CLIMATE RISK ASSESSMENT

Louisville, Kentucky

AUTHORS | Dominick Dusseau, Joshua Driscol, Kelly Gassert, Christopher Schwalm, Andrew Condia, Abigail Fennelly, Jamie Cummings

LOUISVILLE MSD CONTRIBUTORS | Wesley Sydnor, Stephanie Laughlin, Nicole Refolo

For more information about this analysis, or Woodwell's other climate risk assessments, please contact us at policy@woodwellclimate.org.

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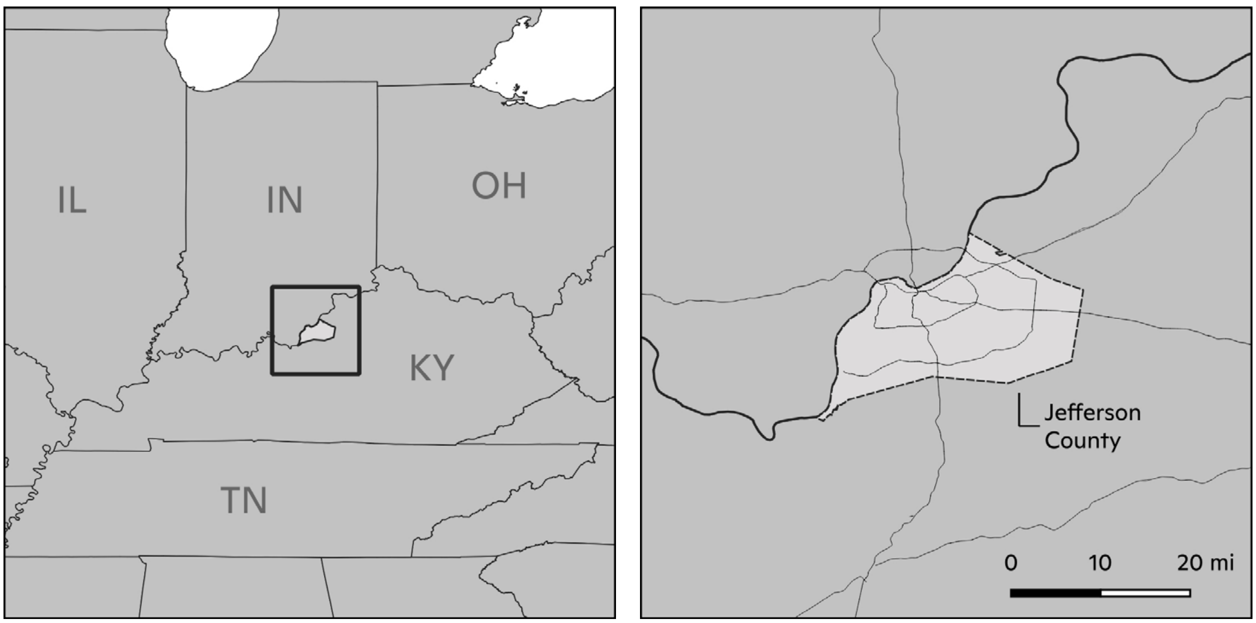
Woodwell Climate Research Center

Introduction

The impacts of climate change on the frequency and severity of physical hazards are putting many communities at risk. As the threat of climate change grows, so too does the need for accessible information, tools, and expertise to support climate-resilient decision making across multiple scales, from communities to countries. Woodwell Climate Research Center believes there is a need to localize and customize climate risk assessments. This information is critical for local government leaders as they make planning decisions, but it is not available to all communities. Woodwell believes that this science should be freely and widely available. To address this gap, Woodwell works with communities across the world, including Louisville, KY, to provide community climate risk assessments, free of charge. This report was generated in partnership with the Louisville Metropolitan Sewer District (Louisville MSD) so we have focused this analysis within the geographic area of Jefferson County, KY.



Results summary

As a result of climate change, the 100-year 24-hour extreme precipitation event amount of rainfall will be 24% greater by 2050 and between 29% and 37% greater by 2070, compared to the 2014 amount of 7.8 inches. Odor days, periods of time with low precipitation and moderate to high temperatures that cause sewage odors, will increase from 140 days per year on average to 145 days by 2050 and 156 days by 2070 under a high emissions scenario. Here we present our findings on extreme precipitation and odor days to help Louisville, KY in its plans to create a more resilient future for all residents.

Extreme precipitation

In 2015, the engineering firm CH2M Hill was contracted by Louisville MSD to conduct an assessment on how climate change would impact extreme precipitation in the near future. We provide a brief comparison of Woodwell's and CH2M Hill's methodologies which will hopefully provide clarity on the differences between the results from the two assessments.

There are several similarities between the methodologies of CH2M Hill and Woodwell to estimate changes in future extreme precipitation. The main similarities are that both use a regional fitting method for the Generalized Extreme Value (GEV) distribution, the delta ratio method for estimating changes between historical and future precipitation, downscaling was done similarly using bilinear interpolation to a 1km resolution, and both use the updated 2014 National Atlas 14 (NA14) Precipitation Frequency Estimates (PFEs) as the baseline that CH2M Hill generated in their analysis. The main differences are as follows and are by no means comprehensive.

① Climate model data

The CH2M Hill analysis used daily precipitation data from CMIP5 which is the previous generation of climate model realizations while Woodwell uses the most recent family of climate models, CMIP6.

② GEV fitting method

NOAA has recommended that instead of using L-moments to fit the GEV distribution from the rainfall data, as was previously done in NA14, the generalized maximum-likelihood estimator (GMLE) be used which allows for the implementation of a non-stationary framework. Woodwell used the GMLE approach while CH2M Hill used the L-moments method.

③ Bias-adjustment

According to their report, CH2M Hill uses a bias-adjustment method called pattern-scaling developed by B.D. Santer in the 1990s. Pattern-scaling is a simple statistical technique that adjusts climate model data by a factor to better match observed data. Woodwell bias-adjusted using a method called parametric quantile mapping that is approximately trend-preserving and adjusts the entire distribution of a climate variable in all quantiles within a climate model. This method is considered more accurate than pattern-scaling because it considers the tails of the distribution and not just the mean which is the focus in pattern-scaling.

④ Nonstationary vs. quasistationary

CH2M Hill uses a quasistationary approach which separates the data time series into time slices while Woodwell uses a nonstationary approach which uses the entire time series. The fitting method is expected to have a big impact on the results since not only do the location and scale parameters scale with time in the nonstationary method, but the shape parameter is held constant throughout the entire time series. The shape parameter has a significant influence on the tails of the GEV distribution, so the rainfall amounts for rare events (i.e., ≥ 100-year) will likely differ between the quasistationary and nonstationary methods.

⑤ Scenarios

Since CH2M Hill completed their report in 2015 when only CMIP5 was available, the scenarios used by CH2M Hill match those of CMIP5. More specifically, CH2M Hill uses RCP8.5 and RCP4.5 while Woodwell uses SSP5-8.5 and SSP2-4.5. An RCP (Representative Concentration Pathway) is a trajectory of emissions while an SSP (Shared Socioeconomic Pathway) represents levels of emissions corresponding to forecasts of population, GDP, and income change.

Woodell projects that extreme precipitation is expected to intensify in Louisville through 2070. By 2050, we estimate that the 100-year 24-hour event will be 9.7 inches and 9.6 inches under SSP2-4.5 and SSP5-8.5, respectively, up from 7.8 inches currently. In comparison, CH2M Hill projects the same event will be 9 inches by 2065 under RCP8.5. By 2070, Woodwell projects the 100-year 24-hour event will be 10.1 inches and 10.7 inches under SSP2-4.5 and SSP5-8.5, respectively. Similar shifts between scenarios, years, and data providers are present in lower return periods and the 3-hour event as can be seen in Figures 1 and 2. As shown in Figures 1 through 4, results for SSP2-4.5 and SSP5-8.5 in 2050 are highly similar. This is because the scenarios do not diverge significantly by 2050 and internal climate variability influences the GEV distribution more than the climate change signal.

Changes in intensity-duration curves are expected to follow similar intensifications. The largest shifts in intensity are expected to be at lower durations as shown in Figures 3 and 4. For the 1-hour 10-year event, rainfall intensity is expected to reach 2.5 inches per hour by 2050 and 2.6 inches per hour under SSP2-4.5 and 2.8 inches per hour under SSP5-8.5, respectively, by 2070. In comparison, the current 1-hour 10-year intensity is 2.1 inches per hour and CH2M Hill projects 2.3 inches per hour by 2065 under RCP8.5. The intensity-duration curves are expected to shift similarly for the 100-year event.

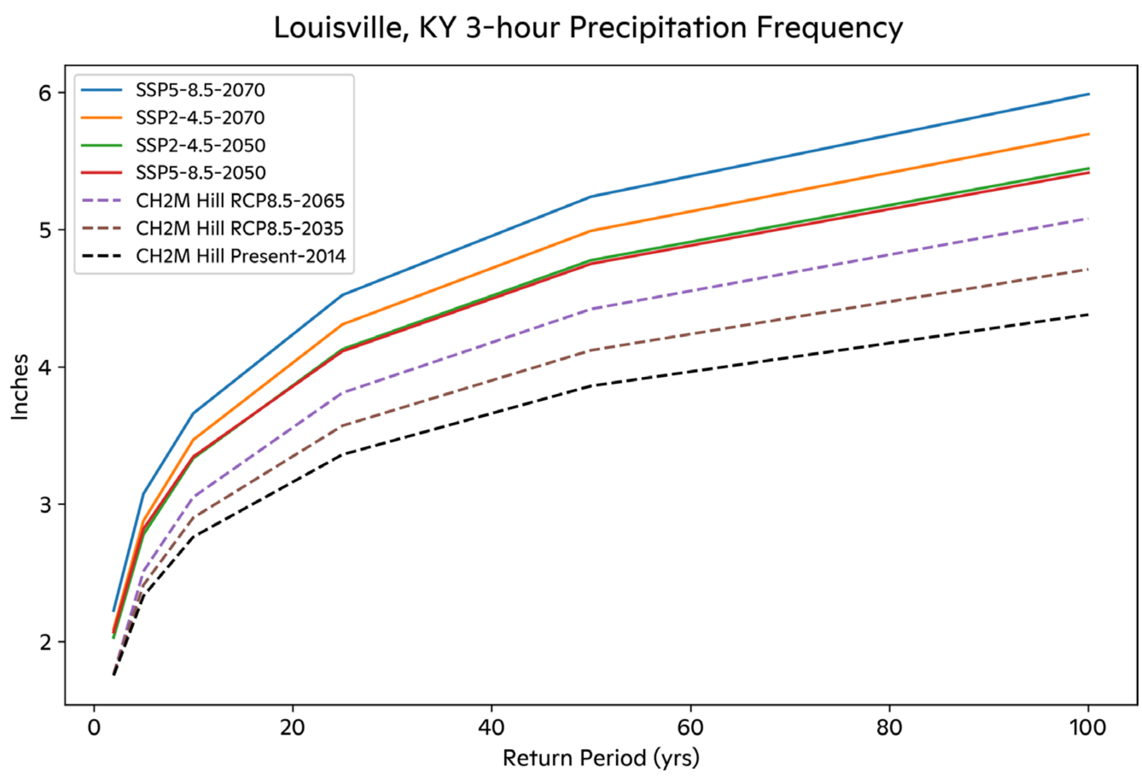


Figure 1: Depth-Frequency curve for the three-station average for historical, CH2M Hill projections, and Woodwell projections of the 3-hour rainfall event.

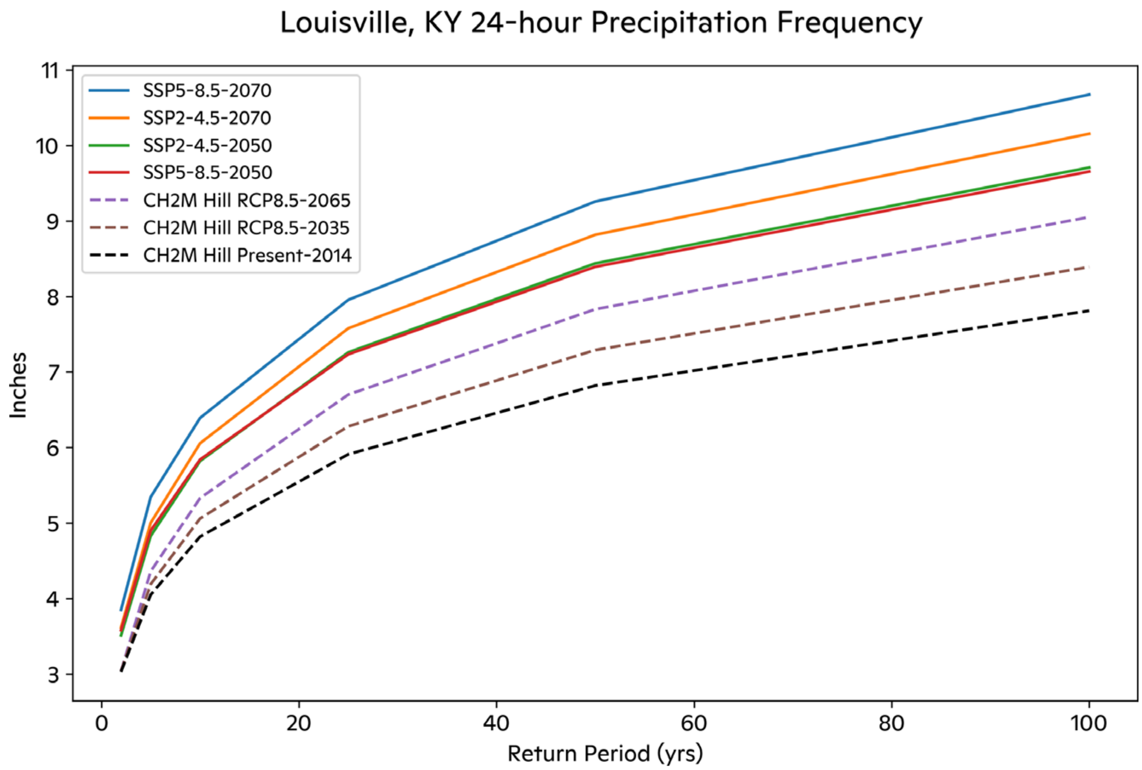


Figure 2: Depth-Frequency curve for the three-station average for historical, CH2M Hill projections, and Woodwell projections of the 24-hour rainfall event.

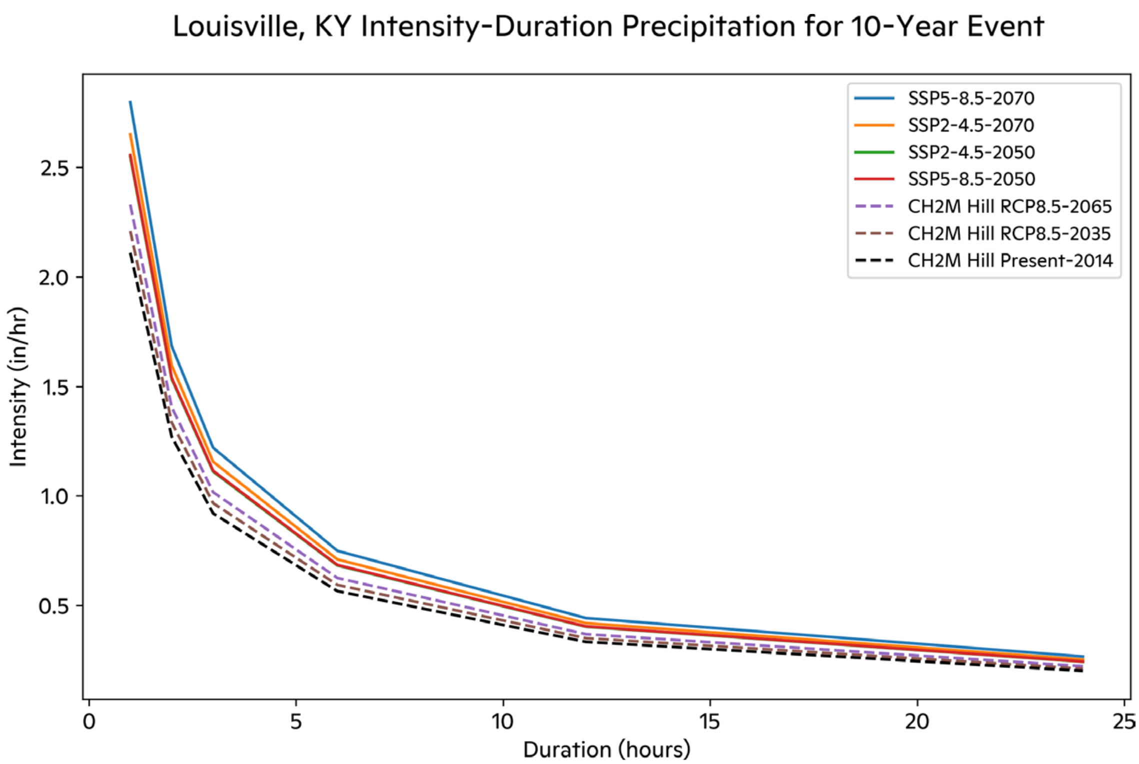


Figure 3: Intensity-Duration curve for the three-station average for historical, CH2M Hill projections, and Woodwell projections of the 10-year rainfall event.

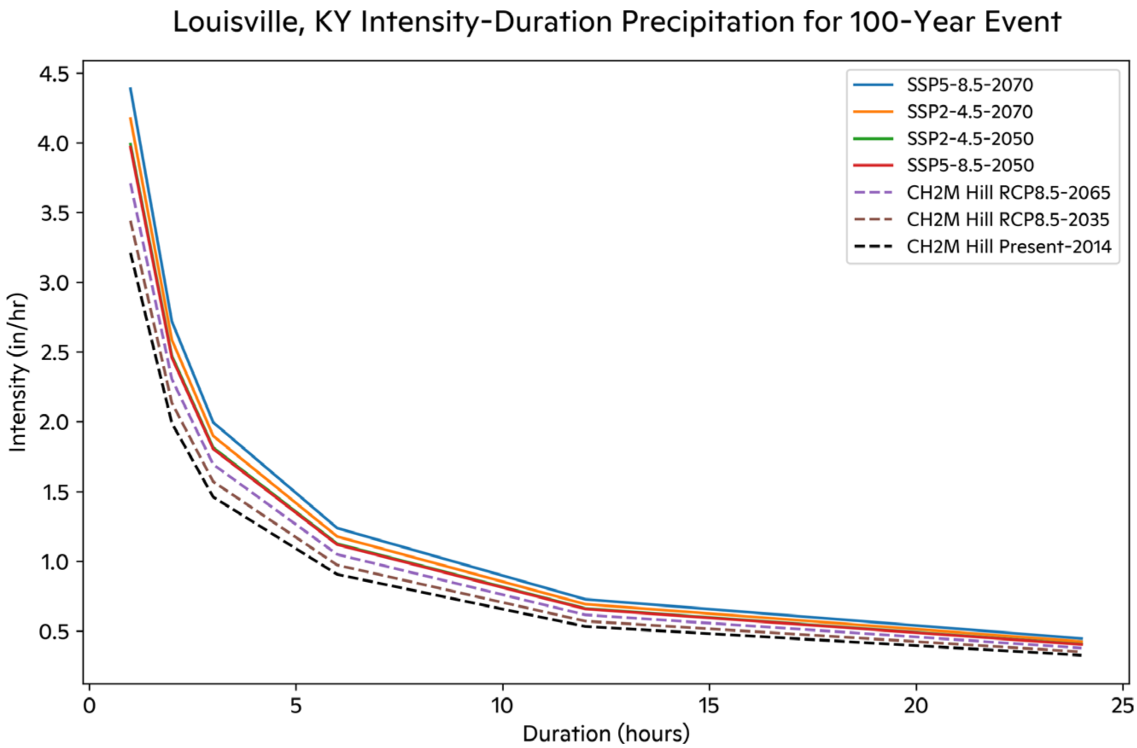


Figure 4: Intensity-Duration curve for the three-station average for historical, CH2M Hill projections, and Woodwell projections of the 100-year rainfall event.

Odor days

Introduction

The Louisville MSD sewer and stormwater infrastructure is a combined system meaning that stormwater runoff and sewage are transported and treated together before being discharged into the Ohio River. Catch basins without water traps that are not regularly flushed by rainfall will develop odors as organic matter accumulates and decomposes. Jefferson County residents can report odors to Louisville MSD through the MSD clAIRity Program,[1] which allows MSD to locate and address potential odor issues. Thus, the odor complaints are caused by a combination of the current sewer infrastructure design and a lack of rainfall. For this analysis, we investigated how changing climate conditions could impact dry spell length to determine if greater resources are needed for odor control in the near future.

Currently, odor complaints are concentrated in the northwestern portions of Jefferson County (Figure 5). Because of this, we attempted to correlate precipitation and temperature data from the location of a rain gauge within the Louisville MSD network of gauges to complaints near the center of where odor complaints are highest. For this analysis, we used daily Louisville MSD rain gauge observations[2] for historical precipitation data and NOAA nClimGrid data[3] at the rain gauge location for historical maximum air temperature data. The odor complaint data comes directly from Louisville MSD's odor complaint archive.[4] Finally, to project future conditions where odors might be an issue into the future, Woodwell used downscaled CMIP6 climate data[5] for both precipitation and maximum air temperature.

[1] https://louisvillemsd.org/odor

[2] https://raingauge.louisvillemsd.org/RainGaugeReports.aspx

[3] Durre et al., 2022

[4] https://louisvillemsd.org/odor/archive

[5] CMIP6 climate model daily data bilinearly interpolated to 1-km resolution and bias-adjusted using Daymet (Thornton et al., 2022) observation data and Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) methodology (Lange, 2019, Lange, 2021)

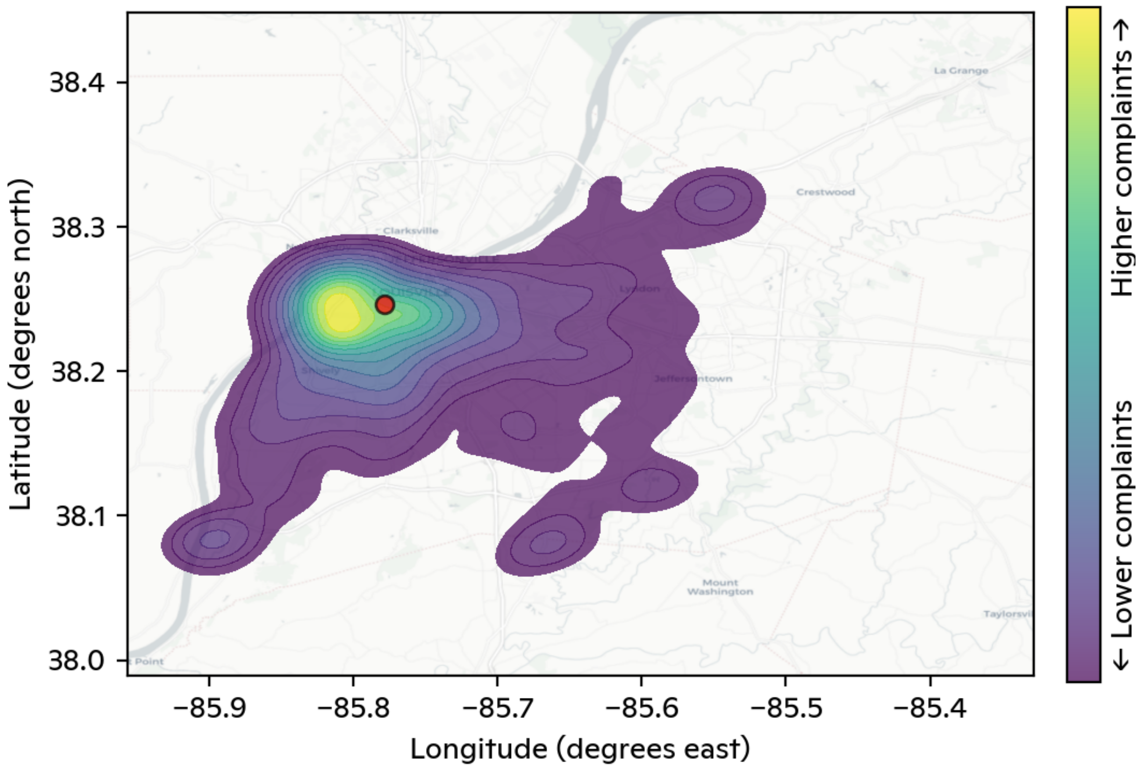


Figure 5: The historical spatial distribution of odor complaints to Louisville MSD over the time period 2021–2024. The red circle represents the location of the Louisville MSD rain gauge that we used for this analysis.

The relationship between precipitation, temperature, and odor complaints

As Figure 6 shows, the bulk of yearly odor complaints primarily comes during the months of August-November, with some years having high counts in June and July, as well. Odor complaints continue during the winter and spring months, though at lower rates than during the summer and fall. Figure 7 shows the relationship between daily precipitation, temperature, and complaints, across all months and years in this analysis. For temperature and precipitation, the correlation with complaints is weak because there are often days with the same average maximum temperature or total precipitation amount resulting in both non-complaints and complaints across the MSD.

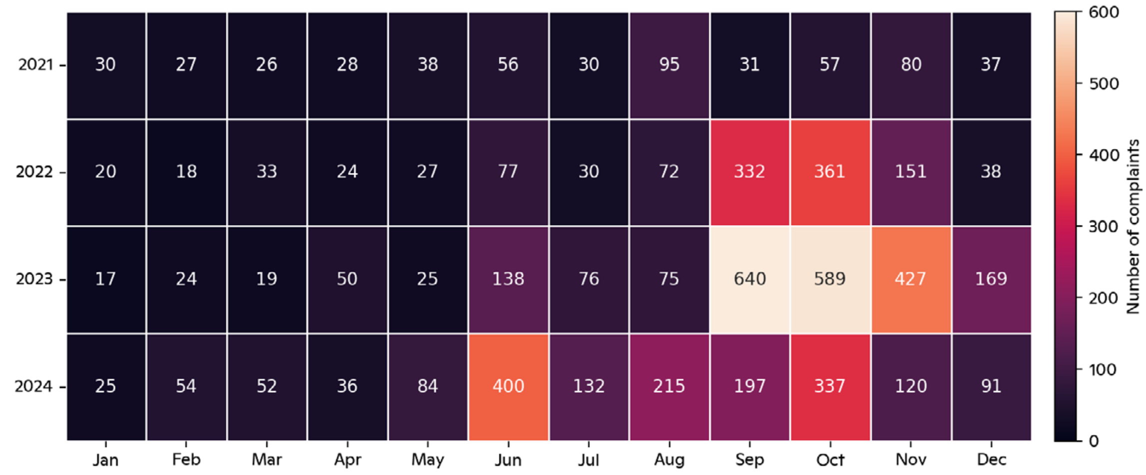


Figure 6: The distribution of odor complaints over the course of the year, for the years 2021–2024.

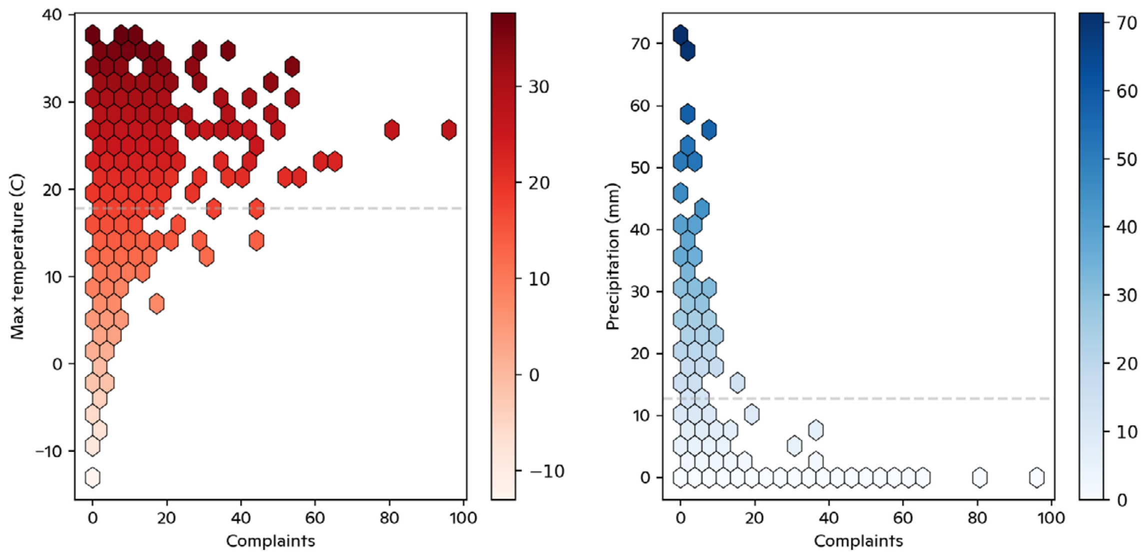


Figure 7: The distribution of daily nClimGrid maximum air temperature (left) and daily total precipitation from the Louisville MSD rain gauge (right) against the total number of odor complaints. The gray dashed lines represent the temperature and precipitation thresholds we used to classify days as potential odor complaint days.

Temperature and precipitation thresholds for odor days

To determine initial estimates of the temperature and precipitation thresholds to define an odor day, we looked at 4 major peaks of complaints: September 27, 2022, September 17, 2023, November 16, 2023, and June 21, 2024, as shown in Figure 6, and determined the number of days since at least 0.2 inches of rain fell. We subsequently took the average of those 4 values for the number of dry days and the minimum of those 4 values for the temperature threshold. We then calculated what was the minimum previous daily maximum temperature 7-day average from each peak. These analyses allowed us to develop initial thresholds to present to Louisville MSD: 20 days with rainfall less than 0.2 inches and the previous 7-day average daily maximum temperature value of 17.86°C (~64°F).

After discussing these initial thresholds with Louisville MSD, we classified an odor complaint day as any day where:

- At least 5 prior days had gone by with daily total precipitation amounts of less than 12.7mm (~0.5in). Any time precipitation rose above this threshold, the number of consecutive potential odor days would reset.
- The day-of daily maximum temperature was above 17.86°C (~64°F).

Historical odor days

From the parameters above, we can draw a few conclusions: first, complaints are more strongly dependent on daily precipitation than with temperature. The lack of rainfall seemed to be the primary driver of complaints, though temperature was still important in determining the total number of complaints, especially in the summer and fall months (refer back to Figure 7). Second, these threshold values do not encompass all days when there are complaints and include times when there are no complaints. For example, with an increase in the precipitation thresholds values, more and more non-complaint days (false positives) are included in the total predicted odor complaint days. As for temperature, there are many hot and cold days where Louisville MSD still receives complaints, regardless of rainfall. In this way, we don't want to overfit this metric. It will always be imperfect since we are applying weather station data at a particular location to complaints coming in from all over the county.

We relied on a number of simplifications for this analysis. First, a simplified set of weather variables (precipitation, temperature) will always be an imperfect proxy for odor complaints that are also heavily dependent on current sewer infrastructure design and complex human behavior. Second, we used an individual rain gauge location to create thresholds that we then applied over all of Jefferson County and the Louisville MSD. We recognize that different parts of Jefferson County likely would have different precipitation and temperature threshold values, but we chose to use a single set of values in order to reduce the complexity of the analysis. Finally, this method does not accurately predict complaints in the winter months or when the daily total number of complaints is low. This method can be best thought of as a predictor of how spring through fall weather conditions that drive complaints, and not complaints themselves, will change into the future.

Still, when we apply this method to the historical precipitation and temperature observations, we can see that we are able to reasonably predict periods of high complaints during the summer and fall months (Figure 8).

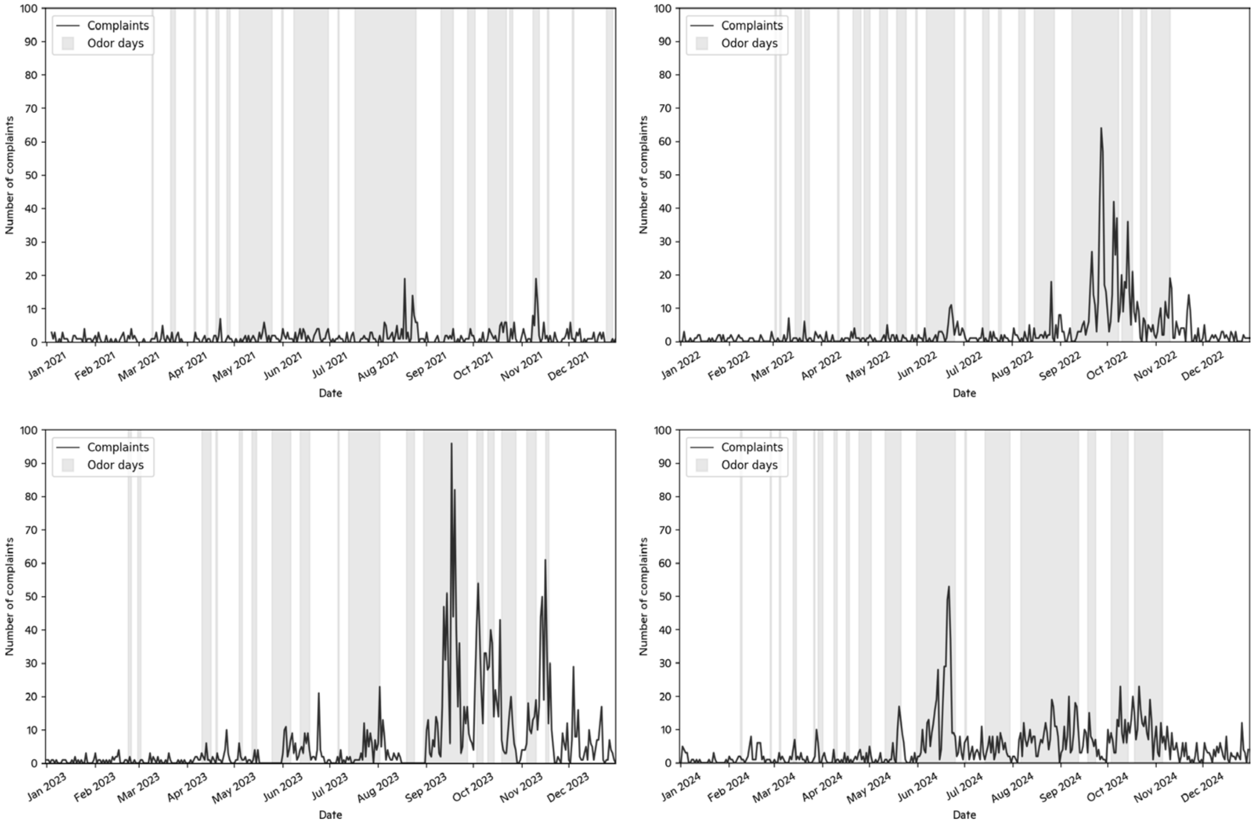


Figure 8: The total historical complaints overlaid on top of the time periods when the dry days algorithm predicts that complaints are likely to occur for 2021 (upper left), 2022 (upper right), 2023 (lower left), and 2024 (lower right).

Odor days in a future climate

Given the reasonable results we received from comparing historical weather observations to complaints data (Figure 8), we then applied this metric to CMIP6 climate data to look at how well the computed potential odor complaint days matched the historical distribution of odor complaints across Jefferson County. Of course, the distribution of potential odor complaint days is not a perfect representation of historical observations, but can instead be used to look at predicted changes in meteorological conditions that lead to complaints. The results can be seen in Figure 9, where this method applied to climate model output produces conditions that could lead to higher complaints along the western side of Jefferson County, where historical complaints have been highest. Figure 10 details how the predicted number of odor days changes between the baseline period, 2050, and 2070 for SSP2-4.5. Figure 11 shows the expected increase in predicted potential odor complaints days for 2050 and 2070 relative to the baseline period under a SSP2-4.5 pathway. Figures 12 and 13 correspond to the same outputs, but for SSP5-8.5 instead of SSP2-4.5. We can see that the results in the baseline periods are similar in both SSP scenarios, but by 2050 and 2070, the number of predicted odor complaint days diverges. Under SSP2-4.5, for example, this method predicts up to an extra 5 odor complaint days. For 2070 under SSP5-8.5 conditions, however, most of Jefferson County surpasses this value by 2050 and might expect an additional 16 odor complaint days based solely on changing meteorological conditions. The number of odor days in the baseline period differs between the SSP2-4.5 and SSP5-8.5 scenarios due to internal climate variability. These two scenarios are slightly different realizations of the same climate and therefore, the internal climate variability is a large factor in determining the number of odors in the baseline period.

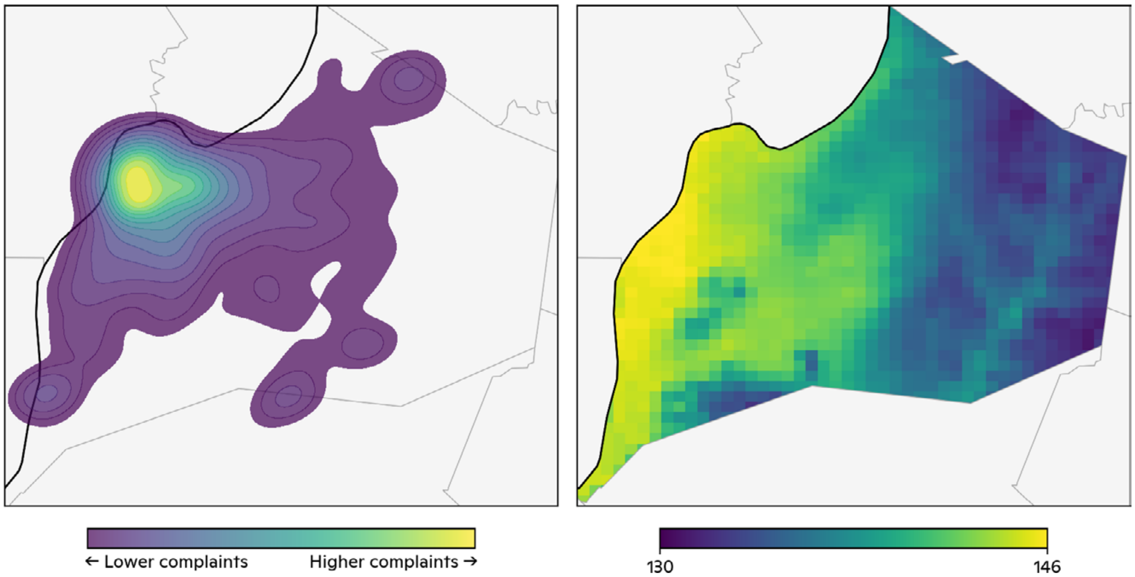


Figure 9: Comparing the historical spatial distribution of odor complaints (left) to the predicted distribution of potential odor complaint days from climate model output under SSP5-8.5 conditions (right). Both figures represent data from 2021–2024, though the historical data is the total sum of complaints while the climate data is the total number of predicted odor complaint days, averaged over all ensemble model members and years.

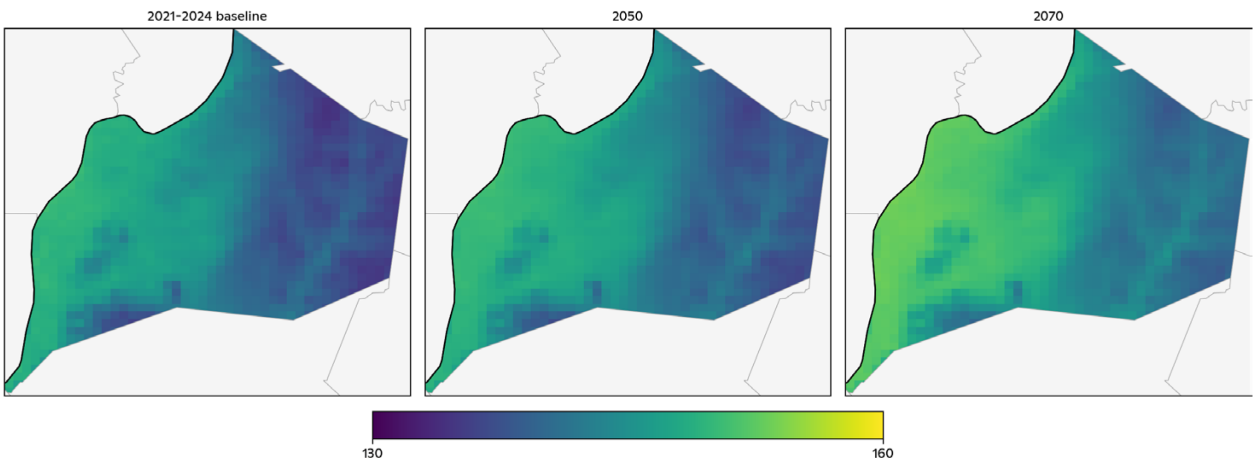


Figure 10: The total number and distribution of predicted dry days from climate model output under SSP2-4.5 conditions for the baseline of 2021–2024 (left), 2050 (middle), and 2070 (right).

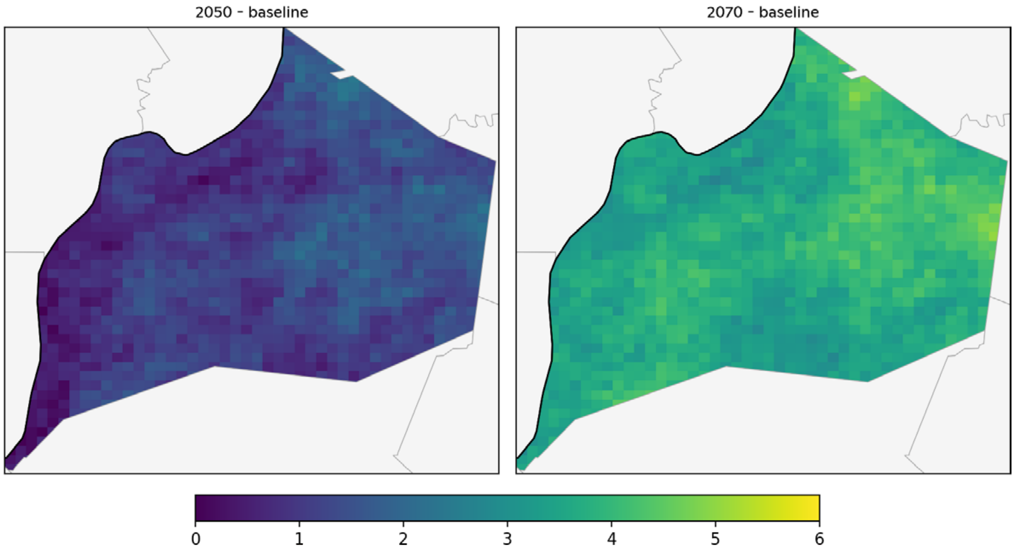


Figure 11: The projected increase in odor complaint days for the years 2050 (left) and 2070 (right), relative to 2021–2024 conditions under a SSP2-4.5 pathway.

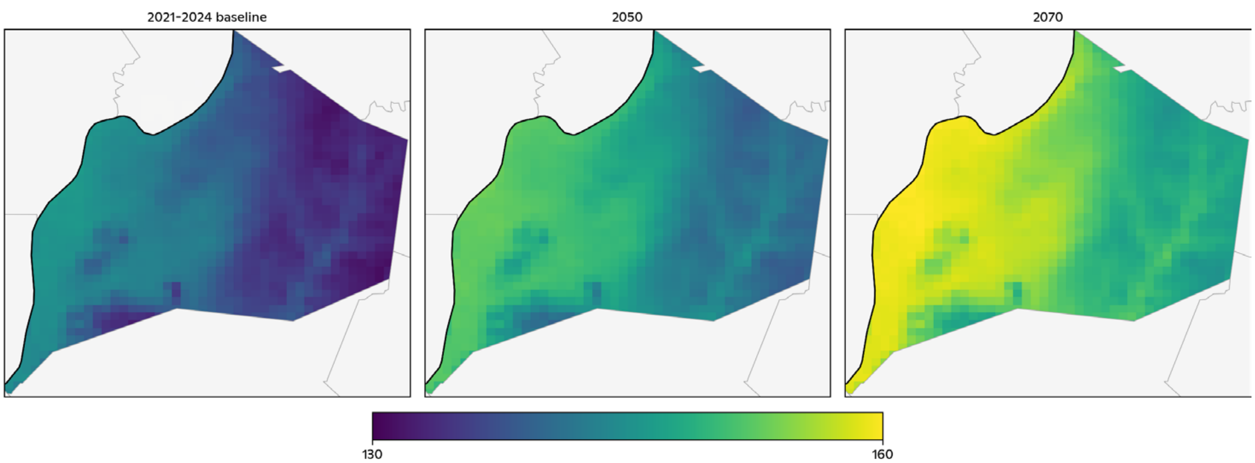


Figure 12: The total number and distribution of predicted odor days from climate model output under SSP5-8.5 conditions for the baseline of 2021–2024 (left), 2050 (middle), and 2070 (right).

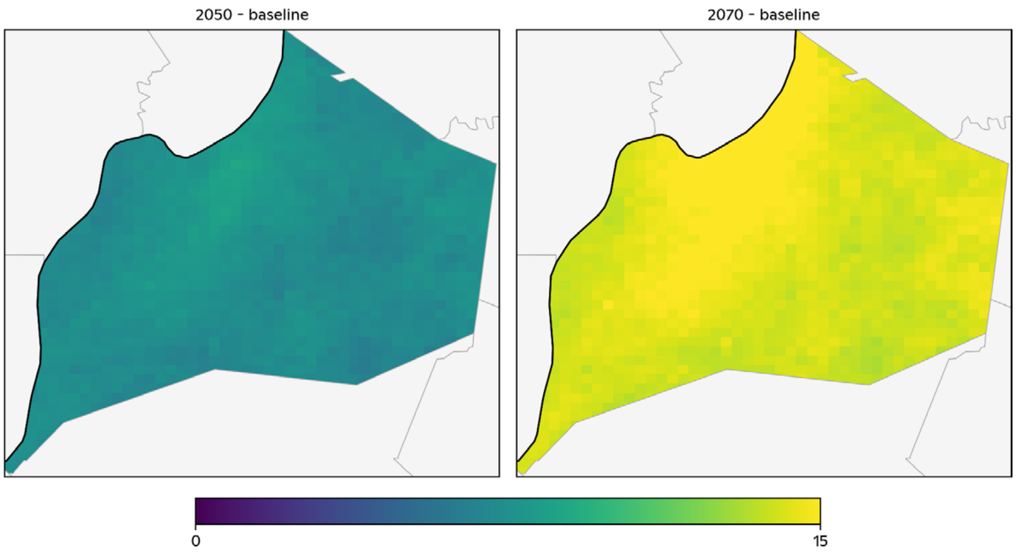


Figure 13: The projected increase in odor complaint days for the years 2050 (left) and 2070 (right), relative to 2021–2024 conditions under a SSP5-8.5 pathway

Conclusion

Louisville, KY is projected to see intensification of extreme precipitation events through the late 21st century. By 2050, Woodwell projects the 100-year 24-hour event to produce 9.6 inches of rainfall, up from 7.8 inches currently. By 2070, Woodwell projects the 100-year 24-hour event will be 10.1 inches and 10.7 inches under SSP2-4.5 and SSP5-8.5, respectively. These changes in the distribution of extreme precipitation will have significant capital and infrastructure planning implications for Louisville MSD.

Additionally, Woodwell has constructed a method using specific weather conditions that reasonably recreates historical periods of high odor complaints across Jefferson County. We then applied this method to future-looking climate data to show how changing conditions could impact the number and extent of odor complaints that Louisville MSD receives. There are on average 130 odor days a year in eastern Jefferson County while western Jefferson County typically experiences 146 odor days per year. There are expected to be an additional week's worth of odor days by 2050 and an additional two weeks of odor days by 2070. This method can easily be interpreted and can be quickly incorporated into future monitoring efforts and regional planning decisions.

Extreme precipitation methodology

In this report, we present results for future-projected extreme rainfall using a nonstationary (NS) methodology for various intensity-duration-frequency (IDF) curves. In a NS approach, precipitation estimates are calculated for the entire time period (i.e., 1971–2100) using a temporal parameter to represent changes in extreme precipitation through time. NOAA recommends using a NS approach since it considers the whole time series in addition to any trends in the data, offering a more robust analysis and more stable estimate of future extreme precipitation in a changing climate. The NS approach is better suited for engineering applications as future relative changes are more realistic compared to a quasistationary approach which compares two rainfall distributions built from two distinct time periods.[6]

The data used in this analysis consist of daily precipitation data from 19 Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models for two different warming scenarios, SSP2-4.5 and SSP5-8.5, that have been bias-adjusted and downscaled to 1-km resolution over Jefferson County using ISIMIP,[7,8] methodology and Daymet[9] observation data. CMIP6 data are first bilinearly remapped from their respective global, coarse resolutions to match the high-resolution Daymet data. Bias-adjustment is then conducted on each of the CMIP6 models over Jefferson County using ISIMIP v2.5 code[4] which implements a parametric quantile mapping method that is approximately trend-preserving in all quantiles. The parametric method allows for better adjustment of biases in extreme quantiles. The code also includes event likelihood adjustment to confine extreme values to the physically plausible range.

We use a regional fitting method to estimate the parameters of the Generalized Extreme Value (GEV) distribution. For each target pixel, a 40-mile radius is used to capture the annual maxima of the surrounding pixels. Each pixel's AMS is given a weight using a triweight kernel function based on distance (e.g., pixels ≥ 40 miles have zero weight). The log-likelihood function of the GEV distribution is then minimized with the Nelder-Mead algorithm using the annual maxima and pixel weights to estimate the GEV parameters. The beta distribution of penalized coefficients ranging between -0.5 and 0.5 is used to constrict the shape parameter as specified by NOAA.[6]

To estimate future daily PFEs, the biases (ratio) between the baseline period and the NA14 daily PFEs are calculated and then multiplied by the future climate model daily PFEs. Future sub-daily PFEs are estimated by first calculating disaggregation factors between the NA14 daily and sub-daily PFEs and then applying those disaggregation factors to the projected daily PFEs for each return period. The NA14 daily PFEs are defined as the 3-station (Louisville Upper Gage, Shephardsville, and Louisville Int. Ap.) 2014 values that were updated by CH2M Hill. Each station was treated independently in the analysis and all figures show the 3-station average.

To incorporate temporal changes through the data series, five parameters are fitted to the annual maxima of 1971–2100. The parameters are a_0, a_1, b_0, b_1, c_0 which are used to represent the GEV parameters:

$$location = a_0 + a_1 RCP$$
$$scale = exp(b_0 + b_1 RCP)$$
$$shape = c_0$$

where RCP represents the radiative forcing under a specific scenario for each annual maximum. Radiative forcing data was acquired from RCMIP[10] for each warming scenario. The natural log of the scale is used to ensure the scale is positive. Three rounds of parameter fitting were completed to ensure convergence for all pixels. The first round is solely for generating

[6] NOAA, 2022
[7] Lange, 2019
[8] Lange, 2021
[9] Thornton et al., 2022
[10] https://www.rcmip.org

initial estimates for a_0, b_0, and c_0 which is done by only using those three values to represent the location, scale, and shape parameters, respectively. The GEV distribution is fitted using the entire time series (1975–2100) with the initial parameters set as location: the mean of the AMS for the target pixel; scale: the standard deviation of the AMS for the target pixel; shape: -0.1, which represents the expected value of the beta distribution.[11] The natural log of the scale is used to ensure the scale is positive. In the second round of fitting, initial parameters to the optimization scheme are set as a_0: the previously fitted location parameter for the target pixel; a_1: zero, which represents no trend; b_0: the previously fitted scale parameter for the target pixel; b_1: zero, which represents no trend; c_0: the previously fitted shape parameter for the target pixel. For the third round of fitting, the initial parameters are set as the average parameter value within a three-pixel radius around the target pixel.

We also compare our results to those generated by CH2M Hill which presented projected IDF changes in 2015 to Louisville MSD. Differences between the two methodologies are described at the end of the results section.

[11] Martins and Stedinger, 2000

Front cover: Downtown city aerial of Louisville, KY. / photo by Nicholas Klein

Back cover: West Main Street, Louisville, KY. / photo by Jon McCallon

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149 Woods Hole Road, Falmouth, MA 02540 ▪ 508-540-9900 ▪ **woodwellclimate.org**