Whistler-Lightning Correlations: Significant or Coincidence?

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Abstract

It is well known that the impulsive VLF emissions produced by lightning strikes travel extraordinary distances in the Earth-ionosphere waveguide. Whistlers observed on the ground are thought to be produced by the dispersive transmission of these impulses along field-aligned ducts of enhanced or depleted plasma density through the magnetosphere. Lightning strikes in one hemisphere are thus responsible for whistlers recorded in the opposite hemisphere. The meagre attenuation of these signals in the waveguide, however, implies that neither the source lightning discharge nor the receiver need necessarily be located close to the footpoints of the magnetic field line. Using a cross-correlation technique we reveal the most likely location of the lightning strikes responsible for whistlers recorded at Tihany, Hungary, and Dunedin, New Zealand. The latter location is of particular interest due to the anomalous diurnal variation in whistler occurrence.

1 Introduction

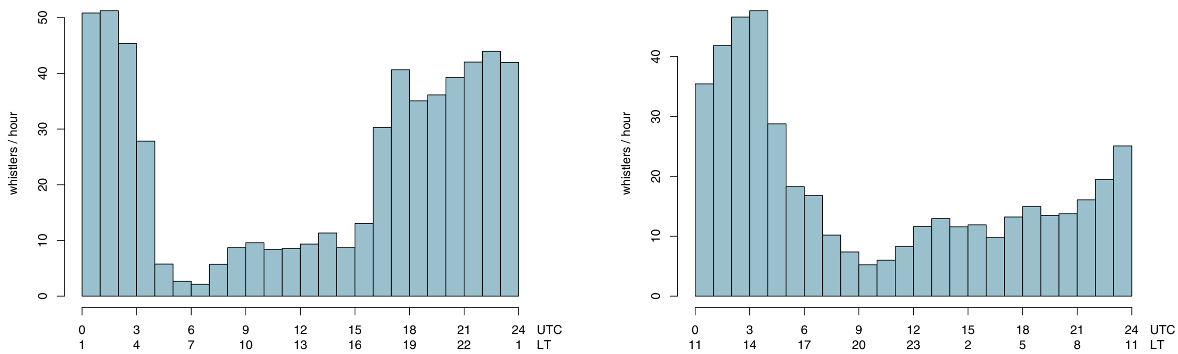
Whistlers are a naturally occurring Very Low Frequency (VLF) radio phenomenon. A whistler is initiated by a lightning strike, which produces an intense pulse of electromagnetic radiation with broad spectral content. Within the Earth-ionosphere waveguide this pulse, or sferic, is not significantly dispersed and can travel considerable distances with low attenuation. Some portion of the initial energy may penetrate upwards through the ionosphere and enter the magnetosphere where it propagates along magnetic field lines in the whistler mode. Since the whistler mode is dispersive, the propagation delay varies with frequency, transforming the initial impulse into a complex tone with a unique frequency-time signature determined by the magnetic field strength and plasma density along the path traversed.

Two scenarios exist for whistler propagation through the magnetosphere depending on whether or not the waves are trapped within a duct of enhanced or depleted plasma density. Since ducted propagation is required for a whistler to re-enter the waveguide at the conjugate point it is generally believed that only ducted whistlers may be detected on the ground. When a whistler is received on the ground it has completed a journey with at least three major components: (i) subionospheric propagation from the source to the footpoint of the duct; (ii) field-aligned propagation along the duct to the opposite hemisphere; and (iii) subionospheric propagation from the ionospheric exit point at the conjugate footpoint to the receiver. There may also be unducted portions of the propagation path through the ionosphere and magnetosphere. Since propagation in the waveguide can occur both before and after the signal's passage through the magnetosphere, it is in principle possible for both the causative discharge and the observer to be significantly distant from the footpoints of the guiding magnetic field line. Indeed the path through the magnetosphere need not have a footpoint at either the source or the receiver, but may be displaced with respect to both [2]. The point at which the electromagnetic pulse penetrates through the ionosphere may lie up to $1500\,\mathrm{km}$ from the lightning discharge [1], so that the effective source region may have a radius $\sim 1500\,\mathrm{km}$ centred on the conjugate point. However, the source region appears to be displaced from the conjugate point towards the magnetic pole [3]. Furthermore, the fact that signal power is inversely proportional to the distance from the source suggests that those strikes closer to the footpoint of a magnetic field line are likely to inject more wave power into a duct.

2 Data

Locations which are more likely to be the source of causative lightning strikes are those for which one finds a lightning strike during the same interval that a whistler was observed or an absence of lightning when no whistlers were observed. Conversely, locations which have lightning when there are no whistlers, or vice versa, are less likely to be within the source region. The location and extent of the effective whistler source region is assessed by performing a cross-correlation analysis of whistler data against global lightning data. Lightning data was acquired from the World Wide Lightning Location Network (WWLLN), which consists of an irregular array of VLF receivers distributed over the Earth. The system detects $\sim 2\%$ of global lightning activity and $\sim 5\%$ of CG strikes, with temporal and spatial accuracy of ~ 1 µs and $\sim 10\,\mathrm{km}$ [6]. Automated whistler detectors are operated at Tihany, Hungary (46.89° N 17.89° E, $L = 1.80$), and Dunedin, New Zealand (45.80° S 170.48° E, $L = 2.75$). These instruments employ two dimensional image correlation to identify whistlers in a stream of broadband VLF data.

Figure 1 reflects the diurnal distribution of whistler observations at Tihany and Dunedin. The data for Tihany conform to the expectation that the majority of whistlers are observed at night when the attenuation of the ionospheric D region is minimised. However, Dunedin appears to receive most whistlers around midday. This anomaly [4] is likely to be related to the occurrence of lightning around the conjugate points of these two locations. The conjugate for Tihany is located off the east coast of South Africa at 33.08° S 28.08° E, which is close to a region of high lightning activity. In contrast, the conjugate for Dunedin is situated near the Aleutian Island chain at 55.85° N 195.34° E, where lightning is extremely scarce. It is thus probable that the lightning triggering the Dunedin whistlers occurs at a significant distance from the conjugate point. This does not in principle present any difficulties, since a sferic may propagate an appreciable distance with little attenuation in the Earth-ionosphere waveguide, but it does pose the question: what is the source region for whistlers observed at Dunedin?



(a) Tihany (27 February 2002 to 18 May 2005)

(b) Dunedin (20 May 2005 to 30 October 2006)

Figure 1: Diurnal distribution of whistlers recorded at Tihany and Dunedin as a function of UTC and local time.

The data from WWLLN and automated whistler detectors both consist of time series, where the former includes spatial information. In order to perform a cross-correlation between the whistler and lightning time series the spatial component of the lightning data is removed by projecting the data onto a 3° by 3° geographic grid. Each grid cell is then assigned a time series of lightning strikes within its domain. The respective time series are then regularised by counting the number of events within each $60\,\mathrm{s}$ interval. The resulting sequences of counts are then reduced to binary sequences simply indicating whether or not there was an event during a given interval. The cross-correlation between these two sequences is then an indication of the likelihood that lightning within a given grid cell was the source of the whistlers.

3 Analysis and Results

Figure 2 displays the correlation between the whistler time series at Tihany and the lightning time series in each of the grid cells. The conjugate point is surrounded by circles at intervals of $200\,\mathrm{km}$ up to a distance of $1000\,\mathrm{km}$. It is apparent that there are regions of non-vanishing correlation, both positive and negative, but that the majority of the cells have correlation close to zero. The range of correlation coefficients is low, from a minimum of -0.043 to a maximum of 0.063, but the results are statistically significant at the 0.01 level.

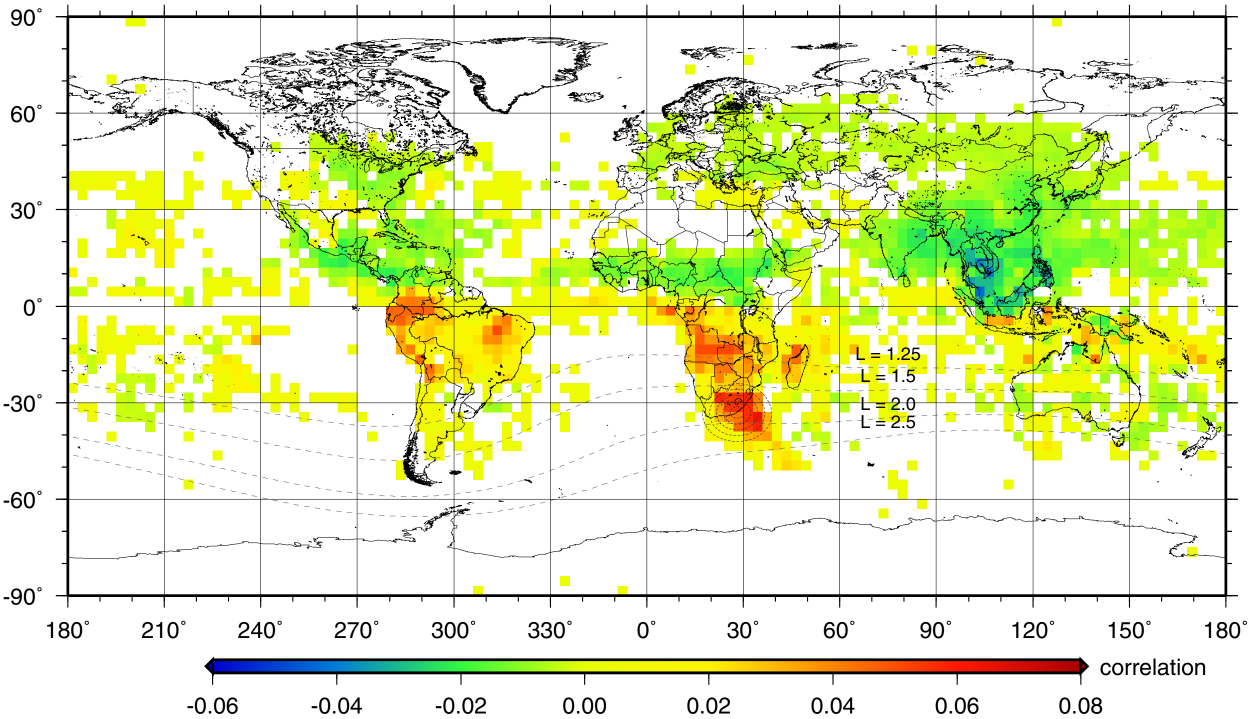


Figure 2: Correlation between whistlers observed at Tihany, Hungary, and global lightning activity.

There is a spatially coherent region of higher correlation surrounding the conjugate point. This indicates that the majority of whistlers are well correlated with lightning activity within a few hundred km of the conjugate point. There are also extended regions of relatively large positive correlation over the sub-tropics of South America and southern Africa, and scattered points over the Indonesian Archipelago. These suggest that lightning at an appreciable distance from the conjugate point may also be the source of Tihany whistlers. Since sferics may travel enormous distances in the waveguide before they become too attenuated to generate detectable whistlers it is not entirely unreasonable that distant but intense lightning discharges (those most likely to be detected by WWLLN) may initiate whistlers.

There is a distinct transition in the correlation across the geographic equator: whereas in the southern hemisphere correlation is predominantly positive, it is mostly negative north of the equator. This effect arises due to the seasonal distribution of lightning and Tihany whistlers: both are more prevalent during the Austral summer, accounting for the generally positive correlation in the southern hemisphere. Lightning activity in the northern hemisphere, however, peaks during the Boreal summer, a time of infrequent whistlers at Tihany. Whistlers and northern hemisphere lightning are thus out of phase, yielding a negative correlation.

Regions of high lightning activity do not necessarily also have high correlation. The maximal correlations occur in an area of only moderate lightning activity. The active area in tropical South America is positively correlated with whistlers, while the whistlers appear to be independent of the lightning in the region of intense activity over Australia. This suggests that sferics generated by lightning over South America are able to propagate across the Atlantic Ocean, while those triggered over Australia do not survive transmission across the Indian Ocean.

The results of an analogous analysis for Dunedin are presented in Figure 3. In contrast to Tihany no specific region stands out as having above average correlation. There is an area in the north Pacific Ocean, just south of the conjugate point, which does display some positive correlation, particularly evident between 02:00 and 08:00 LT, which is when ionospheric conditions are ideal for whistler transmission. Yet this corresponds to a period of only moderate whistler activity. The bottom panel of Figure 3 shows correlations for the period of greatest whistler activity. At these times there are areas of positive correlation scattered over the entire northern hemisphere. It is not yet possible to draw any firm conclusions about the source of Dunedin whistlers on the basis of these results.

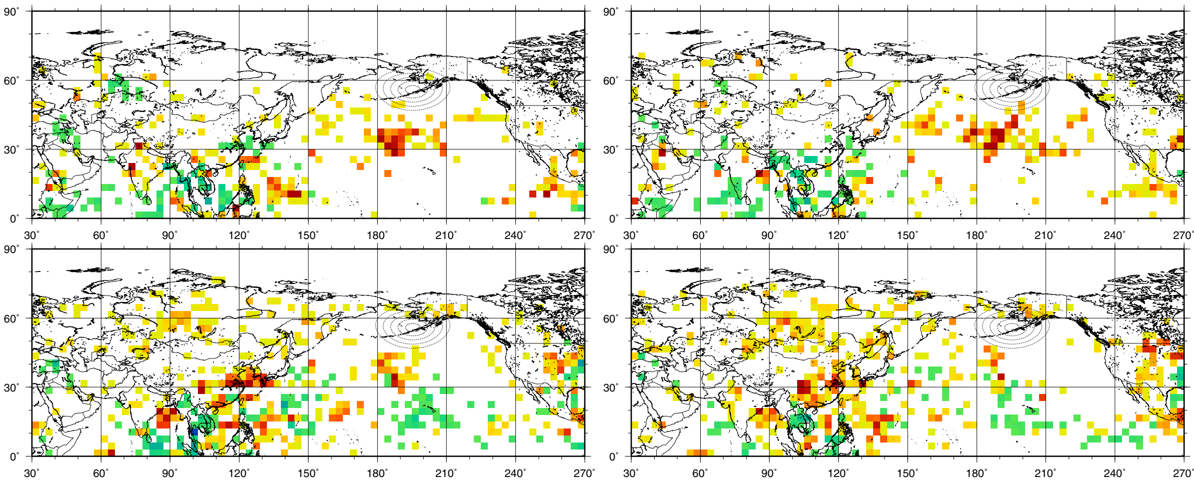


Figure 3: Correlation between whistlers observed at Dunedin, New Zealand, and global lightning activity. Top panel: 02:00 to 05:00 LT and 05:00 to 08:00 LT; bottom panel: 11:00 to 14:00 LT and 14:00 to 17:00 LT.

4 Conclusions

A cross-correlation of whistler and global lightning data reveals that the source of whistlers at Tihany is located within a few hundred km of the conjugate point. The corresponding analysis for Dunedin does not indicate a clearly preferred whistler source region.

References

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