Global Lightning Flash Frequency

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ABSTRACT

Lightning flashes recorded in photographs by two satellites in the Defense Meteorological Satellite Program (DMSP) are used to calculate flash frequencies for land and ocean regions in 10° latitude belts between 60°S and 60°N for dusk and midnight local times. Data are analyzed for the first week of each month between March 1974 and February 1975. We find that the annual land-ocean ratio of global lightning at dusk ranges from 8 to approximately 20, depending on whether lightning near the coast is judged to be from thunderstorms produced predominantly by ocean effects or land effects. A similar analysis for data obtained near midnight yields ratios which range from 4 to 8. The global land-ocean lightning ratio is significantly higher during the northern summer than during the southern summer. The dusk lightning flash frequency as a function of latitude peaks at 10–20°N during the northern summer and 0–10°N during the southern summer. The midnight flash frequency peaks at 0–10°N throughout the year but has a broad equatorial maximum from 10°S–10°N during the southern summer. We estimate an annual global lightning flash frequency from the dusk satellite data to be 123 s^{-1} with average values of 142 s^{-1} for the northern summer and 100 s^{-1} for the southern summer. A similar analysis for the midnight satellite data yields an annual lightning frequency of 96 s^{-1} with average values of 110 s^{-1} in the northern summer and 79 s^{-1} in the southern summer. These flash frequency estimates may be in error by a factor of 2. The ratio of global lightning flash frequency during the northern summer to that in the southern summer is 1.4 for both the dusk and midnight satellite data. A comparison between the global lightning flash frequency as a function of season and the published values for the annual variation of the earth's electric field shows an *inverse* relation.

1. Introduction

"It is often stated, and widely believed, that 100 lightning flashes occur on the earth every second. This figure is sometimes attributed to Humphreys (1940) but he was merely quoting the estimate given by Brooks (1925). Brooks arrived at this estimate by combining the results of his climatological survey of thunderstorm frequencies with a flashing rate observed by Marriott (1908) during a thunderstorm at West Norwood, England, on 4 June 1908. Doubtless, Marriott would have been amazed to see the role played in the meteorological literature by his observations over a single 28-minute period." (Dennis, 1965).

It is indeed surprising that the figure of 100 flashes per second has gone unchecked despite nearly 20 years of satellite observations. In recent years the need for a more precise estimate of the global lightning frequency has been emphasized by several authors. Tuck (1976) illuminated the potential importance of lightning as a source of nitric oxide. Chameides *et al.* (1977) performed studies on NO_x production in laboratory electrical discharges and used Brooks' (1925) estimate to extend the results to a global estimate of NO_x production by lightning. The nitrogen oxides take part in many important photochemical reactions and may exert a controlling influence on the atmospheric ozone content (Crutzen, 1970; Johnston, 1971). Consequently, the satellite studies of lightning in the past decade by Vorphal (1967), Sparrow and Ney (1971) and Turman (1976) are particularly important, but fall short of providing an estimate of the global lightning frequency. It should be carefully noted by the reader that the global lightning frequency is distinctly different from the global thunderstorm frequency first studied by Brooks (1925), whose work is reviewed in the next section.

a. Previous studies

In the first global study of thunderstorms, Brooks (1925) estimated the annual, seasonal and latitudinal thunderstorm frequency for land and sea from

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meteorological station records and ocean ship logs. Unfortunately, the accuracy of each meteorological station in reporting thunderstorms varied considerably; for example, stations within a few miles of each other often reported widely different numbers of thunderstorm days each year. Furthermore, Brooks used the unit "Day of Thunder", defined as a day in which thunder was recorded. It is not an accurate measure of lightning frequency since it does not distinguish between a day with one thunderstorm and a day with several, and it ignores the number and frequency of flashes which occur in the storm. Brooks' data coverage was heavily weighted to central Europe and eastern North America with sparse coverage elsewhere. With these limitations, it is indeed remarkable that his global estimate of 100 lightning flashes per second, including both intracloud and cloud-to-ground, is still the accepted value.

Brooks (1925) also calculated a latitudinal thunderstorm day frequency distribution with a peak between the equator and 10°N in the northern summer and between the equator and 10°S during the southern summer. A mean yearly ratio of land-to-ocean thunderstorm days of 2.5:1 can be calculated from his Table III. The same table indicates that the ratio of the northern summer to southern summer thunderstorm day frequency is 1.1:1.

Following Brooks' pioneering work, 40 years were to pass before two modern techniques were employed to monitor lightning activity over great distances. One is the use of sferics detectors to observe the VLF radiation from lightning. This technique has been used by Takeuti and Nagatani (1974) and Takeuti *et al.* (1975) on voyages in the Pacific and by Heydt *et al.* (1967) from a fixed location in West Germany. These studies have led Dolezalek (1972) to suggest that a worldwide network of sferics detectors could be used to determine the global lightning activity. The second method of observing lightning activity is to monitor the visible and near-infrared radiation from lightning flashes from a satellite. This technique has been used by Vorpahl (1967), Vorpahl *et al.* (1970), Sparrow and Ney (1968, 1971), Turman (1976) and Orville and Vonnegut (1974).

Vorpahl's (1967) data were collected by photometers scanning the globe between 30°S and 30°N on one of the Orbiting Solar Observatory (OSO) satellites OSO-2. Lightning flashes were detected during new moon periods within 4 h of local midnight between February and October 1965. New moon periods were used because reflected moonlight saturated the detectors. Fifteen hundred lightning flashes were observed and she noted that only 30 occurred farther than 400 km from land. Assuming that land affects the production of thunderstorms as far as 400 km out to sea, she estimated a land/ocean lightning flash ratio of 50:1. [A later analysis (Vorpahl *et al.*, 1970) reported a lightning *storm* land/ocean ratio of 10:1.] She calculated a northern summer frequency of 16 flashes s^{-1} and a southern summer frequency of 12 flashes s^{-1} for the regions between 30°S and 30°N. She also observed little dependence of the flash frequency on latitude through this region.

Sparrow and Ney (1971) had a similar experiment aboard OSO-5. Their data were collected during new moon periods from February 1969 to December 1969 during the 4 h period before local midnight and from January 1970 to July 1970 during the 4 h period after midnight. They reported on the observation of 7000 flashes produced by 1000 storm complexes. The results from OSO-5 confirmed the results from OSO-2.

b. Present studies

The launch of several satellites in the Defense Meteorological Satellite Program (DMSP) has produced a series of papers on lightning from satellite data (Orville and Vonnegut, 1974; Croft, 1977; Turman, 1976; Edgar, 1978). Orville and Vonnegut used photographs of two extensive thunderstorm systems, one producing numerous tornadoes, to estimate lightning flash rate densities. Subsequent satellite detector characteristics made available by Croft (1977, private communication) show that these flash rate calculations are in error. A reexamination of these data shows that a series of squall line thunderstorms observed on 14 November 1972 (0627 GMT) off the west coast of Florida had a flash rate density of approximately 0.01 flashes s^{-1} km^{-2} or 1 flash s^{-1} in a 10 km × 10 km area, a reasonable value for an active squall line. Note that this reduces to one flash every 20 s in 5 km^2, which is about the cross-sectional area of a thunderstorm cell and consistent with typical ground observations. Reexamination of the thunderstorm system recorded by the DMSP satellite at 0554 GMT on 4 April 1974 shows an extensive line of storms over the southeastern part of the United States. This system, which was associated with the 3–4 April tornado outbreak, had a flash rate density three times higher than the squall line. No conclusions are possible from such a small example, but it does suggest that lightning flash rates may be one indicator of the presence of a severe storm.

Not all the DMSP satellites have the same lightning detector. While Orville and Vonnegut (1974) used photographs produced by a scanner which will be described later, Turman (1976) used data obtained by a lightning flash detector whose characteristics are mostly classified by the Air Force. From 15 orbits taken in September 1974 and March 1975, Turman reported on the observations of 24 storm complexes producing 10 000 flashes. The field of view was 5×10^5 km^2 and the time resolution was one second. He calculated a midnight mean global flash rate by counting all flashes observed in the 15 orbits and dividing by the total observation time and total field of view to obtain a value of 6×10^{-8} flashes km^{-2} s^{-1}. This corresponds to a global flash frequency of 31 s^{-1}.

From these present studies with the DMSP data, it appeared to us that a detailed study might yield significant information on the characteristics of the global lightning frequency. The results of our efforts are presented here and address the following questions:

1) What is the ratio of lightning over land to that over the oceans?
2) What is the latitudinal distribution of lightning flash frequency?
3) What is the seasonal variation in lightning flash frequency?
4) What is the global frequency of lightning flashes and what does it imply about the relation between thunderstorm activity and the atmospheric electric field?

2. Data source

The data consist of photographs recorded by the high-resolution scanner on the DMSP midnight–noon and dawn–dusk satellites. Before examining an example of the photographs, it is important to understand the basic characteristics of the satellites which are described in detail by Dickenson *et al.* (1974).

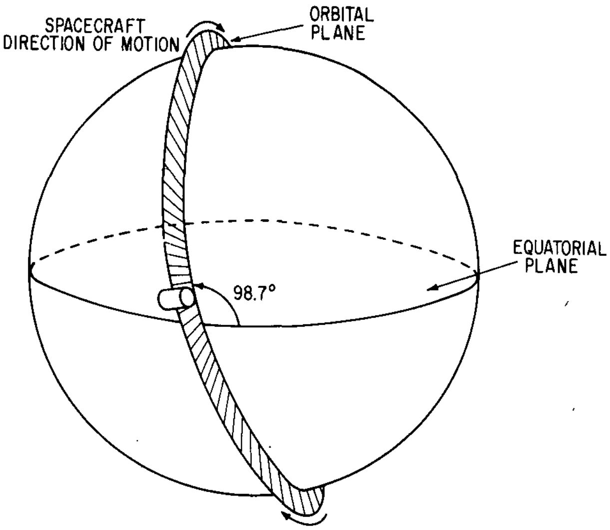

FIG. 1. DMSP orbital inclination (not drawn to scale).

The DMSP satellites are in a sun-synchronous orbit around the earth; that is, the orbit precesses around the earth once a year and passes overhead near the same local time each day. The orbit is circular with an altitude of 830 km and inclined 98.7° to the equator on the northbound pass (Fig. 1). The orbital period is 101.56 min and the highest latitude reached by the subpoint track is 81.3°.

The DMSP satellites' high-resolution detector has a 4.56 mrad field of view, which at 830 km corresponds to an area 3.8 km in diameter on the earth's surface. A rotating mirror with a period of 0.56 s reflects light from the scanned area into the detector and a photograph is composed line by line as the satellite moves in its orbit (Fig. 2). The mirror points toward the earth during part of each rotation period which amounts to 111° of each mirror rotation (360°). Therefore the detector scans the earth 31% of the time and covers approximately 3000 km in each scan line. The time resolution—that is, the length of time a surface point is scanned—and the field of view at the surface vary as a function of scan angle. The angular frequency of the scanning mirror is 11.22 rad s^{-1} which produces at nadir a ground speed of 9.3×10^3 km s^{-1}. For a distance of 3.8 km

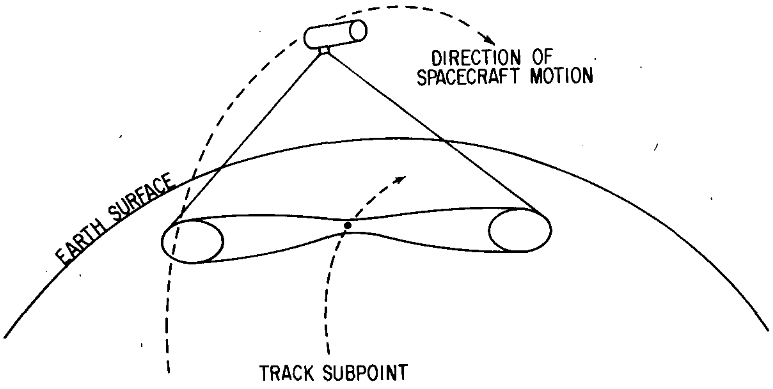

FIG. 2. Geometry of DMSP scan line. A series of scan lines will produce photographs like those reproduced in Fig. 4.

on the ground, this corresponds to a time resolution of 4×10^{-4} s.

The high-resolution detector (Spangler, 1974) is a silicon PN photodiode with the response curve shown in Fig. 3. It provides a linear current output relative to radiance power input over six decades of input power. The gain is controlled either from the ground, by a zero-resolution photometer measuring the illumination from space falling on the earth beneath the satellite, or by a sun position sensor which controls the gain when a scan line crosses the terminator at dusk or dawn. These gain controls allow the satellite to photograph the surface under illuminations from full daylight to one-quarter moonlight. A change in gain changes the saturation threshold of the system. At night the threshold is low enough so that cities, gas and brush fires, and lightning flashes saturate the system.

A DMSP photograph is shown in Fig. 4a which contains images produced by cities, gas fires and lightning flashes. Fig. 4b is a composite photograph produced by combining the negative used for Fig. 4a with the negative produced by the matched IR scanner which operates in the 8–13 μm range. The advantage of the IR image is that clouds are recorded but lights, fires and lightning are not. Consequently, any image thought to be produced by lightning should appear in clouds when the visible and infrared negatives are compared. These photographs were obtained at approximately 0545[2] 22 July 1974 as the satellite moved from north to south over the eastern half of the United States. The large cities in the northeast are readily identified from the bright corridor extending from Washington to Boston. Horizontal streaks attributed to lightning are recorded west of Chicago and off the east coast of Florida. A bright glow in the lower left-hand corner is from gas fires or "flare gas" burning in the oil fields of Yucatan. From a study of these and similar images, Croft (1977) has determined that the DMSP sensor responds to bright sources from an area extending 92.5 km (50 n mi) above and below the path being scanned by the sensor. Thus the area from which the satellite sensor can respond to lightning is defined by a vertical rectangle with dimensions 3.8 km × 185 km. The differential sensitivity, if any, to cloud-to-ground or intra-cloud lightning is unknown.

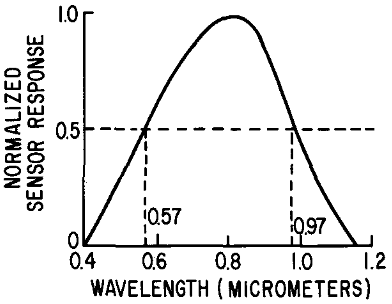

FIG. 3. Normalized DMSP sensor response for a simulated solar radiation source.

We apply this result in Fig. 4a to the area off the east coast of Florida with a group of approximately 20 lightning streaks, the minimum number to specify a flashing rate in a storm to within a factor of 2 at the 5% confidence limit (Dennis, 1970). This area over the ocean, 100–200 km east of Jacksonville, Florida, is approximately 3.4×10^4 km^2. The DMSP satellite detector with a nominal scan diameter of 3.8 km moves at a rate of 9.3×10^3 km s^{-1} at nadir or 3.5×10^4 km^2 s^{-1}. Thus the nominal time to scan the storm complex is 1 sec. However, since the detector is actually sensitive to an area 50 times larger (Croft, 1977) as discussed in the preceding paragraph, the effective viewing time of the storm is 50 s. This corresponds to an astronaut viewing the storm for 50 s and observing 20 flashes or an average of one every 2.5 s.

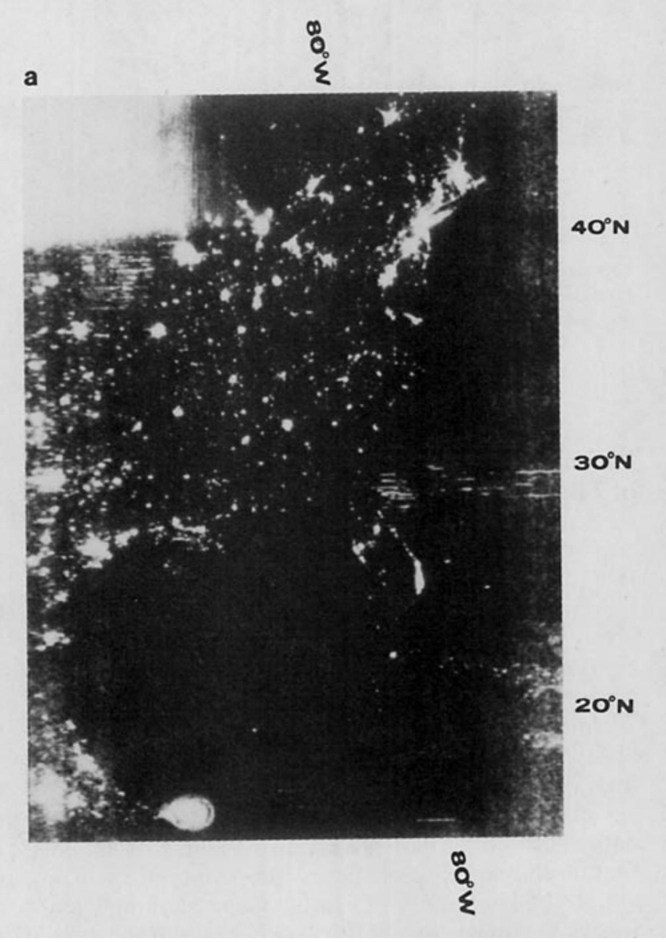

FIG. 4a. DMSP photograph of the eastern part of the United States. Horizontal streaks produced by lightning are visible off the coast of Florida. A gas flare is visible at the bottom in the oil fields of Yucatan.

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[2] All times GMT.

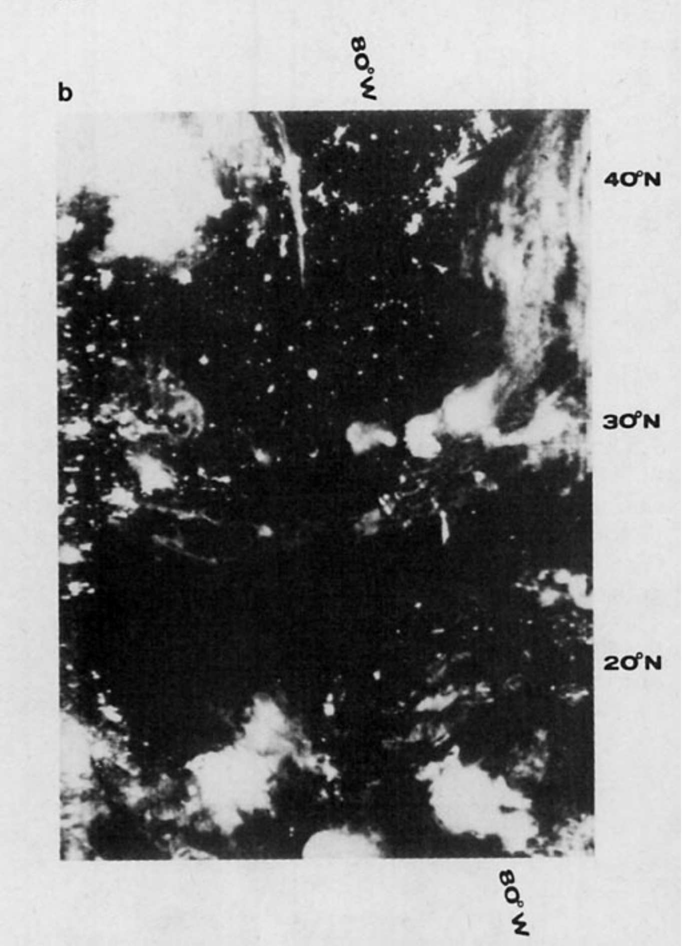

FIG. 4b. An infrared image taken at the same time as Fig. 4a superimposed over the visible image. This composite photograph, produced from the DMSP visible and infrared negatives, shows that the horizontal streaks produced by lightning occur in clouds.

The significance of the above data is that M. Uman's lightning research station at the University of Florida-Gainesville was operating a fast electric field receiving station on the same night that Fig. 4 was obtained, thus providing an opportunity to obtain ground truth. From 0421 to 0527 they recorded lightning waveforms from the northeastern Florida area. At 0545, the DMSP satellite passed over Florida and recorded Fig. 4a. Uman (1978, private communication) has examined their data for the last 20 min preceding the termination of their records at 0527. He estimates a flashing rate of approximately 1 s^{-1} compared to our estimate of (1/2.5) s^{-1} obtained 20 min later from the DMSP satellite data. The comparison is a crude one since it assumes that 1) the satellite observed the same storm from which the University of Florida was receiving waveforms 20 min earlier; 2) the flashing rate of the storm did not change in the intervening 20 min; and 3) the detector sensitivity of the two systems was the same to the thunderstorms in the Jacksonville area. The errors in the above assumptions are unknown, but the rough agreement in the two flashing rates suggests that the DMSP satellite is recording lightning and that the frequencies observed in storms appear to be realistic. This is apparently the first quantitative comparison between lighting satellite data and "ground truth," although a recent abstract by Beasley *et al.* (1978) indicates that several optical events detected by a recent DMSP satellite have been correlated with surface observations of cloud-to-ground lightning.

3. Data collection

The lightning data consists of 22 sets of photographs taken by the high-resolution scanner on the DMSP satellites. The entire globe between 60°S and 60°N is covered in these data and some areas receive more coverage than others. The weighting produced by this effect is ignored in our analysis. Each data set contains all the photographs archived at the University of Wisconsin-Madison Space Science and Engineering Center from the first week of each month from March 1974 to February 1975. These data amount to ~500 m^2 of film which were surveyed for lightning streaks. A survey of all the data for one year was considered unreasonable because of the excessive amount of time to remove the film from files and study the images in detail. Consequently, the first week from each month for one year was considered appropriate for a representative sample. No photographs were available from the midnight–noon satellite for March and from the dawn–dusk satellite for November. Lightning flashes were visible only during nighttime passes, so only photographs from the dusk and midnight passes were used.

The lightning flashes are easy to differentiate from other bright areas such as cities, and gas and brush fires (Fig. 4a). These latter events are several scan lines thick while lightning is only one line thick, and is always associated with clouds (Fig. 4b). Over South America, a different problem arises. A speckled random dot pattern occurs which is caused by the DMSP satellite's entry into the inner radiation belt which dips nearest the earth there (Croft, 1977, p. 29; Freden and Paulikas, 1964). The geomagnetic field is not symmetrically placed around the earth but is offset from the center and tilted relative to the spin axis. The direction of the offset is such that the radiation belt dips near the earth in the vicinity of South America. Short streaks are produced in the DMSP image when the satellite penetrates the belt. Lightning can be differentiated from these short streaks, however, because it occurs in clusters, produces a longer streak, and occurs only where there are clouds (Fig. 4b).

Our analysis required that each lightning streak on a DMSP photograph be marked on a map as near as possible to the location where it occurred. On the same map, we plotted the path of the subpoint of each orbit when the high resolution scanner was on. A total of approximately 1500 lightning flashes were plotted. Over land the flashes could be located on maps to the nearest few degrees, perhaps 1–2°, but over the ocean the errors are larger and a flash location may be plotted with an accuracy no better than 5°.

4. Data reduction

The goal of our data reduction was to calculate the lightning flash frequencies for 10° latitude belts of the globe between 60°S and 60°N. Above these latitudes, data are scarce so that the amount of lightning missed by omitting these regions is considered to be negligible.

The first step in our analysis was to transfer the coordinates of each flash to a card suitable for computer manipulation. The coordinates of the end points of each scan were also recorded so that we could calculate the area scanned in each photograph. To determine the amount of land and ocean area scanned, we compared each degree square within 1500 km of the orbital subtrack with a land-ocean classification compiled by the Air Force Aeronautical Chart and Information Center and supplied by the National Center for Atmospheric Research. This compilation, which is available on nine-track magnetic tape, allows us to determine whether a degree square is entirely open ocean. If it is, the area is summed with other open ocean degree squares. If it is not entirely open ocean, the area is considered land and summed with other degree squares classified as land.

The number of lightning flashes over land and over ocean were classified in two ways. First, flashes which occurred within 50 km of land were considered to be in a storm produced by land influences and therefore classified as land. All other flashes were considered to be ocean flashes, i.e., flashes produced by thunderstorms over the open ocean. Our second classification considered all flashes which occurred within 300 km of land to be associated with thunderstorms produced by land effects. All other flashes were considered to be ocean flashes.

The flash frequency was calculated for each 10° latitude belt as a function of month. This was done by dividing the total number of flashes by the corresponding area and multiplying by the scan rate of the satellite, 1.9×10^8 km^2 min^{-1}. Seasonal flash frequencies were obtained by dividing the year into two "seasons," April–September, or northern summer and October–March, or southern summer.

5. Results and discussion

The results are plotted in Figs. 5–7. No error bars are plotted with the data points for the following reason. The confidence limits obtained by applying the Student's-*t* test to the data produced one standard deviation limit which was greater than 100% of the mean in almost all cases. In other words, the coefficient of variation is usually greater than 1. The hypothesis test for the difference in means, however, did show that many of the monthly means compared were different at the 90% confidence level. This analysis suggests that a change in the means which are plotted in Figs. 5–7 may be significant, but that the numerical values have large uncertainties. With this warning in mind, we will interpret the results.

a. Land-ocean flash frequency ratio

This ratio was calculated in two ways and the results are plotted in Figs. 5a and 5b.

1) FLASHES OVER LAND AND WITHIN 50 KM OF THE COAST

First, lightning flashes that occurred within 50 km of land were classified as land-flashes and all other flashes were classified as ocean flashes. The resulting land-ocean ratio was calculated as a function of month and plotted in Fig. 5a. Data points are missing where data were not available or if available, there were no flashes observed over the ocean. The dusk satellite indicates an average ratio of 8 for the year and the midnight satellite a ratio of 4. This is consistent with our higher expectation of thunderstorms over land at dusk than at midnight. For the first six months, April–September, the average dusk ratio is 10 and for October–March it is 5. This probably reflects the effect of summer over the larger land masses in the Northern Hemisphere compared to the amount of land in the Southern Hemisphere. Note that this effect is absent in the midnight satellite data.

The results in Fig. 5a with some manipulations can be compared to Brooks' (1925) data. He estimated a ratio of 2.5 for land-thunderstorm days to ocean-thunderstorm days for unit area, i.e., land and ocean frequencies were obtained for the same size area. To normalize Fig. 5a to unit area, the ordinate should be multiplied by 2.3, the ratio of the earth's ocean area to land area. Our dusk lightning ratio is then seven times (18/2.5) higher than Brooks' thunderstorm ratio and the midnight lightning ratio is four times (9/2.5) higher. Since it is quite likely that land thunderstorms produce more lightning than oceanic thunderstorms, we would expect our lightning ratios to be higher than Brooks' thunderstorm ratio.

2) FLASHES OVER LAND AND WITHIN 300 KM OF THE COAST

Fig. 5b was obtained by reclassifying all flashes within 300 km of the coast as land flashes and then

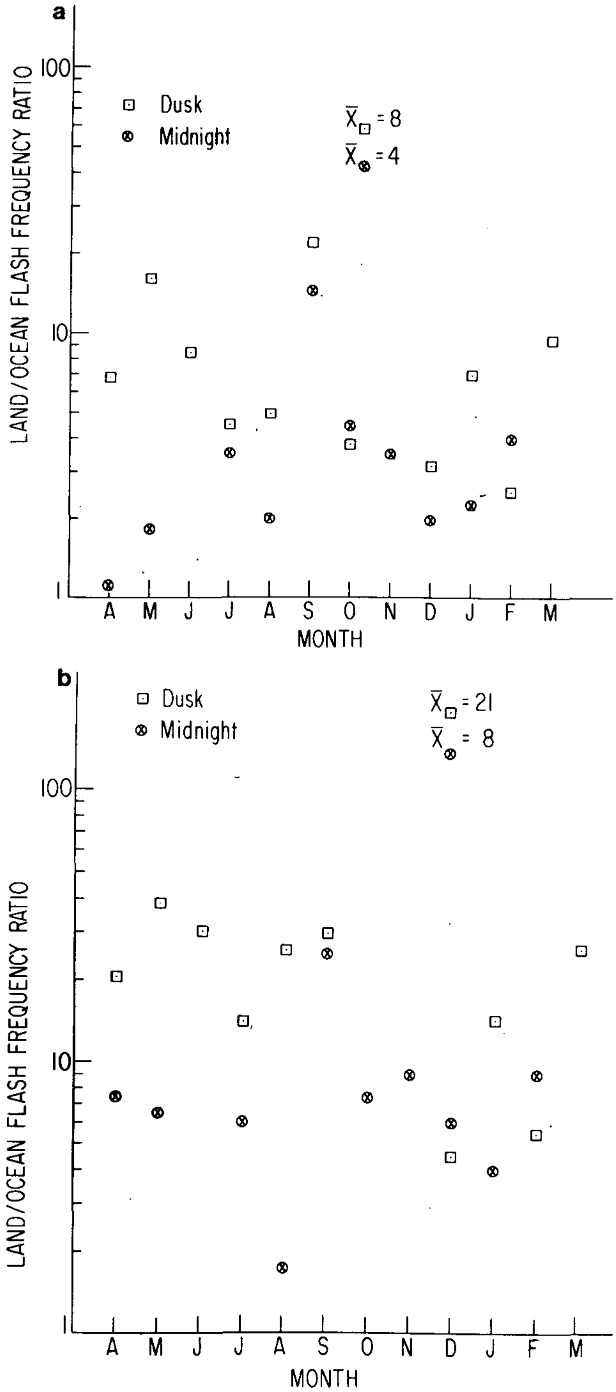

FIG. 5. The land-ocean lightning flash frequency ratio plotted as a function of month. In (a) "land lightning" is considered as lightning occurring within 50 km of a major coast; in (b) the limit is within 300 km of a major coast.

calculating the land-ocean ratio. This classification is similar to the one used by Vorpahl (1967) except that her boundary was placed 400 km off the coast. The dusk satellite data has an average ratio of 21 and the midnight satellite data an average of 8. We suspect that the significantly higher ratios reflect the influence of land in producing lightning near the coast, in this case, within 300 km.

The midnight land-ocean lightning flash frequency ratio of 8 is considerably less than Vorpahl's (1967) estimate of 50 for near-midnight times. It is not obvious, however, why the two values differ by a factor of 6. Vorpahl's data were later grouped into lightning storms (Vorpahl *et al.*, 1970) and a land-ocean ratio of 10 reported. But it is not clear that there is or should be any relation between her lightning *storm* land-ocean ratio and our lightning *frequency* land-ocean ratio.

b. Latitudinal distribution of lightning flashes

Figs. 6a and 6b show the flash frequency as a function of latitude in 10° belts from 60°S to 60°N for the two seasons April–September and October–March. A dominant feature in both figures is the peak flash frequency in the Northern Hemisphere in both seasons. During the April–September season (Fig. 6a) the dusk satellite data peak at 10–20°N and the midnight satellite data have a peak at 0–10°N. For the six-month period October–March (Fig. 6b) both peaks occur at 0–10°N. The isolated peak at 40–30°S is probably the result of a small data sample, i.e., too little area scanned to obtain a representative flash frequency. The peak flash frequencies in the equatorial regions are in approximate agreement with Brooks' (1925) thunderstorm day analysis. He found a maximum at 0–10°N in the April–September period which shifted to 0–10°S in the October–March season.

There are very few lightning flashes below 40°S in any season, undoubtedly due to the small amount of land area there. A wide variation of lightning flash frequency is apparent between 30°S and 30°N and this is supported by the Student's-*t* difference in mean test. This variation is not in agreement, however, with Vorpahl's (1967) observation that there is little lightning flash variation through this region.

c. Global lightning flash frequency

The global frequency for flashes is plotted for each month in Fig. 7. A global frequency is obtained from our data by assuming that the calculated values for each longitude belt obtained from the dusk and midnight satellites apply throughout the globe. This is, of course, incorrect but we decided not to adjust our measured values for other time zones since the correction factor is largely unknown. Also the errors in our plotted values probably exceed any adjustments we could make for other time zones.

In Fig. 7, the dusk-averaged global flash frequency for the year is 123 s^{-1}. The midnight averaged global frequency is 96 s^{-1}. If we examine the frequency for the months April through September, we find a value of 142 s^{-1} from the dusk satellite data and 110 s^{-1} from the midnight satellite data. This period corresponds to the northern summer. For the months October through March, analysis of the average dusk data indicates a flash frequency of 100 s^{-1}. A similar averaging of the midnight data yields a flash frequency of 79 s^{-1}. From these results we see that the seasonal ratio of lightning frequency between the northern summer and the southern summer is 142/100 and 110/79 or 1.4 for both the dusk and midnight satellite data.

It should be noted that the above numbers were obtained by first calculating the flash frequencies over land and ocean separately, combining them, and then plotting the results in Fig. 7. Separate plots of the ocean and land lightning data are not presented, although a few comments are appropriate. The global flash frequencies over land follow closely the points in Fig. 7 because of the high land/ocean ratio in our data which we previously discussed. The frequency of lightning over land is in general higher in the months April–September and relatively lower in October–March. There are too few lightnings observed over the ocean when the data are divided into months to justify a separate graph from Fig. 7. Nevertheless, we do observe a frequency of lightning over the ocean which appears to have maxima in August and January–February. Unfortunately, the variations in these mean data plotted as a function of month are well within the confidence limits, which suggests that the results may be accidental with no physical significance. Clearly, a larger sample size of lightning data over the oceans is needed.

When we compare these results with the previous rough estimate of 100 flashes s^{-1} by Brooks (1925) there is a surprising agreement. More recent studies by Vorpahl (1967) suggest a global lightning frequency of 28 flashes s^{-1} which is obtained by doubling her estimate of 14 flashes s^{-1} between 30°S and 30°N. The lightning flash frequency ratio between the northern summer and the southern summer, 1.4, is in good agreement with Vorpahl's (1967) estimate of 1.3. Brooks (1925) calculated the thunderstorm day ratio and obtained a value of 1.1. There is no reason for this value to be the same as the lightning flash ratio, but we do expect both ratios to be greater than 1 with the flash ratio exceeding the thunderstorm day ratio.

The above results suggest that if thunderstorms are primarily responsible for the maintenance of the earth's atmospheric electric field, we should see variations in the field which reflect the seasonal changes in the lightning variations apparent in Fig. 7. Chalmers (1967, p. 169) summarizes the reports of the annual variations of the electric field and notes that where there is no pollution, the electric field is greater during October–March than in April–September. This is exactly the inverse of what we would expect from Fig. 7 if lightning and their associated thunderstorms are the "battery" in the atmospheric electric circuits. We conclude that the

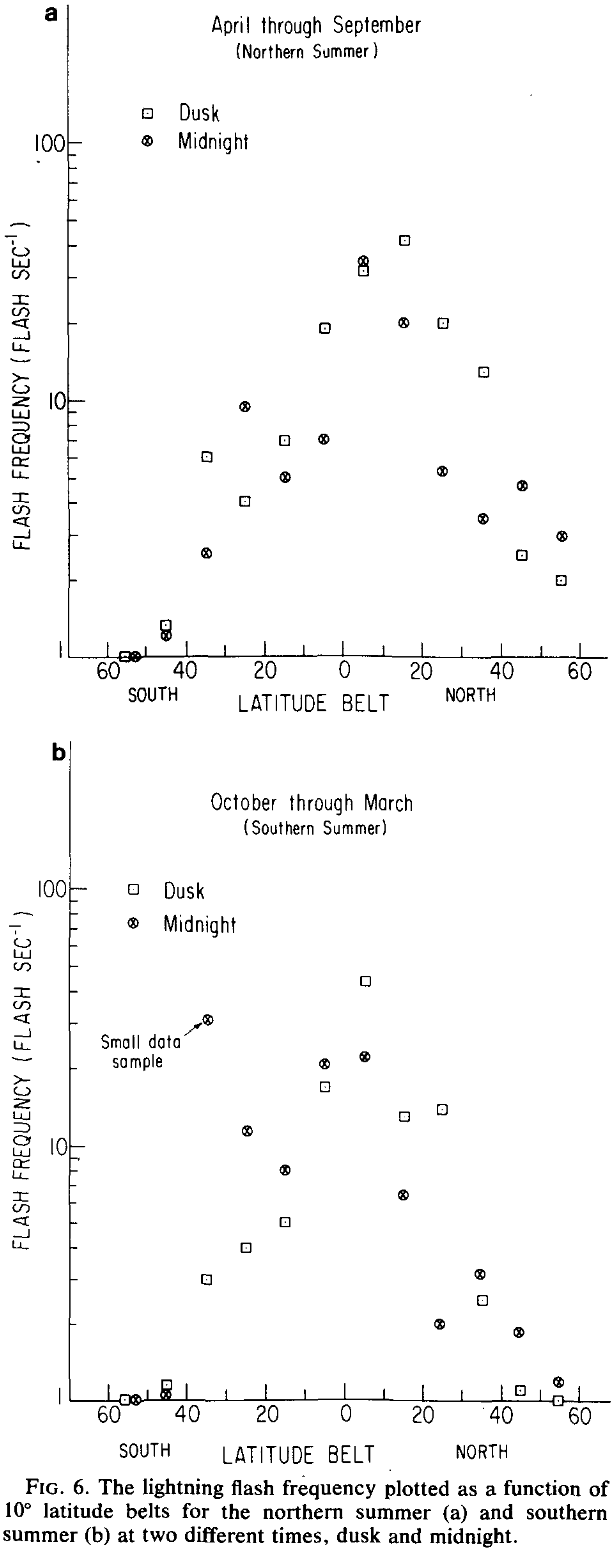

FIG. 6. The lightning flash frequency plotted as a function of 10° latitude belts for the northern summer (a) and southern summer (b) at two different times, dusk and midnight.

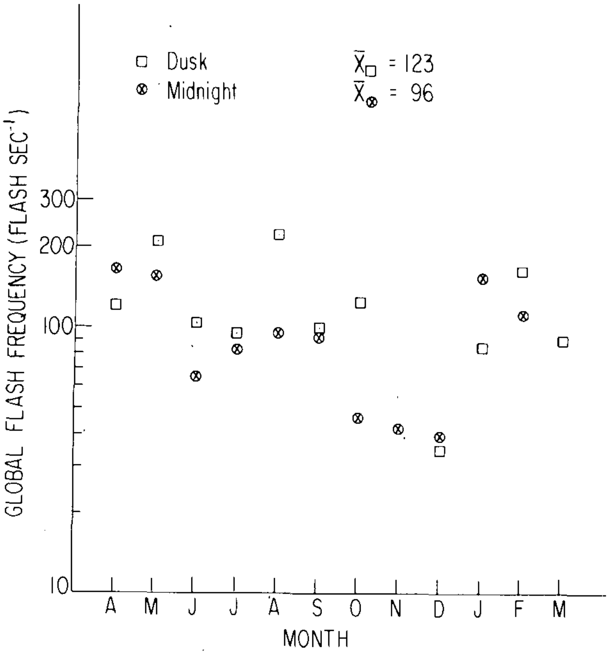

FIG. 7. The global lightning flash frequency as a function of month for the dusk and midnight satellite data.

classical picture of the atmospheric electric circuit is not supported by our data.

It should be noted that these data are not the first set to contradict the hypothesis that thunderstorms are the source for the global atmospheric electric circuit. Dolezalek (1972) reviewed the concept of the atmospheric electric circuit and concluded that we have a globally controlled vertical current flow through the atmosphere, but that the connection to the thunderstorm activity is tenuous and, in fact, is contradicted by the proper interpretation of available measurements. Our data support this conclusion. It appears that the hypothesized relation of the global atmospheric electric current to thunderstorms is far from a settled question and deserves further study.

6. Conclusions

Our present study represents a first attempt to use the DMSP satellite data to obtain the annual global flash frequency between 60°S and 60°N latitude. The errors in our analyses which are presented in Figs. 5–7 are large and the resulting data points are probably accurate to no better than a factor of 2. The plotted points are a mean value for a week in each month with a standard deviation which is approximately equal to the mean. This large variation is a discouraging result. Nevertheless, most of the plotted means in Figs. 5–7 are different at the 90% confidence level as determined by the Student's-*t* test. Consequently, we are able to draw the following conclusions:

1) The annual land-ocean ratio of global lightning at *dusk* ranges from 8 to approximately 20 depending on the allowance made for land effects.

2) A similar analysis for data obtained near midnight yields global land-ocean ratios which range from 4 to 8, again depending on the allowance for land effects on thunderstorms near the coast.

3) The global land-ocean lightning ratio is significantly higher during the northern summer than during the southern summer.

4) The dusk lightning flash frequency as a function of latitude peaks at 10–20°N during northern summer and 0–10°N during the southern summer.

5) The midnight flash frequency peaks at 0–10°N throughout the year but has a broad equatorial maximum from 10°S to 10°N during the southern summer.

6) The annual global lightning flash frequency determined from the dusk satellite data is 123 s^{-1} with average values of 142 s^{-1} for the northern summer and 100 s^{-1} for the southern summer.

7) A similar analysis for the midnight satellite data yields an annual lightning frequency of 96 s^{-1} with average values of 110 s^{-1} in the northern summer and 79 s^{-1} in the southern summer.

8) The ratio of global lightning frequency during the northern summer to that in the southern summer is 1.4 for both the dusk and midnight satellite data.

9) A comparison between the global lightning flash frequency as a function of season and the annual variation of the earth's electric field published by Chalmers (1967, p. 169) and Dolezalek (1972) shows an inverse relation.

The above analysis is only our first attempt to obtain significant global information from the DMSP satellite data. A study is now underway to analyze all the DMSP data from one year, in effect increasing our data source by a factor of 4 for a period similar to that analyzed in this paper.

Other analyses are in progress which parallel our own efforts. Turman *et al.* (1978) and Edgar (1978) are analyzing lightning data from a new DMSP satellite to determine flash frequencies in 10° squares as a function of month. These studies and our own continuing efforts should provide more reliable estimates of the global lightning frequency. We must admit, however, that Marriott's (1908) single observation and Brooks' (1925) analysis have apparently served us well for many years.

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