JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, A03219, doi:10.1029/2010JA016197, 2011

Source region for whistlers detected at Rothera, Antarctica

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Received 8 October 2010; revised 23 November 2010; accepted 28 December 2010; published 23 March 2011.

[1] The accepted mechanism for whistler generation implicitly assumes that the causative lightning stroke occurs within reasonable proximity to the conjugate foot point of the guiding magnetic field line and that nighttime whistlers are prevalent because of low transionospheric attenuation. However, these assumptions are not necessarily valid. In this study we consider whistler observations from Rothera, a station on the Antarctic Peninsula, and contrast their occurrence with global lightning activity from the World Wide Lightning Location Network. The correlation of one-hop whistlers observed at Rothera with global lightning yields a few regions of significant positive correlation. The most probable source region was found over the Gulf Stream, displaced slightly equatorward from the conjugate point. The proximity of the source region to the conjugate point is in accord with the broadly accepted whistler production mechanism. However, there is an unexpected bias toward oceanic lightning rather than the nearby continental lightning. The relationship between the diurnal pattern of the Rothera whistlers and the conjugate lightning exhibits anomalous features which have yet to be resolved: the peak whistler rate occurs when it is daytime at both the source and the receiver and when source lightning activity is at its lowest. As a result, we propose that preferential whistler-wave amplification in the morning sector is a possible cause of the high whistler occurrence, although this does not account for the bias toward oceanic lightning.

Citation: Collier, A. B., J. Lichtenberger, M. A. Clilverd, C. J. Rodger, and P. Steinbach (2011), Source region for whistlers detected at Rothera, Antarctica, *J. Geophys. Res.*, *116*, A03219, doi:10.1029/2010JA016197.

1. Introduction

[2] The mechanism evolved by *Barkhausen* [1930], *Eckersley* [1935], and *Storey* [1953] is generally acknowledged to account for the production of whistlers observed on the ground. Lightning strokes produce sferics, which are intense impulses of electromagnetic energy with a spectrum dominated by the very low frequency (VLF) range. Some fraction of this energy penetrates up through the ionosphere and travels through the magnetospheric plasma in the whistler mode. For longitudinal propagation the whistler mode dispersion relation is

$$\mu^2 = \frac{\Pi^2}{\omega(\Omega - \omega)}, \tag{1}$$

where μ is the refractive index, Π and Ω are the plasma- and gyrofrequency, respectively, and ω is the wave frequency. Since the refractive index depends on frequency, the whistler mode is dispersive. The signal therefore develops a characteristic frequency-time structure which is determined by the electron density and magnetic field strength along the propagation path. The effect of (1) is commonly characterized by the dispersion, $D_0 = T\sqrt{f}$, where $\omega = 2\pi f$ and T is the time delay of the signal at frequency f.

[3] Whistler mode waves are approximately guided by the Earth's static magnetic field. If, in addition, the waves are trapped in a duct of either enhanced or depleted plasma density [e.g., *Béghin et al.*, 1985] then the wave normal is confined to a relatively small range of angles with respect to the magnetic field [*Walker*, 1976]. It has been established that the majority of lightning strokes generate an upgoing, incipient whistler detectable on Low Earth Orbit (LEO) satellites, but only a relatively small fraction of these become ducted [e.g., *Hughes*, 1981; *Li et al.*, 1991; *Hughes and Rice*, 1997; *Holzworth et al.*, 1999]. In the absence of a duct the wave normal deviates progressively from the magnetic field. Due to the increased presence of ions at lower altitudes, the wave is eventually reflected at the lower hybrid resonance (LHR) frequency, generally at some significant height above the ionosphere [*Walter and Angerami*, 1969]. In order for whistlers to pierce the ionosphere from above and enter the Earth-ionosphere waveguide (EIWG), they must have a wave normal which lies within the narrow vertical transmission cone [*Hayakawa*, 1974]. This is most readily achieved closer to the magnetic poles where the magnetic field is highly inclined, yet readily achieved at

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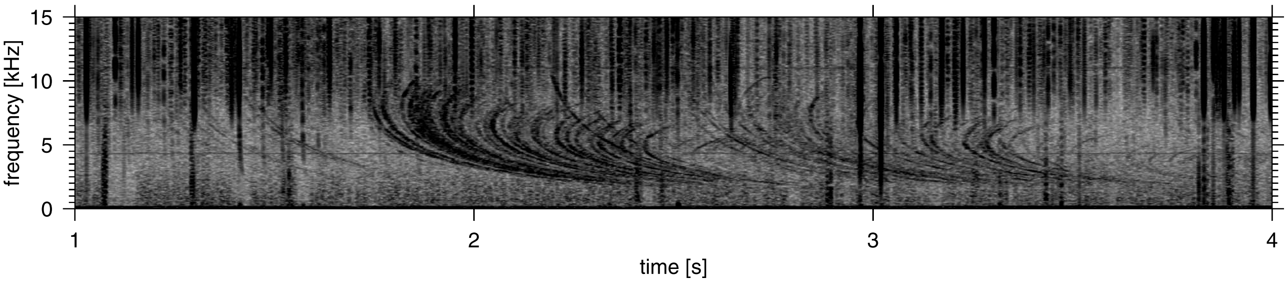


Figure 1. Whistlers recorded at Rothera at 2120:48 UTC on 23 June 2008.

lower latitudes. Wave normals outside the transmission cone undergo total internal reflection at the ionosphere. The presence of a duct is thus necessary, but not sufficient, to ensure transmission of a whistler to the ground.

[4] The causative lightning strokes for whistlers observed at a given location are traditionally thought to occur in the vicinity of the conjugate point. However, in light of the fact that VLF propagation in the EIWG incurs little attenuation (a few dB/Mm), this assumption is somewhat tenuous. A given whistler can be observed at different locations separated by up to at least ~1000 km [*Storey*, 1953; *Crary et al.*, 1956]. Furthermore it has been demonstrated using data from rockets [*Holzworth et al.*, 1999] and LEO satellites [*Chum et al.*, 2006; *Santolik et al.*, 2009] that a sferic can penetrate the ionosphere up to 1000 km from the source lightning stroke. *Fiser et al.* [2010] found that the mean whistler amplitude measured in LEO decreased monotonically with horizontal distance from the lightning stroke up to around 1000 km. It thus seems feasible that the causative lightning can be significantly displaced with respect to the receiver's conjugate point.

[5] Two recent publications [*Collier et al.*, 2009, 2010] have explored the distribution of lightning strokes leading to whistlers at Tihany, Hungary (46.89°N 17.89°E, L = 1.80) and Dunedin, New Zealand (45.78°S 170.47°E, L = 2.75). The causative lightning strokes for Tihany whistlers appeared to occur within a few hundred kilometers of the conjugate point, which is located over the Indian Ocean near the east coast of South Africa, a region of appreciable lightning activity [*Collier et al.*, 2009]. The conjugate point of Dunedin is located close to the Aleutian Islands, a region of extremely sparse lightning activity. It was found that the causative lightning strokes for whistlers observed at Dunedin were generally located on the west coast of Central America, a significant distance (>5 Mm) from the conjugate point [*Collier et al.*, 2010]. The conclusions for Tihany and Dunedin appear to represent two opposite extremes for whistler formation: causative lightning around the conjugate point when conjugate lightning is abundant, and a distant source region when conjugate lightning is sparse.

[6] Whistler analysis provides the electron number density along the path taken by the signal through the plasmasphere. In principle this allows the determination of a plasmaspheric electron density profile as a function of L [e.g., *Sazhin et al.*, 1992]. The manual extraction of the salient information from whistler data is traditionally an extremely arduous undertaking, which is likely to account for it not becoming a routine procedure for plasmaspheric diagnostics. However, with the recent development of an automated technique [*Lichtenberger et al.*, 2008, 2010], systematic whistler analysis has become feasible.

2. Data and Analysis

[7] Broadband VLF observations were made at Rothera, Antarctica (67.57°S 68.12°W, L = 2.71), where the local time is UTC − 4 h. Whistler traces were identified in this data using an Automated Whistler Detector (AWD) system [*Lichtenberger et al.*, 2008]. An example of events identified by the Rothera AWD is plotted as a spectrogram in Figure 1. The AWD employs a two dimensional image correlation technique, using a template whistler with a nose frequency of 20 kHz and covering the dispersion range D_0 = 40–100 $s^{1/2}$, which includes only single hop whistlers. Between 13 May 2008 and 30 December 2009 (a period of 597 days, for which AWD was operational on 591 days), 10.8 million whistlers were detected at Rothera. This corresponds to an average rate of 18309 whistlers per day. This should be juxtaposed with the 575 and 504 whistlers per day observed at Tihany and Dunedin, respectively. It is feasible that the mean rate calculated for Rothera was biased by the presence of a few prodigious days. Indeed, the most active day at Rothera, 27 July 2009, had 186995 whistlers, more than ten times the average rate. Daily whistler rates are plotted alongside representative geomagnetic indices in Figure 2. The high degree of variability in lightning occurrence largely masks the effects of geomagnetic activity. However, the day of highest whistler activity follows a few days after the largest geomagnetic storm in this interval (daily average Dst = −48 nT) on 22 July 2009. This supports the idea that whistlers may be more commonly observed in association with geomagnetic activity, which may be related to the prevalence and efficiency of ducts or the amplification of whistlers by unstable electron distributions [*Thomson et al.*, 1997]. It is also evident from the histogram of daily whistler rates plotted in Figure 3 that this distribution is severely skewed. However, excluding the extreme days by retaining only those with rates below the 95% quantile (which corresponds to 84007 whistlers per day), the mean rate is only reduced to 15372 whistlers per day, which is still vastly in excess of the rates at Tihany and Dunedin.

2.1. Whistlers

[8] The composite diurnal and seasonal distributions of the Rothera whistlers are plotted in Figure 4. It is apparent that the majority of whistlers are observed during July and

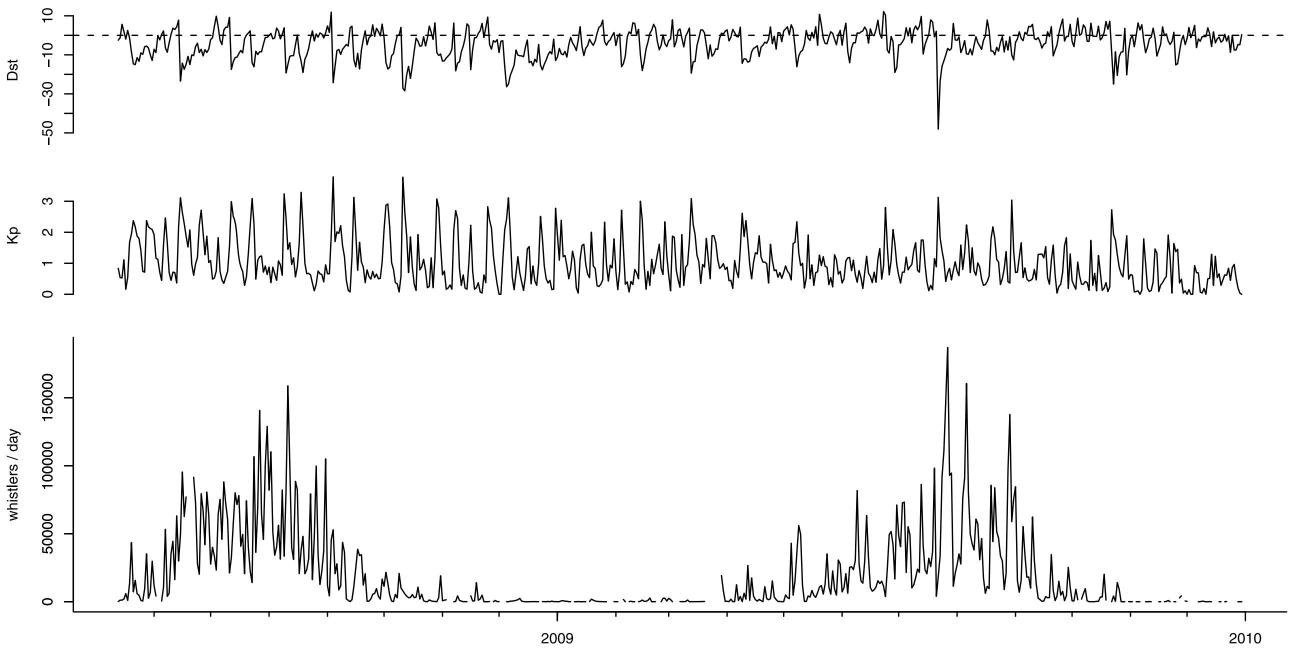


Figure 2. Daily whistler rate at Rothera as observed by the AWD compared to *Kp* and *Dst* indices.

August, which is the peak of the Northern Hemisphere Summer, when lightning is most profuse [*Christian et al.*, 2003, Figure 7b]. The solid curve in Figure 4 indicates the time at which the solar terminator passes over Rothera at an altitude of 100 km. For almost 4 months during the Southern Hemisphere Summer the lower ionosphere above Rothera is in perpetual daylight and this is a period of low whistler activity. During the Southern Hemisphere Winter the duration of illumination is as little as 7 h per day. During this period whistlers are frequently observed at Rothera between around 0700 UTC and 2400 UTC with a diurnal maximum at approximately 1200 UTC, or 0800 LT, which is around sunrise at 100 km altitude over Rothera and a couple of hours after sunrise over the conjugate point. The peak then declines until about 1400 UTC, after which a tail of activity persists until 0000 UTC, which is after sunset over Rothera. Thus both ends of the field line are illuminated at the time of maximal whistler production. Furthermore, the diurnal peak extends on either side of sunrise, so that illumination of the ionosphere above Rothera appears not to have an influence on whistler incidence. A morning maximum in the frequency of whistler occurrence contradicts the conventional diurnal pattern, where most whistlers are generally observed on the ground at night [*Helliwell*, 1965; *Collier et al.*, 2006,

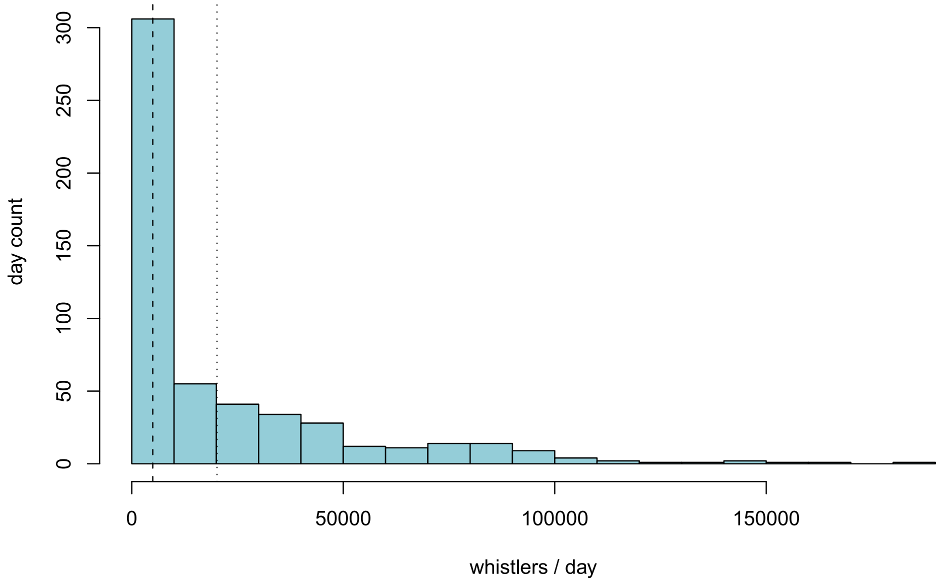


Figure 3. Empirical distribution of the number of whistlers observed per day at Rothera. The ordinate reflects the number of days on which a given whistler frequency was observed. The median (dashed) and mean (dotted) daily rates are indicated by vertical lines.

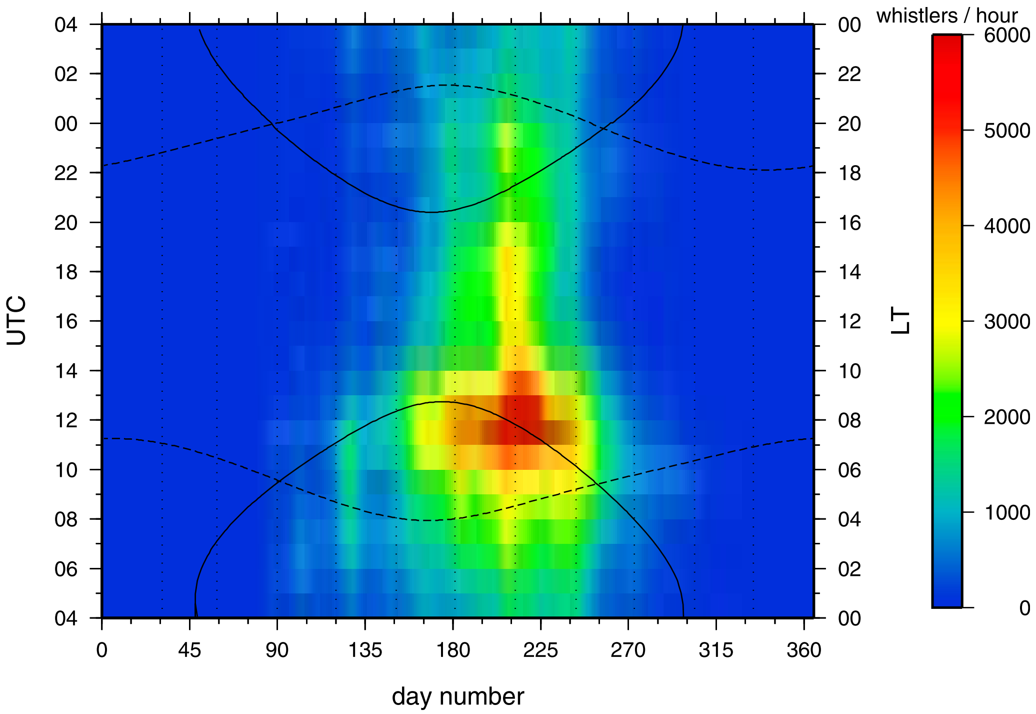


Figure 4. Average whistler occurrence rates at Rothera as a function of UTC/LT and day number. Solid curves indicate the passage of the terminator at an altitude of 100 km over Rothera, while the dashed curves apply to the conjugate point.

2009]. However, as illustrated by *Rodger et al.* [2008], not all locations support the conventional model, with whistler rates in Dunedin, for instance, exhibiting a peak near local noon.

2.2. Lightning

[9] The conjugate point for Rothera is at 42.74°N 70.66°W, near Boston, Massachusetts. The locations of Rothera, Tihany and Dunedin as well as their respective conjugate points are indicated in Figure 5. Global lightning flash rates determined from satellite observations [*Christian et al.*, 2003] indicate that the intensity of lightning activity in the immediate vicinity of Rothera's conjugate is comparable to that near Tihany's conjugate, yet the whistler rate at these two sites differs enormously. However, Rothera's conjugate is not too distant from large regions of intense lightning activity over the Gulf Stream and extending from Texas to Florida, a zone roughly 1500 km across, where the lightning flash rate is roughly two times higher than over the adjacent ocean.

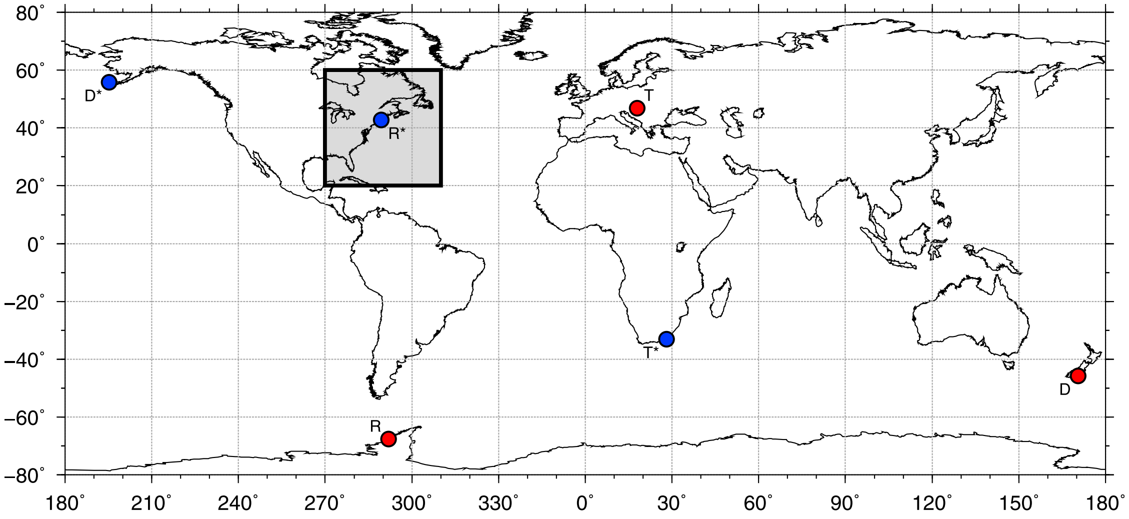
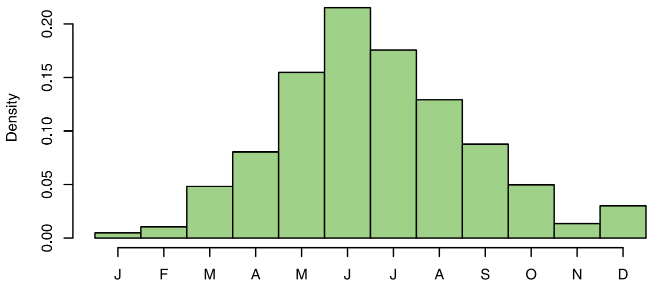
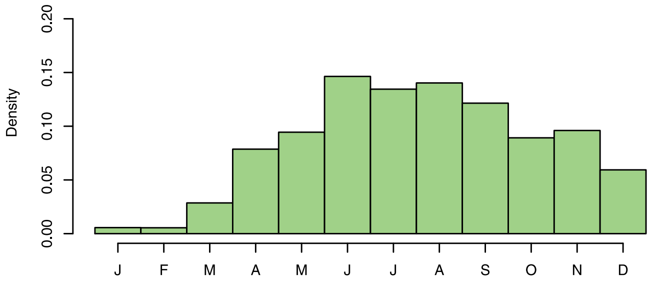


Figure 5. Locations of Rothera (R), Tihany (T), and Dunedin (D) indicated by red dots and their conjugate points represented by blue dots and labeled with stars.



(a) land



(b) ocean

Figure 6. Seasonal variation in relative lightning activity reported by WWLLN over ocean and land in the region from 20°N to 60°N and 90°W to 50°W, indicated by the grey block in Figure 5. The plots represent the fraction of the total annual lightning activity associated with each of the months.

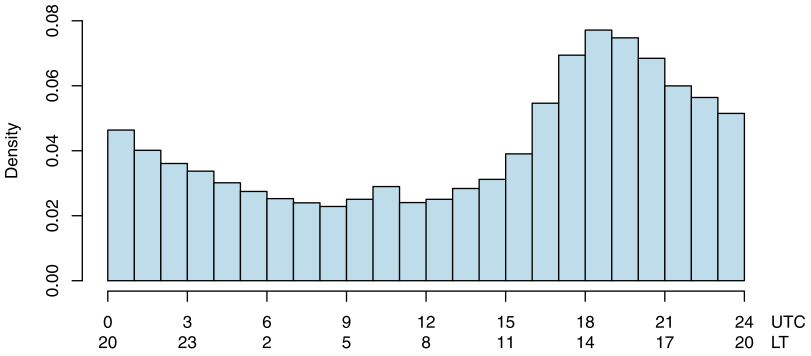
[10] Lightning data were acquired from the World Wide Lightning Location Network (WWLLN). WWLLN operates in the VLF range, where attenuation is low, and is thus able to detect global lightning activity with only a limited number of receivers [*Dowden et al.*, 2002, 2008; *Lay et al.*, 2004]. WWLLN is capable of identifying cloud-to-ground (CG), cloud-to-cloud (CC), and intracloud (IC) lightning discharges, but does not distinguish between them [*Lay et al.*, 2004; *Rodger et al.*, 2005a, 2006]. However, it appears that WWLLN is more sensitive to CG discharges [*Lay et al.*, 2007] and as a result of the coincidence algorithm employed by WWLLN, the network is biased toward more intense lightning discharges. *Lay et al.* [2004], in a case study of lightning over Brazil, observed that the mean peak current of WWLLN events was between 70 and 80 kA, while *Dowden et al.* [2008] found that strokes with peak current less than 25 kA were seldom identified by WWLLN. The apparent peak current threshold results in a global detection efficiency of ~5–6% for all lightning strokes and ~15% for CG strokes [*Rodger et al.*, 2009]. *Abarca et al.* [2010] compared 3 years of WWLLN data over the contiguous United States to the corresponding National Lightning Detection Network (NLDN) data, finding that the detection efficiency for CG flashes in the vicinity of Rothera's conjugate point improved from 3.9% to 10.3% between 2006 and 2009, and confirming the relationship of detection efficiency to lightning peak current and polarity. The WWLLN detection efficiency in that region is as high as 35% for the most intense discharges [*Abarca et al.*, 2010]. Despite this bias toward more intense discharges, comparison of WWLLN with other lightning detection systems has established that it still provides a representative reflection of global lightning activity. Refinements to the location algorithm and the installation of additional receivers in the network have resulted in consistent improvements in the sensitivity of WWLLN and consequently the total number of lightning strokes reported. From 2005 to 2009 the total number of discharges identified rose from 39 to 115 million per year. This has also been associated with appreciable progress in detection efficiency when contrasted with regional commercial lightning detection networks. For example, comparison of WWLLN data with the New Zealand Lightning Detection Network (NZLDN) over the same period shows detection efficiencies have improved from 3.3% to 18.3% for all lightning, and from 12.7% to 46.7% for intense lightning discharges (absolute current > 50 kA).

[11] Figure 6 presents the seasonal distribution of WWLLN lightning activity in the region 20°N to 60°N and 90°W to 50°W, which is roughly centered on Rothera's conjugate point, divided into contributions from strokes occurring over land and the adjacent ocean. Consistent with the findings of *Collier et al.* [2009, 2010] there is some agreement between the seasonal variation in whistler occurrence at Rothera and lightning activity around the conjugate point, although the lightning peak, which is centered in June, precedes the whistler peak by 1 month. Additionally, the whistler peak occurs during the time of declining lightning activity over land in the conjugate region, suggesting a limited correlation between the two.

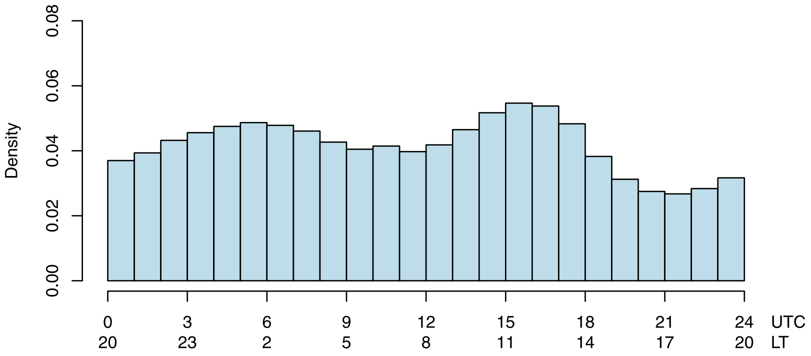
[12] According to *Lay et al.*'s [2007] analysis of WWLLN data, lightning activity in North America has a rather narrow diurnal peak at around 1900 LT, which corresponds to 2300 UTC on the east coast and 0300 UTC on the west coast. The diurnal pattern of WWLLN lightning around the conjugate point is displayed in Figure 7. It is evident that over land there is a pronounced midafternoon maximum at 1400 LT, with a broad minimum centered on around 0500 LT. Although *Abarca et al.* [2010] reported that WWLLN failed to capture the diurnal cycle, it is apparent that the diurnal pattern in Figure 7a is consistent with expectations. The oceanic lightning is described by a weakly bimodal distribution with two lesser peaks at 0100 LT and 1100 LT. These two peaks do not differ significantly from the diurnal mean, the maximum variation being 35.1% over the ocean as opposed to 79.1% over land. *Lay et al.* [2007] also found two broad, shallow peaks in oceanic lightning activity. The small diurnal variation over the ocean can be attributed to the high thermal inertia of water which dampens the daily changes in sea surface temperature. Figure 7 shows that in the region of interest (shown by the box in Figure 5) there are about equal amounts of lightning on land and ocean that could contribute to the Rothera whistler rates.

2.3. Correlation Analysis

[13] Following the technique described by *Collier et al.* [2009, 2010], the capability of a given region of the globe to produce whistlers was assessed by performing a correlation between lightning occurrence on a 1° by 1° spatial grid and whistler incidence at Rothera. The period between



(a) land



(b) ocean

Figure 7. Diurnal variation in relative lightning activity reported by WWLLN over ocean and land in the region from 20°N to 60°N and 90°W to 50°W, indicated by the grey block in Figure 5. The plots represent the fraction of the total diurnal lightning activity associated with each hour of the day.

13 May 2008 and 30 December 2009 was divided into $\Delta t =$ 1 min intervals. The number of events during each interval was then determined. Of the 858240 time intervals, 35.9% contained whistlers. Although *Collier et al.* [2009, 2010] reduced the lightning and whistler counts to Boolean values, both WWLLN and AWD operated in a consistently reliable fashion throughout the period of this analysis and it was thus not necessary to accommodate short-term changes in the efficacy of either system. Total event counts were thus used for the correlation analysis.

3. Results

3.1. Conventional Technique

[14] Figure 8 displays the correlation between the whistler sequence at Rothera and the lightning sequence in each of the spatial grid cells. Data are only plotted for cells in which the correlation is significant. The requirement of statistical significance was in part imposed in order to clarify the data presented in Figure 8 and eliminated much spurious detail. It is immediately evident that the maximal correlation is to be found in a narrow band off the east coast of North America, somewhat further south than the conjugate point, but corresponding to the location of the Gulf Stream. There are also regions of high correlation located further a field, principally over Southeast Asia and off the west coast of Central America.

[15] By virtue of the enormous disparity between the whistlers rate at Rothera and the frequency of WWLLN lightning in the three tropical chimney regions, it might be expected that a simple correlation analysis would favor these regions of prolific lightning. Yet Figure 8 indicates that this is, in fact, not the case. South America, Central Africa and much of the Maritime Continent are actually anticorrelated with Rothera whistlers. This results from the fact that, although there are bound to be numerous coincidental occurrences of lightning within these regions during the period of maximal whistler activity (yielding a positive correlation), the lightning within these tropical regions is perennial and there is just as much activity during the period of reduced whistler activity (contributing a negative correlation).

[16] The range of correlation coefficients depicted in Figure 8 is relatively small, only extending from −0.042 to 0.109. Certainly these are not values which would normally be reported with much fanfare! Even the maximal positive value corresponds to a mutual variance of only 1.2%. The reason for this is the disparate occurrence frequency of the two phenomena under consideration: whereas on average 18309 whistlers per day are observed at Rothera, roughly 86000 lightning flashes occur per day within 1000 km of the conjugate point (based on an average flash rate density of ~10 $\text{km}^{-2}\ \text{yr}^{-1}$ from *Christian et al.* [2003]). Taking into account the expected flash multiplicity, the number of

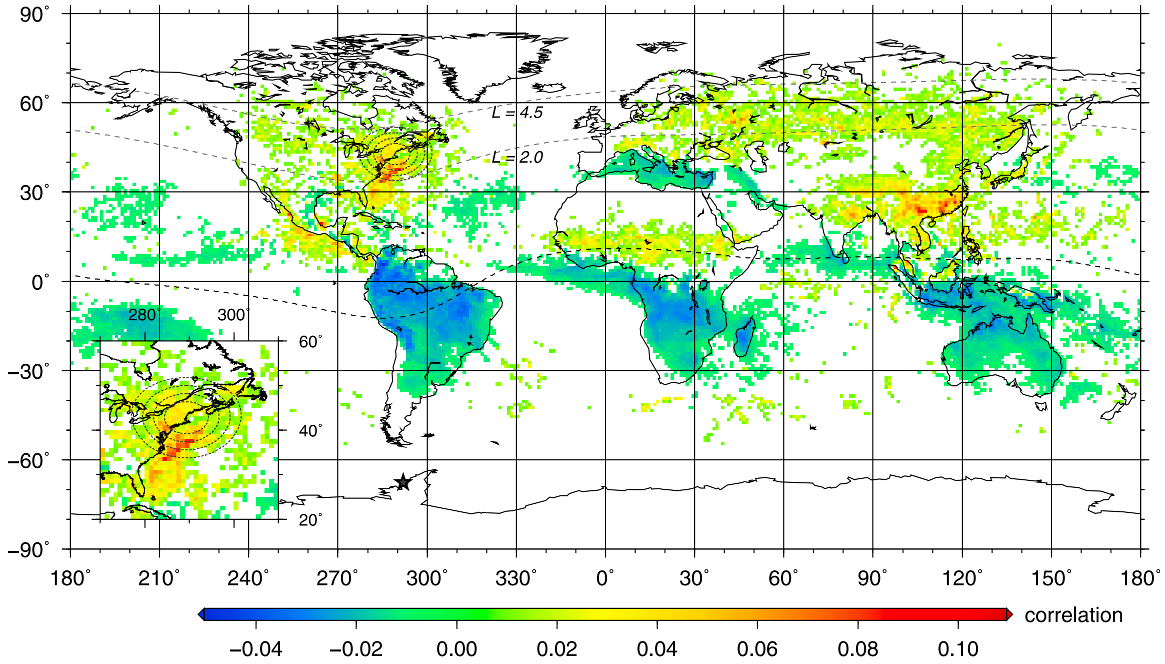


Figure 8. Correlation between whistler observations at Rothera, Antarctica, and global lightning strokes for the period from 13 May 2008 to 30 December 2009 with Δt = 1 min. Data are only plotted in cells for which the correlation is statistically significant. The geomagnetic equator and the Northern Hemisphere L = 2.0 and 4.5 contours are indicated by dashed curves. The location of Rothera is indicated by a star. The conjugate point is surrounded by circles at intervals of 200 km.

lightning strokes around the conjugate point exceeds the number of whistlers by an order of magnitude or more. An analogous estimate for Tihany and Dunedin indicates that at these locations the number of lightning strokes per whistler is even higher. Naturally, taking into account the imperfect efficiency of WWLLN, the inequality between the whistler and flash rates is appreciably diminished, yet the general conclusion still holds. Partitioning of the lightning data onto the 1° by 1° spatial grid further reduces the correlation coefficient: a coarser grid naturally results in improved correlation but has poorer spatial resolution. Here it should be noted that *Collier et al.* [2009, 2010] employed a 3° by 3° grid and achieved a comparable range of correlations, indicating the relative strength of the correlation between Rothera whistlers and conjugate lightning.

3.2. Direct Technique

[17] Figure 9 displays an analogous result to that in Figure 8 but obtained using a more direct algorithm. A time window extending from 1.3 s to 0.2 s prior to each whistler is considered, since this is the period in which the majority of causative lightning strokes are expected to occur. For every grid cell, the number of WWLLN lightning strokes that occurred within this window is counted. This metric is strictly positive and will thus not identify regions with lightning which is anticorrelated with the whistlers on a seasonal basis. The shorter 1.1 s window used also reduces the occurrence of chance coincidence as a result of intense lightning activity in some areas. Although a direct measure of the statistical uncertainty associated with this method is not available, these results have been compared with reference results obtained from a completely randomized sequence of synthetic whistler times. As one would expect, in the latter case the three principle lightning regions are identified as being the source region. Since the distribution displayed in Figure 9 differs appreciably from this, one can conclude that this result does not conform to the null hypothesis. The source region identified using this completely independent technique concurs with that arising in Figure 8.

[18] Perhaps the most striking feature of Figure 9 is the extremely well defined band along the southeast coast of the United States, which strongly suggests that oceanic or coastal lightning, as opposed to continental lightning, is more likely to generate whistlers at Rothera. This effect is also apparent, but somewhat less blatant, in Figure 8. Despite being at a similar distance from the conjugate point, the regions of profuse lightning over land do not appear to make a major contribution to the generation of Rothera whistlers. This poses the tantalizing possibility that the characteristics of oceanic or coastal lightning strokes are in some way more conducive to the production of whistlers. The high conductivity of seawater also reflects the charge distribution, forming an image dipole which effectively doubles the strength of the electric field. It is possible that the orientation or peak current may also play a role. Lightning is certainly appreciably less frequent over the oceans than over land [*Christian et al.*, 2003]. *Lyons et al.* [1998], using data from the NLDN, found that large peak current (>75 kA) negative CG discharges occurred preferentially over the southeastern United States and the coastal waters of the Gulf of Mexico. However, *Abarca et al.* [2010]

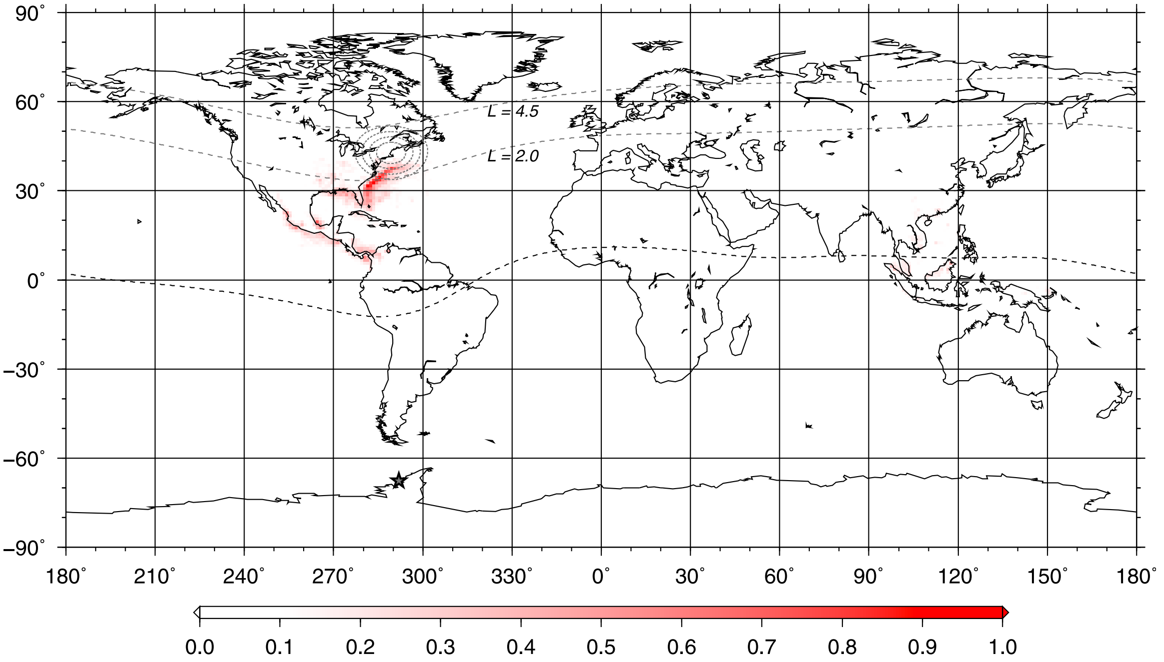
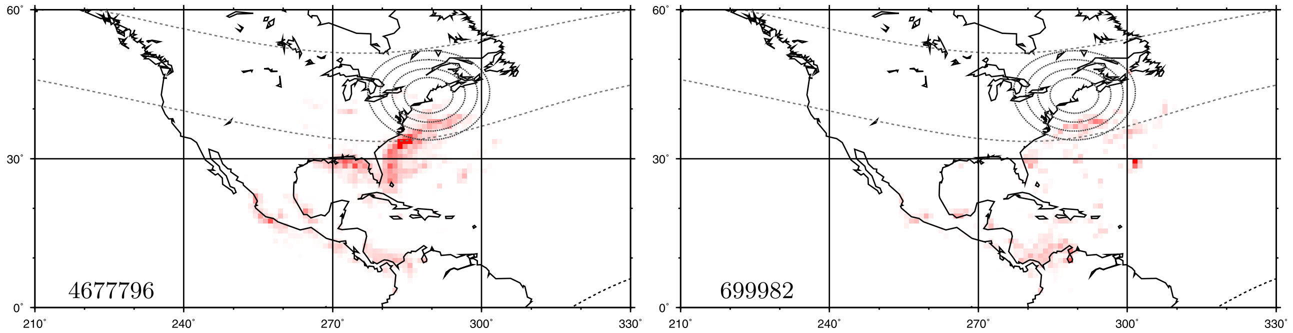


Figure 9. Relationship between whistler observations at Rothera, Antarctica, and global lightning strokes assessed using the direct technique. The color scale has been renormalized to cover the interval from 0 (not significant) to 1 (significant).

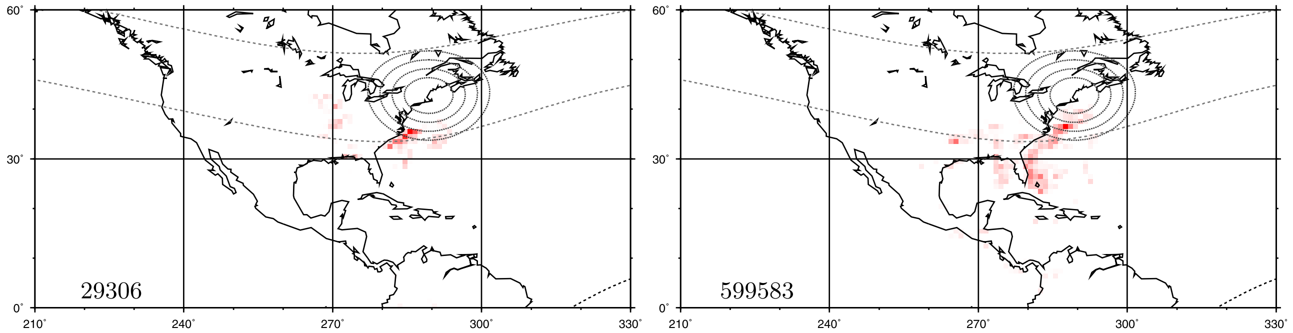
found that WWLLN failed to capture the contrast in lightning activity between continental and oceanic regions around Florida, suggesting that WWLLN was biased in favor of the oceanic lightning due to the higher average peak currents over the oceans.

[19] Figure 10 displays the seasonal variation in the correlation between global lightning and Rothera whistlers derived using the same technique as in Figure 9. With reference to Figure 6 it is apparent that over land the seasonal variation in lightning activity is quite dramatic, peaking in June and almost disappearing between November and February. The seasonal change over the ocean though is less profound, with a roughly constant level of activity from April to December and lower levels between January and March. Consider first Figures 10a and 10e, which reflect the correlations around the conjugate point between June and August in 2 successive years. This is the middle of the Northern Hemisphere Summer and there is abundant lightning over both land and ocean. However, during both years the pattern of correlation is similar, with the majority of positively correlated cells over the ocean, while land areas (specifically Mexico, Cuba, Hispaniola and Florida) generally have a negligible correlation. Figures 10b and 10f characterize two consecutive intervals from September to November, a period during which oceanic lightning is sustained at a relatively high level but that over land is declining. In keeping with the shifting pattern in lightning activity, significant correlation around the conjugate point is predominantly over the ocean. Correlations for December to February are presented in Figure 10c. During the Northern Hemisphere Winter there is only sparse lightning over land and only December has reasonable levels of activity over the ocean. The scarcity of lightning is reflected in the fact that there are far fewer cells which manifest a significant correlation. What is particularly compelling about Figure 10c is the fact that there is almost no contribution from the region of intense lightning activity over Central America. Finally, Figure 10d presents the correlations for March to May, when lightning levels are ascending both over land and ocean. Again the most significantly correlated cells are located over the ocean, with only scattered regions over land. The data in Figure 10 thus demonstrate that the pattern of correlation in Figure 8, derived between 13 May 2008 and 30 December 2009, persists during all seasons, with the areas of positive correlation being observed consistently over the ocean.

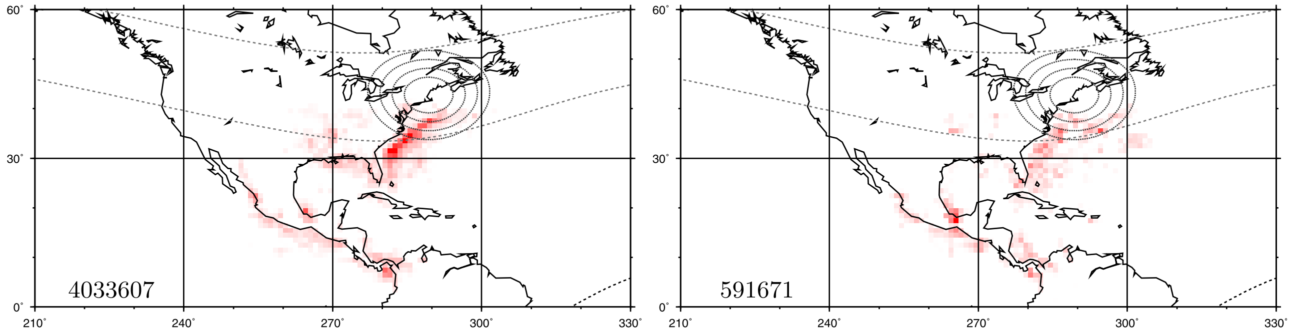
[20] Figure 11 shows a map of seasonal total lightning activity, plotted in geomagnetic coordinates and then reflected across the geomagnetic equator, as a broad indicator of the likely whistler rate. The data is derived from the Lightning Imaging Sensor (LIS)/Optical Transient Detector (OTD) High Resolution Monthly Climatology (HRMC) data set (version 2.2), which includes 5 years of observations from OTD (May 1995 to April 2000) and 8 years from LIS (January 1998 to December 2005). Lightning near the geomagnetic equator is suppressed as the magnetic field mapping becomes unreliable at very low magnetic latitudes. Note that the seasonal plots for Autumn and Spring are very similar to the maps for Summer, especially in the longitudes of the Americas, albeit with ~5 times lower lightning activity. In American longitudes the Winter lightning densities decrease by more than a factor of 10, and also move equatorward. During the Northern Hemisphere Summer there are very high lightning densities across North America, which, as illustrated in Figure 11, mirror across the geomagnetic equator to slightly west of the Antarctic Peninsula. In light of the intensity of conjugate lightning, it is not



(a) 1 June 2008 to 31 August 2008 (b) 1 September 2008 to 30 November 2008



(c) 1 December 2008 to 28 February 2009 (d) 1 March 2009 to 31 May 2009



(e) 1 June 2009 to 31 August 2009 (f) 1 September 2009 to 30 November 2009

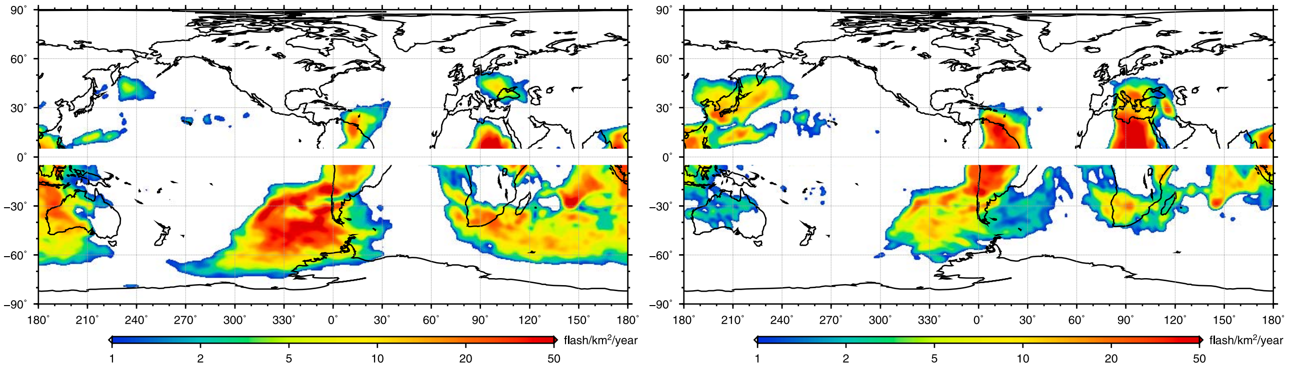
Figure 10. Seasonal variation in correlation between whistler observations at Rothera, Antarctica, and global lightning activity. The color scale is the same as that in Figure 9. The number of whistlers observed during each season is indicated at the bottom left of each panel.

surprising that the whistler rates from Rothera are considerably higher than Tihany or Dunedin, and peak in the Northern Hemisphere Summer. However, while the North American lightning decreases by only ~5 times in Autumn, the whistler rates drop by a factor of 10 or more, and remain very low outside of the Summer season. The seasonal variation of North American lightning is not, therefore, the primary driver for the variation in whistlers detected at Rothera.

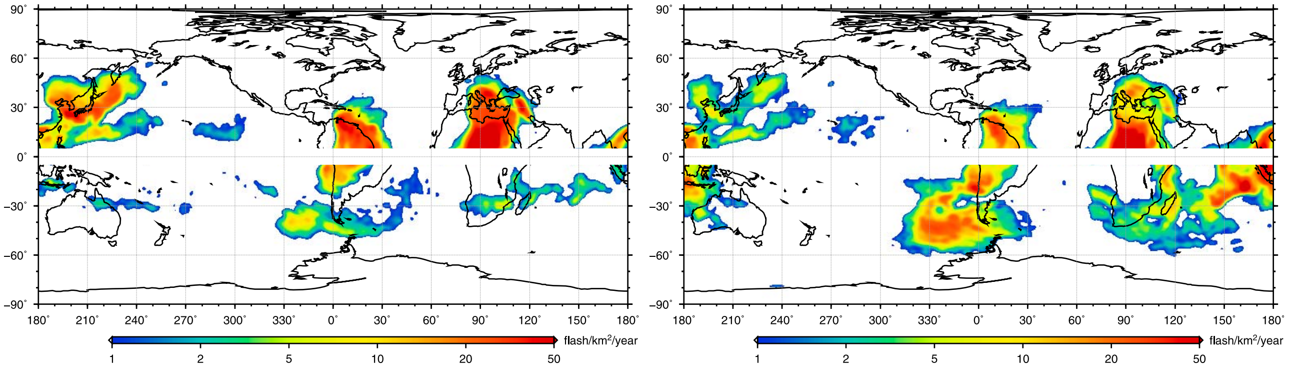
4. Discussion

[21] The results of two distinct analysis techniques have been presented. One relies on a statistical correlation between global lightning and whistlers, not taking into account any of the requirements of causality. In contrast the direct technique only considers those lightning strokes which occur within a time window which would allow for them to be causally related to a whistler. The principal merit of the latter technique lies in the fact that it employs a physical constraint in selecting those lightning strokes which might feasibly be associated with a given whistler. The statistical technique, on the other hand, is simply based on the relative levels of lightning activity during a period in which whistlers are observed, but has the advantage of providing confidence intervals.

[22] The classical correlation between lightning and whistler activity can be divided into four cases according to the presence or absence of either phenomenon, as illustrated in Table 1. Positive contributions occur in the joint presence



(a) Summer (b) Autumn



(c) Winter (d) Spring

Figure 11. Seasonal (Northern Hemisphere) variation in satellite-observed seasonal lightning activity expressed in flashes km^{-2} yr^{-1}, plotted in geomagnetic coordinates and then reflected across the geomagnetic equator. Each panel is labeled with the Northern Hemisphere season.

or absence of both whistlers and lightning, while negative contributions arise from the presence of one phenomenon in the absence of the other.

[23] Because of the relatively low efficiency of WWLLN it is quite feasible that some of the real causative strokes were not identified by WWLLN and thus do not enter into the calculation of the correlation coefficient. Indeed, there is some evidence that horizontal IC or CC flashes may produce whistlers [*Lichtenberger et al.*, 2005], but these discharges are less often detected by WWLLN as it is strongly biased to the vertical currents found in CG [*Lay et al.*, 2007]. The assumption that the orientation of CG discharges is close to vertical appears, however, to be rather simplistic in light of recent very high frequency (VHF) observations [e.g., *Rison et al.*, 1999; *Hager et al.*, 2010]. The low WWLLN detection efficiency will, of course, also have an impact on the direct method, but in this case simply fails to make a positive contribution rather than inflicting a negative one. However, in these cases, intervals without observed lightning (either of the right hand quadrants in Table 1), could in principle have had lightning activity (the corresponding left hand quadrants), thus changing the sign of the contribution in the classical method. Furthermore, intervals with both lightning and whistlers (the upper left hand quadrant) may also occur by chance due to the relatively large $\Delta t = 1$ min window employed. It is worthwhile noting that while the direct method is applicable to stations which receive a large number of whistlers, for locations with lower whistler frequency, like Tihany or Dunedin, it has only limited utility since the spurious contributions from the three principal tropical lightning areas become comparable to those from the true source region. For these locations only the statistical technique is applicable.

[24] Although there is evidence to suggest that some ducted whistlers originate from lightning strokes poleward of the field line foot point [*Helliwell*, 1965], *Santolik et al.* [2009] found that the majority of fractional-hop whistlers observed on DEMETER entered the ionosphere equatorward of the satellite's magnetic foot point. This is consistent with the data presented in Figure 8 where the potential source region over the Gulf Stream lies equatorward of the conjugate point. There is disagreement in the literature as to whether the coupling from the neutral atmosphere into the ionosphere is more effective when the lightning stroke is poleward [*Helliwell*, 1965] or equatorward [*Strangeways*, 1981] of the magnetic field line. However, the magnetic field around Rothera's conjugate point has an inclination of

Table 1. Schematic Illustration of the Four Cases Contributing to the Classical Correlation Between Whistlers and Lightning

	Lightning	No Lightning
Whistlers	+	−
No whistlers	−	+

69.25°, so that coupling is rather insensitive to the direction of arrival [*Helliwell*, 1965, Figure 3–23].

[25] The anomalous diurnal variation of whistler occurrence at Rothera is inconsistent with the daily pattern of lightning activity near the conjugate point. The principal factors determining the diurnal distribution of Rothera whistlers are likely to be a combination of the spatial and temporal occurrence of lightning, the transparency of the ionosphere, the availability of ducts and wave-particle interactions along the magnetic field line, which may lead to the amplification of even very weak signals.

[26] The fact that the majority of whistlers are observed at Rothera when the conjugate point is in daylight is quite extraordinary. It is conventionally held that the ionosphere is almost opaque to VLF signals during daylight due to significant attenuation in the D region. There is a substantial support in the literature for this idea. Figure 3–35 of *Helliwell* [1965] indicates that at a magnetic latitude of $|\lambda_m| \approx 50°$, the attenuation of a 2 kHz signal due to the ionosphere is 9 dB lower at night than during the day. *Němec et al.* [2008] observed that power line harmonic radiation (PLHR) events, extending over the extremely low frequency (ELF) and lower portion of the VLF range, observed at LEO were significantly less intense during the day. *Fiser et al.* [2010] observed that for a given lightning stroke current, the average whistler power at night was roughly 10 dB higher than during the day. Satellite observations of the transmitted power from a high-output VLF communications transmitter operating at 19.8 kHz were ~1200 times weaker by day than night [*Gamble et al.*, 2008]. Weaker signals during the day are attributed to absorption due to electron-neutral collisions in the lower D region of the ionosphere. However, it appears that the attenuation effects in the D region may be significantly smaller than was once thought [*Tao et al.*, 2010].

[27] If the occurrence of lightning and the transparency of the ionosphere cannot explain the diurnal variation of whistlers at Rothera one is forced to consider either the availability of ducts or wave-particle interactions as possible mechanisms. *Clilverd et al.* [2001], using data from the Antarctic Peninsula for two 10 day periods in June and August 1993, showed that duct occurrence frequency was highest at night, lowest during the day, and had a very small secondary peak during the Winter months at around sunrise (1000–1400 UTC). This pattern of duct occurrence is inconsistent with the diurnal variation in whistler occurrence at Rothera. Thus duct availability cannot explain the diurnal variation of whistler occurrence at Rothera.

[28] Whistlers propagating along magnetic field lines are involved in resonant wave-particle interactions with counter streaming electrons. During the course of these interactions the electrons can lose energy and the waves become amplified. As a result some electrons are scattered, and at the longitudes of America, will be reflected at low altitudes in the Northern Hemisphere, and subsequently precipitate in the Southern Hemisphere close to the Antarctic Peninsula. High rates of Whistler-induced Electron Precipitation (WEP) events have been observed from the Antarctic Peninsula. WEP appear to be triggered by lightning activity in an area over the Gulf Stream, south of the Rothera conjugate point [*Clilverd et al.*, 2002, 2004]. Most of the WEP observed from the Antarctic Peninsula occur from 0700 to 1130 UTC during the late Winter [*Clilverd et al.*, 1999], which is consistent with the timing of the peak in whistler rate. *Rodger et al.* [2005b] identified a range of magnetic latitudes between $|\lambda_m| \approx 45°$ and 60° where the majority of WEP (and thus wave-particle interactions) occurred. Rothera lies in this range, consistent with the idea that wave-particle interactions are playing a significant role in the whistler propagation. This may explain the vastly greater number of whistlers observed at Rothera compared with the low-latitude site at Tihany, despite the comparable level of conjugate lightning activity at the two sites. Thus wave-particle interactions may influence the diurnal variation of whistlers observed at Rothera by providing amplification of the whistler waves.

[29] The dramatic seasonal variation in whistler occurrence at Rothera was illustrated in Figures 2 and 4, where the majority of whistlers were observed during the Northern Hemisphere Summer. This is broadly consistent with the seasonal changes in lightning incidence near to the conjugate point presented in Figure 6. However, the degree of seasonal variability in whistler occurrence far exceeds that of the conjugate lightning, suggesting the influence of factors other than weather. Geomagnetic activity exhibits a well defined semiannual variation, with equinoctial maxima [*Russell and McPherron*, 1973]. However, although the peak whistler rate at Rothera during this survey followed shortly after a geomagnetic storm, there is no evidence of a systematic elevation in whistler rates around the equinoxes. This suggests that, although individual intense storms may enhance whistler activity, the general level of geomagnetic activity is ineffectual.

5. Conclusion

[30] A complete understanding of the generation mechanism for whistlers requires knowledge of the location of the causative lightning stroke. The principal source region for whistlers detected at Rothera is equatorward and westward of the conjugate point. Not only is the longitudinal distribution of lightning in the vicinity of the conjugate point biased toward the west, but a source region to the west is favored due to the asymmetry in zonal propagation conditions, where eastward propagation incurs less attenuation than westward [*Crombie*, 1963]. *Smith et al.* [2010] found that thunderstorms over South America made a larger contribution to the 9.3 kHz VLF/ELF Logger Experiment (VELOX) channel recorded at Halley, Antarctica, than those over Africa, producing a power peak at around 1900 UTC, and attributed this to the east-west VLF propagation asymmetry. This is probably related to the fact that eastward propagation is associated with larger ionospheric reflection coefficients [*Jacobson et al.*, 2009].

[31] At Rothera the causative lightning is located in close proximity to the conjugate point yet the majority of whistlers are observed around and after dawn rather than at night. *Collier et al.* [2009] found that the causative lightning strokes for whistlers observed at Tihany Hungary, were mostly clustered around the conjugate point, but in that case whistlers were most commonly observed during the hours of darkness. The idea that whistlers are an exclusively nocturnal phenomenon because of reduced transionospheric attenuation at night seems not to apply at Rothera. Furthermore, the peak in whistler occurrence occurs when the

conjugate lightning source is at its least active on a seasonal basis, although it should be noted that oceanic lightning does not exhibit a strong diurnal cycle and persists at night and during the morning hours. The diurnal pattern of whistler occurrence at Rothera must thus depend on factors other than the spatial and temporal distribution of the lightning source. Other factors which are likely to influence whistler occurrence are the existence of appropriately located ducts and conditions which are amenable to the amplification of whistler mode signals. Previous work has not shown any significant enhancement of duct occurrence around dawn [*Clilverd et al.*, 2001], but high rates of WEP events have been observed. Thus we conclude that wave-particle interactions are a potential cause of the anomalous dawn peak in whistler rates at Rothera.

[32] We have shown that in the lightning source region close to the conjugate of Rothera there are similar levels of lightning activity on the land and over the ocean. Inexplicably, the correlation between whistler observations at Rothera and lightning activity indicates that the primary source of whistlers is oceanic lightning, with little contribution from lightning on the land. There is evidence to suggest that the proportion of positive CG is higher over the ocean than over land [e.g., *Gill*, 2008], and positive CG discharges are known to expend higher peak currents than negative CG [*Rakov and Uman*, 2003, Figure 4.34]. However, *Orville and Huffines* [2001] observed a dramatic discontinuity between continental United States and the adjacent ocean in the peak current of negative CG first strokes, with events over the ocean having peak currents generally >30 kA. No such discontinuity was apparent for positive CG discharges. An explanation for the oceanic source of Rothera whistlers is thus still unresolved.

[33] In considering the correlations presented here, due consideration must be given to the fact that WWLLN detects only a fraction of all lightning activity and is biased toward larger peak currents. It is also possible that the diurnal variation in VLF propagation conditions and the nonuniform distribution of the WWLLN receivers may bias the lightning locations identified by the network.

[34] **Acknowledgments.** This research was conducted within the framework of a South Africa/Hungary collaboration agreement. The authors are grateful to Brett Delport for assisting with the data analysis. We acknowledge the numerous sites hosting WWLLN (http://www.wwlln.com/) nodes and their efforts in maintaining the consistent global coverage of the network. The authors would like to thank the NASA LIS/OTD science team and the Global Hydrology Research Center (GHRC) (http://ghrc.msfc.nasa.gov/) for collecting and providing the satellite lightning data.

[35] Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

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