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Balloon observations of temporal variation in the global circuit compared to global lightning activity

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Abstract

Vertical electric current density was obtained from direct electric field and conductivity measurements on two stratospheric balloon payloads during the 2nd polar patrol balloon (PPB) campaign from Syowa Station in Antarctica during January 2003. Payloads of these two flights were identical and were launched 8-h apart resulting in separation distances of a few hundred km during the time of overlapping data. The float altitude of each was a little over 30 km. The global circuit return current derived from these measurements is compared to the global lightning activity determined by the world wide lightning location (WWLLN) network. The total number of lightning events detected anywhere in the world are simply summed to form an hourly lightning flash rate for the time of the PPB data. The WWLLN and return current density data are shown to have a strong correlation, often with a strong universal time daily variation, similar to that expected for the global circuit.

Keywords: Polar patrol balloon; Balloon; Stratosphere; Electric field; Global circuit; Lightning; World wide lightning location

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1. Introduction

Months of simultaneous, stratospheric balloon-borne electric field and conductivity measurements during two different experiments have shown that the vertical current density, measured by widely separated balloons, varies coherently, and is suggested to be representative of the large scale regional and global circuit return current (Holzworth et al., 1984; Norville and Holzworth, 1987). The global return current, measured in this manner, should be representative of the instantaneous level of global electrical activity, as suggested originally by Wilson (1920) (see also Holzworth and Volland, 1986). Until now, there has been no direct proof that the stratospheric vertical current density variations follow the global electrical activity, because until recently there

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has not been a successful experiment to simultaneously measure both the real time return current density and the global electrical source variation.

Wilson's global circuit hypothesis implies that there should be a daily variation in the global return current due to the uneven distribution of land mass around the globe (cf. Chalmers, 1967). This daily universal time (UT) variation was discovered in the data from shipboard electric field measurements taken on the Carnegie and other ships as they sailed in various oceans. These data, now referred to as 'the Carnegie Curve' were found to be organized in UT in a manner agreeing with Wilson's global circuit hypothesis coupled with a crude model for the distribution of global land mass (Whipple and Scrase, 1936) over which most thunderstorms occur. This was seen as strong support for Wilson's global circuit hypothesis, and subsequent measurement have also found this same correlation in heavily averaged data (cf. Holzworth et al., 1984; Woosley and Holzworth, 1987; and others.)

However, in the 1984 paper by Holzworth et al., it was pointed out that, while the average of two weeks of data agreed with the Carnegie curve, it was seen that on shorter time scales of 1 day or less, the Carnegie curve shape was not always evident on individual days. That is, while two simultaneous measurements agreed, the resulting curve did not resemble the Carnegie curve. Holzworth et al. (1984) attributed this to variations in the regional or global source current on scales of 10 min to one day. Such variations can be caused by changes in the various possible global current sources, such as the instantaneous distribution of global thunderstorms, or to other changes in the global circuit elements, such as cloudiness or cosmic ray effects on ground-to-ionosphere electrical resistance.

The theoretical 'land mass' argument about the manner in which the global circuit ought to vary does not include the possibility of weather variations on daily and regional scales. Thus, the data of Holzworth et al. (1984) can be interpreted as still representative of the global return current variations, but that the source function is not constant day to day. However, until recently there has been no independent measure of the global electrical source function which might drive the global circuit. For instance, if the source is in fact the action of global thunderstorms, as Wilson proposed, then a measure of the global thunderstorm activity should have a variation that is correlated with the global return current, at least on time scales longer than the time constant for the global circuit, variously suggested to be between 5 and 40 min (cf. Hays and Roble, 1979).

This paper presents the first data set in which long duration, simultaneous stratospheric balloons took return current measurements, while at the same time, a new, real time measure of global lightning activity was available. This paper will describe these data sets, and show the comparison of the temporal variations. The data were taken in January 2003 during the polar patrol balloon (PPB) experiment of the National Institute of Polar Research (NIPR) of Japan in conjunction with the University of Houston and the University of Washington. Bering et al. (this issue) has described the electric field detector (EFD) and the conductivity measurements taken during the campaign. Also, Dowden et al. (2002) and Lay et al. (2004) have described the world wide lightning location (WWLLN) network, which detects individual lightning strokes anywhere in the world.

The results from comparing the count rate of lightning strokes as it varies in time, with the variations in the return current density indicate a positive correlation, even though the WWLLN network was covering the world with uneven efficiency at the time.

We will present the vertical current density and WWLLN data with hourly time resolution, where a clear correlation will be evident. Since the WWLLN data did not have the coverage extent now available from the network (see http://webflash.ess.washington.edu) this correlation must be considered as a preliminary step at demonstrating the global circuit is driven by real time variations from thunderstorms. The lightning count should be considered as a thunderstorm index and not as a direct measure of the source current because only cloud-to-ground lightning actually affects the global return current, but the WWLLN data include both cloud to ground and intercloud lightning.

2. Vertical current density

The polar patrol balloon (PPB) project has a long and productive history as discussed in Bering et al. (this issue) and included the electric field detector (EFD) for vector electric field measurements. This set of probes and amplifiers involves a set of orthogonal, high impedance, Langmuir probes. This technique for measuring electric field and conductivity has been in use since the 1960s (see Kellogg and Weed, 1968; Mozer and Serlin, 1969) with updated electronics discussed in Holzworth and Bering (1998).

As discussed in Bering et al. (this issue) PPB balloons PPB-8 and PPB-10 were flown in January 2003 and we obtained about two weeks of simultaneous EFD data from each. The EFD is also used for conductivity measurements by the relaxation technique; the conductivity data are the subject of Bering et al. (this issue). The present paper will use the results of those negative conductivity measurements (which are not effected by photoemission, as shown by Byrne et al., 1990), coupled with the vertical electric field measurements to form the vertical current density $Jz = Ez * 2 * \sigma\_$, where Ez is the vertical electric field and $\sigma\_$ is the negative polar conductivity, which is doubled here to account for both positive and negative conductivity (i.e. total conductivity σ). We use the vertical current density both because it is the relevant quantity for global current comparisons, as well as the fact that the small vertical motions of these balloons will not confuse the vertical current density, which is relatively constant with altitude (Holzworth, 1991); unlike Ez and σ each of which varies roughly exponentially with height as $e^{-z/H}$ and $e^{+z/H}$, respectively, where H is the scale height being typically between 6 and 8 km at this altitude.

Fig. 1 presents the magnitude of the vertical current density from both PPB-8 and PPB-10 for the duration of the time we have overlapping data, along with the average of these two measurements (black line.) The direction of this vector current density is vertically downward, with an average magnitude between 2 and 4 pA/m^2. The strong diurnal variation of the current density is evident in this plot. One can also notice that there are times when the vertical current densities from the two payloads measure slightly different values, and furthermore that Jz for PPB-8 is about 1 pA/m^2 larger than for PPB-10 throughout most of these two weeks. This could be due to many factors, such as some as yet unaccounted for but slight electronic offset for one payload which is different than the other. However, since we are interested in comparing the daily variations with the global lightning data, we will remove the dc offset and just look at the variation in the data when we calculate the correlation coefficient. Also, times when Jz is significantly different between the two payloads may indicate one or the other is being strongly influenced by local electrodynamic phenomena, such as thunderstorms, electrified clouds, orography, etc.

As shown by Bering et al. (this issue), the conductivity is relatively constant in time to within a few tens of percent, whereas the diurnal variation of Jz is typically a factor of 2 or more. Additionally, the balloon altitude was very constant during this time in each flight, and did not begin significant altitude variations until late in the time interval (after January 26 about). As noted, such altitude variation should not strongly effect the Jz, in any event. This is the value of considering Jz instead of comparisons with either Ez or σ directly.

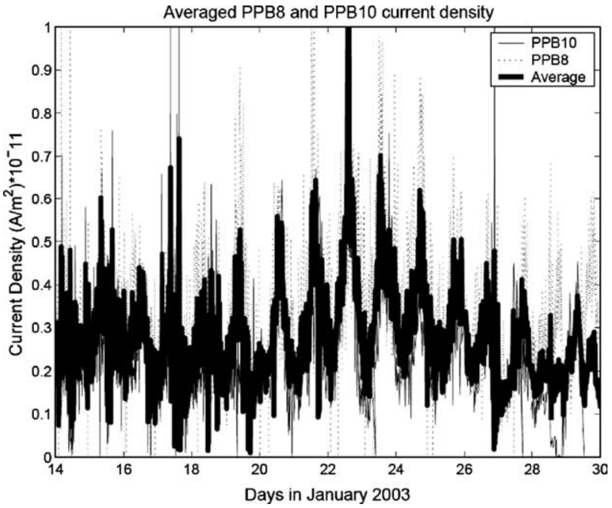

Fig. 1. Average current density from balloons PPB8 (dotted line) and PPB10 (thin line) for 16 days during which we obtained simultaneous data. The dark, solid line in the middle is the average.

Therefore, we argue that the large diurnal variations seen in Fig. 1 are not caused by either the balloon motion or by the conductivity. The black line is the average of the two values of Jz from the two independent data sets from PPB-8 and PPB-10, whose trajectories are given by Bering et al. (this issue).

3. WWLLN global lightning data

The WWLLN Network uses VLF sferic detection at multiple stations to locate lightning. The network has been described by Dowden et al. (2002); and Lay et al. (2004) and its data base is presently available in real time at http://webflash.ess.washington.edu. Each station time tags detected sferics and sends a short data packet to a central computer with the highly accurate time (using GPS – Global Positioning System, which is accurate to much better than a microsecond.) Dual central processing computers (in Seattle, Washington, USA, and Dunedin, New Zealand) calculate the best fit positions using only sferics detected by 4 or more receivers, and conduct careful error analysis. The Network has been running for several years in the Pacific region, and it expanded globally in the middle of 2002. The network is continuing to expand, and has nearly twice as many sferic receiving stations today than it did in January 2003 during this PPB experiment. Nevertheless, the network has been shown to be highly accurate in time (within a microsecond timing) and to within about 10 km in distance, even for lightning over continents where no detectors existed (Lay et al., 2004).

We have taken all the located lightning events during the PPB campaign and developed a running global total of lightning events detected by the WWLLN Network. Every hour we add up all the lightning events everywhere in the world as detected by WWLLN. These data during the PPB campaign are shown in Fig. 2 where a strong diurnal variation is easily seen. In this figure, we note the Poisson error bars; the individual lightning events are located with high accuracy in time and space, so these are not error bars for measurement error. Also note that during this interval there was about a two day interval in which the WWLLN data were unavailable. Our primary data comparison below will focus now on the time after this data dropout, and up to the time when the two balloons were seeing the largest daily variations – from noon on January 21 to about January 27.

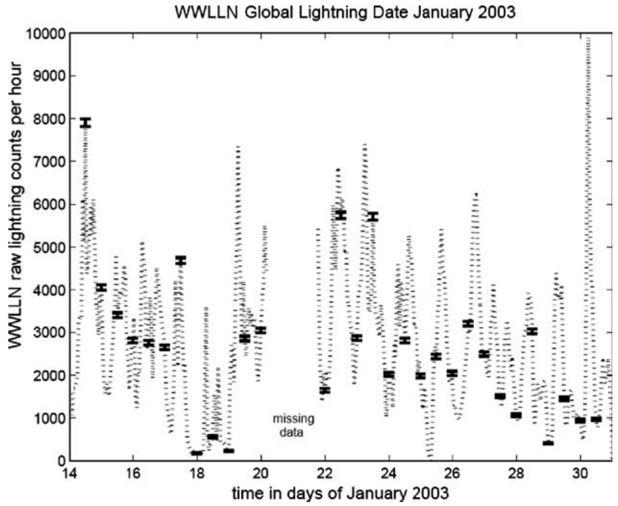

Fig. 2. World wide lightning location network (WWLLN) data for January 2003. The line represents the running average, proportional to total lightning, and the error bars are the Poisson statistical error. Note there were two days in the middle when no data were available during these early days of the WWLLN network.

Lay et al. (2004) conducted a comparison study with a conventional ground based lightning location network in Brazil and found that the average peak current for the WWLLN events was between 70 and 80 kA which is about 3 or 4 times larger than the average lightning event seen with the ground based networks. This shows that the WWLLN data are biased to the larger lightning events, and will disproportionately miss weak lightning strokes compared to strong events. This is primarily due to the fact that we require four sites to detect each located lightning event before we publish it. This usually means that stations that measure an event are between 1000- and 5000-km away from the lightning, in most cases. VLF in the 3–24 kHz band travels in the earth–ionosphere wave guide with relatively little attenuation, especially over water (Wait, 1962). In our case, we conducted a station by station analysis to see the region over which each station is likely to participate in the location of global lightning. This region varies day and night, because of the difference in ionospheric conditions, but is typically about 6000- or 7000-km radius in the day, and 10,000–12,000 km for night time propagation.

4. Lightning and return current comparison

Fig. 3 presents a comparison between the PPB *Jz* electric current density and the WWLLN hourly lightning counts for the duration of the overlap between the two PPB balloons. The dotted line presents the raw lightning count data from Fig. 2, and the black line the average *Jz* for the two PPB data sets. It can be seen that there are some apparent general agreements at times, but other times the curves are less well correlated.

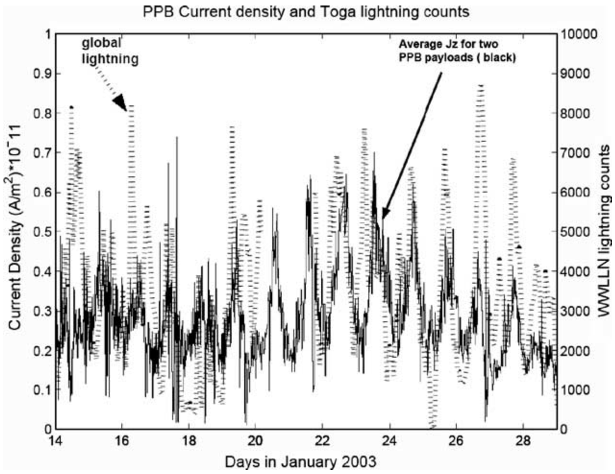

Fig. 3. Data from Figs. 1 and 2 are combined. Here, the WWLLN data from Fig. 2 are dotted and the *Jz* average from Fig. 1 is the solid line.

We then focused on the times when the strongest diurnal signal was seen in the *Jz* data to make a close up comparison with the WWLLN data. Fig. 4 presents about a week subset of the data in Fig. 3. Here, it can be seen that there is an apparent correlation between the average *Jz* and the lightning for much of the time interval. The specific times when the comparison is the worst are usually around 0600 UT on many of the days, when the lightning and the *Jz* data appear to be sometimes out of phase. This represents a time when the Pacific ocean is in the late afternoon where the sensitivity of WWLLN network was a maximum for this time in January 2003. Therefore, this may be an artifact of the methodology, and not really representative of a local maximum in global lightning.

We have conducted a cross-correlation between the hourly average *Jz* (black line in Figs. 1, 3, and 4) and the raw WWLLN lightning counts (Fig. 2, and green

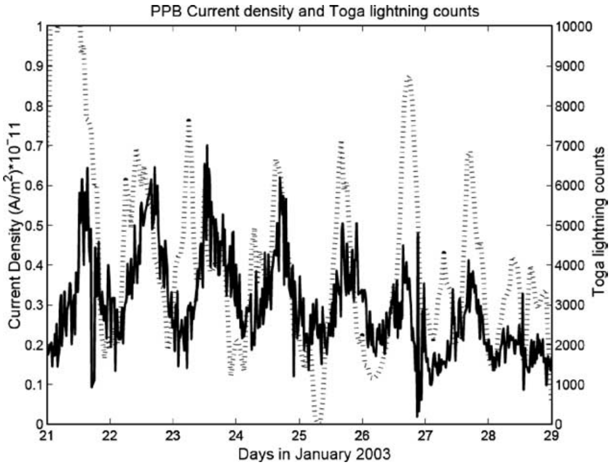

Fig. 4. This is an expanded set of data from Fig. 3 showing a week of comparison between *Jz* and WWLLN total lightning variation estimate.

line in Figs. 3 and 4) for the times in Fig. 4 (between 2130 January 21 and 00 January 29). Even with the obvious times of disagreement, the correlation coefficient $r = 0.46$ which indicates that the probability the data sets could be produced by random noise is extremely low (<4 in 10^9).

5. Discussion

We have reported a fortuitous set of overlapping observations from stratospheric balloons over Antarctica and a new global lightning data set. The PPB balloon flights 8 and 10 from Syowa, Antarctica, a station operated by NIPR (National Polar Research Institute) of Japan, resulted in simultaneous vertical current density (Jz) measurements for over two weeks in January 2003. Such simultaneous vertical current density measurements from separated balloons have been shown to be representative of regional and global circuit return current density as long as both balloons are not close to local electrical influences. Such local influences as thunderstorms or electrified clouds are rare in Antarctica, so we have taken the average of the very similar values for Jz from the two PPB flights to form a running value we expect is closely related to the global circuit return current. This method has been reported and analyzed by Holzworth et al. (1984) and Norville and Holzworth (1987) and proposed by Holzworth and Volland (1986) as the basis for a geoelectric index.

It is worth noting that others are also looking at this comparison of global lightning activity and possible effects on geoelectric activity. Recently, Troshichev et al. (2004) found no relationship between surface electric field variations at Vostok, Antarctica and the occurrence of intense lightning, as determined by extremely low frequency (ELF) magnetic field fluctuations. Such magnetic fluctuations in this Schumann Resonance band have been shown to have a strong nodal effect, depending on lightning source and receiver locations (Sentman (1987)), which is unlike the vertical electric field, which has no such nodal pattern at ELF.

As it turns out, just a few months prior to these balloon flights, a new global lightning detection system was just coming on line. The WWLLN or world wide lightning location network started to produce global maps of lightning locations in real time beginning just 6 months prior to the PPB campaign (Dowden et al., 2002). The WWLLN network is still expanding, and is not yet at full, uniform global coverage, but nevertheless, in January 2004 there was a data set of lightning occurrence which was worthy of being compared to the global return current measurements.

In the meantime, the WWLLN team had conducted analysis to determine the accuracy of the lightning detection by direct comparison between different lightning location data sets (Lay et al., 2004). These studies showed that the WWLLN lightning locations were both highly accurate, and representative of the higher peak current lightning strokes. The Lay et al. (2004) study also showed that WWLLN, although accurate, was detecting only a few percent of the global strokes.

We used the average Jz from the PPB balloons and the raw lightning count rate to show a direct correlation in temporal variation (Figs. 3 and 4). This correlation is evident even by eye, although there were some residual uneven efficiency effects which could not be eliminated from the WWLLN count rate data. Even with these effects the correlation coefficient between two time series, hourly averages of Jz and raw hourly WWLLN count rate, was $r = 0.46$, indicating a high likelihood the two independent data sets are correlated. Note that we simply used the average Jz from the two payloads, but we could rightly have removed any times when the two values of Jz did not generally agree (as done by Norville and Holzworth, 1987) for these times may not be representative of a global signature.

These are preliminary observations and need to be repeated since the WWLLN network has more than twice as many receivers as in January 2003. Furthermore, this is only our first attempt at developing a global index using these WWLLN data. We know that the WWLLN data set includes both CG and IC lightning, so it is not a direct measure of the source function. Furthermore, we do not directly measure the lightning current moment, the main stimulant of the VLF sferic waves, so we cannot categorize our measurements as a function of source strength, or stroke polarity. Therefore, the WWLLN data in Figs. 2–4 should be considered as a preliminary attempt to develop a proxy index for the source variations of the global circuit.

With all these limitations, we nevertheless have shown that this comparison is very promising, and may be a useful technique for finally answering the question of what drives the global circuit, and how the return current is distributed. This is the first time a well accepted global return current measurement has been compared to a parameter related to the real time source function for the global circuit.

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