

Ⓞ Variability of CONUS Lightning in 2003–12 and Associated Impacts

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ABSTRACT

Changes in lightning characteristics over the conterminous United States (CONUS) are examined to support the National Climate Assessment (NCA) program. Details of the variability of cloud-to-ground (CG) lightning characteristics over the decade 2003–12 are provided using data from the National Lightning Detection Network (NLDN). Changes in total (CG + cloud flash) lightning across part of the CONUS during the decade are provided using satellite Lightning Imaging Sensor (LIS) data. The variations in NLDN-derived CG lightning are compared with available statistics on lightning-caused impacts to various U.S. economic sectors. Overall, a downward trend in total CG lightning count is found for the decadal period; the 5-yr mean NLDN CG count decreased by 12.8% from 25 204 345.8 (2003–07) to 21 986 578.8 (2008–12). There is a slow upward trend in the fraction and number of positive-polarity CG lightning, however. Associated lightning-caused fatalities and injuries, and the number of lightning-caused wildland fires and burn acreage also trended downward, but crop and personal-property damage costs increased. The 5-yr mean LIS total lightning changed little over the decadal period. Whereas the CONUS-averaged dry-bulb temperature trended upward during the analysis period, the CONUS-averaged wet-bulb temperature (a variable that is better correlated with lightning activity) trended downward. A simple linear model shows that climate-induced changes in CG lightning frequency would likely have a substantial and direct impact on humankind (e.g., a long-term upward trend of 1°C in wet-bulb temperature corresponds to approximately 14 fatalities and over \$367 million in personal-property damage resulting from lightning).

1. Introduction

As a result of the Global Change Research Act (GCRA) of 1990, the National Climate Assessment (NCA) was formed to analyze the effects of global change on the natural environment, human health and welfare, human social systems, agriculture, energy production and use, land and water resources, transportation, and biological diversity. The NCA analyzes natural and human-induced trends in global change and projects major trends 25–100 yr out. The GCRA requires that regular NCA reports be submitted to the president and Congress. These reports are based on observations and climate-system-model predictions

that provide the status of climate-change science and impacts and also integrate, evaluate, and interpret the findings of the U.S. Global Change Research Program. An objective of the NCA is to incorporate advances in the understanding of climate science into larger social, ecological, and policy systems so that impacts and vulnerabilities can be clearly identified/analyzed and the effectiveness of mitigation and adaptation strategies can be better evaluated.

The NCA reports to date unfortunately contain very little reference to lightning. The 2000 and 2009 NCA reports largely neglected lightning as an important parameter associated with climate change. The 2000 report did not mention lightning, and the 2009 report only briefly mentioned it (one pie chart on hazard-related deaths and

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a plot about insurance claims). The most recent NCA report that was finalized in 2014 also contained very little reference to lightning, but we anticipate that the findings in the study that is presented here will eventually be adopted in future NCA reports, since the NCA is a continuous assessment process.

The primary observations employed in this study are cloud-to-ground (CG) lightning data obtained from the National Lightning Detection Network (NLDN) that is described in [Cummins and Murphy \(2009\)](#). The NLDN locates and characterizes CG lightning across the conterminous United States (CONUS, i.e., the lower 48 states and the District of Columbia). For a brief overview of the geographical expansion of the network, including expansion into regions outside the CONUS, see Fig. 2 of [Orville \(1991\)](#), Fig. 1 of [Orville et al. \(2002\)](#), and Fig. 1 of [Orville et al. \(2011\)](#). During its developmental phase (1984–89), three independent lightning networks evolved: one operated by the State University of New York at Albany, one operated by the National Severe Storms Laboratory, and one operated by the Bureau of Land Management. By 1989, these three regional networks had begun to share data to establish the NLDN. The CG flash detection efficiency was only ~70% at the time. Following this initial phase, both increases in the number of sensors and improved sensor technology allowed for an improved CG detection efficiency (now 90%–95%), and a CG location accuracy of better than 500 m across the CONUS ([Cummins et al. 2006](#); [Cummins and Murphy 2009](#)). In particular, significant upgrades to the NLDN occurred during the period 2002–03 wherein all NLDN sensors were replaced by higher-quality Vaisala, Inc., “IMPACT ESP” (Enhanced Sensitivity and Performance) sensors, and eight additional sensors were added to the network ([Orville et al. 2011](#); [Rudlosky and Fuelberg 2010](#)). Because of these improvements, high-quality and stable (uncertainty below 10%) climate-assessment products that are based on the NLDN data from the period 2003–present are now feasible.

This study examines national lightning data and associated lightning-related impact statistics from 2003 onward to provide beneficial assessment products that contain analyses, trends, and alerts pertinent to a changing climate. The lightning-caused impacts (and affected U.S. economic sectors) of primary focus in this study include death/injury (human-health sector), crop-damage costs (agriculture sector), insurance claims by home owners (personal-property sector), and the frequency and burn acreage of wildland fires (forestry sector).

To meet the needs of a “sustaining assessment” of the impact of global climate change on these U.S. economic sectors, we developed a National Aeronautics and Space Administration (NASA) Lightning Analysis Tool (LAT)

that is used to ingest, calculate, and visualize all of the NLDN datasets and lightning-impact statistics employed. The intention is to routinely apply the LAT to continually extend the analysis beyond the decade (2003–12) provided in this initial paper. The LAT is written in the Interactive Data Language and was recently expanded to routinely examine satellite-based Lightning Imaging Sensor (LIS; [Christian et al. 1999](#)) total lightning-flash count across the southern portion of the CONUS. Overall, the LAT provides the most comprehensive and up-to-date diagnosis of the spatial and temporal evolution of lightning across the CONUS.

This study begins by providing a brief overview of the important interconnections among climate, lightning, and associated lightning-caused impacts ([section 2](#)). [Section 3](#) provides CG characteristics across the CONUS that are based on the NLDN data, and [section 4](#) provides statistics on associated lightning-caused impacts. [Section 5](#) provides total (CG + cloud flash) lightning counts derived from the LIS data. Impact assessments of climate-induced changes in lightning, adaptations, and additional biases are addressed in [section 6](#). Simple linear extrapolations are used to estimate climate-induced changes in lightning-caused impacts that involve human health (injury/death), crop/property damage, and wildfires. [Section 7](#) provides a summary.

2. Physical linkages and impacts

Observations of lightning frequency provide one of the most vital, simple, and direct means for examining the spatial and temporal evolution of atmospheric convection across large geographic regions. The cloud buoyancy that drives vertical motions in thunderstorms results from a temperature differential on the order of only 1°C; this means that temperature perturbations of this order are clearly important in the context of the highly nonlinear process of cloud electrification as well as in the context of global warming ([Williams 2005](#)). The study by [Price and Rind \(1994\)](#) predicted increases in lightning as a result of a warmer climate, and several studies that support the positive correlation between lightning amount and temperature have been summarized by [Williams \(1999, 2005\)](#).

The physical link between lightning and temperature depends on more than the sensitivity of convection to temperature. Detraining thunderstorm anvils act as an “ice factory” at tropopause levels and contribute to upper-tropopause water vapor via sublimation ([Baker et al. 1995, 1999](#)). [Price \(2000\)](#) finds excellent agreement between lightning activity and upper-tropospheric water vapor, which is a more important greenhouse substance than boundary layer water vapor. In addition, laboratory results in [Petersen et al. \(2008\)](#) suggest that the

presence of ice can increase the probability of lightning initiation.

Lightning also produces nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) that affect the concentration of ozone (O_3), an important greenhouse gas. Since climate is most sensitive to O_3 in the upper troposphere, and since lightning NO_x is the most important source of NO_x in the upper troposphere at tropical and subtropical latitudes, lightning is a particularly useful parameter to monitor for climate assessments (Lee et al. 1997; Huntrieser et al. 1998). Lightning NO_x also impacts O_3 estimates made by regional air-quality models, as recently demonstrated by Koshak et al. (2014). In addition, there is coupling between ice and lightning chemistry; that is, Peterson and Beasley (2011) suggested that ice helps to catalyze lightning NO_x formation, and Peterson and Hallett (2012) suggested that NO enhances ice-crystal growth.

Still other interconnections may exist. First, according to the 1995 Intergovernmental Panel on Climate Change report (Bolin et al. 1995) and Kunkel (2003), a warmer climate implies a larger number of extreme events (e.g., flash floods and severe storms that are associated with much lightning), but Williams (2005) indicates that mean thunderstorm flash rate (a reasonable indicator of storm severity) may not be larger in a warmer climate. Second, a threefold enhancement of CG lightning over Houston, Texas, has raised the issue of heat-island and pollution effects (Huff and Changnon 1972; Orville et al. 2001; Steiger et al. 2002) on lightning production. Albrecht et al. (2011) provide additional connections between CG lightning and pollution/deforestation. Third, increases in positive-polarity CGs have been attributed to elevated equivalent potential temperatures (Williams and Satori 2004; Williams et al. 2005) and to the thunderstorm's ingestion of smoke from fires (Lyons et al. 1998; Murray et al. 2000). Moreover, it has long been known that aerosols play an important role in climate because they affect the radiative balance of the Earth-atmosphere system (Mitchell 1971), and at the same time increased aerosol loading has been linked to enhancements of CG lightning activity (Kar et al. 2009; Yuan et al. 2011).

Even though CG lightning typically makes up only about 25% of all lightning flashes over the CONUS (Boccippio et al. 2001), it impacts humankind significantly. The current study examines various CG lightning impacts (e.g., human death/injury, crop and property damage, and wildfires), but several other impacts are not considered. For example, there are lightning-caused deaths/injuries to livestock and costly lightning-related delays to outside operations at airports, launch sites, and mining facilities. There are also increased power outages and consequent increased use of generator power

(especially by hospitals, operational radars, emergency managers, and military facilities). Owing to the difficulty in getting representative lightning-caused power-outage statistics across the CONUS (which is relevant to the U.S. energy sector), the LAT does not presently ingest lightning-related power-outage information. In addition, municipal, state, and federal agencies and other stakeholders use the Community Multiscale Air Quality (CMAQ) modeling system to evaluate the impact of air-quality-management practices for multiple pollutants at a variety of spatiotemporal scales and to guide the development of air-quality regulations and standards (Koshak et al. 2009). Many state and local air-quality agencies use the CMAQ modeling system to determine compliance with the National Ambient Air Quality Standards (NAAQS). At the national level, emission-reduction scenarios that could cost billions of dollars are tested using CMAQ to determine the most efficient and cost-effective strategies for attaining the NAAQS. Increases in O_3 that result from increases in lightning NO_x make meeting the standards both more difficult and more costly.

There are other complicating factors to consider. As mentioned above, a warmer climate implies more, and possibly stronger, thunderstorms—a condition that would give rise to more lightning (all else being equal). This in turn implies more impacts/costs to the United States, including more potential warming as a result of enhancement of upper-tropospheric O_3 by lightning NO_x . Williams (2005) suggests that, although lightning is sensitive to temperature on many time scales, the sensitivity appears to diminish at the longer time scales. In addition, increases in cloud albedo that result from increases in thunderstorm frequency/intensity would result in a cooling that would oppose the positive-feedback warming cycle. Moreover, as will be shown in this study, temperature alone is an inadequate indicator of expected CG lightning amount. One must also consider the availability of atmospheric moisture (see sections to follow regarding the drought of 2012 that was associated with record high temperatures but a marked drop in CG activity). The pattern of the atmospheric jet stream, which affects storm tracks, is another important variable that is critically linked to lightning count, but it is not investigated here.

In summary, it is important to recognize that both weather and climate affect the frequency and physical characteristics of thunderstorms and lightning; thunderstorms and lightning, in turn, produce feedbacks that affect weather and climate. Because lightning is intimately tied to climate in this way, it not only serves as a useful proxy for climate monitoring but is also one of many important driving forces to climate that requires monitoring.

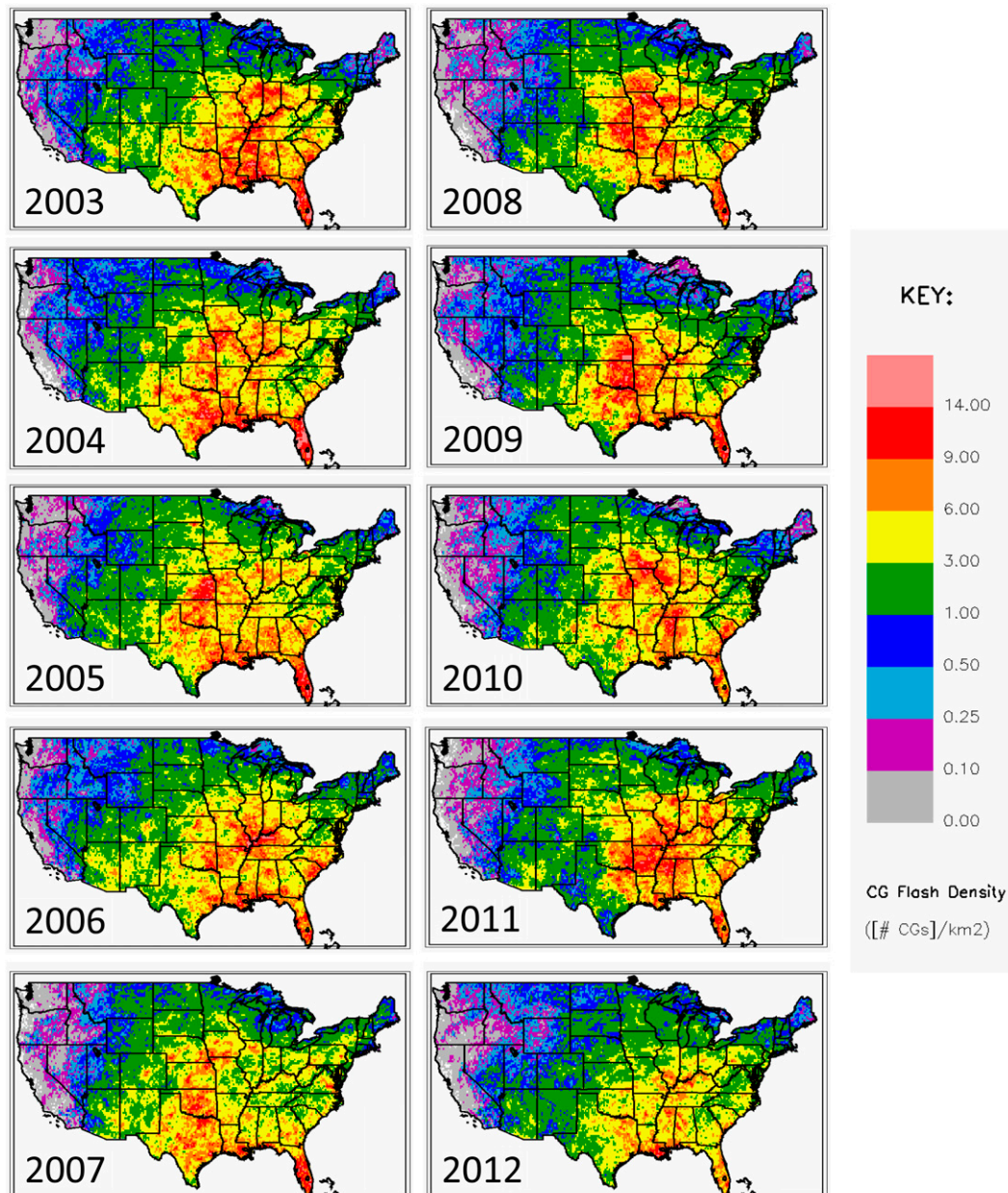


FIG. 1. The CG lightning flash density for 2003–12.

3. Geographical variations in CG lightning

This section summarizes the (year to year) geographical variations in several CG lightning characteristics (CG flash density, average peak current, and the average number of strokes in a CG flash) during the analysis period 2003–12 as obtained by the LAT. These characteristics are plotted for all CGs, as well as for positive-polarity CGs (+CGs) and for negative-polarity CGs (–CGs). Note that “peak current” represents the peak of the current waveform (at the ground) of the first

return stroke in a CG flash. We also provide plots of the ratio of +CGs to all CGs. For all NLDN data plots, the LAT employs a $0.2^\circ \times 0.2^\circ$ (~ 22 km) horizontal grid resolution and a geographical mask for the CONUS.

Figure 1 summarizes the total CG flash density (in units of number of CG flashes per kilometer squared per year). Regions exceeding 9 flashes per kilometer squared (red color in Fig. 1) shift around across portions of the midsection of the United States and southern states from year to year, but a fairly consistent and prominent maximum occurs over the Florida peninsula

TABLE 1. Summary of CG lightning count, +CG fraction, and related impacts (\$M indicates millions of U.S. dollars).

Year	NUMALL	PRATIO	NFAT	NINJ	DCROP (\$M)	DPROP1 (\$M)	DPROP2 (\$M)	NFIRE	NACRES
2003	25 312 151	0.044	41	236	0.00	25.70	No data	12 704	1 501 204
2004	26 515 549	0.051	32	280	0.00	26.10	735.50	11 114	504 995
2005	25 733 836	0.054	38	309	0.40	52.40	819.60	8012	2 736 097
2006	25 110 025	0.057	44	246	0.00	63.80	882.20	16 111	5 349 927
2007	23 350 168	0.060	45	138	0.06	82.06	942.40	12 060	5 412 681
2008	22 888 321	0.069	27	216	0.10	60.11	1065.50	8781	1 801 686
2009	22 233 574	0.068	33	201	0.01	43.86	798.00	8943	941 330
2010	22 793 791	0.073	29	182	0.45	71.13	1033.50	6834	1 100 615
2011	23 825 025	0.080	26	187	0.11	45.32	952.50	10 111	3 086 814
2012	18 192 183	0.084	28	139	0.45	47.89	969.00	9302	6 572 942

during most years. A distinct exception is 2012 wherein a large drop in CG flash count occurs for the CONUS region (see Table 1) and the maximum over the Florida peninsula largely vanishes. This drop occurred during a period in which the CONUS region experienced widespread drought conditions (Hansen 2013).

Figures 2 and 3 summarize the geographical variations in the +CG and -CG flash densities, respectively, and Fig. 4 provides the variations in the +CG fraction (i.e., the ratio of the number of +CGs to the total number of CGs). The +CG fraction is a particularly good climate-assessment variable because many of the storms that are characterized by relatively high +CG flash densities during the mature phase are associated with severe weather such as large hail and tornadoes [Carey and Rutledge (1998), Carey et al. (2003), and references therein]. From the figures, -CGs substantially outnumber the +CGs, and therefore there is little noticeable difference between the -CG distributions (Fig. 3) and the total CG distributions (Fig. 1). Of interest, Fig. 2 shows that the maximum in +CG count (a broad corridor extending from the southern states to the upper Midwest) is prominent during 2008–11 and then decreases in 2012. In addition, Fig. 4 clearly indicates that there is a consistent relative maximum in the +CG fraction roughly across Minnesota, North Dakota, South Dakota, Nebraska, and Kansas.

Figure 5 provides the geographical variations in the average annual peak current (of the first return stroke) of all CGs during the 2003–12 analysis period. As is customary, small positive (0–15 kA) events are removed from the analysis because they likely are cloud flashes that have been misclassified as ground flashes (Biagi et al. 2007). Figures 6 and 7 provide similar plots for the +CGs and -CGs, respectively. It is interesting that regions where the +CG fraction is high (Fig. 4) are also regions with relatively high average +CG peak-current values (Fig. 6).

The effect of the drought in 2012 (on the changes in the various CG flash densities, +CG fraction, and peak currents shown in Figs. 1–7) is related to more than a drought-induced decrease in thunderstorm activity.

Drought conditions are also linked to increases in aerosol concentrations, an extreme example being the great “dust bowl” of the 1930s. The increase in aerosols, in turn, affects cloud electrification and lightning [see, e.g., the “aerosol hypothesis,” as described in Williams et al. (2002) and the study by Mansell and Ziegler (2013)]. Our study does not employ aerosol concentration measurements, and therefore it is particularly difficult to evaluate cause-and-effect relationships. Hence, assessing the potential complicating factors that are due to aerosols is beyond the scope of this work.

Figure 8 provides the geographical variations in the average annual number of strokes in a CG flash (or so-called multiplicity) during the 2003–12 analysis period. Figures 9 and 10 provide similar plots for the +CGs and -CGs, respectively. The +CGs in the western United States tend to have more strokes. As expected, where the +CG fraction is high (Fig. 4) the average multiplicity in all CGs tends to be lower (Fig. 8). In addition, where the +CG fraction is high (Fig. 4) the average multiplicity in both +CGs and -CGs tends to be less (Figs. 9 and 10). Note also that the +CG multiplicity drops appreciably across the CONUS from 2010 to 2011 and again from 2011 to 2012 (see the three lower-right plots in Fig. 9). We believe that this is due largely to a network-upgrade effect (see section c of appendix A for additional discussion), rather than solely to natural fluctuations.

Overall, the geographical patterns for all of the variables plotted in Figs. 1–10 are reasonably stable from year to year, with the main exceptions noted above. Note that our plots continue and supplement, for the CONUS, several previous studies (Orville 1991, 1994; Orville and Silver 1997; Orville and Huffines 1999, 2001; Huffines and Orville 1999; Zajac and Rutledge 2001; Orville et al. 2002, 2011; Rudlosky and Fuelberg 2010; Makela and Rossi 2011).

4. Bulk variations and associated impacts

Although the geographical patterns provided above appear, for the most part, to be reasonably stable, changes

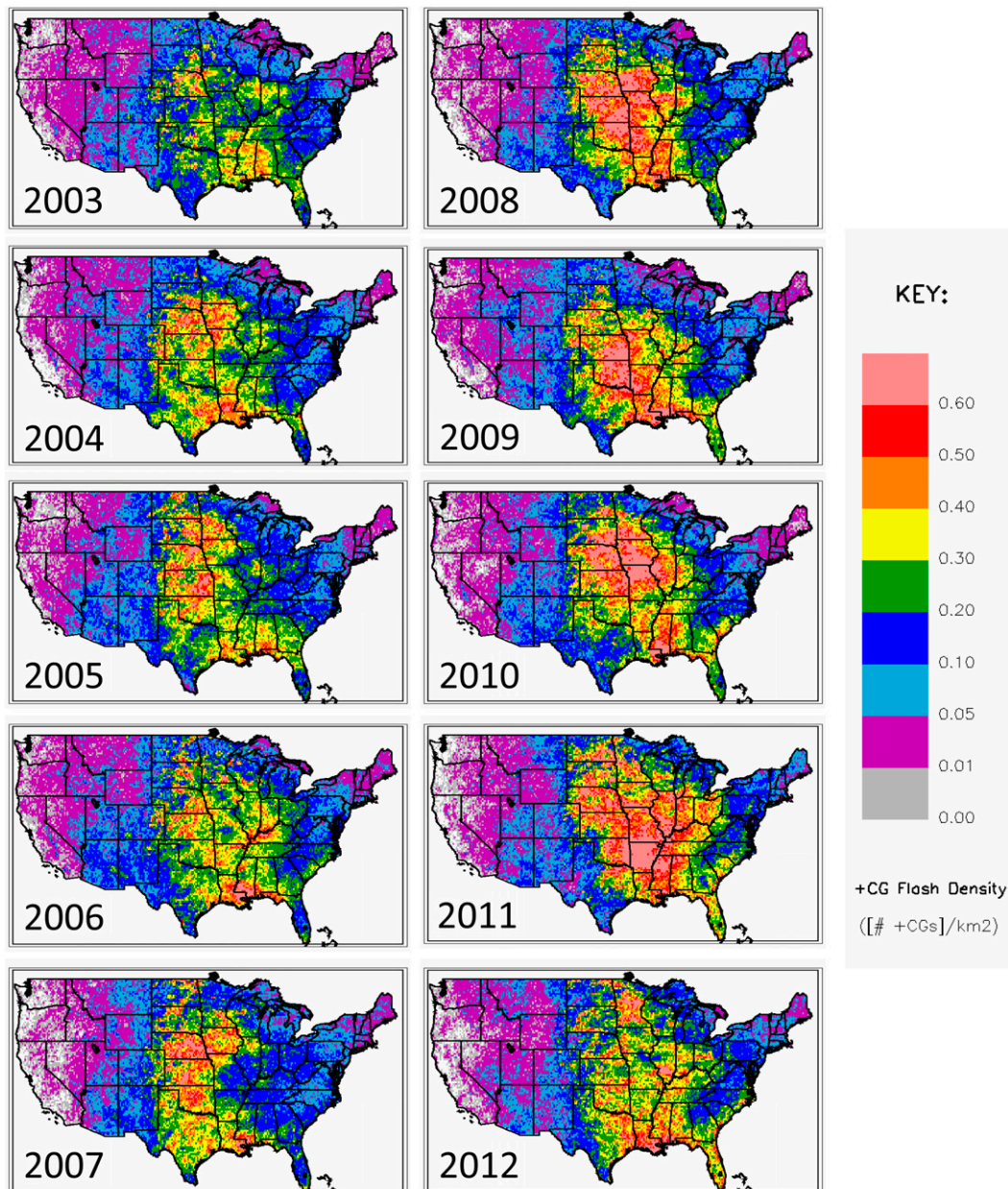


FIG. 2. The +CG lightning flash density for 2003–12.

from year to year are evident when one sums or averages across the entire CONUS domain. The column headings (NCA assessment products) in [Tables 1](#) and [2](#) represent the desired sums or averages: NUMALL is the number of CGs (CG count), NUMPOS is the number of +CGs, NUMNEG is the number of -CGs, and PRATIO is the +CG fraction as given by the ratio NUMPOS/NUMALL. The average annual peak current for all CGs (kA) is given by CURALL, and the average annual multiplicity for all CGs is given by MULALL. Similar definitions hold for the +CGs (i.e., CURPOS and MULPOS) and the -CGs

(CURNEG and MULNEG). The number of lightning-caused fatalities and injuries is given by NFAT and NINJ, respectively. The crop and property damages, in millions of dollars, are given by DCROP and DPROP, respectively. The number of lightning-caused wildland fires and the associated number of acres burned are given by NFIRE and NACRES, respectively.

[Table 1](#) provides numerical details on the bulk variations in CG lightning frequency, the +CG fraction, and associated lightning-caused impacts (fatalities, injuries, crop and property damage, and wildland fires). A discussion of the

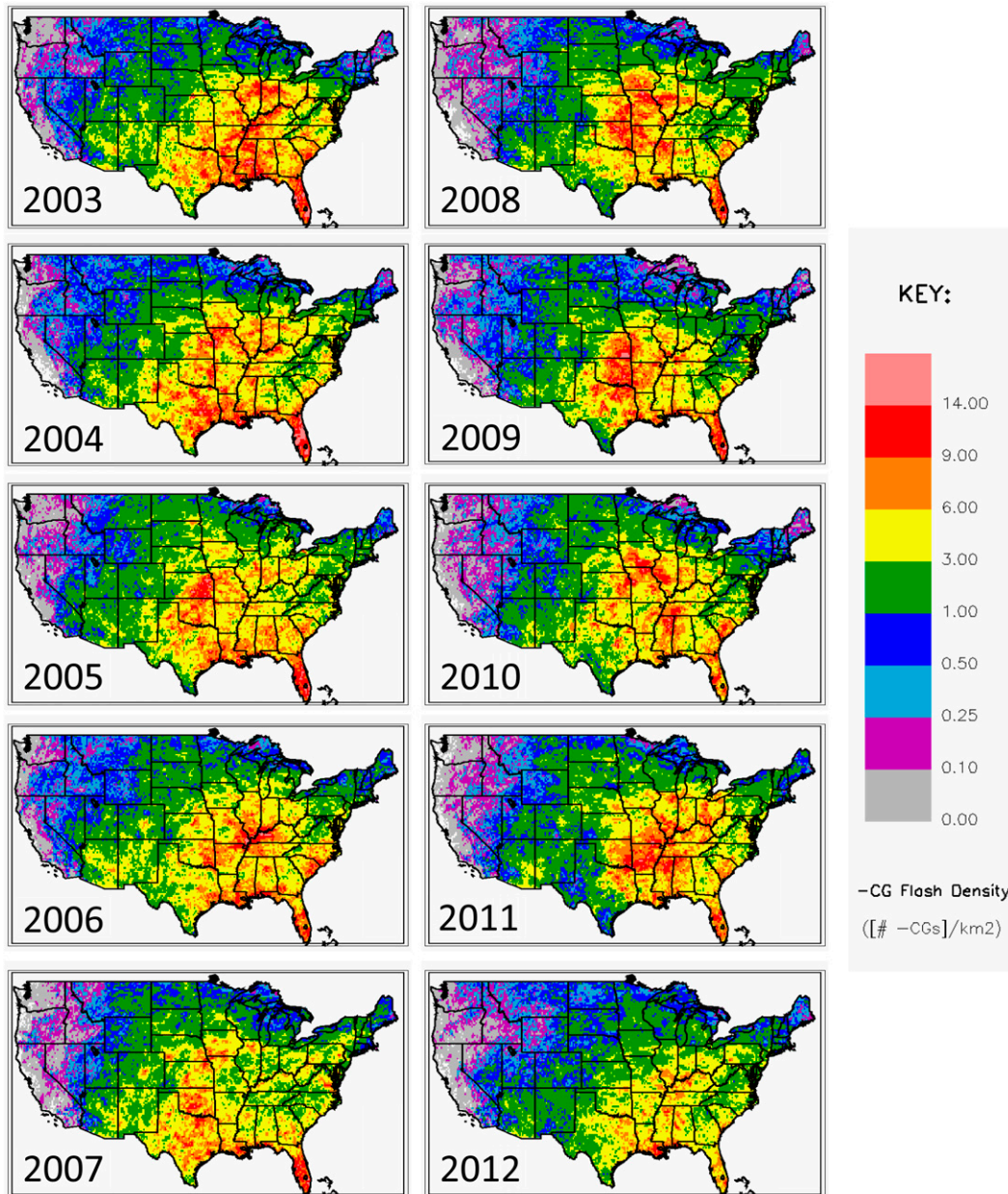


FIG. 3. The -CG lightning flash density for 2003–12.

key attributes and quality of the lightning-caused-impacts data is provided in sections a and b of appendix A. Table 2 provides the numerical details for the bulk variations in CG peak current and multiplicity. The +CG multiplicity (MULPOS) noticeably drops in 2011 and again in 2012—a phenomenon that we believe is due to a specific upgrade in the NLDN network (see section c of appendix A for a discussion).

Table 3 provides a summary of the percent changes in the mean values of the assessment variables. Note that the 5-yr average of CG count (NUMALL) decreases

from 25 204 345.8 (2003–07) to 21 986 578.8 (2008–12), or a drop of 12.8%. This drop could be responsible for some of the decreases in several lightning-caused impacts (deaths, injuries, number of wildfires, and wildfire burn acreage, as provided in Table 3). In general, CG count is just one of many contributing factors. For example, even if CG count were to increase, the number of fatalities could potentially still drop if there were improvements made to weather warnings and emergency-response-crew assistance. Drops in fatalities and injuries could also be attributable to improved campaigns that promote

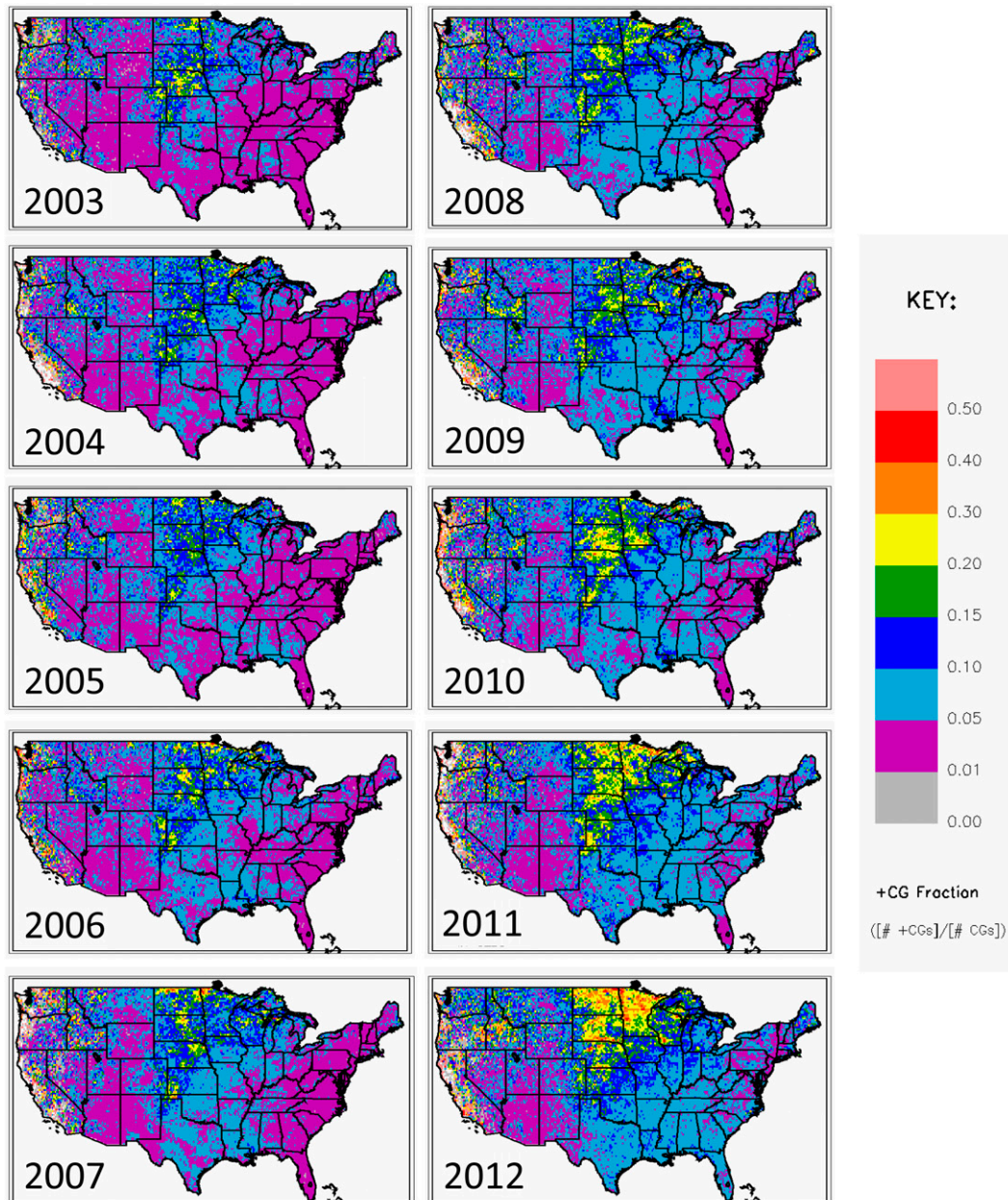


FIG. 4. The +CG lightning fraction for 2003–12.

lightning safety (see, e.g., <http://www.lightningsafety.noaa.gov>) and/or to changes in human outdoor activity.

Despite the 12.8% drop in CG count, lightning-caused property and crop damage increased (Table 3). Property damage can be regarded as having a highly nonlinear dependency on lightning; that is, lightning can strike anything from a small shed to an expensive mansion. In addition, if CG lightning count increases appreciably in a region without much property, there will be no corresponding increase in the property-damage-assessment variable. In other words, a low-population region has

few property owners and fewer people to file insurance claims, and therefore increases in CG lightning in such a region would have little effect on increasing lightning-caused property damage and associated claims. In a similar way, the specific market value and location of crops are important in determining net losses from lightning-caused crop damage. These nonlinear responses should always be kept in mind (particularly when interpreting and evaluating our impact assessments as given in section 6). Nonetheless, for sufficiently large changes in CG lightning count across a populated region or a region of high

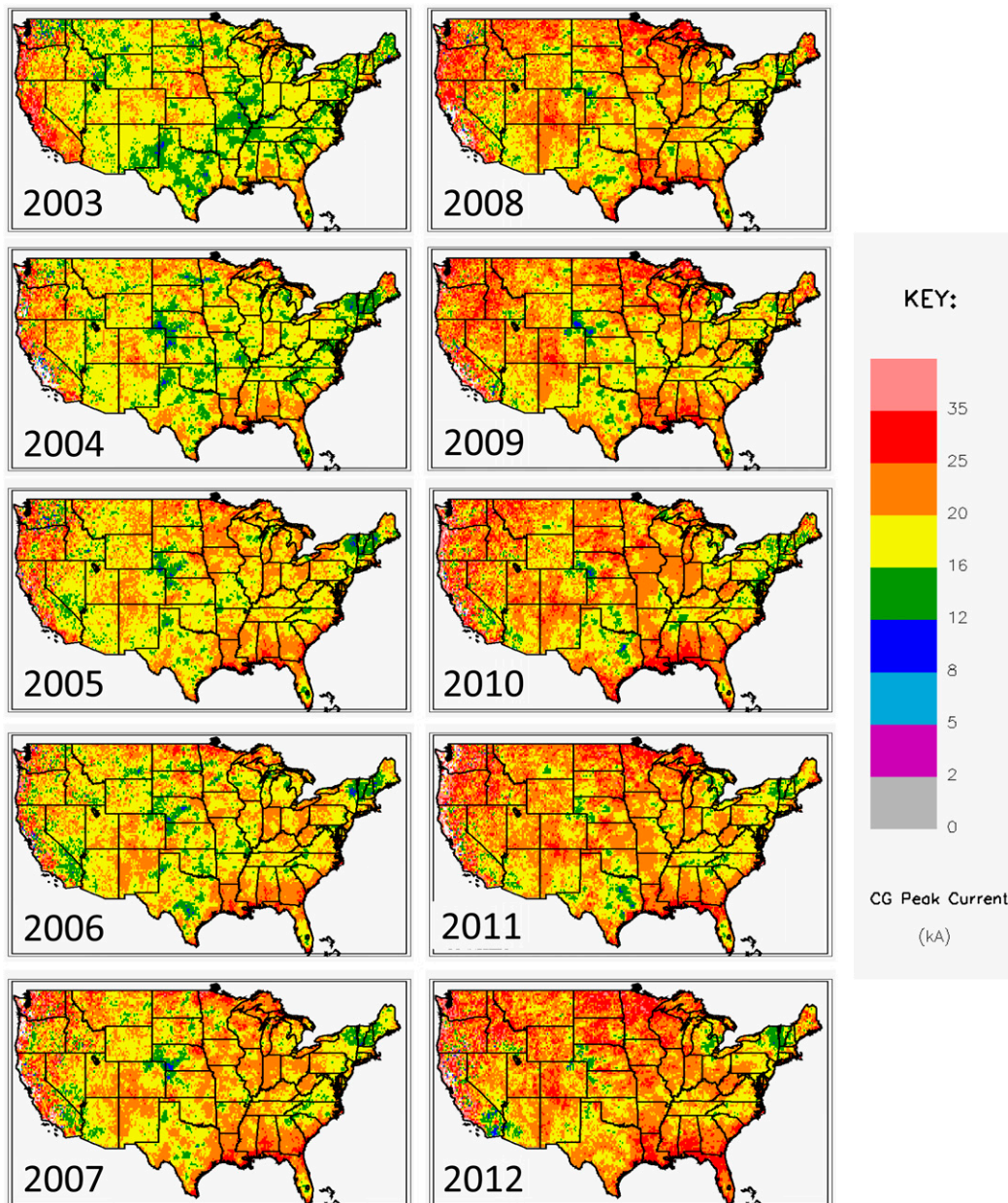


FIG. 5. The annual-average peak current in the first return stroke of CG lightning for 2003–12.

crop value, property and crop damages are expected to be positively correlated with the CG count.

It is interesting that, as shown in Table 3, the 5-yr-average peak currents (CURALL, CURPOS, and CURNEG) all increase by more than 5% but the multiplicity decreases by 4% or less. Hence, on average, there is an indication that we are getting fewer CG flashes, but with slightly larger peak currents and a slightly smaller number of strokes per flash. At the same time, both the number of +CG flashes (NUMPOS) and the +CG fraction (PRATIO) are trending upward.

Figure 11 summarizes the lightning characteristics over time (i.e., as annual time series plots). These are routine LAT products that supplement the previous geographical plots. The most notable features in Fig. 11 are 1) NUMPOS trends mostly upward over time; 2) there is a significant drop in NUMALL, NUMPOS, and NUMNEG in 2012; 3) PRATIO increases substantially from 2007 to 2008 and monotonically trends upward over the entire analysis period except between 2008 and 2009; 4) the peak currents slowly trend upward; and 5) the multiplicity is fairly constant, but we suspect that

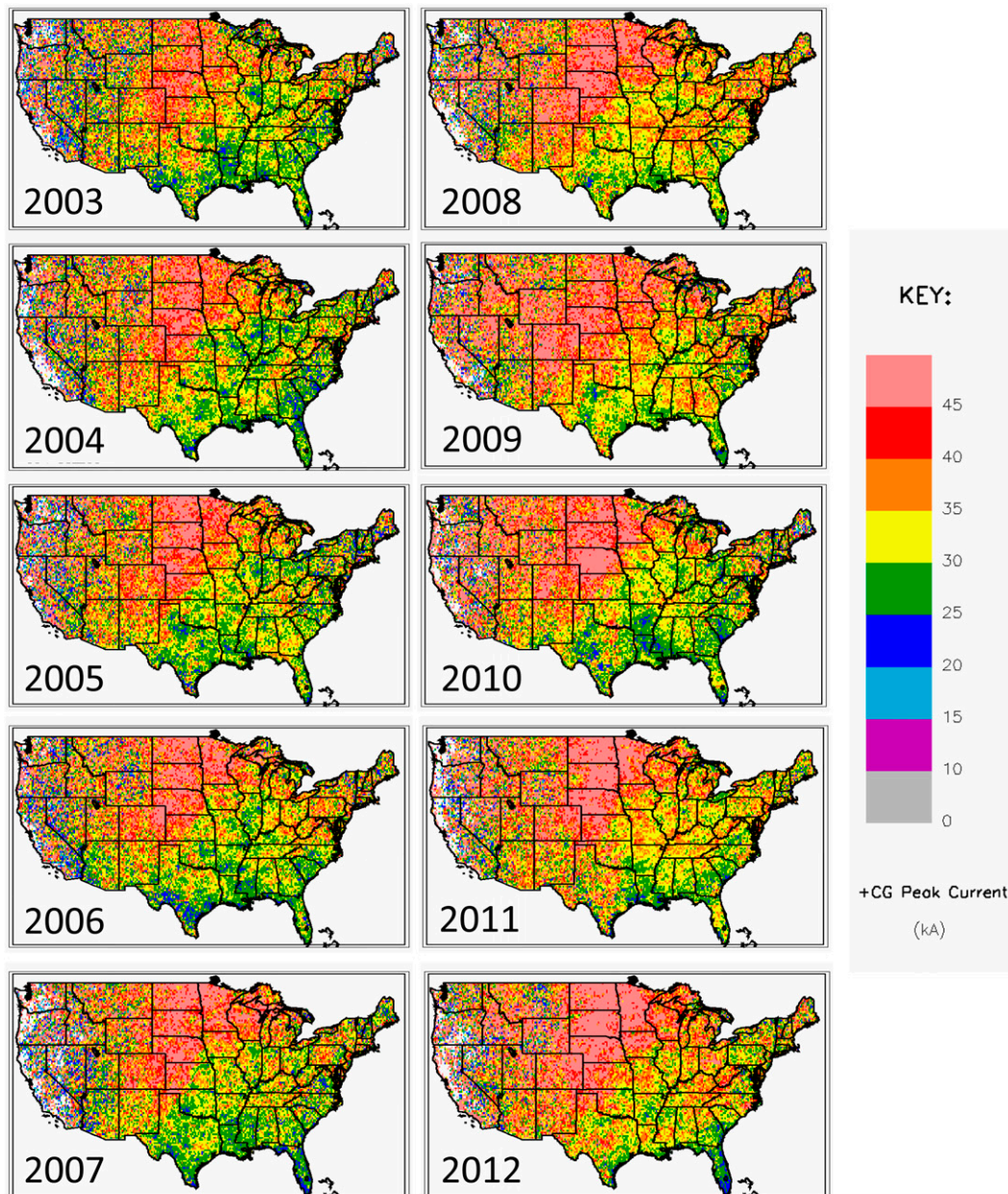


FIG. 6. The annual-average peak current in the first return stroke of +CG lightning for 2003–12.

the MULPOS noticeably drops in 2011 and again in 2012 because of a network upgrade, as mentioned above.

5. Lightning observations by satellite

Observations from the Tropical Rainfall Measuring Mission (TRMM) LIS provide additional insights. Details on the LIS instrument, calibration, performance, and observations can be found in [Christian et al. \(1999\)](#), [Koshak et al. \(2000\)](#), [Boccippio et al. \(2002\)](#), and [Cecil et al. \(2014\)](#), respectively. The low-Earth-orbiting LIS

provides total (CG + cloud flash) lightning across approximately $\pm 38^\circ$ of latitude. Apart from an orbital boost in August of 2001 (i.e., prior to our analysis period), the LIS does not involve numerous “upgrades” as discussed in the previous section for NLDN. In addition, the LIS has shown no appreciable performance degradation during its time in orbit ([Buechler et al. 2014](#)), and, even though LIS does not cover the entire CONUS region, it does capture the regions of the CONUS with the most lightning activity.

The LAT reads in the LIS orbit granules and tallies up the raw LIS flash counts that occur across the CONUS;

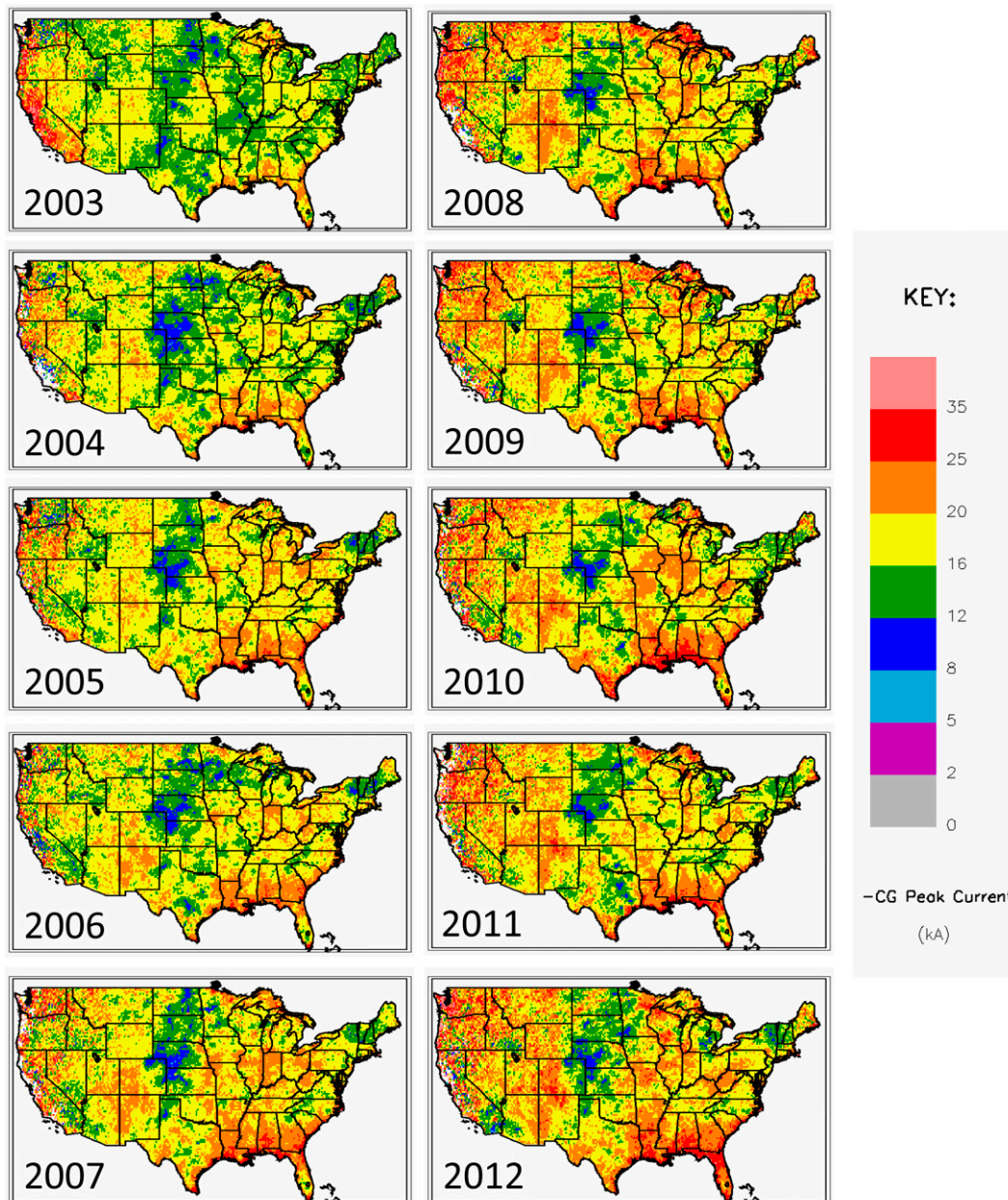


FIG. 7. The annual-average peak current in the first return stroke of $-CG$ lightning for 2003–12.

the raw counts are then adjusted to account for certain effects. The raw counts are adjusted (i.e., increased) by dividing by the appropriate LIS detection efficiency (DE), which depends on the local time of flash observation; the DEs range from about 0.693 to 0.880 for local periods 11–12 and 3–4, respectively [see Table 2 of Cecil et al. (2014)]. Second, these DE-adjusted counts are corrected again to account for the limited view time of the LIS over a region. To specify how long a particular region is viewed by the LIS in a given orbit, the standard LIS dataset employs a grid with a $0.5^\circ \times 0.5^\circ$ spatial

resolution, and an LIS orbit “view time” (VT, measured in seconds) is provided in the orbit granule for each grid cell. Hence, to determine how long LIS views a particular grid cell during an entire year, one sums up each orbit VT for that grid cell. Most of the CONUS grid cells viewed by LIS have typical annual view times of $15\text{--}30\text{ hr}^{-1}$, with some exceeding 30 hr^{-1} . The VT adjustment for a grid cell is carried out by dividing the DE-adjusted counts in the cell by the fraction of the year that that cell is viewed by LIS.

In addition, note that the LIS orbit precesses slowly in relation to the sun, taking 49 days to return to its original

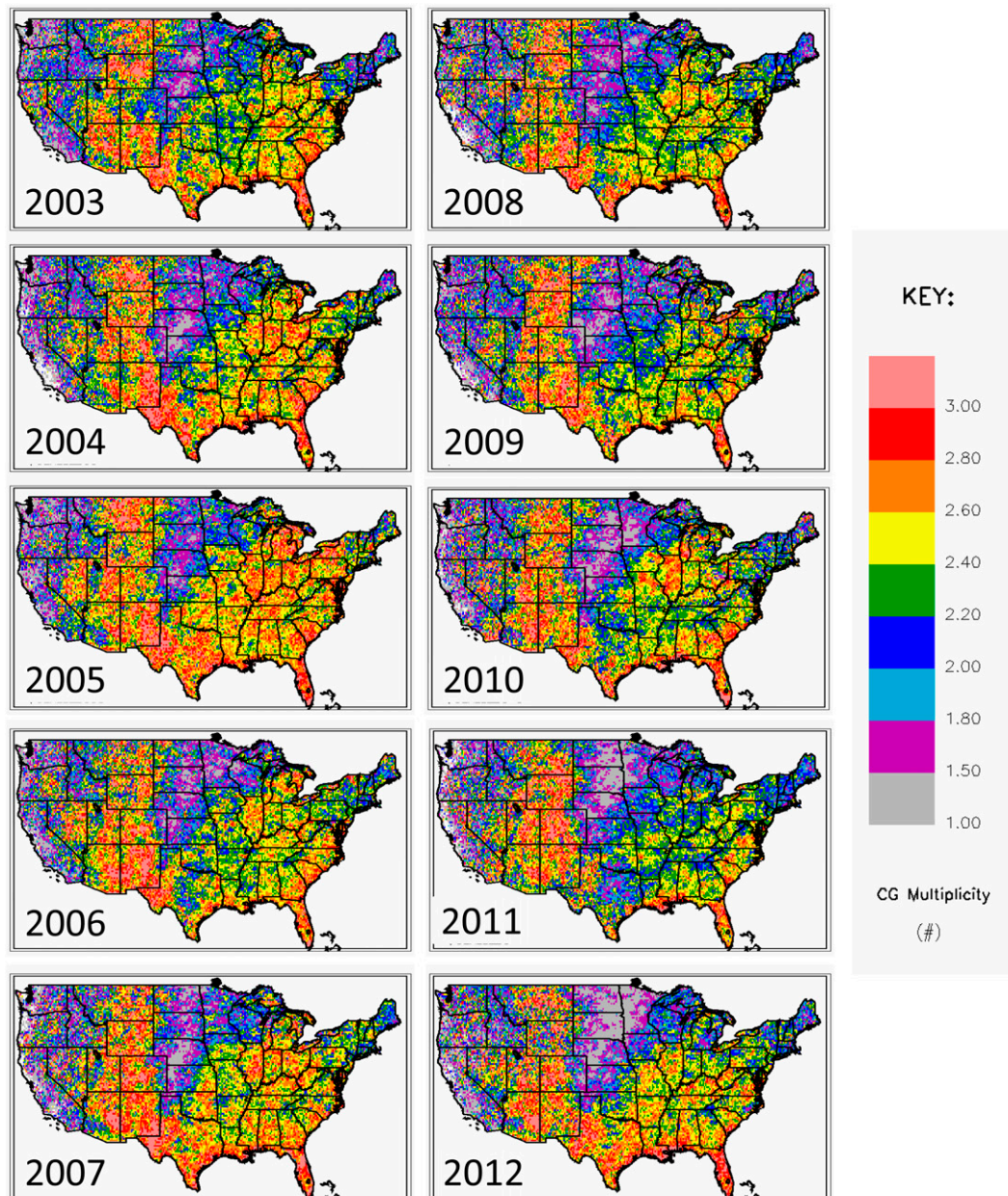


FIG. 8. The annual-average multiplicity in CG lightning for 2003–12.

position (Williams et al. 2000). Hence, a 49-day minimum is required to sample the entire diurnal cycle of lightning. Our annual (365 or 366) day sampling is more than adequate to capture the diurnal variability and hence to avoid aliasing biases. To get a feel for the number of times that a typical grid cell is visited in a year, one can multiply a 20 hr^{-1} annual VT by 3600 s h^{-1} and then divide by approximately 90 s per visit to a grid cell (the approximate time for LIS to pass over the grid cell). This gives about 800 visits of the grid cell by LIS per year, which is more than adequate to

resolve seasonal variability. Dividing 800 visits per year by 365 days per year gives ~ 2.19 visits per day on average, and so one might wonder how such a frequency captures the diurnal cycle, but multiplying the 49-day period mentioned above by 2.19 visits per day gives about 107 visits all spread out across the diurnal cycle (and thus the diurnal cycle is adequately captured).

Figure 12 provides the geographical distribution of the LIS flash density for the 2003–12 analysis period; the spatial resolution is 0.5° , and the flash counts have been corrected for both DE and VT. The distributions are

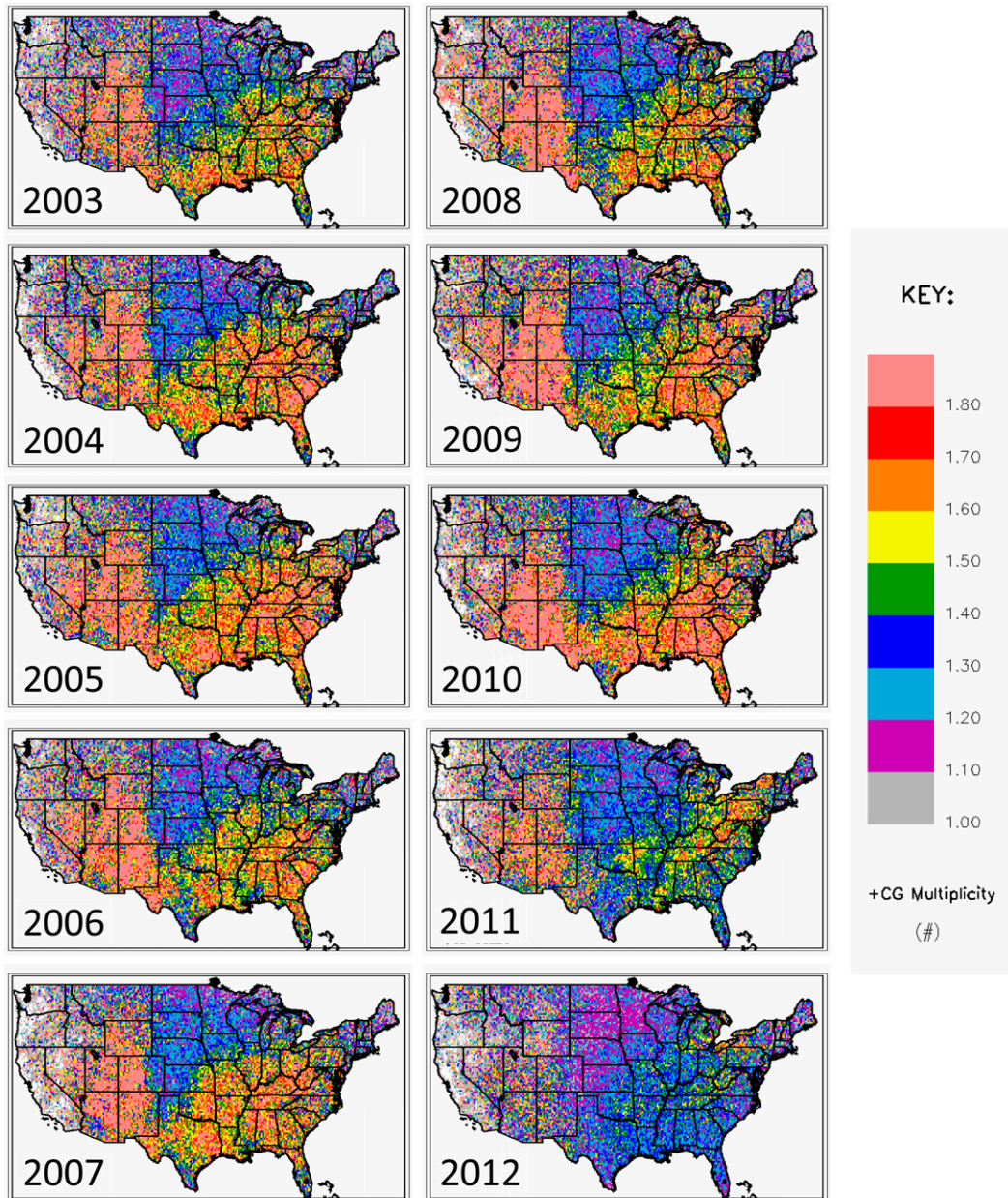


FIG. 9. The annual-average multiplicity in +CG lightning for 2003–12.

fairly stable from year to year, but there are actually drops in flash density in 2006 and 2012 (see Table 4). Note that the flash-density scale provided in the key of Fig. 12 differs from the scale employed in Fig. 1 for CGs because total lightning outnumbers CG lightning.

Table 4 provides the raw and corrected LIS flash count, with the NLDN-derived CG count included again to facilitate comparison. The last column in Table 4 is regarded as the best estimate of total lightning count because corrections for both DE and VT have been made. Of interest is that the minimum LIS flash counts

occur in 2006, whereas the minimum NLDN-derived CG counts occur in the drought year of 2012. The LIS total flash count drops by a significant amount from 2011 to 2012 (i.e., a 9.9% drop using the DE- and VT-corrected column in Table 4). The NLDN-derived CG count dropped by 23.6% in this same interval. To make a better comparison with LIS (which is limited to 38°N), we also include in Table 4 the NLDN CG count over the CONUS when CGs located above 38°N are removed; the associated drop in this count from 2011 to 2012 is 15.6%. Therefore, since the NLDN and LIS are independent

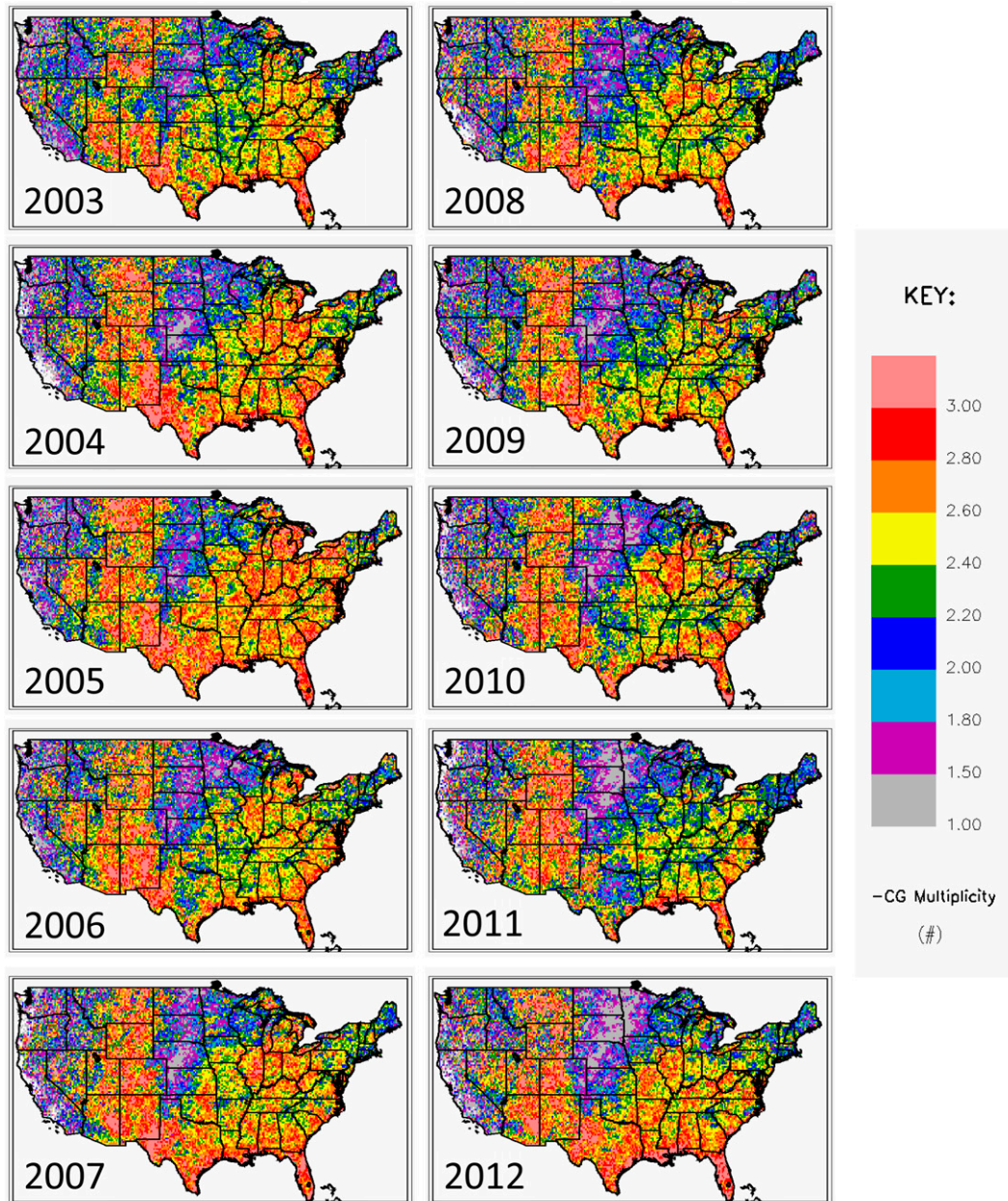


FIG. 10. The annual-average multiplicity in $-CG$ lightning for 2003–12.

datasets that each show significant drops in lightning frequency in 2012, we are confident that lightning is a good indicator of the drought conditions that evidently depleted thunderstorm activity in 2012. In addition, since the drop in CG count reported by the NLDN in 2012 is likely real (i.e., is not due to any network-upgrade effects), the results in Table 4 also support the idea that CG lightning count is more sensitive to climatic conditions than is cloud-flash count, in concert with the findings of Price and Rind (1994) discussed in appendix B.

Table 5 gives the changes in the 5-yr-average counts for NLDN and LIS. Whereas the NLDN average CG count drops by 12.8%, and by 14.8% when the 38°N maximum-latitude filter is applied, the LIS total flash count average is remarkably stable (i.e., it increases by only 0.38%). From Fig. 2 in Boccippio et al. (2001), the climatological ratio of cloud flashes to ground flashes (i.e., climatological “Z” ratio) varies by nearly a factor of 10 over the CONUS, and the Z ratio itself varies widely among individual thunderstorms (Carey and

TABLE 2. Summary of CG average annual peak-current and multiplicity variations derived from the LAT. The 2003 currents are slight underestimates (see section c of appendix A).

Year	CURALL (kA)	CURPOS (kA)	CURNEG (kA)	MULALL	MULPOS	MULNEG
2003	17.67	34.52	16.88	2.50	1.47	2.55
2004	18.51	35.01	17.62	2.52	1.52	2.58
2005	19.63	36.08	18.70	2.58	1.53	2.64
2006	19.49	35.30	18.54	2.47	1.49	2.53
2007	20.27	36.60	19.23	2.52	1.49	2.59
2008	20.10	37.42	18.81	2.41	1.47	2.48
2009	19.95	36.91	18.71	2.42	1.53	2.49
2010	20.87	36.75	19.61	2.43	1.52	2.51
2011	20.38	37.86	18.87	2.33	1.40	2.41
2012	21.84	38.72	20.28	2.48	1.29	2.59

Rutledge 1998). Thus, depending on the locations of storms from year to year and the timing of LIS overpasses of these storms, one would not necessarily expect the number of LIS flashes and NLDN CG flashes always to vary in the same way.

6. Impact assessments and adaptation strategies

An overarching goal of the NCA is to enhance the ability of the United States to anticipate, mitigate, and adapt to changes in the global environment; this goal involves clearly characterizing what threats to the United States are expected and with what certainty and determining how best to mitigate these threats or otherwise to adapt to the changing circumstances imposed by the threats. Figure 13 provides a conceptual overview of the process. Fundamental to this discussion are the two sensitivities S_1 and S_2 shown in Fig. 13. In broad terms, the sensitivity S_1 is measured by the change in a particular lightning characteristic given (only) a change in a particular climate variable. Similarly, the sensitivity S_2 is measured by the change in a particular lightning-caused impact given (only) a change in a particular lightning characteristic. Specific examples and associated estimates of these sensitivities are provided in appendix B. In this work, we have attempted to identify changes in the measured lightning characteristics that could compromise our S_2 estimates, as reflected in the bottom row of Fig. 13. As noted earlier, this analysis is provided in appendix A (section c).

This study is interested in characterizing certain climate-driven lightning-caused impacts. In broad terms, the NCA process defines risk as the product of the likelihood of an event occurring multiplied by the consequences of that event. Therefore, even if the likelihood is small, if the consequences are extremely large then the risk will still be considerable. Assigning a value to the likelihood that a particular climate variable will change is beyond the scope of this study. Rather, we will assess lightning-caused

impacts for a given (assumed) change in the climate variable.

To link our impact analysis directly to the results of Reeve and Toumi (1999) discussed in appendix B (section a), the particular climate-change variable considered is ΔT_w , assumed to be a 1°C average landmass wet-bulb temperature change. How sensitive CG lightning count N is to this change is estimated by using the sensitivity formula $S_1 \equiv \partial N / \partial T_w$. We have discussed several impacts I that help to quantify the consequences, and each impact is associated with a sensitivity $S_2 \equiv \partial I / \partial N$. So a simple linear model of the climate-induced lightning-caused impact sensitivity S can be written as

$$S \equiv \frac{\partial I}{\partial T_w} = \frac{\partial I}{\partial N} \frac{\partial N}{\partial T_w} = S_2 S_1. \tag{1}$$

Multiplying the estimated value of S_1 [~9.44 million CGs per 1°C, from appendix B (section a) and from the Reeve and Toumi (1999) analysis] by the various

TABLE 3. The 5-yr means of the assessment variables and their percent change. The percent changes in current are slight overestimates (see section c of appendix A).

Variable	Mean (2003–07)	Mean (2008–12)	Change (%)
NUMALL	25 204 345.80	21 986 578.80	–12.8
PRATIO	0.053	0.075	41.5
NFAT	40.00	28.60	–28.5
NINJ	241.80	185.00	–23.5
DCROP	0.092	0.224	143.5
DPROP1	50.01	53.66	7.3
DPROP2	844.93*	963.70	14.1
NFIRE	12 000.20	8794.20	–26.7
NACRES	3 100 980.80	2 700 677.40	–12.9
CURALL	19.11	20.63	8.0
CURPOS	35.50	37.53	5.7
CURNEG	18.194	19.256	5.8
MULALL	2.518	2.414	–4.1
MULPOS	1.500	1.442	–3.9
MULNEG	2.578	2.496	–3.2

* Mean is for 4-yr period of 2004–07.

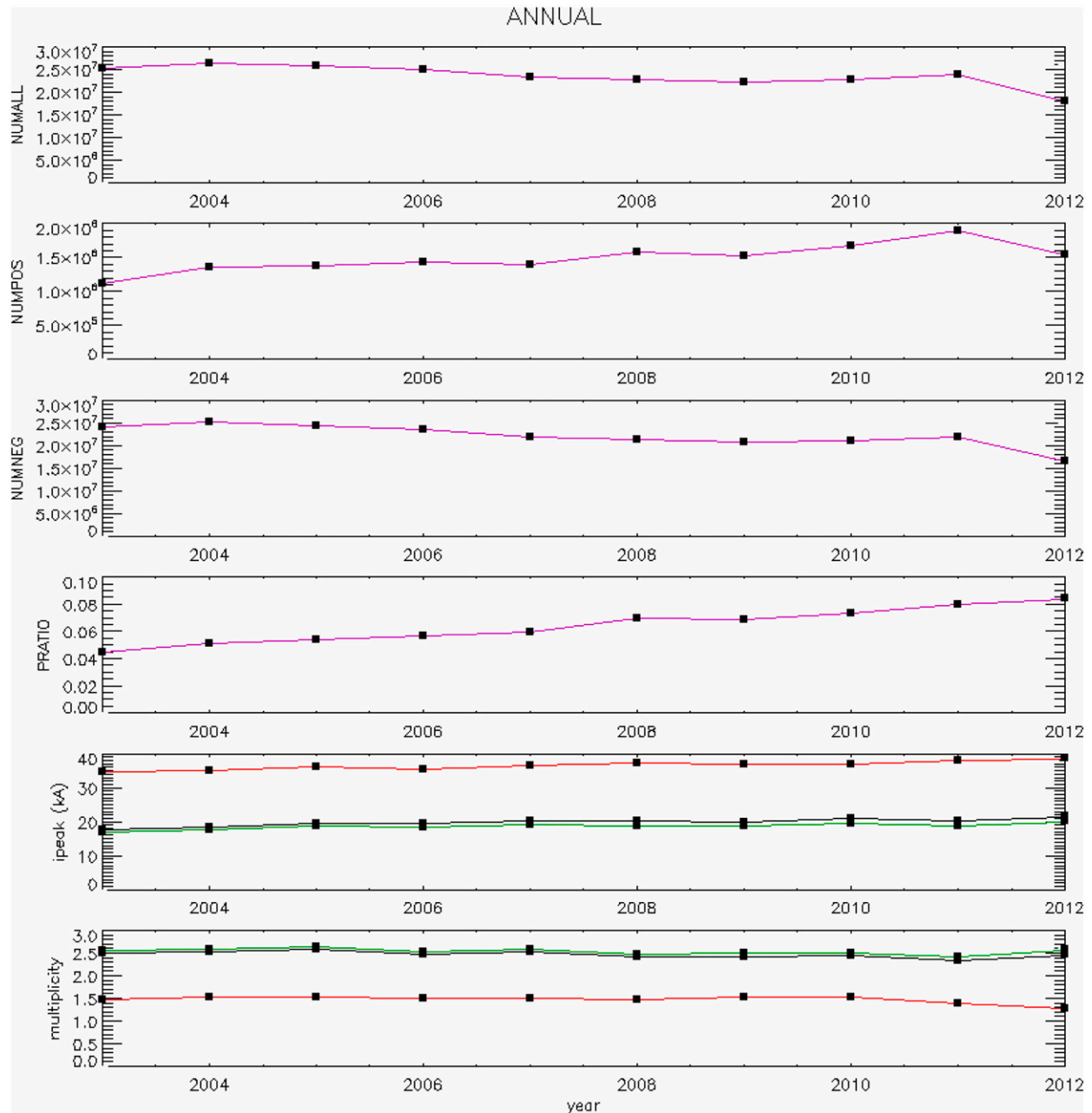


FIG. 11. The annual variation of several CG characteristics (see main text) for 2003–12. The last two plots provide the average annual peak current and average annual multiplicity, respectively (all CGs: black curve, +CGs: red curve, and –CGs: green curve).

impact-dependent sensitivities S_2 estimated in [appendix B \(section b\)](#) gives the following approximate values of S for the CONUS analysis region for different economic sectors:

- 13.7 fatalities and 85.4 injuries per 1°C (human health),
- \$63,200 in crop damage per 1°C (agriculture),
- \$367 million in home-owners' insurance claims per 1°C (personal property), and
- 4160 wildland fires and 1.16 million acres burned per 1°C (forestry).

One can alternatively obtain an estimate of S_1 that is based directly on our CG lightning counts and our computed average CONUS wet-bulb temperatures; see [Fig. 14](#) and [appendix B \(section a\)](#) for additional details on the estimation method. Lightning count is known to be particularly sensitive to wet-bulb temperature ([Williams et al. 1992](#); [Williams and Renno 1993](#); [Jayaratne and](#)

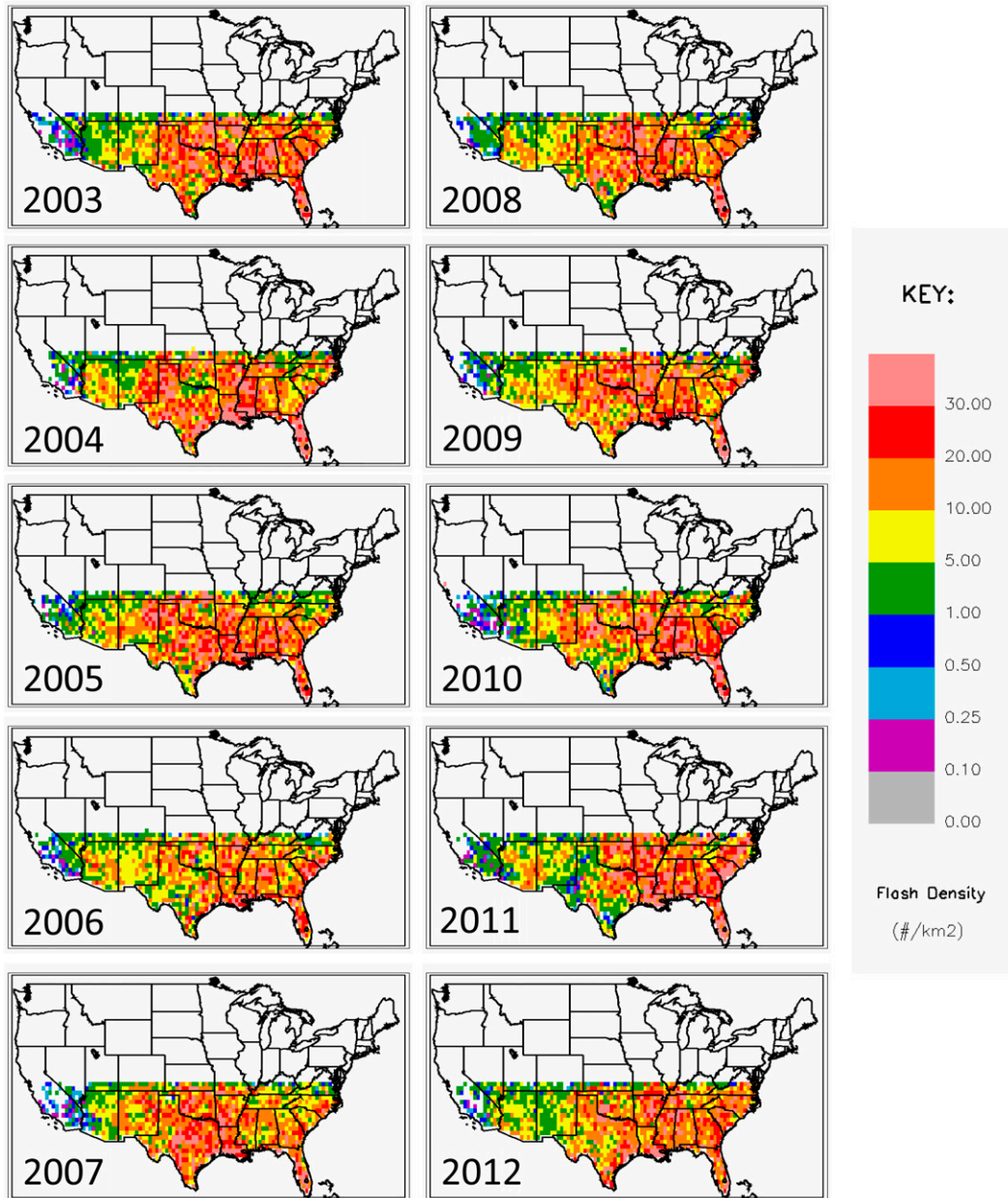


FIG. 12. The LIS total lightning flash density for 2003–12; raw flash counts in each grid cell have been corrected for LIS detection efficiency and view time (see main text for details).

Kuleshov 2006). The National Climatic Data Center (NCDC) average dry-bulb temperature for the CONUS (top plot) and the average CONUS dewpoint temperature are included in Fig. 14 for comparison. Note that the trends are opposite over time for these two temperature measurements. The estimation approach (which basically takes the ratio of the slope of the lightning count trend line to the slope of the wet-bulb temperature trend line) results in a value of S_1 that is about one-half of the value obtained above using the

Reeve and Toumi (1999) results. Hence, employing this estimate of S_1 would in turn reduce the estimates of S shown above by about one-half.

Given that the human-health, agriculture, personal-property, and forestry sectors are vulnerable to fluctuations in CG lightning count, it is important to be prepared. Properly adapting to these sensitivities requires promoting existing mitigation steps, as represented in the top-right corner of Fig. 13. Fatalities and injuries can be decreased by improving and promoting lightning-safety

TABLE 4. Comparison between the NLDN CG counts and the LIS total flash counts.

Year	NLDN	NLDN (up to 38°N)	LIS (raw)	LIS (DE corrected)	LIS (VT corrected)	LIS (DE and VT corrected)
2003	25 312 151	16 819 393	100 090	122 517	41 156 813	50 435 202
2004	26 515 549	16 647 869	100 695	125 233	41 597 393	51 831 376
2005	25 733 836	15 772 975	96 522	119 007	38 790 425	47 837 176
2006	25 110 025	15 976 127	78 787	98 561	32 443 824	40 511 787
2007	23 350 168	14 443 339	87 181	109 318	35 426 713	44 373 486
2008	22 888 321	13 572 750	90 307	110 991	36 409 453	44 772 072
2009	22 233 574	15 095 649	95 793	118 209	39 453 652	48 724 951
2010	22 793 791	13 385 444	93 751	116 310	39 882 740	49 250 190
2011	23 825 025	14 003 266	96 680	118 996	39 810 156	48 989 029
2012	18 192 183	11 817 271	86 766	107 653	35 519 619	44 139 720

education. There are signs in Table 1 that better education on lightning safety is possibly already having a positive impact (see, e.g., the educational website at <http://www.lightningsafety.noaa.gov/>). Mitigation of lightning-caused damage to agricultural crops and forestry lands depends in part on better warning of impending thunderstorm activity, implementation of up-to-date lightning-ignition-efficiency maps (routinely provided at <http://www.wfas.net/index.php/lightning-efficiency-fire-potential--danger-33>), and better mobilization of crews to the damaged areas. Injuries, fatalities, property damage, and lightning-caused power outages can be reduced by applying lightning protection where it is not presently being used and by improving lightning-protection technologies and methods.

7. Summary

For the 2000 and 2009 NCA reports, lightning data have not been utilized in any coordinated and formal way to directly help to promote U.S. climate-assessment efforts; the most recent NCA report that was finalized in 2014 also contained very little reference to lightning. The importance of lightning for climate assessments has been highlighted in this study, however.

Lightning is a sensitive parameter to global temperature given its linkage to atmospheric convection. It also has important feedback consequences to climate since increases in thunderstorm frequency and/or intensity imply increases in upper-tropospheric water vapor (a greenhouse gas) and increases in lightning NO_x lead to increases in tropospheric ozone (a greenhouse gas). Changes in thunderstorm frequency also imply changes in Earth albedo. In addition, both climate and lightning are affected by aerosol concentrations. Given all of

these interrelationships and feedbacks, it is important to monitor lightning closely to better assess climate.

Hence, we have developed the NASA Lightning Analysis Tool to monitor both cloud-to-ground and cloud-flash lightning over the conterminous United States. The LAT is an NCA “sustaining assessment tool” that routinely ingests both national ground-based-network CG lightning data and TRMM LIS satellite-based total (CG + cloud flash) lightning data and provides geographic and time-series data-visualization products.

The LAT-processed lightning results were compared with lightning-caused-impact statistics (death/injury, crop/property damage, and wildfires). We found that CG lightning count has primarily decreased during the analysis period 2003–12. The 5-yr-average CG lightning count dropped by 12.8% from 2003–07 to 2008–12. The associated 5-yr-average LIS total lightning (up to 38°N) was remarkably stable over the decadal period, however. There were also drops in several lightning-caused impacts (fatalities, injuries, and wildfires), but, because of ancillary factors, property and crop damage increased. The CG multiplicity (i.e., the number of strokes in a CG flash) was the most stable CG lightning parameter, decreasing by only 4.1%, whereas CG peak current increased by approximately 5.6% (after corrections are made for a specific network upgrade in 2004). The +CG fraction (and number of +CGs) trended upward through the decade of 2003–12. In addition, the geographical patterns of CG lightning characteristics across the analysis region showed modest spatial variability from year to year. A notable exception was a pronounced drop in CG and total lightning in 2012, which we attribute primarily to the summer drought conditions in that year. We inspected all upgrades to the

TABLE 5. The 5-yr-average flash counts and associated percent changes.

Period	NLDN	NLDN (up to 38°N)	LIS (raw)	LIS (DE and VT corrected)
2003–07	25 204 345.8	15 931 940.6	92 655.0	46 997 805.4
2008–12	21 986 578.8	13 574 876.0	92 659.4	47 175 192.4
Change (%)	−12.77	−14.79	0.005	0.38

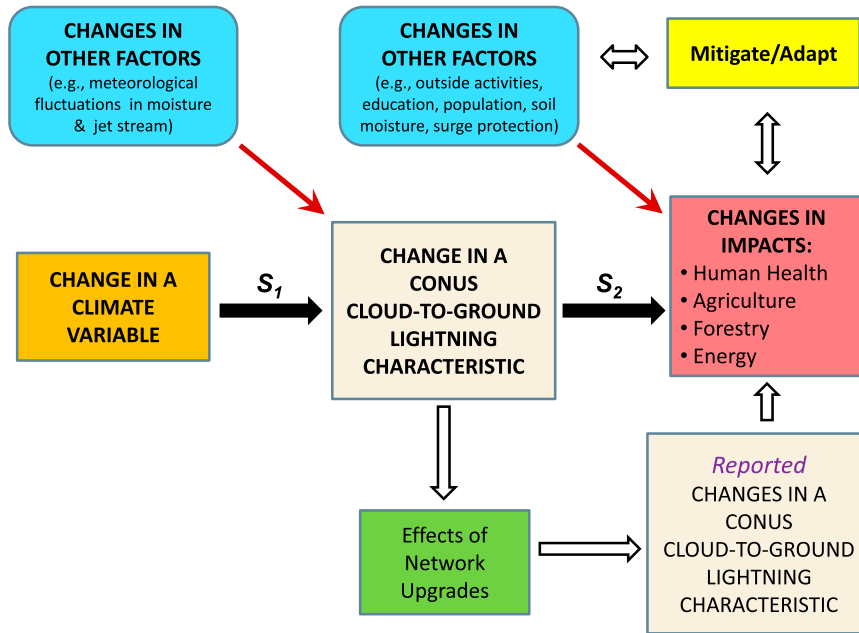


FIG. 13. An overview of the basic considerations in regard to climate-induced changes in CONUS CG lightning. The sensitivities S_1 and S_2 are fundamental to the assessment process.

national CG network across the decadal analysis period and concluded that the upgrades have little effect on the interpretation of our overall results. One exception is that the 2011–12 upgrade to LS7001 sensor technology (see appendix A) is likely responsible for the large decreases in +CG multiplicity during 2011 and 2012.

This study also reviewed and synthesized findings from the literature and from the LAT analyses to obtain simple (preliminary) linear-model estimates of the impacts associated with climate-induced changes in CG lightning count. The model suggests that climate-induced changes in CG lightning frequency would likely have a substantial and direct impact on humankind (e.g., a long-term upward trend of 1°C in wet-bulb temperature corresponds to approximately 14 fatalities, 85 injuries, \$63,000 in crop damage, 4000+ wildfires associated with over 1 million burn acres, and over \$367 million in personal-property damage, all as a result of lightning). Given the assumptions of the model, these estimates are regarded as conservative, and our most conservative estimates are about a factor of 0.5 smaller. It is difficult to make fully confident projections given that CG lightning count and CG lightning-caused impacts all depend on many variables (see appendix B). Nonetheless, the linear model results do encourage improvements in lightning-safety education and awareness, thunderstorm warnings, lightning protection, and other mitigation strategies. In addition, we mentioned several other lightning impacts that we did not examine or that we only partially examined. In particular, lightning-caused power outages and the

associated costs to utilities and consumers are extremely important to the U.S. energy sector and deserve more attention in future studies.

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APPENDIX A

Additional Details of the Datasets

a. NOAA Storm Data

There are various sources for the data in Table 1. Lightning-impact statistics (Table 1, columns 4–7) were obtained from the National Weather Service (NWS) Office of Climate, Water and Weather Services and the NCDC that together compile a summary of U.S.

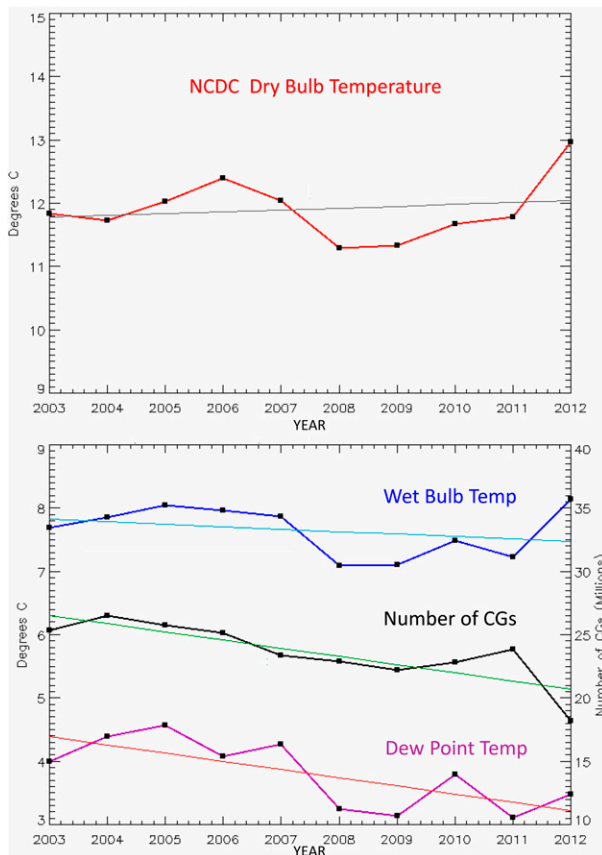


FIG. 14. The CONUS (top) temperature from the NCDC archive, which trends upward, and (bottom) wet-bulb temperature, CG lightning count, and dewpoint, which each trend downward.

natural-hazard statistics from the National Oceanic and Atmospheric Administration (NOAA) publication *Storm Data*; source data are found online (<http://www.nws.noaa.gov/om/hazstats.shtml>). The statistics for lightning-caused property damage (DPROP1 in column 7) are known to be substantial underestimates of the true lightning-caused property damage. That is, a study by Holle et al. (1996) that examined personal and commercial insurance claims from Colorado, Utah, and Wyoming obtained an extrapolated total U.S. lightning-caused property-damage cost of \$332 million, which is larger than the mean of the values shown in column 7 by a factor of 6.4. Moreover, estimates of lightning-caused property damage that are based only on personal home-owners' insurance claims (DPROP2; column 8) were computed by the Insurance Information Institute in cooperation with the State Farm Insurance company, and these values are even larger than the \$332 million estimate provided by Holle et al. (1996).

Note that the impact of CG lightning on the human-health sector that was provided in section 6 is likely an underestimate. To understand why, it is helpful to

review how information in the NOAA *Storm Data* publication is collected. NWS forecasters in each state are responsible for compiling the *Storm Data* information. They accomplish this task by using several outlets: NWS storm-report logs (as completed by trained spotters, law enforcement officers, and the general public), newspapers (using commercial clipping services), private meteorologists, and electronic media. Lopez et al. (1993) assessed the accuracy of the lightning-caused death and injury statistics reported in *Storm Data* for Colorado. The periods analyzed were 1980–91 for deaths and 1988–91 for injuries. The investigators used Colorado Health Department death certificates and Colorado Hospital Association hospital-discharge records to obtain a ground truth by which to evaluate *Storm Data* accuracy. The motivation for this case study came from meetings held at the Lightning Data Center (LDC) at St. Anthony's Hospital in Denver, Colorado. The LDC was established in 1992 and serves as headquarters for an international resource studying the effect of lightning on human health. It brings together professionals from medical, scientific, and related fields as well as the public to explore health-related lightning phenomena and issues. The primary conclusions of the Colorado Case Study (Lopez et al. 1993) are that NOAA's *Storm Data* appears to underestimate lightning fatalities by at least 28% and lightning injuries (that require hospitalization) by at least 42% (for those injuries that do not require hospitalization, the underestimation is suspected to be even higher). The Lopez et al. (1993) case study went on to say that there were two places in which significant data-reporting losses might occur: 1) from police, fire, and ambulance personnel to the newspapers and 2) from the newspapers to *Storm Data*. Hence, these are areas in which improvements in both communication and coordination will lead to improved benchmarking of human-health-related threats from lightning.

Corrections to the source data were made, when feasible. The fatality and injury statistics in Table 1 have been corrected to remove fatalities and injuries that occurred in Alaska, Hawaii, Puerto Rico, Guam, and the Virgin Islands (i.e., places outside our analysis domain). We were unable to correct the DCROP and DPROP1 numbers in Table 1 in the same manner because these statistics were not broken down in a state-by-state or territory fashion as were the fatality/injury statistics. We believe the resulting errors are relatively minimal [e.g., according to the Economic Research Service of the U.S. Department of Agriculture (USDA), the farm income for the CONUS is 99.7% of the total U.S. farm income]. Also, the numbers of wildland fires and acres burned that are given in Table 1 are appropriate since they have

been corrected to remove contributions from Alaska (the original dataset did not include contributions from Hawaii, Puerto Rico, Guam, or the Virgin Islands, and so corrections for these regions were not necessary).

b. Fire data

Columns 9 and 10 in [Table 1](#) include statistics for lightning-caused wildland fires. This information was obtained from the National Interagency Fire Center; source data were found online (http://www.nifc.gov/fireInfo/fireInfo_statistics.html).

The probability of lightning-caused wildfire ignition depends not only on lightning count but also on lightning type, the characteristics of the wildland being struck by lightning, and the amount of precipitation during lightning. With regard to lightning type, it is recognized that +CG flashes have a greater likelihood of causing fires because, even though they have fewer strokes than –CGs on average, they have larger peak currents and a greater fraction of them have long continuing currents. A long continuing current is a current surge (typically of 150-ms duration and 150-A amplitude) that can occur in a CG after the return stroke and that follows along the same return-stroke channel path. Because of their relatively long duration, continuing currents are particularly efficient at heating up a vegetative fuel to the combustion point ([Latham and Schlieter 1989](#)). In fact, about 75% of the +CGs contain continuing currents whereas only about 30% of –CGs have continuing currents ([Saba et al. 2010](#)). With regard to the characteristics of the wildland, the U.S. Fire Service Wildland Fire Assessment System (<http://www.wfas.net/index.php/lightning-efficiency-fire-potential-danger-33>) explains this in detail: “Ignition in fuels with long and medium length needle cast, such as Ponderosa pine and Lodgepole pine, depend[s] on the fuel moisture. Ignitions in short-needled species, such as Douglas fir depend far more on the depth of the duff layer than on the moisture. Spread of the fire after ignition usually depends on fuel moisture in all cases.” Moreover, even if the sources and numbers of potential ignitions do not change, a warmer climate may facilitate increased drying of fine surface fuels of less than 8 cm in diameter over a longer period, thereby allowing more potential ignitions to become actual ignitions that initiate wildfires (2012 NCA technical input report by D. L. Peterson and J. S. Littell with title *Risk Case Study: Wildfire in the Western United States*; available online at http://www.usda.gov/oce/climate_change/effects_2012/FS_Climate1114%20opt.pdf as pp. 249–252 in *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector* edited by J. M. Vose

et al.: USDA Forest Service Gen. Tech. Rep. PNW-GTR-870). With regard to precipitation amount, the occurrence of so-called dry lightning is of critical importance to land-management agencies since this type is most likely to cause wildland fires. Dry lightning is CG lightning with little or no accompanying rainfall. Dry-lightning research has focused on employing upper-air observations such as atmospheric stability and moisture content to predict dry-lightning episodes in advance ([Rorig and Ferguson 2002](#)). These spatial products give managers an idea of where dry lightning has occurred immediately after the storms have passed.

c. NLDN network upgrades

We mentioned the overall evolution of the NLDN network in [section 1](#). In this section, we take a closer look at the upgrades that could potentially affect the results provided in this study.

The first to consider is the major upgrade that started in the spring of 2002 and was completed in 2003. This upgrade involved replacing aging and old technology sensors with third-generation IMPACT ESP sensors. Eight of these sensors were also added to the network. This provided increased network sensitivity, implying improved CG detection efficiency (90%–95% for CG flashes and 60%–80% for CG strokes). Because our analysis begins in 2003, the impact of this upgrade on our NCA analyses is negligible. Again, we specifically began our analysis in 2003 to take full advantage of this major network upgrade and still obtain a decade-long analysis period.

Next, the NLDN Propagation Model used to estimate peak current was changed on 1 July 2004 to compensate for the changes in sensor baselines and network geometry that occurred in the 2002–03 upgrade. Parameters were changed in the model used to correct measured peak magnetic-field values for losses due to propagation over finite-conductivity ground [see [section 4.2](#) of [Cummins et al. \(2006\)](#) for details]. The impact of this upgrade was to increase NLDN median and mean peak current estimates by approximately 12%. By examining the mean currents (second column in [Table 2](#)), one can retroactively apply the 12% correction to 2003, which gives $1.12 \times 17.67 \text{ kA} = 19.79 \text{ kA}$. This would change the 5-yr (2003–07) mean from 19.11 kA ([Table 3](#)) to 19.54 kA, or a change of only 2.3%. This in turn would reduce the 8% increase cited in [Table 3](#) to 5.6%.

There were several upgrades in 2006. For example, two sensors were added southeast of Florida to improve coverage over the northern Caribbean Sea. Because we have applied a CONUS mask to our results, this has little effect on our flash-density results in [Figs. 1–3](#). There was also a vendor-recommended 15-kA rule upgrade associated with the NLDN data-file content that began in

2006: from 5 April 2006 through 2 February 2008, all CGs in the NLDN data files having positive peak currents between 0 and 15 kA were removed from the data files by the vendor because these discharges were likely cloud flashes. This does not affect our analyses at all, because we always remove the 0–15-kA discharges for all years in our analysis period. The vendor also implemented an electric-field waveform-detection-criteria upgrade in 2006; the processing algorithm admitted short peak-to-zero waveforms to allow limited cloud-flash detection. This upgrade has the possible effect of increasing the CG stroke count overall but also increases the chance of misclassifying cloud pulses as CG flashes [see Fleenor et al. (2009) for details]. Because we see a decrease in the total CG count from 2005 to 2006 and from 2006 to 2007 (see Table 1) and because we analyze flashes rather than strokes, we believe the impact of this upgrade is negligible.

In 2008, the NLDN location algorithm was modified to extend the network range (i.e., to provide better offshore reporting and to increase coverage in northern Mexico). Because we apply a CONUS mask and because total CG count drops from 2007 to 2008 (see Table 1), this upgrade has little effect on our results; for example, increased lightning counts outside the mask do not affect counts inside the mask. It is not known whether the modification of this (proprietary) algorithm contributed to the relatively large (0.009) increase in the +CG fraction (PRATIO) in 2008 (see Table 1, third column). Because the PRATIO trends upward across our entire analysis period (except between 2008 and 2009, for which it drops by only 0.001), however, it is likely a legitimate change rather than a network-upgrade effect. Therefore, it will be important to continue tracking the PRATIO assessment parameter. In addition, in June of 2008, an upgrade was implemented that improved the removal of duplicate and poorly located CG events. This change is expected to decrease the CG count by perhaps a couple of percent. Although there is a drop in CG count from 2007 to 2008, note that there are larger drops in CG count from 2006 to 2007 and from 2008 to 2009 (see Table 1). Therefore, the impact of this upgrade appears to be small.

Beginning in 2011 and continuing into 2012, the NLDN was further upgraded to Vaisala LS7001 sensors. As mentioned in section 3, we believe that this upgrade is responsible for the drop in the +CG multiplicities from 2010 to 2012. Table 2 (MULPOS column, for 2010–12) shows that the respective CONUS-averaged +CG multiplicities trend downward as follows: 1.52, 1.40, and 1.29. (Note: by comparison, the CONUS-averaged –CG multiplicity drops from 2010 to 2011 and then rises from 2011 to 2012.) Computing the average and standard deviation of the MULPOS values in Table 2 from 2003

to 2010, one obtains 1.50 and 0.026, respectively. The steep drop down to 1.29 (or 8 standard deviations below the mean of 1.50) by 2012, combined with the fact that a similar overall drop in the –CG multiplicity does not occur, is highly suspicious. Therefore, we suspect that this polarity-dependent effect is due to the network upgrade to LS7001 sensors. This significant change in positive multiplicity, including its time evolution, is consistent with the steady transition to the new LS7001 sensor. This fully digital sensor [see description in Cummins et al. (2012)] does not suffer from the polarity errors for bipolar discharges that are described in Fleenor et al. (2009). Although this problem affected a very small fraction of discharges, the dominant impact would be to increase the number of reported multipulse positive discharges, resulting in an artificially high multiplicity for positive flashes.

Although we suspect the upgrade to LS7001 sensors has affected the +CG multiplicities, we do not believe it has caused any other significant biases in our results. In particular, it is not responsible for the (drought driven) depletion in lightning count that was observed in 2012, which is independently confirmed by satellite observations (section 5). In general, the slightly better sensitivity of the LS7001 sensors would imply a slightly higher CG count. Implementation of these sensors also improves flash-type classification (CG or cloud flash), however, which results in a higher cloud-flash count and a lower CG count. So, the net effect expected from upgrading to LS7001 sensors is to lower the CG count. Therefore, since the upgrade to LS7001 sensors was largely completed in 2011 (i.e., 62 of 110 were installed by 10 May 2011 and 95 of 110 were installed by 8 November 2011), one would expect a decrease in the 2011 CG count relative to 2010. Because the CG count in 2011 increased relative to 2010 (see Table 1), we believe the impact of this upgrade on CG count is small.

APPENDIX B

Estimating S_1 and S_2

a. Sensitivity S_1

Section 2 provided some background and substantiation for the basic linkage between a warming climate and increases in lightning frequency. The literature generally agrees that, assuming all else is equal, a warming climate would result in more lightning as a result of an increase in the number of thunderstorms and possibly also because of an increase in thunderstorm strength (although this latter cause is debated).

In general, the sensitivity S_1 shown in Fig. 13 depends on many factors: 1) the specific lightning CG characteristic

examined (e.g., count, mean peak current, or multiplicity), 2) the geographical region of the CONUS over which the CG characteristic is examined, 3) the season over which the CG characteristic is examined, and 4) the time of day over which the CG characteristic is examined. The sensitivity S_1 also depends on what climate variable is considered (e.g., global dry-bulb temperature, the global landmass dry-bulb temperature, or the wet-bulb temperature over some prescribed region). In addition, one must keep in mind that there are other complicating factors that could change CONUS CG lightning characteristics *even if a pronounced trend in climate change did not exist*. These “changes in other factors” (the blue element shown in the top left of Fig. 13) include, but are not limited to, normal fluctuations in meteorological (e.g., jet stream and moisture) patterns. Such meteorological factors are indeed important; for example, our results have already demonstrated that a significant drop in CG count can occur as a result of relatively short-term drought conditions.

To gain some baseline estimates of the typical magnitude of S_1 (where the CG characteristic considered is lightning count N), two previous studies are considered. The first study is by Price and Rind (1994), and the second is by Reeve and Toumi (1999).

The study by Price and Rind (1994) conducted a $2 \times \text{CO}_2$ climate scenario (corresponding to a 4.2°C global warming) using the NASA Goddard Institute for Space Studies general circulation model (GCM). They found that the associated increase in total (CG + cloud flash) lightning over the entire globe was 30%; cloud flashes generally outnumber CGs by a ratio of 3:1 or much higher. They also consider a 5.9°C global-cooling experiment (model run) associated with a reduction in the solar constant and obtained a 24% decrease in total global lightning. From these two model runs, they concluded that there exists an overall sensitivity of approximately 5%–6% change in total global lightning per 1°C temperature change. Lightning activity increased 72% per 4.2°C ($=17.1\%$ per 1°C change) over landmasses, as compared with 12% per 4.2°C over oceans. Moreover, they found that CG lightning frequencies showed larger sensitivity to climate change than did cloud-flash frequencies.

We believe that better estimates of the sensitivity were obtained in the Reeve and Toumi (1999) study because they used direct, satellite-based observations of global lightning as provided by NASA’s Optical Transient Detector (OTD). The study by Price and Rind (1994) predated such observations and, therefore, depended on parameterizing lightning-flash rates as a function of the GCM-derived cloud-top height. Such parameterizations are not without error. Using the global OTD lightning dataset, Reeve and Toumi (1999) found

that a change in the average land wet-bulb temperature of just 1°C results in about a $40\% \pm 14\%$ change in total lightning activity globally. This value is substantially larger than either the 5%–6% or 17.1% changes obtained in Price and Rind (1994), but, of course, the analysis methods, regions scrutinized, and type of temperature (dry bulb vs wet bulb) employed differed in general. The wet-bulb temperature has the advantage that it increases with both temperature and absolute humidity and so should track lightning better than does dry-bulb or dewpoint temperature alone. Furthermore, CAPE has been shown to be proportional to the wet-bulb potential temperature in the current climate (Williams and Renno 1993). Moreover, Reeve and Toumi (1999) find a sensitivity (and uncertainty) of $56\% \pm 15\%$ per 1°C average wet-bulb change over the Northern Hemisphere landmass. (Note that the Reeve and Toumi results are particularly useful for this NCA study since error bars in the sensitivity estimates are provided and support a risk-based framing approach; they obtained the error bars by least squares fitting the lightning and wet-bulb temperature datasets.)

From Table 1, the 2003–12 mean (standard deviation) of NUMALL is 23 595 462.30 (2 372 205.48). Using the $40\% \pm 14\%$ increase in CG count per 1°C average land wet-bulb temperature change from Reeve and Toumi (1999) gives $(0.4 \pm 0.14) \times 23\,595\,462.30 \approx (9.44 \pm 3.3)$ million CG per 1°C change in average land wet-bulb temperature.

The sensitivity is defined as the *partial derivative* (i.e., $S_1 \equiv \partial N / \partial T_w$). Note, however, that in the previous paragraph we have made the approximation $S_1 \approx \Delta N / \Delta T_w$, which is a numerical estimate of the *total derivative* dN/dT_w . That is, the CG lightning count is a function of many variables: $N = N(T_w, x_1, x_2, \dots)$, where T_w represents the particular climate variable considered and x_1, x_2, \dots represent all of the other variables (whether related to climate or not) that independently affect lightning count. Because the total change in lightning count can be written

$$dN = \frac{\partial N}{\partial T_w} dT_w + \frac{\partial N}{\partial x_1} dx_1 + \frac{\partial N}{\partial x_2} dx_2 + \dots, \quad (\text{B1})$$

one obtains, with the assumption that $\partial N / \partial x_i \approx 0$ for $i = 1, 2, \dots$,

$$S_1 \approx dN/dT_w. \quad (\text{B2})$$

So the numerical estimate ($S_1 \approx 9.44$ million CGs per 1°C) computed above implicitly assumes that the sensitivity to the other variables x_1, x_2, \dots is negligible. Whether this numerical estimate of S_1 is too large or too

small depends on both the sign and magnitude of the neglected sensitivities ($\partial N/\partial x_i, i = 1, 2, \dots$).

Another estimate of S_1 can be obtained by an alternative approach. The CONUS averages of wet-bulb and dewpoint temperature are obtained from North American Model reanalysis using the 2-m AGL temperature and relative humidity data (the NCDC North American Regional Reanalysis dataset). For each 3-h analysis, the wet-bulb and dewpoint temperatures were calculated at each point before the CONUS average was calculated, and then all times were averaged together to form annual averages. The dewpoint was calculated from the Magnus formula, and wet-bulb temperature was interpolated from a lookup table. A best-fit line $Y = mX + b$ is provided for each of the plots in Fig. 14. By considering the best-fit line for the CG count and the best-fit line for the wet-bulb temperature, one can take the ratio of the slopes associated with these two lines to estimate the sensitivity S_1 . This calculation gives a large value of ~ 16.5 million CGs per 1°C change in average CONUS wet-bulb temperature, but this estimate is profoundly biased by the drought of 2012 (which is a meteorological factor, as indicated in the top-left element of Fig. 13). That is, we are only interested in the sensitivity of CG lightning count to longer-term climate changes and not the sensitivity to abrupt meteorological changes. Therefore, the drought year of 2012 should be removed from the calculation. When this is done, the ratio of the slopes of the best-fit line equations for the period 2003–11 gives a sensitivity of about 4.61 million CGs per 1°C change in average CONUS wet-bulb temperature. The (conservative) estimate from [Reeve and Toumi \(1999\)](#) is larger than this estimate by approximately a factor of 2. Given that different landmasses and methods were employed, however, the estimates are reasonably close, especially given the 3+ million uncertainty associated with the [Reeve and Toumi \(1999\)](#) result. In addition, the best-fit equations for the period 2003–11 imply about an 18% change in CG counts per 1°C change in average CONUS wet-bulb temperature; again, the 40% value mentioned above from [Reeve and Toumi \(1999\)](#) is larger than this estimate by approximately a factor of 2.

Note from the plots in Fig. 14 that T_w is sometimes anticorrelated with N , especially from 2011 to 2012. This is certainly possible from a mathematical point of view since *total* changes in N depend not only on T_w but on other variables as shown in (B1). That is, changes in some of these other variables could drive the net value of N downward even though an increase in T_w was acting to drive N upward. Second, the drought conditions in 2012 imply higher temperatures, less precipitation, fewer thunderstorms, and less lightning (so the dry-bulb temperature increased in 2012 while CG count decreased).

At the same time, the higher air temperatures eventually result in higher evapotranspiration and more atmospheric moisture, each of which lead to an increase in T_w . Therefore, wet-bulb temperature normally tracks CG count, but the correlation is evidently reversed during drought conditions. Overall, we emphasize that it is difficult to obtain any better estimates of S_1 given the lack of precise knowledge of the competing sensitivities ($\partial N/\partial x_i, i = 1, 2, \dots$) and the limited analysis period (one decade) that we currently have available.

b. Sensitivity S_2

To estimate the sensitivity S_2 shown in Fig. 13, one can further examine the LAT results. The values in Table 1 provide some initial insight as to how sensitive the human-health, agriculture, personal-property, and forestry sectors might be to changes in CG lightning count. For example, to estimate the sensitivity of lightning-caused fatalities to changes in CG lightning count, one can sum up the values of NFAT in Table 1 (2003–12) and divide by the total number of CGs in this same period. A similar method can be used for the other parameters. This approach results in the following values of S_2 for various types of impact:

- 1.454 fatalities and 9.044 injuries per million CGs (human health),
- \$6,696 in crop damage per million CGs (agriculture),
- \$38,919,976 in home-owners' insurance claims per million CGs (personal property), and
- 440.6 wildland fires and 122 940 acres burned per million CGs (forestry).

These empirically inferred sensitivities drive home the point that climate-induced changes in CG lightning count would likely have a substantial and direct impact on humankind.

Once again, note that these computed sensitivities are only approximations that are based on total changes. In general, an impact I is a function of many variables; that is, $I = I(N, y_1, y_2, \dots)$, where y_1, y_2, \dots represent all of the other variables that independently affect the impact. Noting that $S_2 \equiv \partial I/\partial N$ and using reasoning that is similar to that used in (B1) and (B2), one obtains

$$S_2 \approx dI/dN. \quad (\text{B3})$$

So the numerical estimates listed above for S_2 implicitly assume that all of the other sensitivities (i.e., $\partial I/\partial y_j, j = 1, 2, \dots$) are negligible. Whether the numerical estimates listed for S_2 are too large or too small depends on both the sign and magnitude of these neglected sensitivities.

In addition, not all impacts are necessarily bad. For example, lightning fixation of the soil can improve crop

growth. That is, energy from a lightning flash causes atmospheric nitrogen (N_2) and water (H_2O) to combine to form ammonia (NH_3) and nitrates (NO_3). Precipitation transports these compounds to the soil where plants assimilate them as fertilizer, enhancing plant growth. In addition, note that not all wildland fires are necessarily bad for the ecosystem (e.g., consider motivations for controlled burns), but detailing and evaluating impacts to the U.S. ecosystems-and-biodiversity sector is outside the scope of this writing.

The results in Table 1 show a general downward trend in CG count that could explain why some of the adverse lightning-caused impacts have decreased (see Table 3). Although we consider this initial study to be important, ultimately a longer LAT trending period will be required to better evaluate and understand S_2 for each of the different impacts. We anticipate that the NLDN will continue to be upgraded (e.g., more/better sensors, higher detection efficiency, and better location accuracy) in the next decade, and this fact alone will improve our understanding of S_2 .

It is also important to emphasize that the mitigation/adaptation practices adopted by key decision makers (see yellow box at top right in Fig. 13) can reduce impacts to the indicated sectors (e.g., improved warnings and emergency response can reduce deaths/injuries). So these evolving practices can profoundly change the magnitude of S_2 . Note also that the sensitivities provided above for lightning-caused deaths/injuries are likely underestimates; that is, one should expect a substantially larger change in deaths and injuries per change in CG lightning count (see discussion in section a of appendix A).

REFERENCES

- Albrecht, R. I., C. A. Morales, and M. A. F. S. Dias, 2011: Electrification of precipitating systems over the Amazon: Physical processes of thunderstorm development. *J. Geophys. Res.*, **116**, D08209, doi:10.1029/2010JD014756.
- Baker, M. B., H. J. Christian, and J. Latham, 1995: A computational study of the relationships linking lightning frequency and other thundercloud parameters. *Quart. J. Roy. Meteor. Soc.*, **121**, 1525–1548, doi:10.1002/qj.49712152703.
- , A. M. Blyth, H. J. Christian, J. Latham, K. L. Miller, and A. M. Gadian, 1999: Relationships between lightning activity and various thundercloud parameters: Satellite and modeling studies. *Atmos. Res.*, **51**, 221–236, doi:10.1016/S0169-8095(99)00009-5.
- Biagi, C. J., K. L. Cummins, K. E. Kehoe, and E. P. Krider, 2007: National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004. *J. Geophys. Res.*, **112**, D05208, doi:10.1029/2006JD007341.
- Boccippio, D. J., K. L. Cummins, H. J. Christian, and S. J. Goodman, 2001: Combined satellite- and surface-based estimation of the intracloud–cloud-to-ground lightning ratio over the continental United States. *Mon. Wea. Rev.*, **129**, 108–122, doi:10.1175/1520-0493(2001)129<0108:CSASBE>2.0.CO;2.
- , W. J. Koshak, and R. J. Blakeslee, 2002: Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor. Part I: Predicted diurnal variability. *J. Atmos. Oceanic Technol.*, **19**, 1318–1332, doi:10.1175/1520-0426(2002)019<1318:PAOTOT>2.0.CO;2.
- Bolin, B., and Coauthors, 1995: IPCC second assessment: Climate change 1995. World Meteorological Organization and U.N. Environment Programme Intergovernmental Panel on Climate Change Rep., 73 pp. [Available online at <http://ipcc.ch/pdf/climate-changes-1995/ipcc-2nd-assessment/2nd-assessment-en.pdf>.]
- Buechler, D. E., W. J. Koshak, H. J. Christian, and S. J. Goodman, 2014: Assessing the performance of the Lightning Imaging Sensor (LIS) using deep convective clouds. *Atmos. Res.*, **135–136**, 397–403, doi:10.1016/j.atmosres.2012.09.008.
- Carey, L. D., and S. A. Rutledge, 1998: Electrical and multiparameter radar observations of a severe hailstorm. *J. Geophys. Res.*, **103**, 13 979–14 000, doi:10.1029/97JD02626.
- , —, and W. A. Petersen, 2003: The relationship between severe storm reports and cloud-to-ground lightning polarity in the contiguous United States from 1989 to 1998. *Mon. Wea. Rev.*, **131**, 1211–1228, doi:10.1175/1520-0493(2003)131<1211:TRBSSR>2.0.CO;2.
- Cecil, D. J., D. E. Buechler, and R. J. Blakeslee, 2014: Gridded lightning climatology from TRMM-LIS and OTD: Dataset description. *Atmos. Res.*, **135–136**, 404–414, doi:10.1016/j.atmosres.2012.06.028.
- Christian, H. J., and Coauthors, 1999: The Lightning Imaging Sensor. *11th Int. Conf. on Atmospheric Electricity*, Gunterville, AL, ICAE, 746–749.
- Cummins, K. L., and M. J. Murphy, 2009: An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the US NLDN. *IEEE Trans. Electromagn. Compat.*, **51**, 499–518, doi:10.1109/TEMC.2009.2023450.
- , J. A. Cramer, C. J. Biagi, E. P. Krider, J. Jerauld, M. A. Uman, and V. A. Rakov, 2006: The US National Lightning Detection Network: Post upgrade status. Preprints, *Second Conf. on Meteorological Applications of Lightning Data*, Atlanta, GA, Amer. Meteor. Soc., 6.1. [Available online at <https://ams.confex.com/ams/pdfpapers/105142.pdf>.]
- , N. Honma, A. E. Pifer, T. Rogers, and M. Tatsumi, 2012: Improved detection of winter lightning in the Tohoku region of Japan using Vaisala's LS700x technology. *IEEJ Trans. Power Energy*, **132**, 529–535, doi:10.1541/ieejpes.132.529.
- Fleener, S. A., C. J. Biagi, K. L. Cummins, E. P. Krider, and X. M. Shao, 2009: Characteristics of cloud-to-ground lightning in warm-season thunderstorms in the central Great Plains. *Atmos. Res.*, **91**, 333–352, doi:10.1016/j.atmosres.2008.08.011.
- Hansen, K., 2013: Plant stress paints early picture of drought. *The Earth Observer*, Vol. 25, No. 1, NASA Goddard Space Flight Center, Greenbelt, MD, 44–45. [Available online at http://eospsa.gsfc.nasa.gov/sites/default/files/eo_pdfs/Jan-Feb_2013_508_color.pdf#page=44.]
- Holle, R. L., R. E. Lopez, L. J. Arnold, and J. Endres, 1996: Insured lightning-caused property damage in three western states. *J. Appl. Meteor.*, **35**, 1344–1351, doi:10.1175/1520-0450(1996)035<1344:ILCPDI>2.0.CO;2.
- Huff, F. A., and S. A. Changnon, 1972: Inadvertent precipitation modification by urban areas. Preprints, *Third Conf. on Weather Modification*, Boston, MA, Amer. Meteor. Soc., 73–78.
- Huffines, G. R., and R. E. Orville, 1999: Lightning ground flash density and thunderstorm duration in the continental United

- States: 1989–96. *J. Appl. Meteor.*, **38**, 1013–1019, doi:10.1175/1520-0450(1999)038<1013:LGFDAT>2.0.CO;2.
- Huntresier, H., H. Schlager, C. Feigl, and H. Holler, 1998: Transport and production of NO_x in electrified thunderstorms: Survey of previous studies and new observations at mid-latitudes. *J. Geophys. Res.*, **103**, 28 247–28 264, doi:10.1029/98JD02353.
- Jayarathne, R., and E. Kuleshov, 2006: The relationship between lightning activity and surface wet bulb temperature and its variation with latitude in Australia. *Meteor. Atmos. Phys.*, **91**, 17–24, doi:10.1007/s00703-004-0100-0.
- Kar, S. K., Y. A. Liou, and K. J. Ha, 2009: Aerosol effects on the enhancement of cloud-to-ground lightning over major urban areas of South Korea. *Atmos. Res.*, **92**, 80–87, doi:10.1016/j.atmosres.2008.09.004.
- Koshak, W. J., M. F. Stewart, H. J. Christian, J. W. Bergstrom, J. M. Hall, and R. J. Solakiewicz, 2000: Laboratory calibration of the Optical Transient Detector and the Lightning Imaging Sensor. *J. Atmos. Oceanic Technol.*, **17**, 905–915, doi:10.1175/1520-0426(2000)017<0905:LCOTOT>2.0.CO;2.
- , M. N. Khan, A. P. Biazar, M. Newchurch, and R. T. McNider, 2009: A NASA model for improving the lightning NO_x emission inventory for CMAQ. Preprints, *Fourth Conf. on the Meteorological Applications of Lightning Data/11th Conf. on Atmospheric Chemistry*, Phoenix, AZ, Amer. Meteor. Soc., J.8.2. [Available online at <https://ams.confex.com/ams/pdfpapers/147334.pdf>.]
- , H. S. Peterson, A. P. Biazar, M. N. Khan, and L. Wang, 2014: The NASA Lightning Nitrogen Oxides Model (LNOM): Application to air quality modeling. *Atmos. Res.*, **135–136**, 363–369, doi:10.1016/j.atmosres.2012.12.015.
- Kunkel, K. E., 2003: Sea surface temperature forcing of the upward trend in U.S. extreme precipitation. *J. Geophys. Res.*, **108**, 4020, doi:10.1029/2002JD002404.
- Latham, D. J., and J. A. Schlieter, 1989: Ignition probabilities of wildland fuels based on simulated lightning discharges. U.S. Department of Agriculture Forest Service Intermountain Research Station Res. Paper INT-411, 16 pp. [Available online at <https://archive.org/details/ignitionprobabil411lath/>.]
- Lee, D. S., and Coauthors, 1997: Estimations of global NO_x emissions and their uncertainties. *Atmos. Environ.*, **31**, 1735–1749, doi:10.1016/S1352-2310(96)00327-5.
- Lopez, R. E., R. L. Holle, T. A. Heitmap, M. Boyson, M. Cherington, and K. Langford, 1993: The underreporting of lightning injuries and deaths in Colorado. *Bull. Amer. Meteor. Soc.*, **74**, 2171–2178, doi:10.1175/1520-0477(1993)074<2171:TUOLIA>2.0.CO;2.
- Lyons, W. A., T. E. Nelson, E. R. Williams, J. Cramer, and T. Turner, 1998: Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke. *Science*, **282**, 77–81, doi:10.1126/science.282.5386.77.
- Makela, A., and P. Rossi, 2011: The daily cloud-to-ground lightning flash density in the contiguous United States and Finland. *Mon. Wea. Rev.*, **139**, 1323–1337, doi:10.1175/2010MWR3517.1.
- Mansell, E. R., and C. L. Ziegler, 2013: Aerosol effects on simulated storm electrification and precipitation in a two-moment bulk microphysics model. *J. Atmos. Sci.*, **70**, 2032–2050, doi:10.1175/JAS-D-12-0264.1.
- Mitchell, J. M., 1971: The effect of atmospheric aerosols on climate with special reference to temperature near the earth's surface. *J. Appl. Meteor.*, **10**, 703–714, doi:10.1175/1520-0450(1971)010<0703:TEOAAO>2.0.CO;2.
- Murray, N. D., R. E. Orville, and G. R. Huffines, 2000: Effect of pollution from Central American fires on cloud-to-ground lightning in May 1998. *Geophys. Res. Lett.*, **27**, 2249–2252, doi:10.1029/2000GL011656.
- Orville, R. E., 1991: Lightning ground flash density in the contiguous United States—1989. *Mon. Wea. Rev.*, **119**, 573–577, doi:10.1175/1520-0493(1991)119<0573:LGFDIT>2.0.CO;2.
- , 1994: Cloud-to-ground lightning flash characteristics in the contiguous United States: 1989–1991. *J. Geophys. Res.*, **99**, 10 833–10 841, doi:10.1029/93JD02914.
- , and A. C. Silver, 1997: Lightning ground flash density in the contiguous United States: 1992–95. *Mon. Wea. Rev.*, **125**, 631–638, doi:10.1175/1520-0493(1997)125<0631:LGFDIT>2.0.CO;2.
- , and G. R. Huffines, 1999: Lightning ground flash measurements over the contiguous United States: 1995–97. *Mon. Wea. Rev.*, **127**, 2693–2703, doi:10.1175/1520-0493(1999)127<2693:LGFMOT>2.0.CO;2.
- , and —, 2001: Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. *Mon. Wea. Rev.*, **129**, 1179–1193, doi:10.1175/1520-0493(2001)129<1179:CTGLIT>2.0.CO;2.
- , and Coauthors, 2001: Enhancement of cloud-to-ground lightning activity over Houston, Texas. *Geophys. Res. Lett.*, **28**, 2597–2600, doi:10.1029/2001GL012990.
- , G. R. Huffines, W. R. Burrows, R. L. Holle, and K. L. Cummins, 2002: The North American Lightning Detection Network (NALDN)—First results: 1998–2000. *Mon. Wea. Rev.*, **130**, 2098–2109, doi:10.1175/1520-0493(2002)130<2098:TNALDN>2.0.CO;2.
- , —, —, and K. L. Cummins, 2011: The North American Lightning Detection Network (NALDN)—Analysis of flash data: 2001–09. *Mon. Wea. Rev.*, **139**, 1305–1322, doi:10.1175/2010MWR3452.1.
- Petersen, D., M. Bailey, W. H. Beasley, and J. Hallett, 2008: A brief review of the problem of lightning initiation and a hypothesis of initial lightning leader formation. *J. Geophys. Res.*, **113**, D17205, doi:10.1029/2007JD009036.
- Peterson, H. S., and W. H. Beasley, 2011: Possible catalytic effects of ice particles on the production of NO_x by lightning discharges. *Atmos. Chem. Phys.*, **11**, 10 259–10 268, doi:10.5194/acp-11-10259-2011.
- , and J. Hallett, 2012: Ice particle growth in the presence of nitric oxide. *J. Geophys. Res.*, **117**, D06302, doi:10.1029/2011JD016986.
- Price, C., 2000: Evidence for a link between global lightning activity and upper tropospheric water vapor. *Nature*, **406**, 290–293, doi:10.1038/35018543.
- , and D. Rind, 1994: Possible implications of global climate change on global lightning distributions and frequencies. *J. Geophys. Res.*, **99**, 10 823–10 831, doi:10.1029/94JD00019.
- Reeve, N., and R. Toumi, 1999: Lightning activity as an indicator of climate change. *Quart. J. Roy. Meteor. Soc.*, **125**, 893–903, doi:10.1002/qj.4971255507.
- Rorig, M. L., and S. A. Ferguson, 2002: The 2000 fire season: Lightning-caused fires. *J. Appl. Meteor.*, **41**, 786–791, doi:10.1175/1520-0450(2002)041<0786:TFSLCF>2.0.CO;2.
- Rudlosky, S. D., and H. E. Fuelberg, 2010: Pre- and postupgrade distributions of NLDN reported cloud-to-ground lightning characteristics in the contiguous United States. *Mon. Wea. Rev.*, **138**, 3623–3633, doi:10.1175/2010MWR3283.1.
- Saba, M. M. F., W. Schulz, T. A. Warner, L. Z. S. Campos, C. Schumann, E. P. Krider, K. L. Cummins, and R. E. Orville, 2010: High-speed video observations of positive lightning flashes to ground. *J. Geophys. Res.*, **115**, D24201, doi:10.1029/2010JD014330.

- Steiger, S. M., R. E. Orville, and G. R. Huffines, 2002: Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000. *J. Geophys. Res.*, **107**, doi:10.1029/2001JD001142.
- Williams, E. R., 1999: Global circuit response to temperature on distinct time scales: A status report. *Atmospheric and Ionospheric Phenomena Associated with Earthquakes*, M. Hayakawa, Ed., Terra Scientific, 939–949.
- , 2005: Lightning and climate: A review. *Atmos. Res.*, **76**, 272–287, doi:10.1016/j.atmosres.2004.11.014.
- , and N. Renno, 1993: An analysis of the conditional instability of the tropical atmosphere. *Mon. Wea. Rev.*, **121**, 21–36, doi:10.1175/1520-0493(1993)121<0021:AAOTCI>2.0.CO;2.
- , and G. Satori, 2004: Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys. *J. Atmos. Sol. Terr. Phys.*, **66**, 1213–1231, doi:10.1016/j.jastp.2004.05.015.
- , S. G. Geotis, N. Renno, S. A. Rutledge, E. Rasmussen, and T. Rickenbach, 1992: A radar and electrical study of tropical “hot towers.” *J. Atmos. Sci.*, **49**, 1386–1395, doi:10.1175/1520-0469(1992)049<1386:ARAESO>2.0.CO;2.
- , K. Rothkin, D. Stevenson, and D. J. Boccippio, 2000: Global lightning variations caused by changes in thunderstorm flash rate and by changes in the number of thunderstorms. *J. Appl. Meteor.*, **39**, 2223–2230, doi:10.1175/1520-0450(2001)040<2223:GLVCBC>2.0.CO;2.
- , and Coauthors, 2002: Contrasting convective regimes over the Amazon: Implications for cloud electrification. *J. Geophys. Res.*, **107**, 8082, doi:10.1029/2001JD000380.
- , V. Mushtak, D. Rosenfeld, S. J. Goodman, and D. J. Boccippio, 2005: Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. *Atmos. Res.*, **76**, 288–306, doi:10.1016/j.atmosres.2004.11.009.
- Yuan, T., L. A. Remer, K. E. Pickering, and H. Yu, 2011: Observational evidence of aerosol enhancement of lightning activity and convective invigoration. *Geophys. Res. Lett.*, **38**, L04701, doi:10.1029/2010GL046052.
- Zajac, B. A., and S. A. Rutledge, 2001: Cloud-to-ground lightning activity in the contiguous United States from 1995 to 1999. *Mon. Wea. Rev.*, **129**, 999–1019, doi:10.1175/1520-0493(2001)129<0999:CTGLAI>2.0.CO;2.