Climate Trends Primer:
Louisville Metro Region, Kentucky

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Introduction

People around the world are experiencing changing conditions that affect their daily lives. Many changes are due to human-caused climate change, resulting from combustion of fossil fuels and deforestation. Climate change is a global problem, yet the impacts and opportunities for action are local. As climate change accelerates with continued greenhouse gas emissions, local communities will need to be prepared for impacts and take action to protect people and the natural resources they depend on. Like other parts of the U.S., Louisville is experiencing rapid change in climate, and people are seeking strategies to increase safety, wellness and resilience.

In Louisville, residents report changes in severe storms and rainy weather, extreme events like heat waves, timing of the seasons, water availability, and plants and wildlife. All of these changes can affect peoples' health, culture, and livelihoods. Local infrastructure such as roads and bridges are also at risk from severe heat, storms, and flooding. Many changes are already occurring, and many more are expected to occur in the future.

If global action to greatly reduce greenhouse gas emissions is taken quickly, the long-term severity of climate change will be reduced, and local strategies to adapt will be more successful. Even if action is taken, however, the next few decades are expected to experience drastic change because

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of long-lasting greenhouse gases already emitted. Local action and planning to reduce the impacts of climate changes are needed.

This climate change primer provides information on the expected trends and impacts expected with climate change specific to Louisville and the 12-county region surrounding the Metro area (Figure 1). Understanding climate change trends and impacts is the first step in identifying climate-related risks and vulnerabilities. The next step will be to develop strategies that build overall resilience for both people and natural resources of the region.

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What Climate Change Means for Louisville

The climate is what defines any given locality and, for many of us, makes it home. There are many vulnerabilities associated with climate change, some more predictable than others. Some predicted impacts of continued climate change in Louisville include:

- In 60 years, Louisville will experience a climate similar to today's Bastrop, LA, Jackson, MS, or Montgomery, AL[1]
- Worsening of severe storms and flooding causing impacts to property, health, and safety[2]
- Lower and warmer streams, degradation of aquatic habitat, and impacts to water quality[2]
- Greater incidence of drought, leading to loss of commercial river transportation and revenue[3]
- Warmer waters increasing the incidence of vector- and water-borne disease, including Zika, West Nile virus, Dengue, and chikungunya[2]
- Disruption and damage to transportation infrastructure, energy infrastructure, and real estate from heat and flooding[2]
- Increased disruptions in electric supply with heat waves and drought[3]
- Reduced air quality as heat increases ground level ozone, which is associated with heart and respiratory disease[2]
- Longer and more severe heat waves affecting the elderly, outdoor workers, infants, homeless residents, and other vulnerable groups[5]
- Increased stress and incidence of mental illness, especially associated with prolonged periods of heat, flooding, and other extreme events[2]
- Increase in economic and racial inequities due to uneven distribution of climate impacts
- Loss of fish and wildlife habitat and forest diversity[2]
- Loss of important benefits from natural systems, including water filtration, flood abatement, and recreational opportunities[2]

Falls of the Ohio / US Army Corps of Eng / Katie Newton, Flickr / CC BY 2.0

Louisville Metro Area

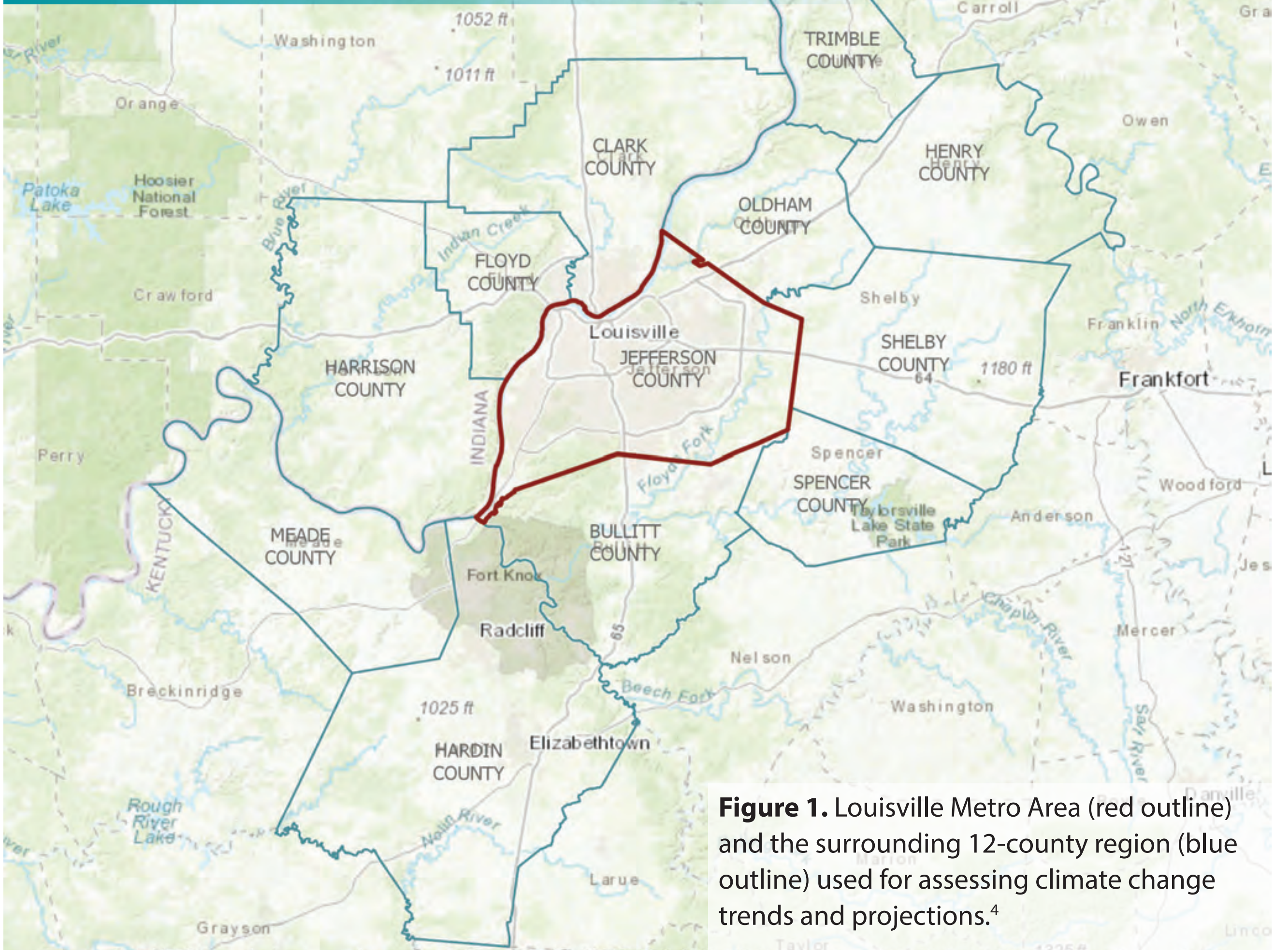


Figure 1. Louisville Metro Area (red outline) and the surrounding 12-county region (blue outline) used for assessing climate change trends and projections.[4]

Climate Trends Snapshot – Louisville, KY

HISTORICAL TRENDS[6] (change since 1961–90)

- Temperature +2.2° F
- Minimum temp. +5.5° F
- Precipitation +9%
- Snowfall –25%
- Two fewer weeks/year below freezing
- 12 additional days/year above 90° F
- 3 wettest years on record in the last decade

MID-CENTURY PROJECTIONS[4] 2040–2069

Averages:

- Temperature +5° to +8° F
- Summer temp. +4° to +11° F
- Precipitation –6% to +16%
- Summer precip. –17% to +11%
- Winter precip. -10% to +31%

Extremes:

- Extreme max. temp. +3° to +14° F
- Extreme min. temp. +6° to +10° F
- Number of frost-free days +35 to +57 days per year
- Moisture deficit (drought stress) +6% to +88%

LATE-CENTURY PROJECTIONS[4] 2070–2099

Averages:

- Temperature +7° to +12° F
- Summer temp. +7° to +17° F
- Precipitation –2% to +21%
- Summer precip. +9% to +14%
- Winter precip. –12% to +48%

Extremes:

- Extreme max. temp. +5° to +20° F
- Extreme min. temp. +9° to +15° F
- Number of frost-free days +53 to +75 days per year
- Moisture deficit (drought stress) +3% to +124%

Climate Change Data and Models

The Earth's climate is regulated by a layer of gases commonly referred to as greenhouse gases for their role in trapping heat and keeping the earth at a livable temperature. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and water vapor (H_2O). CO_2 plays an especially large role due to its long-lasting nature and amount compared to other gases (Fig. 1). The atmospheric concentration of CO_2 has risen from 280 to more than 415 parts per million (ppm) in the past century (Fig. 2), driven largely by the burning of fossil fuel, deforestation, and other human activity.

Information from ice cores allows us a glimpse into CO_2 levels over hundreds of thousands of years. This data shows us that CO_2 has fluctuated between about 175 and 300 ppm over the last 800,000 years and the current level of 415ppm is far above anything detected in that time period As CO_2 levels changed in the past, it has tracked closely with changes in temperature, and we can expect this relationship to hold in the future as CO_2 and other greenhouse gases continue to increase.

For over a century, we have known that increases in the concentration of greenhouse gases in the atmosphere result in warmer temperatures. Long-term tracking data from weather stations and other research support this expected trend. Traditional knowledge from indigenous communities around the globe also indicates that there has been significant change in conditions over time, especially since the end of the last ice age.

In order to look at projected future climate, we use computer models based on our understanding of the Earth's climate. The Intergovernmental Panel on Climate Change (IPCC), which is made up of thousands of leading scientists from around the world, has created a group of 25+ global climate models (GCMs) from different institutions with which to predict future trends.

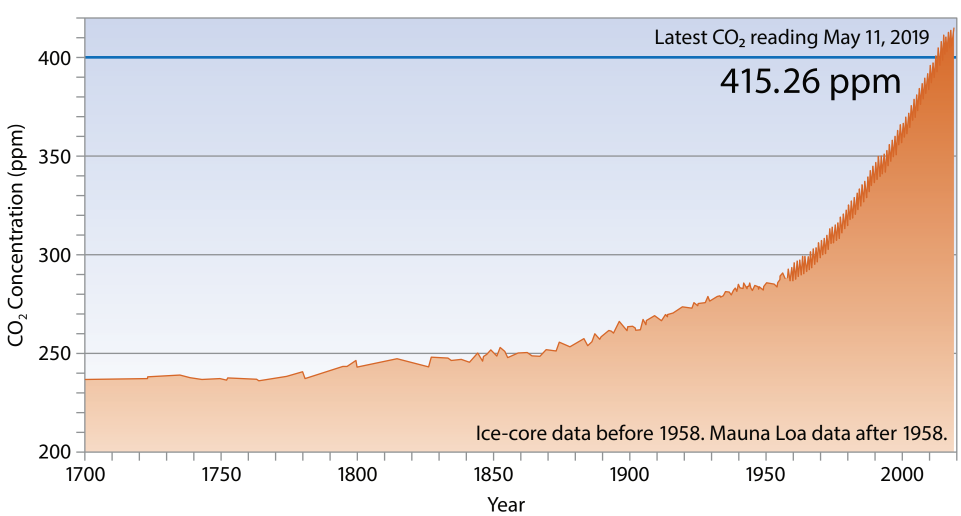


Figure 2. Carbon dioxide levels from 1700 to present. This is the highest in at least 800,000 years and probably over 3 million years. From Scripps Institute of Oceanography.

These models were created independently, and vary substantially in their output. Yet most of the uncertainty in future conditions comes not from the models themselves, but from estimating how much action will be taken to reduce greenhouse gas emissions in the future. The different possible greenhouse gas concentrations (called Regional Concentration Pathways, or RCPs), depend on whether or not the international community cooperates on reducing emissions. In this report, we provide projections based on a lower emissions pathway where emissions are greatly reduced (RCP 4.5) and a higher emissions pathway where emissions are only slightly reduced (RCP 8.5) and that is similar to the current global trajectory. These can also be thought of as best and worst case scenarios.

Many data on future trends in this report are compiled from an average across 15 climate models, which have been adjusted to reflect variation across the local landscape. When these averages are used, it is important to understand the models can vary greatly. In general, projections about rainfall are harder to predict (i.e. more variation among models) while temperature projections are associated with more certainty. Also, short- to mid-term projections are more reliable.

Global Trends

Global climate is changing quickly compared to past climate change throughout the Earth's history. Heat waves and rainfall are increasing in both how often they occur and how severe they are across most of the world.[7]

The hottest year on record was 2016, which was the third consecutive year that a new global annual temperature record was set (Fig. 3). The average global temperature across land and ocean surface areas for 2016 was 1.7° F (about 1° C) above the 20th century average.[7] The fourth hottest year was 2018.[8] The last few years have also seen record-breaking, climate-related weather extremes. In the U.S., there were 14 weather- and climate-related events that cost more than $1 billion each in 2018, making it the fourth largest total on record ($91 billion total) since 1980.[9]

Models project continued average global warming of 5.0° to 10.2° F (2.8° to 5.7° C) by the end of this century and continued warming for the next two centuries if emissions continue as they are today (Fig. 4).[7] Because higher latitudes (closer to the poles) warm faster than areas closer to the equator, the United States is expected to warm significantly more than the global average.

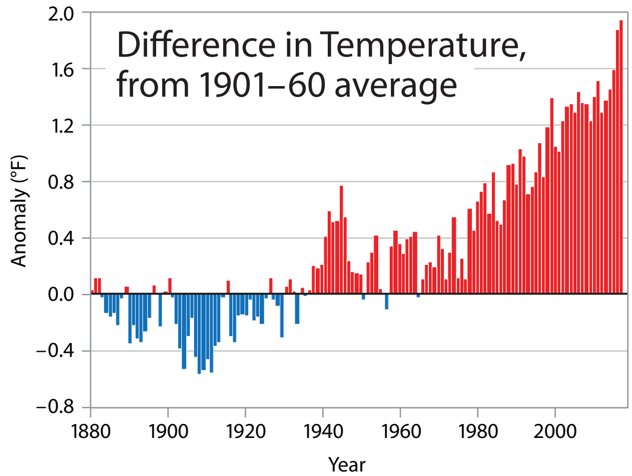


Figure 3. Average global temperature (left) has increased more than 1.7° F (1° C) compared to the historical average (1901–1960), shown as the horizontal black line. Red bars show temperatures above average, whereas blue bars show temperatures below average. Surface temperature change for the period from 1986–2016 is shown on the map on the below.[7] The eastern U.S. has warmed significantly less than most other areas around the globe.

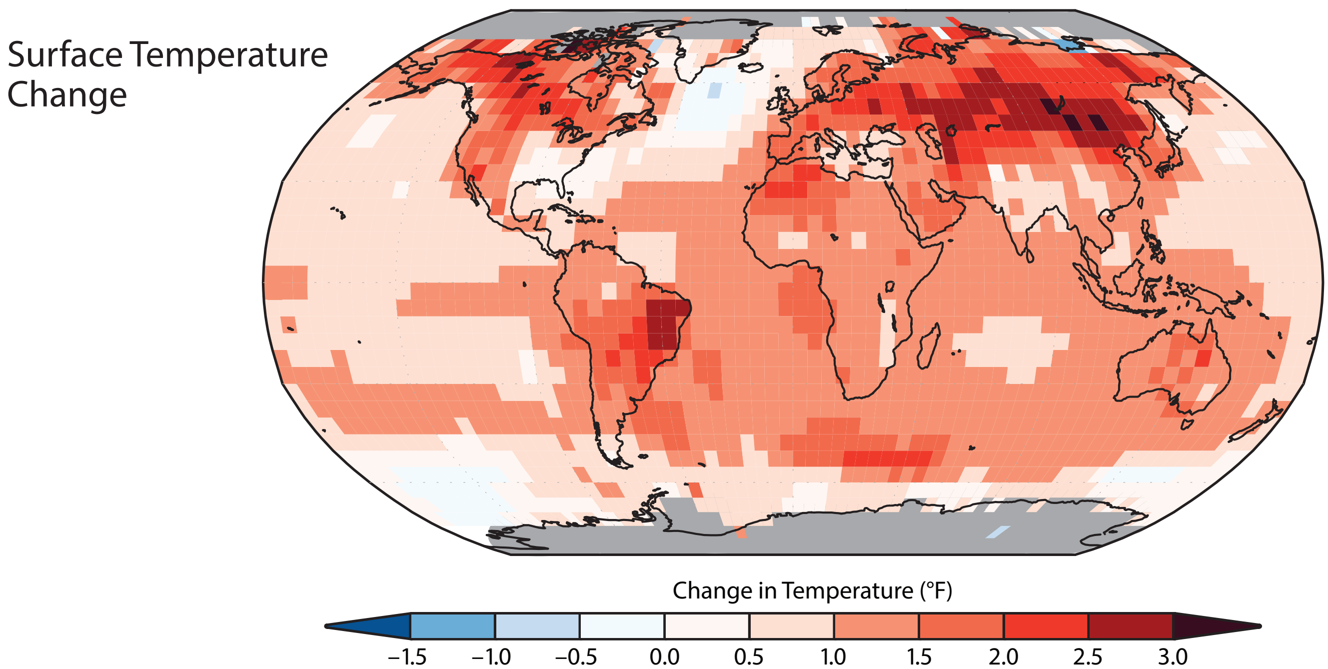
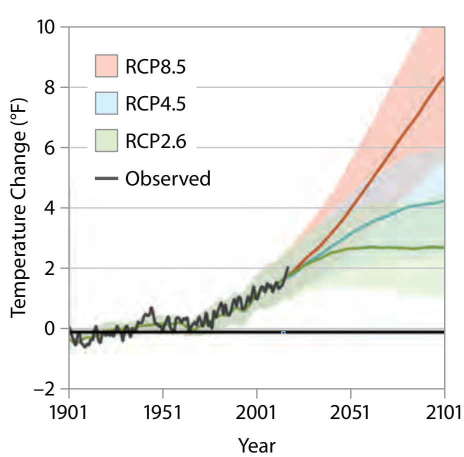
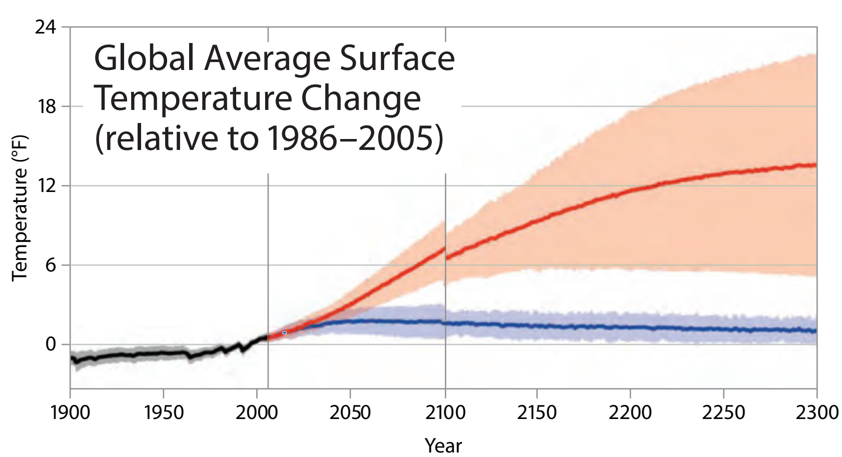


Figure 4. Whether or not people continue to emit large amounts of greenhouse gases will determine how warm the earth gets. By the end of this century (graph on the left), average global temperatures could increase anywhere from 1° F to more than 10° F, based on three different scenarios. Over longer timescales, warming would level off if emissions are reduced, or continue to rise (as much as 23° F) for many centuries if they continue unabated.





Green Roof / Metro Housing Authority

Historical Trends in the Southeastern U.S. and Kentucky

Temperature

Averages – Over the past 120 years, the southeastern U.S. has warmed much more slowly than the rest of the U.S., with average annual air temperature increasing by 0.5° F (Fig. 5),[2] average high temperature by 0.2° F, and average low temperature by 0.8° F.

Frost-free season – The "frost-free season" is the period between the last freezing temperature of the spring and first freezing temperature of the fall. This period is important for many crops

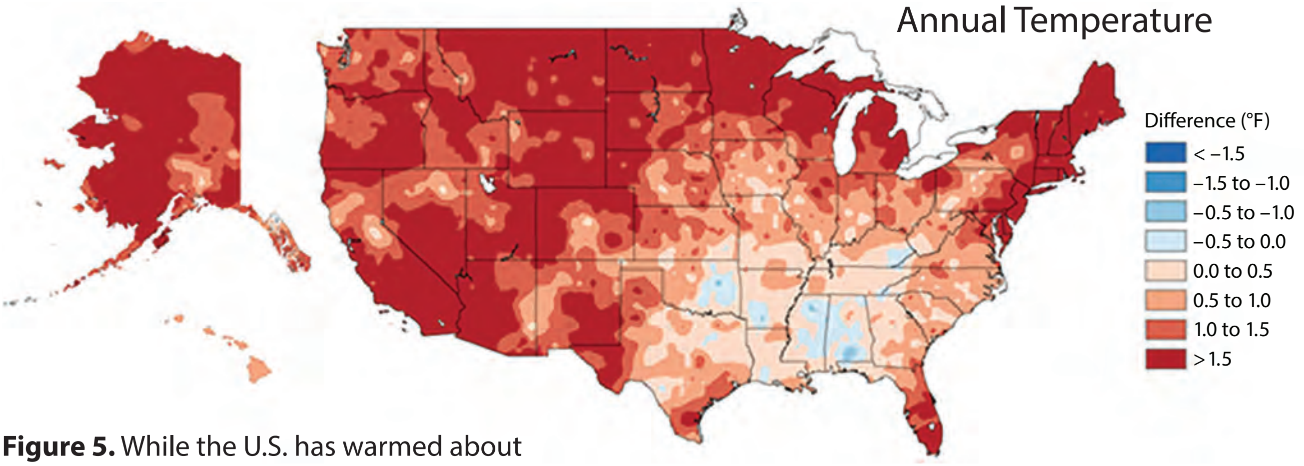


Figure 5. While the U.S. has warmed about 1.2° F on average, the southeastern U.S. has seen the least warming, increasing only about 0.5° F on average, since 1901–1960.[7]

that require a certain number of freezing nights to produce fruit. It can also affect the length of the growing season, pest outbreaks, and fish and wildlife populations. While less pronounced than the rest of the U.S., the Southeast has experienced an increase in the length of the frost-free season as compared to the historical period of 1901-1960 (Fig. 6). The frost-free season in the southeast is now 10 days longer, on average.[7] In addition, most of Kentucky has now moved into Zone 7 of the plant hardiness zone map, up from Zone 6 on the 1990 map.[10]

Victorian Houses, Old Louisville / Wikimedia, Angry Aspie, Public Domain

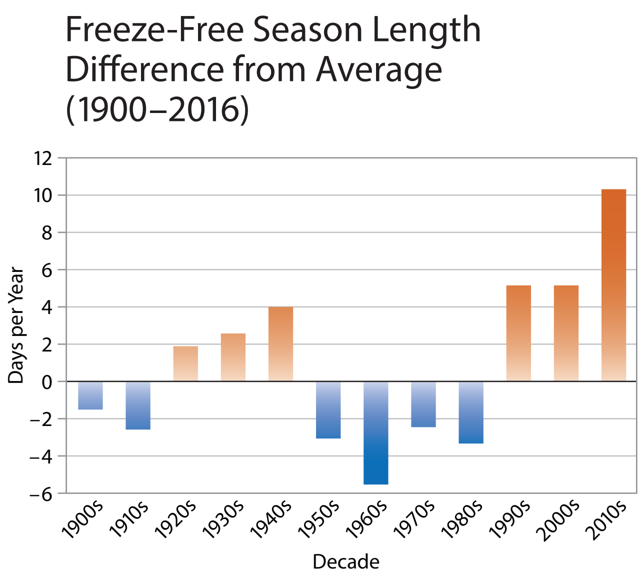


Figure 6. Changes in the length of the frost-free period, across the southeastern U.S.[7]

Tyler Park, Louisville / CC BY-SA 3.0

Severe heat – Cities across the southeast are experiencing more and longer summer heat waves. Sixty-one percent of major southeastern cities are exhibiting worsening heat waves – a higher percentage than any other region of the U.S.[2]

Precipitation

Averages – Annual average precipitation (rainfall and snowfall) is increasing across the U.S., with the largest increases in the fall and lowest in winter. Variation between years is substantial and often linked to large climate patterns and fluctuations such as multi-year droughts, El Niño patterns, and others. Regionally, Louisville has experienced some of the largest increases in precipitation (Fig. 7).

Extremes – Extreme precipitation is also increasing throughout the nation and region. The number of days per year with precipitation above 3 inches has continued to rise (Fig. 8). In addition, since 1958, the amount of precipitation during heavy rainstorms has increased by 27% in the southeastern U.S.[4] This trend is expected to continue.

Days with Precipitation Above 3 Inches (1900–2016)

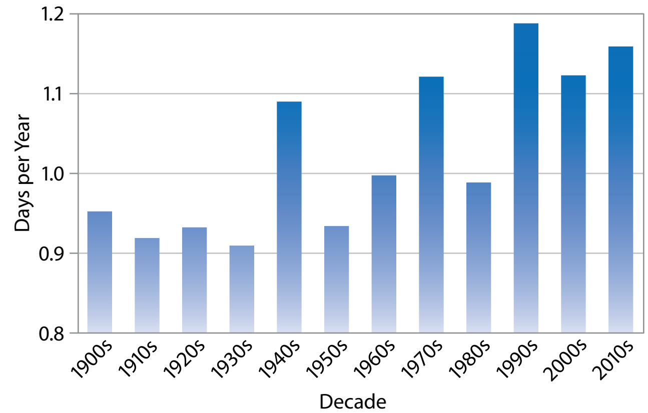


Figure 8. The number of days per year, on average, with more than 3 inches of precipitation, has increased in the southeastern U.S.[7]

Percent change in annual precipitation

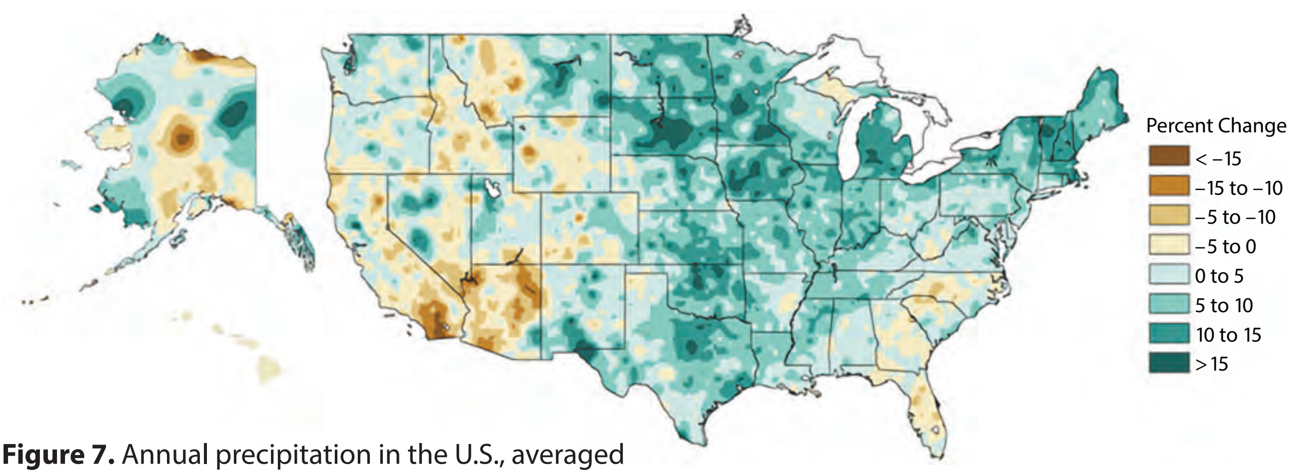
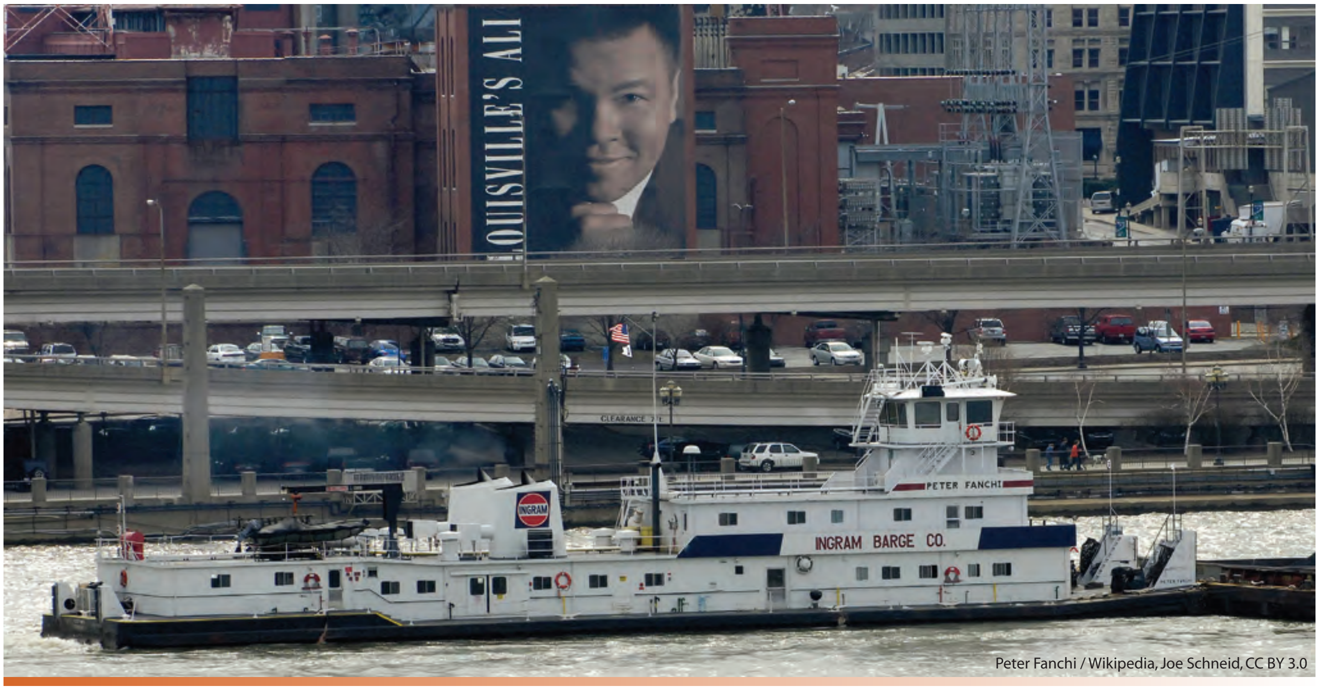


Figure 7. Annual precipitation in the U.S., averaged from 1986-2015, has increased about 4% compared to 1901-1960.[7]



Historical and Future Trends in the Louisville Region

Temperature

Historical – Average temperature in Louisville was calculated for two 30-year periods: 1961-1990 and 1989-2018. Over these periods, average temperature has increased 2.2° F (Fig. 9). While the extreme maximum temperature has only increased by 1° F, on average, (from 96.6° F to 97.6° F), the extreme minimum temperature has increased by 5.5° F on average (from -2.3° F to 3.2° F). The average number of days per year with temperatures above 90° F has increased by 12 days. The average number of nights dropping below 32° F has declined by 14 days.

Averages – Average annual temperatures in Louisville and the surrounding area are expected to rise an additional 6° F by mid-century (2040-69) and 10° F by late-century (2070-99), as compared to the historical period (1961-1990), based on an assumption of continued high greenhouse gas emissions. Lowered emissions result in substantially less warming by late-century (Fig. 10).

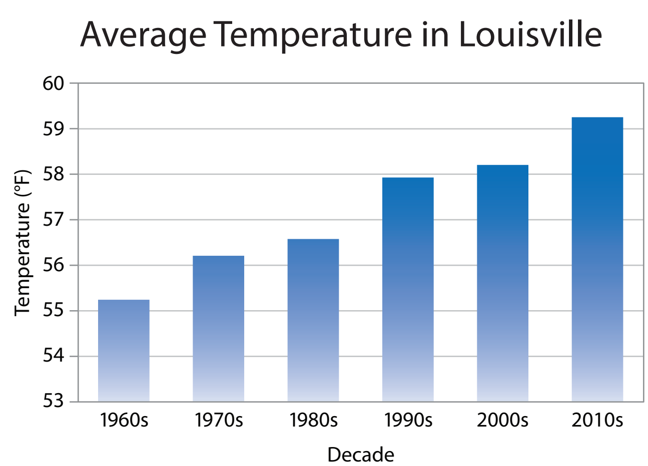


Figure 9. Average temperature (in degrees Fahrenheit) in Louisville from 1960-2018.[6]

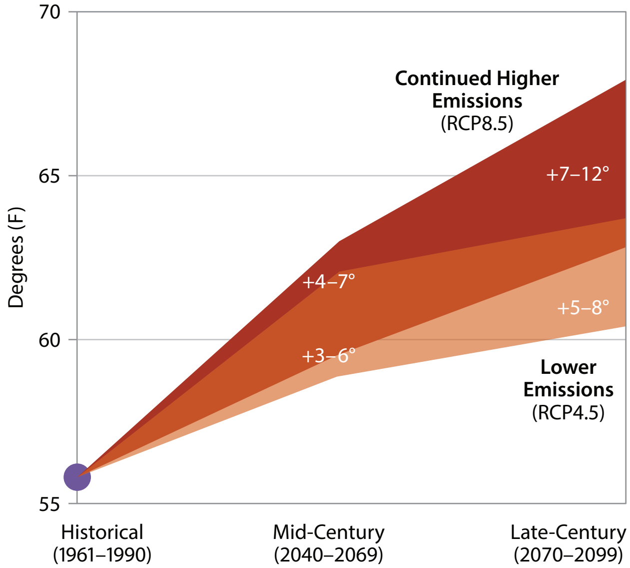


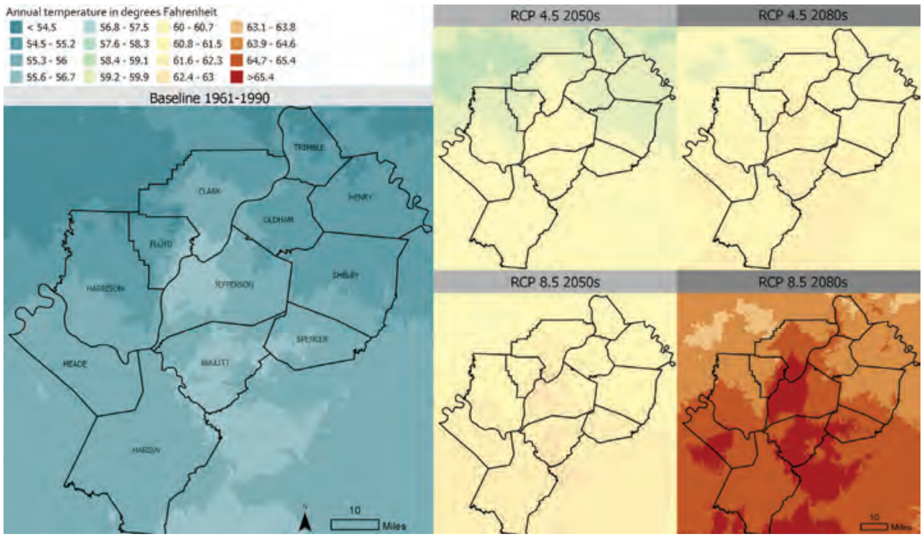
Figure 10. Average warming across the Louisville Metro region. Warming shown for two future time periods, mid-century (2040-69) and late-century (2070-99), based on a lower emissions pathway (RCP4.5) and higher emissions pathway (RCP8.5). Data based on 15-model ensemble from ClimateNA.[4]

Summers are expected to warm more than winters (Figure 11). By mid-century, summers are expected to be 8° F warmer on average (range of 5-11° F) and winters 5° F warmer (range of 4-6° F). By late-century, summers are projected to be 12° F warmer on average (range of 7-17° F) and winters 8° F warmer (range of 7-9° F).

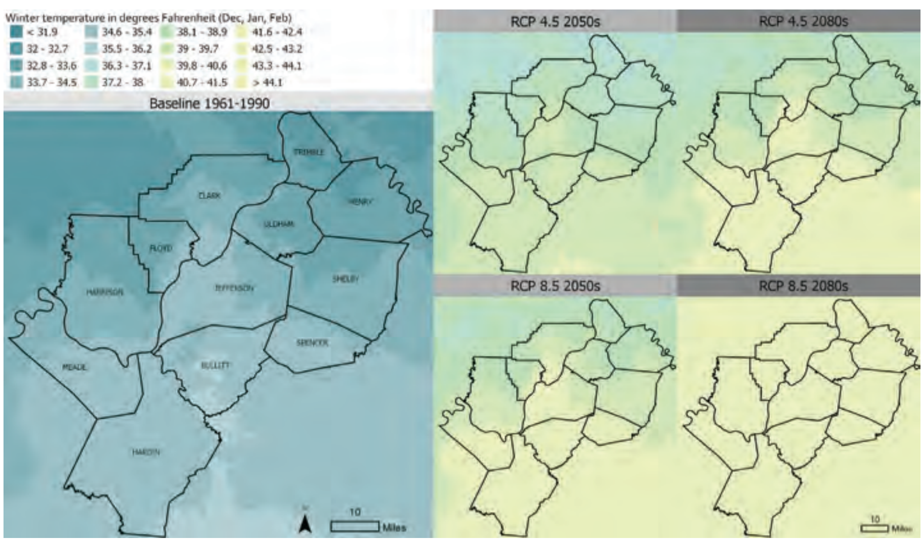
Frost-free season – The number of frost-free days each year is expected to increase from 225 (historical) to 271 by mid-century and 289 by late-century.[4] The length of the frost-free period is projected to be two full months longer by late-century. Longer frost-free season can have both positive and negative impacts. Some crops cannot be grown without sufficient nights below freezing. And longer growing seasons can stress water systems. However, longer growing seasons can mean more farming revenue from the same plot of land.

Broadfields Planting

Average Annual Temperature



Average Winter Temperature



Average Summer Temperature

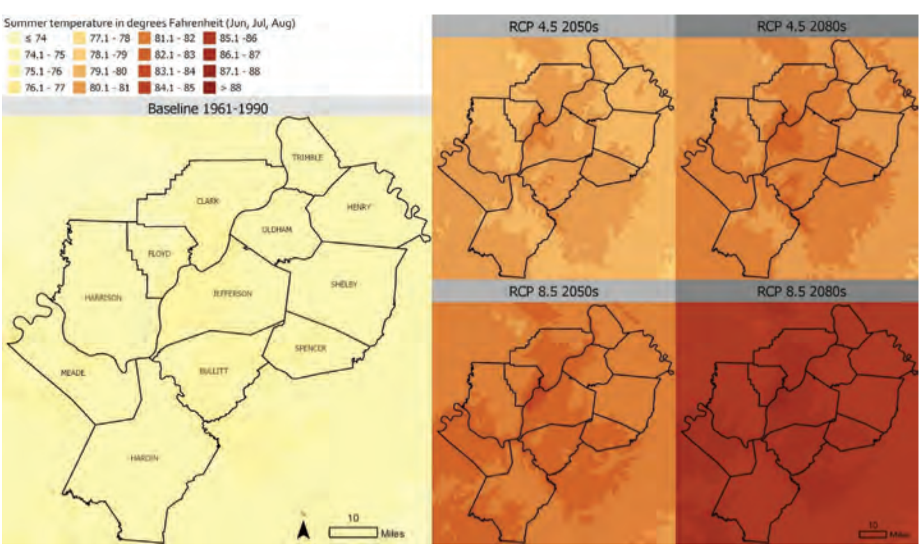


Figure 11. Historical and future projected temperature across Jefferson County and the surrounding region when we reduce our emissions substantially (RCP 4.5) and when emissions remain higher (RCP 8.5). Average annual temperature (top), winter temperature (middle) and summer temperature (bottom) are all shown in degrees Fahrenheit. Data from 15 model ensemble available through the ClimateNA version 5.21 software package based on methodology described by Wang et al.[4]

Severe heat – Exposure to dangerously high temperatures are a health threat expected to increase with climate change. Heat waves have become hotter and longer in Louisville (Fig. 12) and are expected to continue to worsen.[6]

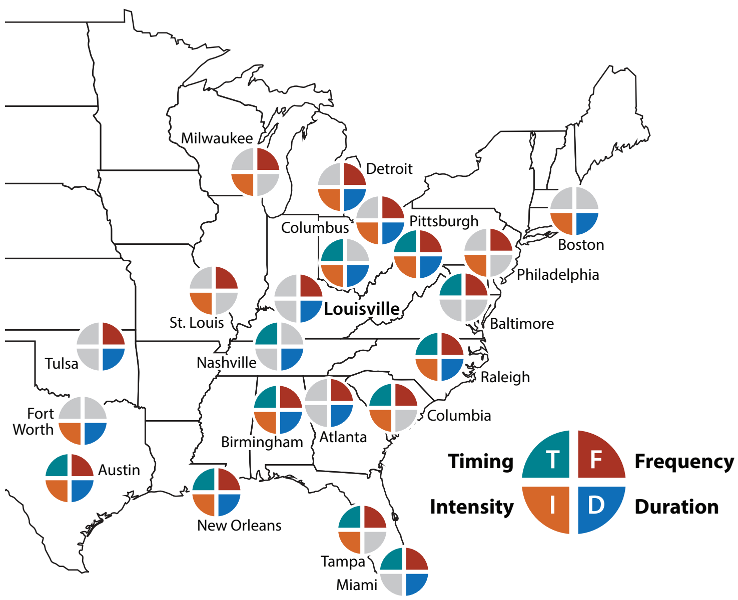
The extreme maximum temperature is expected to increase by 3-14° F (to 113° F on average) by mid-century, and by 5-20° F (to 117° F on average) by late-century.[4] Overall, the number of deaths attributed to extremely hot and/or cold days is expected to increase through the end of the century (Fig. 13).

Precipitation

Historical – Average precipitation in Louisville was calculated for two 30-year periods: 1961-1990 and 1989-2018.[5] Over these periods, average precipitation has increased 9% (Fig. 14). In contrast, average snowfall has declined by 25%.

Average – Precipitation is projected to increase 5% by mid-century on average (range from a 6% decline to 16% increase) and 9% by late-century on average (range from a 2% decline to a 21% increase), assuming continued higher greenhouse

Figure 12. This map shows the significant trends in increasing heat wave timing, intensity, frequency, and duration for major cities of the eastern U.S., from 1961-2010. Louisville shows significant increase in both frequency and duration. Map adapted from Habeeb et al. 2015.[11]



Change in Mortality Rate (deaths per 100,000 people)

Figure 13. Estimated changes in annual net mortality rate due to extremely hot and cold days in 49 U.S. cities for 2080-2099, as compared to the historical period of 1989-2000.[15,16] The nearest city to Louisville was Cincinnati, OH, which showed 8.1-10 additional deaths per 100,000 people with continued higher emissions (right map). These additional deaths are roughly halved if emissions are reduced (left map).

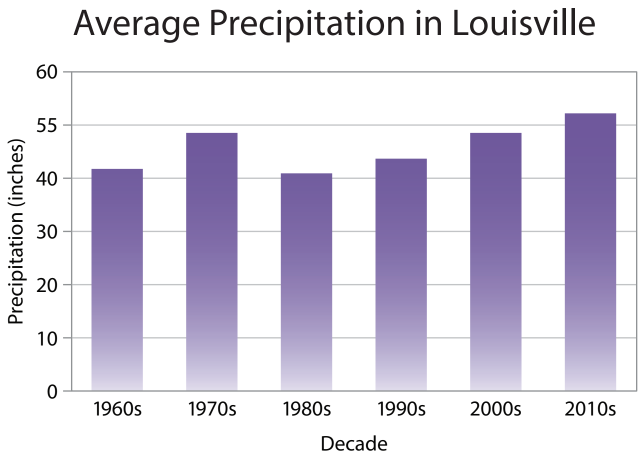


Figure 14. Average precipitation (in inches) in Louisville from 1960-2018.[5]

gas emissions (Fig. 15). Precipitation projections, however, have a high amount of variation among models, ranging from drier to wetter. Projections indicate potentially drier summers and wetter winters. Even with higher precipitation, however, water availability and soil moisture could decline due to increased evaporation from longer growing seasons and higher temperatures.

Drought Stress – Climatic moisture deficit measures how severe a drought is in terms of both temperature and precipitation. This measure is expected to increase over time by 10% to 18% by mid-century and by 10% to 21% by late-century (Fig. 12). Temperature rise can lead to higher evaporation, drier soils, and less runoff to rivers and streams.

Dominant Vegetation

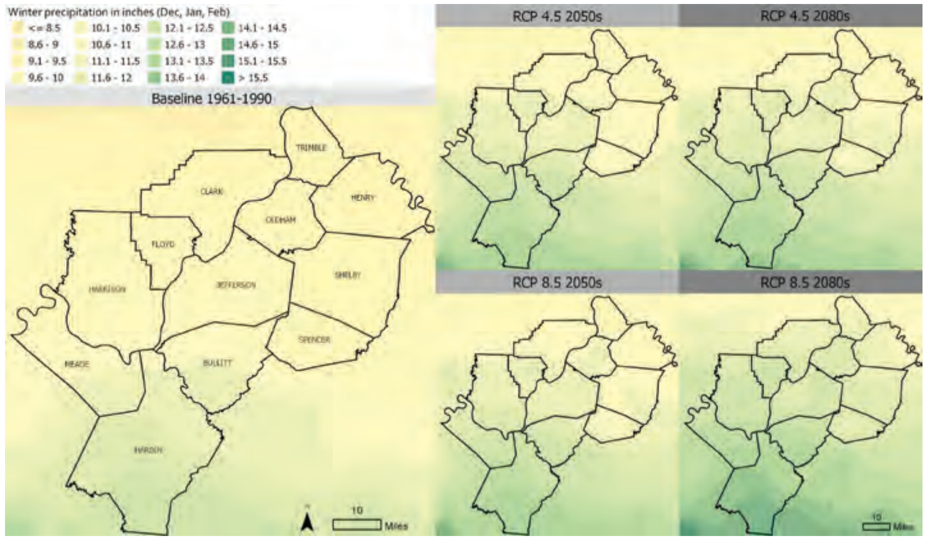
Louisville is in the Bluegrass region of Kentucky, which, prior to large-scale development, was dominated by a savannah of wide grasslands interspersed with deciduous forests. In general, the forests of the southeastern U.S. are expected to gradually change in vegetation type with climate change, with small scale disturbances occurring.[14] Some common native trees of the region include bur oak (*Quercus macrocarpa*), sycamore (*Platanus occidentalis*), white oak (*Quercus alba*), white ash (*Fraxinus americana*), hackberry (*Celtis occidentalis*), sugar maple (*Acer saccharum*), black walnut (*Juglans nigra*), honey locust (*Gleditsia triacanthos*), and shagbark hickory (*Carya ovata*).

Louisville loses 54,000 trees a year due to storms, invasive pests, development, and old age. Climate change could accelerate these losses by bringing in new pests and diseases, changing local conditions so that they are too wet, warm, and/or variable to support some common species, and/or increasing the frequency and severity of extreme events such as wind, flooding, drought, or tornadoes.

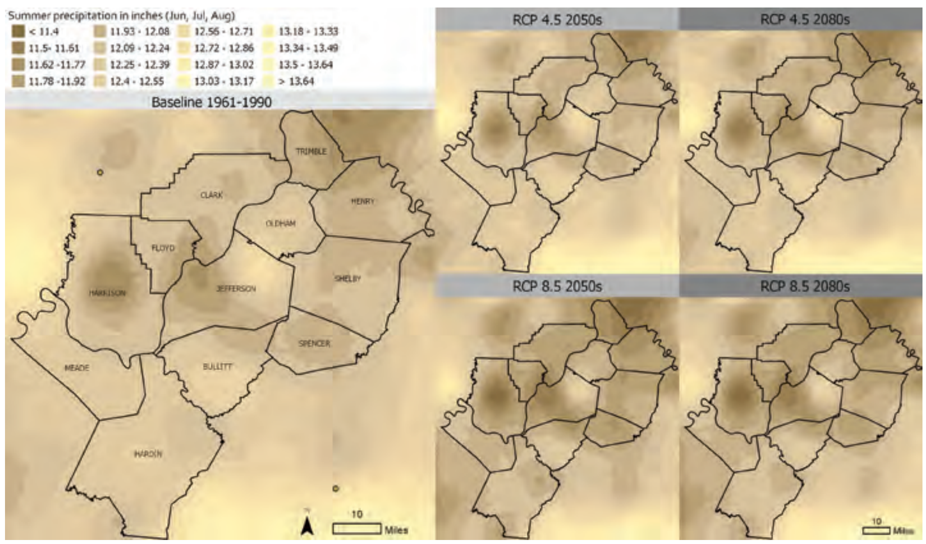
One study of "winners and losers" of climate change found that some of the tree species expected to decline in the Louisville region (based on changes in climate, not other

Figure 15. Historical and future projected precipitation across Jefferson County and the surrounding region when we reduce our emissions substantially (RCP4.5) and when emissions remain higher (RCP8.5). Average winter precipitation (top), average summer precipitation (middle) and climatic moisture deficit (drought stress; bottom) are all shown in inches. Data from 15 model ensemble available through the ClimateNA version 5.21 software package based on methodology described by Wang et al.[4]

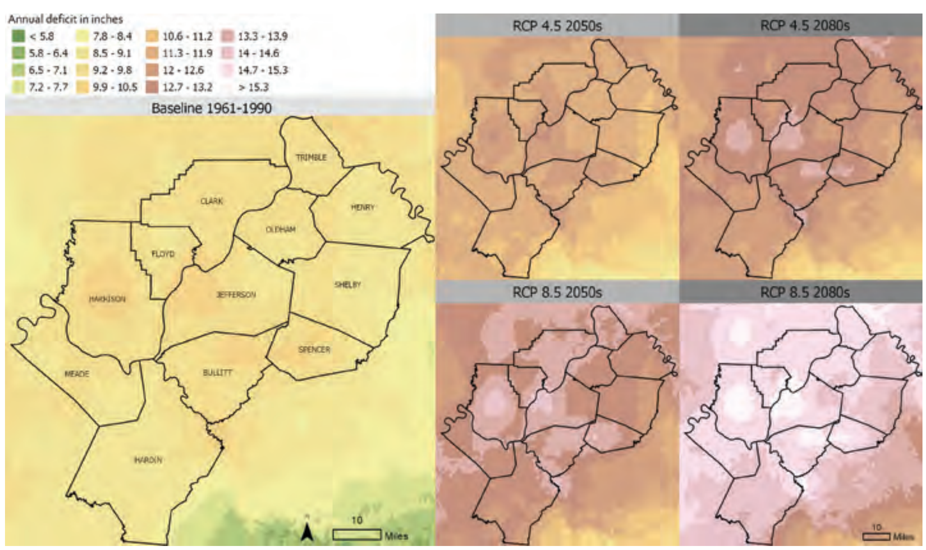
Average Winter Precipitation



Average Summer Precipitation



Average Climatic Moisture Deficit



ecological or social factors) include sugar maple (up to 92% decline), black walnut (up to 75% decline), and white oak (up to 27% decline).[15] In contrast, species expected to substantially increase in abundance include bitternut hickory (*Carya cordiformis*; up to 455%), boxelder (*Acer negundo*; up to 396% increase), and green ash (*Fraxinus pennsylvanica*; up to 90%).[15] As the climate warms and species shift, many species from further south and west could move into the area. Some species expected to become more common in the Louisville region include shortleaf pine (*Pinus echinada*), loblolly pine (*Pinus taeda;* Fig. 16), black hickory (*Carya texana*), sugarberry (*Celtis laevigata*), sweetgum (*Liquidambar styraciflua*), and blackgum (*Nyssa sylvatica*).[15]

Wildfire

Southeastern landscapes are dominated by privately-owned lands and relatively high human populations. These landscapes are expected to experience higher wildfire risk and longer wildfire season as climate change progresses.[16] Lightning-ignited fires are expected to increase by 30% by 2060, while human-ignited wildfire may decrease due to land use changes. More frequent and larger wildfires, combined with increasing development could lead to increasing risks to property and human life. They will also damage local economies and degrade air quality.

The MC2 model is a functional vegetation model that projects changes in natural vegetation types and their associated fire risk. Based on results from the MC2 vegetation model,[17] the projected change in average annual acres burned for the region surrounding Louisville is expected to be relatively small. The estimates are approximately the same regardless of the emissions scenario used (reduced emissions or higher emissions) and the future time period (2036-45 and 2076-85). Because it is strictly ecological, this model does not take into account human land use patterns, fire starts, or lightning strikes.

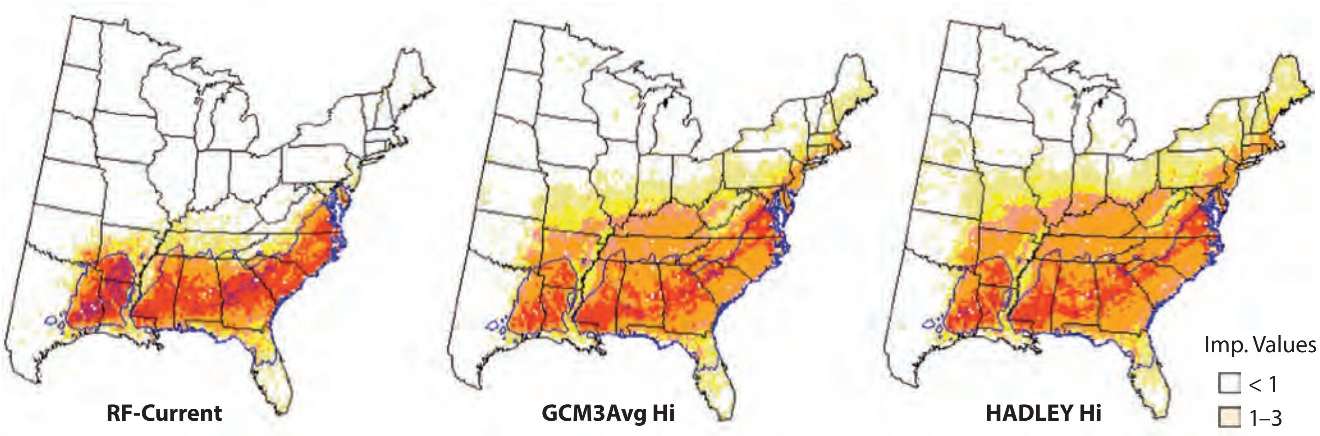


Figure 16. Loblolly pine has historically grown south of Kentucky. Data from the Climate Change Tree Atlas[12] shows how the range of loblolly pine is expected to shift northward if greenhouse gases aren't reduced. Modeled current (left) and future (center and right) range of loblolly pine is shown. Future projections are shown using 2 different models (center and right) and the continued higher greenhouse gas emissions scenario, averaged over 2071-2100 timeframe.

Ecosystem Services

Ecosystem services are the benefits that people gain from intact, healthy and functioning natural ecosystems. These may include water filtration from wetlands, natural flood abatement due to floodplains and meadows, opportunities for fishing, hunting and wildlife viewing, timber harvest, and others. Many ecosystem services are expected to be negatively impacted by climate change.

One of the more important ecosystem services provided by forests in the southeast, and directly affecting efforts to reduce greenhouse gas emissions, is the storage of carbon in vegetation. Increasing tree growth with warmer temperatures and higher CO_2 levels could lead to higher carbon storage rates, but is likely to be out-weighed by increases in forest disturbance expected from prolonged drought, larger storms, insect outbreaks, and other causes.[14]

Key to ecosystem services are intact native ecosystems. With increasing expansion of invasive species, however, ecosystem function is often compromised. Invasive species are often favored by climate change, due to warmer temperatures, increased disturbance, and reduced competitiveness of native species.[18]

Wetlands provide important ecosystem services throughout the southeastern U.S. Wetlands act to store flood waters and abate downstream flooding. They also filter pollutants and provide important wildlife habitat. With increasing temperatures, extreme events, and drought stress, wetlands are expected to become increasingly degraded over time, even with increases in precipitation.

Climate Comparisons

The overall climate of any specific locality is a combination of many individual climate and weather variables. These variables together make up what many people relate to as the defining feature of what they call home. As climate change progresses, it can be useful to identify a place on the map that has climate characteristics similar to those expected in the future. This place becomes a representation of the types of vegetation, natural systems, landscapes, and climate-related behaviors (such as use of air conditioning or outdoor recreation) that could be expected in the future. Cities that currently have a climate similar to that expected for Louisville in 60 years include Bastrop, LA (Fig. 17), Jackson, MS, and Montgomery, AL.[1]

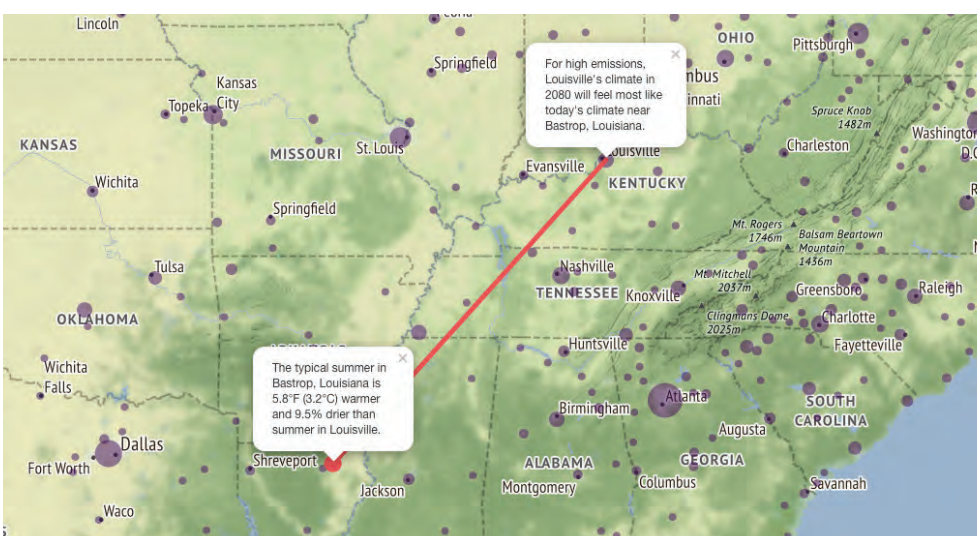


Figure 17. The city of Bastrop, LA has a climate most similar to the future climate of Louisville.

Conclusions

Towboat R.W. Naye upbound in Portland Canal / Wikipedia, William Alden III, CC BY SA 4.0

Climate change is already apparent throughout the U.S. and even in the Southeast, where warming has been slower than other regions. Indications of a changing climate include changes in wildlife populations, frequency of heat waves and floods, and spread of pests and disease.

Warming is expected to continue and to accelerate in the coming decades and century, as greenhouse gases already emitted continue to trap heat and change local weather patterns. The magnitude of late-century warming and impacts depends on whether or not local communities around the world collectively reduce emissions of greenhouse gases such as carbon dioxide and methane.

There is much we can do to reduce the overall impacts of near-term climate change, ensuring that the most vulnerable populations, resources, and infrastructure are protected and resilient to ongoing change. Our ability to adapt to long-term changes will depend heavily on how much we reduce emissions. This Climate Trends Primer is intended to inform the development of a Vulnerability Assessment and Climate Adaptation Plan for the Louisville Metro Area that results in strategies that increase overall resilience for both people and nature.

References

1. Fitzpatrick, M. C. and R. R. Dunn. 2019. Contemporary climate analogs for 540 North American urban areas in the late 21st century. Nature Communications 10:614.

2. Carter, L., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D. Marcy, M. Osland, and P. Schramm, 2018: Southeast. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. doi: 10.7930/NCA4.2018.CH19

3. EPA. 2016. What Climate Change Means for Kentucky. EPA Publication 430-F-16-019.

4. 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.

5. CDC. 2004. Extreme heat: a prevention guide to promote your personal health and safety. http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp

6. NOAA. National Centers for Environmental Information. Daily Summaries for the Louisville Kentucky Airport Weather Station. Accessed 5-1-2019.

7. USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.


ECHO Service Project Tree Planting

8. NASA News Release Feb 6, 2019. https://climate.nasa.gov/news/2841/2018-fourth-warmest-year-in-continued-warming-trend-according-to-nasa-noaa/

9. NOAA National Centers for Environmental Information, State of the Climate: National Climate Report for Annual 2018, published online January 2019, retrieved on February 11, 2019 from https://www.ncdc.noaa.gov/sotc/national/201813 and https://www.ncdc.noaa.gov/billions/

10. USDA. 2012 Plant Hardiness Zone Map. https://planthardiness.ars.usda.gov/PHZMWeb/

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

12. Ebi, K. L. et al. 2018. Human Health: In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. doi: 10.7930/NCA4.2018.CH7.

13. EPA, 2017: Multi-model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency (EPA), Washington, DC, 271 pp.

14. 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., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. doi: 10.7930/NCA4.2018.CH6.

15. Prasad, A. M., L. R. Iverson, M. P. Peters, and S. N. Matthews. 2014. Climate change tree atlas. Northern Research Station, U.S. Forest Service, Deleware, OH. http://www.nrs.fs.fed.us/atlas.

16. Liu, J., S. L. Goodrick, and J. A. Stanturf. 2013. Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. Forest Ecology and Management 294:120-135.

17. Drapek, R.J., J.B. Kim, and R.P Neilson, 2015: Continent-wide Simulations of a Dynamic Global Vegetation Model over the United States and Canada under Nine AR4 Future Scenarios. Global Vegetation Dynamics: Concepts and Applications in the MC1 Model, 73-90.

18. Lipton, D. et al. 2018. Ecosystems, Ecosystem Services, and Biodiversity: In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. doi: 10.7930/NCA4.2018.CH7.