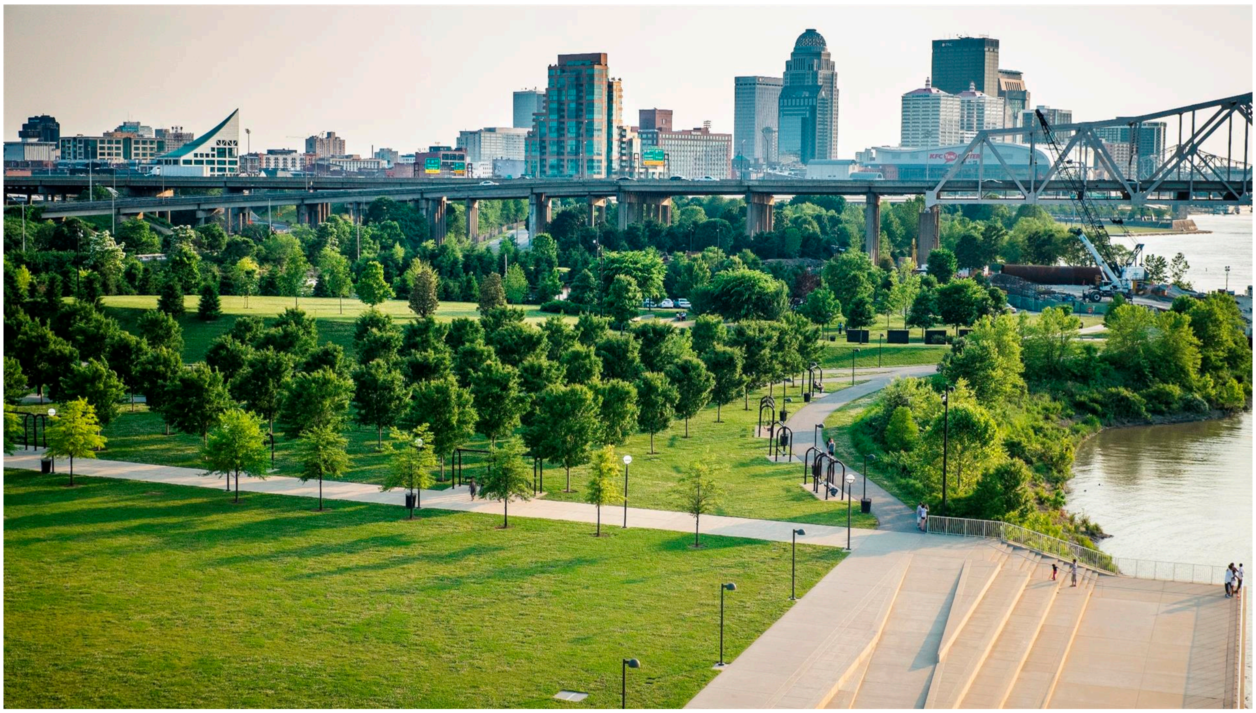
Louisville Metro Climate Hazard Identification

A Climate Change Addendum to the 2016 Louisville Hazard Mitigation Plan

June 30, 2019



Developed by the Geos Institute for Louisville Metro Government Office of Sustainability and Office of Advanced Planning

Executive Summary

The 2016 Louisville Metro Hazard Mitigation Plan[1] (HMP) is a thorough assessment of hazards threatening the jurisdictional area of Louisville Metro (covering the combined areas of Louisville and Jefferson County). For this addendum, ***climate hazards*** were identified by researching how climate change is expected to affect (exacerbate or lessen) existing hazards to the people, resources, and infrastructure of the Metro area. Additional hazards likely to affect the region due to worsening climate change were identified.

Out of 13 hazards described in the HMP, four (extreme heat, flooding, drought, and severe storms) are highly likely to worsen in the near term and over the next 30 years (Table 1). Six hazards (tornadoes, hailstorms, karst/sinkholes, landslide, wildfire, and dam/levee failure) are likely to worsen, but are associated with longer timeframes and/or more uncertainty. Two hazards to the Metro region (hazardous materials and earthquakes) were not considered climate hazards because it was unclear how they would be impacted by climate change. One hazard (severe winter storm) is likely to lessen with warming associated with climate change, but still remain a hazard into the foreseeable future. Finally, one hazard (air quality) was added to the list due to the link between increasing temperatures and the formation of ozone.

Climate Hazards

Louisville Metro hazards and their potential response to climate change. Hazards are ranked by the level of response to climate change, timeframe, and likelihood. The overall risk of each hazard to Louisville Metro is available in the 2016 Louisville Metro Hazard Mitigation Plan. Additional data and projections will need to be incorporated into the next iteration of the HMP to provide a more complete assessment of future risk.

HIGHLY LIKELY/ALREADY OCCURRING

Extreme Heat - Increase in frequency and severity with warmer daytime and nighttime temperatures
Severe Winter Storm - Decrease in frequency and severity with warmer temperatures but still a risk
Flood - Increase in frequency and severity with increasing precipitation and larger storms
Air Quality* - Increasing ozone formation due to temperature rise

HIGHLY LIKELY/OCCURRING MID-CENTURY

Drought - Increase in frequency and severity
Severe Storm - Increase in frequency and severity

LIKELY/MID-CENTURY (unless otherwise noted)

Tornado - Increase in clustering, or the number per occurrence (already occurring)
Hail Storm - Increasing size of hail documented, trend unclear (timeframe uncertain)
Karst/Sinkhole - Increasing risk from precipitation and larger storms
Landslide - Increasing risk from precipitation and larger storms
Wildfire - Increase in wildfire risk with warming and drought
Dam/Levee Failure - Increasing risk from precipitation and larger storms

UNKNOWN OR UNLIKELY

Hazardous Materials - Increasing risk from larger storms, flooding, and heat likely, but timeframe unknown
Earthquake - Local risk associated with climate change unknown and unlikely

* Air quality was not included in the original 2016 Louisville Metro Hazard Mitigation Plan, but was added to the addendum due to high risk associated with climate change.

[1] Louisville Metro. 2016 Louisville Hazard Mitigation Plan. Prepared by Stantec.

Introduction

The 2016 Louisville Metro Hazard Mitigation Plan[2] (HMP) is a state-of-the-art and thorough assessment of hazards threatening the jurisdictional area of Louisville Metro (covering the combined areas of Louisville and Jefferson County). Also in 2016, the mayor of Louisville, Mayor Greg Fisher, signed the Compact of Mayors, committing Louisville to track and reduce greenhouse gas emissions and prepare for the current and future impacts of climate change. This document, which assesses the potential likelihood and future change in hazards associated with climate change, comes in response to that commitment.

This assessment combined the best available information on climate change trends and projections, as well as research into potential changes in hazards in response to those trends and projections, with the information provided in the Hazard Mitigation Plan.

Assessment of the impacts of climate change on natural and human-made hazards to communities is challenging for both scientists and decision-makers. While climate change is unequivocal[3,4] the effects on geo-hydrological hazards (including floods, landslides, drought, etc.) remain difficult to determine and even more difficult to predict. This report documents the state of existing knowledge and information, as well as a qualitative assessment of climate impacts to Louisville's hazards. Throughout this assessment, information needs are noted as well as future research avenues.

The information in this report is intended as a supplement to the 2016 Louisville Hazard Mitigation Plan, providing climate change trends and resources that can inform future updates of the plan. Because the hazard risks in the 2016 plan were calculated and mapped based on historical data on frequency and severity of each hazard, future updates will need to update the risk calculations to reflect future frequency and severity rather than those of the past. We know, for instance that flood frequencies and storm severity are already increasing and expected to continue. Continued reliance on historical data will put Louisville's residents and infrastructure at risk. The availability of data and future projections varies depending on the hazard.

This addendum covers all 13 of the hazards identified in the 2016 plan, in addition to air quality, which was added due to the impacts of increasing temperatures on ground level ozone formation. Of the 13 original hazards, 10 are expected to worsen with climate change, 1 may potentially lessen over longer time frames, and 2 are not associated with substantial climate change responses, although they remain significant hazards to the region.

---

[2] Louisville Metro. 2016 Louisville Hazard Mitigation Plan. Prepared by Stantec.

[3] Diffenbaugh, N. S., and C. B. Field. 2013. Changes in ecologically critical terrestrial climate conditions. Science 341:486-492.

[4] IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland.

METHODS

In reviewing the 2016 Louisville Metro Hazard Mitigation Plan,[5] we documented the 13 specific hazards identified for the Metro region, as well as the types of data that were used in calculating risk for each hazard. For each existing hazard, we assessed the type of climate change data that would be needed to assess potential future trends. A thorough review of the scientific literature and climate change reports was conducted to determine the available data and whether climate is expected to affect the hazard.

Those hazards that are not affected by climate change, or that are associated with too much uncertainty to determine the effects, are not included in the final list of climate hazards. In addition, hazards that were not included in the original HMP, but that had significant information to determine that they are likely to develop with climate change, were assessed and included in the final list. The only hazard added was an Air Quality hazard.

In addition to the scientific literature, historical trends in climate were assessed with data from the Louisville International Airport weather station.[6] The most recent 30-year period (1989-2018) was compared to the historical period of 1961-1990 for a number of specific variables, including average precipitation and temperature, extreme maximum temperature, extreme minimum temperature, extreme maximum precipitation, average annual snowfall, number of days above 90° F, number of days below freezing, and the number of days with more than 1 inch of precipitation.

Future trends for the Louisville Metro region were assessed using historical and projected climate data for North America from ClimateNA.[7] Climate NA software (https://sites.ualberta.ca/~ahamann/data/climatena.html) was used to estimate changes in monthly, seasonal, and annual climate-related variables of interest. Some of these include mean annual temperature, mean annual precipitation, summer or winter temperature and precipitation, winter snowfall, extreme maximum temperature, extreme minimum temperature, climatic moisture deficit (drought stress), growing or chilling degree days, heating or cooling degree days, and others.

Historical data came from the Parameters Regression of Independent Slopes Model (PRISM), which interpolates data from the CRU-TS 3.22 climate dataset.[8] Future data was based on 15 Atmospheric and Oceanic General Circulation Models (AOGCMs) of the Coupled Model Intercomparison Project 5 (CMIP5) dataset, corresponding to the Intergovernmental Panel on

[5] Louisville Metro. 2016 Louisville Hazard Mitigation Plan. Prepared by Stantec.
[6] NOAA. National Centers for Environmental Information. Daily Summaries for the Louisville Kentucky Airport Weather Station. Accessed 5-1-2019.
[7] Wang, T., A. Hamann, D. L. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.
[8] Mitchell, T. D. and P. D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high resolution grids. International Journal of Climatology 25:693-712.

Climate Change (IPCC) 5th Assessment Report.[9] The 15 AOGCMs are CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO Mk 3.6, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, and GISS-E2R.

Climate change projections were based on a lower emissions pathway (RCP 4.5) and a higher emissions pathway (RCP 8.5), in order to determine the magnitude of impact that can be avoided if the global community aggressively reduces emissions. Projections were averaged across 30-year periods, including 2040-69 (2050s) and 2070-99 (2080s), which were then compared to the historical period (1961-90).

Based on the best available information from the scientific literature, reputable government reports, and climate model projections, the climate hazards facing Louisville were ranked based on potential change (how sensitive the hazard is to climate change), timeframe (already occurring/near-term, 2050s/mid-term, or 2080s/long-term), and likelihood (based on model agreement and overall scientific consensus concerning likely impacts). This ranking allowed us to determine which hazards are most likely to worsen and/or change in response to climate change. Such information is vital in identifying future research and data needs to inform future HMPs.

The following hazards are listed in the order in which they appear in the HMP.

[9] IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T. F., et al. (Eds.). Cambridge University Press. Cambridge, UK and New York, NY, USA.

TORNADO

From the HMP
A tornado is a violent windstorm characterized by a twisting, funnel-shaped cloud extending to the ground. It is spawned by a thunderstorm (or sometimes as a result of a hurricane) and produced when cool air overrides a layer of warm air, forcing the warm air to rise rapidly. The damage from a tornado is a result of the high wind velocity and wind-blown debris with paths that can be in excess of one mile wide and fifty miles long. Tornado season is generally March through August, although tornadoes can occur at any time of year. They tend to occur in the afternoons and evenings; over 80% of all tornadoes strike between noon and midnight.

Tornadoes have been documented as impacting the Louisville Metro area 12 times since the late 1800s. Of these, 5 have occurred since 2000.

Climate Change Trends
The link between tornadoes and climate change is currently unclear. Long term records for tornadoes in the U.S. are not widely available, so it is difficult to detect changes or trends. Many tornadoes in the early part of the 20th century went undetected because there were fewer people, and most tornadoes are detected as sightings by witnesses. Improved technology, such as advanced radar, also helps us “see” tornadoes that may not have been detected decades ago, thus muddying long term datasets.

In addition to a lack of historical data, researchers are still learning how atmospheric instability and wind shear are expected to respond to climate change. It is likely that a warmer, wetter world will lead to increased climatic instability. However, climate change could also lessen chances for wind shear, shift the timing of tornadoes, or shift the regions that are most likely to be hit, causing high uncertainty for any specific location.

In a study published last year[10], researchers found that since 1979, the number of tornadoes has been rising in Mississippi, Alabama, Arkansas, Missouri, Illinois, Indiana, Tennessee, and Kentucky (Fig. 1). The number of tornadoes has been falling in the traditionally tornado-prone states of Texas, Colorado, and Oklahoma. It appears that Tornado Alley is shifting eastward.

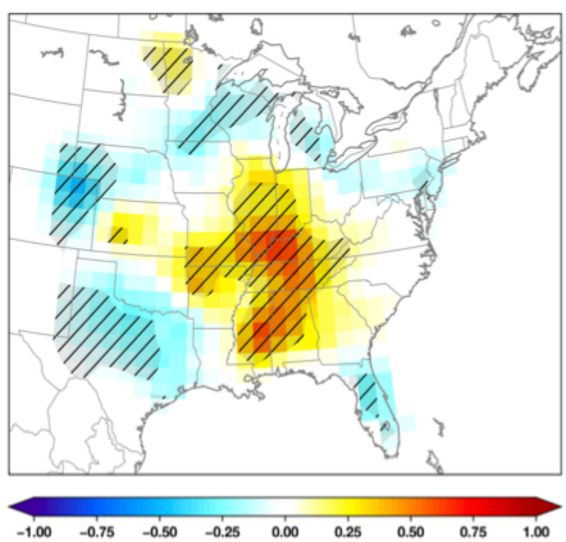


Figure 1. Areas with more tornadoes (warm colors) and fewer tornadoes (cooler colors) based on a Theil-Sen slope analysis of annual tornado reports from 1979-2017.[1]

[10] Gensini, V. A. and H. E. Brooks. 2018. Spatial trends in United States tornado frequency. Climate and Atmospheric Science 1:38. doi:10.1038/s41612-018-0048-2.

In addition to the spatial shift, a seasonal shift in tornado activity was detected. March, April, and May had the greatest increases in tornado detections for the eight-state region called "Dixie Alley". In fact, the deadliest tornado outbreak took place in Dixie Alley in 2011, with more than 350 tornadoes and 324 deaths.[11]

Another recent study[12] found that the frequency of tornado outbreaks is increasing, with more extreme outbreaks increasing fastest. In this study, however, it was unclear whether this trend was related to climate change, and whether it would continue, thus contributing to the uncertainty for future projections.

The National Climate Assessment[13] states with medium confidence that the number of days with tornadoes is actually decreasing in the U.S., but the number of tornadoes on days when they occur is increasing (Fig. 2)[14]. Also, models project changing conditions that would be expected to support an increase in frequency and intensity of tornadoes and other severe storms.

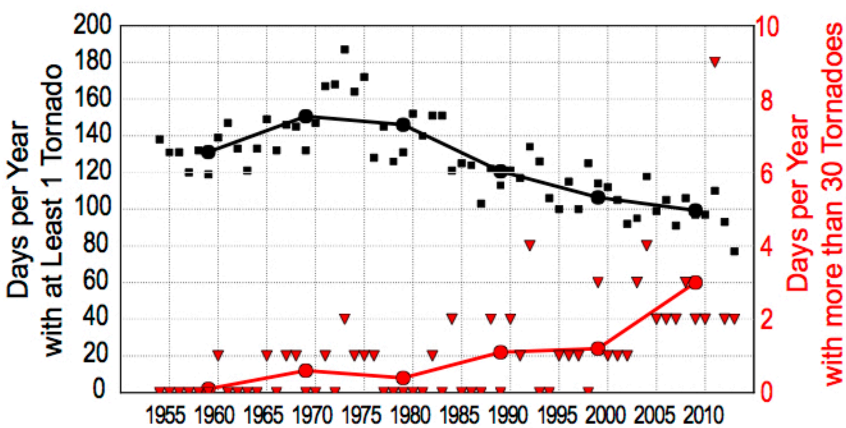


Figure 2. Tornado activity in the U.S. from 1955-2013.[8] Lines show decadal averages. The number of days with tornadoes is decreasing, but clusters of multiple tornadoes are becoming more common.

Tornadoes tend to form under a very specific combination of conditions, including wind shear, differences in wind speed and direction, atmospheric instability, and moisture. There is reason to believe that climate change is making the combination of those conditions increasingly likely to be ripe for tornadoes. This can increase the opportunity for tornadoes, but does not guarantee that they will occur.

---

[11] Friedman, A. and B. Jackson. 2011. Tornado outbreak for the record books: how did the deadly destructive event happen and what does it mean? https://www.washingtonpost.com/blogs/capital-weather-gang/post/tornado-outbreak-for-the-record-books-how-did-deadly-destructive-event-happen-and-what-does-it-mean/2011/04/28/AFLQ942E_blog.html?utm_term=.bfaac288483f

[12] Tippet, M. K., C. Lepore, and J. E. Cohen. 2016. More tornadoes in the most extreme tornado outbreaks. Science 354:1419-1423.

[13] Cossin et al. 2017. Extreme Storms. In *Climate Science Special Report. Fourth National Assessment, Vol. 1.* Wuebbles, D. J. et al., Eds. U.S. Global Change Research Program, Wash. DC. P. 257-276.

[14] Brooks, H. E., G. W. Carbin, and P. T. Marsh. 2014. Increased variability of tornado occurrence in the United States. Science 346:349-352.

Climate Risk

Based on the best available scientific information and trends, it is likely that tornado frequency will increase over the coming decades, but remain highly variable. The number of days with many tornadoes (such as more than 30) is expected to continue to increase with climate change. There is not enough information at this time to do a quantitative assessment of the potential change in tornado frequency based on climate projections, and uncertainty of the impact of climate change on this hazard remains high. Because of the high risk, high potential to cause death, and high cost of damages, preparedness is vital.

SEVERE WINTER STORM

From the HMP
A severe winter storm is defined as an event that drops four or more inches of snow during a 12- hour period or six or more inches during a 24-hour span. Blizzards are characterized by temperatures below 20° F and winds of at least 35 miles per hour. Ice storms occur when freezing rain falls and freezes immediately on impact. During ice storms, surface temperatures are 32° F or below, while moist warm air at higher altitudes create rain that becomes supercooled and then freezes on contact.

Climate Change Trends
Extreme storms have numerous impacts on lives and property. Quantifying how broad-scale average climate influences the behavior of extreme storms is particularly challenging, in part because extreme storms are comparatively rare short-lived events and occur within an environment of largely random variability. Additionally, because the physical mechanisms linking climate change and extreme storms can manifest in a variety of ways, even the sign of the changes in the extreme storms can vary in a warming climate. This makes detection and attribution of trends in extreme storm characteristics more difficult than detection and attribution of trends in the larger environment in which the storms evolve.

Snowfall – Analysis of storm tracks indicates that there has been an increase in winter storm frequency and intensity since 1950, with a slight shift in tracks toward the poles.[15] There was more than twice the number of extreme regional snowstorms throughout the eastern U.S. from 1961-2000 as there were in the previous 60 years. These extreme storms occurred in colder and wetter snow seasons than average. For the next few decades, even with warming temperatures, record storms will continue to be possible.[16]

Contrary to the larger regional trends, extreme snowfall in Louisville has declined from 1948-2018 (Fig. 3). Average extreme snowfall has declined by 20%, in a comparison of the most recent 30-year period (1989-2018) to the historical period of 1961-1990. Assuming continued higher greenhouse gas emissions (RCP 8.5), model projections estimate that snowfall in Louisville will decline by 61-77% by 2045-69 and by 77-91% by 2070-99, as compared to historical averages from 1961-1990.[17] This indicates that, while rainstorms are expected to increase in severity, severe snowstorms could become increasingly rare. Due to high variability and the heavy influence of North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) climate

---

[15] Easterling, D.R., et al. 2017. Precipitation change in the United States. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D.J., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.
[16] Kunkel, K. E. et al. 2013. Monitoring and understanding trends in extreme storms: State of knowledge. Bulletin of the American Meteorological Society. April 2013: 499-514.
[17] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

patterns, which have highly variable and often unpredictable behavior, large and extreme snowstorms will continue on a sporadic basis.

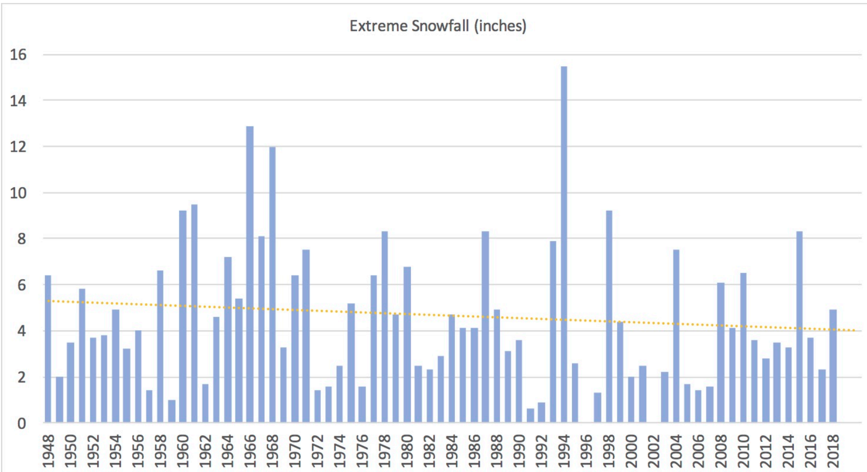


Figure 3. Extreme snowfall (over 6") has been declining in Louisville. Extreme snowfall (shown in inches) within a 24-hour period was measured at the Louisville International Airport weather station from 1948-2018.

Blizzards – Wind projections are needed to assess blizzard risk, but based on snowfall declines, blizzards are expected to become less common mid- to late-century.

Ice Storms – Ice storms occur when precipitation falls as rain, but freezes on contact with ground temperatures at or below 32° F. National and regional trends in the number of freezing rain days show no systematic trends since about 1960.[18]

Based on measurements from the Louisville International Airport weather station, the number of days below freezing has been declining in Louisville (Fig. 4). Average number of days below freezing has declined by 14 days per year, in a comparison of the most recent 30-year period (1989-2018) is compared to the historical period of 1961-1990.

Model projections indicate that the number of days below freezing is expected to continue to decline, with 46 fewer days per year, on average, below freezing by 2040-69 (range = 35-57 fewer days) and 64 fewer days by 2070-99 (range = 63-75 fewer days).[19] This represents 25-40% fewer freezing nights by mid-century and 38-53% fewer by late-century, as compared to the historical period of 1961-90.

[18] Kunkel, K. E. et al. 2013. Monitoring and understanding trends in extreme storms: State of knowledge. Bulletin of the American Meteorological Society. April 2013: 499-514.

[19] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

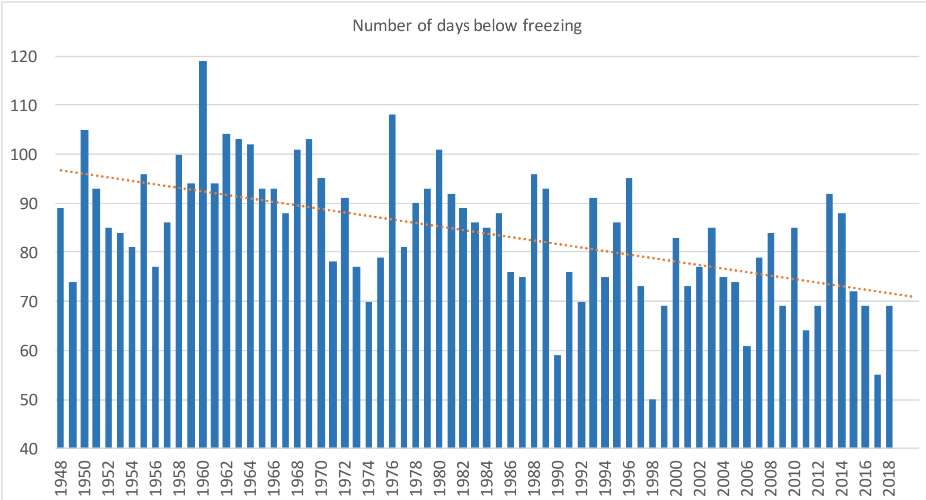


Figure 4. The number of days below freezing has been declining over time. The number of days below 32° F was measured at the Louisville International Airport weather station from 1948-2018.

Climate Risk

Based on the best available scientific information and trends, it is likely that severe winter storms will lessen over the coming century, but extreme winter storms will still occur. The temperature conditions amenable to the formation of ice storms could become 25-40% less common over the next 30 years. Similarly, snowfall is expected to continue to decline by 61-77% over this time period. However, individual storms are also expected to become larger. Severe winter storms are expected to affect the County equally across the geographic area, but some populations may benefit more than others by warmer temperatures and less snow and ice.

SEVERE STORM

From the HMP

A thunderstorm is formed from a combination of moisture, rapidly rising warm air, and a force capable of lifting air such as a warm and cold front, a sea breeze or an obstruction, such as a mountain. All thunderstorms contain lightning and may occur singly, in clusters or in lines. The National Weather Service (NWS) considers a thunderstorm as severe if it develops 3⁄4 inch hail or 50-knot (58 mph) winds.

Additional types of severe storms include straight line winds (also called convective wind gusts, outflow and downbursts). If these winds meet or exceed 58 miles per hours then the storm is classified as severe by the National Weather Service (NWS). Hail, floods, and tornadoes, which are associated with severe storms, are addressed as individual hazards.

Climate Change Trends

Severe thunderstorms are one of the primary causes of catastrophic loss in the U.S. Data from the Coupled Model Intercomparison Project, Phase 5 (CMIP5) indicate that conditions supporting the development of severe thunderstorms are expected to increase over the eastern U.S. in response to continued greenhouse gas emissions (RCP8.5).[20] The most severe events are expected to increase in likelihood due to increasing convective potential energy and strong low-level wind shear. Spring exhibits the largest absolute increase as well as the most consistent response across the different global climate models (Figure 5). The authors note that spring and fall changes are expected to occur even in a lower emissions scenario than the one presented.

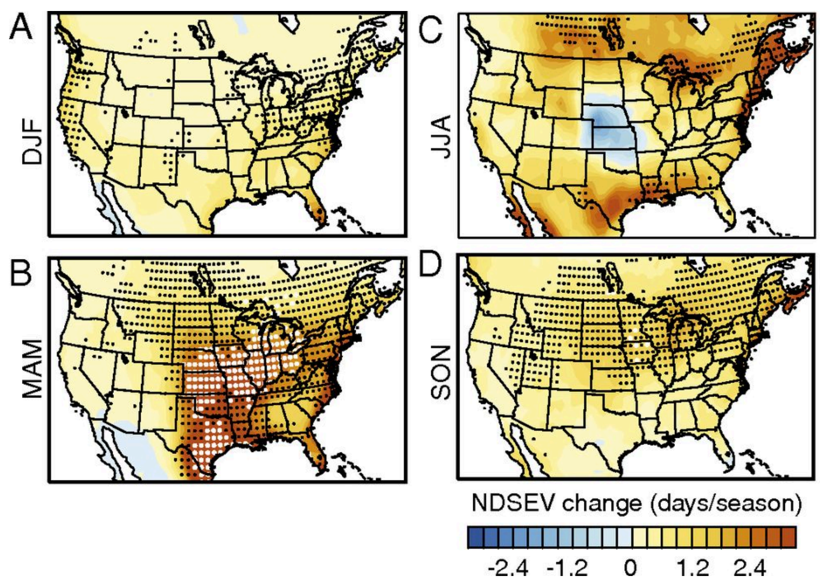


Figure 5. Change in the number of days on which severe thunderstorm conditions (NDSEV) are formed between the 2070-2099 period and the 1970-1999 historical period, based on the RCP8.5 greenhouse gas emissions pathway. Maps show winter, spring, summer, and fall (A-D), and dots indicate areas with stronger model agreement. Adapted from Diffinbaugh et al. 2013.[14]

Although important uncertainties about storm-scale processes still exist, the fact that the projected increases in conditions that support severe storms are robust across a suite of

[20] Diffenbaugh, N. S. M. Scherer, and R. J. Trapp. 2013. Robust increases in severe thunderstorm environments in response to greenhouse forcing. PNAs 41:16361-16366.

climate models and are consistent even with lower emissions suggests that severe thunderstorm occurrence is highly likely to increase, thereby increasing the risk of thunderstorm-related damage.

A NASA study[21] indicates heavy rainstorms will become more common with climate change. When applied to a future with double the current CO_2 and a surface that is 5° F warmer than current conditions, their model indicated more storms would be expected to resemble the strongest storms that we experience today. Specifically, in the southeastern U.S., there is expected to be an increase in the most violent and severe storms that arise when strong updrafts combine with horizontal winds, which are a major source of weather related casualties.

The term "atmospheric rivers" (ARs) refers to the relatively narrow streams of moisture transport that often occur within and across midlatitudes, in part because they often transport as much water as in the Amazon River. They account for a substantial fraction of the precipitation, and thus water supply, often delivered in the form of an extreme weather and precipitation event. Under climate change conditions, ARs may be altered in a number of ways, namely their frequency, intensity, duration, and locations. In association with landfalling ARs, any of these would be expected to result in impacts on hazards and water supply. The 4th National Climate Assessment reported *high confidence* that the frequency of AR storms will increase in association with rising global temperatures.[22]

Climate Risk

Based on the best available scientific information and trends, it is highly likely that severe storms will worsen over the coming century. However, there is not enough information at this time to do a quantitative assessment of severe storm risk associated with climate change. In the HMP, the risk score for severe storms was based on counts of storm events within 25 miles of each cell. These counts are expected to increase with time, but shifts in storm tracts could also cause the spatial distribution of risk to shift over time. More information is needed before a quantitative assessment can be done.

[21] Del Genio, A. D., M-S. Yao, and J. Jonas. 2007. Will moist convection be stronger in a warmer climate? Geophysical Research Letters 34. doi:10.1029/2007GL030525.

[22] Kossin, J.P., et al. 2017. Extreme storms. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D.J., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.

HAILSTORM

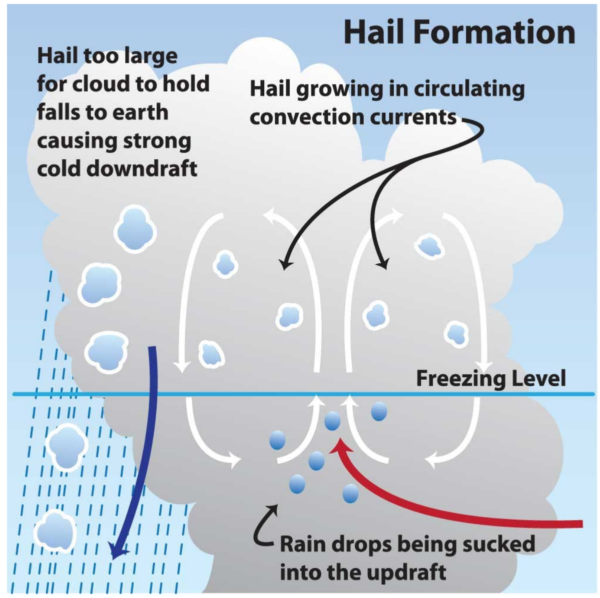


Figure 6. Illustration from *The Conversation* (Univ. of Colorado).

Hail is precipitation that falls in the form of ice. Hailstones form as water is sucked into the upper regions of a thunderstorm, where it freezes (Fig. 6). Supercooled liquid water at these heights can continue to add mass to a small hailstone, which eventually becomes too heavy and falls out of the cloud.

The largest hailstones are found in strong thunderstorms, called supercells. These storms have strong updrafts, allowing hailstones to reach the ice region of the cloud, thus acquiring more mass. Warm and moist conditions promote strong updrafts and also a wind field that strengthens and turns with height.

Climate Change Trends

While the propensity of hail to form is difficult to model, trends indicate increasing sizes of hail in recent years[23] (Fig. 7). One modeling study indicates increasing hail size, but not frequency.[24]

Researchers at the National Center for Atmospheric Research have found that in a future climate, there will be more strong thunderstorms and fewer weak ones. This indicates the potential for an increase in hailstone size, because stronger thunderstorms cause the hail to be cycled through the cloud layer for a longer time.

Climate Risk

Little is known about the impacts of climate change on hailstorms. Compared to tornadoes and hurricanes, hail has received relatively little research attention, although a major international meeting on hail was held in 2018. Researchers hope to develop a better understanding of the characteristics and geography of future hailstorms, in order to inform decision-makers, the insurance industry and the general public. More information is needed before a qualitative or quantitative assessment can be done on the changing risks of hail for the Louisville Metro region.

[23] https://theconversation.com/destructive-2018-hail-season-a-sign-of-things-to-come-102879
[24] Brimelow, J.C., W. R. Burrows, and J. M. Hanesiak. 2017. The changing hail threat over North America in response to anthropogentic climate change. Nature Climate Change 7:516-522.

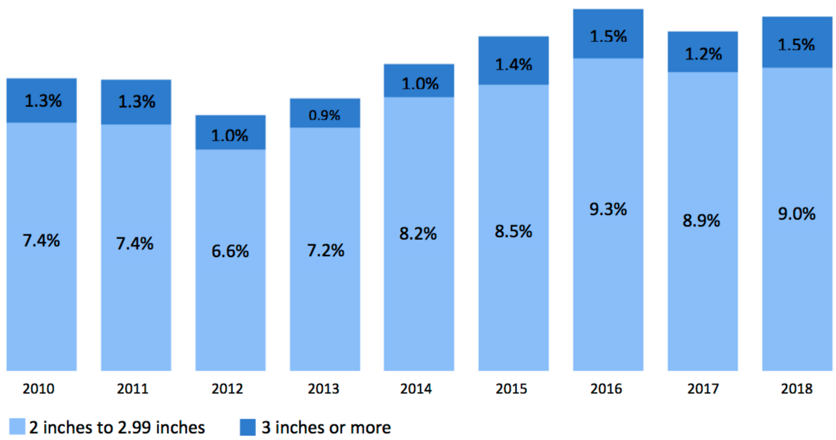


Figure 7. Between 2010 and 2017, 8.8% of U.S. severe hail reports included hail larger than two inches in diameter. Chart from *The Conversation* (data from NOAA's Storm Prediction Center).

EARTHQUAKE

Kentucky is affected by earthquakes from several seismic zones in and around the state. The most important one is the New Madrid Seismic zone, which had significant activity in Kentucky in 1811-1812. The probability of a repeat of the New Madrid 1811-1812 earthquakes in the next 50 years is 7-10% (for a magnitude 7.5-8.0) and 25-40% (for a 6.0-7.5).

Climate Change Trends

While climate change can lead to increases in earthquakes due to melting glaciers and sea level rise, studies on the specific potential impacts are limited. Information from past periods of warming, such as the retreat of glaciers at the end of the last Ice Age, reveal a picture of extreme redistribution of energy and matter in the form of volcanic activity, seismic shocks, and monstrous landslides. This indicates a “seismically turbulent future” as massive amounts of weight are redistributed around the globe, but specific impacts to an inland area such as Kentucky are unknown at this time.[25]

Climate Risk

No information on the risk of earthquakes associated with climate change, and specific to Kentucky of the Eastern U.S., is available at this time. More information is needed before a qualitative or quantitative assessment can be done.

[25] McGuire, W. J. 2010. Potential for a hazardous geospheric response to projected future climate changes. Philosophical Transactions of the Royal Society A 368: 2317-2345.

KARST/SINKHOLE

From the HMP

Karst refers to a type of topography formed in limestone, dolomite, or gypsum by dissolution by rain and underground water. Fifty-five percent of Kentucky sits atop carbonate rocks that are prone to developing karst. Karst hazards include sinkhole flooding, sudden cover collapse, and leakage around dams. The estimated damage caused by karst hazards every year in Kentucky is between $0.5 million and $1 million.

Four geologic hazards are associated with karst. Two common karst-related geologic hazards, cover-collapse sinkholes and sinkhole flooding, cause the most damage to buildings. A third karst hazard is relatively high concentrations of radon, sometimes found in basements and crawl spaces of houses built on karst. Finally, the hydrogeology of karst aquifers makes the groundwater vulnerable to pollution, and this vulnerability may also be considered a type of geologic hazard.

Climate Change Trends

Recent reviews in the scientific literature have shown that sinkhole hazards will likely intensify as a result of climate change.[26] Quantification of the impact on sinkholes, however, has been limited. A case study from Florida[27] showed that for every 0.18° F rise in global temperature, the number of sinkholes in that region increased by 1-3%.

Sinkholes could increase through a variety of different pathways. First, because karst sinkholes and aquifers form through the dissolution of rocks by water, increases in precipitation, and especially in large and severe storms, could increase the rate of substrate weakening, karst sinkhole development, sinkhole flooding, and dam leakage. Second, sinkhole and aquifer collapse is closely linked to drought, and could increase with increasing drought severity and/or frequency. Third, in response to higher temperatures, evaporation rates, and incidence of drought, the human response is likely to be intensification of water pumping, which leads to groundwater level reduction and related sinkhole development.

Average annual precipitation has been increasing in Louisville, with the three wettest years on record all occurring within the last decade (Fig. 8). Precipitation remains highly variable year-to-year. Overall, average precipitation from 1989-2018 was 9% higher as compared to 1961-1990.

---

[26] Rogelio Linares, R., et al. 2017. The impact of droughts and climate change on sinkhole occurrence. A case study from the evaporite karst of the Fluvia Valley, NE Spain. Science of the Total Environment 579:345-358.
[27] Meng, Y. and J. Long. 2018. Global warming causes sinkhole collpase – Case study in Florida, USA. Natural Hazards and Earth Systems Science Discussions. In Review.

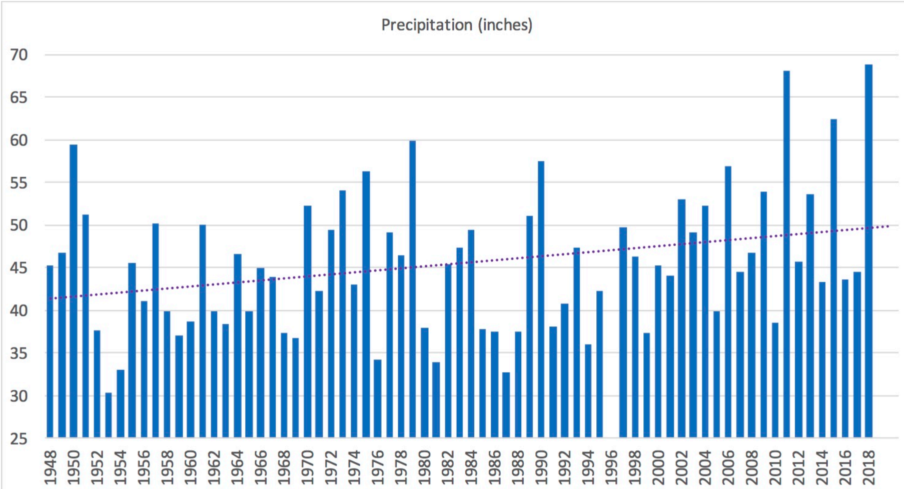


Figure 8. The average annual precipitation has been increasing over time. Average precipitation was measured at the Louisville International Airport weather station from 1948-2018.

Climate change model projections indicate that precipitation could increase an additional 5% to 9%.[28] However, precipitation is expected to occur in fewer, larger storms, which could have more impact on karst sinkhole flooding and dissolution of substrate.

Climatic moisture deficit, a measure of drought stress, is expected to increase 47% by mid-century (2040-69) and 63% by late-century (2070-2099), further contributing to potential increases in karst/sinkholes.

Climate Risk

Based on the best available scientific information and trends, it is likely that karst/sinkhole risk will worsen over the coming century. However, there is not enough information at this time to do a quantitative assessment. In the HMP, the risk score for Karst/sinkholes was based on counts of historical occurrences of sinkholes in the past. The geographic distribution of this risk is not expected to change with climate change, but the total counts could increase over time with larger and more severe storms, and increased incidence of drought. More information is needed before a quantitative assessment can be done.

[28] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

LANDSLIDE

From the HMP

Landslides occur when masses of rock, earth, or debris move down a slope. They are activated by storms, fires, and human modification of the land. Mudslides develop when water rapidly accumulates in the soil, changing the earth into a "slurry" or flow. Areas that are generally prone to landslides include existing old landslides, bases of steep slopes, bases of drainage channels, and developed hillsides where leach-field septic systems are used.

Climate Change Trends

Climate change affects the stability of natural and engineered slopes, and has consequences on landslides. However, climate and landslides act at only partially overlapping spatial and temporal scales, complicating the evaluation of climate impacts on landslides. Because of the uncertainty involved, experts recommend planning for worst-case scenarios that may over-estimate landslide risk in response to climate change. They also recommend full communication of the uncertainties to decision-makers and the public.[29]

In general, increases in precipitation are associated with reduced stability, while decreases in precipitation are associated with a reduction in landslide activity. Increased rainfall intensity is also associated with greater slope instability. Some substrates appear to be more sensitive to changes in precipitation, such as clay substrates that can contract with drought and become highly saturated with rain.

Variation in the overall amount of rainfall was found to influence mostly rock slides, mudflows and earthflows, at both the local and the regional scale. Variation in rainfall intensity, on the other hand, affects rock falls and debris flows/avalanches, in the short-term and at the local scale.

In the Louisville Metro region, precipitation has been increasing in recent years (Fig. 8), with the three highest years on record occurring within the last decade. In addition, the incidence of heavy precipitation (large storms) has increased by 58-74% throughout the eastern U.S. (Fig. 11), indicating a larger regional trend.[30]

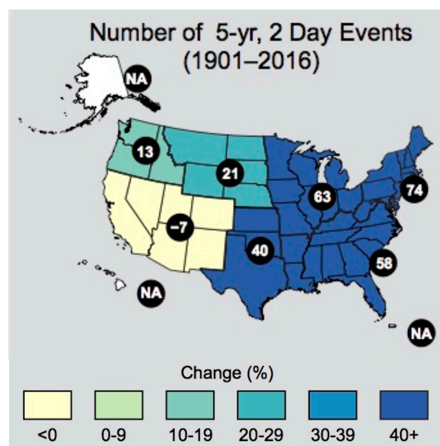


Figure 11. The southeastern U.S. has experienced an increase in large storm events over the last century.[25]

Both the total amount of precipitation and the intensity of storms are expected to affect landslide risk. Model projections for the region indicate an increase in

[29] Gariano, S. L. and S. Fuzzetti. 2016. Landslides in a changing climate. Earth Science Reviews 162:227-252.

[30] Easterling, D.R., et al. 2017. Precipitation change in the United States. *In* Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D.J., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.

precipitation by 5% by mid-century and 9% by late century.[31] When temperature rise, evaporation, and precipitation are all considered, however, the region is expected to experience drier conditions overall, with 47-63% greater drought stress.

Climate Risk

Based on the best available scientific information and trends, it is likely that landslide risk will worsen in Louisville over the coming century, but there is relatively high uncertainty associated with this trend. There is not enough information at this time to do a quantitative assessment. The geographic distribution of this risk is not expected to change with climate change, but the total counts could increase over time with larger, more frequent, and/or more severe storms. Conversely, because of increasing temperature and evaporation, drought stress is expected to increase in the area and could balance out any precipitation increases. More information is needed before a quantitative assessment can be done.

[31] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

Hazardous Materials

From the HMP

Hazardous materials (HazMat) are solids, liquids, or gases that can harm people, other living organisms, property, or the environment and they are often subject to chemical regulations. Hazardous materials include materials that are radioactive, flammable, explosive, corrosive, oxidizing, asphyxiating, biohazardous, toxic, pathogenic, or allergenic. Also included are physical conditions such as compressed gases and liquids or hot materials, including all goods containing such materials or chemicals, or may have other characteristics that render them hazardous in specific circumstances. Hazardous materials in various forms can cause death, serious injury, long-lasting health effects, and damage to buildings, homes, and other property.

Industrial community hazardous materials can be found almost anywhere and releases of the materials into the environment can be deadly events. These releases can occur at almost any time, but in conjunction with another natural disaster such as a flood or earthquake the damages can multiply exponentially. The only 2 releases documented in the HMP were the result of human actions rather than natural disasters.

Climate Change Trends

Heat – Rail lines and roads can become unstable with severe heat. This could create a significant risk for the transportation of hazardous materials, including crude oil and other hazardous freight. Major rail accidents can destroy property and affect peoples' health and safety.[32] "Sun kinks," or buckling from severe heat have already caused about 2,100 train derailments over the last 40 years (about 50 per year, on average).[33] Damage costs about $1 million per derailment. During the heat waves of 2012, the Federal Railroad Administration issued a special advisory due to the "unusually high and prolonged record-breaking temperatures" and the many major derailments that occurred in response.

Temperatures have risen steadily in Louisville since 1948 (Fig. 12). The average annual temperature has increased by 2.2° F, when comparing the most recent 30-year period (1989-2018) with the historical period of 1961-1990. Model projections indicate continued temperature rise for many decades to centuries, with an increase of extreme maximum temperatures of 8.3° F (range = 3.1 to 13.6° F) by 2040-69 and an increase of 12.6° F (range of 5.5° F to 19.7° F) by 2070-99.[34]

---

[32] Chinowsky, P. et al. 2019. Impacts of climate change on operation of the U.S. rail network. Transport Policy 75:183-191.

[33] Magill, B. 2014. Derailments may increase as "sun kinks" buckle tracks. Climate Central. https://www.climatecentral.org/news/climate-change-warp-railroad-tracks-sun-kinks-17470. Accessed 5-2-2019.

[34] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

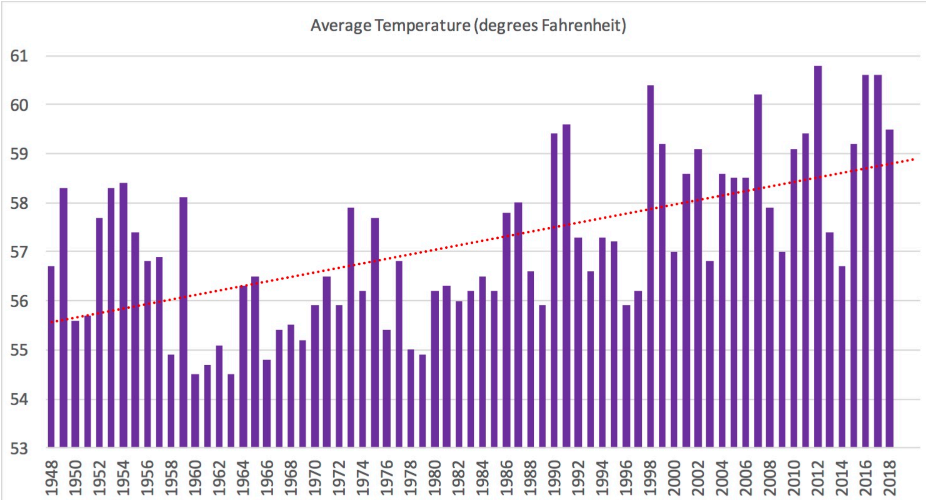


Figure 12. Average temperature in Louisville has been increasing. Temperature (in Fahrenheit) was measured at the Louisville International Airport weather station from 1948-2018.

Precipitation – The most significant impact of storm events on hazardous materials sites will be during a flood emergency, and the vulnerability and risk for the surrounding community will depend largely on responders' ability to contain or manage any hazardous materials that are exposed to flooding.

It is difficult to assess the vulnerability of hazardous materials sites to climate change without knowing what types of wastes are exposed, and how they are stored and managed. Some hazardous materials are likely to be more dangerous and/or costly to mitigate than others. Additionally, some are more sensitive to flooding and/or severe heat than others.

Pipelines may also be affected by increased intense precipitation. For example, federal regulations require that pipelines carrying hazardous materials in the lower 48 states be buried with a minimum of 3 feet of cover—up to 5 feet near heavily populated areas. Intense precipitation can erode soil cover and cause subsidence (i.e., sinking of the earth underneath the pipeline).

Many flood-prone sites, even if the point of operations were to be moved, could leave behind hazardous waste, either above ground or in the form of contaminated land. Other types of facilities that contain hazardous materials, such as wastewater treatment plants, will be very difficult to move.

River levels – During periods of high precipitation, streams and rivers can run much higher than normal. This can slow the movement of barges and increase the likelihood of accidents, like the Dec. 25, 2018 crash that resulted in 7 coals barges sinking on the Ohio River in Louisville. High waters also lead to fewer barges able to travel, and lower revenues for grain growers and coal distributors.

Climate Risk

Based on the best available scientific information and trends, it is likely that HazMat risk will

worsen in Louisville with increased extreme events, including larger storms, more flooding, and increasing heat, but there is relatively high uncertainty associated with this trend. There is not enough information at this time to do a quantitative assessment. The geographic distribution of this risk is not expected to change with climate change, but the total counts could increase over time with larger, more frequent, and/or more severe storms. More information is needed before a quantitative assessment can be done.

DROUGHT

From the Hazard Mitigation Plan
A drought is defined as cumulative deficit of precipitation relative to what is normal for a region over an extended period of time. A heat wave combined with a drought is a very dangerous situation. Some effects of drought include crop failure, water shortage, wildfire, erosion (including loss of topsoil), ecological damage, and land subsidence. Palmer Drought Severity Index was used to classify the level of drought. Between 1945-2015 there were 32 “drought events.” The most severe drought recorded was over a period of almost 5 years from 1952-1957.

Droughts of 2007 and 2010 severely affected agriculture, wildfire risk, power generation, water prices, and ferry traffic. In addition, water quality in streams and rivers declines during drought. Barges on the Ohio river were forced to reduce their cargo weight during drought, due to low river levels.

Climate Change Trends
Climate change increases the odds of worsening drought in many parts of the United States and the world in the decades ahead. Even in regions that may not see changes in precipitation, warmer temperatures can increase water demands and evaporation, putting greater stress on water supplies, drying out soils, and causing widespread declines in many species of trees and other plants.

Warmer temperatures can amplify the impacts of drought. Increased temperatures enhance evaporation from soils, making periodic droughts worse than they would be under cooler conditions. Droughts can persist through a “positive feedback,” where very dry soils and diminished plant cover can further suppress rainfall in an already dry area.

The United States is historically susceptible to drought. Paleoclimate studies show major droughts in the distant past, while some more recent dry periods are still within living memory, such as the Dust Bowl of the 1930s or the drought of the 1950s. These historic examples serve as guideposts to highlight our vulnerabilities to drought as we move into a warmer and, in some places, drier future.[35]

Model projections show, with high agreement among models, that overall drought stress is expected to increase in Louisville, even as average precipitation increases by 9%, on average.[36] Because of much higher temperatures projected for the area, a modest increase in

---

[35] Lall, U., et al. 2018. Water. *In* Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Reidmiller, D.R., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.
[36] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

precipitation is not sufficient for offsetting higher evaporation and evapotranspiration rates. Over time, the deficit in moisture (negative balance between the amount of precipitation and the amount of water used within the natural system) is expected to increase (Figure 13). With continued higher emissions (RCP 8.5) drought stress is expected to increase 10-18% (14% on average) by the middle of this century. By late century, drought stress is expected to increase 10-21% (16% on average). If emissions are reduced (RCP 4.5), drought stress can be limited to 12-13%, on average, by mid to late-century.

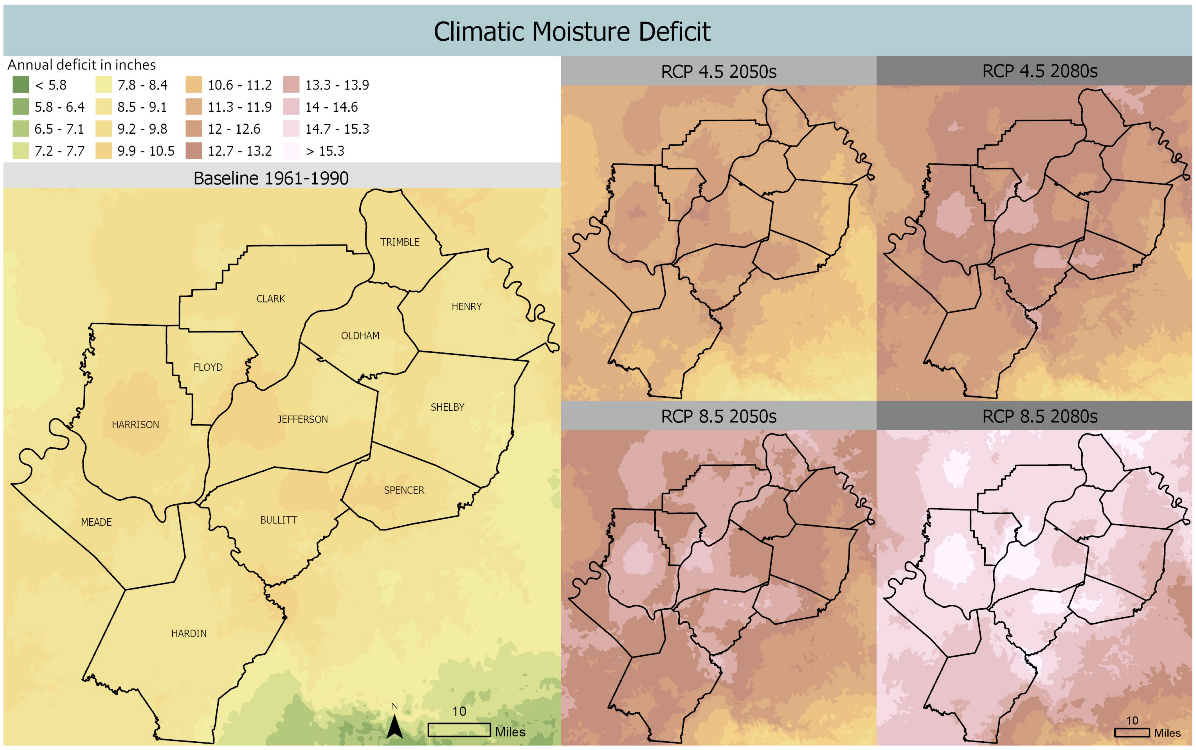


Figure 13. Projected climatic moisture deficit (drought stress) for mid-century (2040-69) and late-century (2070-2099), as compared to the historical period of 1961-1990. The upper two maps show projections based on substantially reduced greenhouse gas emissions (RCP 4.5) while the lower two maps show projections based on continued higher emissions (RCP 8.5).

Some of the biggest impacts of drought are to water quality, with warmer surface waters and lower flows. These can cause challenges to the cost and implications of water treatment, as well as risk to water supplies, public health, and aquatic ecosystems. Decreases in volume can cause high temperatures and lower dissolved oxygen levels, both of which affect aquatic life. When nutrient loading is added to the mix, harmful algal blooms can further threaten waterways and water supplies.[37]

[37] Lall, U., et al. 2018. Water. *In* Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Reidmiller, D.R., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.

Climate Risk

Based on the best available scientific information and trends, it is highly likely that drought risk will worsen in Louisville, driven primarily by increasing temperatures, and even if precipitation increases as well. The geographic distribution of this risk is not expected to change (from that presented in the HMP) with climate change, but the severity could increase. This risk could be lessened if greenhouse gas emissions are reduced.

SEVERE HEAT

From the HMP

Heat is the number one cause of mortality among all weather-related disasters. In fact, heat causes more deaths than floods, lightning, hurricanes, and tornadoes combined. Extreme heat is defined as temperatures that remain 10° F degrees above the average high temperature for the region. Humidity also plays a role in the effects of heat on the human body, because evaporative cooling is reduced when humidity is higher. A temperature of 90°F is significant in that it ranks at the "caution" level of the NOAA's Apparent Temperature chart even if humidity is not a factor.

Main impacts are to public health and safety, especially the very young, elderly, and people working or living outdoors. Additionally, heavy use of utilities (electric and water) cause a strain on the system due to increased air conditioner, fan, and water usage.

Climate Change Trends

Cities across the Southeast are experiencing more and longer summer heat waves. At 61%, the Southeast has a higher percentage of cities experiencing worsening heat waves than any other region of the U.S.[38] Louisville shows significant increases in both frequency and duration of heat waves (Fig. 14). Intensity is expected to increase as temperatures continue to rise.

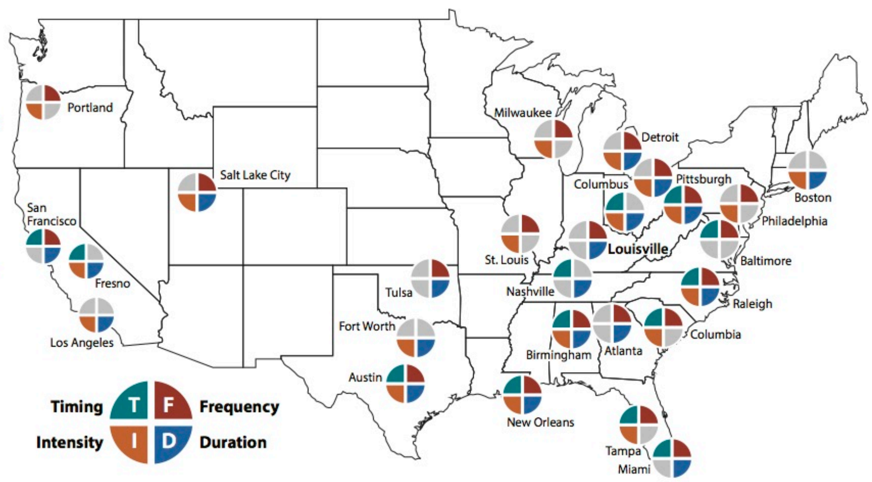


Figure 14. This map shows the significant trends in increasing heat wave timing, intensity, frequency, and duration for major cities of the U.S. from 1961-2010. Map adapted from Habeeb et al. 2015.

Extreme heat can increase the risk of other types of disasters. Heat can exacerbate drought. This, in turn, can encourage more extreme heat, as the sun's energy acts to heat the air and land surface, rather than to evaporate water. Hot, dry conditions also increase the risk of wildfires.

Temperatures have risen steadily in Louisville since 1948 (Fig. 11). The number of days above 90° F has also risen in Louisville (Fig. 15). When comparing the most recent 30-year period

[38] Habeeb, D., J. Vargo, and B. Stone Jr. 2015. Rising heat wave trends in large U.S. cities. Natural Hazards 76:1651-1665.

(1989-2018) with the historical period of 1961-1990, the average number of days above 90° F has increased by 12 days/year.

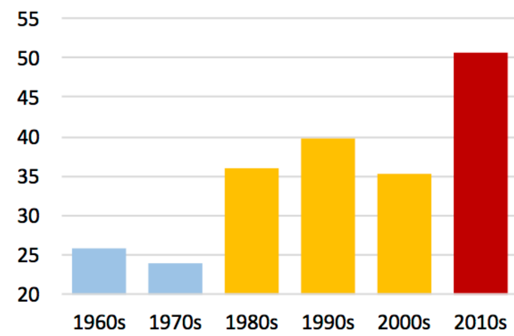


Figure 15. The number of days per year above 90° F, averaged for each decade, in Louisville, KY. Temperature was measured at the Louisville International Airport weather station.

Model projections indicate continued temperature rise for many decades to centuries. If emissions are not reduced, the continued rise is expected to increase extreme maximum temperatures by an average of 8.3° F (range = 3.1° F to 13.6° F) by 2040-69 and 12.6° F (range of 5.5° F to 19.7° F) by 2070-99.[39] If emissions are reduced, these extreme maximum temperatures could be limited to about 5.5° F by mid-century and 7.1° F by late-century.

High humidity and elevated nighttime temperatures greatly exacerbate heat-related illness and mortality. Heat stress occurs in humans when the body is unable to cool itself effectively. Normally, the body can cool itself through sweating, but when humidity is high, sweat will not evaporate as quickly, potentially leading to heat stroke. Exposure to high nighttime minimum temperatures reduces the ability of some people to recover from high daytime temperatures, resulting in heat-related illness and death, especially for the poor and elderly. Daily minimum temperatures in the U.S. are increasing slightly faster than daily maximum temperatures.

The number of days with high minimum temperatures (nighttime temperatures that stay above 75° F) has been increasing across the Southeast[40], and this trend is projected to intensify, with some areas experiencing more than 100 additional warm nights per year by the end of the century (Fig, 14). Louisville, with an average of fewer than 5 warm nights historically, is expected to experience between 20-30 by mid-century and between 50-75 by late century, if emissions are not reduced. If emissions are reduced, warm nights may be limited to between 30-50 by late century.[24]

[39] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

[40] Carter, L., et al. 2018. Southeast. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Reidmiller, D.R., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.

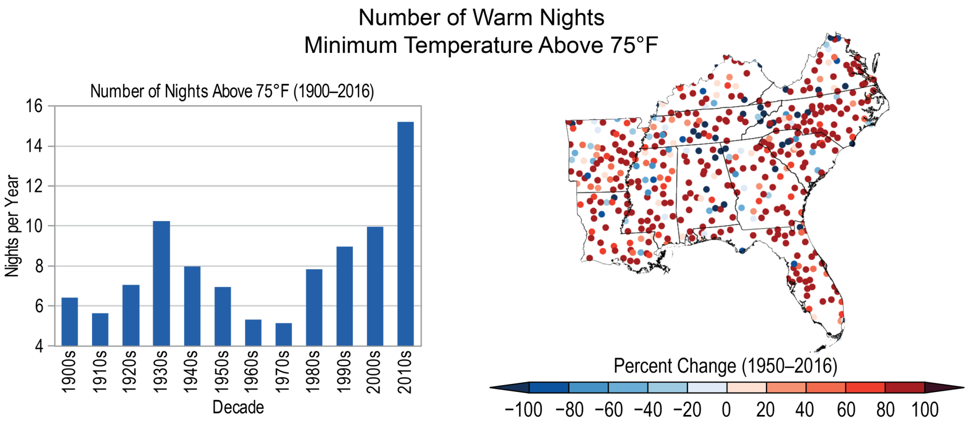


Figure 16. The average annual number of warm nights (remaining above 75° F) has been increasing across the Southeast, especially in the most recent decade. Figure adapted from Carter et al. 2018.[35]

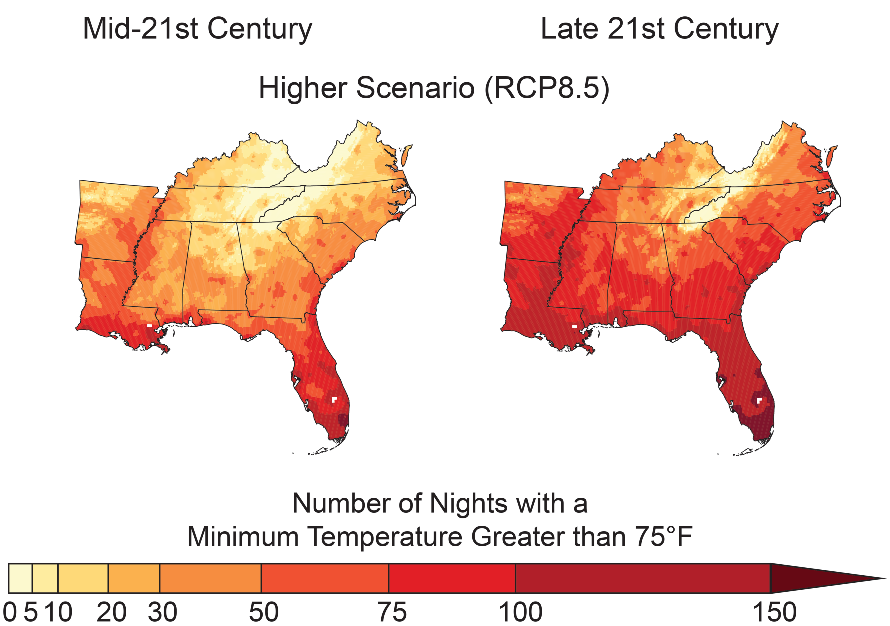


Figure 17. Projected number of warm nights (remaining above 75° F) in the Southeast, assuming continued higher emissions (RCP 8.5). Figure adapted from Carter et al. 2018.[35]

Climate Risk

Based on the best available scientific information and trends, heat risk is already worsening and will continue to worsen in Louisville with extremely high likelihood. The geographic distribution of this risk is not expected to change (from that presented in the HMP) with climate change, but the severity is already increasing and is expected to continue. This risk could be lessened if greenhouse gas emissions are reduced. The future heat risk to Louisville could be mapped using the same methods as the 2016 Hazard Management Plan, but using projected summer temperatures[41] rather than historical summer temperatures (Fig. 18).

[41] ClimateNA v5.21 software package, available at *http://tinyurl.com/ClimateNA*, based on methodology described by Hamann, A. T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America. Bulletin of the American Meteorological Society 94: 1307–1309.

The Hazard Mitigation Plan states that "The Geographic Extent Score was determined by assigning near surface air temperatures to each grid cells. Near surface air temperatures were modeled for the Urban Heat Management Study by the Urban Climate Lab of the Georgia Institute of Technology. Temperatures levels for each grid cell were converted to a 0-1 score."

In addition to the Geographic Extent Score, the Occurrence score was calculated based on the number of additional deaths estimated to occur with each additional degree of temperature during the May through September warm season. By recalculating these values with climate change projections for both mid-century (2040-69) and late century (2070-99), we would then recalculate the Occurrence scores, which are added to the Geographic Extent scores to determine the final risk score for heat.

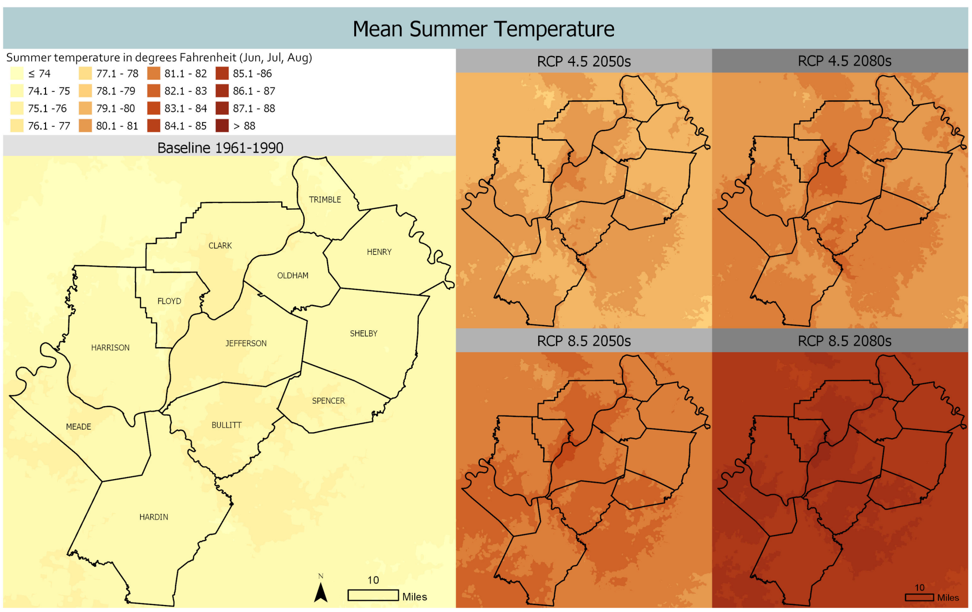


Figure 18. Average Summer temperature across the Louisville region. Spatial data on change in temperature can be used to update the extreme heat risk and vulnerability scores in the 2016 Hazard Mitigation Plan for Louisville Metro.

WILDFIRE

From the HMP

A wildfire is an unplanned fire, which includes grass fires, forest fires, and scrub fires either human-caused or natural in origin. A wildfire is an uncontrolled burning of grasslands, brush, or woodlands. Most wildfires are started by people.

The Wildland-Urban Interface, or the area where human development meets undeveloped lands, is often the area where wildfires start to become significant threats to life and property. From these areas, wildfires can spread into more suburban and urban areas.

Numerous variables affect wildfire frequency and intensity. Those include weather conditions, climate conditions, topography, wind, surface fuels, drought, and fire behavior. The intensity of fires and the rate with which they spread is directly rated to the wind speed, temperature, and relative humidity. Climatic conditions such as long-term drought also play a major role in the number and intensity of wildfires, and topography is important because the slope and shape of the terrain can change the rate of speed at which fire travels.

Climate Change Trends

Interestingly, the HMP mentioned the many variables that affect wildfire, yet only focused on fuels in their assessment. Because climate plays a large role, emissions reductions also contribute to reducing wildfire risk over a longer timeframe.

The growing number of people in wildlands is increasing the risk to life, property and public health. One of the primary impacts associated with wildfire is from air quality associated with smoke. Smoke can cause eye and respiratory illness, especially among children and the elderly. Wildfires can also hasten ecosystem changes and release large amounts of carbon dioxide into the atmosphere—contributing to further climate change.

Large wildfires in the United States burn more than twice the area they did in 1970, and the average wildfire season is 78 days longer.[42] Research shows that changes in climate, especially earlier snowmelt due to warming in the spring and summer, have led to hot, dry conditions that boost this increase in fire activity in some areas. Although land use and firefighting tactics can play a role in lowering or raising risks, observed and anticipated changes in climate are expected to continue to increase the area affected by wildfires in the United States.

The Southeast has the largest proportion of area burned by prescribed fire. Rising temperatures and increases in the duration and intensity of drought, however, are expected to increase

[42] Vose, J. M., et al. 2018. Forests. *In* Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Reidmiller, D.R., et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA.

wildfire occurrence and also reduce the effectiveness of prescribed fire.[43,44] A combination of drought and increased fire activity are expected to transform the forests of the Southeast, but specific timeframes and vegetation changes are unknown. Little information is available on the future expected trends in wildfire in the eastern U.S., making it difficult to determine the change in wildfire risk specific to Louisville.

Climate Risk

Based on the best available scientific information and trends, it is unknown whether wildfire risk will increase, decrease, or remain similar with climate change. With higher temperatures and increased likelihood of drought, however, wildfire is likely to remain a significant risk. In the HMP, the risk score for wildfire was based on the amount of vegetation of at least 3 acres, as well as the historical number of wildfires. Climate impacts to this risk are likely to be similar across the entire region, although different types of vegetation could respond differently to widespread climate impacts such as drought and heat.

[43] Addington, R. N., et al. 2015. Relationships among wildfire, prescribed fire, and drought in fire-prone landscapes of the southeastern U.S. International Journal of Wildland Fire 24:778-783.

[44] Liu, Y., J. Stanturk, and S. Goodrick. 2010. Trends in global wildfire potential in a changing climate. Journal of Forest Ecology and Management 259: 685-697.

DAM/LEVEE FAILURE

From the HMP

Dams have many benefits, but they can also pose a risk to communities if not designed, operated, and maintained properly. In the event of a dam failure, the energy of the water stored behind even a small dam is capable of causing loss of life and great property damage if there are people downstream of the dam.

There are 40 Louisville Metro dams maintained by the Army Corps of Engineers and the Kentucky Cabinet for Natural Resources and Environmental Protection, Division of Water. Nine dams are classified as Class C, or high hazard class. An additional 13 are classified as Class B, or moderate hazard class. Most of the risk is located along the length of the west end of the Louisville Metro area.

Dams and levees are often built for flood protection and are designed to withstand a flood with a computed risk of occurrence, or certain probability of occurring in any one year.

Climate Change Trends

Risk of dam and levee failure, due to larger and more frequent storms, as well as delayed and inadequate dam maintenance, is increasing nation wide. Throughout the Midwest, levees have been breached repeatedly as rivers reach historic levels. In California, major dams are five times more likely to flood than they were last century, due to climate change.[45]

From the Flood (see next section), Severe Storms, and Karst/Sinkhole sections of this addendum, it is apparent that precipitation and large storms have been increasing and are expected, based on model projections, to continue to increase.

Climate Risk

Based on the best available scientific information and trends, it is likely that Louisville Metro's dams will be affected by climate change. Increasing frequency and magnitude of large storms is likely to push more dams into Class C (High hazard class), thereby requiring an Emergency Plan. It can also increase the likelihood of any one dam failing, especially those already listed as Class C. Dam failure can cause serious flooding and damage to lives and property.

While this increase in risk of dam/levee failure cannot be well quantified at this time, models (see Flood section) do indicate that long-term changes in precipitation could lead to 2.5 to 3.5 times the flood risk for 100-year floods. The HMP did not indicate the frequency or magnitude for which the dams and levees were rated. This vital information would be needed in order to determine whether additional dams and levees need to be reclassified as Class C.

---

[45] Mallakpour, I., A. AghaKouchak, and M. Sadegh. 2019. Climate induced changes in the risk of hydrological failure of major dams in California. Geophysical Research Letters 46:2130-2139.

FLOOD

From the HMP

Floods are generally the result of excessive precipitation, and can be classified under two categories: (1) flash floods, the product of heavy localized precipitation in a short time period over a given location; and (2) general floods, caused by precipitation over a longer time period and over a given river basin.

Flooding is the most significant, and costly, natural hazard in Kentucky. The severity of a flooding event is determined by a combination of stream and river basin topography and physiography, precipitation and weather patterns, recent soil moisture conditions and the degree of vegetative clearing. Flood currents also possess tremendous destructive power as lateral forces can demolish buildings and erosion can undermine bridge foundations and footings, leading to the collapse of structures.

Flash flooding events usually occur within minutes or hours of heavy amounts of rainfall, from a dam or levee failure, or from a sudden release of water held. General floods are usually longer-term events and may last for several days. The primary types of general flooding include riverine flooding and urban flooding.

Periodic flooding of lands adjacent to rivers, and streams is a natural and inevitable occurrence that can be expected to take place based upon established recurrence intervals. The recurrence interval of a flood is defined as the average time interval, in years, expected between a flood event of a particular magnitude and an equal or larger flood. Flood magnitude increases with increasing recurrence interval.

Climate Change Trends

Flooding is often preceded by extreme rainfall. The risk associated with extreme rainfall is exacerbated in urban areas, where impervious pavement forces water to run off quickly, filling sewer systems and causing rivers and creeks to swell. Because Louisville is situated along the Ohio River, most of the flood risk comes from riverine flooding. River flooding occurs from snowmelt and rainfall both within the Metro area, as well as upstream.

Extreme rainfall has increased in frequency and intensity in the southeastern U.S. Scientists expect these trends to continue as the planet continues to warm. For each degree of warming, the air can hold about 7% more water vapor. This can lead to larger storms with more precipitation, which is already being seen. The region has experienced a 16% increase in the amount of rain falling during extreme storms. The number of days with more than 3 inches of precipitation has also increased across the region (Fig. 19).

According to the National Climate Assessment, there is high confidence (based on high model agreement) that extreme rainfall will continue to worsen over time with climate change. With

continued higher emissions (RCP 8.5), model projections show a doubling in the number of heavy rainfall events and 21% increase in the amount of rain falling during those events.

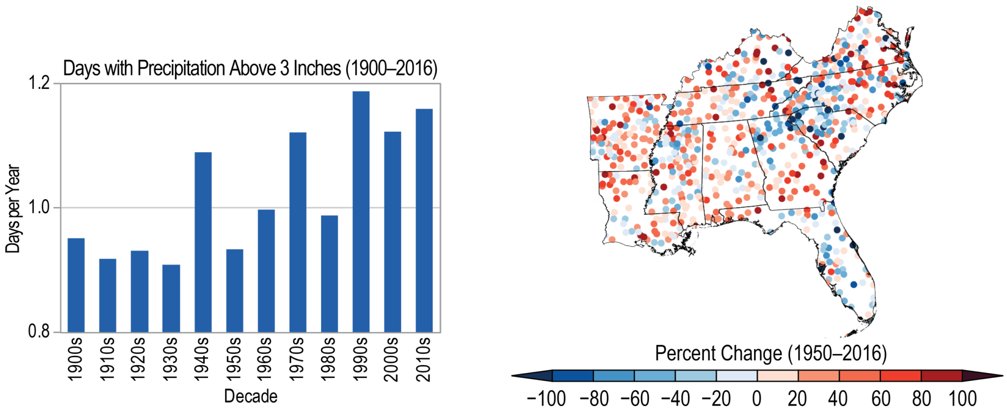


Figure 19. The average annual number of days with more than 3 inches of precipitation has been increasing across the Southeast, especially in the most recent decade. Figure adapted from Carter et al. 2018.[35]

Similar to the rest of the region, precipitation has been increasing in Louisville since about the 1980's. Data from the Louisville International Airport weather station shows that all three of the wettest years on record have occurred within the last decade (Fig. 20). When comparing the most recent 30-year period (1989-2018) with the historical period of 1961-1990, the amount of precipitation in the largest storm has increased by 12% in Louisville.

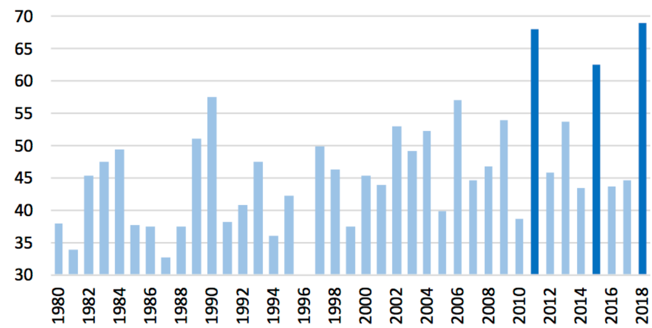


Figure 20. Average annual precipitation, in inches, each year since 1980. Precipitation was measured at the Louisville International Airport weather station.

A study assessing flood risk at the national level provided data on potential flood risk for Louisville Metro.[46] Of note is the fact that these data provide only rough estimates of the potential increase in flood frequency based on climate change model projections. Because of the national scale of the analysis, this dataset does not include localized specificity that is needed to map local trends. However, we can use such data to get an idea about the overall magnitude of change that is projected with climate change in this area.

With continued higher greenhouse gas emissions (RCP 8.5), 100-year flood events are expected to become 2.5 times to 3.5 times more frequent, as compared to the baseline (1950-2000) throughout much of the Louisville Metro region (Fig. 21). Of note is the fact that 100-year flood frequencies can be limited to 1.0 to 1.5 times more frequent if emissions are reduced (Figure 22), saving $4 billion per year in flood damages at the national level.

[46] Wobus, C. et al. 2017. Climate change impacts on flood risk and asset damages in mapped 100-year floodplains of the contiguous U.S. Natural Hazards and Earth Systems Science 17:2199-2211.

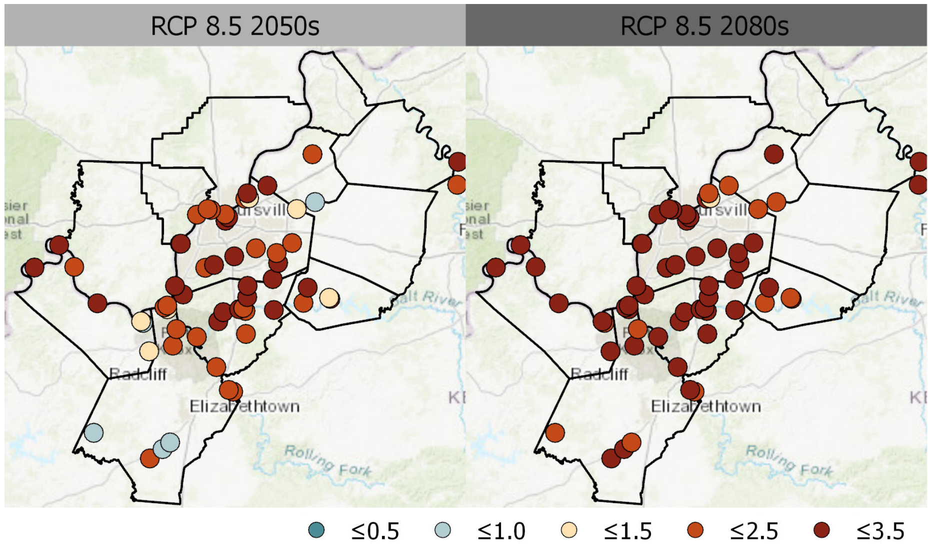


Figure 9. Change in frequency of historical 100-year flood events based on global climate model projections and continued higher emissions (RCP 8.5) for mid-century (2050s) and late-century (2080s). From Wobus et al. 2017.

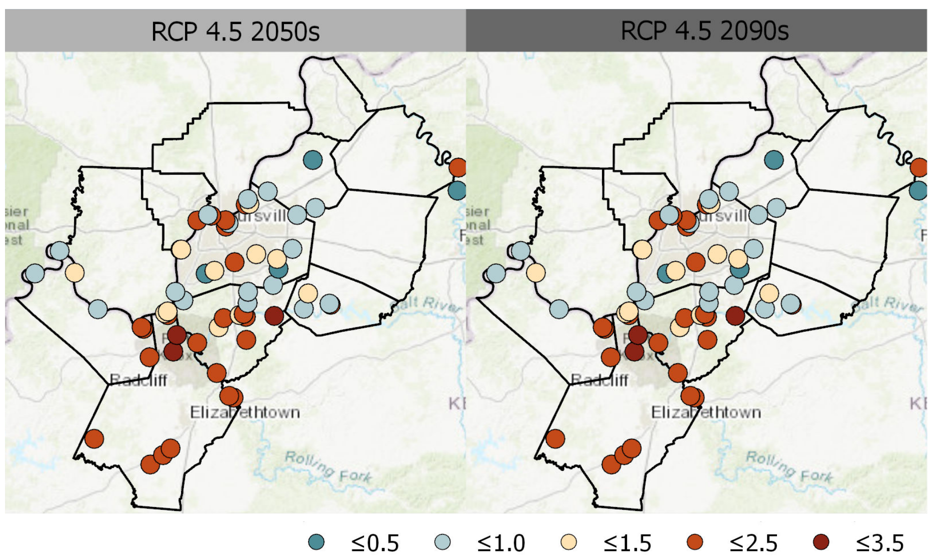


Figure 10. Change in frequency of historical 100-year flood events based on global climate model projections and lower emissions (RCP 4.5) for mid-century (2050s) and late-century (2080s). From Wobus et al. 2017.

Climate Risk

Based on the best available scientific information and trends, it is highly likely that flood risk is already increasing and will continue to worsen with climate change. These impacts cannot be mapped for geographic specificity at this time, but spatial analysis that includes projected changes in precipitation and extreme precipitation events could be conducted. Changes in precipitation for the larger area, including upstream on the Ohio River, would need to be conducted to fully assess future flooding potential.

AIR QUALITY

Air quality was not included as a hazard in the 2016 Louisville Metro Hazard Mitigation Plan. The research conducted for this climate impacts addendum, however, revealed that the link between air temperature and air quality was significant enough to warrant inclusion as a stand-alone hazard. Air quality impacts associated with ground level ozone already account for tens of thousands of hospital visits, millions of cases of acute respiratory symptoms, and thousands of premature deaths each year in the U.S.[47]

Higher temperatures associated with climate change leads to increased rate of formation of ground-level ozone.[48,49] In addition, this reduces the effectiveness of emission reductions taken to achieve air quality standards, a phenomenon known as the "climate penalty."[50] Unless offset by additional and even stricter emissions reductions, these increases in ozone will cause more premature deaths, hospital visits, acute respiratory symptoms, heart disease, and lost school days.[51]

Climate Risk

Based on the best available scientific information and trends, it is highly likely that ozone formation is already increasing and will continue to worsen with climate change. These impacts cannot be mapped for geographic specificity at this time, but spatial analysis that includes projected changes in temperature as well as historical data on ozone-related health impacts could allow spatial mapping of this risk.

---

[47] Fann, N. et al. 2012. Estimating the national public health burden associated with exposure to ambient 2.5 and ozone. Risk Anlaysis 32: 81-95.

[48] Jacob, D. J., and D. A. Winner. 2009. Effect of Climate Change on Air Quality. Retrieved from https://dash.harvard.edu/handle/1/3553961

[49] Mickley, L. 2007. A future short of breath? Possible effects of climate change on smog. Environment *49*: 32–43.

[50] Rasmussen, D. J., J. Hu, A. Mahmud, & M. J. Kleeman. 2013. The ozone-climate penalty: past, present, and future. Environmental Science & Technology *47*: 14258–14266.

[51] Fann, N. et al. 2016. Chapter 3: Air Quality Impacts. The Impacts of Climate Change on Human Health in the United States. A Scientific Assessment. U.S. Global Change Research Program. Washington D.C. Pp. 69-98.