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A 25-year record of 10 kHz sferics noise in Antarctica: Implications for tropical lightning levels

Nicholas W. Watkins, Mark A. Clilverd, Andy J. Smith
British Antarctic Survey, Cambridge, UK

Keith H. Yearby
Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield, UK

Abstract. We report measured levels of very low frequency (VLF) radio noise at $\sim$ 10 kHz, due to lightning sferics, observed at Halley Station, Antarctica (76° S, 27° W) between 1971 and 1996. The observed VLF noise levels at Halley are a product of the thunderstorm source function and the transfer function for propagation to the receiver in the waveguide formed by the Earth's surface and the ionosphere. Least squares fitting enables us to confirm the characteristic diurnal, annual and semi-annual periodicities found by the present authors in a separate paper. That method and also cross correlation of annual averaged 10 kHz VLF power with sunspot number shows a $\sim$ 4 dB peak-to-peak fluctuation at the $\sim$ 11-year solar cycle period, believed to be due to the influence of EUV flux on the the ionospheric D region. Finally we constrain any linear trend to 1.4 ± 2.6 dB in 25 years. If a positive trend is present and is interpreted as a change in tropical South American lightning flash rate, it is less than 10 %.

Introduction

As noted by *Williams*, [1992], the global (surface dry-bulb) temperature variability this century (of order several tenths ° C) is of similar size to the reported global warming trend of $\sim$ 0.3° to 0.6° [*Houghton et al.*, 1995,]. To reliably detect the trend in the presence of the variability, the use of a parameter with a known nonlinear dependence on atmospheric temperature has been suggested [*Williams*, 1992]. Because increased surface temperature leads to increased buoyancy in thunderstorm cells, giving increased electrification and hence increased lightning strike rates, *Williams* [1992] suggested that long term monitoring of global lightning activity may provide such a parameter for tropical temperatures. However, non-linear amplification may only be sustainable over short periods i.e. the global circuit may act as a (nonlinear) "high pass filter" to changes in surface air temperature. The nonlinearity is apparent in the relation between monthly mean maximum wet-bulb temperature and mean lightning flashes per day suggested by the local tropical measurements in *Williams* [1992]. In the case considered by *Williams* [1992] the connection to the global AC circuit resulted from the use of standing modes of the Earth-ionosphere waveguide (Schumann resonances) [*Satori and Zieger*, 1996], resulting in a "global tropical thermometer" (i.e. the global measurement of tropical temperature information).

Estimates of the size of this nonlinear amplification of lightning effects have varied substantially. Numerical models of the response of global lightning activity to an increase in global temperature suggest increases of 25% with a change of $4.2°C$[*Price and Rind*, 1994]. Local observations [*Williams*, 1992] may indicate a stronger sensitivity of the order of 400% per $1°C$ thought originally to be explicable by homogeneous forcing [*Williams*, 1994]. This effect may be diluted by an order of magnitude [*Williams*, 1994] if the forcing is regionally heterogenous (e.g. diurnal), and also may be reduced on long timescales by the "high pass filter" effect noted above. The degree of homogeneity of both seasonal forcing and that on El Nino Southern Oscillation (ENSO) timescales of years is currently a matter of debate [*Price*, 1993; *Williams*, 1994].

Because the present work is intended to contribute evidence to the investigation of whether global warming is already occurring, a suitable long term data set must be one which is well enough sampled to detect a trend in the presence of substantial seasonal and interannual variability in the signal. Satellite radio frequency data sets cover too short a time at present. Satellite optical observations, although of great value in characterising spatial variations, have suffered until the last two years from long data gaps, restricted local time coverage and uncertainty about lightning detection efficiency.

Ground-based techniques all make use of radio emissions from lightning. One method uses the aforementioned Schumann resonances, but there is no database longer than $5\frac{1}{2}$ years. Our method exploits the fact that VLF sferics propagate well inside the Earth-ionosphere waveguide to detect directly propagated ELF/VLF radio noise in frequency bands which can be attributed to lightning-generated emissions.

For these reasons, the data set considered here resulting from the measurement since 1971 of 10 kHz radio noise of tropical lightning sferic origin detected at Halley Station, Antarctica (76° S, 27° W), presents a unique opportunity for a long term study spanning 25 years. Although it is not a global dataset, we aim to contribute to the validation of the methods discussed above by constraining the maximum size of any linear trend in emissions of VLF noise from the detected source region, and confirming the presence of a solar cycle effect on ionospheric propagation at these frequencies which investigations using this technique must take into account.

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Table 1. Halley VLF system 1971-present

Dates	Antenna	Receiver	Orientation	Data type
1971-1974	Single Loop	MCR	N–S	Paper Charts
1974-1981	2 Loop and goniometer	Broadband	N–S & E–W	Postprocessed files
1983-1990	2 Loop and goniometer	MCR Mk II	N–S & E–W	Digital files
1992 - Present	2 Loop	VELOX	N–S & E–W	Digital files

Method

The spectrum of the electromagnetic pulse ('sferic') radiated by lightning is broadband [*Smith and Jenkins*, 1998]. The peak is at $\sim$ 5 kHz [*Barr*, 1970], but is severely attenuated in the Earth-ionosphere waveguide at that frequency. The attenuation decreases rapidly above 5 kHz, and at $\sim$ 10 kHz allows detection of strong ground flashes at an order of 10^7 m or more from the source [*Barr*, 1970]. The potentially global view of lightning seen by a VLF receiver at Halley is modified by the occurrence statistics of tropical lightning sources [*Markson*, 1986] and the propagation effects from South America and Africa [*Clilverd et al.*, 1998]. South East Asian sources can be neglected for the reasons illustrated in figure 7 of [*Smith and Jenkins*, 1998]. The propagation paths from these pass over ice for significant distances, giving essentially total attenuation. In addition, the VLF receiver site at Halley has low electromagnetic pollution [*Smith and Jenkins*, 1998] and no local thunderstorms.

The Halley VLF reception system is summarised in Table 1. Broadband VLF measurements have been made since 1967 [*Dudeney et al.*, 1995], but we have used data taken from 1971 onwards when the first logger was installed. Between 1971 and 1974 the system used a 1 kHz bandwidth analogue Multi-Channel Receiver (MCR). We use the channel centred originally at 9.6 kHz, similar to one of the channels of the Ariel-3 satellite's VLF receiver [*Smith and Yearby*, 1987; *Bullough et al.*, 1968]. The MCR, modified for digital rather than analogue data collection, was redeployed between 1983 and 1990, and is termed MCR Mk II. After 1984, the centre frequency was changed to 9.3 kHz to avoid possible contamination from Omega transmissions at 10.2 kHz. From 1992, the digital multichannel VELOX instrument [*Smith*, 1995] was deployed, for which the equivalent data are the 9.3 kHz scalar power. Between 1975 and 1982, the MCR was not deployed, but average power in the 9.3 kHz band can now be obtained in that period by use of post analysis software on broadband tape recordings. This activity is very labour intensive and hence only 4 months' data have been analysed for this paper.

The first antenna system (1971-1974) was a vertical single turn square loop of side 7.6 m. The second (1975 onwards) was a pair of such loops, each 58 m^2 in area and sensitive to the East-West and North-South components of the horizontal wave magnetic field. As with Ariel 3 and the most recent VELOX experiment [*Smith and Jenkins*, 1998] the measured variable is logarithmic average magnetic field energy spectral density in the filter band measured in dB relative to 10^{-33} T^2 Hz^{-1}. This reference level is equivalent to a wave power flux of 2.4×10^{-19} W m^{-2} Hz^{-1} and is 30 dB below 1 fT/$\sqrt{Hz}$, used by [*Füllekrug and Fraser-Smith*, 1997]. The system has a logarithmic response from an instrumental noise level (including the low-noise preamplifier) of about 15 dB. In practise the natural lightning sferics define the noise level in the 10 kHz channel of present interest[*Smith and Jenkins*, 1998].

The frequency of measurement and method of data recording have varied during this time (see Table 1). The original MCR provided paper chart recordings of 30 s averaged power which have been digitised to give hourly readings. The Mk II MCR logged data in digital form, again recording 30 s averages every 5 minutes. The VELOX gives direct digital measurements every second from which one-minute average values were computed. Post-processing software was used to obtain hourly values from broadband tapes.

Although all the datasets used are compatible by design, careful comparison of the receiving system has been required to reduce instrumental effects to order 1 dB or less between the MCR and MCR Mk II, and the MCR Mk II and VELOX. The three receivers are nominally calibrated for constant amplitude signals [*Smith*, 1995; *Smith and Jenkins*, 1998]. However because of their different designs and configurations, they respond differently to impulsive signals, such as sferics. Compared with the VELOX, the response of the Mk II is estimated to be 9.5 $\pm$ 1.5 dB less. In turn, compared to Mk II the response of the MCR is 6.2 $\pm$ 0.8 dB less. These two factors have been applied in the data presented here. The intercalibration factors are insensitive to flash rate. All plotted power values are referred to the VELOX.

Results and Discussion

In Figure 1 we plot the monthly median radio noise in the 9.3/9.6 kHz band since 1971. The signal cannot be treated simply as a stationary noise-like process because it is already known to have both diurnal, annual and semi-annual sys-

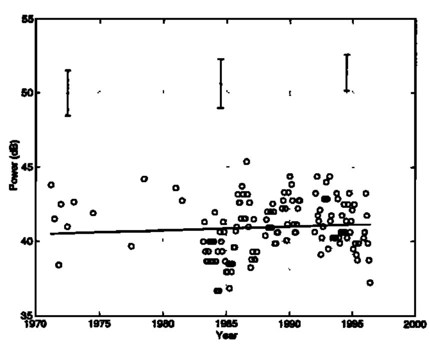

Figure 1. Monthly medians of 10 kHz radio noise at Halley in dB with respect to 10^{-33} T^2 Hz^{-1} (1971-1996). The line is the linear part of a least squares fit, and shows a rise of 0.66 dB in 25 years, which can be explained by uncertainties between the MCR Mk II and VELOX experiments. The bars show the interquartile ranges for data at 1400 UT in July of 1972, 1984 and 1994.

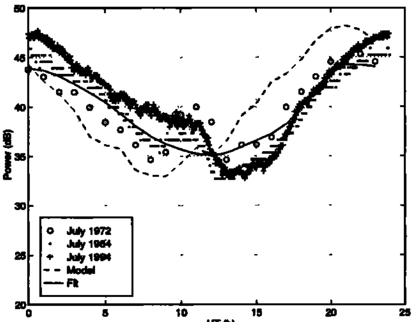

Figure 2. July diurnal ranges for 1972, 1984 and 1994, the best fit to the diurnal variation from complete dataset, and the modelled diurnal variation from *Clilverd et al.*, [1998]

tematic components [*Clilverd et al.*, 1998; *Smith and Jenkins*, 1998] due to changing source and propagation conditions. A solar cycle effect due to propagation may also be expected. An additional large source of variability is intrinsic non-systematic scatter between individual days for the same UT. This is indicated by the bars on figure 1, which are the interquartile range of the measurements at 1400 UT during July 1972, 1984 and 1994, and are of magnitudes 3.05, 3.3 and 2.45 dB respectively.

Inspection of Figure 1 does not suggest an increase in 10 kHz radio noise at Halley over 25 years. The slope of the plotted linear least squares fit to the monthly medians is (0.026) dB yr^{-1}, giving a total change in power over 25 years of 0.66 dB, which is smaller than both the interexperimental calibration uncertainties noted above.

We have treated the data in an alternative way by performing a least squares fit of the data time series P_i sampled at one hour resolution to a function which contains a sum of solar cycle, annual and diurnal terms. The fit function was $f(\{a_j\}, t)$ and is expressed in terms of unknown parameters a_j. The best fit was obtained by finding a set of values of a_j which minimises the sum of the squares of the differences between P_i and the fitting function, i.e. $\sum_{i=1}^{N} |P_i - f(t_i)|^2$, using the IDL procedure CURVEFIT. The advantage of this procedure over conventional Fourier spectral analysis is that it uses all available points without regard to spacing. Our model function was $f(t) = f_{\text{lin}}(t) + f_{\text{day}}(t) + f_{\text{year}}(t) + f_{\text{sol}}(t)$. The linear part is just

$$f_{\text{lin}}(t) = a_0 + a_1 t. \tag{1}$$

The model daily variation is a 5th order harmonic expression

$$f_{\text{day}}(t) = \sum_{n=1}^{5} (a_{2n} \sin n\omega_1 t + a_{2n+1} \cos n\omega_1 t) \tag{2}$$

with $\omega_1 = 2\pi$ day^{-1}. Similar expressions hold for the coefficient s of the yearly ($\omega_2 = \omega_1/365.242$) and solar cycle ($\omega_3 = \omega_2/10.25$) models (with coefficients a_{12} to a_{21} and a_{22} to a_{31} respectively). Thus for example a semiannual variation is naturally included as a_{14} and a_{15}.

The diurnal variation $f_{\text{day}}(t)$ obtained from applying this technique is shown in Figure 2. The fitted curve is seen to have a minumum at 13 UT and a maximum at 23 UT. The difference in shape between this and the familiar Carnegie curve [*Markson*, 1986], is well accounted for by a simple model which sums the activity variation for Africa and South America weighted by representative propagation factors obtained for Liberia and Argentina respectively to Halley [*Clilverd et al.*, 1998]. African thunderstorm activity has relatively little influence on Halley diurnal variation because propagation conditions deteriorate prior to the local afternoon peak in activity. The small peak in spectral power at 10 UT represents the start of the increase in African activity, but sunrise, followed by daytime conditions, along both propagation paths soon reduces any sferic signal strength at Halley. In consequence South America has the dominant effect on the lightning statistics at Halley. In contrast sunset, followed by nighttime conditions, along the propagation path occurs just as the afternoon peak in thunderstorm activity is reached in South America. As noted by *Clilverd et al.* [1998] the combination of attenuation and source factors with the response of the instrument explains a fitted amplitude ($f_{\text{day}}(t)$) of about 8 dB peak–to–peak, the largest in amplitude of the three fundamental frequency components used in $f(t)$. This is larger than the approximately 3 dB discernable in the 8 Hz Schumann resonance mode, see figure 1 of [*Satori and Zieger*, 1996], because of the propagation effects not present in that technique. The fit may be compared in figure 2 with the diurnal curves obtained from medians of hourly values for each day of the months July 1972 (MCR Mk I), July 1984 (MCR Mk II) and July 1994 (VELOX), and also with the model of [*Clilverd et al.*, 1998]. The average behaviour represented by f_{day} would not be expected to match any particular month owing to seasonal variations.

The fitted annual component (a_{12} and a_{13}) is of amplitude 0.8 dB peak to peak. It has a maximum in October and minimum in April. We also see a semi-annual component of amplitude 1.14 dB peak to peak whose physical origin is discussed in *Williams*, [1994] and which is also identified by ELF observations [*Satori and Zieger*, 1996; *Füllekrug and Fraser-Smith*, 1997]. For comparison we estimate the analogous amplitudes from figure 7 of [*Satori and Zieger*, 1996], to be about 1.8 dB peak to peak, and from figure 3 of [*Füllekrug and Fraser-Smith*, 1997] to be about 7 dB peak to peak. Taking the annual and semiannual terms and the 3rd, 4th and 5th harmonics together we obtain a variation f_{year} whose amplitude is ~ 2.4 dB peak–to–peak and again resembles the functional form found in *Clilverd et al.* [1998] i.e. it has peaks in March and October, and a minimum in May. We are indebted to a referee for the observation that the northern hemisphere midlatitudes are not well sampled from Halley, resulting in an underestimation of the northern hemisphere summer lightning (June to August) which may explain the March and October peaks.

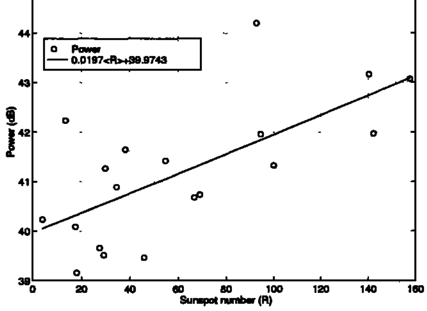

Figure 3. Yearly averages of monthly median power plotted against annual sunspot number.

A factor to be considered with ground-based VLF detection is that the propagation is via the ionosphere, and so a harmonic term due to the 11-year solar cycle is anticipated, making the detection of a trend in a dataset shorter than one cycle (c.f.[*Füllekrug and Fraser-Smith*, 1997]) problematic. To confirm the presence of a solar cycle dependence, we plot the annual means of the monthly medians against sunspot number Figure 3. The value of the correlation coefficient between these signals is 0.67 which for 17 degrees of freedom is significant at the 99.5 % level. We can thus infer the presence of a solar cycle effect with high confidence. The harmonic fit then gives its phase, and amplitude with minima in 1975, 1985 and 1995.

Finally we note that the slope a_1 of the linear part (equation 1) of the full least squares model is (0.058 ± 0.0008) dB yr^{-1} with a mean a_0 of (41.0 ± 0.014) dB. The effect of this slope would be to give a rise of 1.4 ± 0.02 dB in 25 years. However, taken between 1983 and 1995 (where the great majority of points contributing to the fit are found) it would be only 0.7 dB which is less than the uncertainty on the intercalibration factor between the MCR Mk II and VELOX data. Repeating the fitting procedure with CR Mk II to VELOX offsets of $9.5 + 1.5$ dB and $9.5 - 1.5$ dB gives slopes of -0.04 dB yr^{-1} and 0.16 dB yr^{-1}, and thus estimated changes in 25 years of -1.14 and 4.06 dB respectively.

Conclusions

The measured levels of very low frequency (VLF) radio noise at $\sim$ 10 kHz, primarily due to South American lightning sferics, observed at Halley Station, Antarctica between 1971 and 1996, show several clear periodicities. Through least squares fitting of a simple model we have confirmed the presence in the data of the characteristic diurnal 8 dB peak-to-peak and annual 2.3 dB peak-to-peak modulations observed by *Clilverd et al.* [1998]. That method and also cross correlation of annual averages of the monthly median 10 kHz VLF power with sunspot number reveal for the first time a $\sim$ 4 dB peak-to-peak fluctuation at the $\sim$ 11 year solar cycle period. The variation of EUV production rate over the solar cycle is known to influence the ionospheric D region. It is thus likely that that some part of the observed modulation is due to propagation effects, but other atmospheric effects due to solar activity cannot be ruled out at present.

In addition, we consider two estimates of the possible linear change in power over this period. A linear fit to the monthly medians has a small slope of about 0.66 dB in 25 years. An alternative fit including fifth order diurnal, semiannual, annual and solar cycle components gives 1.4 ± 2.6 dB after due allowance for the uncertainty in the intercalibration factors between the 1983-90 and 1992-present data. A receiver with a time resolution of 10 ms and background noise levels of 15 dB (i.e. the VELOX at Halley) would produce spectral powers of about 41 dB (the medians of the MCR Mk II and VELOX data are 41.78 and 41.74 dB respectively) given 60-65 flashes per second, each with a typical received power of 57 dB, and a logarithmic averaging process i.e. (60x57 + 40x15)/100=40 dB [*Clilverd et al.*, 1998]. A increase of 1.4 dB corresponds to an increase of 3 flashes per second i.e 5 %. The large range of estimates of the trend means that we cannot state definitively that a positive trend is present. However, if we use the largest trend possibly present in the data, combined with the $\sim$ 0.5 degree C mean global temperature increase observed since 1970, we can say that this is a similar order of sensitivity to the 10 % per degree C of [*Price and Rind*, 1994] rather than the earliest local estimates [*Williams*, 1992] of order 100 % per degree C.

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References

Barr, R., The ELF and VLF amplitude spectrum of atmospherics with particular reference to the attenuation band near 3 kHz, *J. Atmos. Terr. Phys. 32*, 977–990, 1970.

Bullough, K., A. R. W. Hughes, T. Hudson, D. Hickinson, P. Broomhead, and P. Tomlinson, The Sheffield University experiment on the satellite Ariel 3, *J. Sci. Inst. Series 2, 1*, 77-85, 1968.

Clilverd, M. A., N. W. Watkins, A. J. Smith and K. H. Yearby, Interpreting 10 kHz radio noise variations, submitted to *Radio Sci.*, 1998.

Dudeney, J. R., A. S. Rodger, A. J. Smith, M. J. Jarvis and K. Morrison, Satellite Experiments Simultaneously with Antarctic Measurements (SESAME), *Space Science Reviews, 71*, 705-742, 1995.

Füllekrug, M. and A. C. Fraser-Smith, Global lightning and climate variability inferred from ELF magnetic field variations, *Geophys. Res. Lett., 24*, 2411-2414, 1997.

Houghton, J. T. et al. (Eds.), *Climate change 1995: the science of climate change*, 572 pp., Cambridge University Press, Cambridge, 1995.

Markson, R., Tropical convection, ionospheric potentials and global circuit variation, *Nature, 320*, 588-594, 1986.

Price, C. P., Global surface temperatures and the atmospheric electrical circuit, *Geopys. Res. Lett., 20*, 1363-1366, 1993.

Price, C. P. and D. Rind, Possible implications of global climate change on global lightning distribution, *J. Geophys. Res, 99*, 10823-10831, 1994.

Satori, G. and B. Zieger, Spectral characteristics of Schumann resonances observed in Central Europe, *J. Geophys. Res, 101*, 29663-29669, 1996.

Smith, A. J., and K. H. Yearby, AVDAS - A microprocessor-based VLF signal processing and spectral analysis facility for Antarctica, *Br. Antarct. Surv. Bull., 75*, 1-15, 1987.

Smith, A. J., VELOX: a new VLF / ELF receiver in Antarctica for the Global Geospace Science mission, *J. Atmos. Terr. Phys., 57*, 507–524, 1995.

Smith, A. J. and P. J. Jenkins, A survey of natural electromagnetic noise in the frequency range: $f = 1 - 10$ kHz at Halley station, Antarctica: 1. Radio atmospherics from lightning, *J. Atmos. Sol.-Terr. Phys., 60*, 263–277, 1998.

Williams, E., The Schumann resonance: A global tropical thermometer, *Science, 256*, 1184-1187, 1992.

Williams, E., Global circuit response to seasonal variations in surface air temperature, *Monthly Weather Review, 122*, 1917-1929, 1994.

N. W. Watkins, M. A. Clilverd, A. J. Smith, Upper Atmospheric Sciences Division, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK. (e-mail: m.clilverd @bas.ac.uk; a.j.smith@bas.ac.uk; n.w.watkins@bas.ac.uk)

K. H. Yearby, Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield, S1 3JD, UK. (e-mail: k.h.yearby@sheffield.ac.uk)

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