Analysis of Washington, DC, Wind and Temperature Extremes with Examination of Climate Change for Engineering Applications

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Abstract: Climate projections suggest the frequency and intensity of some environmental extremes will be affected in the future due to a changing climate. These projections raise questions regarding the treatment of future extreme environmental loading for the design of buildings and other structures. One of the more uncertain questions is possible changes in the properties of extreme wind. For this paper, extreme wind events for nearly 70 years from the Washington, DC, area are analyzed from the three major airports [(1) International Airport at Dulles; (2) Washington, District of Columbia, Reagan Airport; and (3) Baltimore/Washington International Airport]. Uncertainties in estimation of extreme wind speeds without considering climate change are identified. Analysis disregarding climate change revealed that thunderstorms control design wind speeds for Washington, DC. As thunderstorms are then important, climate projections with respect to thunderstorms are also introduced. Possible strategies for long-term decision making are outlined such as understanding observed wind speed magnitudes and their relationship to environmental conditions, developing probability-based prediction techniques, and modifying design codes and standards. Extreme heat events occurring in Washington, DC, are discussed in a similar manner. Research needs in linking climate science and engineering design in the long-term are outlaid. **DOI: 10.1061/AJRUA6.0000812.**

Introduction and Problem Statement

Global climate change is generally considered a result of increasing atmospheric concentrations of greenhouse gases, mainly due to human activity. Gillet et al. (2011) states that even if CO_2 (the major greenhouse gas) is no longer released into the environment, the effects of climate changes would continue. The latest report from the Intergovernmental Panel on Climate Change (IPCC 2013) states that nearly 75% of the total radiative forcing increase since the year 1750 is due to CO_2 emissions. Most climate change effects will persist for many centuries even if CO_2 emissions are stopped (IPCC 2013).

Climate change (i.e., global temperature increases) then in turn can modify the frequency (and intensity) of extreme weather and climate events (e.g., heat waves and sea-level rise). The changes in extreme events will likely affect the design of buildings and other structures. The estimation of these extremes has typically taken on some form of probabilistic hazard assessment (PHA) which includes some measure of uncertainty (Ellingwood 1994) for a relatively low-probability event (e.g., annual probability of 0.02 or a so-called 50-year event) as described by Ayyub and McCuen (2011). The PHA in the case of wind and rainfall/flood, for example, incorporate the use of surface-based observational data sets. These observational data are fraught with a number of uncertainties mostly stemming from the space and time resolution associated with the observational networks, and problems with standardization of the data, due to natural (e.g., terrain) or artificial complications (such as changing sampling rates or poor equipment maintenance; Lombardo 2012). These uncertainties can lead to false changes in frequency and intensity. These issues, when potentially coupled with climate change effects could significantly complicate the estimation of extreme environmental loading for infrastructure design.

As low-probability events for infrastructure design usually correspond to time scales similar to those in climate projections (e.g., 50 years), it may be possible to use information from these models. However, the small-scale nature of some extreme events (e.g., tornadoes) precludes the use of direct information from larger-scale climate models. Methods such as taking information from climate models and relating it to so-called ground-truth measurements (i.e., downscaling and upscaling) have been effective for some hazards (Fowler et al. 2007), but remain difficult hazardwide due to a lack of knowledge on specific physical processes that cause the extremes, various space and time scales, forcing scenarios, and parameter outputs. Uncertainty in climate models and measurements described previously makes determining the effect of climate change on infrastructure difficult.

Given this uncertainty, engineers and scientists in relevant fields have an obligation to consider and understand possible changes due to climate, the probabilities and uncertainties (National Academies 2012a) thereof, and how to bridge the gap between their respective disciplines (Wright et al. 2013). These groups also have obligation to work together to coherently communicate information to the stakeholders and the public in an iterative process [U.S. Global Change Research Plan (USGCRP) 2012] to arrive at adaptation strategies. More accurate understanding of both the physical and social processes combined with public engagement will help community-based disaster resilience (National 2012b). A number of

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studies and reports have started to look at adaptation [Union 2012; Federal Highway Administration (FHWA) 2011]; however, since adaptation typically works over longer time scales, its effectiveness in practice is largely unknown at this point (Climate Change Adaptation Task Force 2011).

This paper will take a case study approach by identifying observed extreme wind and heat events in the Washington, DC, area. Information on these observed events will be discussed with future climate change projections on wind speed and temperature. Approaches to analyze observed data with consideration of climate change and potential challenges for adoption into engineering practice will be discussed. The body of the paper will begin by covering background on wind and temperature extremes, and then is a discussion of the data and methodologies used. Analysis using the methodologies is discussed subsequently. The final portion of the paper talks about conclusions for this paper and future steps to be taken.

Background

Wind Speed

Extreme winds typically cause the majority of damage with respect to natural hazards in the United States [National Oceanic and Atmospheric Administration (NOAA) 2013a]. Extreme winds are usually classified by their phenomenological causes (e.g., tornadoes, thunderstorms, tropical systems, and extratropical systems) as the generation and nature of these wind events is different. For infrastructure design, wind speeds are associated with a nominal averaging time of 3 s (i.e., wind gust) and height of 10 m, and so-called open terrain. Outside of tropical cyclone (TC) prone regions wind speeds used for design are based on observations from weather stations (Lombardo et al. 2009). Wind speeds in areas prone to tropical systems are simulated for the United States due to the scarcity of observations (Vickery et al. 2010). The probability distributions from tropical systems are then combined with the probability distributions from the nonhurricane regions in a mixed distribution in areas prone to both storm types. Tornadoes are currently not considered in design of typical structures [ASCE 7-10 (ASCE 2010)] but are for special structures such as nuclear power plants [ANSI 2.3-2011 (ANSI 2011)].

Current Observations

Although extreme wind events occur in many parts of the globe and at times leave visual evidence of their intensity, measuring and understanding the so-called peak (i.e., 3-s gust) wind speeds have proven difficult. One difficulty is the lack of measured extreme wind speed data due to the small scales of some events (e.g., thunderstorms). Another difficulty is the relatively low resolution of reporting stations and the inconsistency in measurement characteristics, such as changing station location (IPCC 2012). Even if extreme wind events are collocated with reporting stations, high winds may damage the measuring equipment (Blanchard 2013) or standardization of data (e.g., surface roughness, averaging time, and measuring height) can introduce differences of up to 50% of the measured value (Lombardo 2012). Studies on observed mean wind speed trends suggested an increase in surface roughness was thought to be responsible for a general overall decline in mean wind speeds (Vautard et al. 2010; Pryor et al. 2009) across surface stations in the United States with the main contribution from extratropical cyclones. However, Vose et al. (2014) stated evidence is mounting that observations have shown increases in the mean frequency and intensity of extratropical storms along the United States east coast, which may suggest increases in wind speed.

Considering other storm types, observational proxies are frequently used to represent wind speed (as is also the case in future projections). For tropical cyclones, no long-term, century-scale trends have been detected in frequency; however, to some extent a modest upward trend has been suggested for stronger storms (Vecchi and Knudson 2008, 2011; Landsea et al. 2010). Since around the year 1980 some studies have discovered a trend in the North Atlantic Basin based on both the observational record and physical models (Knutson et al. 2007; Bender et al. 2010; Zhao et al. 2009). Also the power dissipation index (PDI), a measure of the power and duration of annual tropical cyclone activity, has increased (Emanuel 2005). Remote-sensing measurement techniques such as radar have improved understanding of tornadoes and thunderstorms (Lee and Wurman 2005); however, an extremely small percentage of these events actually are recorded and documented (Markowski and Dotzek 2010). Since the majority of extreme wind events are not physically measured, scientists have typically turned to using structural damage as a proxy for wind speed. However, uncertainties in the rating process stemming from complex physical dynamics and/or variations in structural resistance (Edwards et al. 2013) persist. Efficacy of human reports is also an issue (Doswell et al. 2005) making the detection of observational trends extremely difficult.

Future Projections

Due to their small-scale nature climate models have difficulty reproducing the magnitudes of extreme winds (IPCC 2012). For example, future projections of wind speeds from extratropical cyclones are varied and difficult to quantify (Vose et al. 2014). For areas near the United States east coast, Catto et al. (2011) found very similar parent distributions of wind speeds with slight decreases in the higher wind speeds above the surface. Bengtsson et al. (2009) found approximately a 1 m/s increase for the 99.5th percentile wind speeds above the surface near the United States east coast and for the Atlantic in general a reduction in storms producing wind speeds of >35 m/s. Mizuta et al. (2011) found no significant changes for the United States east coast. However, since these studies mainly include wind speeds above the surface (at a given pressure level), additional uncertainties would be added when translating values down to 10 m, for example.

Future projections of tropical cyclones have been well-studied recently, partly due to significant United States landfalls in the last 10 years. Still there is a low confidence and large uncertainty in future projections based on an incomplete understanding of natural variability (IPCC 2012). The range of frequency changes based on model projections for the Atlantic basin is detailed in tabular form in Knutson et al. (2010). For the Atlantic basin, it has been suggested that there will be a 28% decrease in frequency for all TCs and an 80% increase in Category 4 and 5 storms in a future climate (Knutson et al. 2007; IPCC 2012). Again, these projections refer to cyclone frequency and intensity, and not necessarily wind speed frequency and intensity, a challenge for use of these projections in engineering practice.

Until recently, large-scale processes (i.e., instability and wind shear) known to be partly responsible for thunderstorm wind generation were expected to increase and decrease, respectively, in the future climate (Trapp et al. 2007), possibly canceling the effects out. Recent research (Diffenbaugh et al. 2013) has suggested that even though wind shear will decrease on average, the joint probability of instability and wind shear combinations favorable for thunderstorms will increase for the eastern United States. Based on observations, Brooks (2013) suggests lower wind shear in a future

Table 1. Confidence Level for Global Projections of Extreme Winds

Storm type	Frequency	Intensity	Location
Tropical	Medium, decrease or no change; likely, increase; Categories 4 and 5	Likely, increase	Low
Thunderstorm	Low	Low	Low
Extratropical	Medium, decrease	Low	Low, specific medium, poleward
Tornado	Low	Low	Low

Note: Confidence level is based on two factors, as follows: (1) scientific agreement, and (2) available evidence; more details, including quantitative likelihood, can be found IPCC (2012), p. 21.

climate is more favorable for extreme wind events as opposed to tornadoes and hail. However, exact processes responsible for extreme near-surface winds are largely unknown (Brooks 2013), making future projections extremely difficult.

Tornadoes are thought to be generated by storm-scale processes not represented in climate models, so confidence is low in future projections. As in thunderstorms, however, large-scale conditions known to be favorable for tornadogenesis are expected to increase (Diffenbaugh et al. 2013).

As may be expected, the consensus climate change body, the IPCC, which synthesizes the scientific literature, has relatively low confidence in its future projections of extreme wind generating event (IPCC 2012). Table 1 lists the confidence levels for each storm type.

Washington, DC, Impacts

The Washington, DC, metropolitan area has experienced a number of recent wind events that have caused significant problems. These events include recent tropical systems Irene and Sandy in the years 2011 and 2012, respectively and the June 2012 derecho (thunderstorm complex). Hurricane Sandy, for example, caused approximately 0.5 million power outages in the Washington, DC, area and nearly 2.2 million on the United States east coast. The 2012 derecho caused millions of power outages in the Washington, DC, area, some of which lasted up to 9 days (USDOE 2012), and caused seven direct fatalities. Many other fatalities were caused by the heat wave which persisted after the event. The derecho caused nearly U.S. $3 billion in damage nationwide (NOAA 2014a). Nor'easters (extratropical systems) typically occur several times annually and also produce strong winds (and power outages). Tornadoes are relatively infrequent but there have been significant events in the area such as the College Park, Maryland, F-3 tornado in year 2001 which caused U.S. $100 million in losses, two fatalities, and 55 injuries [National Weather Service (NWS) 2001] and the F-4 LaPlata, Maryland, tornado in year 2002 which caused three fatalities, 122 injuries, and over U.S. $100 million in damages (NWS 2002).

Temperature

Extreme heat has significant effects on the population, especially the health and energy sectors. An extreme heat event in Russia was responsible for the deaths of 55,000 people in year 2010 (Guha-Sapir et al. 2011) and in year 2003 a European heat wave was responsible for 40,000 lives lost (Greene et al. 2011). Extreme heat events are the largest cause of weather-related deaths in the United States (Greene et al. 2011). As population grows and subsequently so does energy demand, increased temperatures will only exacerbate the population need for energy (Miller et al. 2008) and increase exposure to these events. For structural design, temperatures and temperature extremes are important for design of transmission lines, pavement (e.g., freeze/thaw, buckling), rail, HVAC and roofing systems, and energy usage (Olsen et al., unpublished report), among others.

Current Observations and Future Projections

Observations over the last 100 years or so have shown that the entire globe has experienced mean surface warming (IPCC 2013). Based on the IPCC consensus, observed temperature increases since the year 1950 time period are "likely" (IPCC 2013) on the North American continent. Similarly, projections for future changes for temperature are much more confident than wind speed due to its more direct relationship with greenhouse gas emission. Based on the consensus of climate scientists, it is "virtually certain" (IPCC 2013) that increases in frequency and magnitude of maximum daily temperature extremes, and decreases in cold extremes on a global scale, including the North American continent will occur by the end of the 21st century. IPCC (2013) states that for extremes under a "worst-case scenario" (IPCC 2013), it is "likely" (IPCC 2013) that a current 20-year high temperature event will become 2–20× more likely and a 20-year low temperature event will become exceedingly rare. IPCC (2013) generally supports the conclusions of IPCC extremes report (IPCC 2012) in both observations and projections of extreme temperature.

Washington, DC, Impacts

As cities become more urbanized, the well-known effect of contained heat in urban areas, driven partially by infrastructure [i.e., urban heat island (UHI); Gosling et al. 2009] contributes to further temperature forcings in the climate system (McCarthy et al. 2010), and increases the likelihood of additional energy usage and fatalities (McGeehin and Mirabelli 2001). Washington, DC, has been noted to have one of the strongest UHIs in the United States (http://www.nasa.gov/topics/earth/features/heat-island-sprawl.html). From the years 1975–1995, Washington, DC, experienced 16 excessive heat events (EHEs) per year, according to Greene et al. (2011), which contributes an average of five fatalities per 100,000 residents. Greene et al. (2011) also suggests that EHEs could increase fourfold by the year 2100, given certain climate projections. Locally, year 2012 was the warmest year on record as reported at Washington, DC, Reagan National (DCA) and the International Airport at Dulles (IAD), and the third warmest on record at Baltimore/Washington International (BWI; NOAA 2013b). The combination of a projected temperature increases due to climate change and feedback effects from the UHI should contribute to significant changes in all affected sectors (e.g., health and energy).

Data and Methods

Wind Speed

Observed wind speed data for the Washington, DC, area was obtained from three different sources. These sources can all be found on the Internet at http://www.nist.gov/wind and have all been used (or proposed for use) in wind load design. Wind data used for the research reported in this paper were recorded at DCA, IAD, and BWI. For the purposes of this paper, annual maximum wind speeds are used. The length of available annual maximum wind speeds extend back into the 1940s for DCA and BWI, and the 1960s at IAD. All data have been converted to nominally a 3-s gust wind speed at 10 m (33 ft) height (i.e., standardized) as the measurement instrumentation changed over the course of the records at all three

airports. Terrain conditions are assumed to be open. If two or more sources had an annual maximum wind speed for the same year, the maximum value was used.

The simulated hurricane wind speed distribution was provided by ARA (2013) and is based on work in Vickery et al. (2010). Tornado data is available from http://www.spc.noaa.gov, and consists of tornado touchdown and end location, path length and width, and rating, among other variables, but was not analyzed in this paper. Recent work using this database has shown that within an 130 km (80 mi) radius of Washington, DC, there is on average approximately one EF-2 or greater (i.e., produces significant damage) tornado per year, although the probability of striking an individual building for example is much lower (Kuligowski et al. 2014).

Observed wind speeds are analyzed using well-known extreme value analysis techniques (i.e., Type I distribution; e.g., Ayyub and McCuen 2011). Analysis includes fitting a Type I distribution to wind speeds from all three stations individually without considering a phenomenological (thunderstorm, extratropical, or tropical) cause and to a data set that combines wind speeds from all three airports, separating wind speeds by their phenomenological causes.

As projected extreme wind speed changes in the context of climate are of low confidence, upscaling techniques are illustrated to provide some guidance of how to interpret possible changes to extreme wind events in the future. Large-scale parameters come in the form of archived so-called reanalysis data of large-scale environmental parameters, which are extracted from the North American Regional Reanalysis (NARR) database (NOAA 2013a). These gridded data are available on 32 × 32 km resolution and at 3-h intervals.

In addition to the NARR data, the location, date/time, and magnitude of measured convective wind gusts 33.5 m/s (75 mi/h) across the United States were extracted from a National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center (SPC) database from the time period 2006–2012.

Temperature

For the purposes of this paper, recorded and archived temperatures from DCA are used for analysis. The reason for choosing DCA is that it has been shown to have a strong UHI effect and influences from the warm Potomac River. Temperature records for DCA began in the year 1945. Prior to that temperature records were kept in the Georgetown area. To use data from a single location and to be consistent with the information in IPCC (2012), data from years 1950–2012 will be used for this paper and will be assumed more representative of the Washington, DC, area immediately adjacent to DCA, and not the surrounding suburban areas that are less affected by the external factors mentioned previously.

A basic analysis of temperature thresholds, which is an important metric to consider for effects on the health and energy sectors, will be performed from the DCA temperature data.

Analysis

Extreme Wind

Fig. 1 shows the time histories of annual maximum, 3-s gust wind speeds for the three Washington, DC, airports individually. These wind speeds are not separated by storm type. The maximum wind speed was approximately 38.0 m/s (85 mi/h) at both DCA and IAD airports from a thunderstorm on July 5, 1980. All three time histories in Fig. 1 exhibit a slight downward trend over time. Using a least-squares fit the wind speeds trends are −0.02, − 0.06, and −0.12 m/s/year (−0.04, −0.13, and −0.27 mi/h/year) from DCA, IAD, and BWI, respectively. Observed downward mean wind speed trends have been noted in other studies (Vautard et al. 2010), partly related to an increase of surface roughness due to land use changes. Changes in extreme wind gusts as shown in Fig. 2 are more difficult to understand due to (among other factors) the different phenomenological causes of wind speeds. Although the changes in measurement instrumentation were accounted for, apparent changes in frequency and intensity can still persist, due to the small spatiotemporal scales associated with wind gusts and how they are standardized. An example of these apparent changes is shown for IAD in Table 2. This time period for IAD (years 1963–2012) included three instrumentation changes and four related changes in how the wind speeds were recorded. The measurement parameters (averaging time and anemometer height) and wind speed statistics for these time periods are shown in Table 2. Table 2 shows sharp contrasts in the variability of the data

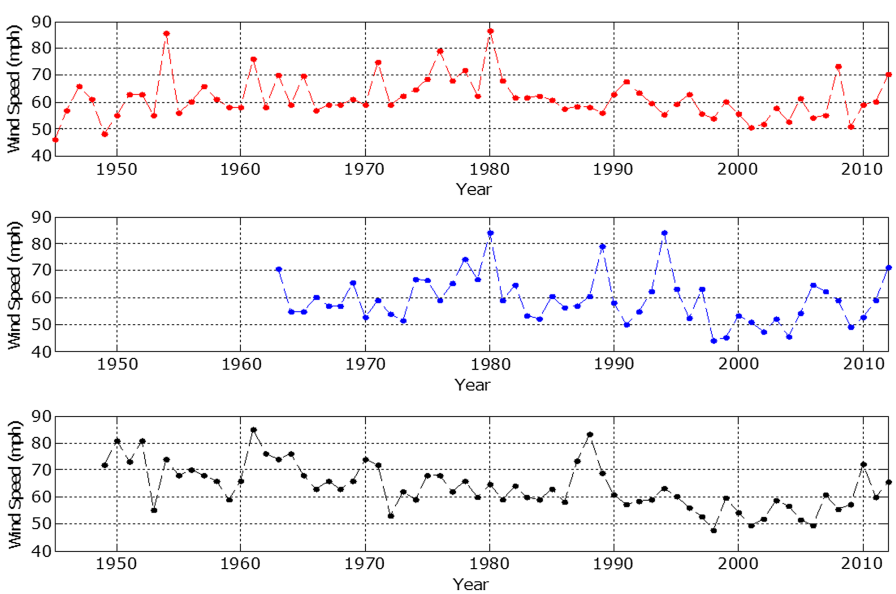

Fig. 1. Time histories of annual maximum wind speeds (3-s gust) at Washington, DC, area airports

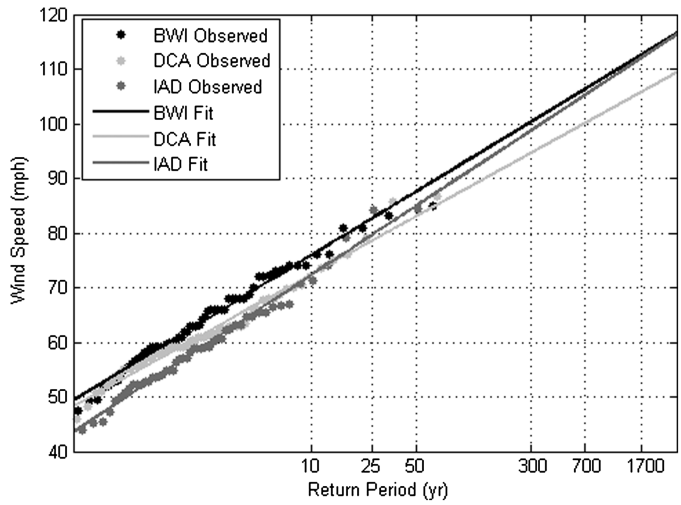

Fig. 2. Type I fit to annual maximum wind speeds from the three Washington, DC, area airports

between certain time periods. This variability is somewhat expected due to the small sample size; however, the largest sample had the highest variability. The likely reason is that conversion from fastest-mile to 3-s gust (years 1963–1972 in Table 2) involves the use of a single factor without any consideration for terrain or storm type influences. This single factor washes out a lot of the natural variability observed in recorded short-term wind gusts (3 s or less). This observation is consistent with other historical annual maximum wind gust data (Lombardo 2012, cf. Fig. 2). This observation suggests that (1) standardization of wind data should be done with caution and cognizant of the possible uncertainties, and (2) any trends or statistical differences in observed wind data (especially gust wind data) are difficult to attribute to any one source (including climate change effects). Differences in wind speed characteristics based on storm type will be discussed in a subsequent paragraph.

Although the data seem to have nonstationary properties, traditional stationary Type I analysis (Ayyub and McCuen 2011) was used on the data. Nonstationary models can be used to estimate wind speeds or other environmental time histories (Ayyub 2003). The results of the Type I analysis are shown in Fig. 2. The results in Fig. 2 suggest that the extreme wind climates at all three airports are similar especially at return periods >10 years. For example the estimated so-called 50-year wind speed (annual probability of 0.02) is around 38.0 m/s (85 mi/h) for all three airports. For return periods of 10–1,700 years from serviceability to ultimate limit state in current wind load design in the United States [ASCE 7-10 (ASCE 2010)], wind speeds range from 33.5–51.4 m/s (75–115 mi/h). This similarity in the extreme wind speed estimation is expected given the short distances between the locations.

Table 2. Measurement Parameters and Annual Maximum Wind Speed Statistics for IAD, Years 1963–2012

Time period	h (m)	t (s)	$\bar{X}$	s	N
1963–1998	6	Varies	61.0	9.0	36
1963–1972	6	Fastest-mile, ~30–60 s	58.6	5.6	10
1973–1997	6	~1–3	61.9	10.0	26
1998–2006	10	5	53.4	6.7	9
2007–2012	10	3	58.0	9.6	6

This similarity between stations also allows for a grouping of wind speeds from all three airports in a Washington, DC, area so-called superstation (Peterka and Shahid 1998). The superstation approach can allow for generalizations of the entire Washington, DC, area wind climate. Since some wind speeds in the each of three airport databases belong to the same event, only the maximum wind speed from the same event were used (Lombardo et al. 2009). In addition to the superstation, annual maximum wind speeds were separated by their phenomenological cause (storm type) if known as storm types are known to possess different probability distributions (Lombardo et al. 2009). Wind speed data where the cause was not known were removed. For the Washington, DC, area, 56% of annual maximum wind speeds were caused by extratropical cyclones (ETCs), 42% were due to thunderstorms (T), and 2% were due to tropical wind speeds (H). Type I distributions were then fit to each storm type. The combination of each of these distributions was then assessed in a so-called mixed distribution [M; Eq. (1)], a more conservative estimation of an extreme wind climate. Simulated tropical wind speed data was provided by ARA (2013)

$$P(v \leq V) = P(v_T \leq V)P(v_{\mathrm{ETC}} \leq V)P(v_H \leq V) \tag{1}$$

Fig. 3 shows the individual probability distributions of each storm type in the Washington, DC, area. Uncertainty was estimated for T and ETC by bootstrapping the observed data 1,000 times with replacement and estimating Type I parameters for those 1,000 datasets. The fifth, 50th, and 95th percentiles for the T and ETC Type I parameters were used to estimate the fifth, 50th, and 95th percentiles of the M distribution. For clarity, the all three percentile values are only shown for the T. As expected the uncertainty becomes larger as the probability of occurrence becomes lower. Considering the expected distributions, Fig. 3 shows that the mixed distribution is a conservative distribution especially for return periods <50 years. At long return periods (>50 years) the M converges to the T distribution which dominates the extreme wind climate, especially those return periods for ultimate limit state design (e.g., 700/1,700 years). The tropical wind climate, although it does produce strong winds from time to time, does not appear to contribute wind speeds relevant for structural design. No uncertainty

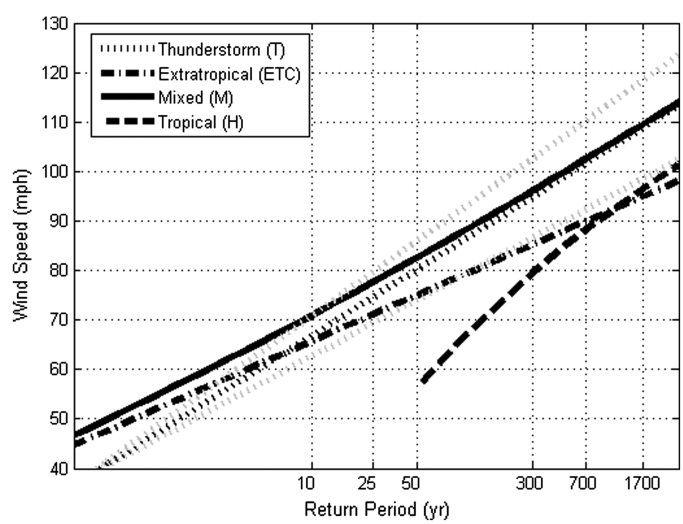

Fig. 3. Probability distributions of thunderstorm, extratropical cyclone, tropical cyclone, and a mixed distribution [as per Eq. (1)] for the Washington, DC, area; gray lines show the fifth and 95th percentiles of the thunderstorm distribution (H distribution provided by ARA 2013)

information was available for the tropical data. The year 2012 derecho (i.e., thunderstorm), which produced gust wind speeds of around 31.3 m/s (70 mi/h) in the Washington, DC, area, is estimated to be a 1-in-10 year event considering any storm type (i.e., 10% annual probability of occurrence). Considering just T and its uncertainty, the annual probability for a 31.3 m/s (70 mi/h) wind gust ranges from 0.10 to 0.25. Over a 10-year span, the probability of T event producing a wind speed exceeding 31.3 m/s (70 mi/h) with uncertainty ranges from approximately 34–65%. Although wind speeds from the year 2012 derecho were associated with a 1-in-10 year event, on average, in the current climate, its effects (e.g., power outage number and duration) could occur at a different frequency and is an important area for future study when considering resiliency to hazards.

As thunderstorms have produced the highest extremes in the Washington, DC, area it is important to attempt to understand if events like the year 2012 derecho will increase in frequency and intensity. As stated previously, there is low confidence in future projections of thunderstorm events due to their small scales and poorly understood mechanisms for generating extreme wind (Peterson et al. 2013). However given future climate scenarios, researchers have suggested that two large-scale parameters related to wind speed potential may change. These parameters are (1) convective available potential energy (CAPE), and (2) wind shear (Trapp et al. 2009). The CAPE is a measure of atmospheric instability while wind shear is loosely defined as the wind vector difference between two heights. Stated in (Trapp et al. 2009) and subsequently (IPCC 2012) is that CAPE should increase due to temperature increases, and wind shear will decrease due to a reduction in temperature gradients over the midlatitudes. However, the joint probability of CAPE and wind shear in parameter space favorable for extreme wind events is expected to increase (Diffenbaugh et al. 2013).

Using the NARR database, CAPE (surface-based) and wind shear [surface to 500 hPa (500 mb)] values were extracted, for the closest time and location (grid point), corresponding to observed thunderstorm generated winds 33.5 m/s (75 mi/h) recorded at the Washington, DC, area airports. This extraction only yielded 25 events. Due to the small sample size, the SPC database was used for all events east of the Rockies (67.5–105° W) from years 2006 to 2012. Setting a condition that CAPE > 0 in the NARR data yielded 833 total events for analysis. Each of the 833 events was assumed independent for the purposes of this paper. Although it is known that conditions in the Plains, for example, are different on average from those in Washington, DC, area (Evans 2010), this method allows for more data and better comparison to climate change projections of large-scale conditions, specifically those of Diffenbaugh et al. (2013, cf. Fig. 4). Fig. 4 shows the location of these 833 events. As expected, the majority of these 833 events occur in the Plains, as observed in many publications (e.g., Smith et al. 2013).

Figs. 5 and 6 show the joint probability density function (PDF) and cumulative distribution function (CDF), of CAPE and shear. The PDF of CAPE and shear in Fig. 5 show that the highest proportion of these jointly occurring values fall around CAPE of 1,400 J/kg and 15 m/s wind shear, which are close to the average values of both variables for the 833 events. This combination is favorable for severe thunderstorms (Rasmussen and Blanchard 1998). There appears to be a favored shear axis between 10 and 20 m/s regardless of CAPE values. There also appears to be a high proportion of lower CAPE (<500 J/kg) and relatively high shear values (>15 m/s). These environments have been shown to be responsible for a majority of the violent tornado subset (EF-4+, Sherburn and Parker 2014), and is more representative of the values more commonly seen in the Washington, DC, area (Evans 2010) and in the so-called cool (i.e., fall) season. The probabilities shown here are conditional on an extreme wind event actually occurring and only reflect two large-scale parameters. Other parameters may

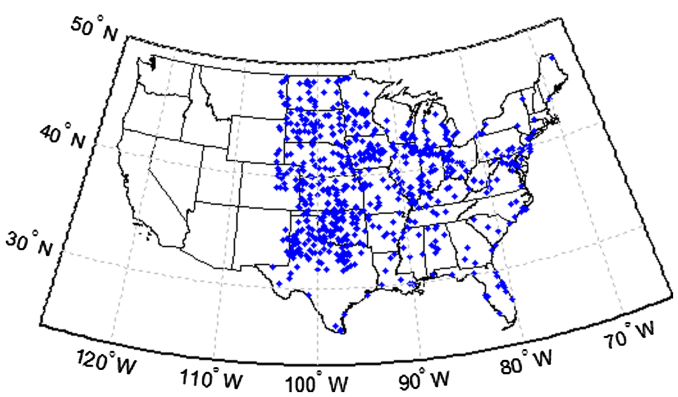

Fig. 4. Location of the 833 events that produced extreme convective wind speeds > 33.5 m/s (75 mi/h)

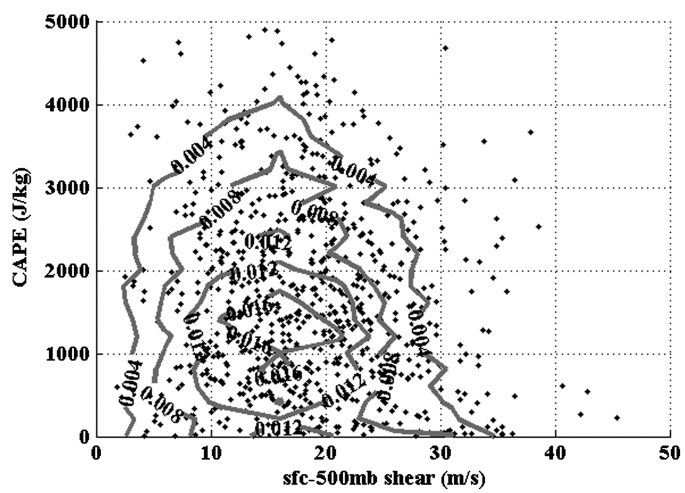

Fig. 5. Joint PDF of CAPE and shear for 833 events producing measured wind gusts of > 33.5 m/s (75 mi/h)

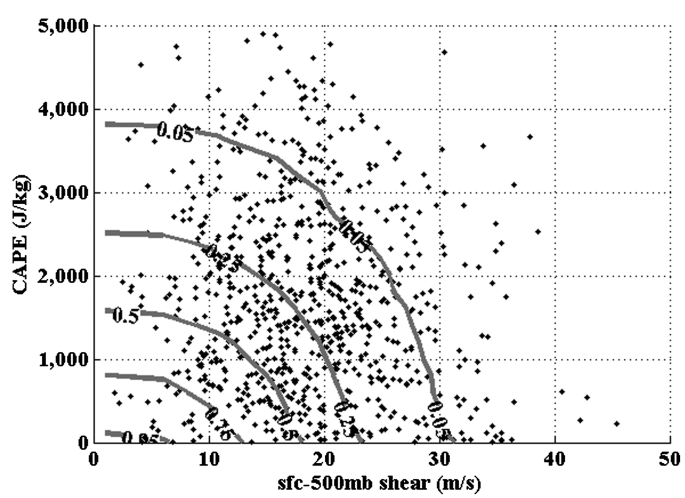

Fig. 6. Joint CDF of CAPE and shear for 833 events producing measured wind gusts of > 33.5 m/s (75 mi/h)

be more favorable when considering near-surface extreme wind production; however, using CAPE and shear can serve as an example of how to compare large-scale parameters with near-surface wind speed measurements. The CDF of CAPE and shear in Fig. 6 show the fifth, 25th, 50th, 75th, and 95th percentiles of the jointly occurring values. For example, about half the time when a convective wind 33.5 m/s (75 mi/h) is measured, CAPE ≥ 1,500 J/kg and shear ≥ 10 m/s, and about 5% of the time when CAPE ≥ 3,000 J/kg and shear ≥ 20 m/s. The latter combination of CAPE and shear is rare in the environment to begin with, so it is possible that this distribution is similar to the overall joint distribution of CAPE and shear. As observed in the PDF, the CDF may be hinting at a preference for lower shear values as a condition for near-surface extreme winds. Lower shear values were found to have higher incidence of extreme wind reports in Brooks (2013). Again, these values are conditional on extreme winds being measured and it is almost a certainty that extreme winds for some events do not have an accurate measurement. Regardless, an area of that could lend some insight into future changes in extreme winds due to climate change, or aid with forecasting is conditional, probabilistic measures of extreme wind events (e.g., 10% chance of observed extreme winds given CAPE > 1,500 J/kg). To that end, results from Figs. 3 and 5 are used in conjunction with those of Brooks (2013) and Diffenbaugh et al. (2013) to construct a simple Bayesian example [Eq. (2)] of a method that can be used to evaluate possible changes in thunderstorm-generated winds due to climate change

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{2}$$

where $P(A)$ = probability of extreme winds 33.5 m/s (75 mi/h); and $P(B)$ = joint probability of CAPE and shear at specific values. From Fig. 6, the probability of CAPE 2,500–3,000 J/kg (given CAPE > 0 J/kg) and shear 15–20 m/s given an observed extreme wind 33.5 m/s (75 mi/h) is approximately 0.08. Based Fig. 3, the probability for Washington, DC, encountering a thunderstorm-generated wind speed 33.5 m/s (75 mi/h) regardless of conditions is approximately 0.04 (1-in-25 year event), which given the rate of 13.6 events/year calculated from the observed data, the probability per event is 0.003. Given some probability of CAPE and shear values jointly being within those values (given CAPE > 0) it is possible to estimate the probability of extreme winds 33.5 m/s (75 mi/h) given certain values of CAPE and shear. From Diffenbaugh et al. (2013) this combination of values [i.e., $P(B)$] is expected to increase in frequency by a fraction of approximately 0.03. If no increase in $P(A)$ is assumed, the probability of extreme winds given those CAPE and shear conditions, $P(A|B)$ will increase by a commensurate factor and ultimately the frequency of extreme near-surface winds. No uncertainty information was readily available from the Diffenbaugh et al. (2013) data; however, due to the inherent uncertainty in climate change projections it is unlikely that the projections will exceed the uncertainty of the observed data, especially for low probability events. For example, the uncertainty in the 700-year event wind speed (currently used for wind load design) based on the observed data for Washington, DC, was estimated to be 40.2–49.2 m/s (90–110 mi/h). A 3% increase in frequency of a 700-year event (annual probability of 0.0014) produces a small change in the return period and is well within the uncertainty of the observed data.

Although thunderstorms were looked at in this example, climate change effects on tropical cyclone frequency and intensity (Mudd et al. 2014) may need to be considered in the Washington, DC, area for not only wind speed but storm surge effects as well.

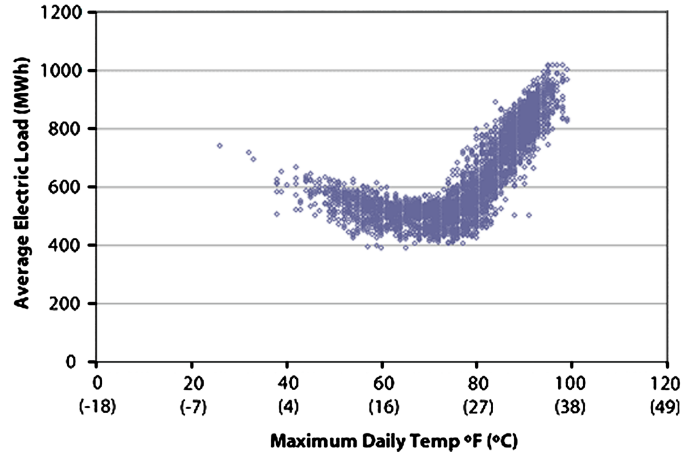

Fig. 7. Average electric load versus temperature (reprinted from EPA 2013)

Extreme Temperature

Based on information presented earlier in this paper, it is safe to assume that the frequency and intensity of extreme temperature events will likely increase in the future. Typically these events cause the most problems (Hajat et al. 2006) when extended over a significant period of time, usually termed a heat wave. Heat waves cause a number of public health (Wu et al. 2014) and energy issues. In general, due to higher temperatures, it is expected that per capita energy usage is expected to increase by 5–15% (Sailor 2001). It has also been shown that a certain temperature threshold (Fig. 7) is related to a large increase in energy usage. As in energy usage, mortality rates with respect to temperature have also shown to be related to some sort of temperature threshold (Ho 2010; Curriero et al. 2002), depending on the climatological conditions of a specific area. Therefore, as extreme temperature/heat wave events increase, the amount of energy usage and the number of heat-related deaths is also likely to increase.

Heat Waves

For the purposes of this paper, a simple heat wave definition is used similar to that of Anderson and Bell (2011). A heat wave is defined as the occurrence of 2 or more consecutive days where the mean daily temperature (T_{mean}) exceeds the 95th percentile threshold of the daily T_{mean} from the so-called normal period of the years 1961–1990.

Fig. 8 shows the number of heat waves per year and the average duration of those heat waves considering warm months only (May 1 through September 30). Over the 63-year period (years 1950–2012), Washington, DC, averaged 1.84 heat waves per year. Looking at Fig. 8, a shift in the number of heat waves seems evident around the year 1980. For example, from years 1950–1980 the average number of heat waves per year was 1.13. From years 1981–2012 that average jumped to 2.53. In addition, there were 13 years with no heat waves in the years 1950–1980 period, and only 4 from years 1981–2012. The maximum number of heat waves in a year, seven, was reached in the later period (years 1991 and 2010). Fig. 8 also illustrates a possible increase in the duration of Washington, DC, heat waves. Over the entire period the average heat wave duration (not including years with zero heat waves) was 2.8 days. The years 1950–1980 period average was 2.4 days, while the years 1981–2012 was 3.0 days, an increase of 25%. The years 1981–2012 period has also experienced 7 years where the average duration of heat waves was 4.0 days or more. The earlier period

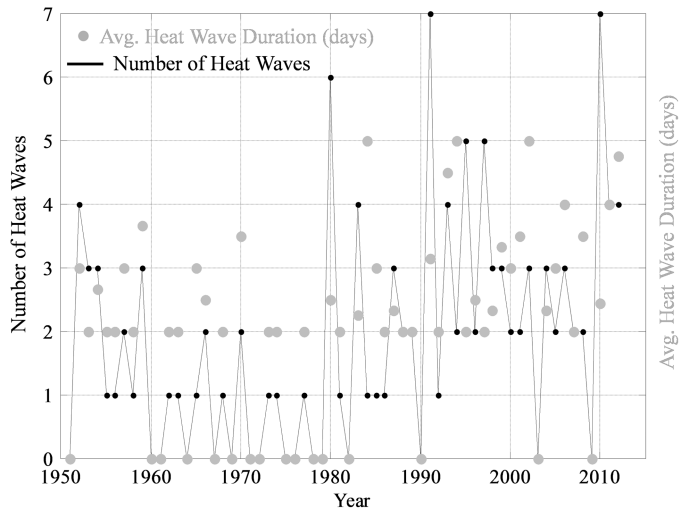

Fig. 8. Number of heat waves (black) and average duration in days (gray) for Washington, DC, (specifically, DCA) from years 1950–2012

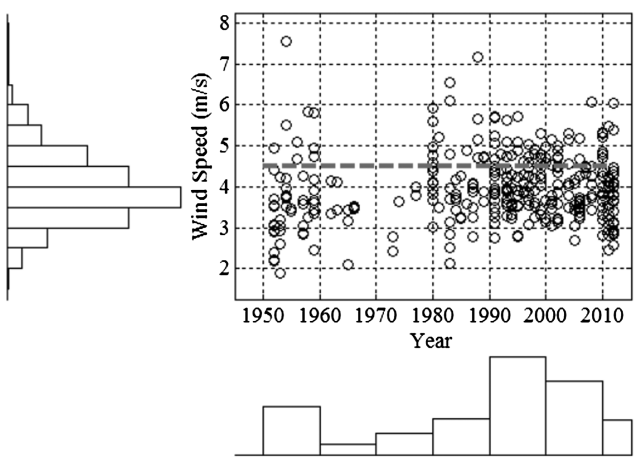

Fig. 9. Mean daily wind speeds (m/s) for heat waves in Washington, DC (DCA) from 1950–2012

had no such years. Whether the increase is an effect of climate change, UHI, or both, an increase in the frequency and duration of heat waves will pose a significant problem for the public. No significant correlation was found between number and duration of heat waves.

Another factor associated with a strong UHI is wind speed. The lower the mean wind speeds, the stronger the UHI effect (Oke 1976) and subsequently more prolonged heat waves could result. Fig. 9 shows daily mean wind speeds for heat wave days at DCA. A decrease in mean wind speeds due to built-up terrain (Vautard et al. 2010) could contribute to additional UHI days for Washington, DC. Mean wind speeds less than 4–5 m/s (9–11 mi/h) are conducive for heat wave/UHI effects while UHI effects drastically reduce for mean wind speeds greater than this value (Oke 1976). In Fig. 9, the majority (76%) of heat wave days had mean wind speeds less than 4.5 m/s (10 mi/h).

Recent research (Li et al. 2013) has also suggested a synergistic effect between heat waves and UHI effects in that UHI effects are amplified in the midst of a heat wave. An increase in heat wave days occurring jointly with low wind speeds could exacerbate UHI effects. Recent mitigation strategies (http://sustainable.dc.gov) and modeling studies (Loughner et al. 2012; Zhang et al. 2011) have shown how UHI effects can be mitigated in the Washington, DC, area.

Public Health/Mortality

Typically June is the first month included in statistical models relating temperature and morbidity (Greene et al. 2011). However, due to possible warming, average temperatures in May could begin to approach temperatures associated with June. An early warm spell could be problematic because the public would not have fully acclimated to the warm temperatures, leaving vulnerable populations at increased risk (Greene et al. 2011). Recent studies (Bobb et al. 2014) suggest the population is adapting to extreme heat, although the public is still at risk. Although the definition of heat waves above was more general, some researchers have suggested specific temperatures in which mortality rate due to extreme temperatures may reach a so-called tipping point. For example, Curriero et al. (2002) suggested that an average daily temperature of approximately 21.4°C (70.6°F) yields the minimum mortality rate for the Washington, DC, area.

Fig. 10 shows the number of days per year in which the average daily temperature exceeded the 21.4°C (70.6°F) mark as well as the number of those days that occurred in the month of May for DCA.

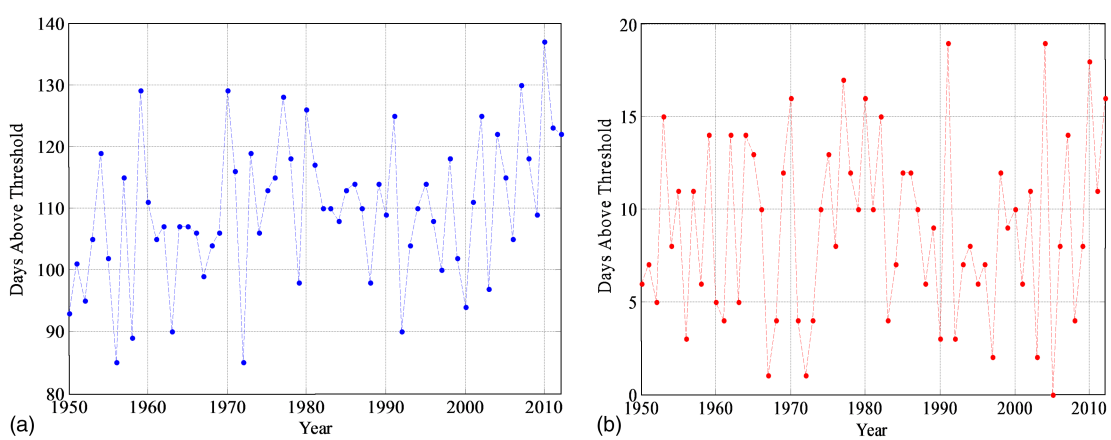

Fig. 10. Days with average temperature above 21.4°C (70.6°F) from 1950 to 2012 at DCA: (a) annually; and (b) in May

Fig. 9 (left) shows that there has been a marked increase in the number of days annually exceeding 21.4°C (70.6°F) since around the year 2000 and an upward trend for the entire time history. Influence on temperature trends due to climate indices known to be correlated with temperatures in the eastern United States such as the North Atlantic Oscillation (NAO) was not explored. The maximum number of days over the 21.4°C (70.6°F) threshold occurred in year 2010, in which 137 days had a daily average temperature above 70.6°F. The number of days in May (Fig. 9, right) which exceed the 70.6°F degree threshold displays little trend but considerable variability. However, 3 of the 6 highest years for number of May days which exceeded the temperature threshold have occurred since the year 2004. Information such as that illustrated in Fig. 10 and described previously can help inform decision makers when faced with challenges associated with extreme temperature and heat events.

Conclusions/Future Work

In this paper, extreme wind and heat events were analyzed and discussed for the Washington, DC, area. Observed data was analyzed and future projections due to a changing climate were discussed.

For the Washington, DC, area, extreme wind events a slight overall decrease in annual maximum wind speeds over the last 50–70 years was observed. The cause of this decrease may be partly due to nonclimate factors such as measurement changes and standardization practices. Assessing future projections for extreme wind events are difficult due to these nonclimate factors and the relatively small scales on which these events occur which precludes the use of climate models. The Washington, DC, area has a so-called mixed wind climate meaning that it receives its extreme wind speeds from a number of sources including thunderstorms, extratropical cyclones, and tropical systems. Of these sources it was determined that thunderstorms produced the highest recorded wind speeds for the area and control wind speeds associated with design of structures. As thunderstorms dominate the extreme wind climate, small-scale observed wind speeds were upscaled to compare with large-scale parameters partially responsible for thunderstorm development and thought to be susceptible to climate change. Using information on the joint distributions of large-scale parameters in current and future climate (and marginal distributions of observed wind speeds) allowed for a methodology in which the frequency (and intensity) of future extreme wind speeds could be assessed. Due to the uncertainty in the projections and in the observations, it is unlikely any discernible changes in a so-called design wind speed would be changed based on the available information. Detailed future work in this area is planned.

In the Washington, DC, area, extreme heat events are expected to increase based on climate model projections. These increases can have significant effects on energy consumption and human health. In built-up areas such as Washington, DC the urban heat island effect is also expected to be magnified. Washington, DC, has been noted to have one of the strongest UHIs in the United States. Preliminary analysis of Washington, DC, area temperatures show a marked increase in so-called heat-wave days, and heat wave duration, since the year 1980, and in days which temperatures are above a mortality threshold annually. For the month of May, a possible critical month due to temperature changes, a great deal of variability is shown in days over this temperature threshold; however, some of the highest number of days over this threshold has occurred in the last 10 years. Both the local and federal governments in Washington, DC, have been proactive in mitigation and adaptation strategies dealing with urban heat effects, and modeling studies exist that document the possible UHI effects (and mitigation thereof). Future work will couple statistical information on extreme heat events with possible mitigation/adaptation strategies at the local level.

As codes and standards usually deal with time scales similar to those of climate projections, the projections can be considered in their development. However, as has been shown throughout this paper, uncertainties from nonclimate, climate, and human factors are large, and in some cases difficult to quantify. Engineers, when considering design of infrastructure for the future, should embrace uncertainties an attempt to identify, attribute, and quantify causes of uncertainty as well as participate in an iterative process with all interested parties (i.e., bridging the gap) for future adaptation. To be conservative for engineering practice in the face of climate change but without highly confident information, engineers could simply utilize uncertainty to their advantage. Instead of using the expected value, some higher and lower percentile could be used depending on the application. In addition, the development of flexible, nonstationary statistical models, continuation of upscaling and downscaling research, and the identification of thresholds and/or tipping points when considering environmental extremes in the context of climate, will help to link climate science and engineering design.

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