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Thunderstorms, Lightning and Climate Change

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Abstract - The distribution of lightning around the planet is directly linked to the Earth's climate, which is driven by solar insolation. On the diurnal scale, lightning activity in the tropics peaks a few hours after the peak solar heating. On a seasonal scale, lightning activity peaks a few months after the peak annual solar heating. And globally, due to the continental asymmetry between the hemispheres, more lightning activity occurs in the northern hemisphere summer relative to the southern hemisphere summer. However, it now appears that anthropogenic activity on the planet is changing the equilibrium state of the climate. With recent projections of a warmer world in the future, one of the key questions is related to the impact of global warming on thunderstorms, and other severe weather. Will lightning activity increase in a warmer world? Will we have more intense storms? If changes in lightning activity occur, this too may have an impact on the Earth's climate. Lightning is a major source of nitrogen oxides (NO_x) in the atmosphere, which are a precursor for ozone (O_3) production in the troposphere. Since O_3 is also a greenhouse gas, changes in lightning activity may result in an additional warming (positive feedback) on the climate system. Lightning also supplies important information about the intensity of convection, which is related to other important climate parameters. Hence, by monitoring global lightning activity we may be able to track changes in numerous parameters that are important in the climate change debate.

1 INTRODUCTION

Lightning discharges in thunderstorms are an indication of the intensity of atmospheric convection. Atmospheric convection occurs under unstable atmospheric conditions, either due to the heating of the boundary layer by solar radiation during the day, or by the mixing of air masses of different densities. Lightning frequencies are therefore related to the regions of greatest instability in the Earth's atmosphere. These regions of instability do not occur randomly around the planet, but have an organized pattern related to the climate of the Earth which is driven by the differential heating of the Earth's surface by the sun. If we change the climate we will change the regions of convection, their intensity, and hence will likely change the lightning patterns around the globe.

In the last decade we have learned a great deal about the spatial and temporal patterns of global lightning and thunderstorms from both satellite and ground-based observations. The two primary satellite sensors that have been used are the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) (Christian et al., 2003), while key ground-based global observations of lightning have been based on Schumann resonance methods (Price and Melnikov, 2004; Price et al., 2007).

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2 GENERAL CIRCULATION OF THE ATMOSPHERE

The distribution of global thunderstorms is directly linked to the Earth's climate, and more specifically, the general circulation of the atmosphere. The maximum solar heating at the surface in the tropics results in rising thermals and vertical mixing in the atmosphere. The region of rising air that occurs along the thermal equator is known as the inter-tropical convergence zone (ITCZ) due to the resulting convergence of surface winds from the northern and southern hemispheres along this boundary. The thermal equator migrates north and south of the geographic equator according to the seasons, with the thermal equator furthest north in June-August during the northern hemisphere summer, and furthest south in December-February during the southern hemisphere summer. Due to the different heat capacity of land versus oceans, the continental regions heat up more rapidly than the oceans, resulting also in longitudinal differences in the location and width of the ITCZ.

More than 2/3 of global lightning occurs in tropical thunderstorms (Christian et al., 2003). However, a significant difference in convective intensity is observed between oceanic and continental convection in the tropics (Lemone and Zipser, 1980; Jorgenson and Lemone, 1989). Updraft velocities in oceanic thunderstorms may reach a maximum of 10 m/s, while over continental regions the updrafts may reach 50 m/s or greater (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 (Figure 1). Williams et al. (2004) have re-addressed this difference in land/ocean lightning, considering two opposing hypotheses. The one deals with the thermal hypothesis where the land surface heats up more rapidly during the day as compared with the oceans, and hence the instabilities, convection and lightning are more vigorous over the land areas. The other deals with the aerosol hypothesis, due to the order-of-magnitude difference in the concentration of cloud condensation nuclei (CCN) between the continents and the oceans, that can influence cloud microphysics and the intensity of deep convective storms. Using islands as miniature continents Williams et al. (2004) concluded that the thermal hypothesis still appears to be the main cause of the land-ocean contrasts in observed lightning activity.

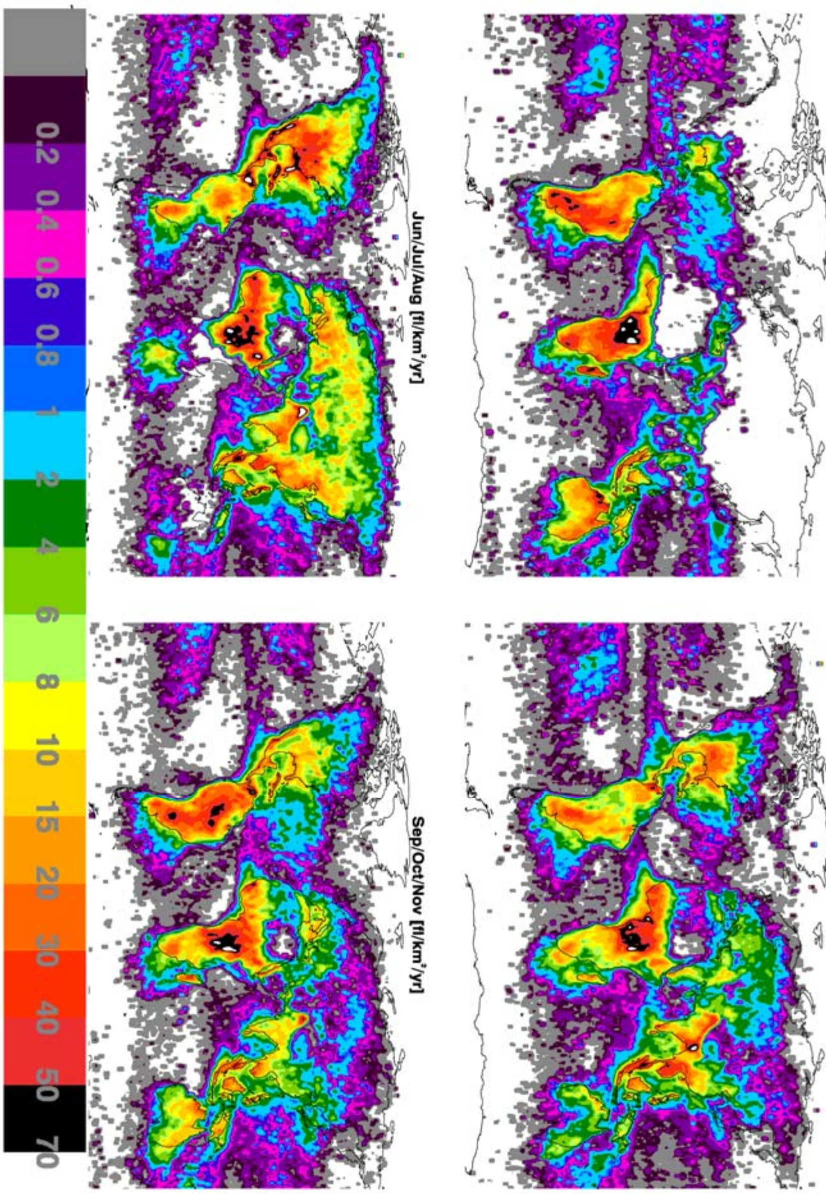

Figure 1: Seasonal maps of the OTD/LIS satellite- observed lightning (http://thunder.masfc.nasa.gov).

It should be noted that 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 activity (Williams and Satori, 2004).

In mid-latitudes, frontal thunderstorms occur at the boundary (front) between different air masses, normally cold-dry polar air meeting warm-moist tropical air. The greater the density differences between the air masses (temperature and humidity) the greater the atmospheric instabilities that develop, and the greater the intensity of these storms. The manifestation of the intensity appears visibly as frequent lightning discharges. 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 the midlatitudes (30-60 degrees latitude) (Price, 2006).

3 LIGHTNING AND CLIMATE

There have been numerous papers in the past few years dealing with the connection between lightning, climate and climate change. An extensive review of the topic of global climate-lightning connections was given by Williams (2005), with additional discussion by Price (2006, 2008), and the reader is directed to these papers for further information.

A. Temperature

Due to the interest in global warming, there have been numerous studies looking at the relationship and sensitivity of lightning activity to changes in surface temperature. Since long term global lightning observations do not exist, relationships are normally investigated on shorter time scales. Many time scales have been explored, from diurnal (Price, 1993; Markson and Price, 1999) and daily variations (Price and Asfur, 2006a), to 5-day waves (Patel, 2001), intraseasonal (Anyamba et al., 2000) and semiannual variations (Williams, 1994; Satori and Ziegler, 1996; Fullekrug and Fraser-Smith, 1998; Nickolaenko et al., 1999), and the annual (Heckman et al., 1998; Christian et al., 2003, Toumi and Qie, 2004) and interannual scales, dominated by the El Nino (Williams, 1992; Reeve and Toumi, 1999; Satori and Ziegler, 1999). On all these timescales we observe a positive relationships between temperature and lightning, with lightning increasing anywhere from 10-100% for every one degree surface warming.

Recent studies continue to show the high positive correlation between surface temperatures and lightning activity (Williams et al., 2005; Price and Asfur, 2006a; Sekiguchi et al., 2006). Figure 2 shows the daily regionally averaged surface temperatures over Africa compared with the regional lightning activity, based on Schumann resonance measurements, over a 2-month period (Price and Asfur, 2006a). It is clear that for the tropical lightning centers, surface temperature is a key driving factor of daily lightning activity. However, there does not appear to be any long term trend detected in lightning activity over the last fifty years (Price and Asfur, 2006b; Markson, 2007).

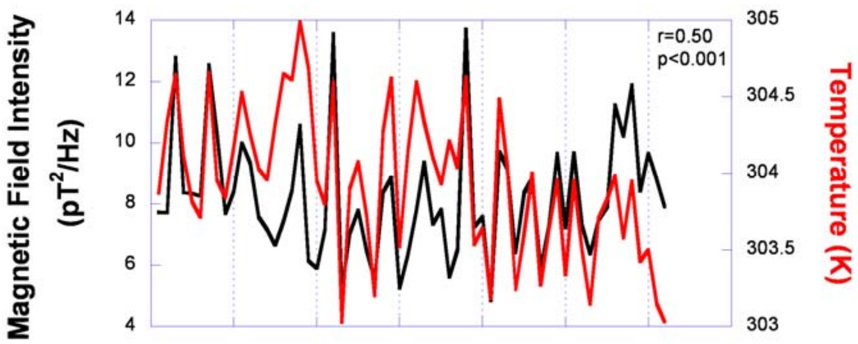

Figure 2: Daily regional lightning activity (black) and regional mean surface temperatures over Africa over a 2-month period (from Price and Asfur, 2006a).

B. Water Vapor

Water vapor in the atmosphere is the primary natural greenhouse gas influencing the climate of the Earth. Since water vapor absorbs infrared radiations emitted from the Earth's surface, increases in water vapor in a warmer climate would result in a positive feedback, amplifying the initial warming (Del Genio, 2002). In general, the Earth's climate is believed to be much more sensitive to changes in water vapor in the upper troposphere, where the concentrations are naturally very low. Recently it has been shown that thunderstorms deposit large amounts of water in the upper troposphere, moistening of the upper tropospheric environment (Price, 2000; Price and Asfur, 2006a), with important consequences for the Earth's climate (Rind, 1998). Figure 3 shows the relationship between daily lightning activity over Africa, based on Schumann resonance measurements, and the specific humidity in the upper troposphere (300 hPa). The curves have been shifted by 24 hours to show the agreement, however, the lightning peaks one day before the peak humidity fields in the upper troposphere. The lightning activity is a means of monitoring the intensity of deep convection, and hence is well correlated with the vertical transport of water vapor by thunderstorms into the upper atmosphere.

Related to water vapor, Sato and Fukunishi (2005) showed a connection between tropical lightning activity and high cloud coverage in the tropics, while strong connections between lightning and upper tropospheric ice water content (Petersen et al., 2005) and ice crystal size (Sherwood et al., 2006) have recently been demonstrated. Water vapor, cloud cover, ice water content, and ice particle size all have direct impacts on the Earth's radiation balance, and therefore lightning may supply an important tool for studying the variability and changes in these important climate parameters.

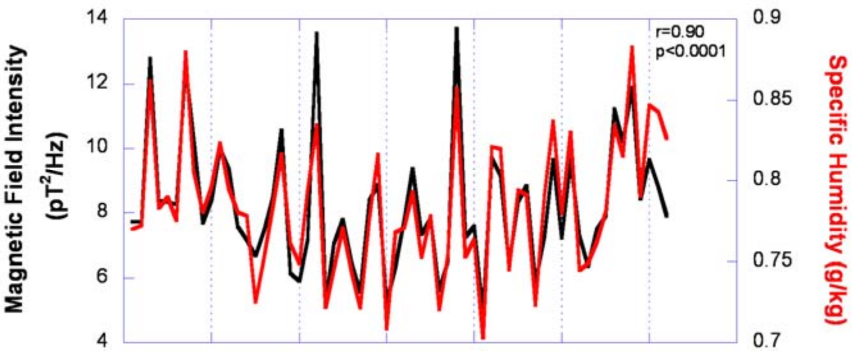

Figure 3: The daily relationship between lightning activity (black) and upper troposphere specific humidity (300 hPa) over Africa during a 2-month period. The lightning curve has been shifted forward one day to show the excellent agreement (from Price and Asfur, 2006a).

C. Tropospheric Chemistry

Lightning itself can influence the climate via the production of nitrogen oxides ($NO + NO_2 = NO_x$) followed by the production of ozone, another efficient greenhouse gas. A comprehensive review of this topic is given by Schumann and Huntrieser (2007), with references therein. Recent field experiments such as TROCCINOX (Huntriesser et al., 2007) show greatly enhanced NOx concentrations in thunderstorm anvils, with enhanced ozone concentrations downwind. Ryu and Jenkins (2005) and Grewe (2007) have also shown the significant influence of lightning on tropospheric ozone concentrations.

The global amount of NO_x produced by lightning and thunderstorms is still highly uncertain. There are a wide variety of lightning flashes and thunderstorms, and therefore measurements in individual field experiments may not be reliable for extrapolating globally. It is also difficult to assign a certain concentration of NO_x in a specific storm to a specific lightning discharge. Even if this was possible, the important parameters of the lightning discharge (energy, length, peak current, tortuosity, altitude, number of return strokes, etc.) are needed in order to extrapolate the results to other lightning discharges around the globe. Nevertheless, lightning is believed to be the largest source of NOx in the upper troposphere, where lifetimes of a few days result in NOx playing an important role modulating the Earth's climate (Price et al., 1997).

4 FUTURE CLIMATE CHANGE

There is solid evidence that global temperatures are increasing, and the cause is very likely due to the increasing anthropogenic greenhouse gases in the atmosphere (IPCC, 2007). However, since we do not know how lightning and thunderstorms will react to a warmer world, we need to either use climate change proxies from the present and past, or we need to run computer simulations of how global warming may impact thunderstorms in a future climate. There are numerous caveats regarding the use of present day climate variations as proxies for future climate change. Lindzen et al. (1995) has discussed the problems of using the annual cycle as a proxy for future climate change. Furthermore, regional climate variability such as the ENSO cycle is more related to shifts in circulation patterns in the atmosphere than changes in temperature. Hence, we need to be cautious when extrapolating present day variability to future global warming.

With that said, we now have a decade of measurements of lightning from space. The Tropical Rain Measuring Mission (TRMM) satellite has provided great insights into global lightning distributions (Christian et al., 2003), allowing us to examine the relationship between lightning and Earth's climate. It is well known that global lightning is divided between the three hot-spots, or chimneys, over the tropical land masses (Africa, South America and Southeast Asia) (Figure 1), while tropical precipitation is more continuous around the tropics following the intertropical convergence zone (ITCZ) (Price, 2008). We also know that the three thunderstorm chimneys are ranked 1) Africa, 2) South America and 3) Southeast Asia, from the most active to the least active regions. However, the opposite trend is observed for precipitation, with the chimneys ranked 1) Southeast Asia, 2) South America, and 3) Africa. On a regional annual mean climate scale, less precipitation implies more lightning, which appears contradictory (Price, 2008).

Williams and Satori (2004) looked into this difference in more detail, examining the differences between tropical Africa and tropical South America. They showed that the main difference between Africa and South American lightning activity was due to African being hotter and drier than South America. The greater continentality of Africa is attributed to its greater elevation above sea level, and to the asymmetry of the synoptic scale delivery of moisture to the region. In addition, Williams et al. (2005) showed that as the height of thunderstorm cloud base increased, so did the lightning activity. Higher cloud base implies drier surface conditions, which would support these observations. Carey and Buffalo (2007) also recently demonstrated that thunderstorms with predominantly positive lightning (often associated with severe weather) were more likely in a drier environment.

This apparent paradox also appears evident on the ENSO timescales (Hamid et al., 2001) where during the strong El Nino of 1997-8 severe drought conditions persisted across Indonesia, while the lightning activity increased by 57%. This could occur if we had fewer thunderstorms, with each thunderstorm more vigorous, producing more lightning, or possibly by raising the cloud base, promoting the mixed phase electrification (Williams et al., 2002) with less warm rain production (Williams et al., 2005). In support of this, Hamid et al. (2001) showed that the thunderstorms during the drier El Nino period had greater vertical development, while the mixed-phase precipitation zones were thicker.

When looking at modeling studies of global warming scenarios, the recent IPCC report (IPCC, 2007) presents results from more than 20 different models, together with the responses of these models to rising concentrations of greenhouse gases. As related to tropical convection and lightning, once again a paradox arises. All models show that the greatest warming due to increasing greenhouse gases will occur not at the surface, but in the equatorial upper troposphere. The reason for this is that the models predict a moistening of the upper troposphere, due to enhanced deep convection in the tropics, and this extra water vapor in the upper troposphere is a strong greenhouse gas, absorbing infrared radiation emitted from the Earth's surface. However, if the upper atmosphere is warmed relative to the surface, the atmospheric lapse rate (dT/dz) becomes more stable, tending to inhibit future convection. So we would expect that the stabilization of the atmosphere as the climate warms would reduce the amount of thunderstorms, and hence lightning.

However, numerous climate model simulations have shown that lightning activity will increase in a warmer climate (Price and Rind, 1994; Grenfell et al., 2003; Shindell et al., 2006). Although the parameterizations of lightning in global climate models are quite crude (Price and Rind, 1992; Allen and Pickering, 2000; Futyan and Del Genio, 2007), the models nevertheless manage to duplicate the present global lightning climatologies (Shindell et al., 2006). All of these modeling studies indicate an approximate 10% increase in lightning activity globally for every 1 K global warming, with most of the increase occurring in the tropics, exactly where we expect the atmosphere to become more stable. This paradox was dealt with in more depth by Del Genio et al. (2007) where they showed that in a doubled-CO_2

climate the updrafts strengthen by ~1m/s, due to a rise in the height of the freezing level in the model. They showed that in certain regions, such as the western United States, the drying in a warmer climate reduces the frequency of thunderstorms, but the strongest storms occur 26% more often. In other words, the drier climate produces less thunderstorms overall, but those storms that do develop are more intense in a warmer climate. This agrees with recent observations (Williams et al., 2005) showing increased electrification in the drier regions of the Great Plains of the United States.

5 DISCUSSION AND CONCLUSIONS

It is clear that the spatial and temporal distributions of lightning activity on Earth are governed by the climate itself. The diurnal solar heating, the latitudinal temperature gradient, the general circulation of the atmosphere, the location of regions of convergence and divergence, static and baroclinic instabilities, etc., all influence the global distributions of thunderstorms. In addition, we know that thunderstorms track the motion of the sun during the seasons, with most lightning activity being in the summer hemisphere.

On short time scales (hourly, daily, monthly and annual) there appears to be a robust positive correlation between tropical lightning activity and surface temperature, upper tropospheric water vapor, cloud cover, and anvil ice content. Whether these relationships hold on longer time scales is still uncertain, although climate models do support the positive correlation between lightning and global temperatures.

Since lightning can be monitored easily, and continuously, from ground networks, lightning may become a useful tool for monitoring changes in important climate parameters in the future. Furthermore, lightning itself is an important source of nitrogen oxides (NO_x) in the atmosphere, with implications for ozone production, and the Earth's radiation balance. Lightning is likely the major source of NO_x in the upper troposphere.

On climatic scales, when considering the tropical continental centers of lightning activity, they rank in the opposite order when considering lightning and precipitation. While Africa has the highest lightning activity of the three chimney regions, it has the lowest rainfall, while being the hottest. When we look at the impact of the ENSO cycle on tropical lightning and rainfall, a similar negative relationship is observed, with hot drought-stricken Southeast Asia during the El Nino years having more lightning than during the wetter cooler La Nina periods. Hence, when considering lightning-climate relationships, we need to also consider the moisture availability and not only temperature.

Climate models provide some insight into this paradox that shows more lightning with less rainfall, since they too predict increasing lightning activity as the climate warms and dries. Both regionally and globally climate models predict increases in lightning activity in a warmer climate, even though the atmosphere becomes more stable and the surface tends to dry as the climate warms.

All of these relationships showing less rainfall associated with more lightning may be explained if drier climates have fewer thunderstorms, with each storm being more intense. This is what model studies show happens in a warmer climate. This has also now been documented in the Mediterranean region over the past 50 years, where the total rainfall has been decreasing, while the intense rainfall events have been increasing (Alpert et al., 2002).

Previous studies have indicated that increased lightning activity will moisten the upper troposphere (Price, 2000; Price and Asfur, 2006). Hence, a drier surface resulting in a wetter upper atmosphere also appears to present a contradiction. However, the upper troposphere is naturally extremely dry, and therefore increasing the intensity of thunderstorms in a drier climate will indeed moisten the upper troposphere. This enhanced moistening is what drives the maximum warming in climate models in a double-CO_2 world.

One factor that has not been addressed here is the role of aerosols in thunderstorms electrification. It is possible that drier climates result in more suspended aerosols and cloud condensation nuclei, hence influencing cloud microphysics and cloud electrification (Williams et al., 2002). However, it should be pointed out that all model simulations discussed here do not include any aerosol effects on lightning, and address only thermodynamic changes in their simulations. Whether aerosol effects would enhance these changes is a topic for future studies.

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