GLOBAL THUNDERSTORM ACTIVITY

Colin Price
Department of Geophysics and Planetary Science, Tel Aviv University, Ramat Aviv, Israel.

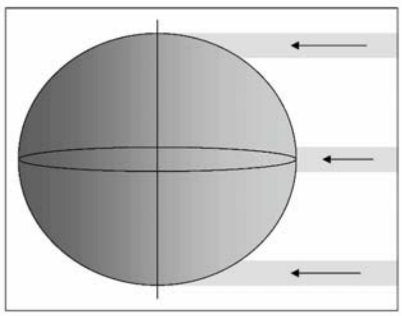
Abstract Sprites, elves and other transient luminous events (TLEs) are known to exist only above thunderstorms. It is therefore important to know where these thunderstorms occur around the globe, and how their distribution varies temporally and spatially. The majority of thunderstorms on Earth occur within the tropical regions between $\pm 30°$ latitude of the equator ($\sim$50% of the surface area of the globe). This is due to the maximum solar heating in the tropics, and the atmospheric general circulation patterns between the tropics and the subtropics (Hadley Circulation). Along the thermal equator, which migrates with the seasons, air masses from the northern and southern hemispheres converge along the intertropical convergence zone (ITCZ). This is the latitudinal position of the majority of the globe's rainfall and thunderstorm activity. However, in the tropics these thunderstorms are concentrated mainly over the continental regions (Americas, Africa and southeast Asia) with little thunderstorm activity observed over the oceans. The reason for the preference of thunderstorms to continental regions is likely related to the larger daily surface heating over land as compared with the oceans. In the extra-tropical regions thunderstorms form along the polar front, the boundary between warm moist air from the tropics, and cool dry air from polar regions. Recent satellite measurements of lightning indicate a mean global rate of $\sim$45 flashes/second. In fair weather regions the integrated effect of global thunderstorms and other electrified clouds can be observed via the atmospheric global electric circuit. The global thunderstorms charge the Earth's surface negatively with a mean charge of 500,000 Coulombs, and a mean potential between the ionosphere ($\sim$80 km) and the Earth's surface of 250 kV. The diurnal variation of the atmospheric electric circuit (and global thunderstorms) has a maximum around 18 UT and a minimum around 03 UT known as the Carnegie Curve.

4.1 The Earth's Energy Balance

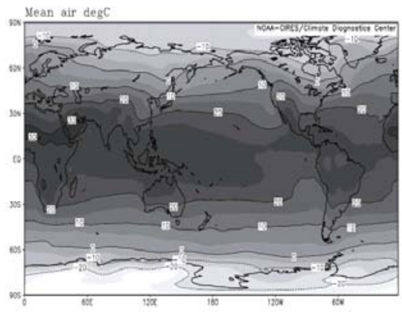
The Earth is located at a mean distance of 150 million km from our Sun, and at this distance we receive on average 1367 W/m^2 of energy, known as the solar constant ($S_\circ$). However, since we live on a sphere, the solar radiation does not intersect with the surface at the same angle at all latitudes. When the solar rays are perpendicular ($90°$) to the equator (at noon), the rays are tangential ($0°$ or just above the horizon) at the north and south poles (Figure 1a). Hence

M. Füllekrug et al. (eds.),"Sprites, Elves and Intense Lightning Discharges", 85–99.

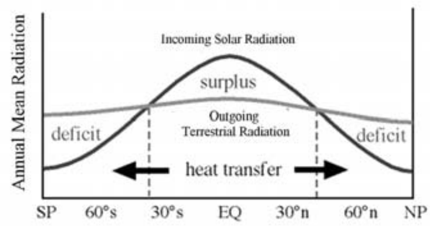
as we move to higher latitudes, the same energy from the sun is spread over larger areas, resulting in less energy absorbed per unit area. This is the prime reason why the tropics are warmer than the higher latitudes (Figure 1b). When we compare the incoming absorption of energy from the sun (short wave radiation) relative to the outgoing terrestrial radiation (long wave radiation) we notice a latitudinal imbalance (Figure 1c). The latitudinal gradient of incoming energy (black curve) is much larger than the latitudinal gradient in the outgoing energy (grey curve). The climate system tries to adjust for this imbalance by transporting excess heat from the tropics to high latitudes. This transport is done via the atmosphere and the oceans. Ocean currents transport warm waters away from the equator, while bringing cooler waters equatorward, helping to



(a)



(b)



(c)

Figure 1. (a) The dependence of absorbed solar radiation on latitude; (b) The annual mean surface temperatures showing the warmest areas in the tropics (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml); c) Latitudinal energy balance of the Earth showing the incoming energy from the sun (black curve) relative to the outgoing radiation from the Earth (grey curve). The surplus of energy in the tropics results in large poleward transports of heat via the atmosphere and oceans.

reduce this imbalance. In the atmosphere, the transfer of heat poleward occurs primarily through the meridional general circulation of the atmosphere, where thunderstorms have a major role in the transport of this energy both away form the warm surface, and then away from the warm tropics.

4.2 The General Circulation of the Atmosphere

The maximum heating at the surface in the tropics results in rising thermals and convection in the atmosphere. The resulting region of rising air along the thermal equator is know as the intertropical convergence zone (ITCZ) due to the convergence of air masses from the northern and southern hemispheres along this boundary. The thermal equator migrates north and south of the geographic equator according to the seasons, where the thermal equator is furthest north in June-August during the northern hemisphere summer, and furthest south in December-February during the southern hemisphere summer.

Although the region of maximum heating by the sun covers a broad region of thousands of kilometers, the ITCZ is actually very narrow and compact ($\sim$100 km over the oceans). This narrow region of convergence is due to the extra driving force of the convection along the ITCZ resulting from the release of latent heat as water vapor is condensed to form cloud droplets as the air rises and cools in the atmosphere. The release of latent heat adds additional heat to the cloud parcel and enhances the buoyancy in the deep convective clouds, increasing the vertical updrafts.

In general, a significant difference in updraft intensity is observed between oceanic and continental convection in the tropics (Lemone and Zipser, 1980; Jorgenson and Lemone, 1989). The reason for this difference is still a topic of research, but updraft velocities in oceanic thunderstorms may reach 10 m/s, while over continental regions the updrafts may reach 50 m/s (Price and Rind, 1992; Williams and Stanfill, 2002; Williams et al., 2004). Since updraft intensity plays a major role in thunderstorm electrification and lightning frequencies (Baker et al., 1995, 1999), this dramatic difference in thunderstorm dynamics results in the lightning activity over the oceans being an order of magnitude less than over the continents. In fact the boundary between land and ocean is very clearly seen in satellite images of tropical lightning activity, for example in Figure 2 (Christian et al., 2003). However, not all tropical continental thunderstorms are intense lightning generators. The tropical monsoon periods are characterized by the seasonal onshore flow of moist oceanic air, resulting in heavy rainfall in continental thunderstorms, however with low lightning rates (Petersen et al., 2002; Williams et al., 2002). This occurs in the Indian Monsoon, the African Monsoon, the Brazilian Monsoon and the Australian Monsoon. Intense lightning activity prefers a somewhat dry environment, which may explain the difference between African and South American lightning ac-

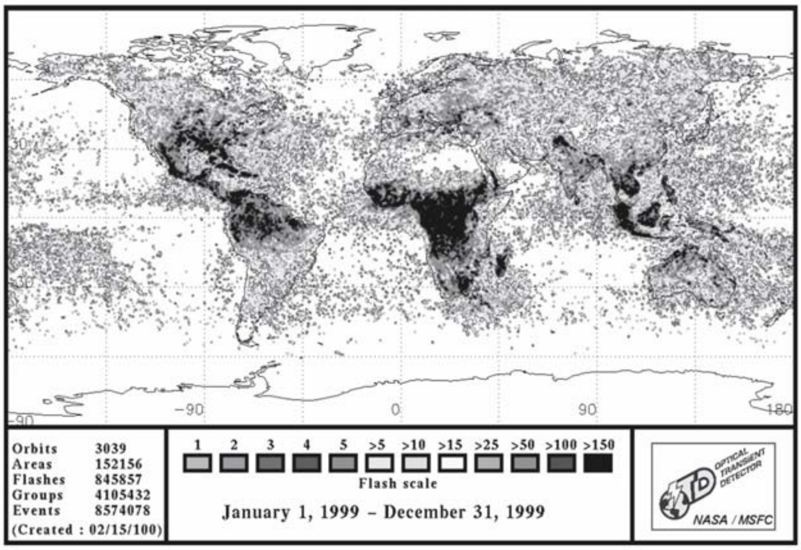


Figure 2. Global lightning activity for 1999 from the satellite OTD sensor showing lightning activity over the tropical land areas (http://thunder.msfc.nasa.gov/otd).

tivity (Williams and Satori, 2004). A field campaign to observe sprites during the monsoon season is not recommended.

The air that rises within the tropical convective storms eventually reaches the tropopause and the stable stratosphere between 15-20 km altitude, and then is forced to flow north and south away from the equator. Large amounts of water vapor are deposited in the upper troposphere resulting in the moistening of the upper tropospheric environment (Price, 2000). This poleward moving air is influenced by the Coriolis force, resulting in a deviation of the winds towards the east in both hemispheres. This air continues to radiate heat to space and hence cools and sinks as it is transported northeast/southeast away from the tropics (Figure 3). The air continues to subside up until 30° north and south, heating adiabatically as it sinks. These regions of subsidence in the sub-tropics define the regions of our planet where deserts are found. Both the subsidence (resulting in high pressure at the surface) and the heating of the air as it sinks (resulting in low relative humidity) result in minimal precipitation in these regions. This meridional circulation pattern, with rising motion along the ITCZ and sinking motion in the subtopics, is know as the Hadley circulation (Figure 4), and is extremely important in the redistribution of heat, moisture and momentum on the planet. Near the surface, the sub-tropical regions and the ITCZ are connected via the north-easterly (northern hemisphere) and south-easterly (southern hemisphere) trade winds that blow between $\pm 30°$

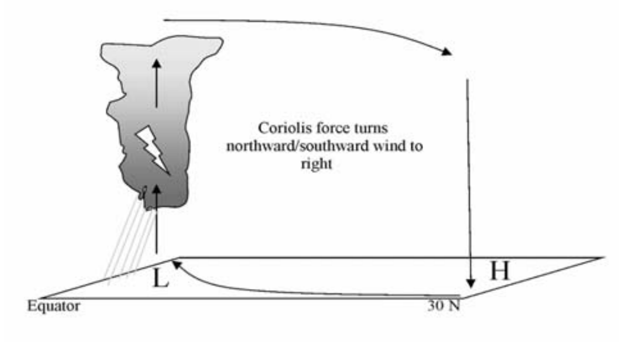


Figure 3. Schematic description of the Hadley circulation between the continental tropics and subtropics in the northern hemisphere.

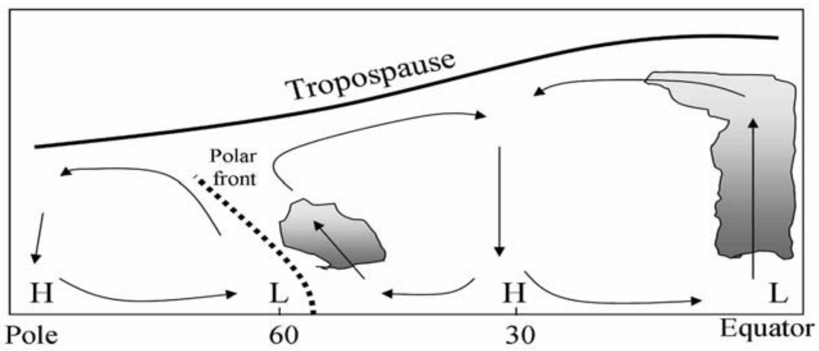


Figure 4. Schematic representation of the general circulation of the atmosphere showing 3 cells in each hemisphere, with 2 regions of convective activity in each hemisphere along the ITCZ and the polar front.

latitude. In addition to the return flow towards the equator at the surface in the Hadley circulation, part of the tropical air reaching the surface around 30° moves poleward, where it meets cold dry air arriving from the Arctic (northern hemisphere) and Antarctic (southern hemisphere) (Figure 4). This additional region of convergence, known as the polar front, is another region of forced uplift and hence the development of thunderstorms, lightning, and transient luminous events (TLEs). The polar front also migrates with the seasons from around 50-60° latitude in the summer, to 30-40° in the winter. These are the latitude bands of the midlatitude synoptic storm systems, associated with cold and warm fronts. These regions are associated primarily with summer thunderstorm activity over the mid-latitude continents, although oceanic winter thunderstorm activity and sprite formation also occurs in these regions. Sprites have been observed above winter thunderstorms in Japan and the former Yugoslavia (Takahashi et al., 2003; Jenniskens et al., 2000). As we move further poleward we encounter another region of subsidence in the polar regions, where again few thunderstorms are observed. Regions of surface convergence are normally associated with low surface pressure (L) while surface subsidence results in high atmospheric pressure at the surface (H).

4.3 Frontal Thunderstorms in Mid-Latitude Regions

Frontal thunderstorms occur at the boundary (front) between different air masses, normally cold-dry polar air meeting warm-moist tropical air. The greater the differences between the air masses (temperature and humidity) the greater the atmospheric instabilities that develop, and the greater the intensity of these storms. The intensity appears visibly as frequent lightning discharges, and sometimes sprite activity. Mid-latitude storms generally rotate around a region of low pressure (anti-clockwise in the northern hemisphere (cyclonic rotation) and clockwise (anti-cyclonic) in the southern hemisphere), while simultaneously propagating eastward around the globe with the general westerly flow in midlatitudes (30-60° latitude). Each storm has two fronts that separate the cold polar air from the warm tropical air (Figure 5a). The warm front (represented by red semi-circles) is defined by the forward motion of warm air over colder air, while the cold front (represented by blue triangles) is defined by the forward motion of cold air into regions of warm air (Figure 5a). The symbols point in the direction of frontal motion. Since cold-dry air is denser than warm-moist air, the cold air behind the cold front digs under the warm moist air, forcing it upward over a short distance (Figure 5b). The rapid uplift of air results in strong convective storms often associated with intense lightning activity. The line of thunderstorms that often form along the cold front is called a squall line (Figure 5c). On the other hand, along the warm front the warm air slowly rises over the colder denser air, resulting in a broad region of weak rainfall and showers and weak electrical activity. Therefore, for sprite observations in regions of mid-latitude storms, the cold front regions would provide the best conditions for intense lightning activity, and perhaps TLE observations. Large instabilities in the atmosphere can also occur along frontal zones that divide warm-moist air from cold-dry air around high pressure cells (e.g. The Bermuda High). The flow around a High Pressure Cell is clockwise in the northern hemisphere, opposite to the direction of flow around a low pressure system (Figure 5a). The air is stable at the center of the high pressure resulting in clear, hot and humid weather in the summer months. At the edges of the high pressure region, the mixing of cool dry air and warm moist air along the polar front allows afternoon convection to be initiated. This afternoon convection often produces a ring of thunderstorms around the high pressure center which will also rotate in a clockwise manner around the high pressure cell. This often produces the common "ring of fire" thunderstorm pattern which often develop into mesoscale convective systems (MCSs) which can produce complexes of thunderstorms called mesoscale convective complexes (MCCs). These huge thunderstorm complexes are prolific lightning producers, with many of the U.S. sprite observations occurring above these storms (Lyons et al., 2003).

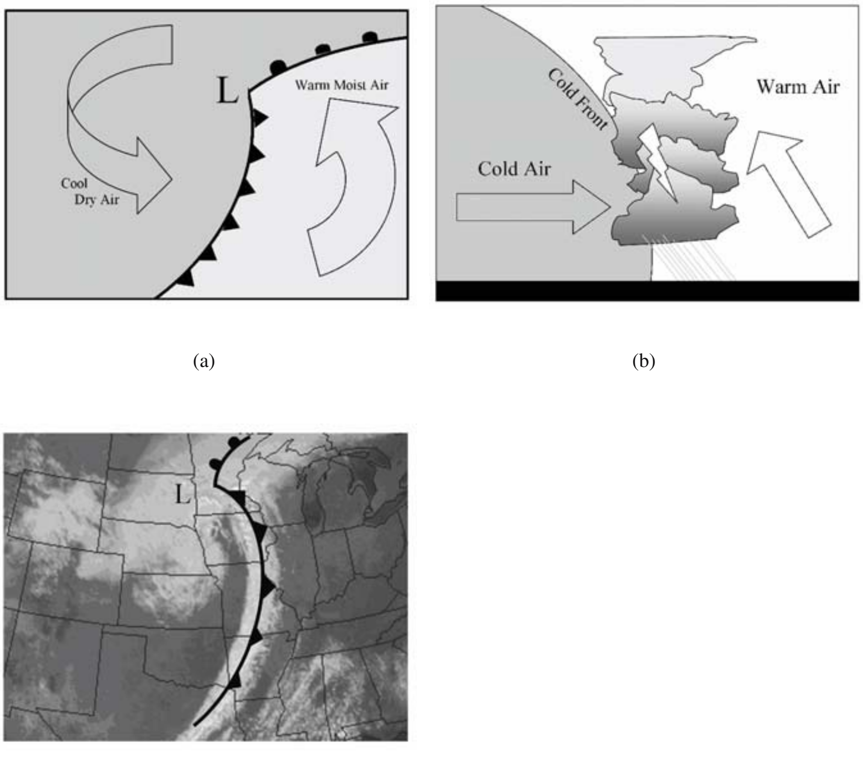


Figure 5. (a) Schematic representation of a midlatitude low pressure system with the cold and warm fronts shown with triangles and semi-circles respectively. In the northern hemisphere the rotation is anticlockwise around the low pressure center; (b) a cross section through a cold front showing the thunderstorm development along the cold front; and (c) a satellite image showing the cloud formation along the cold front.

Global thunderstorms can therefore occur in two very different environments. First, the tropical airmass type thunderstorms resulting from the diurnal heating of the surface of the Earth. These late afternoon thunderstorms occur mainly in the tropics but can also occur during summer months in mid-latitudes where instabilities (static instabilities) can develop in the afternoons on hot summer days. Second, the frontal thunderstorms occur primarily in mid- to high latitudes where different types of air masses interact and result in instabilities (baroclinic instabilities) along cold, warm and stationary fronts. Frontal thunderstorms can occur at any hour of the day, over continent and ocean, and during summer and winter. What is needed for these thunderstorms to develop is a strong density gradient between adjacent air masses. These density gradients can be caused either by temperature differences, humidity differences, or a combination of both. In general these instabilities are largest in the summer months in mid latitudes, however over the relatively warm oceans the instabilities can also be large in the winter months.

It should be noted that in addition to the above ways of producing thunderstorms we also observe thunderstorms due to orographic forcing (uplift over topography). Mountain ranges and islands force air to flow upwards and can initiate instabilities that trigger the formation of thunderstorms. Hence locations to the south of the Himalayas have very intense lightning activity due to the forced uplift of moist air penetrating inland from the Indian Ocean.

4.4 Global Observations of Lightning

In the last decade we have acquired a great deal of knowledge about global lightning and thunderstorms from satellite observations. The two primary sensors used were the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) (Christian et al., 2003; Williams, 2005). The OTD sensor obtained data over a 5-year period from 1995-2000, while the LIS sensor was launched in December 1997 aboard the Tropical Rain Measuring Mission (TRMM) satellite, and is still working to this day (http://thunder.msfc.nasa.gov).

The satellite data show the annual migration of global lightning into the northern hemisphere during the northern hemisphere summer, and then southward into the southern hemisphere during their summer, in agreement with the seasonal migration of the ITCZ and the atmospheric circulation patterns. During spring and fall the distribution of lightning is fairly symmetric about the equator. Approximately 90% of the global lightning observed from space is over the continental regions, while located in the summer hemisphere. The oceanic lightning that does exists is primarily over the relatively warm oceans in the winter hemispheres along the polar front (southeast of South America, Africa and Australia during JJA and north Atlantic, Mediterranean Sea and Japan Sea during DJF). Since lightning is mainly a continental phenomenon, which occurs more often in the summer hemisphere, the northern hemisphere has more lightning activity than the southern hemisphere summer. Hence on a global basis, the Earth's lightning activity peaks in July-August, with a minimum activity in January- February (Figure 6). This asymmetry in mid-latitude land area between the hemispheres, which affects the global lightning, is not seen in the tropical lightning activity. In fact, in the tropics there is slightly more lightning in January than in June (Figure 6). This could be due to the eccentricity of the Earth's orbit around the Sun, resulting in the maximum/minimum solar radiation in the tropics in January/July. Although the satellite detectors sample only a fraction of the global lightning, being in a polar orbit, it is estimated that the global flash rate is approximately 45 flashes/second (Christian et al., 2003). This is less than 50% of the long standing estimate of 100 flashes/second (Brooks, 1925).

On a diurnal basis, tropical thunderstorms are generally active in the late afternoons, and into the evening hours as a result of the solar forcing as the sun heats up the surface during the day (Figure 7). The satellite data show that the continental thunderstorms peak between 1600-1700 local time (dominated by the tropical thunderstorms), with a minimum activity in the early morning hours (06:00-10:00 local time). Over the oceans the thunderstorms are equally distributed during the day, since the ocean temperatures are fairly constant throughout the day. While solar radiation is absorbed only within a few millimeters of the land surface during the day, the same radiation over the oceans is absorbed within 10-100 meters of the ocean surface. Hence the diurnal temperature range over the continents is much greater than over the oceans, with direct impacts on the instabilities that develop on a daily basis, influencing the diurnal thunderstorm activity. Due to the large diurnal variability, the global mean of 45 flashes/second can vary from less than 10 flashes/second, to more than 80 flashes/second. It should be noted that only part of the globe is found at local afternoon at any one time.

4.5 The Global Atmospheric Electric Circuit

If we consider the universal time variations of thunderstorm activity, we find three maxima during each 24 hour period, displayed in Figure 8a (Whipple, 1929). These three maxima correspond to the three tropical thunderstorm regions (Figure 2) that each peak in the late afternoon hours (Figure 7) as a result of solar heating of the surface during the day. The first peak at 09 UT is due to thunderstorm activity in southeast Asia, the second peak at 14 UT is due to lightning activity in Africa, while the third peak at 20 UT is a result of thunderstorm activity in South America. Plotting the global thunderstorm activity as a function of universal time (Figure 8a "world") shows a minimum in thunderstorm activity near 03 UT, when the sun is over the Pacific Ocean,

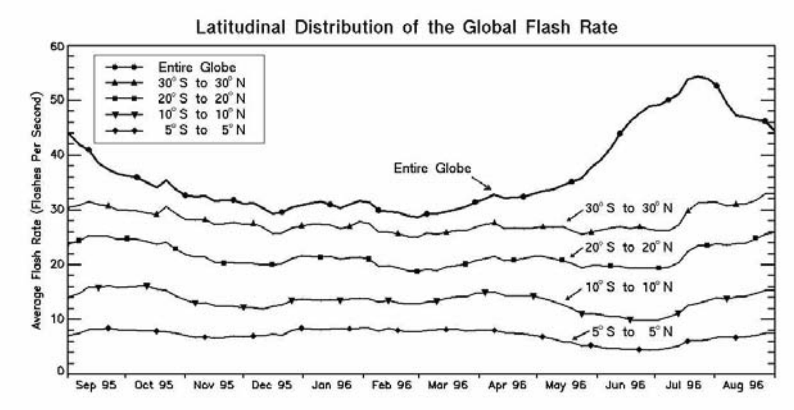


Figure 6. The monthly variations of lightning flash rate for different latitude bands (http://thunder.msfc.nasa.gov)

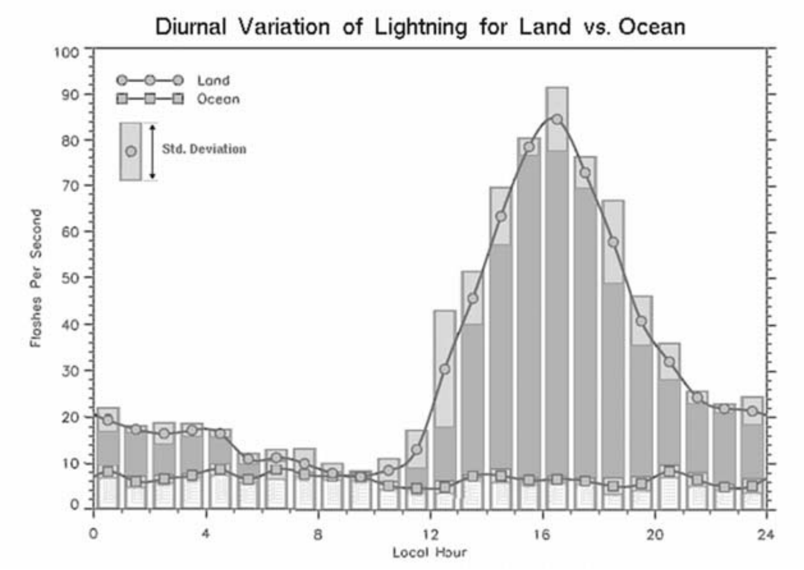
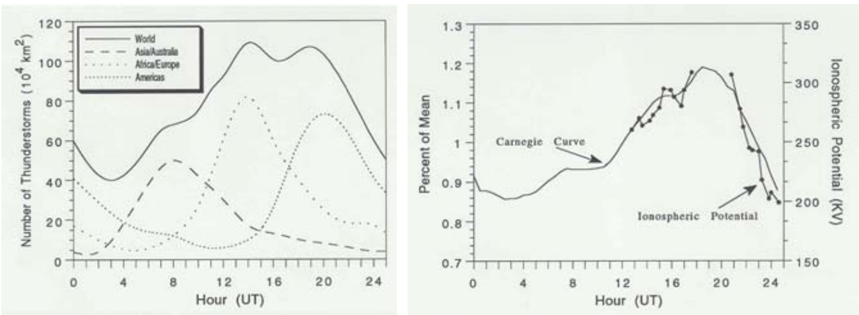


Figure 7. Local hour variations of global lightning activity over land and ocean (http://thunder.msfc.nasa.gov)

and a maximum in thunderstorm activity between 14 UT and 19 UT. Over many years researchers have measured the electrical potential gradient close to the Earth's surface in fair weather regions (no clouds, rain or precipitation nearby, and low pollution levels) and have noticed that often the electric field (mean value of 100 V/m) shows a similar diurnal variation as described above (Mauchly, 1923; Hoffman, 1923). Measurements aboard the Carnegie research vessel in the 1920s showed that the mean electric potential at the surface in clear-sky conditions varies in a way very similar to global thunderstorm activity (Figure 8b). Furthermore, integrating the vertical electric potential with height (using balloons or aircraft) gives the potential difference between the ionosphere and the Earth, know as the ionospheric potential, that has a mean value of 250 kV (Markson, 1985). Since the electric field drops rapidly with altitude, a good estimate of the ionospheric potential can be obtained by integrating the field within the troposphere (up to altitudes of 20 km). The ionospheric potential has also been shown to exhibit a diurnal cycle similar to the Carnegie Curve with a maximum near 18 UT and a minimum around 03 UT displayed in Figure 8b (Markson, 1986). It is therefore believed that the Earth-atmosphere system acts like a global electric circuit (Bering et al., 1998; Rycroft et al., 2000). The thunderstorms and regions of electrified storms act as the generators (batteries) of the circuit. Conduction currents flow upward above the storms to the ionosphere. The ionosphere is close to an equipotential surface and therefore the currents flow horizontally around the globe, and return to the Earth's surface in the fair weather regions. These currents can be measured at the surface and are of the magnitude of 2 pA/m^2 (1 pA = 10^{-12} Amperes). The Earth is also highly conductive and hence the currents flow back within the Earth to the regions of thunderstorm activity to close the electric circuit. The currents observed in the atmosphere are due to the finite conductivity of



(a) (b)

Figure 8. (a) The diurnal variations of thunderstorm area in the three tropical continental regions (adapted from Whipple, 1929), and (b) The diurnal variations of the fair weather potential gradient PG about the mean value of 1, together with measurements of the ionospheric potential (Markson, 1986).

the atmospheric dielectric. It is easy to show that if all thunderstorm activity were to cease, the global electric circuit currents, fields, and charges would decay and disappear within 10 minutes (Bering et al., 1998). Hence the constant charge on the Earth (500,000 Coulombs), the fair weather fields and currents are maintained by the never ending thunderstorm activity around the globe.

4.6 Future Directions

As has been described above, there are different types of thunderstorms around the globe, however, the global studies of sprites are limited to a small number of locations. Only now are we starting to use space platforms to investigate global sprite distributions (Yair et al., 2004; Chern et al., 2003). One recommendation would be to expand field experiments to additional regions of the globe (Lyons, Chapter 2). Most research has actually focused in mid-latitude thunderstorms, while the large majority of thunderstorms occur in the tropics. How does tropical sprite activity differ from mid-latitude sprite activity above thunderstorms (Mende, Chapter 6)? How do the parent lightning flashes that trigger sprites differ (if at all) between regions. Winter thunderstorms are generally much smaller physically than summer thunderstorms, yet still produce sprites. What is special about the winter storms that produce sprites? Most sprites are produced by positive polarity lightning. Is this true in all sprite-producing thunderstorms? Are sprites over the oceans also produced by positive lightning? Studies show many large (charge moment) negative discharges over the oceans (Füllekrug et al., 2002; Greenberg and Price, 2004), although few sprite observations have been targeted above oceanic thunderstorms. Do the physical characteristics of sprites differ according to the type of thunderstorm, region, season and lightning type? And finally, how important are sprites and their associated lightning to the global atmospheric electric circuit ? Are sprite-producing storms the main contributors to the global atmospheric electric circuit ?

Bibliography

Baker, M. B., Blyth, A. M., Christian, H. J., Latham, J., Miller, K. L., and Gadian, A. M. (1999). Relationship between lightning activity and various thundercloud parameters: Satellite and modeling studies. *Atmos. Res.*, 51:221–236.

Baker, M. B., Christian, H. J., and Latham, J. (1995). A computational study of the relationships linking lightning frequency and other thundercloud parameters. *Quart. J. Roy. Met. Soc*, 121:1525–1548.

Bering, E. A. III, Few, A. A., and Benbrook, J. R. (1998). The global electric circuit. *Phys. Today*, 51(10):24–30.

Brooks, C. E. P. (1925). The distribution of thunderstorms over the globe. *Geophys. Mem.*, 3(24):147–164.

Chern, J. L., Hsu, R. R., Su, H. T., Lee, L. C., Mende, S. B., Fukunishi, H., and Takahashi, Y. (2003). Global survey of upper atmospheric Transient Luminous Events on the ROCSAT-2 satellite. *J. Atmos. Sol.-Terr. Phys.*, 65(5):647–659.

Christian, H. J., Blakeslee, R. J., Boccippio, D. J., Boeck, W. L., et al. (2003). Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.*, 108(4005):doi:10.1029/2002JD002347.

Füllekrug, M., Price, C., Yair, Y., and Williams, E. R. (2002). Intense oceanic lightning. *Ann. Geophys.*, 20:133.

Greenberg, E. and Price, C. (2004). A global lightning location algorithm based on the electromagnetic signature in the Schumann resonance band. *J. Geophys. Res.*, 109(D21111):doi:10.1029/2004JD004845.

Hoffman, K. (1923). Bericht über die in Ebeltofthafen auf Spitzbergen in den Jahren 1913/4 durchgeführten luftelektrischen Messungen. *Beitr. Phys. Atmos.*, 11(1). Leipzig.

Jenniskens, P., Butow, S., and Fonda, M. (2000). The 1999 Leonid multi-instrument aircraft campaign – an early review. *Earth, Moon and Planets*, 82-83:1–26.

Jorgenson, D. P. and Lemone, M. A. (1989). Vertical velocity in oceanic convection off tropical Australia. *J. Atmos. Sci.*, 51:3183–3193.

Lemone, M. A. and Zipser, E. J. (1980). Cumulonimbus vertical velocity events in GATE. Part I: Diameter, intensity and mass flux. *J. Atmos. Sci.*, 37:2444–2457.

Lyons, W. A., Nelson, T. E., Williams, E. R., Cummer, S. A., and Stanley, M. A. (2003). Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective system. *Mon. Wea. Rev.*, 131:2417–2427.

Markson, R. (1985). Aircraft measurements of the atmospheric electric global circuit during the period 1971–1984. *J. Geophys. Res.*, 90:5967–5977.

Markson, R. (1986). Tropospheric convection, ionospheric potential and global circuit variations. *Nature*, 320:588–594.

Mauchly, S. J. (1923). Diurnal variations of the potential gradient of atmospheric electricity. *Terr. Magn. Atmos. Electr.*, 28:61–81.

Petersen, W. A., Nesbitt, S. W., Blakeslee, R. J., Cifeli, R., Hein, P., and Rutledge, S. A. (2002). TRMM observations of intraseasonal variability in convective regimes over the Amazon. *J. Clim.*, 15:1278–1294.

Price, C. (2000). Evidence for a link between global lightning activity and upper tropospheric water vapor. *Nature*, 406:290–293.

Price, C. and Rind, D. (1992). A simple lightning parameterization for calculating global lightning distributions. *J. Geophys. Res.*, 97:9919–9933.

Rycroft, M. J., Israelsson, S., and Price, C. (2000). The global atmospheric electric circuit, solar activity and climate change. *J. Atmos. Sol.-Terr. Phys.*, 62:1563–1576.

Takahashi, Y., Miyasato, R., Adachi, T., Adachi, K., Sera, M., Uchida, A., and Fukunishi, H. (2003). Activities of sprites and elves in the winter season, Japan. *J. Atmos. Sol.-Terr. Phys.*, 65:551–560.

Whipple, F. J. W. (1929). On the association of the diurnal variation of the electrical potential gradient in fine weather with the distribution of thunderstorms over the globe. *Quart. J. Roy. Met. Soc.*, 55:1–17.

Williams, E., Chan, T., and Boccippio, D. (2004). Islands as miniature continents: Another look at the land-ocean lightning contrast. *J. Geophys. Res.*, 109(D16206):doi:10.1029/2003JD003833.

Williams, E. and Stanfill, S. (2002). The physical origin of the land-ocean contrast in lightning activity. *Compt. Rend. Phys.*, 3:1277–1292.

Williams, E. R. (2005). Lightning and climate: A review. *Atmos. Res.*, 75:272–287.

Williams, E. R. et al. (2002). Contrasting convective regimes over the Amazon: Implications for cloud electrification. *J. Geophys. Res. - LBA Special Issue*, 107(D20-8082):doi:10.1029/2001JD000380.

Williams, E. W. and Satori, G. (2004). Thermodynamic and hydrological comparison of the two tropical continental chimneys. *J. Atmos. Sol.-Terr. Phys.*, 66:1213–1231.

Yair, Y., Israelevich, P., Dvir, A. D., Moalem, M., Price, C., Joseph, J. H., Levin, Z., Ziv, B., Sternlieb, A., and Teller, A. (2004). New observations of sprites from the Space Shuttle. *J. Geophys. Res.*, 109(D15201):doi:-10.1029/2003JD004497.