10.1029/2005JA011017.

Ukhorskiy, A. Y., B. J. Anderson, K. Takahashi, and N. A. Tsyganenko (2006), The impact of ULF oscillations in solar wind dynamic pressure on the outer radiation belt electrons, *Geophys. Res. Lett.*, *33*, L06111, doi:10.1029/2005GL024380.

Vennerstrøm, S. (1999), Dayside magnetic ULF power at high latitudes: A possible long-term proxy for the solar wind velocity?, *J. Geophys. Res.*, *104*(A5), 10,145–10,157, doi:10.1029/1999JA900015.
Waters, C., B. Harrold, F. Menk, J. Samson, and B. Fraser (2000), Field line resonances and waveguide modes at low latitudes: 2. A model, *J. Geophys. Res.*, *105*(A4), 7763–7774, doi:10.1029/1999JA900267.
Zhu, X., and M. Kivelson (1988), Analytic formulation and quantitative solutions of the coupled ULF wave problem, *J. Geophys. Res.*, *93*(A8), 8602–8612, doi:10.1029/JA093iA08p08602.
Zong, Q.-G., et al. (2007), Ultralow frequency modulation of energetic particles in the dayside magnetosphere, *Geophys. Res. Lett.*, *34*, L12105, doi:10.1029/2007GL029915.
Zong, Q.-G., et al. (2009), Energetic electron response to ULF waves induced by interplanetary shocks in the outer radiation belt, *J. Geophys. Res.*, *114*, A10204, doi:10.1029/2009JA014393.

V. Angelopoulos, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Boulder, CO, USA.

J. Bonnell, Institute of Geophysics and Planetary Physics, University of California-Los Angeles, Los Angeles, CA, USA.

R. Ergun, W. Liu, X. Li, and T. E. Sarris, Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, Boulder, CO, USA. (liu@lasp.colorado.edu)

K. H. Glassmeier, IGEP, Technical University of Braunschweig, and MPS, Katlenburg-Lindau, Germany.