Lightning activity as an indicator of climate change

By N. REEVE and R. TOUMI*

Imperial College, UK

(Received 29 June 1998; revised 16 October 1998)

SUMMARY

Data from the Optical Transient Detector lightning sensor are analysed to investigate the hypothesis that global lightning activity will increase should the average global temperature increase. It is shown that changes in global monthly land lightning activity are well correlated with changes in global monthly land wet-bulb temperatures. The correlation is strongest in the northern hemisphere and weak in the southern hemisphere. The conclusion is that a high land-area to sea-area ratio is necessary for a good correlation. Contrary to expectation, the tropics show no correlation. The results predict that a change in the average land wet-bulb temperature of the globe of just 1K would result in a change in lightning activity of about 40%.

KEYWORDS: Optical Transient Detector Satellite observation

1. INTRODUCTION

The investigation of lightning in the global circuit has been hindered by the absence of adequate measurement methods. In the past, lightning observations could only be made locally, and obtaining a global picture was difficult; indeed, until recently, the most accessible global lightning dataset was based upon the record of ‘thunderdays’, i.e. those days on which a rumble of thunder was heard at local stations. Techniques for studying lightning underwent somewhat of a revolution with the development of sensors that could be deployed in space to view lightning on a large scale by the Ionospheric Sounding Satellite-b and Defense Meteorological Satellite Program (DMSP) (Mackerras et al. 1998). The DMSP greatly improved coverage but could only observe lightning during the night-time (Orville and Henderson 1986). In April 1995 the Optical Transient Detector (OTD) was successfully deployed in space via the Pegasus 4 rocket. It is the first lightning sensor to have the capability of viewing lightning activity, day and night, across the globe, and the dataset it produces provides us with the most comprehensive lightning dataset currently available. In this report we use observations of lightning activity from the OTD as an indicator of recent changes in climate.

It has been suggested (Williams 1992, 1994) that, because of lightning’s local sensitivity to surface temperature, lightning activity might be used as a sensitive indicator of changes in the average global temperature. Williams successfully correlates surface wet-bulb-temperature anomalies with an indirect measurement of global lightning activity called the Schumann resonance. The Schumann resonance is thought to be a standing electromagnetic wave in the earth–ionosphere cavity excited by global lightning. The dataset from the OTD gives us the best current global mapping of lightning; it is our aim in this report to show a similar relationship by correlating monthly land lightning activity, measured in flashes per month, with the monthly averaged land wet-bulb temperature. We have focussed on lightning over land because earlier work (MacKerras et al. 1998, and references therein) has shown that this is where lightning occurs and is sensitive to deep convection. We use wet-bulb temperatures, rather than dry-bulb temperatures, as it is thought to be a better proxy for convective available potential energy (Williams and Renno 1993).

There is further interest in lightning activity as a source of nitrogen oxides and, hence, tropospheric ozone. A positive climate-feedback process has recently been proposed (Toumi et al. 1996; Sinha and Toumi 1997). Lightning is also associated closely with

* Corresponding author: Department of Physics, Imperial College, London SW7 2BZ, UK.
extreme rainfall (e.g., Peterson and Rutledge 1998). There is a great deal of interest in
the possibility of more extreme rainfall events in global warming scenarios (IPCC 1996).
Lightning may therefore be a useful additional indicator in this context.

In section 2 we describe the structure, collection and handling of the datasets used
and the characteristics of the OTD sensor and parent satellite. In section 3 we attempt to
correlate lightning activity with wet-bulb-temperature variations. In section 4 we look at
the interannual variations of lightning for different regions, and an estimation of a global
flash rate is given in section 5. Conclusions are given in section 6.

2. RESOURCES AND DATA COLLECTION

The lightning data (May 1995 to February 1998) were gathered by the OTD, an
instrument aboard the Microlab-1 satellite (Christian et al. 1989; Christian and Latham
1998, and references therein). The satellite orbits at an altitude of 740 km in a plane inclined
at an angle of 70° to the equator and has an orbital period of 100 minutes. This means that
in a 24-hour time period the satellite completes 14 full orbits and falls 60 minutes short of
completing a 15th. The OTD sensor is based on a 128 by 128 photo diode array and has a
wide field-of-view lens. Any pulses of light associated with lightning activity are detected
by the photo diodes and are recorded. The instrument can process the data in situ to filter
out the background noise, allowing the instrument the capability of measuring cloud-to-
ground, cloud-to-cloud and intra-cloud lightning, day and night, with a 90% detection
efficiency. The detector has a spatial resolution of 10 km, a temporal resolution of 2 ms,
and a field of view that is 1300 km by 1300 km; it can, therefore, only view approximately
0.3% of the earth’s surface at a time. The OTD sensor produces four lightning data products;
‘event’ data are those produced by the triggering of a single detector pixel in the array and,
as such, can be thought of as the lowest level of the data categories. Processing, done by
the OTD instrument, uses these data to identify single lightning strokes, individual lightning
flashes and entire storms. A lightning stroke is called a ‘group’ and corresponds to one or
more adjacent events detected within the same 2 ms time frame; a ‘flash’ is the occurrence
of one or more groups sufficiently close together in space and time; while an ‘area’ is a
cluster of ‘flashes’ that are sufficiently separate and may be considered a ‘storm’. Here,
we use the ‘flash’ record. The OTD is assumed to have a lightning detection efficiency of
45–60% depending on conditions.

We map the seasonal changes to the land and sea lightning distribution. The map is
based on a Cartesian grid defined between 77.5°N and 77.5°S: the number of flashes found
to occur in each 2.5° by 2.5° grid square were normalized to account for viewing time by
the OTD sensor, thus removing the OTD’s bias to view high latitudes.

A further problem with the OTD data is due to the near-polar orbit the local time
of observations shifts, so that approximately a full local diurnal cycle is achieved in 55
days. Given that lightning has a strong diurnal cycle (Mackerras et al. 1998) this causes
problems when comparing the same months in different years. Ideally, one would want to
correct for this effect. However, a correction would require knowledge of the full diurnal
cycle for all the major zones. The current dataset is not sufficiently complete to achieve
this. This therefore must be considered a major uncertainty in our conclusions. We have
attempted to overcome this limitation partially by also calculating bi-monthly and seasonal
sensitivity; our conclusions remain unaffected.

The Analysis Branch of the Climate Prediction Centre (AB/CPC) produces the cli-
mate data at the National Oceanic and Atmospheric Administration of the United States
(NOAA). The climate data we use are produced at the CPC and are calculated from a
model based on ongoing measurements; monthly mean data values are given as functions
of latitude and longitude on a Cartesian grid with a resolution of 2.5°. Values for the wet-bulb temperature were not directly available and were calculated from two sets of data: 1000 mb pressure-level temperature (K) and 1000 mb pressure-level specific humidity (kg kg⁻¹).

3. **Correlation between Lightning and Wet-Bulb Temperature**

Figure 1 shows the seasonal variation of land lightning activity and land wet-bulb temperature for the northern and southern hemispheres. The northern hemisphere exhibits the strongest periods of lightning activity when the wet-bulb temperature is at its peak, and suggests a strong correlation between the two parameters. There are some fluctuations in the lightning graph (most notably June 1995 and August 1997) which are expected as a consequence of deep convection and lightning being dependent on a multitude of factors, not just on the wet-bulb temperature. The southern hemisphere exhibits a strong dependency on the wet-bulb temperature as well, but the relationship is considerably
noisier. We conclude that land temperature-driven convection is important to the production of lightning in the southern hemisphere but that the process is more susceptible to other influences. The difference between the northern and southern hemispheres is accounted for by the different land fractions. The northern hemisphere, as a result of its large land-to-ocean ratio, is influenced greatly by solar heating, and convection is likely to be deep and driven by changes in surface temperature. In the southern hemisphere, however, the land area is considerably less than the ocean area, and temperature-driven convection is likely to be dominated by larger-scale circulation patterns. Using just land wet-bulb temperature is thus a poor proxy for conditional instability.

Figure 1 also shows the seasonal variation for the globe and for the tropics. Since the variations in the southern hemisphere signal are small, the global response is dominated by the northern hemisphere and shows a good correlation. The tropics, however, show no clear correlation; we note that the wet-bulb-temperature variation in this region is very small (an order of magnitude less than that for the northern hemisphere); any temperature-dependent signal, therefore, might be obscured by noise or be completely eclipsed by dominant large-scale convection patterns, such as monsoons (e.g. Bhattacharya et al. 1997). It should be noted that the quality of the reanalysis data is poorest in the tropics (particularly Africa), so that the lack of sensitivity may also be due to errors in the calculated temperature anomaly. The National Centers for Environmental Prediction (NCEP) data are far from perfect, with deficiencies in boundary-layer and moisture parametrizations (e.g. Yucel et al. 1998). Nevertheless, it probably represents the best current estimate of regional-scale temperature.

To assess how variations in lightning activity are related to changes in temperature, we attempt to remove the seasonal cycle from the dataset. This is done using a scatter plot of the lightning and wet-bulb-temperature monthly anomaly (i.e. variations compared with the mean of like months). The scatter plot gives us a direct way of viewing the relationship between lightning activity and wet-bulb temperature, and allows us to quantify the magnitudes of the changes involved.

Figure 2 shows the monthly anomalies of land flash count and land wet-bulb temperature for different areas of the globe. All of the anomaly plots exhibit a broad scatter in the distribution of data points. The northern hemisphere exhibits the strongest correlation and the greatest sensitivity to variation. The gradient of the best-fit line indicates that we might expect a 56% increase in lightning activity should the average land wet-bulb temperature in the northern hemisphere rise by just 1 K. In comparison, the southern hemisphere anomaly plot shows very little correlation even though some dependency might have been inferred from the seasonal cycle shown in Fig. 1. We note that the range of temperatures in the southern hemisphere is significantly smaller than for the northern hemisphere and, as such, any temperature-dependent change in lightning activity is likely to be obscured by the noisiness of the plot. If we restrict ourselves to looking at a similar range of temperatures for the northern hemisphere a good correlation would not be obvious.

As expected, the global anomaly plot is a combination of the strong northern hemisphere response and the weak southern hemisphere response. From the gradient we predict an average global increase in lightning activity of 40% should the average global wet-bulb temperature rise by 1 K. This figure is several times larger than the 5–6% lightning sensitivity estimated from the Goddard Institute for Space Studies general-circulation model and a parametrization of lightning frequency in terms of cloud-top height (Price and Rind 1994). Another indirect method (Price 1993) using observations of the ionospheric potential estimates a lightning sensitivity of 7% K⁻¹. We note that our estimate is a more direct measure of interannual lightning sensitivity and is perhaps more germane to global warming.
Figure 2. Monthly flash-count anomaly (%) against wet-bulb surface-temperature anomaly (K) for land surface only in (a) the northern hemisphere, (b) the southern hemisphere, (c) the globe, (d) the tropics, (e) the extratropical region of the northern hemisphere, and (f) the extratropical region of the southern hemisphere.
TABLE 1. LAND LIGHTNING SENSITIVITY TO WET-BULB TEMPERATURE FROM THE SLOPE OF LEAST SQUARE FIT, STANDARD ERROR OF SLOPE AND CORRELATION COEFFICIENT, $R^2$, OF FIT.

<table>
<thead>
<tr>
<th>Region</th>
<th>Monthly Sensitivity (% K^{-1})</th>
<th>Monthly $R^2$</th>
<th>Bi-monthly Sensitivity (% K^{-1})</th>
<th>Bi-monthly $R^2$</th>
<th>Seasonal Sensitivity (% K^{-1})</th>
<th>Seasonal $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globe</td>
<td>40 ± 14</td>
<td>0.20</td>
<td>41 ± 20</td>
<td>0.22</td>
<td>49 ± 25</td>
<td>0.30</td>
</tr>
<tr>
<td>Northern hemisphere</td>
<td>56 ± 15</td>
<td>0.32</td>
<td>61 ± 22</td>
<td>0.33</td>
<td>65 ± 32</td>
<td>0.32</td>
</tr>
<tr>
<td>Southern hemisphere</td>
<td>11 ± 14</td>
<td>0.02</td>
<td>4 ± 16</td>
<td>0.00</td>
<td>-2 ± 24</td>
<td>0.00</td>
</tr>
<tr>
<td>Tropics</td>
<td>1 ± 12</td>
<td>0.00</td>
<td>-1 ± 16</td>
<td>0.00</td>
<td>-1 ± 20</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Values are for monthly, bi-monthly (Jan., Feb., March April, May June, July Aug., Sept. Oct., Nov. Dec.) and seasonal (December to February, March to May, June to August and September–November) analyses.

The tropical anomaly plot exhibits no clear correlation. Williams (1992), using local measurements at different stations in the tropics, inferred that tropical lightning would exhibit the strongest sensitivity to wet-bulb temperature (in excess of 100% K^{-1} at local stations). Our results, however, indicate that though this sensitivity might be evident locally, it is not a feature on a wider scale, at least when using current NCEP reanalysis data. We conclude that it is not appropriate to attempt to characterize the tropics using large-scale averages. Extremely low-frequency observations (Satori and Ziegler 1996; Fulkekrug and Fraser-Smith 1997) seem to support increased sensitivity in the tropics. However, their analysis is also based on a seasonal sensitivity. Here, we use interannual sensitivity, which may be more appropriate for global-warming scenarios.

The anomaly plots for the extratropical regions of the northern and southern hemispheres (Fig. 2) provide us with an insight into the effect of the tropical convection patterns on the correlation. What is of interest is that the removal of the tropical signal results in a better correlation for the southern hemisphere ($29 \pm 14\% K^{-1}$, $R^2 = 0.18$ where $R$ is the correlation coefficient) but a worse correlation for the northern hemisphere ($40 \pm 15\% K^{-1}$, $R^2 = 0.13$). This might be explained by the lesser proportion of land between the equator and 23.5°S, compared with that between the equator and 23.5°N. By considering latitudes greater than 23.5°S, we remove a region in which local temperature-driven convection is less significant than large-scale convection patterns. As a result, the signal is improved. If, on the other hand, we consider only latitudes greater than 23.5°N, we remove a region which, by virtue of a greater land area, may contribute positively to the correlation, and the signal is weakened. We note that if we remove the tropics from the southern hemisphere signal, then the land area we view is very small (just the tip of South Africa and South America and south Australia). Clearly, the results of the extratropical plots should be treated tentatively. Global mean monthly dry-bulb temperatures show a lower sensitivity of $24 \pm 22\% K^{-1}$ with a poor correlation ($R^2 = 0.04$). This poor correlation is largely due to the inclusion of sea surface temperatures, which are co-incident with less than 10% of the global lightning activity. The northern hemisphere dry-bulb sensitivity is thus somewhat larger $27 \pm 17\% K^{-1}$ with a better fit ($R^2 = 0.07$).

Table 1 shows calculated sensitivity and correlation using monthly, bi-monthly and seasonal wet-bulb-temperature anomalies and seasonal lightning observations. The global sensitivity is larger when using seasonal values, but the standard error of the slope is also considerably enhanced. The tropics shows no signal in all cases and the southern hemisphere shows weak sensitivity. Although a diurnal bias cannot be completely excluded, the lack of a tropical sensitivity is a consistent feature. It is also noteworthy that both the tropics and northern hemisphere analyses cover the same local time range, but only the northern hemisphere as a whole shows a positive sensitivity.
Figure 3. Seasonal (June to August) total flash count for the northern hemisphere for (a) 1995, (b) 1996 and (c) 1997.

4. THE GLOBAL LIGHTNING DISTRIBUTION

Figure 3 shows the global lightning activity for the northern hemisphere summers for 1995–97. We identify the four dominant regions of activity as North America, Central Africa, India and Nepal, and East Asia. There has been an increase in lightning activity over North America and Central Africa. The increase is characterized by the appearance of local,
highly intense (greater than one million flashes) regions of activity, which are consistent with observed precipitation patterns (Bell and Halpert 1998). The other seasons exhibit no clear regional changes over the three years. The broad feature apparent over South America and the South Atlantic in all seasons is a result of the South Atlantic Anomaly (SAA). This is a region where the satellite passes through the earth’s magnetic-field lines causing spurious lightning detection (Wohman, personal communication). This is most clearly apparent in the northern hemisphere summer, when we expect little lightning activity in that region. Since the SSA is mostly over the ocean and a systematic offset it should not affect our earlier sensitivity study.

To investigate details of changes in lightning distribution, we consider six large-scale convection regions: North America (70°N to 12.5°N, 55°W to 167.5°W), South America (12.5°N to 57.5°S, 32.5°W to 57.5°W), Africa (35°N to 35°S, 60°E to 15°W), India (45°N to 5°N, 92.5°W to 60°W), Micronesia (22.5°N to 10°S, 160°E to 92.5°E), East Asia (50°N to 22.5°N, 160°E to 92.5°E). Figure 4(a) shows the total number of lightning flashes for North America over the three years. We see that the summer lightning count for 1997 is greater than for previous summers. The increase for the total flashes for the regions is not the consequence of uniform changes over the entire region but is due to strong local enhancements. Inspection of the NCEP surface temperature record for North America does not show 1997 summer to be warmer than in 1996. This points to a limitation of defining regional lightning–temperature sensitivities, using regionalscale average temperatures and regional flash count. The issue of diurnal sampling further complicates the picture for regional analysis. Micronesia (Fig. 4(b)) exhibits an increase in lightning activity for all seasons in 1997. This is surprising, as we would anticipate decreased convection over this region during El Niño (Bell and Halpert 1998). In 1997 India (Fig. 4(d)) also shows an increase over all seasons. East Asia (Fig. 4(f)) shows a suppression of the summer maximum of lightning activity, but an increase in autumn and winter. Africa and South America (Figs. 4(c) and (e)) show little interannual variations. These are regions characterized by large total flash counts and weak seasonal cycles. The South American signal is dominated by the SSA obscuring the seasonal cycle with a systematic offset. Africa is the most active region of the globe, owing to its large land mass and equatorial position. Africa dominates the total tropical lightning count, but accounts for less than half of the tropical land mass. This may also explain the poor correlation between tropical temperature (averaged over the entire tropical land mass) and tropical lightning activity.

5. ESTIMATION OF A GLOBAL FLASH RATE

The number of flashes recorded and the number of orbits completed by the OTD are counted and used to calculate the number of flashes per orbit for a particular month. The OTD records the flash data in a file labelled with the day number and the orbit number. Typically, 16 files are created per day; 14 files are required to hold the flash data taken from the 14 whole orbits and two corresponding to the 60 minutes of coverage for that day. It is the two additional files that prove to be a complication when counting the number of monthly orbits, since it is difficult to assign them the correct time weighting. We count the flash data in the additional files towards the total for the month, but ignore the time they represent when counting the number of orbits for the month. This means that we slightly (≈5%) overestimate the number of flashes per month. Having also removed the latitude bias of the OTD, it was possible to estimate the annual average lightning flash rate. We estimate a global flash rate of 35 ± 14 flashes per second. However, this value is not corrected for any diurnal bias in the dataset. This figure includes both intra-cloud
Figure 4. Bar charts showing seasonal lightning activity for (a) North America, (b) Micronesia, (c) Africa, (d) India, (e) South America and (f) east Asia from June 1995 to February 1998. Su = Summer (June to August), A = Autumn (September to November), W = Winter (December to February), and Sp = Spring (March to May).
and cloud-to-ground flashes and is considerably smaller than the widely used value of 100 flashes per second (Brooks 1925).

6. CONCLUSION

The analysis in this report has shown interannual correlation between land lightning activity, as measured by the OTD, and land wet-bulb temperature. This correlation is significant on a global scale and leads us to estimate an increase of $40 \pm 14\%$ should the average land wet-bulb temperature of the globe increase by 1 K. The response of lightning to changes in temperature is strongest in the northern hemisphere, where we predict an increase in lightning activity of $56 \pm 15\%$ for a 1 K rise in wet-bulb temperature. The correlations were found to improve with increasing land-area to sea-area ratio. The tropical region was found to exhibit no correlation, contrary to the expectations of Williams (1992). This may be due to the disproportionate contribution of Africa to the tropical total. Our conclusions are limited by the relatively short time span for which observations were available. They do demonstrate the potential use of satellite-based lightning sensors. It would seem that lightning can be used as a global thermometer, and that in a warmer world, lightning would be, on average, more prevalent. The lightning correlations examined here could also indicate a future increase in the frequency of extreme rainfall events.

ACKNOWLEDGEMENTS

Richard Wohlm and Sherry Harrison of the Global Hydrology Resource Centre at the National Aeronautics and Space Administration/Marshall provided the OTD data (http://wwwghcc.msfc.nasa.gov/otd.html), and the AB/CPC at NOAA (http://wesley.wwb.noaa.gov/ncep_data/index_sgi62.html) supplied the climate data. We thank Adam Hicks and Ashley Tomsett for some of the data manipulation. RT thanks the New Energy and Industrial Technology Development Organization, Japan for support, and Earle Williams for pointing out possible diurnal bias.

REFERENCES


