Climate Change Projections

For the District of Columbia

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INTRODUCTION

Global climate change is no longer an issue that is distant in space, affecting only polar bears in the Arctic, or people on low-lying islands in the tropical seas. It is no longer an issue that is distant in time either, a challenge for future generations to adapt to. Climate change is affecting both average conditions and the risk of many types of weather extremes right here, in the United States, and right now, today.

For cities, states, and agencies charged with managing and maintaining public infrastructure and services, climate change matters because it introduces non-stationarity into our systems. Infrastructure, building codes and many other types of planning are all build on the assumption that past climate can reliably predict the range of future conditions expected in a given place: the hundred-year flood event, the risk of summer heat waves, even the length of the growing season. And for many decades, that assumption has been relatively solid. Today, however, climate is changing so rapidly that, often, the only thing we know for sure is that using the past as a guide to the future will give us the wrong answer.

Daily records at Washington Reagan International Airport began in 1947. Since then, average temperatures have increased by an average of 0.3^{o}F per decade for a total warming of 2^{o}F from 1947 to 2014 (Figure 1). Summers are warming faster, at a rate of 0.4^{o}F per decade, while winters are warming more slowly, at 0.2^{o}F per decade (NOAA, 2013). While annual precipitation has not changed much, there are strong seasonal trends. Fall and winter precipitation has been increasing at a rate of 0.4 and 0.1 inches per decade, respectively. There has been little change in spring precipitation, and a decrease in summer precipitation of 0.3 inches per decade (NOAA, 2013).

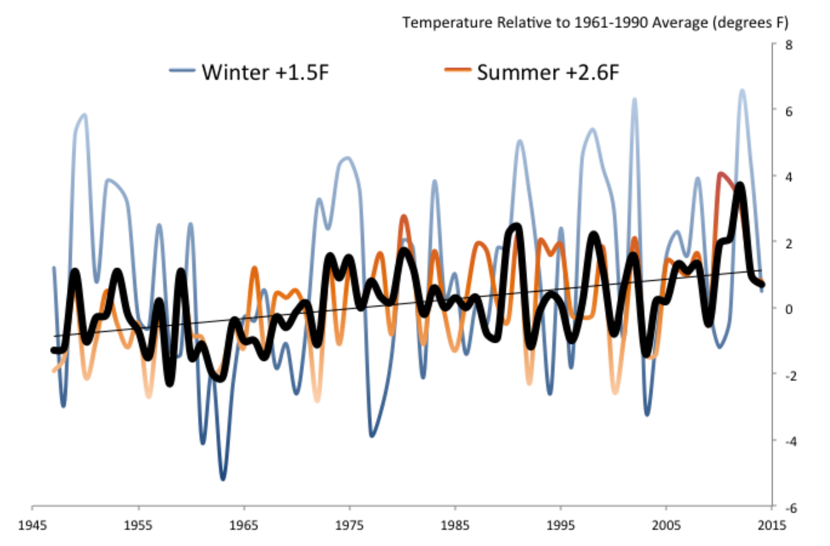


Figure 1. Observed change in average temperatures (in degrees F relative to the 1961-1990 average) for winter (Dec-Jan-Feb, blue), summer (Jun-Jul-Aug, orange) and annually (black) at the Washington Reagan National Airport weather station from the beginning of the record in 1947 to 2014.

High temperature and precipitation extremes are also increasing. Compared to 1950, there are now an average of 9 more days per year with maximum temperature greater than 95^{o}F, and the average amount of precipitation in the wettest day of the year has increased by 1/5th of an inch.

These trends are consistent with those documented across the greater mid-Atlantic region, and the U.S. as a whole. The District of Columbia straddles the dividing line between the Northeast and the Southeast regions. Across the Northeast, the frequency of heavy precipitation, including both rain and snow events, has increased by 71% from 1958 to 2012, accompanied by an increase in the magnitude of floods (Figure 2; Walsh et al., 2014a). Smaller but consistent increases of +27% have been observed over the same time period throughout the Southeast region. Across the entire U.S., extreme heat days are becoming more frequent, while extreme cold days become less frequent (Walsh et al., 2014a).

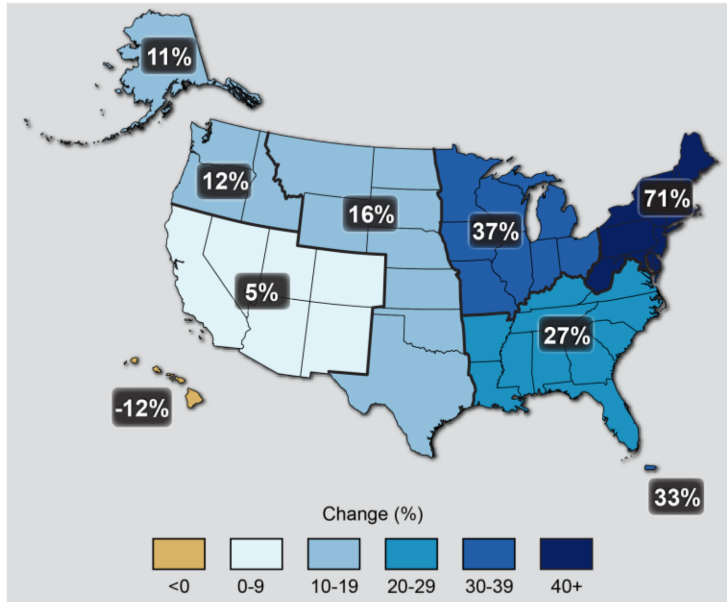


Figure 2. Observed change in very heavy precipitation events (defined as the heaviest 1% of all daily events) from 1958 to 2012. The District of Columbia lies on the divide between the Northeast and the Southeast regions. Source: Walsh et al. 2014a

This increasing non-stationarity of the climate system is the motivation for developing long-term climate projections for the District of Columbia. Through relying on a combination of historical observations, global climate model simulations, and high-resolution empirical statistical downscaling models, it is possible to identify the direction of future trends and, for some indicators, even the likely magnitude of expected changes within a range of scientific and human uncertainty.

The future is still uncertain. However, that uncertainty can be broken down into three specific causes, and each of these causes can be accounted for in developing future projections, as follows:

1. **Internal (natural) variability of the climate system** is the result of interactions between different components of the climate system, such as the exchange of heat energy between the ocean and the atmosphere. It is most important over the short term and at smaller spatial scales. Beyond these time frames, long-term climate trends become meaningful. In this assessment, we account for natural variability by averaging climate variables and projected impacts over 20-year "climatological" periods for most variables, and 31-year periods for extreme precipitation quantiles, to adhere to the methodology already in use by the city.

2. **Scientific uncertainty** arises because scientists' ability to model and predict the response of the climate system to global change is limited and incomplete. Feedbacks within the climate system act to magnify or diminish the response of the planet to human activities. To account for scientific uncertainty in this assessment, we use simulations from nine different climate models from the newest (Intergovernmental Panel on Climate Change Fifth Assessment Report) database, as the average of a large set of simulations is nearly always closer to reality than any individual model or sub-set of models.

3. **Scenario uncertainty** is the result of not being able to predict human behavior. Future emissions of heat-trapping gases will be driven by human choices including population, technology, and policy. This uncertainty becomes most important past mid-century. To encompass the range of possible futures, in this assessment we develop projections for a higher and lower Representative Concentration Pathway.

More detail on the various models and scenarios used in this analysis is provided in the next section. The bottom line, however, is that these model- and scenario-based projections of future climate can inform long-term planning by providing information on possible future conditions. In some cases that information is qualitative (identifying the existence and/or direction of a trend), while in others it can be quantitative (estimating the difference between a near-term vs. a future time period, or between the changes expected under a higher vs. a lower future scenario).

This report summarizes projected changes in average temperature and precipitation and selected temperature and precipitation thresholds and extremes for the District of Columbia.

RESEARCH METHODS

Scenarios. Over the next few decades, climate will continue to change regardless of which scenario or emissions pathway the world follows. This is due to two reasons: first, the inertia of the climate system in responding to human emissions, and second, the inertia of the global economy in transitioning from carbon-emitting to clean sources of energy. After several decades, however, the amount of future climate change increasingly depends on the magnitude of human emissions of carbon dioxide and other heat-trapping gases. Higher scenarios of carbon emissions, that assume continued dependence on fossil fuels such as coal, gas, and oil, produce greater amounts of temperature change (Figure 3). Lower scenarios, that envision a transition from fossil fuels to non carbon-emitting renewable energy sources, result in smaller amounts of temperature change.

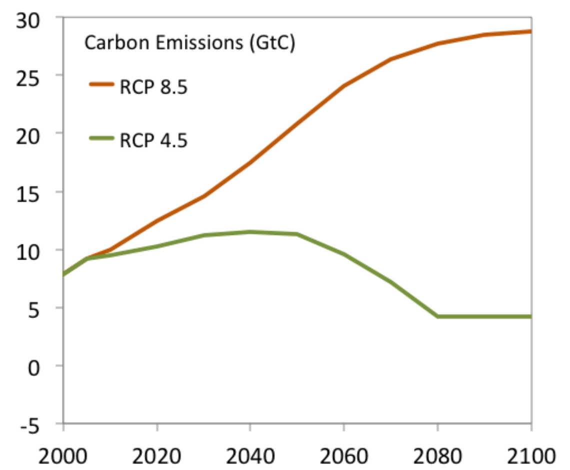


Figure 3. Climate change projections for the District of Columbia correspond to two scenarios: the higher RCP 8.5 scenario, where human emissions of carbon dioxide and other heat-trapping gases continue to rise, and the lower RCP 4.5 scenario, where emissions peak and then begin to decline by mid-century. This figure compares the carbon emissions corresponding to each scenario.

To quantify the range of plausible human choices over this century, in this analysis we use two scenarios from the Intergovernmental Panel on Climate Change Representative Concentration Pathways (IPCC RCPs; Moss et al. 2010): the higher RCP 8.5 and lower RCP 4.5 scenarios. At the higher end of the range, atmospheric carbon dioxide levels increase by more than three times compared to pre-industrial levels by 2100. At the lower end, carbon emissions peak around mid-century and then decline.[1] Atmospheric carbon dioxide levels approximately double relative to pre-industrial levels by 2100. Global mean temperature changes resulting from higher and lower scenarios range from 4°F (under lower) to 9°F (under higher) by 2100. This range is based on the Intergovernmental Panel on Climate Change's best estimate of climate sensitivity: that global mean temperature would increase by 3°C (5.4°F) under a doubling of atmospheric carbon dioxide relative to pre-industrial levels.

[1] For atmospheric concentrations to decline, there would need to be a net uptake of carbon from the atmosphere. In other words, humans would have to take up more carbon than they emit. The relationship between emissions and concentrations is discussed in detail in the 2011 National Research Council report, "Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia," available online at http://dels.nas.edu/Report/Climate-Stabilization-Targets-Emissions-Concentrations/12877

Global Climate Models. Future scenarios are used as input to global climate models (GCMs) to quantify how climate would change in response to human activities. GCMs are complex, three-dimensional models that are continually evolving to incorporate the latest scientific understanding of the atmosphere, oceans, and Earth's surface. Originally, "GCM" stood for General Circulation Model, since the original focus of these physics-based models was to simulate the circulation of the atmosphere and ocean. Today, however, global climate models incorporate many other facets of the Earth's climate system, including chemistry, biospheric processes, land use, etc.

Some GCMs are better than others at reproducing important large-scale features of certain regions, such as sea ice in the Arctic (e.g. Wang et al., 2007). However, it is not valid to evaluate a global model on its ability to reproduce local temperature or rainfall over a given city or region. Such limitations are to be expected in any GCM, as they are primarily due to spatial resolution rather than any inherent shortcoming in the physics of the model. In fact, previous literature has showed that it is difficult, if not impossible, to identify sub-set of "better" GCMs for the continental U.S. (e.g. Knutti, 2010; Randall et al. 2007). For this reason, no attempt was made to select a sub-set of GCMs that performed better than others over the District of Columbia; rather, we used multiple GCMs with a long development history spanning the range of likely climate sensitivity (Table 1).

Table 1. CMIP5 global climate modeling groups and the models used in this analysis.

ORIGIN	CMIP5 model(s)	CMIP5 scenario(s)
National Center for Atmospheric Research, USA	CCSM4	4.5, 8.5
Centre National de Recherches Météorologiques, France	CNRM-CM5	4.5, 8.5
Commonwealth Scientific and Industrial Research Organisation, Australia	CSIRO-MK3.6.0	4.5, 8.5
Geophysical Fluid Dynamics Laboratory, USA	-	-
Max Planck Institute for Meteorology, Germany	MPI-ESM-LR	4.5, 8.5
UK Meteorological Office Hadley Centre	HadGEM2-CC	4.5, 8.5
Institute for Numerical Mathematics, Russian	INMCM4	4.5, 8.5
Institut Pierre Simon Laplace, France	IPSL-CM5A-LR	4.5, 8.5
Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies, Japan	MIROC5	4.5, 8.5
Meteorological Research Institute, Japan	MRI-CGCM3	4.5, 8.5

Empirical Statistical Downscaling. Global climate model output is usually too coarse to be able to resolve a specific city or state. For that reason, downscaling is typically used to generate location-relevant information. Downscaling incorporates new information – here, long-term historical observations for weather stations within the District of Columbia – into GCM projections to produce locally-relevant projections of temperature, precipitation, and humidity at a given location.

This study uses the Asynchronous Regional Regresson Model version 1 (ARRM1; Stoner et al., 2012) to downscale daily maximum and minimum temperature, 24h cumulative precipitation, and daily maximum and minimum relative humidity to local weather station locations. ARRM can be trained on any observational dataset to produce future projections at the temporal and spatial scale of those observations. For this project, high-resolution projections were developed for the three long-term weather stations in the District (Table 2): Dalecaria Reservoir, National Arboretum, and Reagan National Airport. Relative humidity projections were calculated for Reagan National Airport only, as this was the only weather station with long-term humidity obervations available.

ARRM is based on parametric quantile mapping, a statistical technique that corrects each individual point on the distribution of daily values from historical GCM simulations to match observed values over the same time period. This correction is then applied to future projections to produce a distribution that is allowed to change over time, but more closely matches the conditions expected at the weather station on which the model is trained (Figure 4). More information on the ARRM method is provided in the peer-reviewed journal article, “An asynchronous regional regression model for statistical downscaling of daily climate variables” by Stoner et al. (2012).

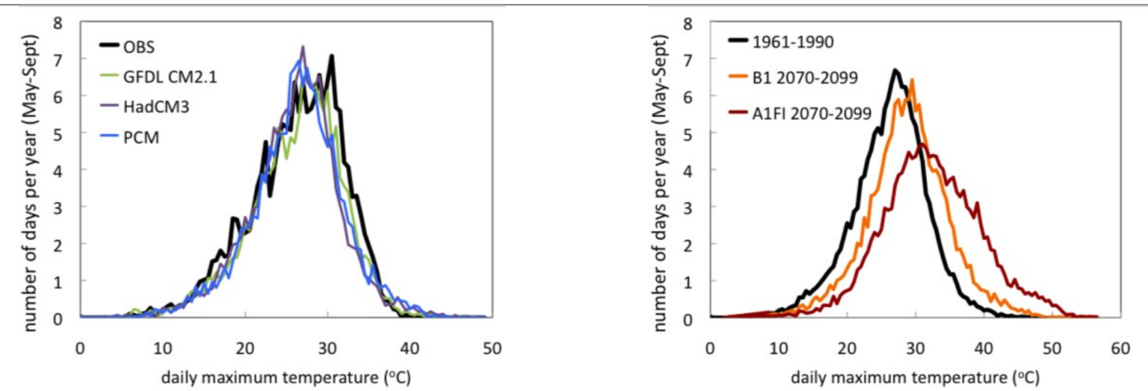


Figure 4. (a) This figure illustrates the ability of ARRM1 to transform raw GCM output into distributions closely matching those observed (black). This example shows three GCMs for a Chicago weather station.

(b) For the same Chicago weather station, this figure shows how projected future distributions (orange, red) will be not only warmer (further to the right) but also more extreme (broader or fatter) than historical (black) maximum summer temperature.

Table 2. Weather stations used in this analysis to generate high-resolution climate projections.

STATION NAME	ID	LOCATION		VARIABLE	LENGTH OF RECORD
DALECARIA RESERVOIR	USC00182325	38.94	-77.11	Tmax, Tmin, Pr	1950-2012
NATIONAL ARBORETUM	USC00186350	38.91	-76.97	Tmax, Tmin, Pr	1950-2012
REAGAN NATIONAL INTL AP	USW00013743	38.85	-77.03	Tmax, Tmin, Pr	1950-2010
				RH	1990-2012

Time Horizons. For the majority of temperature- and precipitation-related indicators, this assessment uses three twenty-year planning horizons, centered on the decades 2020s (2015-2034), 2050s (2045-2064), and 2080s (2075-2094). Summer average temperature and extreme precipitation indicators are calculated relative to a matching historical reference period centered on 1990 (1981-2000). These time periods apply to all indicators, with two exceptions.

1. **Extreme heat indicators** are calculated relative to a historical reference period centered on 2000 (1991-2010). The reason for the different historical reference period is purely logistical. It arises because most of the extreme heat indicators include humidity. However, as indicated in Table 2 above, observations of humidity at Reagan National Airport did not begin until 1990. For that reason, the historical reference period used for extreme heat indicators is centered on 2000 (1991-2010).
2. **Precipitation quantiles** (the 80th, 90th, and 95th percentiles of wet-day precipitation) are calculated for three 31-year planning horizons centered on the same decades as the 20-year horizons used for the other variables: 2020s (2010-2040), 2050s (2040-2070), and 2080s (2070-2100). Changes are calculated relative to a 31-year historical reference period, 1977-2007. The length of these periods and the years used to define the historical reference period match those already in use by the city.

This twenty-year averaging period was carefully selected to balance between two competing needs. The first is the need for a shorter period to accurately capture the rate of climate change (too long an averaging period could result in important differences between conditions at the beginning versus the end of the same period). The second is the need for a longer period reduce the influence of interannual and decadal variability on the long-term mean (too short an averaging period means that proejcted values could be strongly affected by the variability that arises naturally from the climate system and its cycles, such as El Niño/La Niña and North Atlantic Oscillation).

To address the uncertainty due to natural variability, climate projections were averaged over twenty-year (or 31-year) timeslices *and* over individual simulations from 9 different GCMs. For the model simulations, this means that in the bar chart, each bar represents a mean value that is similar to averaging over the natural variability of 180 years, and each “whisker” (the thin lines on the bar) represents the range for 9 models, each averaged over 20 years. In the time series chart, each solid line represents a point averaged over 9 values, while the shaded areas show the range of year-to-year variability in the individual simulations. For observations, however, we only have one outcome. Observations are shown by the black bar in the bar charts (which represents the average over 20 years) and the black line in the time series plots (which represents the value for 1 year).

For certain variables, therefore, observations over a 20-year period are still subject to significant natural variability. For example, for the indicator of days with more than 2 inches of rain in 24 hours, the observations include large swings that are evident in the range, but not the average, of 9 climate model simulations over the same time period (see Figure 9, bottom row).

RESULTS

Regional Trends. The U.S. National Climate Assessment predicts increases in average temperature and extreme heat, as well as decreases in the frequency of extreme cold events. Precipitation patterns are expected to shift, with heavy precipitation continuing to become more frequent across the entire U.S. (Figure 5, Walsh et al., 2014a). At the scale of global climate models (accurate to broad regions, rather than individual states) these patterns are expected to persist over the mid-Atlantic region: warmer average temperatures, more frequent high temperature extremes, and wetter winters.

Using the methods described above, this analysis transforms these qualitative projections into quantitative information tailored to the individual weather stations in the District. This report highlights the main results from the climate analysis; data and charts for all the climate indicators calculated in this analysis are available in the accompanying files.

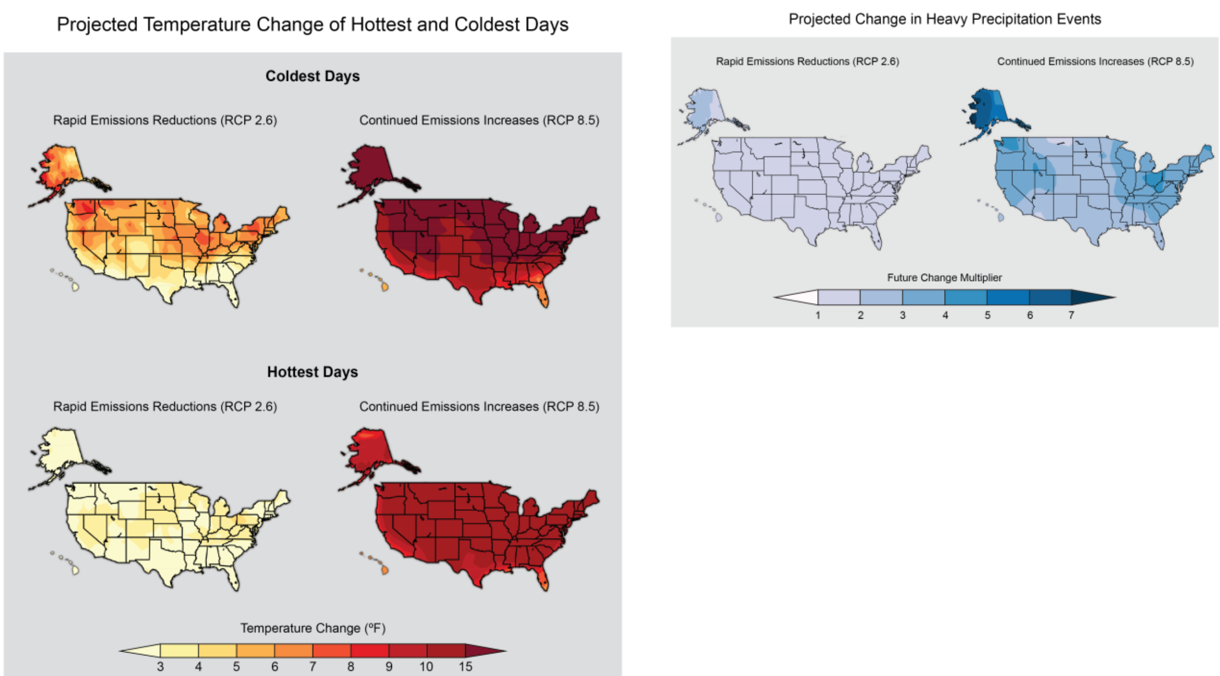


Figure 5. (Right) Projected future changes in the average temperature of the hottest and coldest days in each 20-year period (degrees F) and (Left) increase in frequency of the wettest day in 20 years (how many times more frequent will this event be) by 2081-2100 relative to 1981-2000. Source: Walsh et al., 2014a

Summer Average Temperatures. Climate change is expected to increase average and seasonal temperatures in the District. Summer maximum temperatures historically average 87°F during the day while minimum temperatures average 66°F at night. These values are projected to increase by 2.5-3°F by the 2020s, 5-7°F by the 2050s, and 6-10°F by the 2080s, depending on the scenario (Figure 6). For an individual time period and scenario, the scientific uncertainty is slightly lower for maximum as compared to minimum temperature. Overall, however, the magnitude of projected changes is similar for both day and nighttime temperatures.

All values presented here are the average across the three weather stations listed in Table 2.

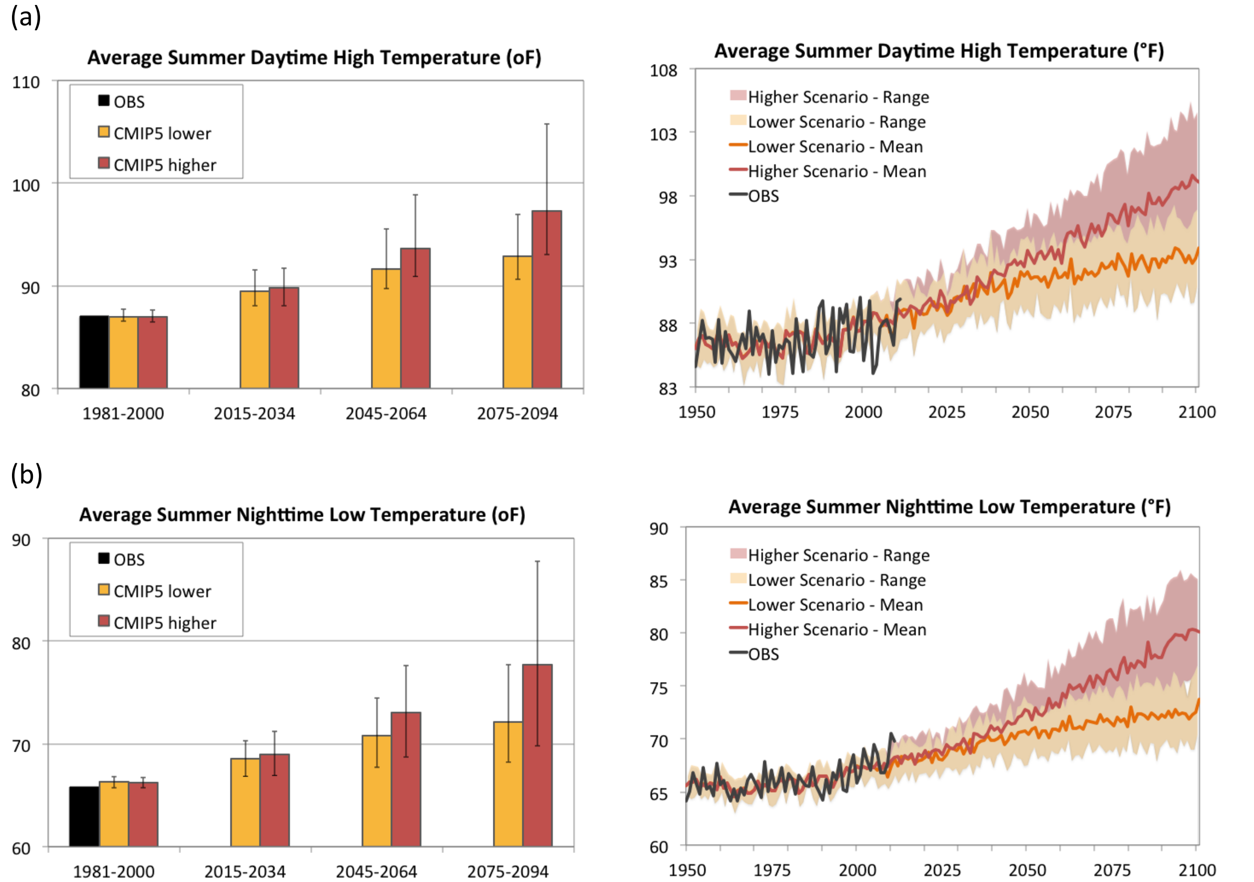


Figure 6. Historical and projected summer (Jun-Jul-Aug) (a) average daytime maximum or high and (b) average nighttime minimum or low temperature averaged across the three weather stations used in this analysis under higher (red) and lower (orange) future scenarios.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis.

For the time series plots, the solid line indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models.

In each plot, the black bar or line indicates observed values.

Summer Temperature Extremes. If the shape of the distribution of daily temperature changes in the future, as illustrated by Figure 4b, a change in mean temperature will not be proportional to projected changes in extremes. For that reason, it is important to calculate projected changes in temperature extremes individually. For extreme temperature indicators, projections are based on Reagan National Airport only, since that is the only station for which relative humidity observations are available. Hence, the historical period was defined as 1991-2010 since relative humidity data was not available prior to this date.

Historically, there are an average of 11 days per year with maximum daytime temperature over 95^{o}F at Reagan National Airport. In the future, the number of days is projected to increase. The number of days over 95^{o}F is projected to increase by 7-9 days by the 2020s. By mid-century, changes under higher scenarios are much greater than changes under lower scenarios. By the 2050s the number of days is expected to increase to between 30 and 45, depending on whether projections correspond to the lower or higher scenario. By the 2080s the number of days above 95oF could average around 40 days under the lower and 70 days per year under the higher scenario, respectively (Figure 7, top row).

Summer Heat Index. The heat index, which incorporates both temperature and humidity to assess how hot weather conditions actually feel to the human body, offers a different way to look at the intensity of summer heat. Historically, there are 11 days per year over with maximum temperature over 95^{o}F, but more than double that number, about 30 days per year, with a heat index over 95^{o}F. By the 2020s, these numbers are expected to increase to around 50 days per year. By mid-century, 70 to 80 days per year are expected, depending on the scenario. By the 2080s, the number of days per year with heat index over 95^{o}F could average around 75 under the lower scenario and 105 under the higher scenario (Figure 7, bottom row).

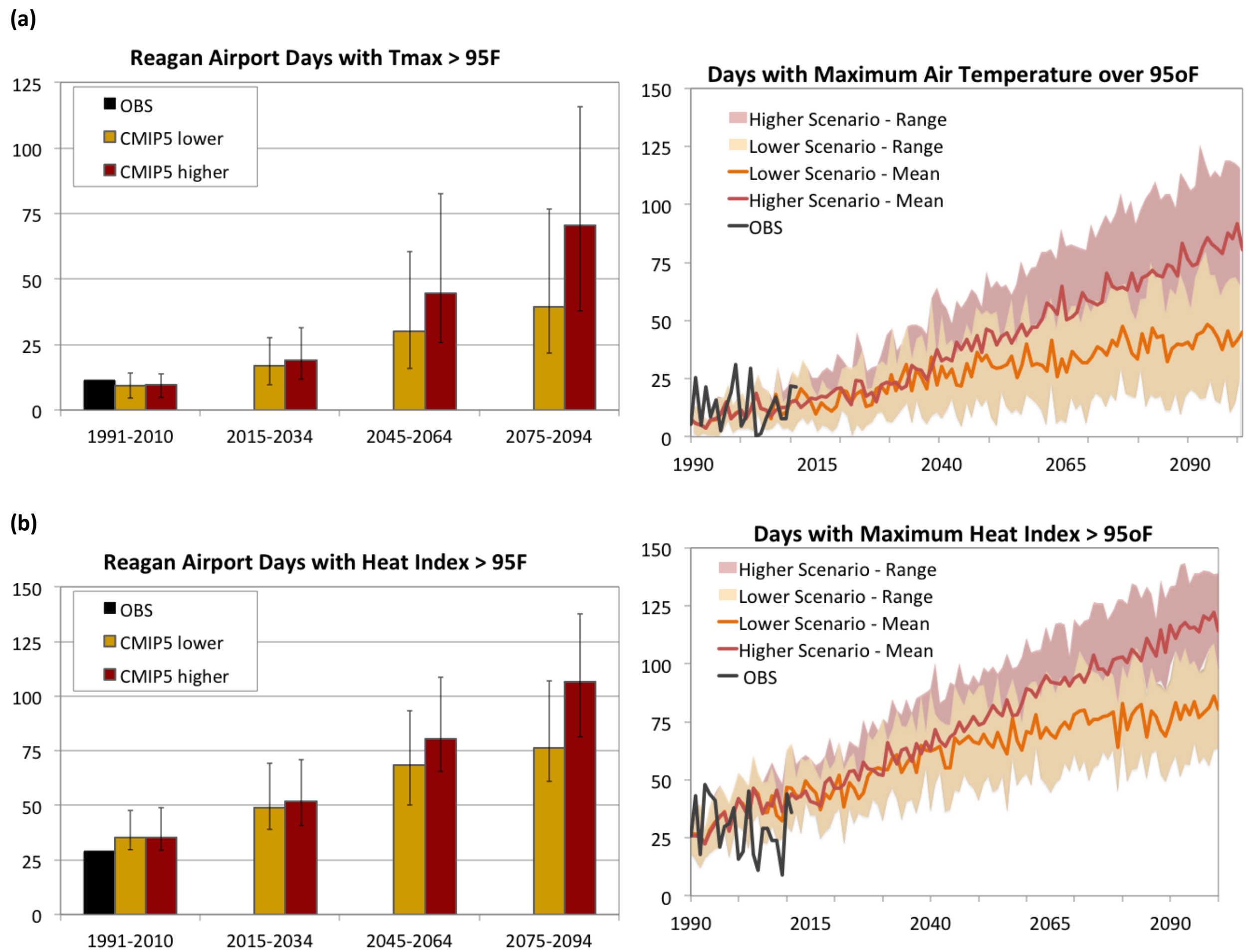


Figure 7. Observed (black) and projected future days per year with (a) daytime maximum air temperature (averaged over all three weather stations) and (b) daytime maximum heat index over 95°F (for the Washington Reagan National Airport station only, since the other weather stations do not have the relative humidity observations required to calculate heat index) under higher (orange) and lower (yellow) future scenarios. 1990 is the first date of relative humidity observations at Reagan National Airport.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each coloured bar represents the average of 180 years of simulations (9 models each run for 20 years), while each black bar represents the average of 20 years of observations.

For the time series plots, the solid coloured lines indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models. The solid black line indicates the single annual value for observations that year. As such, the black line is much more similar to the shaded range (which shows year to year values) rather than the coloured lines (which average across 9 model-years).

The primary reason for differences between the observed and multi-model mean values for the historical period is the lack of data in the historical observed record (beginning at 1990 only).

Summer Heatwaves. The District currently defines a heat wave as three or more consecutive days with daily maximum heat index values exceeding 95°F. According to this definition, historically there has been anywhere from 0 to 8 heat waves per year, averaging four heat waves per year over the period 1991-2010. The number of heat waves per year is expected rise to an average of 6 events per year by the 2020s, 7 events per year by the 2050s, and 8 events by the 2080s (Figure 8, top panel). There is little difference in the number of events projected to occur under a higher as compared to a lower future scenario.

This result is explained, at least in part, by projections that the duration of the average heat wave is also expected to increase, with noticeable differences between a higher vs a lower scenario by end of century (Figure 8, middle panel). During the historical period, the average heatwave as recorded at Reagan National Airport lasted between 4 to 10 days, averaging just under 5 days for the historical period 1991-2010. In the future, the average length is expected to be around 6 days by the 2020s, 8 to 9.5 days by mid-century, and around 9.5 days under the lower or 12 days under the higher scenario by the 2080s, albeit with large scientific uncertainty (as demonstrated by the black uncertainty ranges on each bar).

In contrast to the projected increases in days per year above 95°F, the number of heatwaves per year shows a slower increase and relatively little difference between higher vs. lower scenarios through the end of the century. This suggests that the risk of the weather patterns that bring multi-day heat events to DC is likely to increase slightly, but this risk will not necessarily be much greater under higher amounts of global warming. However, these weather patterns may last longer, bringing more extended heat waves under the lower as compared to the higher scenario.

In 2012, the District experienced an unprecedented heatwave event. During this event, which lasted 11 days from June 28 to July 8, many long-standing records at the Reagan National Airport weather station were broken, including a number of record daily maximum and minimum temperatures.

Specifically, the 2012 heatwave was characterized by:

- 11+ consecutive days with daytime maximum temperatures over 95°F
- 4+ consecutive days with daytime maximum temperatures over 100°F
- 8+ nights with minimum temperatures over 75°F
- 3+ nights with minimum temperatures over 80°F

Using these four criteria, we calculated the frequency of 2012-like heatwaves now and in the future. During the historical period, these events are very rare (zero, in the observations, since the historical period of 1991-2010 does not include 2012!), although we know one occurred in 2012. By the 2020s, there is a 66% chance of one such event happening every 10 years (Figure 8, bottom panel). By the 2050s, there could be between 0.4 (under lower) and 1 (under higher) events each year (with a high degree of uncertainty, since this is such a rare event), and by the 2080s the number of these events is projected to be average between 0.8 and 2.8 events per year, depending on scenario.

End of century values are very uncertain, since this is an extremely rare event. Under both scenarios, however, the scientific uncertainty does not include zero. This means that the chance of a 2012-like heatwave recurring during the 2080s is virtually certain.

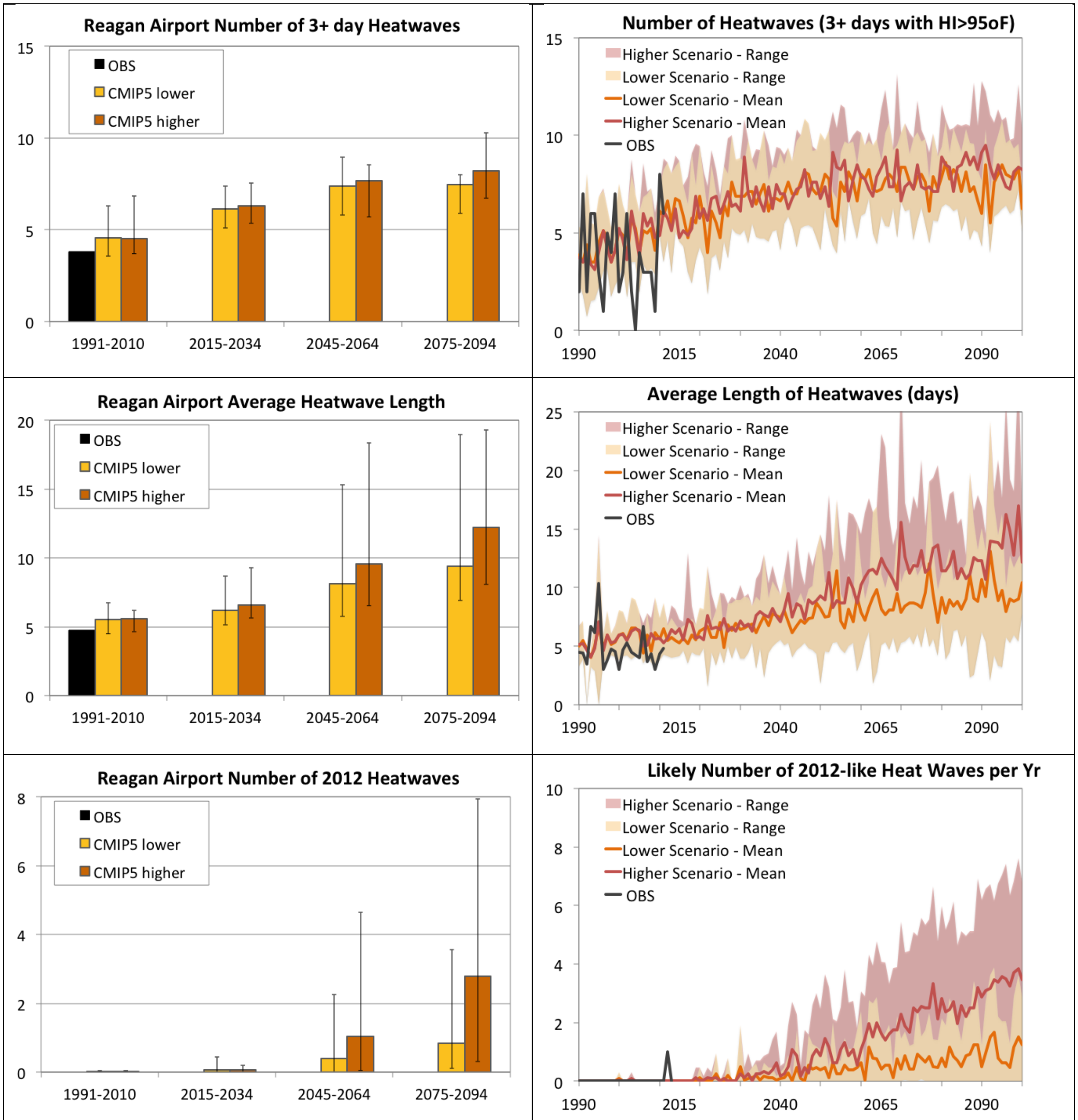


Figure 8. (Top) Average number of heat waves per year, where heat waves are defined as three or more consecutive days with maximum heat index values greater than 95°F. (Middle) Average length of a typical heatwave, defined as in (a), in days. (Bottom) Average number of 2012-like heat waves per year, defined by the four criteria listed on page 11.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each coloured bar represents the average of 180 years of simulations, while each black bar represents the average of 20 years of observations.

For the time series plots, the solid coloured lines indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models. The solid black line indicates the single annual value for observations that year. As such, the black line is much more similar to the shaded range (which shows year to year values) rather than the coloured lines (which average across 9 model-years).

The primary reason for differences between the observed and multi-model mean values for the historical period is the lack of data in the historical observed record (beginning at 1990 only).

Extreme Precipitation. In addition to temperature, this analysis calculated three types of indicators of extreme precipitation: (1) days with more than 1 or 2 inches of precipitation in 24 hours; (2) the record 24h storm every 1 or 2 years; and (2) the precipitation amounts associated with the historical and projected future 80th, 90th, and 95th percentile of wet days.

It is important to note two differences in the ways these precipitation indicators were calculated. First, the method used to calculate the 1 and 2 year storm events was based on empirical data, rather than on a theoretical distribution, as in the main report. In other words, to calculate the record 24h storm event per year, we first identified the wettest 24h storm for each year of the 20-year period, and then averaged those values over the entire period. Similarly, to calculate the wettest 24h storm in 2 years, we first identified the wettest 24h in each two-year interval, then averaged those values over the 20 year period. Second, the 80th, 90th, and 95th percentile values were calculated based on 31-year periods, as described previously in the methods section, to match the methodology currently in use by the city to define historical thresholds. In addition, in order to obtain historical values that matched those in use by the city, the value of precipitation that was considered to be "trace" was increased from 0.01" to 0.08", and all wet-day precipitation below that threshold was removed prior to calculating the quantile values. For the 90th percentile, this gave values of 1.17, 1.12 and 1.13" for Dalecarlia, Reagan, and the National Arboretum, respectively, which compare well with the values of 1.17, 1.13 and 1.10" in use by the city for those stations.

All metrics of extreme precipitation show increases in the future. These increases are greater by end of century as compared to earlier time periods. By the 2080s, there is some indication of greater changes under higher as compared to lower scenarios. In contrast to extreme temperature metrics, however, for extreme precipitation metrics the differences between scenarios are not significant (as demonstrated by the fact that the scientific uncertainty bars overlap almost entirely).

Averaged across the three long-term weather stations described in Table 1, the District currently receives an average of 10 days per year with more than 1 inch of rain in 24 hours and between 0 to 5 days per year, with an average just over 1 day per year for the period 1981-2000, with more than 2 inches of rain in 24 hours (Figure 9). For days per year with more than 1 inch of rain, the number of events per year is projected to increase by about 1 day by the 2020s, 2 days by the 2050s and 3 days by the 2080s. The number of days per year with more than 2 inches of rain is projected to increase to 2 days by the 2020s, to an average of 2.5 days per year by the 2050s and to between 2.5 to 3.5 days per year by the 2080s.

In terms of the 1-year and 2-year storms, historical values average 2.5 inches and just over 3 inches, respectively (Figure 10). These amounts are also projected to increase. For the 1 year storm, a few tenths of an inch more rain is expected on average by the 2020s. By the 2050s, the amount of precipitation falling in the 1-year storm is projected to increase by about 2/3 of an inch, and by the 2080s the precipitation amount is projected to increase by a total of about 1 inch relative to the historical period. Larger changes are expected for the 2-year storm: between 0.5 to 1 additional inches are expected by the 2020s, 1 more inch by the 2050s, and 1.5 to 2 more inches by the 2080s.

Finally, small but consistent increases are projected in the amount of precipitation falling in the 80th, 90th, and 95th percentile of events in each future 20-year period (Figure 11). For the 80th percentile event, increases of only a tenth of an inch are projected by end of century. For the 90th percentile, increases of 0.1" are expected by the 2020s, 0.1-0.2" by the 2050s and 0.1-0.25" by the 2080s, with slightly greater increases under the higher scenario. Slightly greater increases (from +0.05 to +0.1" more) are projected for the 95th percentile of wet day precipitation.

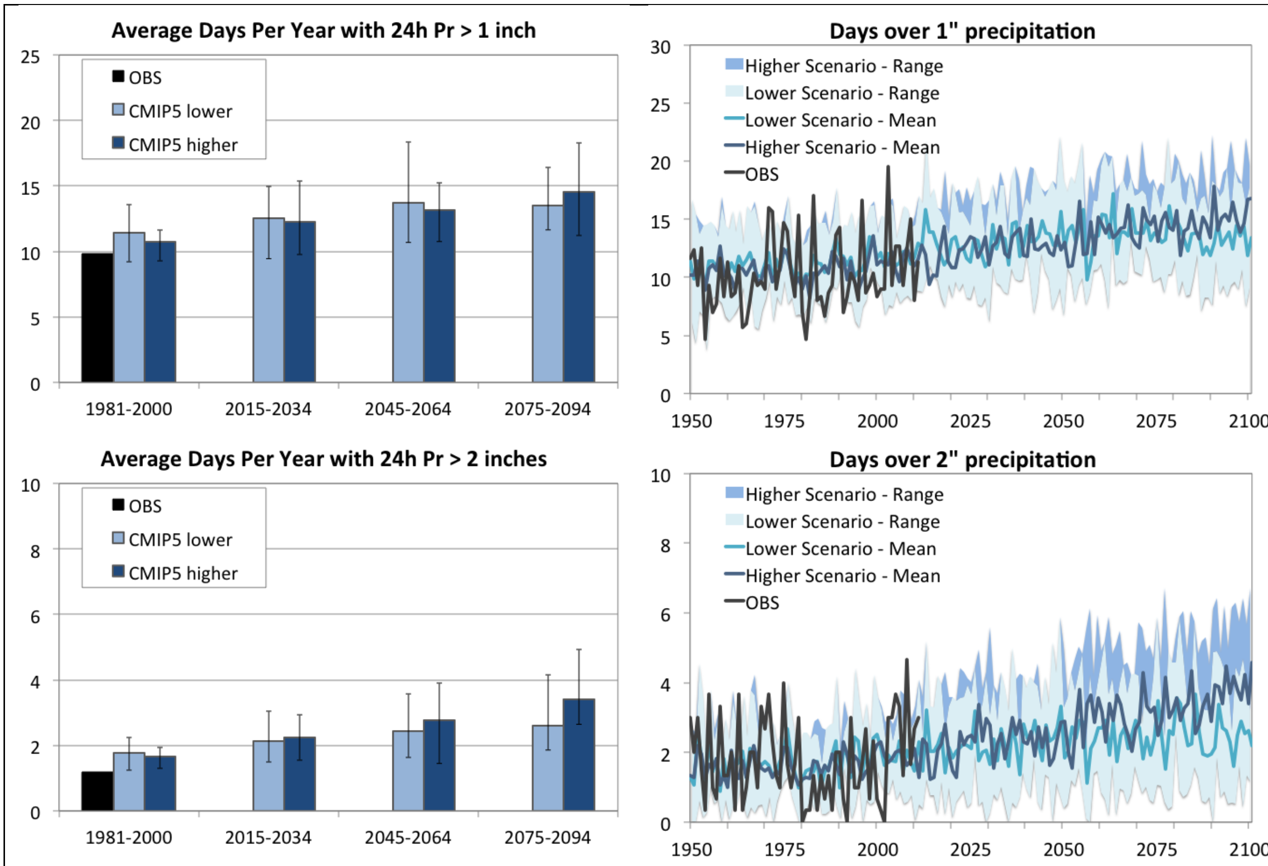


Figure 9. Number of days per year with more than 1" (top) and 2" (bottom) of precipitation in 24h. Values are averaged across the three weather stations used in this analysis under higher (dark blue) and lower (light blue) future scenarios.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each coloured bar represents the average of 180 years of simulations, while each black bar represents the average of 20 years of observations.

For the time series plots, the solid coloured lines indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models. The solid black line indicates the single annual value for observations that year. As such, the black line is much more similar to the shaded range (which shows year to year values) rather than the coloured lines (which average across 9 model-years).

It is important to note in this figure that, by chance, the historical period 1981-2000 encompasses the lowest part of the historical range of days per year with more than 2 inches of precipitation in 24 hours. This is reflected by the fact that the model observations, downscaled using the full 60-year record, are higher than observed for the historical period.

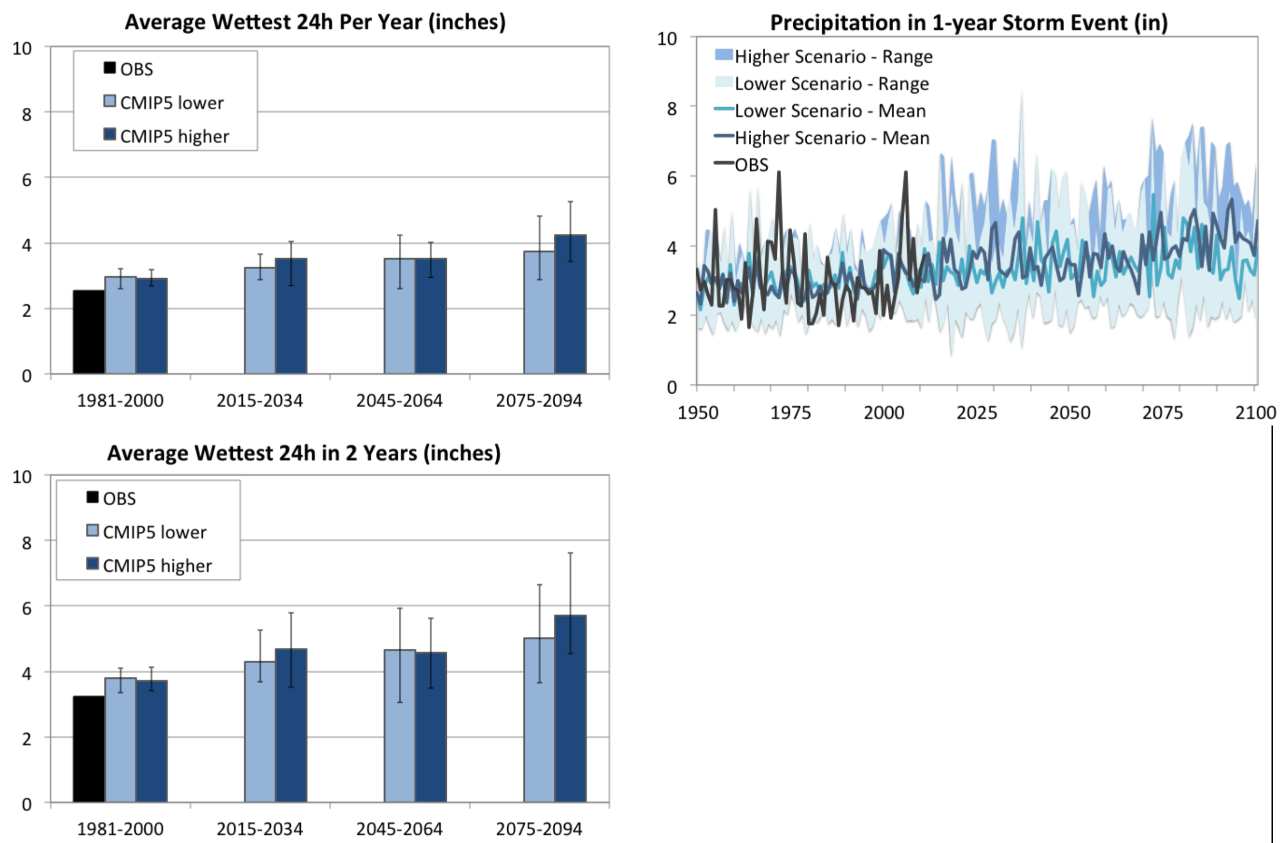
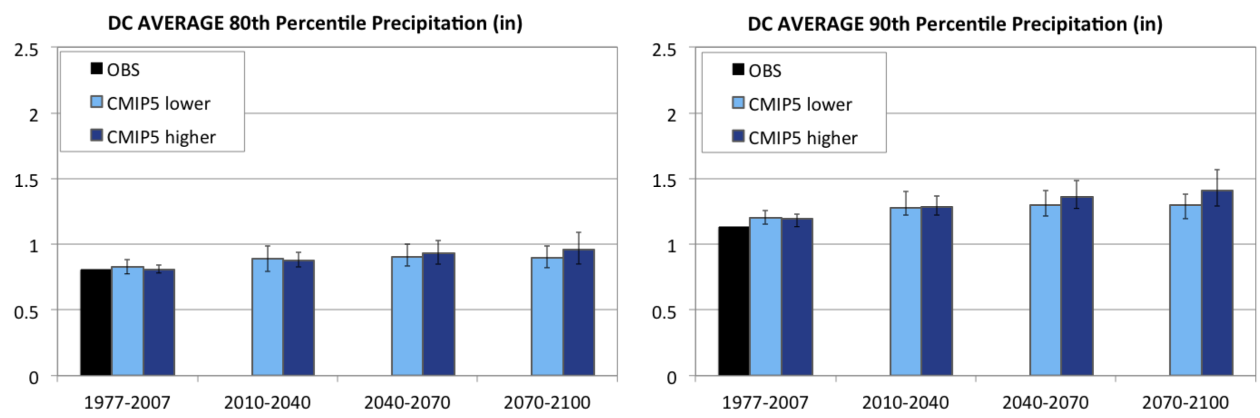


Figure 10. Amount of precipitation falling in the wettest 24h period in 1 (top) and 2 (bottom) years, averaged across the three weather stations used in this analysis under higher (dark blue) and lower (light blue) future scenarios.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each blue bar represents the average of 180 years of simulations, while each black bar represents the average of 20 years of observations.

For the time series plots, the solid blue lines indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models. The solid black line indicates the single annual value for observations that year. As such, the black line is much more similar to the shaded range (which shows year to year values) rather than the blue lines (which average across 9 model-years).

There is no time series plot for the 2-year storm since, by definition, this indicator does not have annual values.



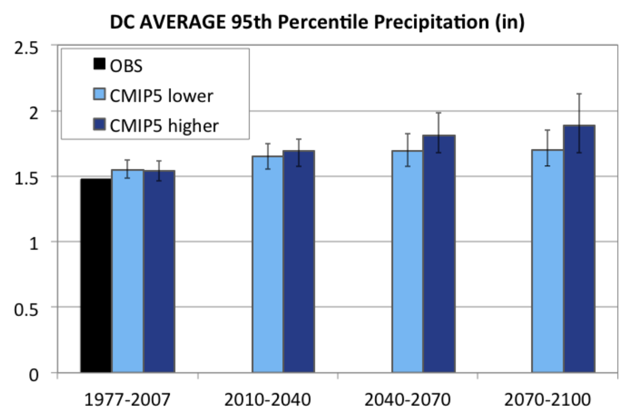


Figure 11. Changes in rainfall amounts associated with the 80th, 90th and 95th percentile of wet days, averaged across the three weather stations used in this analysis under higher (dark blue) and lower (light blue) future scenarios.

The uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each blue bar represents the average of 180 years of simulations, while each black bar represents the average of 31 years of observations, as indicated by the x-axis labels

In each plot, the black bar or line indicates observed values.

CONCLUSIONS

Climate projections for the United States show that observed temperature increases are projected to continue, as are increases in high temperature and heavy precipitation extremes. These projections for the District of Columbia, based on three long-term weather stations at Reagan National Airport, Dalecarlia Reservoir, and the National Arboretum, show similar trends in summer average temperature and high temperature extremes, with higher changes projected under higher scenarios as compared to lower, and by later time periods as compared to earlier.

Comparing these projections with others projections generated for the mid-Atlantic region will not yield the same values for several reasons. First, the projections are for a different geographic region. In particular, DC's proximity to the ocean can mitigate projected warming and stabilize humidity levels compared to inland locations. Second, the projections are for weather stations as compared to a gridded set of observations. Third, the projections could have been generated using a different combination of global climate models and/or a different type of statistical downscaling model. For all of these reasons, the projections summarized in this report can be expected to be *similar*, but not *identical* to, projections generated by other regional efforts.

It is also important to note that future climate projections are uncertain for multiple reasons. At the global scale, the rate and magnitude of future change will be affected by emissions from human activities, and by the sensitivity of the climate system to those emissions. In this assessment, we address these uncertainties explicitly by basing our projections on simulations from 9 different GCMs with different levels of sensitivity to carbon dioxide and other climate drivers, and on a higher and lower future scenario (RCP 8.5 and 4.5). However, we acknowledge that actual emissions, and hence atmospheric carbon dioxide levels and global temperature, could lie above the higher scenario (if carbon emissions continue to increase at the rate they have since 2000, for example) or be reduced below the lower scenario (if carbon-free energy solutions are implemented rapidly at the global scale, for example, or if new technologies are invented capable of removing large quantities of carbon dioxide from the atmosphere).

It is also important to note that, over the next few decades, there is no statistically significant difference between the changes projected under a higher as compared to a lower scenario at the local scale. This is due to the inertia of both the climate system and human impacts. Climate projections for the 2050s and 2080s, on the other hand, can be scenario-dependent, particularly for temperature. This means that, past the 2020s, projections must be considered separately for the higher versus the lower scenarios.

At the local to regional scale, climate projections are additionally uncertain due to natural variability (which is much greater at smaller temporal and spatial scales than for national or global averages), selection of weather stations (do they adequately capture the range of climate variability over the region?), and the downscaling method used (since statistical methods will not be able to capture changes in local physical processes that operate at finer scales than the GCMs can simulate, such as the intensification of land/sea breezes during hot summer days, as the land surface warms faster than the ocean in the future).

The first uncertainty is addressed through use of the 20-year time periods discussed previously. Uncertainties involved with choice of weather stations are addressed, to some extent, by using projections from three weather stations in District of Columbia. Inclusion of a greater number of long-term, high-quality stations (particularly Baltimore and Dulles Airports) would improve on this uncertainty. This is particularly important for extreme heat projections for which data from only one weather station was available.

Within the scope of this project, it is not possible to reduce the uncertainty in downscaling as the issue of stationarity can only be fully addressed by use of an ultra-high-resolution regional climate model and such simulations, corresponding to multiple scenarios and GCMs, are not available for the latest generation of RCP scenarios and GCMs. Experimental work has shown, however, that the ARRMv1 method is capable of quantifying projected changes in average and extreme temperature and precipitation well into the tails of the distribution. For extreme heat days that are currently very rare (occurring 1x per year or less), the method is biased towards the higher end of the distribution: in other words, resulting values are greater than those generated by a 25km high resolution global model over the same area (Hayhoe et al – *in preparation*).

Regional projections for northern mid-latitudes show increases in winter and spring precipitation, as well as increases in extreme precipitation. Again, projections for the District show similar trends, with increases in the frequency of heavy precipitation events and the amounts of precipitation associated with 1-year, 2-year, and percentile storms. In contrast to temperature, there are few significant differences between changes projected under higher as compared to lower future scenarios. In general, however, changes projected by 2070s are usually slightly larger than those projected by 2020s.

Based on these results, and on the sources of uncertainty discussed above, there is *greatest certainty* in the direction of projected increases in summer average temperatures and high temperatures, all of which show increases consistent with observed trends that are greater by end of century relative to the 2020s and under a higher as compared to a lower scenario. There is *moderate certainty* in the projected changes in the amounts of extreme precipitation (although *greatest certainty* in the upward direction of the trend). Although these reflect observed regional trends, they are more strongly affected by regional and local climate variability.

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