Investigating Dunedin Whistlers using Volcanic Lightning

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Whistlers detected at Dunedin, New Zealand are an anomaly: there is little lightning around Dunedin's conjugate point yet whistlers appear in relatively large numbers. These surplus whistlers have consequently inspired investigations into their origins. Dunedin's lightning-sparse conjugate point lies in the Aleutian Islands, a region populated with active volcanoes. Their presence has allowed us to perform a novel analysis: the correlation of whistlers to volcanic lightning. We report on our investigation, which successfully yielded the first observations of 'volcanic whistlers'. It was found that the single July 2008 Mount Okmok eruption had an impressive effect on the number of whistlers at Dunedin. The eruptions at Mount Redoubt in 2009 also caused a sporadic flow of whistlers in Dunedin.

1. Introduction

Whistlers are Very Low Frequency (VLF) electromagnetic emissions that originate from lightning discharges. During a lightning stroke some of the discharged energy may penetrate the ionosphere and enter the magnetosphere. Here the electromagnetic wave, or whistler, will undergo dispersion. Most of the time, whistlers are only roughly aligned with the field lines and and will progressively deviate from these. They thus end up undergoing numerous magnetospheric reflections. If however a whistler enters the magnetosphere at a field-aligned plasma density irregularity, it will be closely guided along the magnetic field lines to the opposite hemisphere. Upon reaching the magnetic conjugate point its small incident angle may allow a portion of the energy of the wave to penetrate the ionosphere at that point. When detected by receivers at ground stations these signals will have acquired a descending tone due to the propagation delay varying with frequency (the dispersive nature of whistlers). The analysis of whistler spectrograms is thus an effective way of sampling the plasmasphere.

The classical model of whistler generation was developed by *Storey* [1953] and suggests that a whistler detected on the ground originates from a lightning discharge in proximity to the magnetic conjugate point. Although this model has been broadly supported by observations, the historical paucity of both lightning and whistler data left many of the details of the model untested. Specifically, the strength of the spatial relationship between the source lightning and the magnetic conjugate point was not known. Studies have since emerged showing that whistlers can travel sub-ionospherically over considerable distances before penetrating the ionosphere (e.g. *Holzworth et al.* [1999] reported sub-ionospheric distances of ∼2500 km).

The World Wide Lightning Location Network (WWLLN) [*Dowden et al.*, 2002] and the Automatic Whistler Detector and Analyzer (AWDA) [*Lichtenberger et al.*, 2008] have provided fresh data which shed additional light on this question. *Collier et al.* [2009] used a correlation technique to explore the relationship between whistlers observed at Tihany, Hungary, and global lightning activity. They found a statistically significant positive correlation in a region of radius ∼ 1000 km centred on Tihany's conjugate point just off the east coast of South Africa, consistent with Storey's model. However, they also found regions of significant correlation further afield, in South America and the Maritime Continent. In a later study, *Collier et al.* [2011] applied the same technique to whistlers observed at Rothera station on the Antarctic Peninsula. Once more, distant regions of positive correlation were found over Central America, Equatorial Africa and the Maritime Continent in addition to the Gulf Stream which is in proximity to the conjugate point.

Using the same technique, *Collier et al.* [2010] considered the correlation of whistlers observed at Dunedin with global lightning activity. Whistlers recorded at Dunedin, New Zealand ($45^\circ\ 47'S$, $170^\circ\ 28'E$, $L = 2.7$) are perplexing. Dunedin's magnetic conjugate point (55.84° N 195.30° E), is situated close to the Aleutian Islands, and is far from any strong lightning activity. Yet the number of whistlers detected at Dunedin is relatively large [*Rodger et al.*, 2009]. Furthermore, the whistler rate at Dunedin peaks during the day [*Rodger et al.*, 2009], despite the fact that whistlers are usually observed at night due to trans-ionospheric absorption. The source of Dunedin's whistlers was thus a conundrum. However, *Collier et al.* [2010] found that Dunedin's whistlers were generally not being generated anywhere near the conjugate point. Instead the lightning-to-whistler correlation was strongest along the west coast of Central and North America, 6000 km away from the conjugate point, confirming the speculation put forward by *Rodger et al.* [2009]. This created uncertainty in the paths the majority of Dunedin whistlers had travelled. *Collier et al.* [2010] discussed two possible paths: (1) by entering a duct in the proximity of the source region and travelling sub-ionospherically across to Dunedin, or (2) by travelling sub-ionospherically across to the Aleutian Islands and entering a direct duct to Dunedin. After considering the attenuation whistlers would suffer along either path, they advocated path (1).

Lightning activity within Dunedin's proposed whistler source region in the Americas is particularly profuse, with around 20 flashes/km^2/year [*Christian et al.*, 2003] as compared to fewer than 0.01 flashes/km^2/year near the conjugate point in the Aleutian Islands. However, the fact that lightning near the conjugate point is so rare presents a unique opportunity. It allows us to directly investigate another local source of lightning: volcanoes. During a volcanic eruption the electrified plume can produce copious lightning,

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with discharges occurring intermittently for several hours after the eruption as the plume rises and drifts.

Interest in volcanic lightning has risen considerably. However, being remotely located and unpredictable, the eruptions of these high latitude volcanoes are difficult to study. Analyses of individual volcanic eruptions [*Thomas et al.*, 2007; *Behnke et al.*, 2012] as well as global surveys [*McNutt and Williams*, 2010] have helped illuminate conditions in which volcanic lightning is likely to occur. The dominant mechanism of electrification is speculated about in a handful of publications (e.g [*Mather and Harrison*, 2006; *James et al.*, 2008]). WWLLN has recently been applied to the problem of detecting volcanic eruptions and has proven to be very effective in identifying lightning originating in volcanic plumes [*Ewert et al.*, 2010].

Of the several thousand volcanoes which line the boundaries of tectonic plates on land as well as under water, between 50 and 70 are active every year. In this paper we will use observations of lightning in the plumes of active high latitude volcanoes to identify individual lightning discharges which can be linked to whistlers observed at Dunedin. To the best of the authors' knowledge, this is the first report of whistlers known to be produced by volcanic lightning, showing that volcanoes are able to couple into the inner magnetosphere.

2. Data and Analysis

The data for this analysis came from the World Wide Lightning Location Network (WWLLN) and the network of Automatic Whistler Detectors and Analyzers (AWDAs).

Details on the operation and efficiencies of WWLLN can be found in *Lay et al.* [2004] and *Hutchins et al.* [2012]. A comparison with a regional North American lightning network found that in this region WWLLN had a detection efficiency of roughly 35% for powerful 130 kA strokes, dropping off to only around 1% for 3kA strokes [*Abarca et al.*, 2010]. The events detected by WWLLN have a spatial and temporal accuracy of $\sim 30\mu s$ and ~ 10km respectively.

The Automatic Whistler Detector and Analyzer (AWDA) identifies and analyses whistlers in broadband VLF data [*Lichtenberger*, 2009; *Lichtenberger et al.*, 2008]. The detection efficiency of the AWDA is in the order of 90%. The analyzer implements a whistler inversion algorithm which gives as output the electron density distribution and the L shell of the whistler path, assuming a longitudinal path connecting the receiver and its conjugate point.

This analysis is based on data for the period 25 May 2005 to 31 December 2013, where the records from both WWLLN and Dunedin's AWDA are essentially complete. Date and location data for prominent volcanic eruptions that occurred within this period at latitudes above 23° of the Northern Hemisphere as well as Hawaii were gathered from the Global Volcanism Program Volcano Database (http://www.volcano.si.edu/index.cfm). WWLLN strokes within a distance of 300 km of an erupting volcano, which occurred within a 24 hour period centred on the eruption time were selected for further processing. The AWDA data were then filtered to identify whistlers detected within less than 2 seconds after any one of these lightning strokes. These data were first used to construct summary histograms which compared the number of lightning strokes in the vicinity of an erupting volcano to the number of whistlers observed in the same period at Dunedin. This step was illuminating since neither WWLLN nor AWDA are perfectly efficient, so that it was entirely possible that for any given causative lightning-whistler pair, either the lightning or the whistler might not have been detected. A detailed analysis was then undertaken for volcanoes where noticeable activity in both lightning events within a 300 km radius and Dunedin whistler events around the eruption time was evident.

3. Results

Figure 1 shows the spatial relationship between the magnetic conjugate point of Dunedin (blue diamond in the Northern Hemisphere), and the three nearby active volcanoes, Okmok, Redoubt and Kasatochi (red triangles). Mount Okmok is found at 53.42° N 168.13° W, only 350 km away from Dunedin's magnetic conjugate point. Somewhat further away, Mount Redoubt lies at 60.48° N 152.75° W, 870 km from the magnetic conjugate point. Finally, Kasatochi Island lies at 52.17° N 175.52° W, at a distance of 815 km from the conjugate point. All of these volcanoes have been active in the last 10 years.

All dates and times are quoted in AKST(UTC-9)/AKDT(UTC-8).

3.1. Daily Whistler Counts

Daily whistler counts observed by the AWDA at Dunedin are plotted in Figure 2. There is an annual variation of increased whistler activity during the Northern Hemisphere summer and a decrease during winter, detailed by *Collier et al.* [2010]. This is in accordance with Northern Hemisphere lightning activity.

3.2. Typical Whistler Rates

The Dunedin whistler data were binned according to the number of whistlers recorded per local day. These data are presented in Figure 3. It is clear that on the majority of days (around 85%) the whistler count is between 0 and 1000 (although the count for the majority of these days is in fact below 500). At the opposite end of the spectrum, days with 8000 counts or more are rare, representing just 0.3% of the days in the sample period.

3.3. Eruptions in the Aleutian Islands

Mount Okmok erupted without warning at 11:43 AKDT on 12 July 2008, creating a 15 km high ash plume. Some 35 minutes after the eruption, whistler counts at Dunedin rose significantly. The correlation between whistlers and lightning detected around Mount Okmok is shown in Figure 4. WWLLN started reporting lightning strokes in the vicinity of the volcano 35 minutes after the eruption. Several lightning strokes were detected every hour until 20:00 AKDT, all of which occurred within a 21±10 km radius of the volcano and mostly concentrated around 10±10km.

The total number of whistlers detected from a couple of minutes after the eruption until 20:00 AKDT, when WWLLN-detected lightning ceased, is 21021. Reference to Figure 3 confirms that such a high daily count is exceedingly rare. Whistler counts for previous and subsequent days and nights drop down into the range 150-770. One can therefore assume that almost all (if not all) of the 21021 whistlers were from the eruption.

Although not as impressive as the effects of Mount Okmok, Mount Redoubt also clearly contributed to Dunedin's whistler counts. Mount Redoubt erupted several times in 2009. The first series of eruptions began on 23 March 2009. It then continued sporadically from 26 March to 4 April 2009.

During the month of March, there was no WWLLN-detected lightning activity in the region up until the very early hours of 23 March 2009. Two eruptions took place a few hours before midnight on 22 March and a further five eruptions took place between midnight and 5:00 am AKDT. In total around 180 lightning strokes were detected between 1:00 am and 6:00 am AKDT. However, little or no whistler activity was reported by Dunedin that day. A further series of eruptions occurred between 23 March and 26 March, but largely unaccompanied by either lightning or whistler activity. The clearest correlation was evident in lightning and whistler detection a few minutes after several eruptions occurred between late evening on 26 March until early morning on 28 March 2009 (refer to Figure 5). This led to spikes in whistler activity, accompanied by lightning activity mostly within a 20 km radius of the volcano, ranging from 23 to 258 counts after each of the 7 eruptions that occurred during this time. The total count between the first and last eruption is 808 whistlers. To put this value into context, $\sim 66\%$ of days across this 8.5 year time period have a count below 500. Lightning as well as whistler activity died down after 28 March 2009. There was a spike in lightning activity of $\sim$30 counts after the last eruption on 4 April 2009, however there was no whistler activity at that time.

Finally, Kasatochi Island erupted on 7 August 2008 at 14:00 AKDT in a $\sim$ 14 km ash plume and appeared to generate a stream of 36 whistlers at Dunedin (ceasing at 15:45 AKDT) and a lightning stroke count of 8. There is no detected lightning activity before the eruption. Another eruption at 17:50 AKDT gave rise to a trickle of 11 whistlers within the next half hour. A peak of 11 lightning strokes accompany these. Three further eruptions were reported within the next 10 hours. There was intermittent lightning activity during these times, but never more than 2 strokes per hour. The eruptions were most likely electrical, as the first two are signified by two clear peaks in lightning activity, of 8 and 11 strokes, respectively. Only one correlated lightning-whistler pair was found during the two eruptions, however, considering the low statistics this is not surprising. Although there was prominent whistler activity around the times of eruption, there was also infrequent whistler activity in Dunedin before this period. During a 48 hour time window extending from 21 hours before the first eruption to 21 hours after the second eruption the whistler rate reached two peaks of 13 and 22 whistlers/hour before the first eruption and peaks of 6, 45 and 23 whistlers/hour after the second eruption. It is possible that the subsequent peaks are related to electrical activity in the continuing eruptions, however the low rate of lightning activity detected at these times, as well as the whistler activity prior to the onset of eruptions – comparable in magnitude to the eruption-accompanying activity – make a correlation inconclusive.

3.4. Other eruptions

Due to the increased background lightning activity, the method employed for Aleutian Island eruptions was not expected to work as well for volcanic eruptions in Central America. Furthermore, unlike the Aleutian Islands, Central America is not overly populated with active volcanoes; only two volcanoes in Mexico, Colima and Popocatépetl, could be subject to our investigation.

Major eruptions at Colima and Popocatépetl were found to be devoid of Dunedin whistler activity. However, there was also no electrical activity or, at least, no lightning strokes were recorded by WWLLN over these volcanoes during those times. The seemingly non-electrical eruptions meant that no conclusions could be made. We noticed that monthly activity plots on occasion revealed a general match between lightning activity in the volcano's region and Dunedin whistler counts: a rise and fall in lightning counts (unrelated to the volcano eruption time) would match a rise and fall in whistlers counts.

No connections between lightning and whistlers were found for volcanic eruptions in Russia and Hawaii (both regions have numerous active volcanoes, but none lie close to the conjugate point).

4. Discussion

The number of whistlers observed on 12 July 2008 was one of the highest counts recorded by the AWDA over more than 8 years of operation at Dunedin. This is particularly noteworthy in light of the fact that there was a vigorous volcanic eruption in the vicinity of the conjugate point on that day. Additionally impressive is that both the eruption and associated whistlers occurred during daylight hours, despite that fact that whistlers are thought to traverse the ionosphere most efficiently at night. Although *Collier et al.* [2010] noted the peak in whistler activity on 12 July 2008 (a peak of 15218 whistlers in UTC time), they did not realise the likely connection to the eruption of Mount Okmok. This result and the other result found for Mount Redoubt are useful. The scarcity of lightning in the Dunedin conjugate region, which contains rare but intense volcanic activity is a great advantage. Not swamped by crowded statistics and false correlations, lightning strokes and whistlers could be uniquely linked to each other.

The studies presented by *Collier et al.* [2009]; *Collier et al.* [2010]; *Collier et al.* [2011] were correlation analyses, which compared whistler counts to global lightning activity on a statistical basis. In contrast to these global analyses, our study has isolated a specific set of lightning discharges located close to the conjugate point. These discharges occurred within the ash plumes of three volcanoes, all of which are located in remote areas of the North Atlantic. WWLLN has good coverage over this portion of the globe and was thus able to identify these unique lightning events. Having proceeded to find an unambiguous correlation between whistler activity at Dunedin and discharges at two of these volcanoes, we can verify that the lack of correlation at the conjugate point found in *Collier et al.* [2010] is not due to the inefficiency of whistler generation at that point, but due to the paucity of lightning.

The finding of a definite link between whistlers and lightning events has allowed us to observe whistlers guided through a direct magnetic field line path from a lightning stroke to the receiver – a rare link that was otherwise swallowed by the high statistical background in *Collier et al.* [2010]'s global analysis. In contrast to the majority of whistlers analysed at Dunedin, they offer us a precise value for the propagation time as well as the local meridian of their path with certainty. Other differences in volcanic and normal whistlers have yet to be confirmed. Judging by the lightning to whistler ratio during the Mount Okmok eruption (35:21000), the efficiency of volcanic lightning detection appears to be rather low, considering WWLLN's coverage of this region. Volcanic lightning may therefore have low peak current or nearly horizontal discharge channels which are less likely to be detected by the network. A lower peak current in volcanic lightning than what is typical in meteorological thunderstorms has been suggested in *Arason et al.* [2011], a study of an eruption at the Icelandic volcano, Eyjafjallajökull. How low current lightning would generate well-defined whistlers is an open question. Horizontal lightning strokes or favourable conditions for duct formation surrounding a volcanic eruption or these volcanic eruptions specifically are alternative explanations.

5. Conclusion

The plasmasphere is a vital link between solar activity and the subsequent effect on our atmosphere and improvements in plasmaspheric modelling aid us in predicting disruptive space weather events. For this reason whistlers are

an important field of research: if their path is known, they can serve as probes to the properties of the plasmasphere, namely the plasma density and the magnetic field strength. Contradictory evidence to the standard model for whistlers originating in the proximity of the conjugate point has been found in various studies: long distance sub-ionospheric whistler propagations and statistically significant global lightning-whistler correlations further afield, an exemplary case of which is Dunedin's whistlers.
The undoubtable link between conjugate volcanic lightning and whistler detection in Dunedin has given us a collection of whistlers that are certain to have originated in the proximity of the conjugate point and travelled along a direct path over the connecting magnetic field line to the opposite hemisphere. They gives us two valuable parameters: the local meridian and the time of propagation. The propagation time measurement can improve the accuracy of the whistler inversion algorithm used by the AWDA, as one out of three parameters in the optimization process is eliminated. As it has not been established how whistlers originating over the west coast of Central America travel to Dunedin, the whistlers linked to volcanic lightning in the Aleutian Islands are a portion of the minority of whistlers detected at Dunedin for which we can be certain of the local meridian along which these whistlers are sampling the electron density distribution. Identifying whistlers as 'volcanic' in origin at other high-latitude active volcanoes will reduce the uncertainty of their source location and improve analysis along a further range of meridians.

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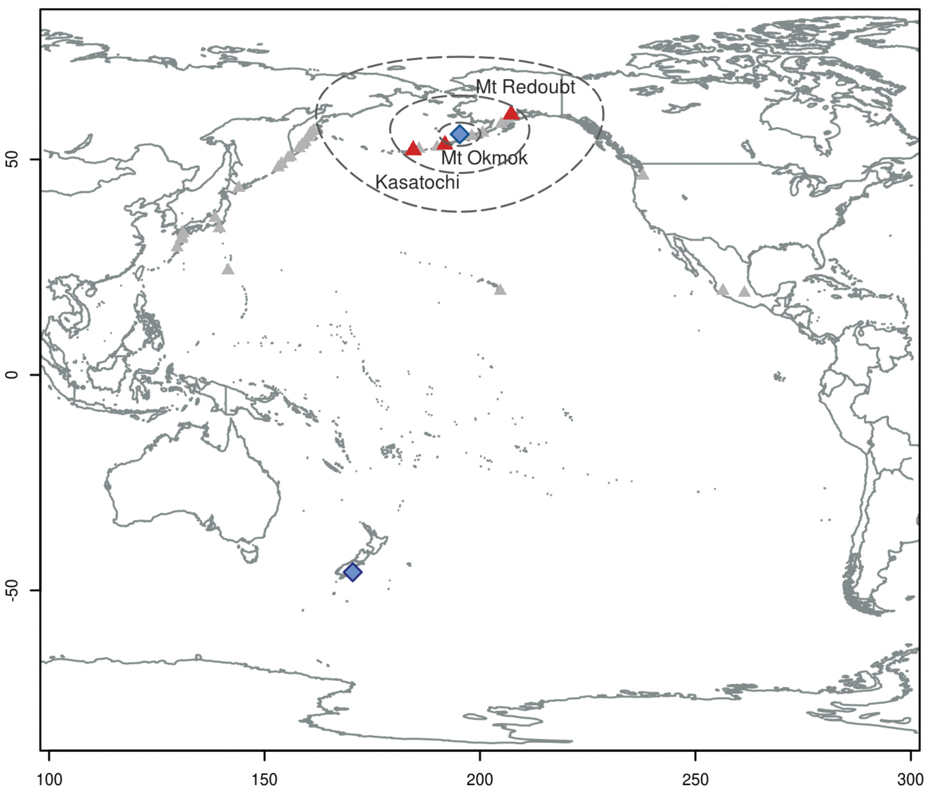
Figure 1. A map of active volcanoes around the north Pacific Rim. Mount Okmok, Kasatochi and Mount Redoubt are labelled. Dunedin and its conjugate point are marked by blue diamonds. The circles around the conjugate point have radii of 300, 1000 and 2000 km.

Figure 2. 24 hour whistler counts from year 2005 to 2013 (binned by AKST/AKDT time). Blue and yellow bars represent whistler counts on odd and even days. *Black line with gray bands* the rolling mean with a period window of 31 days and an uncertainty band of 2σ.
The day of Mount Okmok's eruption is the 3rd highest peak in this time period (However, if binned by UTC time, this day drops down to the 6th highest peak). The eruption dates of the three active Aleutian Island volcanoes are marked by dashed lines.

Figure 3. Histogram showing the frequency of daily whistler counts (number of whistlers/day) in AKST/AKDT time from years 2005-2013. Each bin width is 1000 whistler counts. On the local day of Mount Okmok's eruption, the whistler count reached over 21 000 whistlers. Only 0.3% of all days in the dataset had a whistler count fall into a range higher than 8000 counts.

Figure 4. Hourly lightning events and whistler correlation counts for Mount Okmok from 4.00 AKDT, 12 July 2008 - 5.00 AKDT, 13 July 2008 *(yellow and light blue bars)* and hourly total whistler counts at Dunedin during the same time frame *(dark blue bars)*. Eruption time was 11.43 AKDT.

Figure 5. Hourly lightning events and whistler correlation counts for Mount Redoubt from 22.00 AKDT, 26 March 2009 - 3.00 AKDT, 28 March 2009 *(yellow and light blue bars)* and hourly total whistler counts at Dunedin during the same time frame *(dark blue bars)*. Eruptions on these days were reported to have occurred at 22:48 (26 March), 8.39, 17:35, 19:20, 23:20 (27 March) and 1:20 (28 March) AKDT .



Mt Redoubt
Mt Okmok
Kasatochi
50
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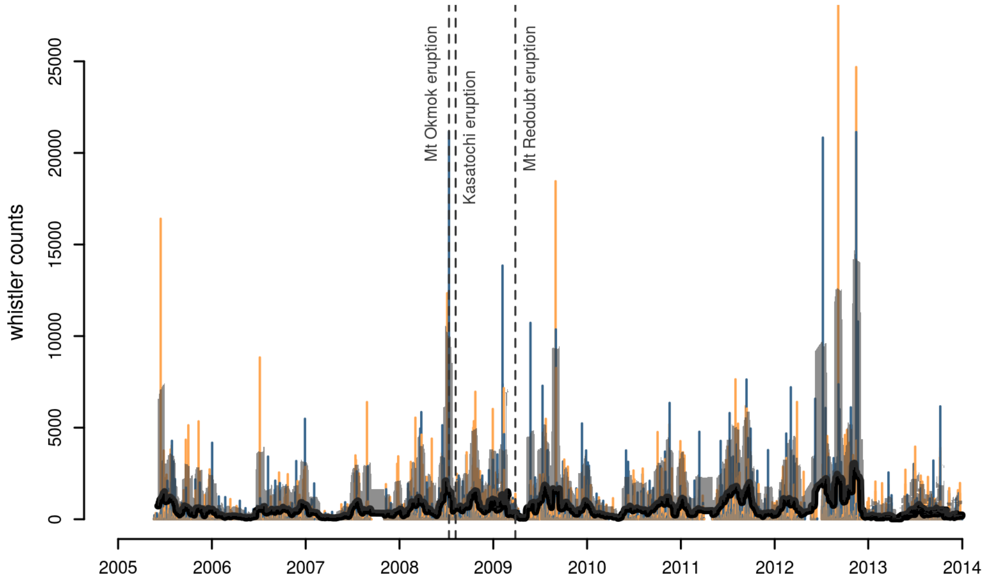
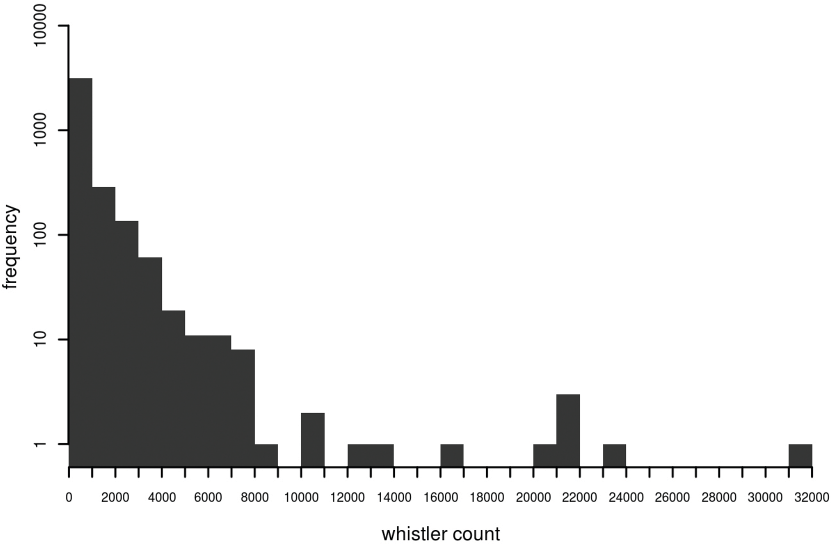
100
150
200
250
300



whistler counts
0
5000
10000
15000
20000
25000
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Mt Okmok eruption
Kasatochi eruption
Mt Redoubt eruption



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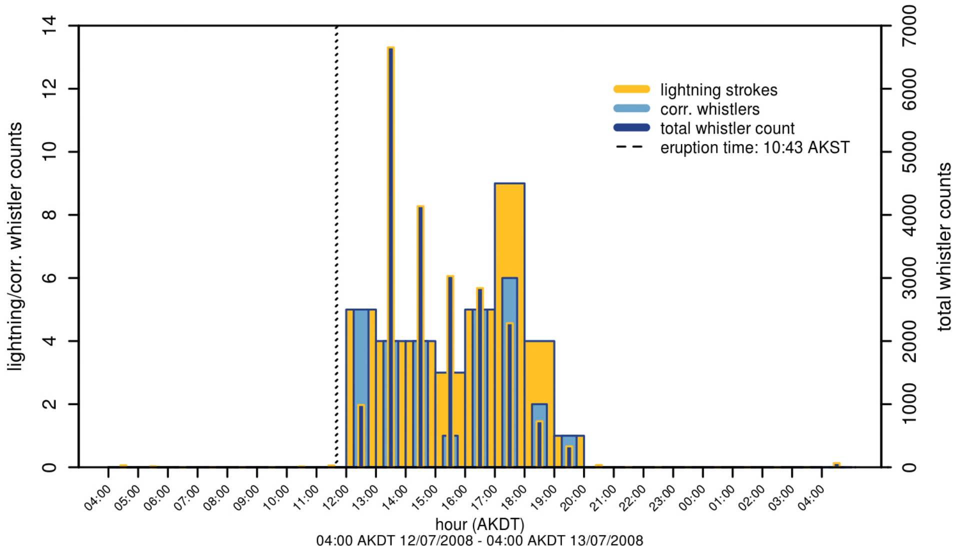
30000
32000
whistler count



lightning strokes
corr. whistlers
total whistler count
eruption time: 10:43 AKST
lightning/corr. whistler counts
total whistler counts
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12
14
0
1000
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3000
4000
5000
6000
7000
04:00
05:00
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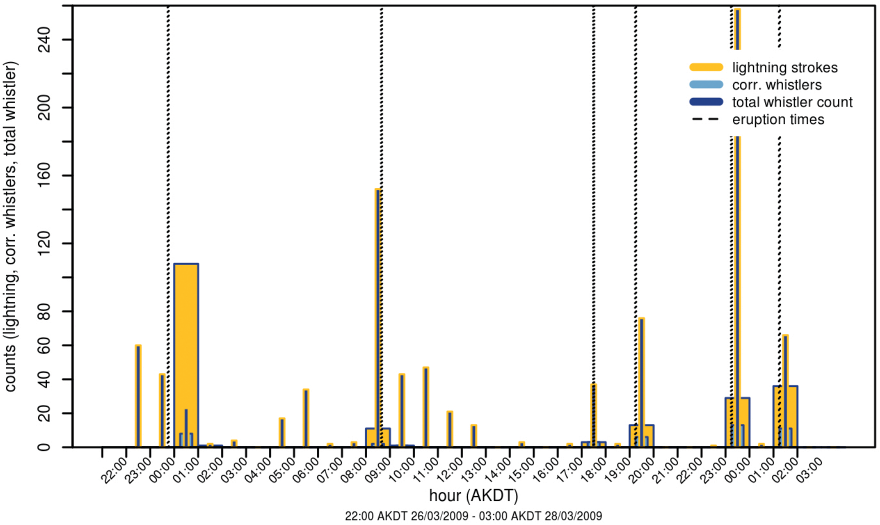
lightning strokes
corr. whistlers
total whistler count
eruption times
counts (lightning, corr. whistlers, total whistler)
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hour (AKDT)
22:00 AKDT 26/03/2009 - 03:00 AKDT 28/03/2009