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Urban Lightning: Current Research, Methods, and the Geographical Perspective

J. Anthony Stallins* and L. Shea Rose
Department of Geography, Florida State University

Abstract

This review of urban lightning research begins with a description of cloud-to-ground flash data and some of the conditioning practices related to their use. Urban lightning studies from the United States and internationally are then examined to distill findings as well as to compare and contrast the modes of inquiry among the meteorologists, climatologists, engineers, and geographers who study lightning. In summary, these investigations convey how urban heating, building-induced surface friction, aerosols, and specificities such as local physiography and synoptic setting are intertwined causal mechanisms underlying urban flash modification. A tension among methodological approaches in these studies circumscribes how questions are posed, and how findings are valued and ultimately synthesized. Flash research tends to follow either a descriptive phenomenological approach or a foundational approach in which prediction and mechanism are paramount. Selecting the spatial extent of an urban lightning study and the methods to assess the statistical embeddedness of flash counts within thunderstorms events are two other methodological points of contention. City-to-city comparisons and integrated analysis of aerosols, precipitation, and flashes over multiple scales are important directions for future research.

Introduction

Cities have long been recognized for a propensity to modify their weather and climate (Ruddiman 2003; Von Storch and Stehr 2006; Yow 2007). The first meteorological studies in North America to assess changes in thunderstorm activity around urban areas relied on direct observational and instrumental evidence. These investigations articulated the first formal hypotheses about how urban areas modify convection and the frequency of thunderstorms (Changnon et al. 1971; Huff and Changnon 1973). With the advent of lightning detection networks in the mid to late 1980s and the computational power to analyze large volumes of strike data, a range of studies has verified that cities modify the patterns of lightning in their vicinity. Urban lightning studies now seek to build more understanding of mechanisms, the relative importance of different explanatory variables, and how cities vary in their flash patterns.

In industrialized nations, land cover change for urbanization in and around cities outpaces population growth in them (Pickett et al. 2001). And as evidence for a range of urban weather effects has become more certain, an interest in urban weather hazards has grown among forecasters, planners, and the insurance industry (Best 2006; Dabberdt et al. 2000). With burgeoning urban populations and land use conversion, the question of how these densely built areas will influence local weather patterns and the hazards that emerge from them takes on more urgency (Pickett et al. 2001).

The goal of this article is to review recent studies of urban lightning. We focus on findings from the second wave of studies that utilize ground-based lightning detection networks. These networks archive the location and time of cloud-to-ground flashes. We begin with a review of cloud electrification and the flash data available for urban research. Next, we report the findings of the relatively small number of urban lightning investigations relying on these ground-based networks. We describe studies conducted in Atlanta, Georgia; Houston, Texas; and among several cities of the US Midwest as part of Westcott's (1995) characterization of urban flashes. Significant work has also emerged in Brazil, Spain, France, and Korea. Where appropriate, we introduce findings from research on urban convection and precipitation that provides insight into how cities modify lightning production. The last third of this article is a discussion of methodological tensions within urban lightning research and a synopsis of directions for future research.

Cloud-to-Ground Flash Data

A basic understanding of cloud electrification is a prerequisite for undertaking research on urban lightning. Even though there are a few contrasting views on the details of lightning initiation (Dwyer 2005), most introductory meteorology texts (Ahrens 1994) should communicate the basic principles of the non-inductive charge separation process that electrifies clouds (MacGorman and Rust 1998; Saunders 1993; Takahashi 1978). Thunderstorms contain hydrometeors of different sizes with different surface properties. Within the mixed phase region of a developing thunderstorm, collisions of hail, graupel, and ice crystals in the presence of supercooled water leads to the transfer and accumulation of positive and negative charges. Under the influence of updrafts and gravitational sedimentation, these particles and their characteristic polarity segregate into different regions within a developing cumulonimbus. Eventually, the voltage potentials that build within individual clouds, between clouds, and between the cloud and the ground break down, leading to the production of positive or negative polarity flashes. Most of the flashes produced by a thunderstorm are intracloud strikes (Prentice and Mackerras 1977). A wealth of phenomena is embedded in a single flash, from step leaders, dart leaders, and multiple return strokes, giving rise to an underestimated complexity of what comprises a single 'flash' (Rakov and Uman 2007).

Ground-based detection networks generate highly precise locational datasets of cloud-to-ground lightning strikes. The US National Lightning Detection Network maintained by Vaisala Inc. (Vaisala 2007) consists of an array of more than 100 detection sensors distributed across North America (Grogan 2004). These sensors process time and position information for each flash and its subsequent return strokes (Krider et al. 1976). Prior to network upgrades in 1995, detection efficiency was 65–80% and positional accuracy ranged from 2–4 km. After upgrades in 1994–1995, detection efficiencies of 80–90% and locational accuracies of 500 m were achieved. Upgrades in 2002–2003 resulted in greater than 90% detection efficiencies. Other improvements made in 2002–2003 include a greater sensitivity to the detection of low minimum peak current and flash multiplicity. In general, detection efficiencies may show some slight geographic variability due to the location of National Lightning Detection Network (NLDN) sensors relative to the flash (Biagi et al. 2007).

Users of NLDN data need to consider several data conditioning issues. Because upgrades in 1995 and 2002–2003 began to detect low amperage positive polarity intracloud flashes, it is recommended that positive polarity flashes <10–15 kiloamps be removed from the analysis dataset (Cummins et al. 1998; Wacker and Orville 1999). Second, studies spanning the intervals over which these upgrades went online must decide whether or not to combine periods that have different detection efficiencies. The decision as to whether or not to combine pre-1995 data with post-1995, or pre-2002–2003 with later data should be a function of how the data are to be used. The bin size, or grid cell resolution, to count and summarize flashes is also important (Schultz et al. 2005). Urban lightning maps have varied from a resolution of 2×2 km (Stallins et al. 2006) to grid cells 5 km on a side (Steiger and Orville 2003), up to 9×9 km (Pinto et al. 2004).

Research using lightning data is no longer limited to a single data provider. The US Precision Lightning Network (USPLN 2007) is a ground-based network that has entered the private cloud-to-ground flash detection market. Ground-based lightning sensor arrays are found in many countries, including China, Australia, throughout Europe. Smaller regional networks, built for specialized research or safety interests, are also becoming more common. A growing number of vendors provide satellite-detected flash data. NASA's Global Hydrology and Climate Center (GHCC 2007) archives intracloud and cloud-to-ground flash data collected by the Lightning Imaging Sensor (LIS) aboard the Tropical Rainfall Measuring Mission satellite as well as older flash data collected by the Optical Transient Detector. These data are at coarser resolutions and larger spatial extents than NLDN data (Boccippio et al. 2000; Mach et al. 2007).

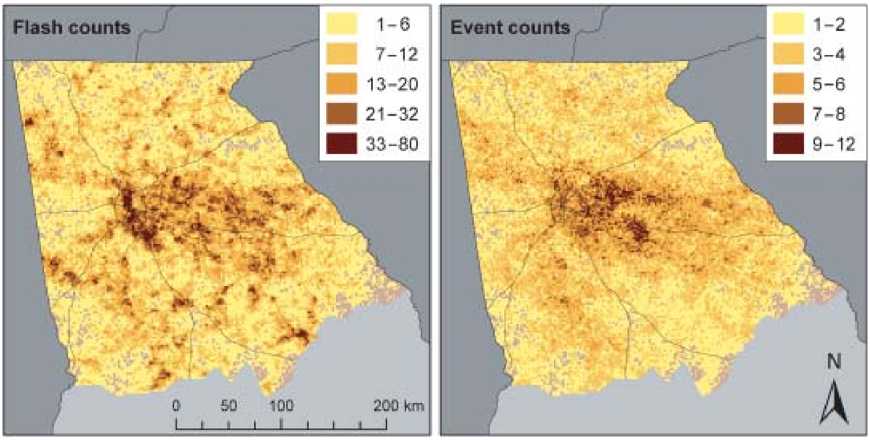

Fig. 1. Downwind augmentation of cloud-to-ground lightning activity for Atlanta, Georgia, when mid-level (700 mb) winds originate out of the northwest. Number of total cloud-to-ground flashes (left) and number of thunderstorms producing flashes (right). Area show is the northern half of Georgia. Counts for flashes and thunderstorm flash events are tallied in 2 × 2 km grid cells. Flashes are from May to September (1995–2003) on days dominated by air mass conditions. Flashes shown represent thunderstorms that produced at least one flash within the circular area to the northeast of Atlanta. Other lines represent interstates. Atlanta city center is within the central interstate loop.

Relevant Studies

Although there have been no pronounced and consistent anomalies in some strike descriptors like multiplicity (the number of return strokes) and peak current in urban areas (Pinto et al. 2004; Steiger et al. 2002), two general findings have remained consistent across many cities (Kar et al. 2007). First, cloud-to-ground flash densities increase, particularly downwind of the city center (Figure 1). Second, the percentage of positive polarity cloud-to-ground flashes has been found to decrease. Yet, when comparing flash characteristics between cities, one should be aware of changes in flash production that vary across latitudes, climatic zones, and altitudes (Orville and Huffines 2001; Reap 1986).

A maximum in lightning flash density (3 flashes/km^2/year) developed over the northwest of Bilbao, a city in the Basque country of Spain with a sizeable industrial component (Areitio et al. 2001). This maximum was persistent for 3 years of a 4-year study. In a 2-year survey (1992–1994) of nine small towns in central Spain, ranging in size from several thousand to 300,000, only two lacked increases in downwind flash counts (Soriano and De Pablo 2002). Although these two towns did not manifest downwind flash augmentation, one had a peak directly over the city, and the other had strong topographic controls. Belo Horizonte, a large urban region of 12 million in Brazil, exhibited a 100% increase in negative polarity flashes and a 25% decrease in percent positive flashes over and downwind of the city from 1989–1996 (Pinto et al. 2004). Similar findings were also reported for São Paulo, Brazil, where flash densities increased 60–100% when moving from surrounding rural to urban areas (Naccarato et al. 2003). Higher urban flash densities corresponded to the outline of urban land uses defining the São Paulo urban region. Positive flashes declines of 7–8% were also attributed to urban effects.

In a North American context, one of the first urban flash studies was conducted by Westcott (1995). Using 4 years of NLDN data (1989–1992), Wescott found that 13 of 16 cities in the central United States had a significantly higher number of flashes (40–85%) at downwind locations across different sizes of thunderstorms. The three cities that did not exhibit significant increases were Detroit, Michigan, and two cities in Ohio, Cincinnati and Toledo. Lake effects may have limited development of urban flashes in Detroit. Cincinnati's complex terrain was invoked to explain its lack of flash augmentation. Wescott discussed several mechanisms to explain the higher densities of downwind flashes, including the size of the urban area, sulfur dioxide and aerosol concentrations in the atmosphere, and the proximity to geographic features like river valleys. River valleys were hypothesized to help initiate convection in the downwind direction.

For all the cities of her study, Westcott (1995) employed thunderstorm size categories to compare patterns of flash production upwind, downwind and directly over each city's urban core. Size categories were defined by the number of flashes that fell within a given thunderstorm over a given period of time. For example, if a flash occurred within 1 h of another within a set radius of the city, it was considered part of the same thunderstorm. By examining flash distributions in groups stratified by these production categories (1–10 flashes, 11–100 flashes, 101–1000 flashes, etc.) the effects of individual large storms that may disproportionately contribute to augmentation were filtered out. Other studies have followed this approach, often by employing the number of flashes in a day as a means to standardize comparisons of flash productivity (Stallins et al. 2006; Steiger et al. 2002).

Intensive analyses of urban lightning patterns and processes have been conducted in Houston, Texas, as part of the HEAT (Houston Environmental Aerosol Thunderstorm) Project (Orville et al. 2001; Steiger and Orville 2003; Steiger et al. 2002). These investigations found higher flash densities (45% overall, 58% summer only) over and downwind of the Houston urban area based on 11 years (1989–2000) of data (Steiger et al. 2002). Positive flashes decreased by 20% during the summer months. Days with >100 flashes contributed disproportionately to the higher downwind flash counts (Steiger and Orville 2003). The number of flash days, the

24-h periods in which at least a single flash occurred, was slightly higher over Houston than in two surrounding control areas.

Atlanta has also been the location of a series of studies investigating how urban areas modify not only lightning, but also convection and precipitation (Diem 2007; Diem and Mote 2005; Mote et al. 2007; Shepherd et al. 2002; Stallins and Bentley 2006; Stallins et al. 2006; Watson and Holle 1996). Bornstein and Lin (2000) documented evidence for the urban initiation of six convective precipitation events around the city. Dixon and Mote (2003) found that low-level moisture and urban heat island intensity had complex roles in the initiation of urban-induced precipitation. Diem (2007) statistically confirmed the existence of an area of enhanced precipitation northeast of Atlanta. Based on visualizations of 12 years (1992–2003) of NLDN data, average annual flash densities in Atlanta are 50–75% higher than the surrounding rural areas fringing the city (Stallins et al. 2006). Flash densities to the northeast of Atlanta (6–8 flashes/km^2/year) are as high as those found along Georgia's Atlantic coast. Areas with high flash day counts (a day with at least one observed flash) in Atlanta had many of the same calendar dates when lightning was also observed throughout adjacent rural regions. This suggests that thunderstorms around Atlanta produce not only more flashes but also that these flashes accumulate on days when the larger region has conditions conducive for lightning production.

Explanation

These aforementioned lightning studies recognize multiple causality, whereby natural and anthropogenic factors are highly intertwined. Natural features, like elevation and topography, can influence flash production (Westcott 1995). Local background wind circulations (sea breezes, downslope winds) intersect with urban properties to shape thunderstorm formation (Chen et al. 2007; Gauthier et al. 2005; Thielen and Gadian 1997). However, human land uses and topography may be correlated (Lo and Yang 2002; Ueland and Warf 2006). Broadly, the mechanisms for cloud-to-ground flash modification driven by anthropogenic factors fall in two general categories (Orville et al. 2001; Rosenfeld and Lensky 1998; Thielen et al. 2000; Williams et al. 2002). These categories are diffusely described in the literature and best summarized as urban effects, rather than the more limiting expression urban 'heat island' effects. They are: (i) the enhancement of local wind convergence and convection via urban atmospheric properties and surface roughness and (ii) the modification of microphysical processes leading to cloud electrification by air pollution. Each mechanism is not necessarily exclusive of the other. Recently, Baik et al. (200) outlines the rationale for delineating mechanical mechanisms (surface roughness) from those that are more thermal in origin. Although there may be calls to separate these human influences on observed flash patterns from their natural counterparts, delimiting natural from anthropogenic causal agents can be challenging. A coupled approach, whereby the results from convective modeling and simulation are compared to real-world flash patterns, seems to hold the greatest potential for building and refining evidence for these mechanisms and for discerning the relative importance of natural and anthropogenic factors (Rozoff et al. 2003).

Even though no two urban heat islands are the same (Arnfield 2003; Oke 1982), there are enough similarities in where and when urban flash anomalies develop to suggest that urban atmospheric thermodynamics, surface properties, and air pollution play strong causal roles. However, it is mainly observational and simulation-based studies of urban convection and precipitation that substantiate this coupling of pattern and process for lightning. Thielen et al. (2000) found that as urban heating intensity increases, precipitation moves closer to the source or heating. Changes in the extent of surface roughness may induce changes in downwind precipitation patterns. Simulations by Baik et al. (2001) illustrated how urban heating leads to the formation of a downwind updraft cell that increases in intensity as the heat island intensity increases or wind speed decreases. Updraft cells may move closer to the city center as wind speed decreases and urban heating intensity increases. Rozoff et al. (2003) found that nonlinear interactions among the friction of urban surfaces, momentum drag, and urban heating could induce downwind convergence. Bornstein and LeRoy (1990) described how on days with calm regional flows, the New York City initiated convective activity and produced a radar echo frequency maximum over the city. Moving thunderstorms were observed to bifurcate and move around New York City due to building barrier effects. Future urban lightning studies may consider incorporating tall building datasets (Burian et al. 2006) as proxies for the urban circulations induced by city morphology and surface roughness.

Observed cloud-to-ground flash patterns support the findings of these modeling and radar-based studies. Downwind augmentation of flash production is by far the most consistent finding among urban flash studies. Lightning is sensitive to the underlying land surface and the motion of the thunderstorms in which they are embedded. For example, the distribution of higher flash densities in São Paulo, Brazil, corresponded to the outline of the city (Naccarato et al. 2003). Air mass thunderstorms that arise under calmer conditions had flash density peaks that were drawn more tightly around urban land uses in Atlanta, while moving frontal thunderstorms had density peaks at nodes on the perimeter of the city (Stallins and Bentley 2006). Mesoscale modeling (MM5) of land cover influences on urban circulation for Atlanta produced three areas of confluence associated with three urban temperature maxima (Craig and Bornstein 2002). Without the urban heat island component in this simulation, wind convergence did not develop. The deepest simulated convection was to the northeast of the city, where increases in rainfall (Diem 2007) and lightning (Stallins et al. 2006) have also been observed. Craig and Bornstein's MM5 study also observed a ring of rural wind divergence produced from the descending outflow of urban convection initiating near the city center. The location of these surface divergence zones outside of the city center are reflected in a ring of decreased flash activity surrounding Atlanta (Stallins et al. 2006).

In a simulation of how land cover change modifies convection over Sydney, Australia, Gero and Pitman (2006) observed that an intense convective storm developed within the central city only when land cover types were included in the model. This convection was attributed to sea breezes and increased agricultural land cover in the periphery of the city. This suggests that other land use categories besides urban, and their arrangement, may be a factor for defining urban atmospheric properties (Rozoff et al. 2003). In this light, urban lightning studies should be sensitive to the definitions of what defines 'urban' and 'city' (Mills 2007) as well as the overall sensitivity of climate and weather to land use change (Pielke 2002; Pielke et al. 2007). The concept of an isolated urban heat 'island' is to an extent simplistic because the type and geometry of land uses surrounding a city will constrain the specifics of urban heating and thermodynamically driven circulation.

Particulate matters, or aerosols, are a common component of air pollution in cities. Aerosols are intrinsic to the formation of precipitation though their role as cloud condensation nuclei. Increased anthropogenic aerosol content in cities may influence cloud electrification by shaping how atmospheric water droplets coalesce and are transported by updrafts to freezing levels. At these levels, the forms of precipitation necessary for lightning (supercooled water, graupel, hail, ice) can coexist. In this process, increased cloud condensation nuclei slow the collision and coalescence of water droplets. This leads to the development of deeper updrafts because of a delay in the formation of downward-moving precipitation. Stronger, deeper updrafts transport more precipitable water to elevated mixed phase levels. Under this scenario, initial suppression and delay of precipitation may be followed by increased electrification.

Most of the evidence for these aerosol effects has been synthesized from observations of cloud vertical temperature profiles, base heights, and precipitation production along urban/rural and maritime/continental transitions (Givati and Rosenfeld 2004; Kaufman et al. 2005; Lensky and Drori 2007; Rosenfeld 2000; Rosenfeld and Lensky 1998; Shepherd 2005). The modification of lightning production via this mechanism, in the context of observation-based research, is less developed. Radar imagery of urban thunderstorms in Houston, Texas, has shown that flash maxima are associated with peaks in precipitation ice mass (Gauthier et al. 2006). Recent work by Boussaton et al. (2007) found a high degree of variability in the temporal sequencing of radar reflectivity intensity with lightning production. In some thunderstorm events over Paris, high reflectivities indicative of heavy precipitation developed after peaks in lightning production. In other storms, reflectivities peaked and then decreased before maxima in flash production. These contrasts may be indicative of how the variable sizes and compositions of urban aerosols can influence cloud electrification and thunderstorm behavior.

Urban lightning studies have found significantly positive correlations (Naccarato et al. 2003), variable correlations (Westcott 1995), and weak correlations (Kar et al. 2007; Soriano and De Pablo 2002) between aerosol concentrations and flash production. In part, this may reflect the resolution of point-specific air pollution measurements (typically only a few stations per city) relative to the wide areal distribution of flashes. More problematically, pollution and aerosol abundance can be conflated with urban heat island strength and city size. Cities with more pollution typically have larger populations, urban areas, and thermodynamically modified urban circulations. The role of aerosols in lightning production has been most strongly established through studies that found a spatial correspondence among aerosols-generating facilities, higher flash densities, and decreased positive flashes in non-urban locations. Stallins et al. (2006) found a decrease in the percentage of positive flashes downwind of large stretches of a heavily traveled north-south trending interstate passing through Atlanta, Georgia. This aerosol effect may be seen in rural areas 100 km downwind from the congested traffic emerging out of the Atlanta city center. Steiger and Orville (2003) detected higher flash densities and a lowered percentage of positive flashes in the Lake Charles – Baton Rouge Louisiana corridor. This location has a dense infrastructure of aerosol-producing refineries and chemical production facilities, but overall low population numbers. Urban development is slight when compared to neighboring Houston to the west. For these non-urban locales, the spatial association among atmospheric particulate matter, increased flash densities, and decreases in the percent positive flashes more strongly supports a role for aerosols and air pollution as a mechanism for generating increased flash densities within cities.

In simulations to examine the effect of aerosols on convection, aerosol size and relative abundance was shown to influence the timing of convection and its location (Van Den Heever and Cotton 2007). Convergence driven by urban effects on local circulation was the central factor determining whether thunderstorms actually developed in the downwind direction. Once they developed, aerosols influenced the amount of liquid water and ice present in the atmosphere, the surface precipitation totals, the strength and timing of updrafts and downdrafts, and the longevity of updrafts. The effect of aerosols decreased with their increasing concentration, suggesting that more heavily polluted areas may not necessarily have greater aerosol-driven influences on precipitation and cloud electrification.

Methodological Considerations

Thinking about the modes of inquiry for any research topic yields a more robust understanding of the subject under investigation. Although an urban lightning study may seem straightforward, there are several tensions related to the methods used and what conclusions we can make from them. Like many kinds of inquiry, urban lightning research tends to be polarized between a phenomenological view and a foundational view (Casti 2002). A phenomenological view has as its goal the detection and description of patterns. Form is prioritized. Geographers often take a phenomenological view through their use of visualization and the practice of data exploration (Fotheringham 1999; Hallisey 2005). Visualization enhances the exploratory, or abductive, aspects of pattern analysis. It facilitates a process of learning through the creation and observation of abstract images (Hallisey 2005). Such description is a selective account of patterns against a background that might otherwise obscure their detection (Grimaldi and Engel 2007). One of the hazards of this phenomenological approach is that the researcher must steer clear of the fallacy of proving the consequent, of accommodating a hypothesis by developing it after observations have been collected (Lipton 2005; Weins 1984). Yet, affirming the consequent can be a valid mode of inductive reasoning. Visualization, description, inference, and hypothesis formulation recursively inform each other to develop a contextual, yet best possible explanation for observed patterns.

Foundational views focus on the basic physical processes. Here, process is more important than form. The conditions or phenomena hypothesized to explain the pattern of interest are modeled to gauge their explanatory power. Modeling can range from regression to simulation, with a continuum of ties to real-world observations. A hazard of the foundational view is that it may emphasize instrumentalist and predictive capabilities through its internal logic at the expense of a contextual natural philosophy (Dear 2006). Given contingencies in the interactions between urban atmospheric circulation, urban land use change, and background fluctuations in the synoptic conditions that set up thunderstorm formation, an overriding emphasis on prediction under a foundational view presupposes that the system is rigid and operating under rules that produce a range of expected outcomes. More realistically, lightning production in urban areas results from a complex intersection of variability in thunderstorm tracks, land use patterns, local circulations, aerosol content, and topography. In this complex systems view, data exploration and explanation via a phenomenological perspective may be more tractable than prediction, at least in the early stages of research (Bradbury 2002).

A process-oriented foundational approach in an urban lightning study might examine the internal microphysics of an urban thunderstorm with Doppler radar over local scales in one or perhaps several thunderstorms.

A form-based, phenomenological study might visualize multiple years of cloud-to-ground flash strikes to document climatological trends over broad temporal and spatial scales. Both are valid enterprises, each with different questions and different modes of reasoning. Cross-scale integration of these two modes ties their advantages together. The HEAT (Houston Environmental Aerosol Thunderstorm) Project in Houston, Texas, makes use of a local ground-based flash network that can provide flashes for individual thunderstorms as well as longer-term climatologies. Doppler radar and radiosonde soundings are used to peer inside developing urban thunderstorms to reveal processes and mechanisms that generate the large climatological patterns of urban flash enhancement. Ongoing research in Atlanta by the authors takes a cross-scale approach by clustering flashes into discrete thunderstorm flash events. Each flash event is the collection of cloud-to-ground flashes occurring with a set timeframe (within 15 min) and within a spatial window (within 15 km). By examining single events, or groups of several events aggregated according to their relative motion over the central city, a more scalable mode of inquiry is possible.

Probably, one of the more basic and ultimately critical methodological decisions to make when starting an urban lightning study is at what spatial extent to examine urban flash patterns. The larger the spatial extent, the greater the likelihood of introducing mesoscale to synoptic-scale variables that shape thunderstorm types and storm tracks within the area of study (see Gauthier et al. 2005). Larger study extents may therefore overemphasize, or conversely, diminish the resolution of urban flash augmentation. On the other hand, restrictive narrow extents prohibit comparisons with the adjacent rural areas. Following Tobler's simple yet deceptively complex advice, near things are more related than those at a distance. In this view, it is up to each researcher, in the context of their particular study area, to follow a Goldilocks rule whereby the scale chosen is 'just right'. Such a scale is a finite area or range over which functional linkages of relevance operate. 'All other things being equal' within a coupled urban–rural corridor will hold over a limited range, and even then, imperfectly (Phillips 2004). Most studies have found flash augmentation within 100 km of the city center (Table 1). Urban precipitation anomalies may have similar areal distributions (Mote et al. 2007). Nonetheless, areal parameters should be different from study to study, thus requiring each investigator to reason through (and argue for) the scales over which their investigation is conducted.

The distributional assumptions underlying the measurement and statistical analysis of flash patterns are also of methodological relevance. If flashes are considered to be a random spatial point process, independent from each other and identically generated, flashes should have an equal probability of occurring at any point. However, the distribution of flashes in time and space is dependent on the distribution of thunderstorms. Variability in the conditions that produce thunderstorms can in part

Table 1. Study area extents employed in several urban lightning investigations

Cities	Metro population (millions)	Urban–rural flash extent (km)	Study area extent (km)
São Paulo, Brazil (Naccarato et al. 2003)	17.7	150 × 100	300 × 200
Houston, Texas (Steiger et al. 2002)	4.7	75 × 75	250 × 250
Atlanta, Georgia (Stallins et al. 2006)	4.2	50 × 50	160 × 160
Belo Horizonte, Brazil (Pinto et al. 2004)	2.5	45 × 60	100 × 120
Bilbao, Spain (Areito et al. 2001)	0.4	50 × 50	150 × 150

explain the variability in annual and monthly number of lightning counts. Thunderstorms may follow particular tracks during certain times of the year, or change in their frequency and intensity in space and time as a result of large-scale atmospheric oscillations like El Niño/Southern Oscillation. This embeddedness of flashes, their dependence on the spatial and temporal patterns of thunderstorms, complicates the assumption of spatial randomness (Waller and Gotway 2004).

Consequently, when trying to ascertain flash trends it becomes necessary to decouple the effects that thunderstorm frequency may have on flash production. One method is to map flashes as densities or counts without accounting for thunderstorm frequency. Standard deviation metrics, from month to month, or from year to year, may then be used to shed light on the consistency of flash production over a time period. High standard deviations indicate that flashes and/or thunderstorms are not uniformly distributed. Another method is to take flash counts for a given area or pixel and divide them by the number of flash-producing events or the number of days with flashes to derive an average value that reflects frequency (number of events, or thunderstorms) as well as intensity (number of flashes). A third method is to utilize mean intensity functions. Mean intensity functions sum the mean rate of occurrence of lightning per day per thunderstorm at a given location and time. They can then be applied spatially through a kernel estimator to develop a measure of flash intensity (number of flashes) that accounts for thunderstorm frequency (Ntelekos et al. 2007).

Geographic information systems (GIS) provide another method by using space as an alternative way to combine flash counts and thunderstorm frequency. Rather than folding intensity and frequency into each other on a single map as with the mean intensity function, intensity and frequency variables in GIS can be deployed simultaneously and analyzed spatially. The mean intensity function produces only an intensity map; GIS can be used to perform overlays, intersections, and unions of intensity and frequency data and to develop integrated metrics. In Stallins and Bentley (2006), intensity and frequency were fused through a spatial intersection to isolate a hotspot experiencing large number of days with flashes and high flash counts. For the scholar undertaking an urban lightning study, they will find that very little has been written on the statistical nature of lightning, and specifying its distributional properties remains a challenge (Ntelekos et al. 2007).

Future Research

Research that explicitly integrates aerosol data with urban flash data is underdeveloped. Epidemiological studies that monitor particulate matter concentration in detail (Hansen et al. 2006; Peel et al. 2007) may be worthwhile air pollution data sources to complement routine regulatory air pollution sampling conducted by environmental protection agencies. Epidemiological studies can provide detailed information about composition of urban pollutants, which may be as important as the size of particles in the non-inductive charge separation process (Jungwirth et al. 2005). For example, smoke from forest fires has been linked to increased positive flash activity, while urban areas and their air pollution characteristics are linked to decreased positive flash activity (Fernandes et al. 2006). These differences may be attributable to contrasts in the diameter and/or the composition of the aerosols. Even pollen concentration and type may influence the non-inductive charge separation process by functioning as condensation ice nuclei at relatively warm temperatures (Diehl et al. 2001).

Most of the research on how urban areas modify convective phenomena has focused mainly on precipitation (Shepherd 2005). Because lightning ultimately originates from same mechanisms that produce rain, there is a need to assess urban precipitation and flash production conjointly. Areas of high rainfall in Atlanta (Diem 2007; Diem and Mote 2005) roughly coincide with an area of increased flash production in the northeast (downwind) side of the city (Stallins et al. 2006). More detailed mapping of precipitation and lightning onset within storms tracking across the city would be one way to examine the variability in the temporal sequencing of radar reflectivity and flash production. Yet, to date, there are no studies that have fused urban precipitation and flash data with the explicit goal of elucidating the mechanisms of urban thunderstorm modification, although studies by Boussaton et al. (2007) and Ntelekos et al. (2007) have opened initial inroads. Several related questions emerge from this potential integration. Because of aerosols: (i) is their more variability in the coupling of precipitation and flash production in urban thunderstorms? (ii) how do the peaks in precipitation and lightning production coincide geographically? and (iii) how do factors that influence the abundance of aerosols (like day of the week, traffic volume, and dust-producing drought) influence rain and flash production?

Along another research track, hazards scholars may find it insightful to consider the risks emerging from high frequency, low-intensity weather phenomena like urban lightning. A city shapes its own hazards through its propensity to modify local weather. The contingent distribution of land uses and local topography, in terms of their geometry relative to storm tracks and predominant winds, influences the distribution of hazards. Furthermore, there is a need to incorporate urban flash patterns into public safety and infrastructure planning. Many industries and research centers have electrically sensitive operations whose interruption can be costly if not catastrophic. Although figures are difficult to obtain and integrate, the costs of airport closures, electrical outages, and fires in flash-prone urban and fringing suburban areas may be immense. Urban lightning may be a significantly underestimated liability for maintaining sophisticated technologies in densely built and occupied regions prone to thunderstorms.

The Geographic Perspective

Urban lightning research is still in the descriptive, pattern-identifying stage, with some inroads into mechanism. Without the identification of patterns, there is no basis or direction for the exploration of mechanism. Pattern analysis can collectively steer inquiry toward insights into process and mechanism. Description, from simple observation to more advanced visualizations, remains highly valued in science (Grimaldi and Engel 2007; Schroder and Seppelt 2006). So long as one does not make undue or hasty claims as to the finality of driving mechanisms, geographical research on urban lightning provides patterns – maps, visualizations, trends – to fuel mechanistic, process-based verifications. Yet, the geographic approach is not forbidden from informing mechanism. At first glance, phenomenological–geographical approaches may seem to be severely limited in their search for mechanism. But by framing the coupled atmosphere-surface system of a city as a model (see Creager et al. 2007) from which to run flash mapping scenarios of different combinations of wind directions, dates, times, levels of air pollution, and synoptic conditions, one can test hypotheses about where flashes might develop in order to support or refute mechanisms. Establishing causality for some researchers will necessitate controlled experiments and observations of microphysical processes on small temporal and spatial scales. For other disciplines, larger scales of observational evidence are more complete. The conciliatory interpretation is that both sides of the causality spectrum recursively inform each other.

To lessen the temptations and criticisms of proving the consequent, more emphasis should be placed on making geographic comparisons. An example of this is found in the deployment of a 'synoptic' comparative approach (Phillips 2001). 'Synoptic' used in this sense does not imply synoptic meteorology, at least not directly, although synoptic meteorology is an excellent example of this approach. It refers to a manner of conducting research that is sensitive to the way local contingencies influence patterns within the context of more geographically consistent deterministic mechanisms. For example, the microphysical processes of precipitation formation proceed in a deterministic fashion at any location. However, the spatial and temporal contingencies of aerosol content, moisture availability, and boundary-layer instability are the more geographically variable phenomena that constrain thunderstorm formation and lightning production. Replicate methodologies employed in several cities, as well as comparisons of results from methodologies evolving from individual city-specific studies, are both viable means to reveal this interplay of determinism and contingency.

Gauthier et al. (2006) admonish that causal explanations of lightning anomalies have to explain either increased frequency and/or intensity of convection that must then be related to enhancement of precipitable ice mass and lightning production. However, a single researcher should not be expected to substantiate independently all the links in this causal chain in order for their research to have merit. Pragmatic approaches, in which a pluralism of methods and goals are practiced by researchers with different levels of experience (and funding) is more likely to lead to collective insight and progress than a single, best-method-for-all approach. Even so, the remark by Gauthier et al. (2006) underscores the need for more understanding of the indirect and direct mechanisms and a tighter coupling between phenomenological pattern studies and foundational process studies.

Cities exemplify the overall sensitivity of the atmosphere to human impacts. In fact, urban climate change can be seen as an analog for global climate change (Changnon 1992; Mills 2007; Price and Rind 1994). This is stated not so much in the sense that urban populations and their material habits contribute sizeably to anthropogenic CO_2 concentration, although they certainly do (Grimmond 2007). It is that urban climates have undergone considerably rapid and focused environmental change in light of the pervasive urbanization and suburbanization of the last and present century. The United Nations projects that in 2008, for the first time in history, more than half its human population, 3.3 billion people, will be living in urban areas. By 2030, almost five billion people are projected to be urban dwellers (United Nations Population Fund 2007). Based on an integration of global and regional climate simulations, large cities like Atlanta or New York City may experience more frequent severe thunderstorms in the late 21st century (Trapp et al. 2007). Given these historical trends and hypothesized futures, urban lightning studies provide observational evidence of how convection may play out on a planet with an increasingly anthropogenic atmosphere.

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Short Biographies

J. Anthony Stallins is an Associate Professor in the Department of Geography, Florida State University, Tallahassee, FL, USA. His interests include urban weather and climate, ecological biogeomorphology, and complexity theory. He holds a BS in Geology from Florida State University, a MS in Biology from Georgia State University, and a PhD in Geography from the University of Georgia.

L. Shea Rose is a doctoral candidate in the Department of Geography, Florida State University, Tallahassee, FL, USA. Her interests include urban weather and climate, human/environment interactions, and sustainable development. She holds a BA in Energy and Environmental Studies from the Evergreen State College.

Note

* Correspondence address: J. Anthony Stallins, Department of Geography, Florida State University, Rm. 323 Bellamy Building, Tallahassee, FL 32306, USA. E-mail: jastallins@fsu.edu.

References

Ahrens, C. D. (1994). *Meteorology today: an introduction to weather, climate and the environment*. New York: West Publishing Company.

Areitio, J., Ezcurra, A., and Herrero, I. (2001). Cloud-to-ground lightning characteristics in the Spanish Basque Country area during the period 1992–1996. *Journal of Atmospheric and Solar-Terrestrial Physics* 63, pp. 1005–1015.

Arnfield, A. J. (2003). Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* 23, pp. 1–26.

Baik, J. J., Kim, Y. H., and Chun, H. Y. (2001). Dry and moist convection forced by an urban heat island. *Journal of Applied Meteorology* 40, pp. 1462–1475.

Baik, J. J., et al. (2007). Effects of boundary-layer stability on urban heat island-induced circulation. *Theoretical and Applied Climatology* 89, pp. 73–81.

Best, M. J. (2006). Progress towards better weather forecasts for city dwellers: from short range to climate change. *Theoretical and Applied Climatology* 84, pp. 47–55.

Biagi, C. J., et al. (2007). National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004. *Journal of Geophysical Research-Atmospheres* 112, D05208; doi:10.1029/2006JD007341.

Boccippio, D. J., et al. (2000). The Optical Transient Detector (OTD): instrument characteristics and cross-sensor validation. *Journal of Atmospheric and Oceanic Technology* 17, pp. 441–458.

Bornstein, R., and Leroy, M. (1990). *Urban barrier effects on convective and frontal thunderstorms*. AMS Conference on Mesoscale Processes Conference, Boulder, Colorado.

Bornstein, R., and Lin, Q. L. (2000). Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmospheric Environment* 34, pp. 507–516.

Boussaton, M. P., Soula, S., and Coquillat, S. (2007). Total lightning activity in thunderstorms over Paris. *Atmospheric Research* 84, pp. 221–232.

Bradbury, I. (2002). Environments and livelihoods: strategies for sustainability. *International Development Planning Review* 24, pp. 225–226.

Burian, S. J., et al. (2006). *Emerging urban databases for meteorological and dispersion modeling*. Preprints, AMS Annual Meeting, Sixth Symposium on the Urban Environment, Atlanta, Georgia.

Casti, J. L. (2002). Risk, natural disasters, and complex system theory. *Complexity* 7, pp. 11–13.

Changnon, S. A. (1992). Inadvertent weather-modification in Urban areas – lessons for global climate change. *Bulletin of the American Meteorological Society* 73, pp. 619–627.

Changnon, S. A., Huff, F. A., and Semonin, R. G. (1971). Metromex – investigation of inadvertent weather modification. *Bulletin of the American Meteorological Society* 52, pp. 958–967.

Chen, T.-C., Wang, S.-Y., and Yen, M.-C. (2007). Enhancement of afternoon thunderstorm activity by urbanization in a valley: Taipei. *Journal of Applied Meteorology and Climatology* 46, pp. 1324–1340.

Craig, K., and Bornstein, R. (2002). *MM5 simulation of urban induced convective precipitation over Atlanta*. Fourth AMS Conference on the Urban Environment Conference, Virginia, Norfolk, pp. 5–6.

Creager, A. N. H., Lunbeck, E., and Wise, M. N. (2007). *Science without laws: model systems, cases, exemplary narratives*. Durham, NC: Duke University Press.

Cummins, K. L., et al. (1998). A combined TOA/MDF technology upgrade of the US national lightning detection network. *Journal of Geophysical Research-Atmospheres* 103, pp. 9035–9044.

Dabberdt, W. F., et al. (2000). Forecast issues in the urban zone: report of the 10th Prospectus Development Team of the US Weather Research Program. *Bulletin Of The American Meteorological Society* 81, pp. 2047–2064.

Dear, P. (2006). *The intelligibility of nature: how science makes sense of the world*. Chicago, IL: The University of Chicago Press.

Diehl, K., et al. (2001). The ice nucleating ability of pollen Part I: Laboratory studies in deposition and condensation freezing modes. *Atmospheric Research* 58, pp. 75–87.

Diem, J. E. (2007). Detecting summer rainfall enhancement within metropolitan Atlanta, Georgia USA. *International Journal of Climatology* 28 (1), p. 129; doi:10.1002/joc.1560.

Diem, J. E., and Mote, T. L. (2005). Interepochal changes in summer precipitation in the southeastern United States: evidence of possible urban effects near Atlanta, Georgia. *Journal of Applied Meteorology* 44, pp. 717–730.

Dixon, P. G., and Mote, T. L. (2003). Patterns and causes of Atlanta's urban heat island-initiated precipitation. *Journal of Applied Meteorology* 42, pp. 1273–1284.

Dwyer, J. R. (2005). The initiation of lightning by runaway air breakdown. *Geophysical Research Letters* 32, L20808; doi:10.1029/2005GL023975.

Fernandes, W. A., et al. (2006). New findings about the influence of smoke from fires on the cloud-to-ground lightning characteristics in the Amazon region. *Geophysical Research Letters* 33, L20810; doi:10.1029/2006GL027744.

Fotheringham, A. S. (1999). Trends in quantitative methods III: stressing the visual. *Progress In Human Geography* 23, pp. 597–606.

Gauthier, M. L., et al. (2005). Dissecting the anomaly: a closer look at the documented urban enhancement in summer season ground flash densities in and around the Houston area. *Geophysical Research Letters* 32, L10810; doi:10.1029/2005GL022725.

——. (2006). Relationship between cloud-to-ground lightning and precipitation ice mass: a radar study over Houston. *Geophysical Research Letters* 33, L20803; doi:10.1029/2006GL027244.

Gero, A. F., and Pitman, A. J. (2006). The impact of land cover change on a simulated storm event in the Sydney basin. *Journal of Applied Meteorology and Climatology* 45, pp. 283–300.

Givati, A., and Rosenfeld, D. (2004). Quantifying precipitation suppression due to air pollution. *Journal of Applied Meteorology* 43, pp. 1038–1056.

Global Hydrology and Climate Center. (2007). *Lightning & atmospheric electricity research at the GHCC*. [online]. Retrieved on 7 November 2007 from http://thunder.msfc.nasa.gov/

Grimaldi, D. A., and Engel, M. S. (2007). Why descriptive science still matters. *Bioscience* 57, pp. 646–647.

Grimmond, S. (2007). Urbanization and global environmental change: local effects of urban warming. *Geographical Journal* 173, pp. 75–79.
Grogan, M. J. (2004). Report on the 2002–2003 U.S. NLDN system-wide upgrade. *Vaisala News* 165, pp. 4–8.
Hallisey, E. J. (2005). Cartographic visualization: an assessment and epistemological review. *Professional Geographer* 57, pp. 350–364.
Hansen, D. A., et al. (2006). Air quality measurements for the aerosol research and inhalation epidemiology study. *Journal of the Air and Waste Management Association* 56, pp. 1445–1458.
Huff, F. A., and Changnon, S. A. (1973). Precipitation modification by major urban areas. *Bulletin of the American Meteorological Society* 54, pp. 1220–1232.
Jungwirth, P., Rosenfeld, D., and Buch, V. (2005). A possible new molecular mechanism of thundercloud electrification. *Atmospheric Research* 76, pp. 190–205.
Kar, S. K., Liou, Y. A., and Ha, K. J. (2007). Characteristics of cloud-to-ground lightning activity over Seoul, South Korea in relation to an urban effect. *Annales Geophysicae* 25, pp. 2113–2118.
Kaufman, Y. J., et al. (2005). The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean. *Proceedings of the National Academy of Sciences, USA* 102, pp. 11207–11212.
Krider, E. P., Noggle, R. C., and Uman, M. A. (1976). Gated, wideband magnetic direction finder for lightning return strokes. *Journal of Applied Meteorology* 15, pp. 301–306.
Lensky, I. M., and Drori, R. (2007). A satellite-based parameter to monitor the aerosol impact on convective clouds. *Journal of Applied Meteorology and Climatology* 46, pp. 660–666.
Lipton, P. (2005). Testing hypotheses: prediction and prejudice. *Science* 307, pp. 219–221.
Lo, C. P., and Yang, X. J. (2002). Drivers of land-use/land-cover changes and dynamic modeling for the Atlanta, Georgia Metropolitan Area. *Photogrammetric Engineering and Remote Sensing* 68, pp. 1073–1082.
MacGorman, D. R., and Rust, W. D. (1998). *The electrical nature of storms*. New York: Oxford University Press.
Mach, D. M., et al. (2007). Performance assessment of the optical transient detector and lightning imaging sensor. *Journal of Geophysical Research-Atmospheres* 112, D09210; doi:10.1029/2006JD007787.
Mills, G. (2007). Cities as agents of global change. *International Journal of Climatology* 27, pp. 1849–1857.
Mote, T. L., Lacke, M. C., and Shepherd, J. M. (2007). Radar signatures of the urban effect on precipitation distribution: a case study for Atlanta, Georgia. *Geophysical Research Letters* 34, L20710; doi:10.1029/2007GL031903.
Naccarato, K. P., Pinto, O., and Pinto, I. (2003). Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of Southeastern Brazil. *Geophysical Research Letters* 30, pp. 1674–1677.
Ntelekos, A. A., Smith, J. A., and Krajewski, W. F. (2007). Climatological analyses of thunderstorms and flash floods in the Baltimore metropolitan region. *Journal of Hydrometeorology* 8, pp. 88–101.
Oke, T. R. (1982). The energetic basis of the urban heat-island. *Quarterly Journal of the Royal Meteorological Society* 108, pp. 1–24.
Orville, R. E., and Huffines, G. R. (2001). Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. *Monthly Weather Review* 129, pp. 1179–1193.
Orville, R. E., et al. (2001). Enhancement of cloud-to-ground lightning over Houston, Texas. *Geophysical Research Letters* 28, pp. 2597–2600.
Peel, J. L., et al. (2007). Ambient air pollution and cardiovascular emergency department visits in potentially sensitive groups. *American Journal of Epidemiology* 165, pp. 625–633.
Phillips, J. D. (2001). Human impacts on the environment: unpredictability and the primacy of place. *Physical Geography* 22, pp. 321–332.
——. (2004). Laws, contingencies, irreversible divergence, and physical geography. *Professional Geographer* 56, pp. 37–43.
Pickett, S. T. A., et al. (2001). Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. *Annual Review of Ecology and Systematics* 32, pp. 127–157.

Pielke, R. A. (2002). Overlooked issues in the US National climate and IPCC assessments. *Climatic Change*, 52, pp. 1–11.

Pielke, R. A., et al. (2007). An overview of regional land-use and land-cover impacts on rainfall. *Tellus* 59B, pp. 587–601.

Pinto, I., et al. (2004). Urban effect on the characteristics of cloud-to-ground lightning over Belo Horizonte-Brazil. *Annales Geophysicae* 22, pp. 697–700.

Prentice, S. A., and Mackerras, D. (1977). Ratio of cloud to cloud-ground lightning flashes in thunderstorms. *Journal of Applied Meteorology* 16, pp. 545–550.

Price, C., and Rind, D. (1994). Possible implications of global climate-change on global lightning distributions and frequencies. *Journal of Geophysical Research-Atmospheres* 99, pp. 10823–10831.

Rakov, V. A., and Uman, M. A. (2007). *Lightning: physics and effects*. New York: Cambridge University Press.

Reap, R. M. (1986). Evaluation of cloud-to-ground lightning data from the western united-states for the 1983–84 summer seasons. *Journal of Climate and Applied Meteorology* 25, pp. 785–799.

Rosenfeld, D. (2000). Suppression of rain and snow by urban and industrial air pollution. *Science* 287, pp. 1793–1796.

Rosenfeld, D., and Lensky, I. M. (1998). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bulletin of the American Meteorological Society* 79, pp. 2457–2476.

Rozoff, C. M., Cotton, W. R., and Adegoke, J. O. (2003). Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *Journal of Applied Meteorology* 42, pp. 716–738.

Ruddiman, W. F. (2003). The anthropogenic greenhouse era began thousands of years ago. *Climatic Change* 61, pp. 261–293.

Saunders, C. P. R. (1993). A review of thunderstorm electrification processes. *Journal of Applied Meteorology* 32, pp. 642–655.

Schroder, B., and Seppelt, R. (2006). Analysis of pattern-process interactions based on landscape models – overview, general concepts, and methodological issues. *Ecological Modelling* 199, pp. 505–516.

Schultz, M. D., Underwood, S. J., and Radhakrishnan, P. (2005). A method to identify the optimal areal unit for NLDN cloud-to-ground lightning flash data analysis. *Journal of Applied Meteorology*, 44, pp. 739–744.

Shepherd, J. M. (2005). A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interactions* 9 (12), pp. 1–27.

Shepherd, J. M., Pierce, H., and Negri, A. J. (2002). Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM satellite. *Journal of Applied Meteorology* 41, pp. 689–701.

Soriano, L. R., and De Pablo, F. (2002). Effect of small urban areas in central Spain on the enhancement of cloud-to-ground lightning activity. *Atmospheric Environment* 36, pp. 2809–2816.

Stallins, J. A., and Bentley, M. L. (2006). Urban lightning climatology and GIS: an analytical framework from the case study of Atlanta, Georgia. *Applied Geography* 26, pp. 242–259.

Stallins, J. A., Bentley, M. L., and Rose, L. S. (2006). Cloud-to-ground flash patterns for Atlanta, Georgia (USA) from 1992 to 2003. *Climate Research* 30, pp. 99–112.

Steiger, S. M., and Orville, R. E. (2003). Cloud-to-ground lightning enhancement over southern Louisiana. *Geophysical Research Letters* 30 (19), p. 1975; doi:10.1029/2003GL017923.

Steiger, S. M., Orville, R. E., and Huffines, G. (2002). Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000. *Journal of Geophysical Research-Atmospheres* 107, p. 4117.

Takahashi, T. (1978). Riming electrification as a charge generation mechanism in thunderstorms. *Journal of the Atmospheric Sciences* 35, pp. 1536–1548.

Thielen, J., and Gadian, A. (1997). Influence of topography and urban heat island effects on the outbreak of convective storms under unstable meteorological conditions: a numerical study. *Meteorological Applications* 4, pp. 139–149.

Thielen, J., et al. (2000). The possible influence of urban surfaces on rainfall development: a sensitivity study in 2D in the meso-γ-scale. *Atmospheric Research* 54, pp. 15–39.

Trapp, R. J., et al. (2007). Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences, USA* 104, pp. 19719–19723.

Ueland, J., and Warf, B. (2006). Racialized topographies: altitude and race in southern cities. *Geographical Review* 96, pp. 50–78.

United Nations Population Fund. (2007). *The state of world population 2007*. [online]. Retrieved on 7 November 2007 from http://www.unfpa.org/swp/2007/presskit/pdf/sowp2007_eng.pdf

United States Precision Lightning Network. (2007). *USPLN*. [online]. Retrieved on 7 November 2007 from http://www.uspln.com

Vaisala. (2007). *Lightning detection*. [online]. Retrieved on 7 November 2007 from http://www.vaisala.com/weather/products/lightning

Van Den Heever, S. C., and Cotton, W. R. (2007). Urban aerosol impacts on downwind convective storms. *Journal of Applied Meteorology and Climatology* 46, pp. 828–850.

Von Storch, H., and Stehr, N. (2006). Anthropogenic climate change: a reason for concern since the 18th century and earlier. *Geografiska Annaler: Series A, Physical Geography* 88, pp. 107–113.

Wacker, R. S., and Orville, R. E. (1999). Changes in measured lightning flash count and return stroke peak current after the 1994 US National Lightning Detection Network upgrade – 1. Observations. *Journal of Geophysical Research-Atmospheres* 104, pp. 2151–2157.

Waller, L. A., and Gotway, C. A. (2004). *Applied spatial statistics for public health data*. New York: Wiley.

Watson, A. I., and Holle, R. L. (1996). An eight-year lightning climatology of the southeast United States prepared for the 1996 Summer Olympics. *Bulletin of the American Meteorological Society* 77, pp. 883–890.

Weins, J. A. (1984). Understanding a non-equilibrium world. In: Strong, D. R., et al. (eds) *Ecological communities: conceptual issues and the evidence*. Princeton, NJ: Princeton University Press, pp. 439–457.

Westcott, N. E. (1995). Summertime cloud-to-ground lightning activity around major midwestern urban areas. *Journal of Applied Meteorology* 34, pp. 1633–1642.

Williams, E., et al. (2002). Contrasting convective regimes over the Amazon: implications for cloud electrification. *Journal of Geophysical Research-Atmospheres* 107, p. 8082; doi:10.1029/2001JD000380.

Yow, D. M. (2007). Urban heat islands: observations, impacts, and adaptation. *Geography Compass* 1 (6), pp. 1227–1251.