

RECONSIDERING THE EFFECTIVENESS OF QUASI-STATIC THUNDERSTORM ELECTRIC FIELDS FOR WHISTLER DUCT FORMATION

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ABSTRACT

It has been suggested that $\mathbf{E} \times \mathbf{B}$ mixing of magnetospheric plasma can lead to geomagnetic field aligned ionization enhancements termed whistler ducts. DC electric fields from thunderstorms have been put forward as the source of the required radial electrostatic field. Recent experimental observations have indicated that quasi-static radial thunderstorm electric fields are not responsible for duct formation. This evidence appears to be in contradiction to the current theoretical calculations. In this paper we reconsider duct formation through quasi-static thunderstorm electric fields. We find that more realistic thunderstorm charge distributions produce high altitude electric fields that are insufficient to create ducting.

INTRODUCTION

Whistlers result from the penetration of lightning discharge-produced electromagnetic radiation through the ionosphere and into the magnetosphere [1]. The geomagnetic field is not sufficient to guide the signal into the conjugate hemisphere and allow ground-based reception of the whistler in that hemisphere. However, reception of whistlers in the conjugate hemisphere is not uncommon, with the signals showing evidence of propagating along distinct field-aligned paths. It was therefore suggested that field aligned “ducts” might trap and guide signals from one hemisphere to the other [2]. Ducts are regions of enhancement or depletion from “normal” ionization densities and hence have different values of refractive index from the surrounding plasma.

Reference [3] suggested that the formation of whistler ducts might be due to localized electric fields in the magnetosphere interacting with the geomagnetic field according to the hydromagnetic relation $\mathbf{v} = \mathbf{E} \times \mathbf{B} / B^2$. A 0.1 mV m^{-1} electric field in the equatorial plane could produce a whistler duct in 30 minutes through this mechanism [4], where the duct has an enhancement of the order of 5%, as experimentally observed [5]. Typical duct formation times are about 0.5 – 2 hours [6]. A 0.1 mV m^{-1} field geometrically maps down into the lower regions of the ionosphere to a field of about 1 mV m^{-1} at 150 km [7]. Reference [4] suggested that thunderstorms could be the source of radial electrostatic fields in the ionosphere, and hence drive duct formation.

Reference [7] developed formalisms to investigate the concept of thunderstorm driven whistler duct creation. Using a simple conductivity profile these authors concluded that the mechanism was indeed plausible. This was supported by some later studies [8; 9; 10]. Recently it was reported that thunderstorm electrostatic fields were unlikely to drive whistler duct creation [11]. This conclusion was based on calculations undertaken using the [7] theoretical formulation but making use of several more realistic conductivity profiles.

Experimental evidence comparing whistler duct numbers with thunderstorm activity [12] has supported the conclusions of [11]. The experimental study sought possible correlations between thunderstorms occurring in eastern North American and whistlers observed at Faraday in Antarctica. Using National Lightning Detection Network (NLDN) observed lightning as a proxy for thunderstorm location, the authors concluded that quasi-static thunderstorm electric fields do not play a significant role in whistler duct formation.

However, an error has subsequently been found in the theoretical calculations of [11], the correction of which suggests that thunderstorms could indeed be significant in duct formation [13]. In this paper we reconsider whistler duct formation through quasi-static thunderstorm electric fields, given the apparent disagreement between experimental and theoretical evidence.

COMPARISONS WITH PREVIOUS CALCULATIONS

For the derivation of the model see [7] and [14].

Experimentally Derived Thunderstorm Charge

Reference [14] made theoretical calculations and compared these with the experimental measurements of [15]. These measurements were undertaken using several rockets plus a long duration balloon, which together produced observations of the atmospheric electrical conductivity and the radial and vertical components of the electric field. Using the observed conductivity profile and electric field measurements, [14] determined the effective charge of the thunderstorm around which the measurements were taken. However the error in [11] also affects the computations of [14]. We have calculated the effective charge magnitudes found within the [15] thunderstorm as discussed in [14] but correcting for the computational error and confirmed their results. Large negative screening charges around thunderstorms can reduce the effective charge within thunderstorms to 6 – 10 C.

Radial Electrostatic Fields and Duct Creation

Reference [11] used a number of historic conductivity profiles to see if quasi-static radial electric fields from thunderstorms were a plausible duct creation mechanism. They concluded that under “typical” conductivity conditions the high altitude electric field would be insufficient to produce whistler ducts even for giant thunderclouds over a 5 hour window. However, these authors have reported that an error in their calculations means that such thunderstorms could possibly drive whistler duct formation over a 5 hour period [13].

This time period is unrealistically long given typical whistler duct formation times (0.5 – 2 hours). It has been shown that the time required to produce a whistler duct is inversely proportional to the electric field magnitude [4], and hence the effective thunderstorm charge. Taking a reasonable duct creation time requirement of 1 hour, Table 2 of [13] suggests that the thunderstorm effective charge required will range from 32 – 370 C, depending on the ionospheric model. For example [13] reported that a duct would be formed in 5 hours by a ~7 C thunderstorm effective charge, which indicates that a ~35 C effective charge will produce a realistic duct after 1 hour. Even for the smallest required effective thunderstorm charge, the 32 C found using the [15] C1 ionospheric model, this is still ~3 – 6 times the experimentally derived thunderstorm effective charge found above.

These calculations suggest that thunderstorm electrostatic fields are unlikely to drive whistler duct formation. However, the dipole charge arrangement with a positive charge at 15 km and an equal negative charge at 5 km (hereinafter referred to as a 15km-5km dipole) is based on rather dated assumptions. Thus we need to consider the validity of these assumptions and their effect on the calculations.

THUNDERCLOUD CHARGE DISTRIBUTION

The upper charge height (15 km) used in previous calculations is rather extreme. This has been recognized by several studies, which have suggested that a more “typical” height for the upper thunderstorm charge is 10 km [7; 11]. Evidence for this can be seen in a study of about 5000 thunderstorms which found that 90% of mid- to high-latitude storm-tops were located at less than ~14 km with the median being ~11 – 12 km altitude [16].

Taking a more representative dipole with an upper charge at 10 km and the lower charge at 5 km (herein after referred to as a 10km-5km dipole) leads to a smaller electric field at 150 km than for a 15km-5km dipole. This decrease in electric field strength suggest that typical thunderstorms will need to contain more charge to generate whistler ducts than found above. Table 1 specifies the results for the various conductivity profiles, the sources of which are described in greater detail in [11]. The 10km-5km dipole leads to fields that would not create whistler ducts in a reasonable time period for reasonable thunderstorms.

The dipole charge arrangement employed above is, however, an extremely simplified model of thundercloud charge structure. Recent balloon soundings of thundercloud charge structure have identified a layered model of cloud charge distribution, comprising 4 main charge areas within the updraft [17]. These four charge areas have been termed the upper negative charge (UNC), upper positive charge (UPC), main negative charge (MNC), and lower positive charge (LPC) areas. The charge structure for the most recent and complete dataset presented by [18] has been converted into point charges (given in Table 2). These have been used in the calculation of high altitude fields from thunderstorms. It

Table 1. Normalized night-time radial electric field at 150km calculated for a 10km-5km dipole required to produce a minimal whistler duct in 1 hour.

Conductivity Profile		Maximum E_r/Q at 150 km altitude ($V m^{-1}C^{-1}$)	Radial Distance of $E_{r,max}$ (km)	Required value of effective Q (C)
<i>Park and Dejnakintra</i> [1973]	[7]	3.98×10^{-7}	39	1256
<i>Park and Dejnakintra</i> [1977]	[8]	1.63×10^{-6}	40	307
<i>Hale</i> [1984]	[19]	2.03×10^{-6}	47	246
<i>Holzworth et al.</i> [1985] S1	[15]	1.29×10^{-6}	45	387
<i>Holzworth et al.</i> [1985] S3	[15]	7.18×10^{-7}	44	696
<i>Holzworth et al.</i> [1985] C1	[15]	4.54×10^{-6}	44	110
<i>Holzworth et al.</i> [1985] C3	[15]	2.52×10^{-6}	44	198

should be noted that the ground level for the thunderstorm sounding measurements was at 3.2 km above sea level. This was taken into account by changing the ground level of the conductivity profile in the simulation to 3.2 km. The maximum radial electric fields resulting from this charge distribution for the various conductivity profiles are shown in Table 3. These are not normalized field values, as the calculation used charge magnitudes taken from experimental measurements. Such field strengths would require many days to form a whistler duct, if we were to assume a stationary thunderstorm, containing constant charge, along with constant night-time ionospheric conditions.

The radial electric field strengths calculated using the [18] charge distribution are smaller than that calculated for other, simpler, charge distributions. It therefore appears that more realistic thunderstorm charge distributions, as opposed to the simplified models (such as the dipole we have used above), are less likely to cause whistler ducts.

DISCUSSION

We have undertaken a series of calculations to determine whether it is plausible that whistler ducts can be created through quasi-static radial thunderstorm electric fields. While the result is somewhat dependent upon on the thundercloud charge profile (both heights and charge magnitudes), it is clearly critically dependent upon the choice of ionospheric profile. It is recognised that there is significant disagreement as to the parameterisation of the night-time ionosphere, particularly at lower altitudes.

In order to examine the possible link between thunderstorms and whistler duct creation, authors have attempted to improve the model of the ionospheric conductivity (e.g., [8]), effective charge value [14], as well as the charge representation and distribution [10]. Our current modelling has included most of these factors, but has not shed light on a solution for the disagreement between experiment and theory. We therefore suggest that additional effort needs to go into the assumptions of the model especially the atmospheric conductivity, due to the age of the profiles used here.

CONCLUSIONS

We have confirmed the [14] conclusion that, for the seemingly average thunderstorm observed by [15], the effective thunderstorm (dipole) charge lies in the range 6 – 10 C, depending on the ionospheric conductivity profile used.

The sensitivity of the calculations to differing charge distributions was investigated using a number of representative ionospheric profiles, which have been employed by previous studies. Dipole charge distributions (15km-5km and 10km-5km) were considered along with a more complex distribution derived from experimental measurements taken inside thunderstorms. These calculations suggested that thunderstorm driven duct formation is unlikely, due to the effective charges required and/or the time scales involved.

Table 2. Cloud charge density profile based upon balloon sounding within a thunderstorm converted to point charges. July 31, 1993 data from Fig. 1 of [18].

Charge Centre	Charge Height (km)	Charge Magnitude (C)
Unnamed	9.5	- 0.8
UNC	8.5	- 1.92
UPC	7.5	15.6
MNC	6.1	- 20.4
LPC	5.1	4

Table 3. Night-time radial electric field at 150km calculated for the cloud charge distribution described in Table 2, required to produce a minimal whistler duct.

Conductivity Profile		Maximum E_r at 150 km altitude (V m^{-1})	Radial Distance of $E_{r,max}$ (km)	Required Time for Storm to exist (hr)
<i>Park and Dejnakintra</i> [1973]	[7]	2.17×10^{-7} (C)	39	2306 (~96 days)
<i>Park and Dejnakintra</i> [1977]	[8]	7.17×10^{-7}	38	697 (~29 days)
<i>Hale</i> [1984]	[19]	9.59×10^{-7}	46	522 (~22 days)
<i>Holzworth et al.</i> [1985] S1	[15]	6.95×10^{-7}	44	719 (~30 days)
<i>Holzworth et al.</i> [1985] S3	[15]	3.18×10^{-7}	42	1573 (~66 days)
<i>Holzworth et al.</i> [1985] C1	[15]	2.44×10^{-6}	44	205 (~9 days)
<i>Holzworth et al.</i> [1985] C3	[15]	1.12×10^{-6}	42	447(~19 days)

ACKNOWLEDGEMENTS

C.J.R. was partially supported by the New Zealand Marsden Research Fund contract LFE801. R.J.M. was partially supported by a New Zealand FiRST Bright Future Top Achiever Doctoral scholarship TAD867.

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