EXECUTIVE SUMMARY

Incorporation of the Effects of Future Anthropogenically-Forced Climate Change in Intensity-Duration-Frequency Design Values

SERDP Project RC-2517

SEPTEMBER 2020

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<td>annual maximum series</td>
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<td>ARI</td>
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<td>EP</td>
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<td>GHG</td>
<td>greenhouse gas</td>
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<td>IDF</td>
<td>Intensity-Duration-Frequency</td>
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<td>NAM</td>
<td>North American Monsoon</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>precipitation causes</td>
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<td>partial duration series</td>
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<td>precipitable water</td>
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<td>tropical cyclone</td>
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1.0 INTRODUCTION

Numerous scientific assessments have shown that human-induced climate changes are occurring, and more changes are expected as atmospheric composition is altered. This research focused on how these changes affect extreme precipitation (EP) rates and, specifically, Intensity-Duration-Frequency (IDF) design values that are used by engineers and others for planning, design, and operations. The most comprehensive set of existing IDF curves developed over the past two decades is based on the assumption of a stationary climate. The key overarching objective of this work was to transform IDF values into a new set that accounts for a non-stationary climate with varying degrees of climate change.

The development of non-stationary IDF values was based on an analysis of historical trends of EP events and the weather and climate conditions known to affect these events. Weather events of interest included those systems that generate upward vertical velocity over geographies with ample water vapor. One dimension of the research focused on the development of automated and objective methods to identify those weather types, not only in past data but in the enormous quantity of data generated from various global climate model (GCM) simulations.

Although GCMs are the backbone of understanding past and future climate, they are known to have deficiencies in simulating the EP rates of interest here. A number of methods have been developed to help overcome many of these deficiencies. Key objectives of this work included building on these existing methods to enable robust uncertainty estimates of future IDF values and, most importantly, provide an understanding of why changes in the IDF values are expected for specific locations and future times.

2.0 OBJECTIVES

The overriding objective of this project was to develop a framework for incorporating future climate change into IDF values. The work leveraged the large amount of previous work on extreme precipitation (EP) the project team had completed, as well as the development of IDF values done by the developers of National Oceanic and Atmospheric Administration (NOAA) Atlas 14. The underlying basis for incorporating non-stationarity into IDF values is the robust, physically based projection of global warming with increasing greenhouse gas (GHG) concentrations. Global warming, in turn, will increase atmospheric water vapor concentrations with an equally high level of confidence, producing the potential for more intense precipitation. Actual changes in IDF values will result from changes in atmospheric water capacity (i.e., vertically integrated water vapor concentrations) and opportunity (i.e., the number and intensity of heavy precipitation–producing storm systems). The project team evaluated these two components at frequencies and durations relevant to civil engineering and provided adjusted IDF values, along with uncertainty estimates, that are based on a fundamental understanding of future changes in the climate system, an understanding that was more fully developed in this project.

Estimates of projected future climate changes were derived from the suite of future projections from global climate model experiments that simulate the response of the climate system to different scenarios of future changes in atmospheric composition. These projections were analyzed with respect to extreme precipitation (EP) using two different methods.
In the first method, called precipitation downscaled (PD), EP estimates were derived from GCM downscaled precipitation estimates that simulate future conditions. The second method, called precipitation causes (PC), made use of projected GCM-derived changes of atmospheric water vapor (without which precipitation does not occur) and specific weather systems that trigger EP events. In the PC approach, actual changes in IDF values are derived from both changes in atmospheric water vapor capacity and triggering mechanisms (the number of precipitation-producing atmospheric circulation systems, such as fronts and storm systems). This method enables an understanding of the key drivers of EP events and their changes in intensity, duration, and frequency. By contrast, with the PD method, it is uncertain what the primary meteorological causes are for changes in the IDF curves because typical downscaling methods are not explicitly connected with meteorological processes.

The two methods were applied to a wide range of IDF values used by civil engineers. The range of IDF values spans all but the lowest durations (less than six hours) of the IDF values used in NOAA Atlas 14, but for a changing climate.

2.1 HYPOTHESES

The research was organized around the following scientific hypotheses:

**Hypothesis 1:** Historically observed and anthropogenically forced future changes in IDF values used in the engineering community arise primarily from two principal meteorological sources: 1) changes in atmospheric water vapor concentration (potential) and 2) changes in the frequency and intensity of the weather systems that cause heavy precipitation (triggers).

**Hypothesis 2:** As the time horizon increases, IDF values will increase primarily because GCMs project increasing temperature and related water vapor altered by concomitant changes in the frequency and intensity of fronts and storm tracks and other changes in circulation.

**Hypothesis 3:** Regional variations in the changes of IDF values arise primarily from regional differences in water vapor, weather/climate systems, and regional aspects of terrain and ocean influence.

3.0 TECHNICAL APPROACH

Present-day extreme precipitation (EP) IDF design values were revised using two complementary methods that enabled us to assess uncertainty of future projected changes in EP. This two-phased effort included 1) a generalized extreme value (GEV) analysis (Coles 2001) of projected changes of precipitation in the downscaled projections of GCMs and 2) the use of relationships identified in this project between extreme rainfall events and the key synoptic meteorological/climatological systems known to directly affect EP rates. This two-phased effort enables us to more effectively assess the degree of confidence in projected changes of EP.

In the first method, the project team made use of downscaled GCM precipitation estimates to estimate future values of EP denoted by EPD (D for downscaled). This is written as:

\[
EPD_{d,f}^{ut}(x,y,t) = \frac{EP_{d,f}^{NA14}(x,y,t)}{GEV_{d,f}[AMS_{D\text{GCM}}(x,y,t)]} \frac{GEV_{d,f}[AMS_{D\text{GCM}}(x,y,c\text{urr})]}{GEV_{d,f}[AMS_{D\text{GCM}}(x,y,c\text{urr})]} \]

\(1\)
where:

\[ E_{\text{NA14}}^{d,f}(x,y) = \text{current precipitation design value for duration } d \text{ and frequency } f \text{ at location } (x,y). \] These values will be taken from NOAA Atlas 14,

\[ EP_{d,f}^{fu,t}(x,y,t) = \text{precipitation design value at future year } t \text{ for duration } d \text{ and frequency } f \text{ at location } (x,y) \text{ based on downscaled data}, \]

\[ GEV_{d,f} = \text{the precipitation design value for duration } d \text{ and frequency } f \text{ derived from a GEV analysis of GCM extreme rainfall/snowfall at location } (x,y), \]

\[ AMS_{\text{DGCM}}(x,y,t) = \text{annual maximum series of downscaled GCM extreme rainfall/snowfall at location } (x,y) \text{ for a } 30\text{-year period centered around year } t \]

Because of the known limitations of GCM-simulated extreme rainfall events, including events from downscaled data and the lack of clarity related to the causes of those events from a statistically based downscaled approach, the second means of developing future estimates of EP make use of the relationships between EP and key synoptic meteorological and climate conditions known to directly cause EP. This includes atmospheric water vapor, specifically precipitable water (PW), and the vertical motion associated with synoptic weather and climate systems. The meteorological systems investigated were extratropical cyclones (ETCs), tropical cyclones (TCs), and the North American Monsoon (NAM). The fronts (FRTs) that are part of ETCs were investigated separately. Changes in the causes of EP were assessed for GCM simulations to estimate future values of EP and this is denoted as EPC (C for causes).

Recent assessments of future changes in TCs with regard to extreme rainfall have indicated that the highest confidence is associated with changes in water vapor while there is low and mixed confidence about changes in the frequency of TCs. Water vapor is considered separately; thus, the equation for EPC does not include a TC frequency component. Regarding the NAM, future changes remain uncertain. Depending on the model, model resolution, and bias corrections, projections range from an intensified circulation with more intense rainfall to reduced early-season circulation and less rainfall. As a result, the project team did not include a factor for the frequency of NAM systems.

With these simplifications, the equation for changes in EP as a result of meteorology is:

\[ EPC_{d,f}^{fu,t}(x,y,t) = EP_{d,f}^{\text{NA14}}(x,y) F(PW) G(FRT,ETC) \quad (2) \]

where \( F \) and \( G \) are the PW and weather system scaling factors, respectively. These are further defined as

\[ F(PW) = [1 + \alpha \Delta \ln PW(x,y,t)] \quad (3) \]

\[ G(FRT,ETC) = \left\{ 1 + F \sum_{s=1}^{4} \beta \left( FRT(x,y,s) \Delta FRT(x,y,s,t) + ETC(x,y,s) \Delta ETC(x,y,s,t) \right) \right\} \quad (4) \]

where weather system influences are quantified by:

\[ FRT(x,y,s) = \text{the fraction of all events at point } (x,y) \text{ that are caused by fronts in season } s \text{ for the current climate}, \]
\[ ETC(x,y,s) = \text{the fraction of all events at point } (x,y) \text{ that are caused by extratropical cyclones in season } s \text{ for the current climate}, \]

\[ \Delta FRT(x,y,s,t) = \text{fractional change in frontal frequency in season } s \text{ at point } (x,y) \text{ at future year } t, \]

\[ \Delta ETC(x,y,s,t) = \text{fractional change in frequency of extratropical cyclones in season } s \text{ at point } (x,y) \text{ at future year } t, \]

\[ \Delta PW(x,y,t) = \text{fractional change in precipitable water in future year } t \text{ at point } (x,y), \]

\[ G = \text{function that transforms the weather system frequency changes into quantitative changes in IDF values}, \]

\[ \alpha, \beta, \gamma = \text{coefficients defined by the empirical relationships between the respective variable and extreme precipitation amounts in the observed data} \]

### 3.1 HISTORICAL ANALYSIS

A network of observing stations taking daily observations (24 hour) of total precipitation was used to perform the analysis of historical trends of EP and associations with meteorological conditions. These data came from the Global Historical Climatology Network-Daily (GHCND), which is made up of observing stations from the U.S. Cooperative Observer Program that was established in the late 1800s and managed by the National Weather Service. There were some specialized datasets that were also used. The project team obtained from the Air Force 14th Weather Squadron daily precipitation data for Fort Wainwright and Eielson Air Force Base in Alaska, both with long periods of record. The period of historical EP trend analysis was 1949-2016.

For certain regional summarizations, the National Centers for Environmental Information (NCEI) regional definition for the 48 contiguous United States was used. A total of 35 combinations of duration (one-day, two-day, three-day, five-day, 10-day, 20-day, and 30-day) and frequency (one-year, two-year, five-year, 10-year, and 20-year) were analyzed. Although sub-daily data are available, the period of record and spatial density of available stations at that frequency are too short and sparse to allow a robust analysis, and thus sub-daily observations were not analyzed.

To better understand the relationship between EP events and PW, two similar EP metrics were computed for each station that the project team used in the GHCND dataset. First, the time series of the yearly maximum daily precipitation, or annual maximum series (AMS), was identified. This is the starting point for the development of many IDF curves. Second, the amount of precipitation on those days exceeding the one-year one-day recurrence threshold was identified. This is referred to as the partial duration series (PDS), and it simply consists of the highest 68 daily events for a station with a complete 68-year period of record in the GHCND dataset. Not surprisingly, the project team found considerable overlap between these two metrics; on average, more than two-thirds of the PDS and AMS values are the same events.

For analysis of the association of meteorological systems with EP events, the period of analysis was 1980-2017. Software from a previous project to identify ETC centers was applied. New software using machine learning was developed to identify FRTs. In operational meteorological analysis, FRTs are identified visually based on the approximate spatial coincidence of a number of quasi-linear localized features: a trough (relative minimum) in air pressure in combination with gradients in air temperature and/or humidity and a shift in wind direction.
The project team developed a deep learning neural network to mimic the visual fronts-recognition task performed by meteorologists. This was applied to the MERRA-2 reanalysis.

4.0 RESULTS AND DISCUSSION

The major scientific finding is that atmospheric water vapor concentration is the major determining factor for the magnitude of EP events. An analysis of historical events showed that EP amounts scale closely with PW (vertically integrated water vapor) and that the scaling factor increases with increasing PW magnitude. Analysis of global climate model simulations indicates that global warming leads to increases in atmospheric water vapor concentrations at approximately the Clausius–Clapeyron rate (~7% °C⁻¹). Water vapor is the dominant component in the adjustment factors. This is a consequence of the strong relationship in the observational record between extreme precipitation amounts and water vapor combined with the highly confident projections of large increases of future water vapor. This leads to large (>20%) increases in IDF values by the end of the century under the high emissions scenario (RCP8.5).

Analyses of future changes in weather systems investigated FRTs, extratropical cyclones (ETCs), tropical cyclones (TCs), and NAM moisture surges. Among these weather systems, FRTs are the dominant cause of EP events in most areas of the U.S., followed by ETCs. When broken down by season, summer FRTs are the single most dominant trigger for EP events over much of the eastern two-thirds of the contiguous United States (CONUS). Unlike atmospheric water vapor concentration, with large projected increases everywhere, future changes in the frequency of these systems are regionally and seasonally variable. However, GCM simulations indicate future decreases in fronts and ETCs in many areas. For EP events triggered by weather systems, the most important future projection is a decrease in summer FRTs almost everywhere. This is in conjunction with the fact that FRTs, overall, are the dominant trigger of EP events. Review of recent published research and the own analysis indicate that GCM simulations of TCs and NAM moisture surges are too uncertain to rely on for incorporation into the adjustment factors. Furthermore, atmospheric water vapor appears to be the primary factor for increases in rainfall associated with these systems, and this factor is already incorporated into the adjustment factors. The overall outcome of the weather systems research is that the future changes in FRTs and ETCs tend to decrease IDF values, but the magnitudes of their effects are much smaller than the increases projected as a result of the changes in the water vapor component.

4.1 HISTORICAL EP TRENDS

Figure 1 shows the annual trends (in percent per decade) for the 35 average recurrence interval (ARI)–duration combinations described earlier for both the 1949–2016 and 1979–2016 periods. There is a distinct gradient from west to east in the sign and magnitude of the trends. Large positive trends occur in the Northeast, Southeast, South, Central, East North Central, and West North Central NCEI regions. It is notable that the magnitude and significance of the trends get larger as the ARI gets longer (e.g., one-year versus 20-year recurrence interval), and this is true not just in the eastern part of CONUS but also across the entire country. Furthermore, the trends for both analysis periods (1949–2016 and 1979–2016) show similar results.
Figure 1. Trends (Percent Per Decade) in the Frequency of Occurrences for Each Region During the (a) 1949–2016 and (b) 1979–2016 Periods for the 35 ARI–Duration Combinations.

Decreasing trends are displayed in shades of brown, and increasing trends are displayed in shades of green. Statistically significant trends are shown in red-colored numbers (0.05 significance level for a two-tailed test).
4.2 WATER VAPOR RELATIONSHIPS WITH EP EVENTS

The analysis of historical EP events shows that there is a strong positive relationship between PW and EP (Figure 2a). An important consideration in the work was to establish whether the relationship between PW and EP scaled differently with EP events at high versus low values of PW. At first approximation, this relationship scales linearly, but closer examination shows that is not the case. The ratio of EP/PW when plotted against PW (Figure 2b) shows that for a given amount of increase in PW, the increase in EP is greater at higher values of PW compared to lower values. This non-linear scaling is an important consideration in the application of equation (2), because $\alpha$ then becomes dependent on the value of PW.

The data in Figure 2a form the basis for determining an appropriate function to represent the non-linear scaling of the coefficient $\alpha$ with PW. More than 3,000 stations across CONUS enable rather robust statistics. Using an interweaving method (to ensure stability), differentials of the observational averages from Figure 2a were calculated based on the change in EP with PW. However, end-point issues arise, and this fit was bookended by fixed values of $\alpha$. The combined piecewise function is given by:

\[
\alpha(PW) = \begin{cases} 
0.47 & PW < 25 \text{ mm} \\
0.00577 PW^2 - 0.0272 PW + 0.794 & 25 \text{ mm} \geq PW \leq 65 \text{ mm} \\
0.04781 (PW - 65) + 1.464 & 65 \text{ mm} > PW < 76 \text{ mm} \\
2 & PW \geq 76 \text{ mm}
\end{cases}
\]

and shown graphically in Figure 3.

Changes in PW were calculated from 13 CMIP5 models for each decade of the 21st century from the 2020s to the 2080s for two emissions scenarios, RCP4.5 and RCP8.5. An example is shown in Figure 4. Some key characteristics of these calculations:

- The changes in water vapor are upward for all locations globally.
- By the end of the 21st century under a high emissions (RCP8.5) scenario, the changes are very large, exceeding 20% everywhere and exceeding 30% over most of the mid- and high latitudes.
- The spatial variability is relatively small in comparison to the changes by the mid- and late 21st century. For example, the changes over CONUS for the end of the 21st century under the RCP8.5 scenario vary by only 5–10%.
Figure 2a and b. Boxplot Distributions for the One-year, One-day Partial Duration Series of (a) Precipitation Event Amount vs the Same-day Three-hour Maximum PW Sorted into 10mm Interval Bins and (b) as in Panel (a) but for the Amplification Factor A (EP/PW).

Boxplot parameters include mean (green diamonds), median (orange horizontal lines), 25th and 75th percentiles (box limits), and 5th and 95th percentiles (whiskers). Statistical significance (0.05 level) of the difference between A across adjacent intervals of PW is denoted where “−” and “+” denote a significant decrease and increase, respectively (the value of A in the higher PW bin minus lower PW bin). The observation count in panel (b) used in the statistical tests is depicted above the top whisker, and the 95th percentile value for bin 0–10 is 10.75.
Figure 3. Observed and Fitted Relationship between PW and $\alpha$.
These are the values of $\alpha$ that are used in equation (2).

Figure 4. Projected Change (%) in Maximum Daily Precipitable Water (PWmax) by Late 21st Century Relative to Late 20th Century Under the High Emissions (RCP8.5) Scenario.
This is an average of 13 CMIP5 models.
4.3 WEATHER SYSTEMS

The project team used the automated software to create a master dataset of EP events and associated meteorological causes for the 3000 stations used in the historical trend analysis. This dataset was analyzed to determine the distribution by meteorological cause for $10^\circ\times10^\circ$ grid boxes. The results for one-day duration events exceeding the one-year recurrence level threshold are shown in Figure 5. Fronts are the dominant cause in every box except for a single north-central box, where ETC events occur slightly more often than frontal events. Extratropical cyclones are the 2nd most common cause in every other box except for the Florida peninsula, where tropical cyclones (TCs) are the 2nd most common cause. In addition to the Florida peninsula, TCs cause more than 10% of events in south Texas, the south Atlantic coastal area, and the Northeast. The monsoon is responsible for more than 10% of events in the desert Southwest grid box.

![Figure 5. Percentages of Meteorological Causes for One-day Duration Extreme Precipitation Events for Each 10°×10° Grid Box for 1980–2017.](image)

Analysis of future changes in the frequency of FRTs was completed for simulations from 4 CMIP6 models and the Community Atmospheric Model version 5 (CAM5). The project team found that future changes are generally small for winter (December–February), spring (March–May), and summer (June–July), while the largest changes were found for the summer. Figure 6 shows multi-model mean summer season results for the RCP8.5 scenario by the end of the 21st century averaged over $10^\circ\times10^\circ$ grid boxes. Decreases in frontal frequency are projected for western and southern regions. Little change is projected for much of the north. This behavior is consistent with a northward shift of the mid-latitude jet stream during the summer.
Figure 6. Change (%) in the Frequency of Fronts During 2070–2099 (relative to 1985–2015) Under the High Emissions Scenario (RCP8.5) from an Ensemble of Five Global Climate Models.

Decreases are projected across the southern and western United States. The changes are small for the northern United States.

Analysis of future changes in the frequency of ETCs was completed for 23 CMIP5 models. Results for 2070–2099 under the high emissions (RCP8.5) scenario are shown in Figure 7. In all seasons, there are decreases in a majority of the grid boxes. The decreases are most widespread in the summer and fall (September–November), especially in the northern United States.
Figure 7. Future Change (%) in the Number of ETCs for 2070–2099 Under the High Emissions (RCP8.5) Scenario.

These are averages of 23 CMIP5 models.

Figure 8 shows the results for the historical meteorological analysis identifying the meteorological causes of EP events in Alaska, Hawaii, and Guam. In Central Alaska, most events occur in the summer (JJA), with FRTs and ETCs being the main meteorological cause. In Southern Alaska there is a similar pattern in the summer; however, the activity carries into the fall, with nearly as many heavy events in the fall as in summer. Hawaii shows a winter peak in the number of heavy events mainly caused by FRTs and ETCs. A secondary peak in the number of events occurs in the fall, again with FRTs and ETCs being the main two causes. Guam has a nearly identical maximum in heavy events in the summer and fall, with TCs accounting for the highest number of heavy events followed by air mass convection.
Figure 8.  Meteorological Causes of Heavy Precipitation Events, by Season, for Four Regions: Central Alaska, Southern Alaska, Hawaii, and Guam.

Five different causes were included: tropical cyclone (blue), extratropical cyclone (orange), front (gray), subtropical low (yellow), and air mass convection (green).

4.4 GEV ADJUSTMENTS

The GEV analysis used the Localized Constructed Analogs dataset. This dataset includes daily precipitation data for 32 CMIP5 models covering the period 1950–2100. Spatial resolution is 1/16th degree. The project team performed GEV analysis on the annual maximum series of one-day, five-day, 10-day, 20-day, and 30-day precipitation totals for four 30-year periods (1976–2005, 2006–2035, 2036–2065, and 2070–2099) to estimate future changes in various return period amounts. The following conclusions are derived from this GEV analysis:

- The future changes in return period threshold values increase with return period, 100-year changes being greater than five-year changes.
- The future changes increase substantially with increased GHG forcing.
- The future changes are very large by the end of the century under the RCP8.5 scenario.
- The spatial variability is relatively small compared to the magnitude of the changes by the mid- to late 21st century.
- Future changes generally decrease slightly with increasing duration.
4.5 WEB SITE IMPLEMENTATION

A website was developed to display adjusted IDF values for a user-selected location. The user also selects the future time period and the emissions scenario. There are seven options for future time period: 2025, 2035, 2045, 2055, 2065, 2075, and 2085. Each of these actually represents a 30-year period centered around that date (e.g., 2055 equates to the period 2041–2070). There are two options for scenarios: RCP4.5 (moderate emissions) and RCP8.5 (high emissions).

Figure 9 is a screenshot of the website showing an example of the military installation selection option. A list is given as a popup menu for the state of Texas, and Fort Hood is selected. Figure 10 displays adjusted IDF values for Fort Hood for 2055 under the high emissions (RCP8.5) scenario. Values are displayed for a range of durations from one-hour to 30-days and a range of recurrence intervals from one-year to 100-years.

Figure 9. Display of Website Showing Installation Selection Dropdown Menu.
Figure 10. Display of Website Showing Adjusted IDF Values for 2055 under the RCP8.5 Emissions Scenario.
4.6 EXAMPLES OF IDF CHANGES

The magnitude of future changes in IDF values depends on the assumed emissions scenario and the future period. The changes also depend on the magnitude of current design values. Larger percentage changes are estimated for areas with large current values. Two examples illustrate these characteristics, both using the 24-year, 100-year return period design condition.

For Norfolk Naval Station, the current design value is 9.21 inches. For mid-century (2055) under the low emissions (RCP4.5) scenario, the design value changes to 10.27 inches, an increase of 11.5%. For mid-century (2055) under the high emissions (RCP8.5) scenario, the design value changes to 10.84 inches, an increase of 17.7%. For late-century (2085) under the low emissions (RCP4.5) scenario, the design value changes to 10.65 inches, an increase of 15.6%. For late-century (2085) under the high emissions (RCP8.5) scenario, the design value changes to 12.18 inches, an increase of 32.2%.

For Minot Air Force Base, the current design value is 4.66 inches about half that of Norfolk Naval Station. For mid-century (2055) under the low emissions (RCP4.5) scenario, the design value changes to 5.11 inches, an increase of 9.7%. For mid-century (2055) under the high emissions (RCP8.5) scenario, the design value changes to 5.19 inches, an increase of 11.4%. For late-century (2085) under the low emissions (RCP4.5) scenario, the design value changes to 5.15 inches, an increase of 10.5%. For late-century (2085) under the high emissions (RCP8.5) scenario, the design value changes to 5.59 inches, an increase of 20.0%.

The percentage changes for Norfolk Naval Station are about 20–60% larger than the changes for Minot Air Force Base. For the high emissions (RCP8.5) scenario, the late-century (2085) value of 12.18 inches for Norfolk Naval Station is above the NOAA Atlas 14 90% uncertainty confidence interval (7.64–11.78 inches). However, the late-century value of 5.59 inches for Minot Air Force Base is within the 90% confidence interval (2.73–7.80 inches).

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

There are several areas of additional investigation that could help improve estimates of future IDF values. First, a thorough analysis of the new CMIP6 simulations, involving an analysis of the three key meteorological features used—water vapor, FRTs, and ETCs—should be undertaken. A small set of CMIP6 simulations were analyzed late in this project for the frontal analysis, which required three-hourly time resolution climate model data, which was generally unavailable in CMIP5. While it is unlikely that major features found in the current study would change, there would likely be some increased regional confidence.

Second, an investigation of sub-daily resolution precipitation data could improve the quality of the sub-daily IDF adjustments. This would require a development of a spatially dense, high-quality hourly precipitation dataset spanning an adequate number of years. Additionally, models with very high spatial resolution (cloud-resolving) would be extremely useful. Model simulations at these resolutions are becoming increasingly available and are the best tool to investigate super-Clausius–Clapeyron scaling at high time resolutions. In the current work, it was necessary to apply the daily-time-resolution water vapor scaling to sub-daily IDF resolutions. High-resolution observations and model simulations can provide information on whether this scaling holds.
Third, an investigation similar to what the project team performed would be useful in other areas outside CONUS, Alaska, Hawaii, and Guam.

Fourth, a further look at TC and ETC intensities would be useful. There is increasing evidence that these weather systems will change their probability frequency distribution related to storm intensity as the climate warms. A better understanding of how these interplays with more water vapor could be important for some regions.

Lastly, a thorough testing of the combination of statistical, structural, and GCM uncertainties using historical observational data would be very useful to help validate uncertainty estimates.

The adjusted IDF values developed in this research are suitable for application to Department of Defense installations. The research found that water vapor is the dominant factor in determining EP amounts. Future increases in water vapor are one of the climate model projections in which scientists are most confident. Thus, use of current IDF values that do not incorporate the non-stationarity of the climate will increasingly underestimate extreme rainfall as time horizons of interest increase.