DOD INSTALLATION EXPOSURE TO CLIMATE CHANGE AT HOME AND ABROAD

APRIL 2021

Developed for the Office of the Deputy Assistant Secretary of Defense, Environment and Energy Resilience




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EXECUTIVE SUMMARY

Executive Order (EO) 14008, "Tackling the Climate Crisis at Home and Abroad" (January 27, 2021), Sec. 211. Climate Action Plans and Data and Information Products to Improve Adaptation and Increase Resilience requires the Department of Defense (DoD) and other federal agencies to submit a draft action plan to the National Climate Task Force and the Federal Chief Sustainability Officer within 120 days that describes steps the agency can take with regard to its facilities and operations to bolster adaptation and increase resilience to the impacts of climate change. A key requirement of this task is a description of each agency's climate vulnerabilities, particularly in the area of installation, building and facility energy, and water efficiency. This report, and the data development effort it represents, supports DoD's response to this EO through the analysis of installation exposure to climate change hazards at home and abroad.

EO 14008, Section 103 also requires the DoD to produce a Climate Risk Analysis (CRA) of the security implications of climate change for incorporation into modeling, simulation, war-gaming, and other analyses. The CRA is to be submitted to the President within 120 days. Information in this report, combined with other DoD data and analytical results, will be used to support that Climate Risk Analysis.

Climate change has been identified by the DoD as a critical national security threat and a threat multiplier. Improvements to master planning and to infrastructure planning and design are recognized as vital for reducing current and future vulnerability to climate hazards to installations, missions, and operations worldwide. Understanding installation exposure to climate hazards—individually as well as across the installation portfolio—is the critical first step in the assessment of vulnerability.

In mid-Fiscal Year (FY) 2019, Office of the Deputy Assistant Secretary of Defense, Environment and Energy Resilience chose to proceed with the development of the DoD Climate Assessment Tool (DCAT), a Department-wide, screening-level climate hazard assessment tool based on an existing geospatial tool developed by the U.S. Army Corps of Engineers (USACE) for the Department of Army (Office of the Assistant Secretary for the Army for Installations, Energy, and Environment). The DCAT is consistent with the language of Section 326 of the FY 2020 National Defense Authorization Act (NDAA), "Development of Extreme Weather Vulnerability Assessment and Tool," produced after initiation of DCAT.

The DCAT relies on the best available data and model outputs already produced and processed into forms amenable for producing actionable assessments of future climate exposure to eight hazards: coastal flooding, riverine flooding, heat, drought, energy demand, land degradation, wildfire, and historical extreme weather events. It includes customizable reports that can be used to prioritize installations for further, more detailed study of exposure, sensitivity, and adaptive capacity (ESAC); support effective and efficient planning; and identify climate resilience measures.

This report includes high-level information on resilience measures installations can deploy to reduce their vulnerability to changes in both chronic and extreme climate hazards (Appendix 3). It recommends implementing a "multiple lines of defense" approach that can include a mix of management, temporary, structural, nature-based, and nonstructural measures in order to deliver performance and resilience over the intended project lifecycle [e.g., Naval Facilities Engineering Command 2017, USACE 2015]. This approach also provides redundancy and robustness to multiple and compound hazards.

The DCAT assesses climate hazard exposure for two scenarios—lower future warming and higher future warming—and two future epochs: 2035–2064 (reported at 2050) and 2070–2099 (reported at 2085). The DCAT provides a consistent framework allowing for the addition of more installations, additional indicators, and new hazard categories at a later time. Thus, the user is able to both expand and refine the knowledge available to them as further data become available. Analysis of the data in the screening-level DCAT shows that:

1. Climate hazard exposure across all installations increases through time for scenarios of both lower and higher warming.
2. Climate hazard exposure is more pronounced for the later epoch (2085) and the scenarios of higher warming.
3. For most hazards, there is close similarity in values between the 2085 lower and 2050 higher conditions.
4. Differences in the degree of exposure to hazards are similar across both scenarios until mid-century, when they diverge.
5. Hazards more directly tied to temperature change (e.g., heat, drought, wildfire) show larger increases in exposure under the 2085 higher scenario than other hazards.
6. Slower increases in exposure with time are evident for other hazards (e.g., coastal flooding, energy demand, land degradation).
7. Drought is the dominant indicator across all epoch-scenarios for DoD and for the individual Departments.
8. There is no epoch-scenario combination under which installation exposure to climate hazards is projected to decrease.

Exposure to climate hazards is broadly similar across the Departments within CONUS, Alaska (AK), and Hawaii (HI). The Air Force installations are often located in areas where long-term aridity or recurring short-term drought are anticipated to increase, driving more wildfire risk. Army installations have a similar pattern of exposure but are more frequently located in areas where exposure to heat, drought, and riverine flooding increase with time. The Navy has a significant exposure to coastal and riverine flooding, but there is great variability: some installations are highly exposed, and some are not. Like other Departments, the Navy's drought exposure increases stepwise based on the time and scenario.

Across the rest of the world (ROW) installations, the dominant hazard across all the Departments is also drought, and heat is also a common concern. Navy and Air Force ROW installations have large exposure to coastal and riverine flooding, and to land degradation. Army ROW installations in the DCAT, however, are predominantly located in inland urban environments where coastal erosion, coastal inundation, and riverine flood exposure is low.

This assessment helps identify the climate hazards to which DoD installations are most exposed, which is the first step in addressing the potential physical harm, security impacts, and degradation in readiness resulting from global climate change. Assessing the sensitivity of an installation to its climate hazard exposure is the next step, followed by identifying measures to reduce exposure and sensitivity.

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DEVELOPED FOR THE OFFICE OF THE DEPUTY ASSISTANT SECRETARY OF DEFENSE, ENVIRONMENT AND ENERGY RESILIENCE

INTRODUCTION

BACKGROUND

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EO 14008, Section 103 also requires the DoD to produce a Climate Risk Analysis (CRA) of the security implications of climate change for incorporation into modeling, simulation, war-gaming, and other analyses. The CRA is to be submitted to the President within 120 days. Information in this report, combined with other DoD data and analytical results, will be used to support that Climate Risk Analysis.

Climate change has been identified by the DoD as a critical national security threat and threat multiplier. As a result, DoD has undertaken several actions to assess the impacts of changing climate and severe weather to missions and operations. These include assessments of the capability of military locations to prepare effectively to reduce disruption though improved master planning and infrastructure planning and design, considering the weather and natural resources most relevant to them [DoD, 2014a, 2014b, 2018, 2020a].

In 2018, the military Departments contributed high-level assessments of selected installations based on operational roles to five climate- and weather-related hazards. These were included in the DoD January 2019 submittal to Congress, "Report on the Effects of a Changing Climate to the Department of Defense" [DoD, 2019] per Section 335 of the Fiscal Year (FY) 2018 National Defense Authorization Act [NDAA, 2018]. Following these assessments, the DoD recognized the need to produce a consistent assessment of climate hazards across Departments, both within the contiguous U.S. (CONUS) and outside the CONUS (OCONUS), using best available science to support prioritization for further action.

In mid-FY 2019, the Office of the Deputy Assistant Secretary of Defense, Environment and Energy Resilience chose to expand an existing geospatial tool that had been developed by the U.S. Army Corps of Engineers (USACE) at the request of the Department of Army (Office of the Assistant Secretary for the Army for Installations, Energy, and Environment) to meet the requirements of Section 335 of NDAA 2018. This existing geospatial tool provides a screening-level assessment of the exposure of 113 Army locations to six climate hazards (coastal flooding, riverine flooding, desertification, wildfire, thawing permafrost, drought).

The DoD Climate Assessment Tool (DCAT) relies on the best available information already produced concerning historical and projected future hydro-climate conditions derived from a number of sources including the U.S. Geological Survey, the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, the U.S. Global Change Research Program, the National Science Foundation's National Center for Atmospheric Research, and the National Aeronautics and Space Administration.

No single source can supply all necessary historical or projected future hydro-climate information for all installation locations evaluated here. Installations in the CONUS have common sources of information; installations in Alaska (AK) have common sources; installations in Hawaii (HI) have common sources; and installations in the rest of the world (ROW) have common sources. In each case, the most useful sources of information already created were employed for evaluation with the DCAT; no new hydro-climate input information was created. Using those common sources means that comparisons of evaluation endpoints are legitimate within the geospatial regions identified here but should be viewed as merely suggestive of actual differences when comparing across those geospatial regions. This high-level exposure screening assessment can be used to identify locations in each geospatial subdomain where additional, local information could help refine questions related to hydro-climate exposures and responses but cannot support comparisons across specific locations in different geospatial regions.

Methods for evaluating climate exposure and development of resilience measures are based on existing engineering best practices, including previous USACE assessments. DCAT is consistent with the language of Section 326 of the FY 2020 NDAA, "Development of Extreme Weather Vulnerability Assessment and Tool," written after initiation of DCAT. DoD will provide a response to Congress on the implementation of Section 326, including the results of an evaluation of the DCAT by a Federally Funded Research and Development Center.

USACE recently completed a report that presents an overview of the DCAT, and provides an analysis of the results for 157 installations in CONUS, AK, and HI (White et al., 2021). The report contains tables of potential climate resilience measures, along with rough order of magnitude costs. In addition, the report includes a notional installation having characteristics of the most vulnerable military installations based on their exposure to climate hazards. A high-level assessment of the exposure, sensitivity, and adaptive capacity (ESAC) of installation assets to climate hazards is provided. The notional installation includes a geospatial depiction of current exposure to climate hazards and exposure for lower and higher future climate change scenarios. Potential resilience measures are applied to the notional installation, along with information on the parametric cost of appropriate resilience efforts.

This report expands the assessment of DoD installation exposure to climate change hazards to 1055 installations in CONUS, AK, and HI, as well as 336 ROW installations. It provides an assessment of exposure across all Departments and also examines hazard exposure for each Department. A more detailed assessment of exposure to changes in heat stress and energy demand is also provided, along with deeper dives into wildfire and coastal and riverine flood resilience. These examples show the power of the DCAT in leveraging nationally consistent, authoritative data to provide robust, screening-level assessments of exposure across the DoD installation portfolio.

The results of the DCAT assessments support prioritizing installations for further, more detailed study to enable focused attention on installation climate exposure that affects readiness in the face of climate hazards. DCAT and the notional installation example also support effective and efficient planning and implementation of climate preparedness and resilience measures where necessary.

This report includes an example assessment of a notional installation having characteristics of the most vulnerable military installations based on their exposure to climate hazards (Appendix 2). A high-level assessment of the exposure, sensitivity and adaptive capacity of installation assets to climate hazards is provided. The notional installation includes a geospatial depiction of current exposure to climate hazards and exposure for lower and higher future climate change scenarios. Potential resilience measures are applied to the notional installation, along with information on the parametric cost of appropriate resilience efforts.

CLIMATE VULNERABILITY = CLIMATE EXPOSURE, SENSITIVITY, AND ADAPTIVE CAPACITY

Although many definitions exist for climate vulnerability, three common factors that contribute to vulnerability are the **exposure** of the asset or activity to one or more climate hazards, the **sensitivity** of the asset or activity to the hazards, and the degree of **adaptive capacity** to reduce this exposure and sensitivity [e.g., Smit and Wandel, 2006; Füssel, 2010; Naval Facilities Engineering Command, 2017]. Though other frameworks exist, the exposure, sensitivity, and adaptive capacity (ESAC) framing supports simple to complex assessments of vulnerability at multiple scales as needed by DoD with its local, regional, national, and global scope.

Climate exposure occurs at nested spatial scales, as shown in Figure 1. While large-scale trends such as warming global average temperatures and changing sea level are evident at a global scale, the specific hazards of interest to installations are more apparent at finer scales (regional to local) where interaction with topography, land cover, and human activities plays an important role in the magnitude of the hazard. These regional-to-local scale hazards can affect soil moisture, local precipitation and temperature effects, and local relative sea-level rise, which in turn impact installation missions and operations, ecosystems, and social systems important to the functioning of installations.

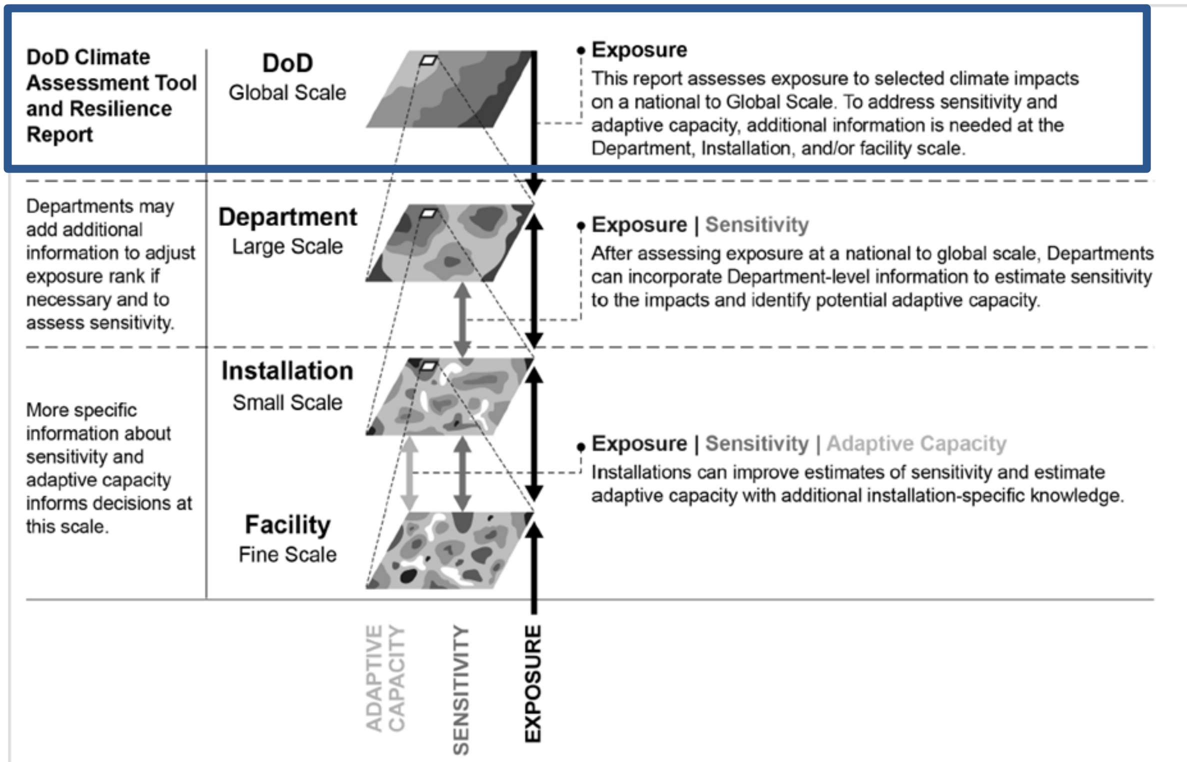


Figure 1. Spatial scales over which vulnerability assessments can occur. This report addressed DoD-scale decision making (blue rectangle), while the output developed here (blue rectangle) can be combined with other information for Department and installation-level-decision making (spatial nesting after Berg, 2012].

For the purpose of identifying resilience measures in this report, estimates of the sensitivity of installation mission or operational requirements to climate hazards are performed at local-to-regional scales because many of the most important factors contributing to sensitivity exert their influence at this scale. Adaptive capacity—the ability of installations to adjust to climate disruptions, take advantage of opportunities, or to respond to consequences—is influenced largely by site-specific local factors [Adger and Vincent, 2005, Engle 2011]. Additional complexities arise where combined or correlated events occur, particularly when they have the potential to synergistically increase exposure and sensitivity [Zscheischler et al., 2018].

The information gained from simple conceptual-level vulnerability analyses (Figure 1) can help to orient decision makers to the primary hazard exposure, reflect level of vulnerability (Figure 2, top), determine the level of effort for further study (Figure 2, bottom), and guide investments in future more detailed analyses. To a certain degree, this depiction of scales plays a role in the range of strategic to tactical responses (Figure 3).

The utility of the exposure-sensitivity-adaptive capacity (ESAC) framing in estimating vulnerability through ESAC is shown in Figure 2a. An asset may be exposed to climate hazards, but if its sensitivity is low, its vulnerability may also be low and there may be little need to implement resilience measures. If the same asset is sensitive to the hazard but adaptive capacity is high, measures can be implemented to ameliorate the effects, thereby decreasing vulnerability. On the other hand, if the asset is exposed, sensitive, and the adaptive capacity is low, the adaptive measures may be limited, expensive, or difficult to implement, making it more difficult to implement measures that reduce vulnerability.

Where resources are constrained, it is especially important to focus on efforts with high value proposition [Ford et al., 2018] and leverage existing knowledge. For example, a wide suite of standardized adaptation measures may be applicable for installations with high adaptive capacity (e.g., skilled technical staff, financial resources, sufficient land, or facilities for relocation). Those with low adaptive capacity (e.g., constrained financial resources, socially vulnerable populations, deteriorated critical infrastructure, and threatened ecosystems) may require tailored evaluations and solutions that entail a much larger level of effort to plan and implement solutions that improve resilience and reduce vulnerability.

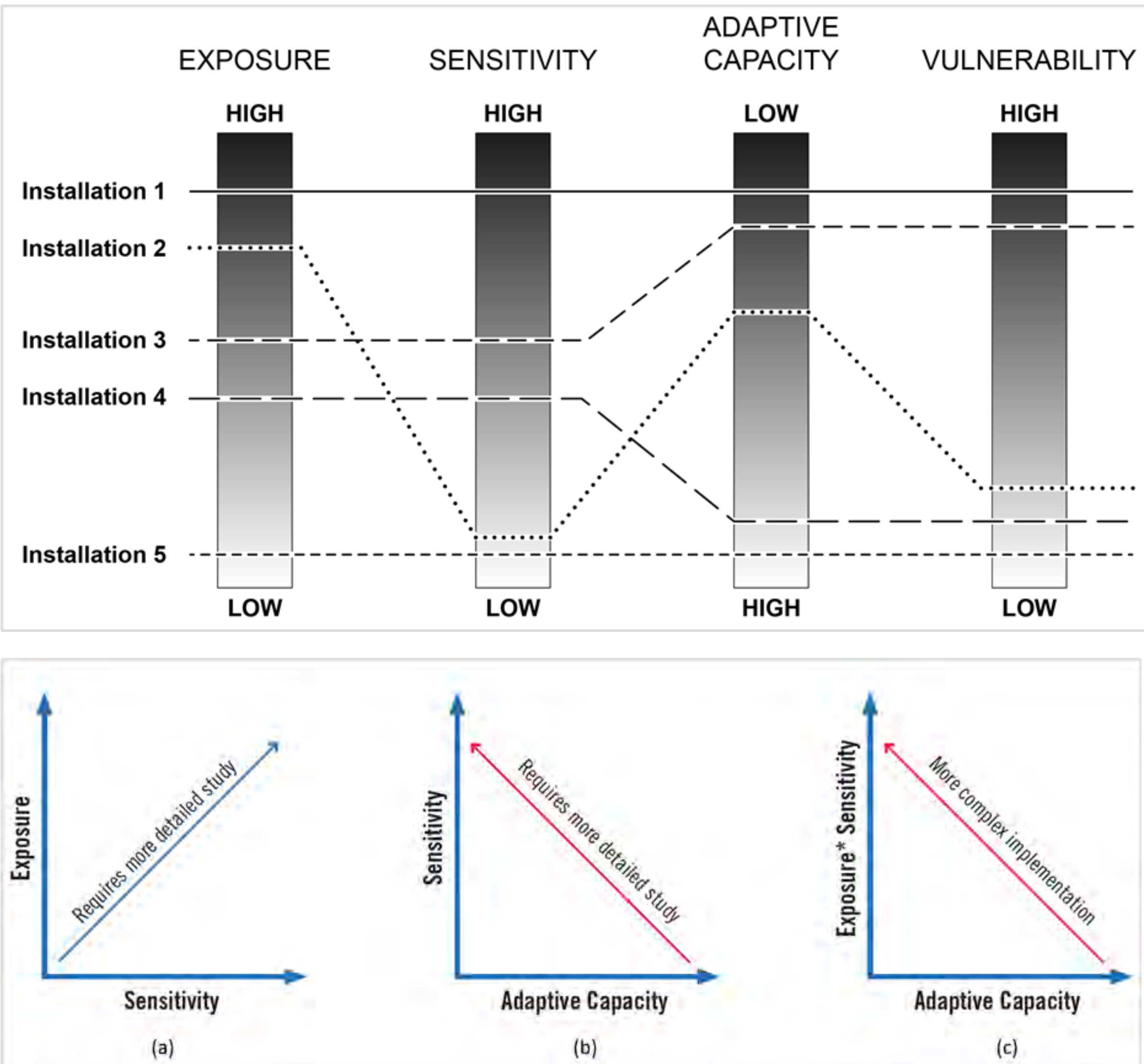


Figure 2. (top) Qualitative assessment of exposure, sensitivity, and adaptive capacity (ESAC) evaluation can aid in assessing vulnerability. (bottom) Level of effort can vary: (a) Assets or activities with greater exposure and sensitivity require more detailed study to determine adaptive capacity. (b) Assets or activities with greater sensitivity and lower adaptive capacity require more detailed study to determine climate risk reduction measures. (c) Implementation is more complex for activities with higher combinations of exposure and sensitivity and lower adaptive capacity. [After Veatch and White, 2019].

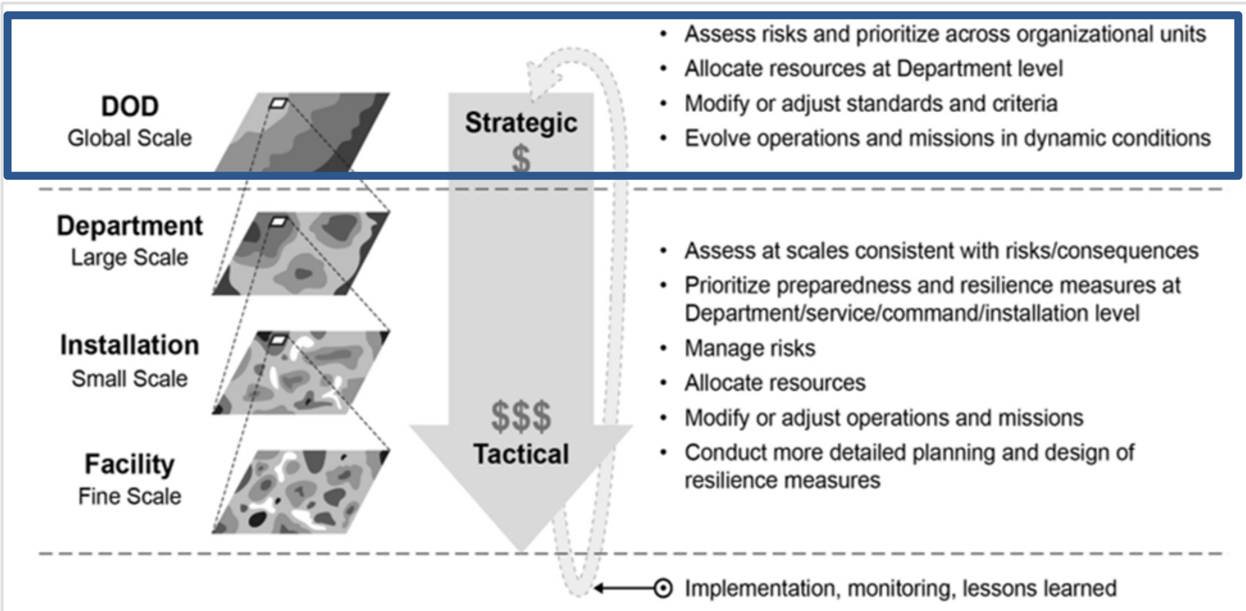


Figure 3. Global scale assessments are often strategic, while local assessments are often tactical. [After Berg, 2012]. This report deals with strategic DoD-scale decision making (blue rectangle), while the output developed here can support strategic-to-tactical Department-level decisions and tactical installation-level decision making.

DOD CLIMATE ASSESSMENT

As noted above, understanding exposure at a large scale supports an iterative process to extend understanding exposure-sensitivity-adaptive capacity at progressively finer scales where regional-to-local information becomes important in decision making. The DCAT considers two 30-year epochs of projected climate, centered at 2050 and 2085. These ensure consistency with other national and international analyses while representing a near-term and long-term planning horizon (30- and 65-year time horizons). This high-level screening assessment provides exposure information at the installation level (Figure 4). This will help Departments to identify where additional investments may be needed to determine sensitivity and adaptive capacity to help installations plan for climate resilience [e.g., Department of the Navy, 2017; Pinson et al., 2020; Department of the Air Force, 2020; DA, 2020].

The DCAT provides a consistent screening-level assessment of exposure to projected current and future climate hazards across 1391 selected DoD installations: 1055 in CONUS, AK, and HI, and 336 in the ROW. ROW locations are located in Asia, Africa, Pacific Islands, Europe, the Caribbean, and Greenland (Figure 5). The climate hazards considered are drought, coastal flooding related to changing sea level, riverine flooding, heat, energy, land degradation, wildland fires and wildfires, and historic extremes (e.g., hurricanes, tornadoes, ice storms, ice jams, drought).

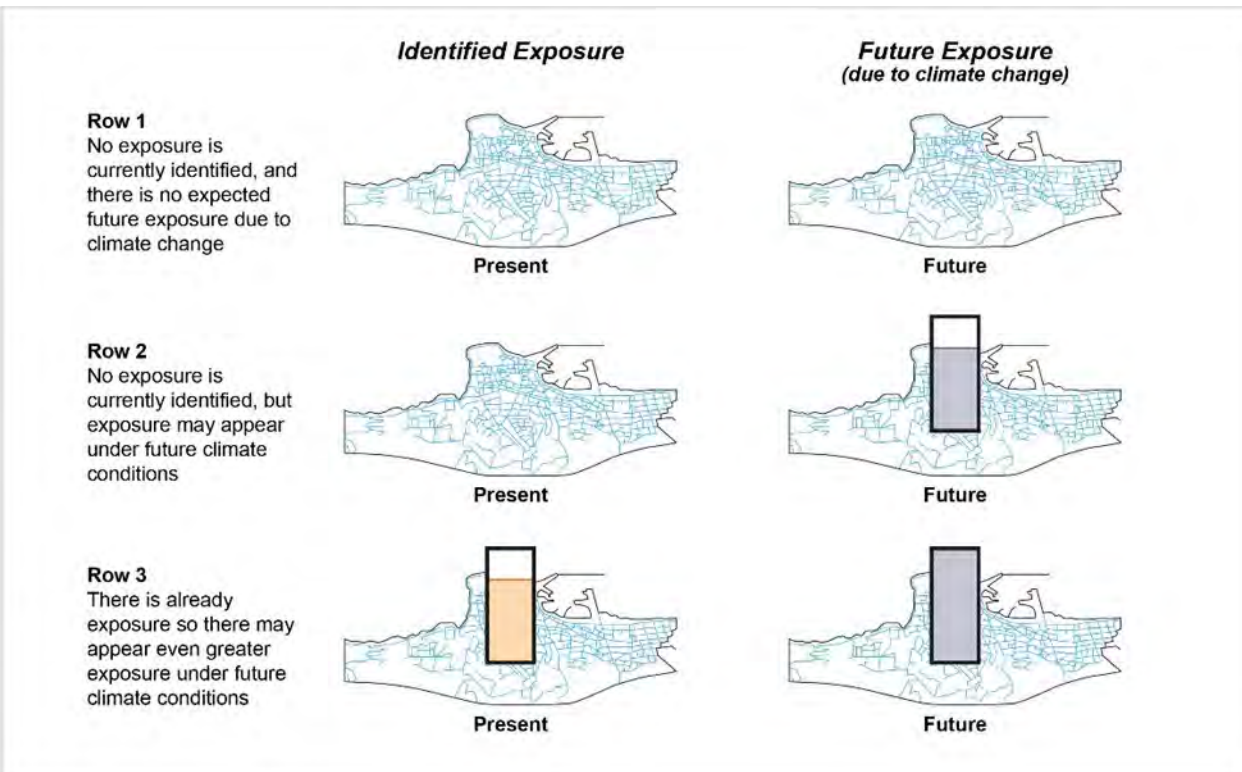


Figure 4. Climate exposure cases: current (buff) and future (gray) climate scenarios indicating (top row 1) no exposure currently or in the future, (middle row 2) no current exposure but projected future exposure, and (bottom row 3) current exposure and projected exposure. Exposure in rows 2 and 3 would receive higher priority for further action than row 1. [After EU-CIRCLE, 2016].

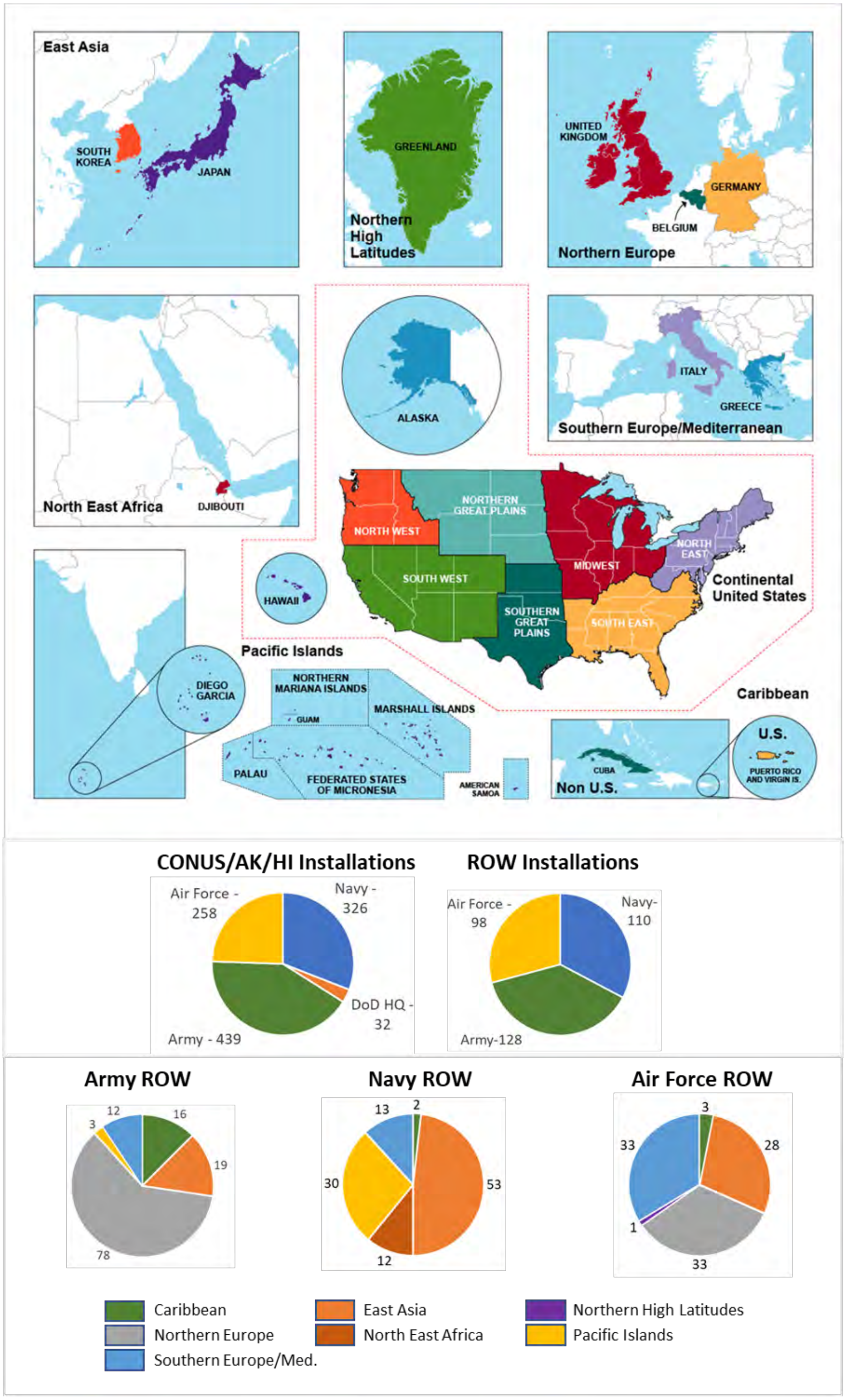


Figure 5. Map and pie charts showing the location of installations in the DCAT. Top: Map showing the three geospatial regions included in the DCAT: CONUS, AK, and HI in the current DCAT, as depicted by the red dotted line and the ROW. Middle: Pie charts showing the counts of installations by Department in the DCAT by geospatial region. Bottom: Pie charts showing counts of installations by ROW subregion for each Department in the DCAT.

DATA

Not all climate hazard exposure data are available for all geographies. Different model outputs were used in the three geospatial regions report—CONUS, AK and HI, and ROW—because this project was designed to answer high-level screening questions only, not closely resolved questions about either historical climate or projected future possible climate. Different model outputs were also used because this project was not designed to create any new hydro-climate outputs. Therefore, this assessment uses consistent simulation sets within each region.

The tool aggregates exposure assessments across the eight hazard areas listed above. For all but Historical Extreme Conditions, the tool provides information on how these hazards are projected to change over the 21st Century. Assessments are averaged for three epochs: base (1950–2005), 2050 (2035–2064), and 2085 (2070–2099). An exception is the historical extreme conditions hazard, which refers to known, significant, and current hydroclimate threats. In many cases, these threats are infeasible to model (with any certainty) for future scenarios or, as in the case of drought, with any comparability using only climate model datasets. Consequently, this climate hazard is a static (constant) indicator of current risk.

The hazards (except historical extremes) are further grouped into "lower" and "higher" scenarios based on the rate and magnitude of change of the underlying emissions scenarios. Hydroclimate indicators computed for Representative Concentration Pathway (RCP) 8.5 represent the higher future scenario, and those computed for RCP 4.5 represent the lower future scenario. For the changing sea level, the highest scenario from the DoD Regional Sea-Level (DRSL) Database [Hall et al., 2016] represents the higher future scenario, and the lowest DRSL scenario represents the lower future scenario. The term "epoch-scenario" is used to indicate a particular combination of epoch and scenario (e.g., 2050 higher epoch-scenario). Climate hazard indicators are described in more detail in Appendix 1 and summarized in Table 1.

Table 1. Climate hazards and indicators.

CONUS Climate Hazard	Supporting Indicators
Drought	Flash drought frequency, drought year frequency, aridity, consecutive dry days, mean annual runoff[1, 3]
Coastal Flooding	Coastal flood extent, coastal erosion[2]
Riverine Flooding	Riverine flood extent, flood magnification factor[1, 3], maximum 1-day precipitation, maximum 5-day precipitation, extreme precipitation days
Heat	Days above 95ºF, 5-day maximum temperature, high heat days, frost days, high Heat Index days[3]
Energy Demand	Heating degree days, cooling degree days, 5-day minimum temperature, 5-day maximum temperature
Land Degradation	Fire season length, aridity, soil loss[1, 3], coastal erosion, permafrost hazard
Wildfire	Fuel abundance[1, 2], ignition rate[1, 3], fire season length, flash drought frequency
Historical Extreme Conditions	Tornado frequency[1, 3], hurricane wind > 50 knots[3], hurricane maximum precipitation, hurricane frequency, ice storms[3], historic drought frequency[3], ice jams[3], wildland urban interface[1, 3]

[1] Computed differently for Alaska and Hawaii.
[2] Computed differently for ROW locations. Preliminary ROW flood extent data used in this report pending completion of ROW floodplain modeling efforts in Fall 2021.
[3] Not able to compute for ROW locations due to lack of available consistent data.

As described in Appendix 1, the best available data were used for CONUS, AK, and HI. In order to enable comparison of climate exposure across the ROW, it was necessary to use global datasets. Thus, while high quality European, Japanese, and other datasets exist, the more limited data for Africa, Central Asia, the Middle East, the Caribbean, and Pacific Islands necessitated the use of a best-available global dataset.

Hydroclimatology outputs in the three geospatial regions delineated for this project (CONUS; AK and HI; ROW) were derived from slightly different sets of underlying observations and model outputs, though all General Circulation Models (GCM) outputs were ultimately sourced from the World Meteorological Organization (WMO) Coupled Model Intercomparison Project Phase 5 (CMIP-5) set of results. In each case, these are the most complete and consistent model outputs at the finest horizontal grid spacing available when this project began in 2019. For these reasons, comparison of precise vulnerability scores for specific sites across the regions in this high-level screening assessment is not recommended.

In the DCAT, CONUS climate and stream flow (hydro-climate) indicators are derived from the temperature and precipitation datasets used in the Fourth National Climate Assessment [United States Global Change Research Program, 2017]. The AK and HI hydroclimate indicators were produced for USACE in collaboration with the National Science Foundation's National Center for Atmospheric Research using established downscaling methods (see Appendix 4). These indicators are also used in the Army Climate Assessment Tool [Gade et al., 2020]. While the indicator sets for CONUS and AK-HI are different, the three regions are included together in the DCAT to allow for priority-setting for U.S.-based installations. The ROW hydro-climate data are derived from the NASA Earth Exchange Global Daily Downscaled Projections dataset (see Appendix 4).

For each installation, the DCAT also provides screening-level information on riverine and coastal flood extent via a zoomable map. The riverine maps show the current 1% annual exceedance probability (AEP) flood delineation (described in Appendix 1), the 1% flood delineation plus 2 ft of freeboard, and the 1% flood delineation plus 3 ft of freeboard, consistent with a recent Unified Facilities Criteria update [DoD, 2020b]. For coastal flooding, the 1% AEP inundation, the 1% AEP plus the DRSL lowest scenario, and the 1% AEP plus the DRSL highest scenario are shown, covering the range in the recent Unified Facilities Criteria update [DoD, 2020b]. Finally, for circumpolar installations, maps of current permafrost extent are also provided.

Indicator quality and availability varies by geographic location. This disparity is due to the inconsistent availability of historical climate data against which to calibrate and refine global climate models, which extends to the other kinds of hydroclimate data used in this tool. Consequently, while the complete suite of indicators is available for CONUS, some indicators for Alaska and Hawaii were input as static indicators (e.g., fuel abundance), while only a subset of the indicators could be calculated for the ROW locations.

Most of the climate model data outputs used for assessments extend to 2100. However, greenhouse gases already added to the atmosphere will persist for decades to centuries. Consequently, there is every reason to expect warming will continue into the next century except under the most optimistic technological and social scenarios.

DATA AGGREGATION

DCAT uses the Weighted Ordered Weighted Average (WOWA) multicriteria evaluation technique to obtain a score for each installation's aggregated climate hazard exposure [e.g., Torra, 1998; Runfola et al., 2017]. The WOWA method was selected due to its ability to use many different types of information in the creation of a single exposure index or score. DCAT uses this score to make meaningful comparisons of relative climate change exposure between installations, across Departments, and across regions.

WOWA score calculations require two steps that take into account (1) the contribution of individual indicators to aggregated exposure estimates and (2) the risk preference of the decision maker.

1. After indicator data are normalized, subject matter experts determine "importance weights" that reflect the relative contribution each indicator makes to estimates of exposure to a given hazard. For example, although vegetation adjacent to a building contributes to wildfire exposure, actual risk is very low if weather conditions are wet. Consequently, the "fire season length" indicator is given a larger weight than the vegetation indicator ("fuel abundance") (Figure 6).
2. Decision makers capture risk preference using WOWA's ORness measure. ORness is a second weighting scheme that captures the comparative importance of indicator risks to the final assessment of exposure, where ORness is applied to the contribution-weighted indicator values [Blue et al., 2017; Runfola et al., 2017][1].

Each installation's hazard WOWA score for each epoch-scenario is the sum of the normalized ORness and importance-weighted indicator values for that hazard. Figure 6 illustrates a case where three indicators represent a hazard at a model installation. The first line shows the normalized indicator values being multiplied by their importance weights. The second row shows the resulting rank order of these values. In the third line, the indicators are rearranged by their new values, and the appropriate weights for the three indicators with an ORness of 0.7 condition are applied. The fourth line shows how these final indicator values are summed to produce the hazard WOWA score for this hazard at the model installation.

The bottom row in Figure 6 gives an example of how information from multiple hazard categories is combined into the total weighted WOWA score that can be used to compare installation exposure to climate change across all the hazard categories in the tool. As with the hazard WOWA score, the value is a weighted sum. The National Standard View weights all hazards equally (each weighted 100% in this step). The tool also permits the user to adjust these weighting schemes to reflect additional factors that may be important for their analysis, such as accounting for strategic vulnerabilities or damages in the choice of weights for calculating the total weighted WOWA score.

DCAT also allows the user to evaluate the source of exposure represented by the hazard and total weighted WOWA scores. The metric for this is termed the "contribution." For a hazard at an installation, the percent contribution for each indicator is the importance- and contribution-weighted indicator value (Figure 6, line 4) divided by the hazard WOWA score (Figure 7a). Two installations with similar hazard WOWA scores may have different indicator contributions to those scores reflecting the unique conditions at each location.

[1] ORness reflects decision maker risk aversion (highest contribution-weighted indicator value drives the decision, ORness = 1) or risk tolerance (all contribution-weighted indicators are included equally in the decision, ORness = 0.5). The DCAT default value ORness = 0.7 is an intermediate risk preference, where comparative risk importance scales with the contribution-weighted indicator values.

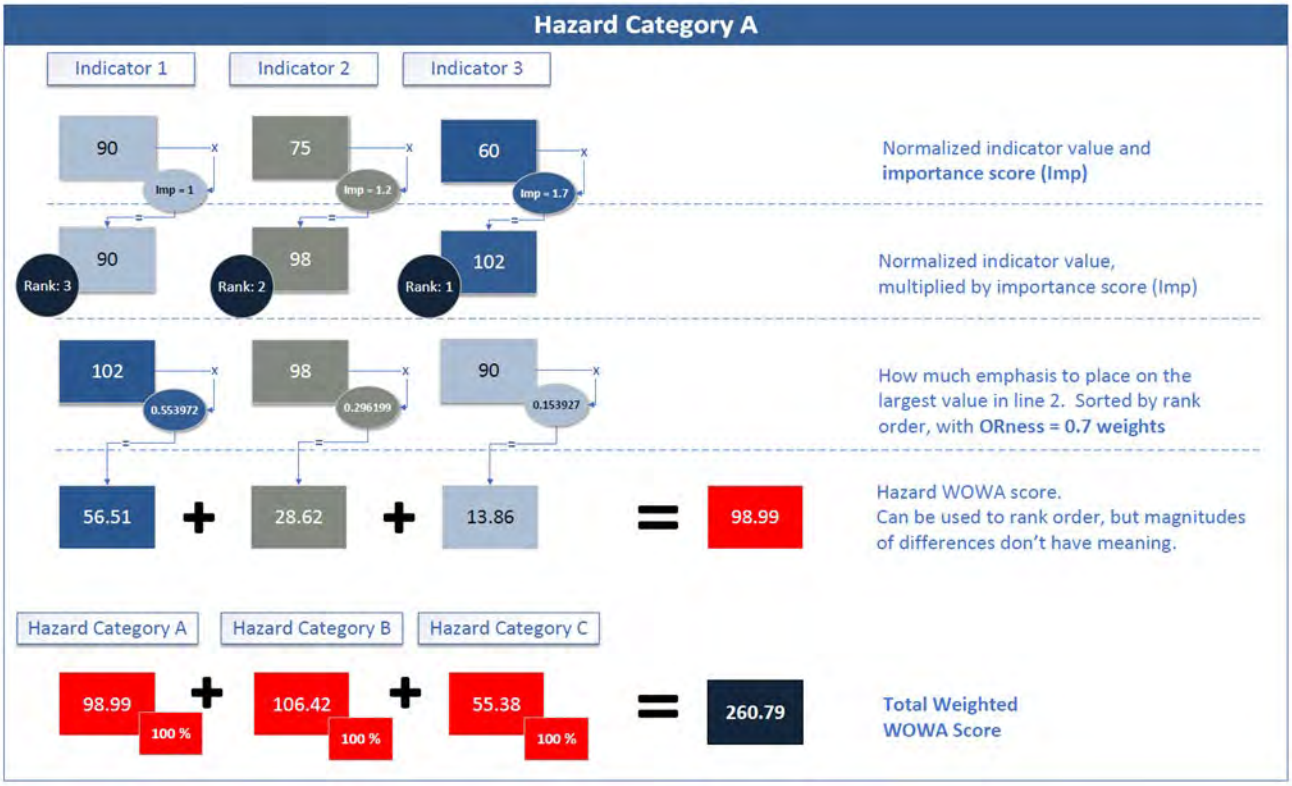


Figure 6. Graphical representation of WOWA score calculations. This graphic shows the calculation of the hazard WOWA score for a given installation for a single hazard category (top). The bottom row shows how the installation's total weighted WOWA score is calculated assuming three hazard categories.

Examining indicator contributions is the first step in understanding the sources of exposure for a given hazard and location. In some cases where the exposure impacts sensitive infrastructure, mission, or operations, this information can suggest resilience measures that might potentially buy down vulnerability to that hazard. Similarly, the contribution of each hazard to the total weighted WOWA score can also be assessed (Figure 7b). This allows users to gain information on the major sources of exposure across installations that may have regional or Departmental significance.

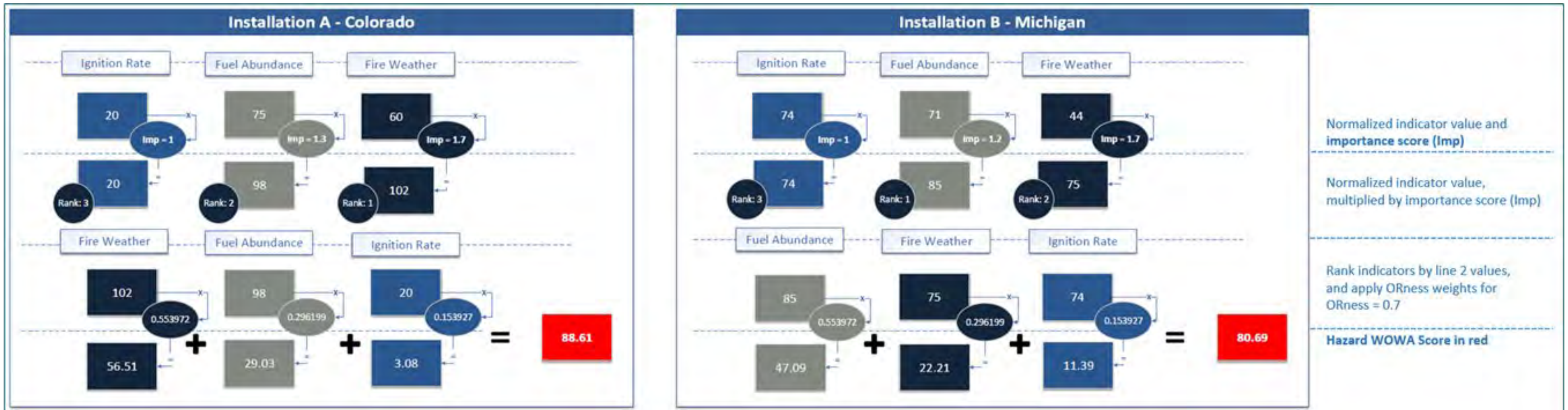
An installation's total weighted WOWA score provides an estimate of the degree of exposure of an installation to the climate hazards identified in the DCAT. However, the numerical value of this score has no objective meaning; its purpose is to provide a means for ranking an installation's exposure relative to other installations in the DCAT.

The same is true of hazard WOWA scores: the absolute value has no objective meaning, it is a means for making comparisons. The example in Figure 8 (top) shows that Installation A in Colorado has a higher overall exposure to wildfire (88.61) than Installation B in Michigan (80.69) using the default values for importance weights and ORness. However, one would need to delve into the indicator values to understand the practical significance of this difference in exposure, which is why indicator values are key to the selection of resilience measures.

Figure 7. Calculating (a) indicator contribution to a hazard score and (b) hazard contribution to total weighted WOWA score using the hazard WOWA score values computed in Figure 6.

It is important to note that each indicator value is divided by the maximum value for that indicator among the installations in the DCAT as part of the data normalization step. Adding more installations to the tool could potentially affect this maximum indicator value. This would change the resulting normalized indicator value for each installation, and therefore the value of all the WOWA scores in the tool. However, these changes would not alter the relative ranking of installations: If Installation A is more exposed than B prior to the addition of data for Installations C-E, then Installation A will still be more exposed than B after the data update. The data used in this report reflects version 1.00 of the DCAT dataset.

An installation's exposure relative to other installations in the tool may be affected by the choice of ORness scheme, as shown in Figure 8. This figure compares two hypothetical installations with respect to their projected exposure to the wildfire hazard using a representative set of indicators. The boxes show the calculation of the WOWA scores for the wildfire hazard using the National Standard View weighting scheme. Notice that after importance weights are applied, the rank order of indicators is different between installations. ORness weights are applied to the importance-weighted, normalized indicator values based on the relative magnitude of these values at the installation level (verses the importance weights, which are the same across all installations).



	Hazard WOWA Score	
	Installation A	Installation B
ORness	Colorado	Michigan
0.5	73.33	77.99
0.7	88.61	80.69
1	102	85

Figure 8. Graphic illustrating relative rankings. This graphic shows how risk sensitivity affects the hazard WOWA score value and therefore, the relative exposure among installations. The importance weight is applied to each indicator (here represented by ignition rate, fuel abundance, and fire weather). These values are then rank ordered. The ORness is applied to the rank-ordered indicators. The default ORness value is 0.7. The range of potential values in the tool is 0.5 to 1.0., which represent weighting all indicators equally (0.5) vs. only considering the indicator with the largest standardized value (1.0). Relative exposure across all installations, as determined by either the hazard WOWA score or the total weighted WOWA score, is influenced by the selection of ORness values.

After the ORness weights are applied, the values are summed to give the hazard WOWA score shown in red (Figure 8). The table below the boxes in Figure 8 compares these hazard WOWA scores with the values that would result if the user's risk preference were different (risk tolerant, ORness = 0.5, or risk averse, ORness = 1.0). Because the indicator values for Installation B are all relatively large, the overall exposure under a risk-tolerant scheme is greater for Installation B than for A. However, two out of three indicator values at Installation A are larger than for Installation B. As the ORness scheme becomes more risk-averse, the influence of this distribution of values is reflected in the larger Installation A hazard WOWA scores.

CLIMATE EXPOSURE RESULTS

OVERVIEW

This report presents results for the CONUS, AK, and HI and ROW geospatial regions. The DCAT provides standardized reports of aggregated climate exposure scores—as represented by WOWA scores—across DoD, which can be broken down by Department, region, climate hazard, and future scenario. Relative exposure is also depicted through visualizations for all climate hazards, individual hazards, and dominant hazards across DoD (again, which can be broken down by Department, by region, and by installation).

Indicator values, their contributions to aggregate WOWA scores, and changes in scores over time provide insight into future changes in climate hazard exposure. Additional visualizations allow the user to drill down into individual installation hazards and indicators, including comparisons of a particular installation's scores to the overall range of WOWA scores. These drill-downs provide context for additional installation-specific evaluations of sensitivity to these exposures to help guide climate resilience planning [e.g., Pinson et al., 2020].

Tables 2 and 3 summarize the range of installation hazard WOWA scores broken down by epoch-scenario. The minimum and maximum scores behave as expected: The largest scores fall under the higher 2085 epoch-scenario, and the lowest scores fall under the lower 2050 epoch-scenario. These scores highlight expected exposure increases over time and under more severe greenhouse gas emissions scenarios. The trend persists across the intermediate epoch-scenarios, with the values increasing between lower and higher scenarios and between the epochs centered at 2050 and 2085.

Table 2. Summary of aggregate climate exposure index (WOWA) scores computed by DCAT for 1055 CONUS, AK, and HI locations.

Climate Hazard	DCAT WOWA Score Range by Future Scenario and Epoch			
	Lower 2050	**Higher 2050**	**Lower 2085**	**Higher 2085**
All Hazards	223-488	221-493	222-493	236-519
Coastal Flooding	0-93	0-96	0-94	0-99
Drought	23-92	22-93	22-93	22-94
Energy Demand	39-79	41-77	41-77	43-71
Heat	27-69	28-71	28-71	29-85
Land Degradation	8-66	9-67	9-68	9-67
Riverine Flooding	24-80	25-82	26-83	26-83
Wildfire	5-75	5-73	5-72	1-76
Historical Extreme Conditions (static)	9-83	9-83	9-83	9-83

Table 3. Summary of aggregate climate exposure index (WOWA) scores computed by DCAT for 336 ROW locations.

Climate Hazard	DCAT WOWA Score Range by Future Scenario and Epoch			
	Lower 2050	Higher 2050	Lower 2085	Higher 2085
All Hazards	212-454	212-488	217-467	227-539
Coastal Flooding	0-74	0-75	0-75	0-81
Drought	18-86	14-85	22-86	20-89
Energy Demand	35-72	36-72	36-70	39-77
Heat	33-69	34-71	34-72	38-80
Land Degradation	6-79	3-79	7-83	10-83
Riverine Flooding	25-70	23-76	24-70	21-88
Wildfire	0-74	0-75	0-79	0-81
Historical Extreme Conditions (static)	0-100	0-100	0-100	0-100

KEY TAKEAWAYS

The results of the DCAT screening-level assessment are described in detail in the technical discussion and the following sections. The key take-aways from the analysis are:

1. Climate hazard exposure across all installations increases through time for scenarios of both lower and higher warming.
2. Climate hazard exposure is more pronounced for the later epoch (2085) and the scenarios of higher warming.
3. For most hazards, there is close similarity in values between the 2085 lower and 2050 higher conditions.
4. Differences in the degree of exposure to hazards are similar across both scenarios until mid-century, when they diverge.
5. Hazards more directly tied to temperature change (e.g., heat, drought, wildfire) show larger increases in exposure under the 2085 higher scenario than other hazards.
6. Slower increases in exposure with time are evident for other hazards (e.g., coastal flooding, energy demand, land degradation).
7. Drought is the dominant indicator across all epoch-scenarios for DoD and for the individual Departments.
8. There is no epoch-scenario combination under which installation exposure to climate hazards is projected to decrease.

TECHNICAL DISCUSSION

Figure 9 compares relative exposure across all hazards for CONUS, AK, and HI installations, broken down by epoch-scenario. In the graphic, color gradients from green to red indicate increasing aggregate climate exposure index (WOWA) scores, with green representing lower scores, yellow representing intermediate scores, and red representing higher scores. The general trend indicates higher WOWA scores for the Southeast, Southwest, and mid-Atlantic Coast. This highlights higher aggregate hazard exposure in these regions. Across ROW (Figure 10), relative exposure is greatest in the subtropics, which have combined high exposure to heat, drought, and in coastal settings, sea-level rise.

When WOWA scores are aggregated for all installations and all hazards, a clear pattern emerges. Figure 11 shows the distribution of WOWA scores over time across all installation (see inset box for guidance on interpreting these and subsequent graphs) for CONUS, AK, and HI (top), as well as ROW (bottom). The approximately bell-shaped curves indicate that most installations in each scenario have scores close to the mean, but those in the upper (lower) tail have higher (lower) WOWA scores, indicating comparatively greater (lesser) exposure. As shown below, curves shift further to the right for epoch-scenarios further in the future and for the higher scenario. When a curve is further to the right, it indicates higher WOWA scores are more likely to occur than lower scores: Levels of exposure are increasing with time, and a greater share of installations in the DoD portfolio in the future are expected to experience greater exposure to climate hazards than the installation average today.

The aggregated climate hazard exposure scores within each Military Department will differ from the scores obtained for the Department as a whole. This difference in climate exposure is partially attributable to the geographic locations, missions, and operations of each Department’s installations.

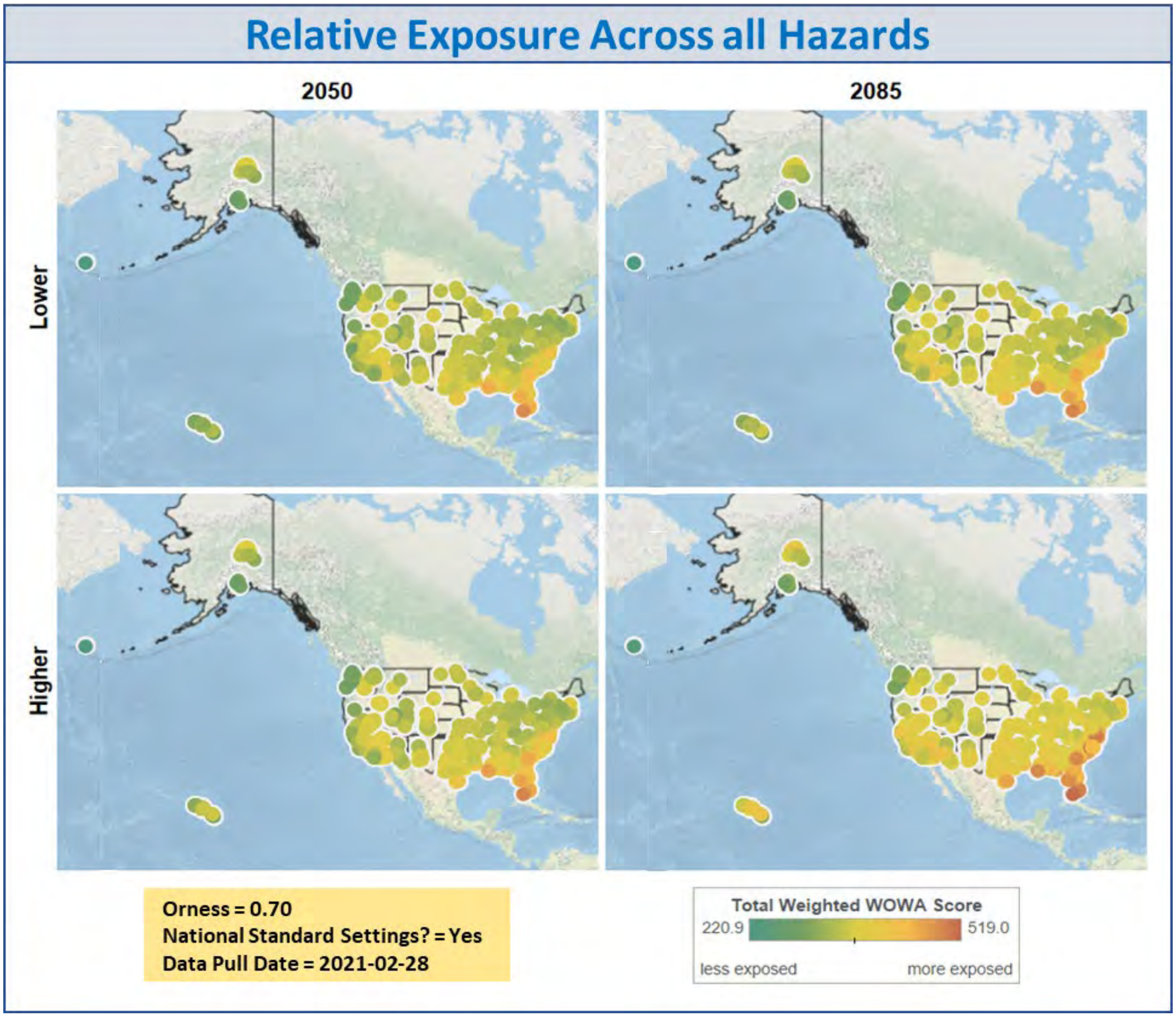


Figure 9. Relative exposure to all hazards across CONUS, AK, and HI installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

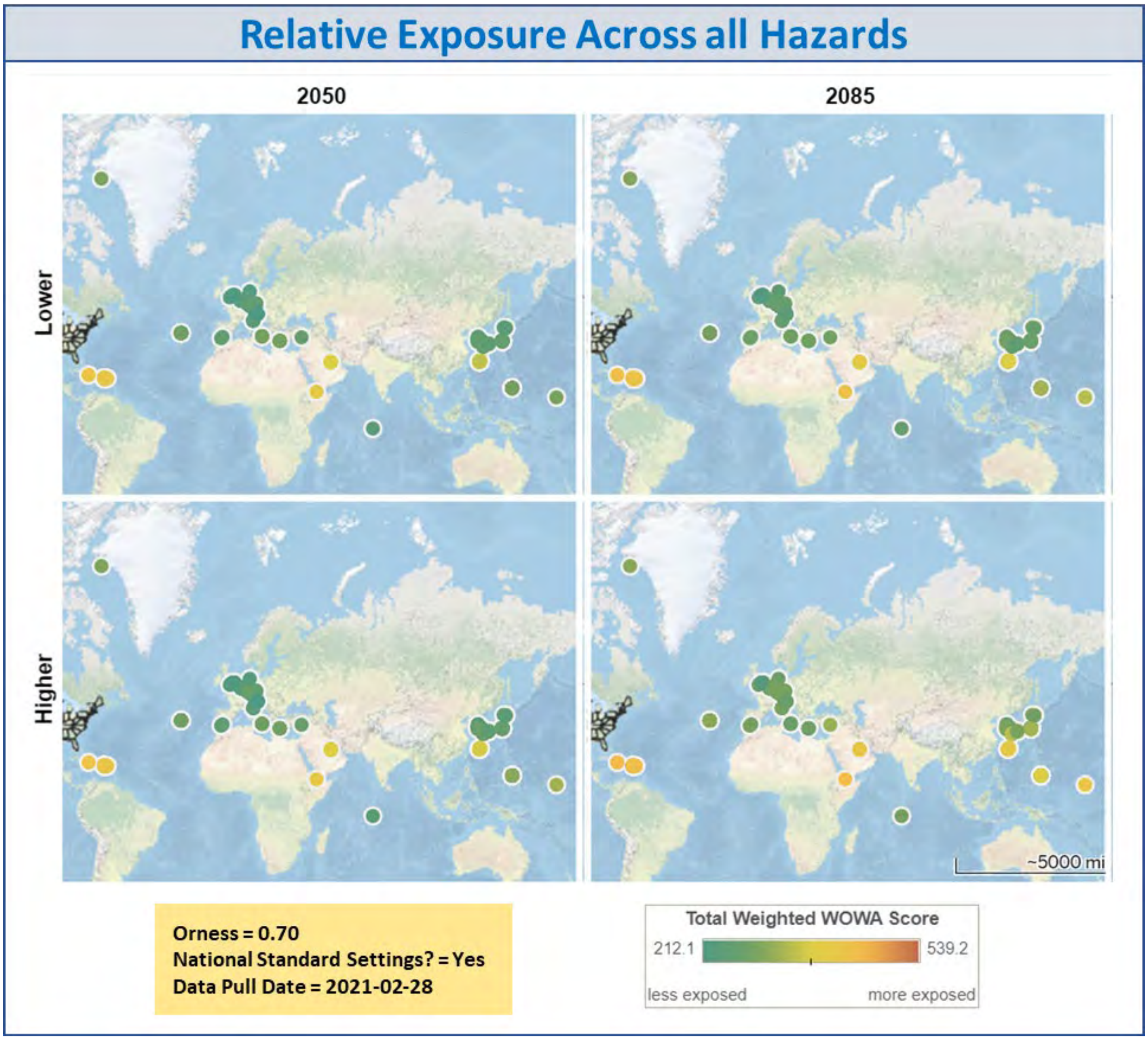
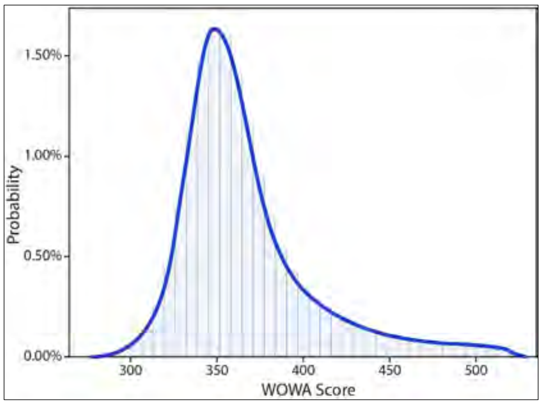


Figure 10. Relative exposure to all hazards across ROW installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

Density plots reflect the probability of a certain score occurring, where higher points on a curve on the y-axis reflect higher likelihoods of occurrence for the corresponding values on the x-axis. The example below shows a density plot of delay in response to stimulus. For our case (left), the y-axis, density, is the indicator score probability, and the x-axis is the WOWA Indicator score. Density plots also allow for the comparison of multiple scenarios at the same time. In this case, when a curve is further to the right than another, it indicates higher WOWA scores are more likely to occur than lower scores for that scenario.



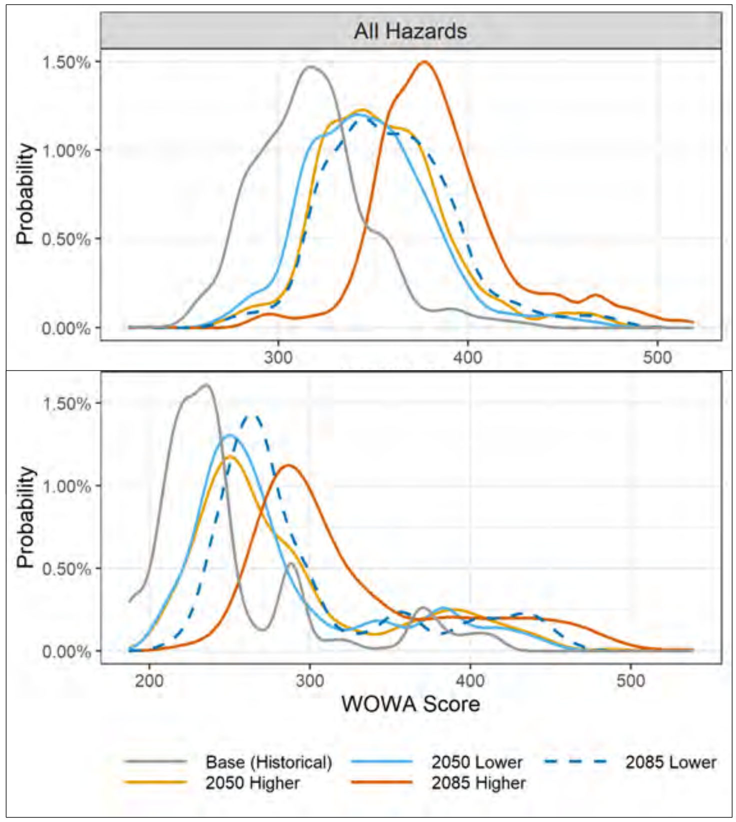


Figure 11. Distribution of aggregated climate hazard exposure (WOWA) scores across installations for both epochs and both scenarios for all hazard categories. (top right: CONUS, AK, and HI; bottom right: ROW). When a curve is further to the right, it indicates higher WOWA scores are more likely to occur than lower scores (i.e., exposure is higher).

At the aggregate level, installation exposure increases over time and under higher scenario conditions. For most climate hazards, the expected late century lower scenario is very similar to the mid-century higher scenario. This indicates that differences between scenarios have little impact until mid-century when they diverge. In addition, the rate of warming represented by the two scenarios strongly determines whether exposure stabilizes close to these new mid-century levels or whether exposure rates increase rapidly in the latter half of the century and beyond.

Under the 2085 higher epoch-scenario, almost all installations have an exposure level to climate hazards greater than most of the installations experience today. There is no epoch-scenario under which installation exposure is expected to decrease. Drought is the dominant indicator across epoch-scenarios (Figure 12 and Figure 13) in both domains.

Figure 14 compares the relationship between WOWA scores and epoch-scenarios but broken out for four individual hazards and aggregated for all CONUS, AK, and HI installations. Similar to Figure 11, a general trend emerges for the aggregate individual hazards: The curves shift to the right. This demonstrates that mean exposure increases with time, and that exposure is more pronounced for later epochs and the higher scenario. Heat and riverine flooding are both good examples of this kind of change.

For most hazard categories in Figure 14, there are smaller shifts between epochs for the lower scenario (e.g., coastal flooding, energy demand). Riverine flooding exhibits a distributional change between 2050 and 2085 at the lower scenario, but otherwise, the distribution of WOWA scores for the 2050 and 2085 lower scenarios are similar. This demonstrates that, under the higher scenario, increases in exposure risk are more pronounced over time than they are under the lower scenario.

Of note, some changes are more dramatic between scenarios for select hazard categories. For coastal flooding, energy demand, and land degradation hazards, exposure increases systematically over time. Yet, for drought, heat, and (to a lesser extent) wildfire hazards, larger shifts in temperature under the 2085 higher scenario produce a step change in exposure. This is highlighted by 2085 higher emission scenario's significant shift to the right (red/orange).

The ROW data (Figure 15) behave less uniformly than the CONUS, AK, and HI data. The source of this problem lies in the different spread of points across the respective domains. Across CONUS, AK, and HI, there are many points with a relatively even distribution across most U.S. regions capturing a diversity of current and future climates. In ROW, most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks whereas the CONUS, AK, and HI domain is more likely to have a single smooth curve that dominates the graph. For some ROW indicators, the response with time and scenario appears non-uniform because one or another of these regions is responding differently from the rest. Energy demand is one of these kinds of graphs where the sensitivity to indicators such as increases in days above 95 varies by region: Some regions of the world see few such days in the future (Northern Europe), some see many (Mediterranean), and there may be relatively small increases in places that already see many, many such days (e.g., Bahrain).

Conversely, one indicator that sees very little change with time in the ROW installations is land degradation. The reason for this is that the majority of ROW installations in the DCAT are located in urban or other built environments where infrastructure inhibits degradation (e.g., hardened coastlines, paved roads). This is in contrast to CONUS, AK, and HI, where many installations have large areas of undeveloped land for test ranges, maneuver areas and other activities where there is little infrastructure to control land degradation (dirt roads, open fields, natural coastlines).

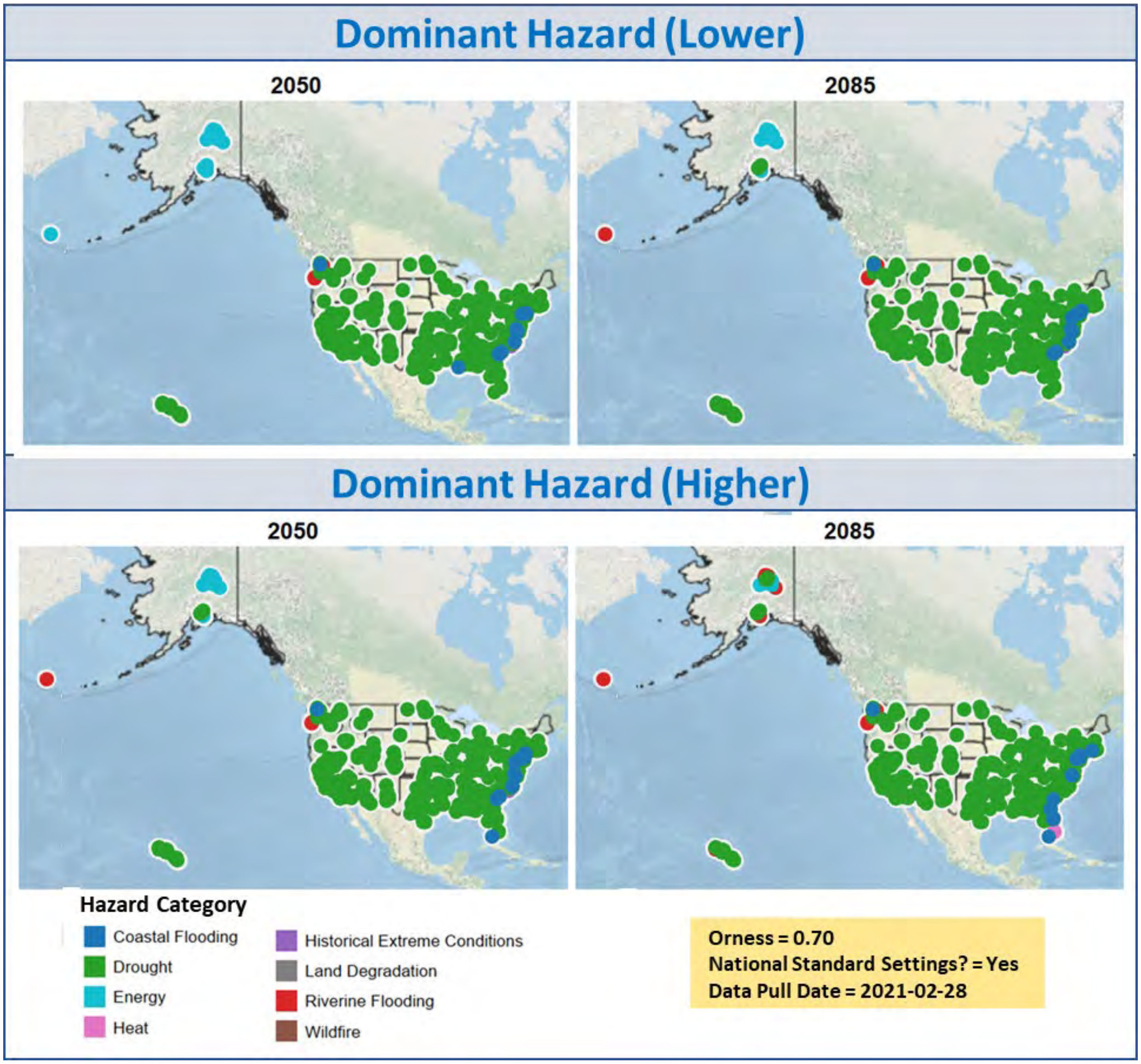


Figure 12. The dominant hazard category identified in DCAT for CONUS, AK, and HI is drought.

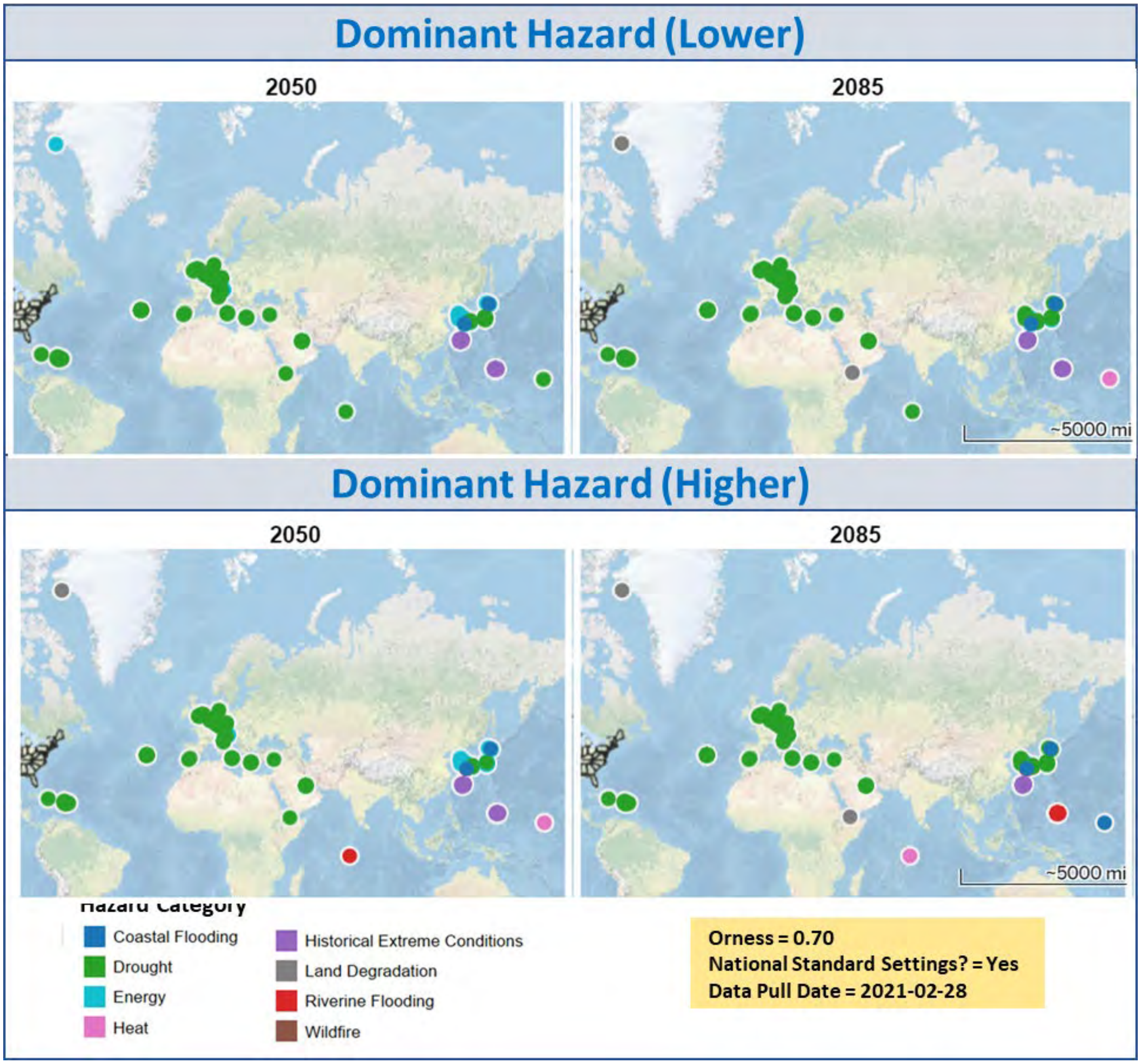


Figure 13. The dominant hazard category identified in DCAT for ROW is drought.

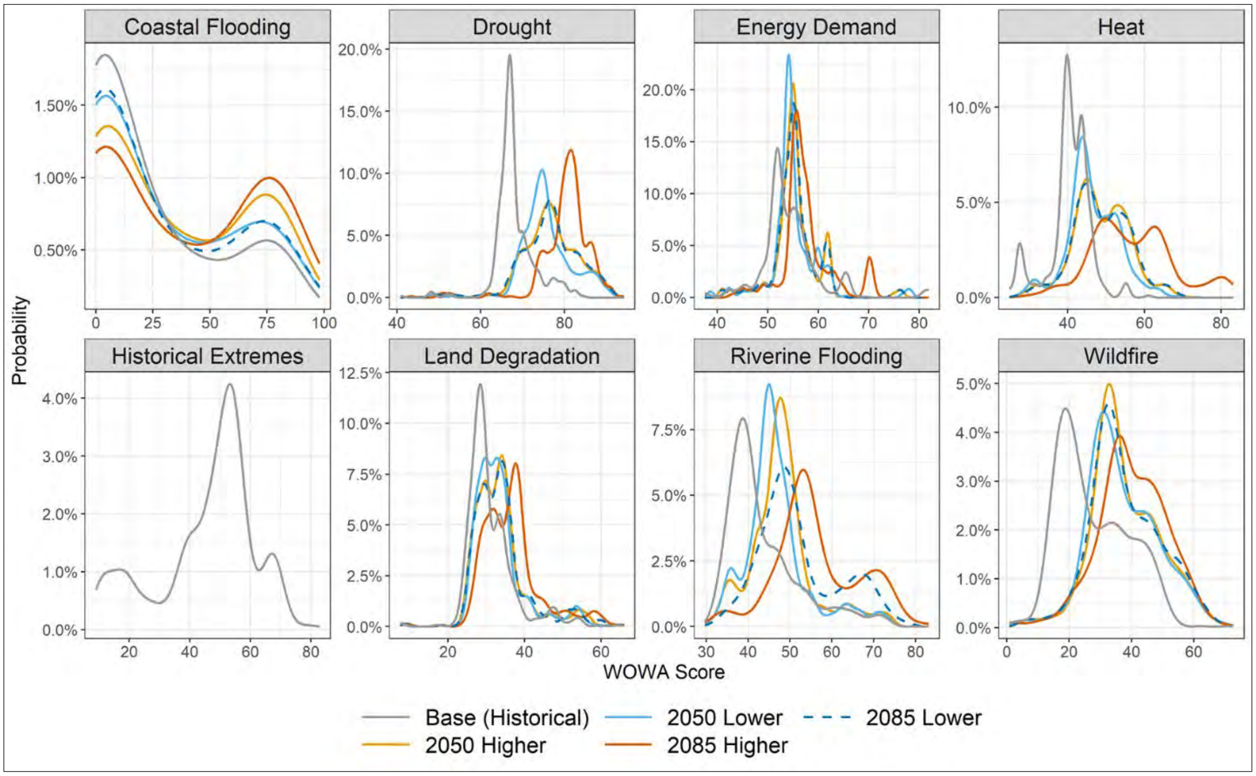


Figure 14. Distribution of climate exposure (WOWA) scores across installations for each epoch and scenario for each hazard category for CONUS, AK, and HI. Installation exposure increases over time and with higher scenarios, though some increases are more pronounced than others.

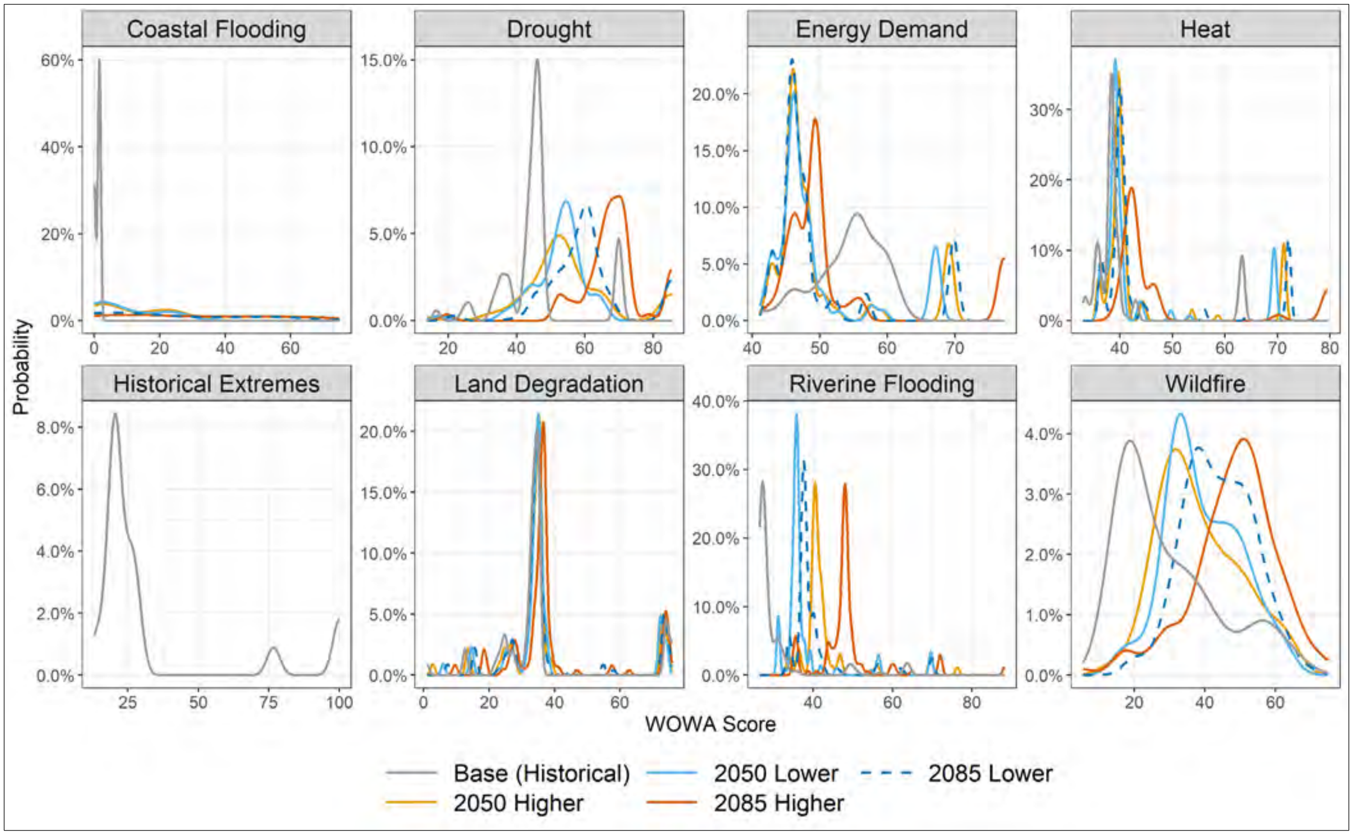


Figure 15. Distribution of climate exposure (WOWA) scores across installations for each epoch and scenario for each hazard category for ROW. The ROW data behave less uniformly than the CONUS, AK, and HI data because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks. For some ROW indicators, the response with time and scenario appears non-uniform because one or another of these regions is responding differently from the rest. Installation exposure increases over time and with higher scenarios, though some increases are more pronounced than others.

DEPARTMENT OF THE ARMY OVERVIEW

The DCAT results for the Department of the Army generally show a similar pattern to the relative exposure of DoD installations as a whole (Figures 16): Army installations experience an increase in exposure to all climate hazards over time. While the approximate mean values through time are similar, a key difference is that the variance is greater for Army installations, exposure of the sites with greater than average exposure is larger, and generally spans a greater range of exposure than is seen for Air Force installations. Drought is the dominant climate exposure hazard impact category as in Figures 12 and 13, but with more variables hazards in East Asia and the Eastern U.S. where coastal and riverine flooding are also dominant hazards.

KEY TAKEAWAYS:

- Relatively higher exposure to climate hazards in the U.S. Southeast and Southwest and subtropics in ROW.
- Higher relative exposure to drought, heat, historical extreme conditions, wildfire, land degradation in the Southwest.
- Higher relative climate exposure to coastal and riverine flooding in the U.S. East and East Asia.
- The dominant climate hazard for all Army installations is drought.

TECHNICAL DISCUSSION

Figures 16–18 depict the distribution of aggregated climate hazard exposure and the hazard categories across the selected Army installations. These appear quite similar to the results aggregated across the DoD. The high climate hazard exposure scores (right tail) shown in Figure 11 are less evident in the Army installation scores for all epoch-scenario combinations (Figure 16). Consistent with the DoD portfolio as a whole, drought again is the dominant climate exposure hazard category for Army (Figures 21–22). Army installation exposure to drought increases stepwise such that almost all installations are experiencing significantly greater exposure to drought under the 2085 higher scenario than they currently experience, and that they are projected to experience under intermediate scenarios. A similar pattern is evident in Army's exposure to riverine flooding.

Coastal flooding exposure is generally less for Army installations than for other Departments (Figures 17 and 18), largely due to geographic locations tied to missions and operations. Almost none of the Army ROW installations are on the coast, so Army's exposure to coastal flooding in ROW is almost zero in all time periods. On the other hand, the riverine flooding under the higher scenario at late century is more widely distributed for Army installations (Figures 17 and 18). The hazard categories of drought and heat exhibit greater exposure to Army installations for the late century higher scenario than for the aggregated results. Army already has a high exposure to wildfire that increases over time and with the higher scenario.

The maps in Figure 19 compare relative exposure across all hazards for Army installations in CONUS, AK, and HI, broken down by epoch and scenario. Figure 20 shows the same maps for Army ROW sites. In the graphics, color gradients from green to red indicate increasing aggregate climate exposure index (WOWA) scores, with green representing lower scores, yellow representing intermediate scores, and red representing higher scores. The general trend indicates relatively higher exposure to climate hazards in the U.S. Southeast and Southwest and in the subtropics in the ROW. This highlights higher aggregate hazard exposure in these regions and correlates with areas of higher relative drought, heat, historical extreme conditions, wildfire, land degradation (Southwest), and riverine flooding (East). As with DoD as a whole, the dominant hazard for Army CONUS, AK, HI, and Northern European ROW installations is drought (Figure 18). In East Asia, although drought is important, indicators related to extreme riverine and coastal flooding are also dominant concerns across the region. These findings are consistent other analyses of climate change for Japan, which highlight the threat from sea-level rise, extreme precipitation events, and the increasing frequency of dry days resulting in drought (MOE, 2018).

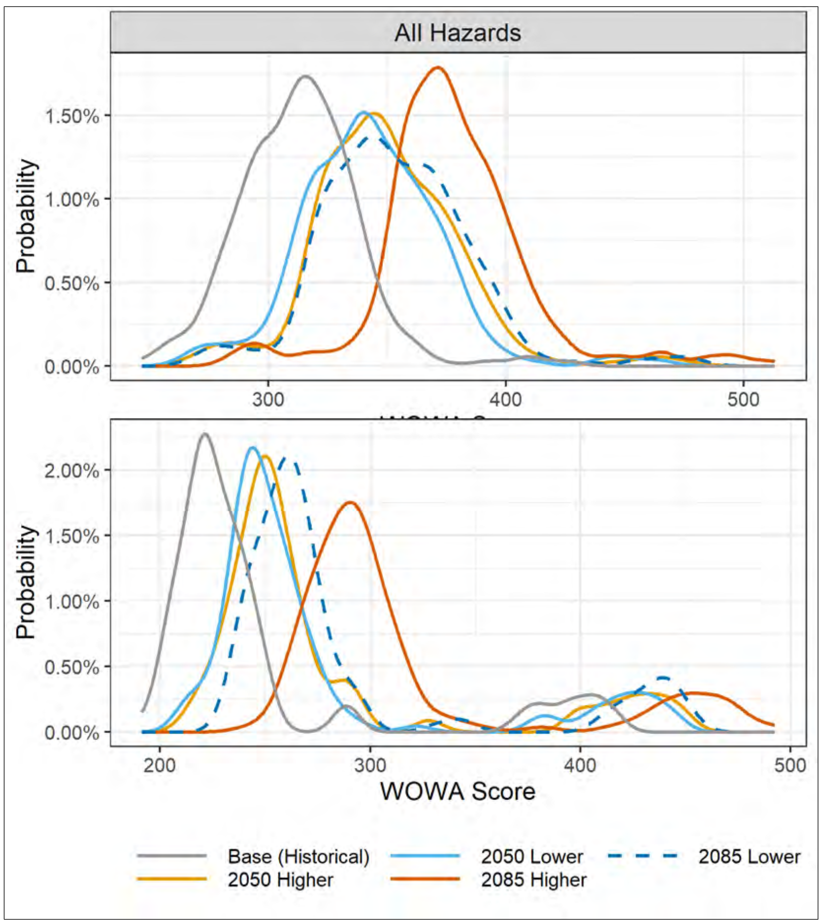


Figure 16. Distribution of aggregated climate hazard exposure (WOWA) scores across Army installations for both epochs and both scenarios for all hazard categories (top: CONUS, AK, and HI, bottom: ROW).

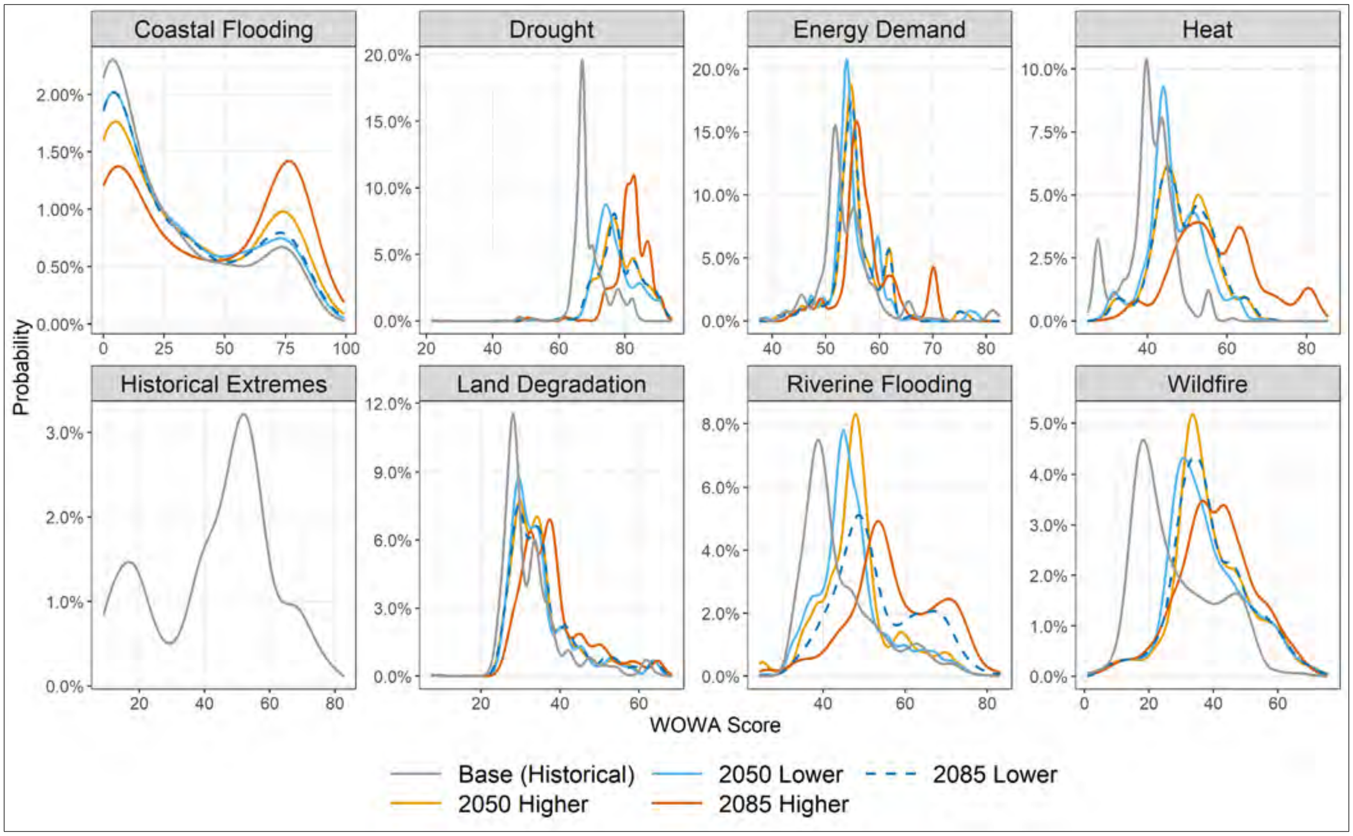


Figure 17. Distribution of climate exposure WOWA scores across Army CONUS, AK, and HI installations for each epoch and scenario. Installation exposure increases over time and with higher scenarios, though some increases are more pronounced than others (drought, heat).

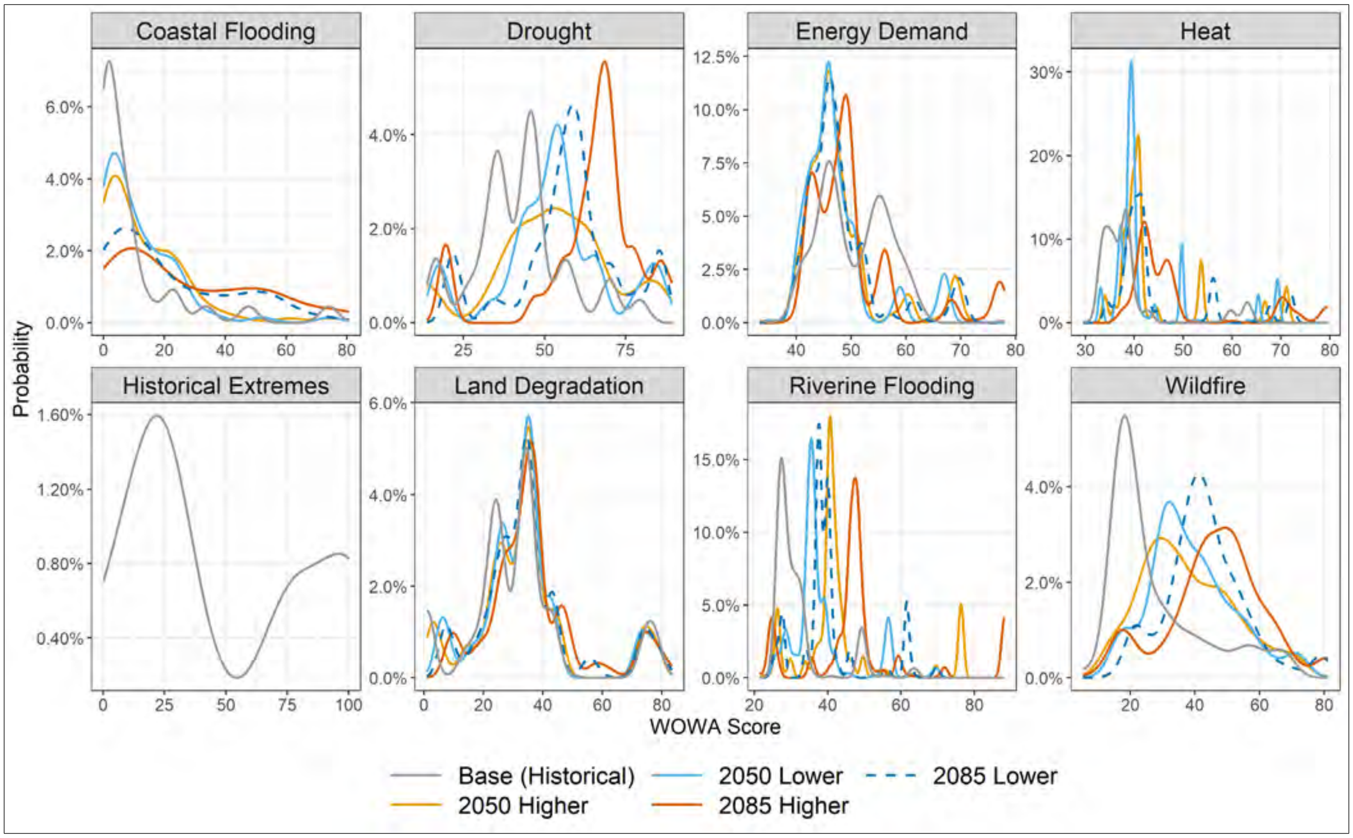


Figure 18. Distribution of climate exposure WOWA scores across Army ROW installations for each epoch and scenario. Note that the historical extreme conditions hazard is static. The ROW data behave less uniformly than the CONUS, AK, and HI data because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks. For some ROW indicators, the response with time and scenario appears non-uniform because one or another of these regions is responding differently from the rest. Installation exposure to other hazards increases over time and with higher scenarios, though some increases are more pronounced than others.

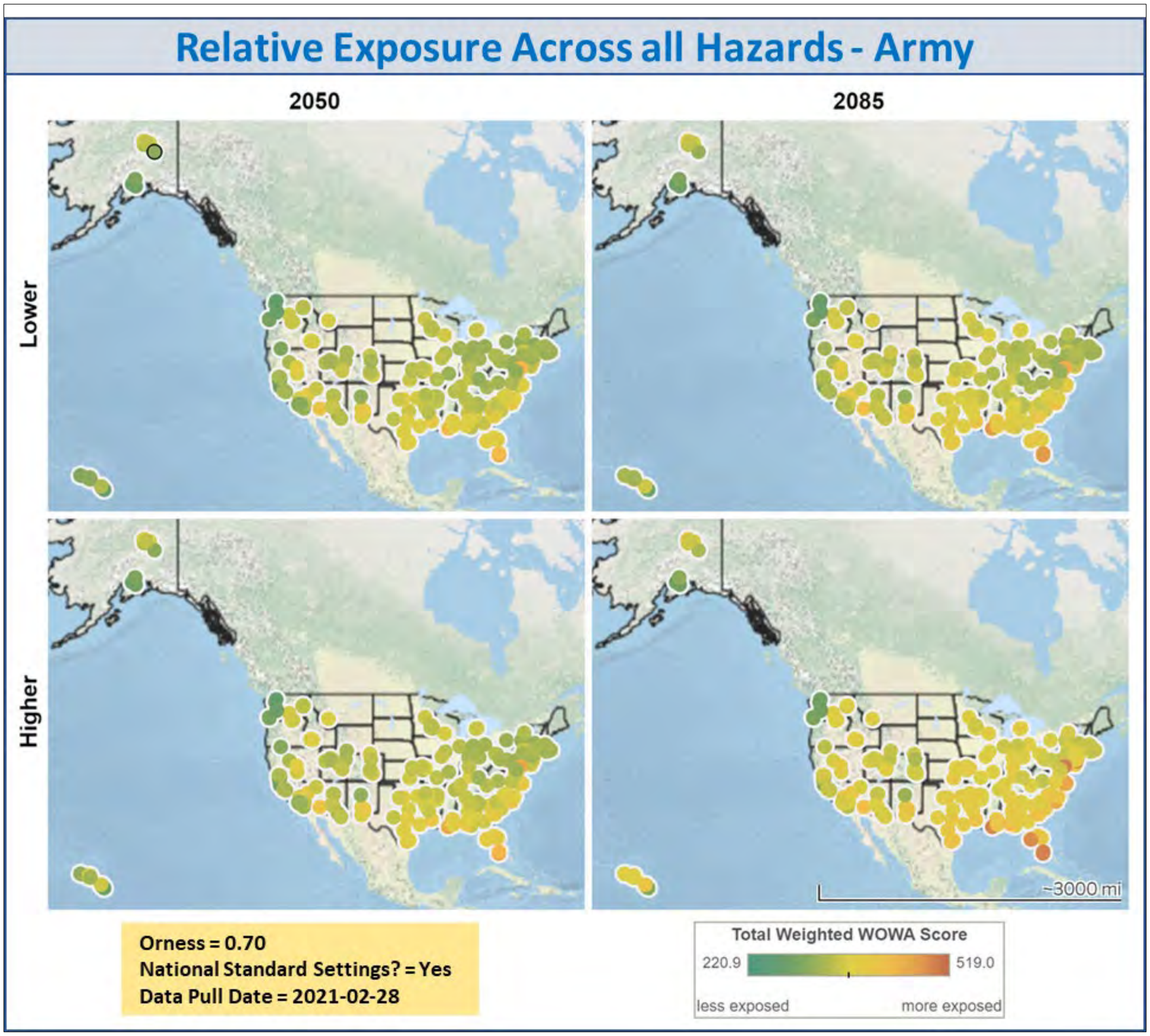


Figure 19. Relative exposure to all hazards across Army CONUS, AK, and HI installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

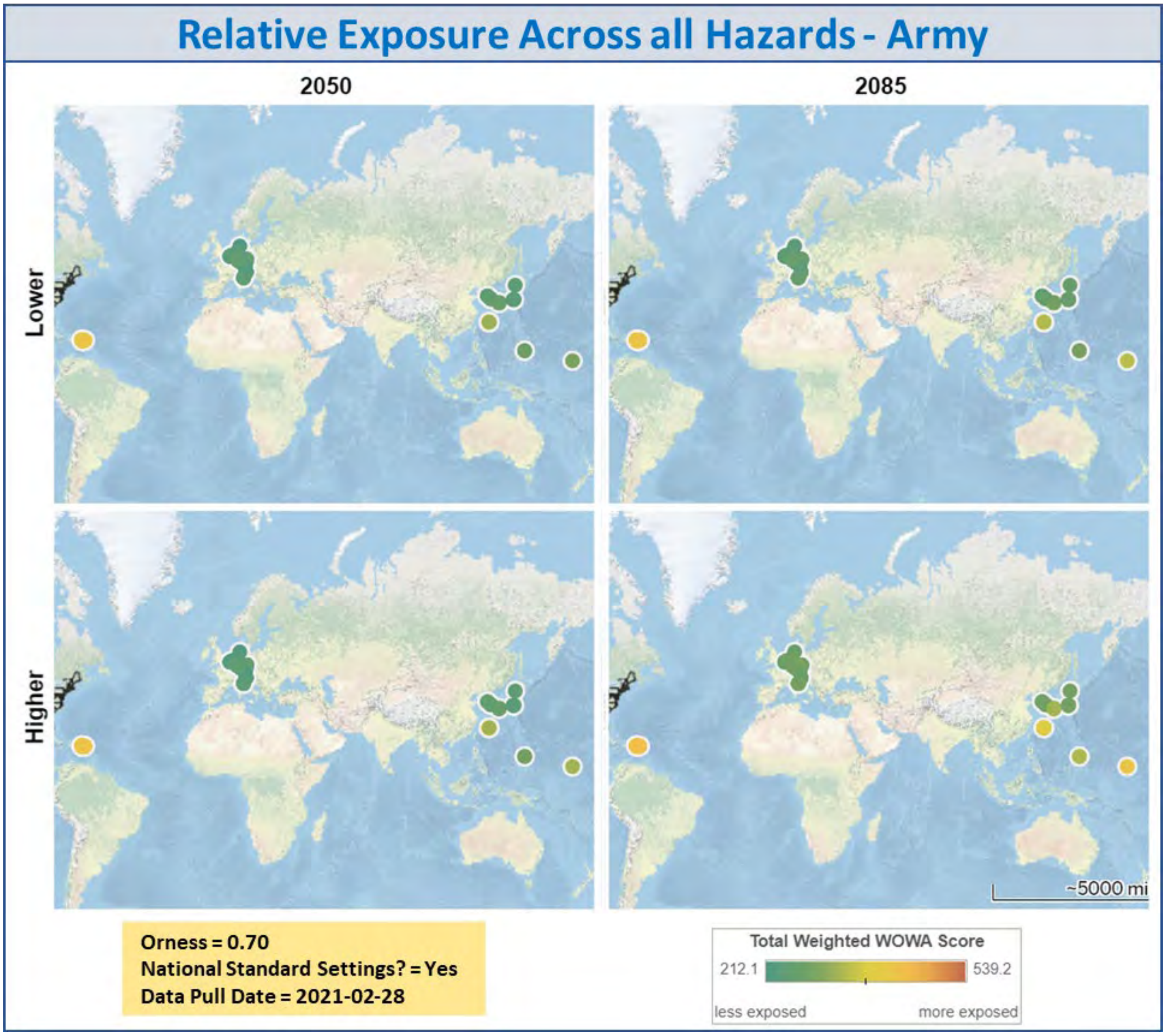


Figure 20. Relative exposure to all hazards across Army ROW installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

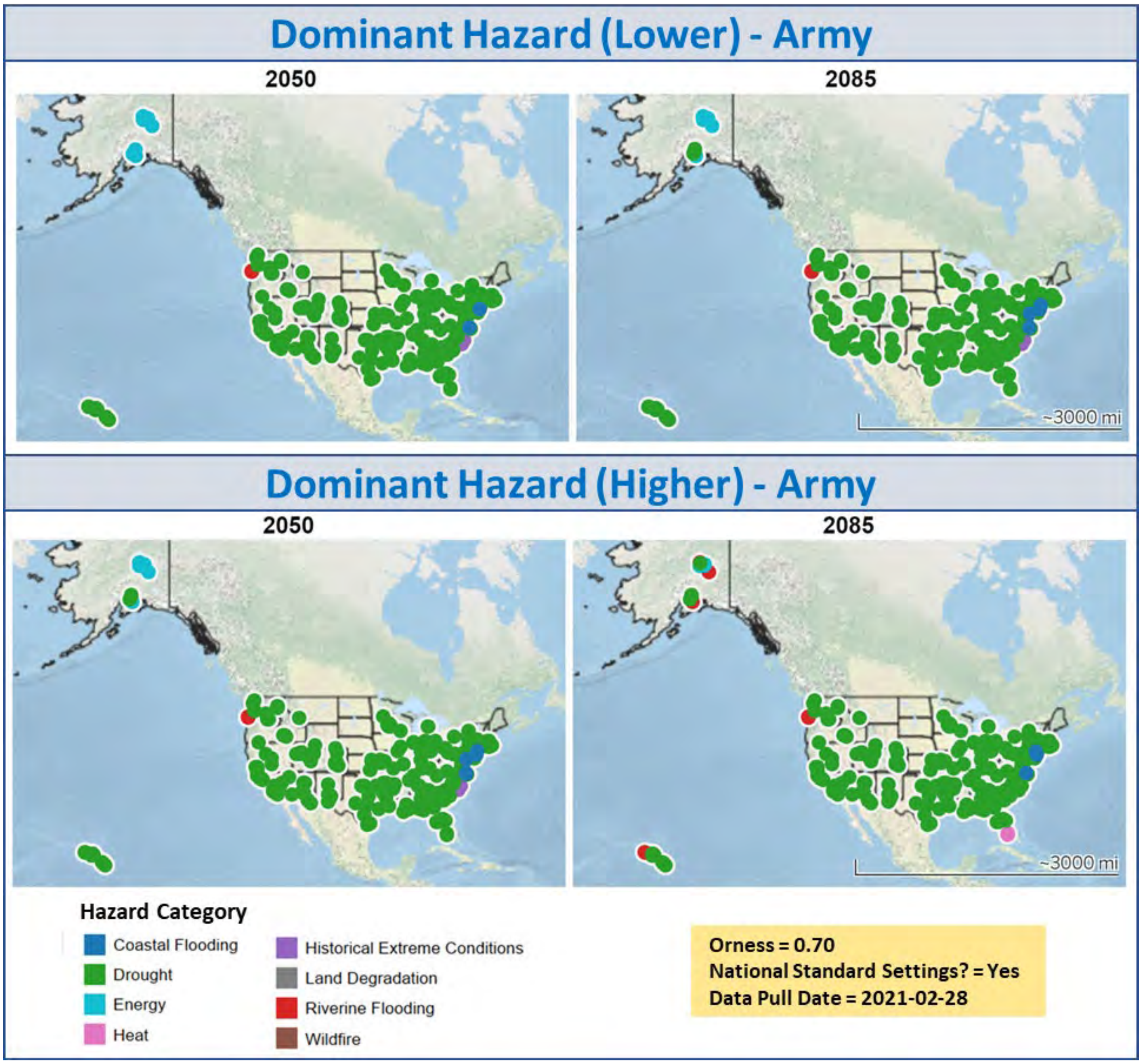


Figure 21. The dominant hazard impact category identified in DCAT for Army installations in CONUS, AK, and HI is drought.

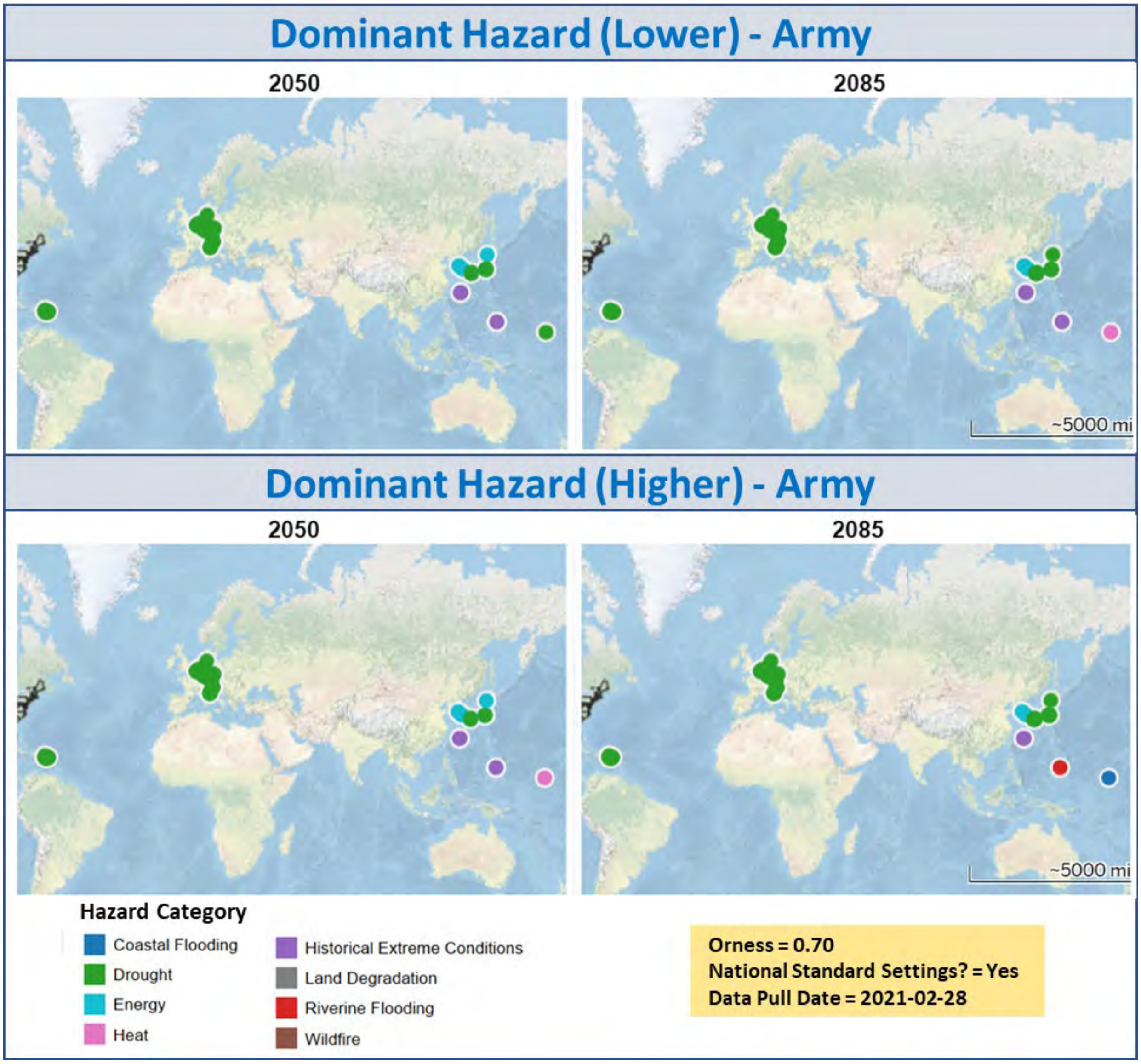


Figure 22. The dominant hazard impact category identified in DCAT for Army installations in CONUS, AK, and HI is drought.

DEPARTMENT OF THE NAVY OVERVIEW

The DCAT results for the Department of the Navy generally show a similar pattern to the relative exposure of DoD installations as a whole (Figure 11), with a much broader exposure profile for both CONUS, AK, and HI as well as ROW installations. Drought is the dominant climate exposure hazard impact category as in Figures 12 and 13, but with more variables hazards in East Asia and the Eastern U.S. where coastal and riverine flooding are also dominant hazards. Figures 23–29 depict the distribution of aggregated climate hazard exposure and the hazard categories across the selected Navy installations.

KEY TAKEAWAYS:

- The distribution of the aggregate climate hazard exposure scores for the Navy is very different than for either the Air Force or Army, or DoD as a whole, indicating a greater range of climate exposure.
- Drought, heat, and coastal flooding are the largest contributors to the difference in the distribution of climate exposure scores for the Navy compared to the DoD as a whole.
- Climate exposure is highest for the Atlantic and Gulf Coasts, the Middle East, and islands in all subtropical waters.
- Exposure to coastal and riverine flooding climate hazards is high for the Navy.
- The dominant hazard for Navy installations is drought.

TECHNICAL DISCUSSION

The distribution of the aggregate climate hazard exposure scores for the Navy is very different than for either the Air Force or Army: The broader, flatter curves in Figure 23 exhibit larger variance compared to Figures 11, 16, and 30, indicating a greater diversity of exposure levels, with higher frequencies at the extremes (highly exposed and hardly exposed) compared to the other Departments. This partly reflects the greater exposure of the Navy's predominantly coastal installations to coastal flooding, but also high exposure to the other hazards, especially riverine flooding.

Exposure to coastal and riverine flooding exposure is generally higher for Navy installations than for other Departments (Figures 24 and 25), largely due to geographic location tied to missions and operations. Land degradation is also more widely distributed, probably because of coastal erosion issues. This pattern is very different from the Army ROW pattern of virtually no land degradation exposure, reflecting concentration of these installations in built environments.

Figure 26 compares relative exposure across all hazards for CONUS and HI Navy installations broken down by epoch-scenario. In the graphic, color gradients from green to red indicate increasing aggregate climate exposure index (WOWA) scores, with green representing lower scores, yellow representing intermediate scores, and red representing higher scores. The general trend indicates higher WOWA scores for the Atlantic and Gulf Coasts with additional western inland sites plus Hawaii. This highlights higher aggregate hazard exposure in these regions and correlates with areas of higher relative sea-level rise for the Atlantic and Gulf Coasts.

For ROW Navy installations, climate exposure is greatest in island locations (Caribbean, Pacific), where coastal flooding and erosion are likely to be important drivers. In Japan, historical extremes (hurricanes, precipitation), drought and changing precipitation all contribute to relatively high exposure for locations in the East China Sea and Western Pacific.

As with DoD as a whole, exposure to drought is the dominant climate hazard for Navy installations (Figures 28 and 29), though riverine or coastal flooding in the Southeast region can be a significant driver of exposure. Drought, heat, and coastal flooding are the largest contributors to the difference in the distribution of WOWA scores for Navy compared to the Departments as a whole.

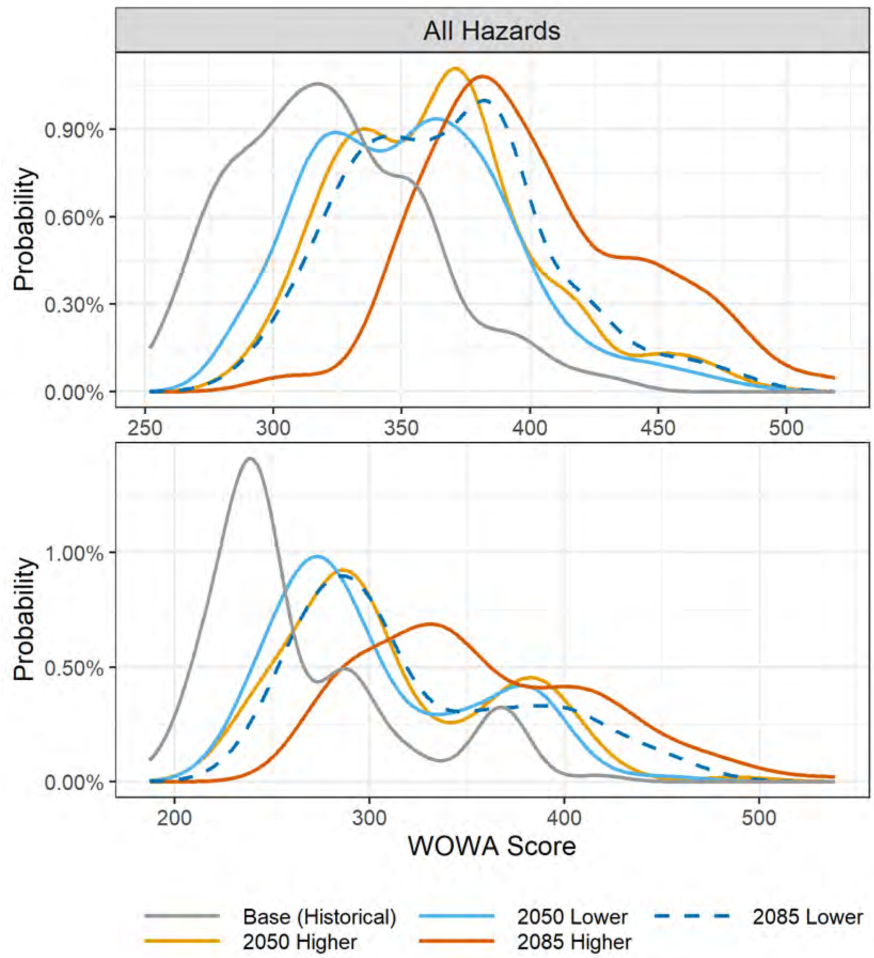


Figure 23. Distribution of aggregated climate hazard exposure (WOWA) scores across Navy CONUS, HI (top), and ROW (bottom) installations for both epochs and both scenarios for all hazard categories.

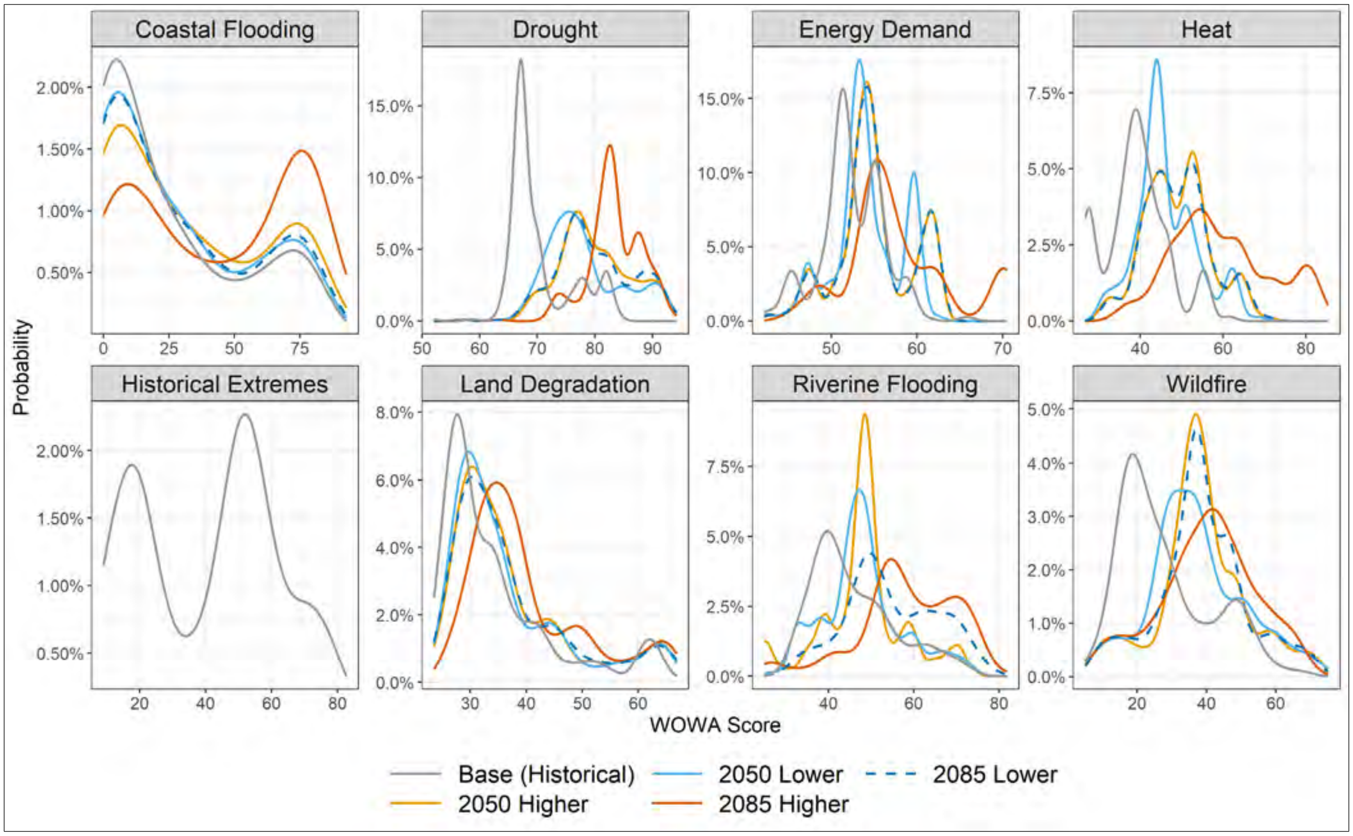


Figure 24. Distribution of climate exposure WOWA scores across Navy CONUS and HI installations for each epoch and scenario. Installation exposure increases over time and with higher scenarios, though some increases are more pronounced than others (coastal flooding). Note that the historical extreme conditions hazard is static.

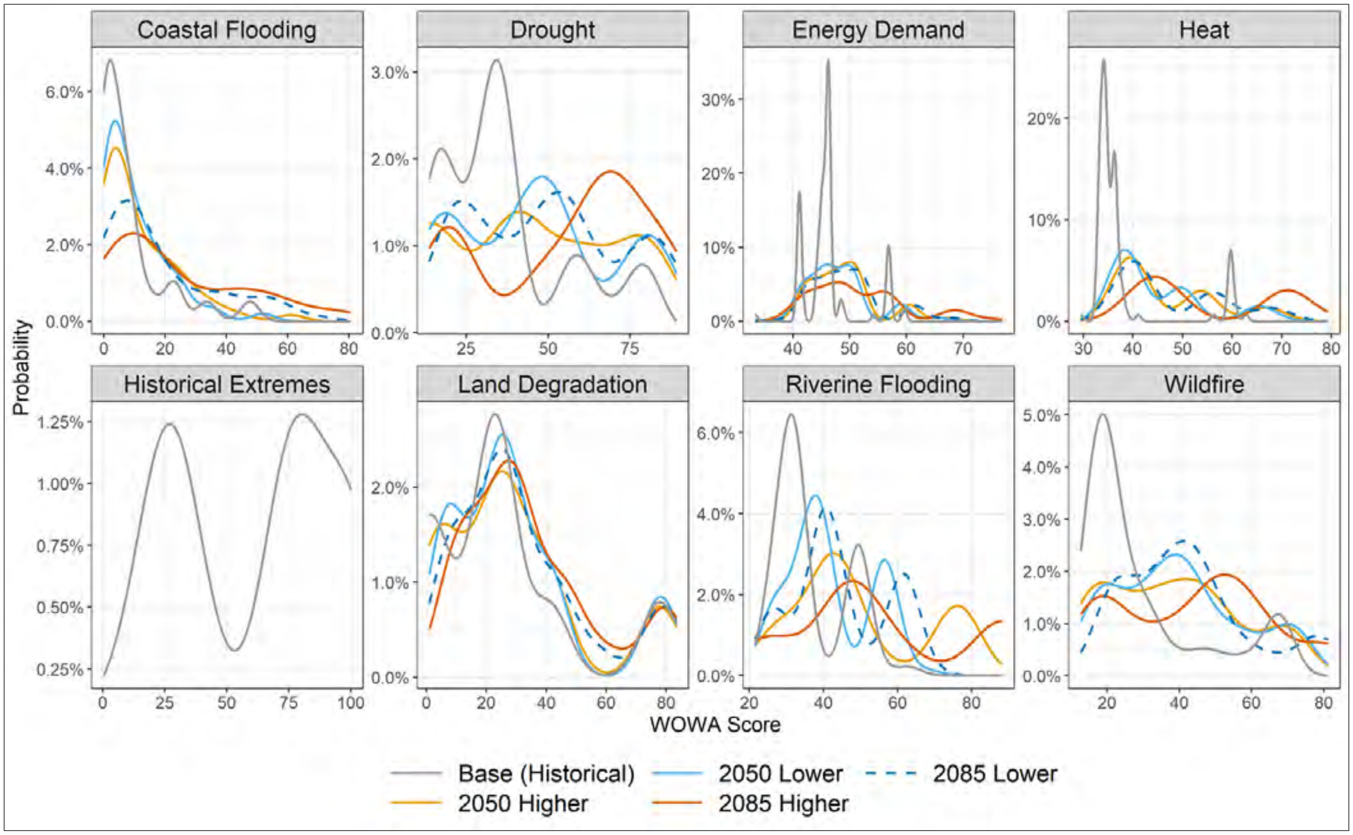


Figure 25. Distribution of climate exposure WOWA scores across Navy ROW installations for each epoch and scenario. The ROW data behave less uniformly than the CONUS, AK, and HI data because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks. For some ROW indicators, the response with time and scenario appears non-uniform because one or another of these regions is responding differently from the rest. Installation exposure increases over time and with higher scenarios, though some increases are more pronounced than others (coastal flooding). Note that the historical extreme conditions hazard is static.

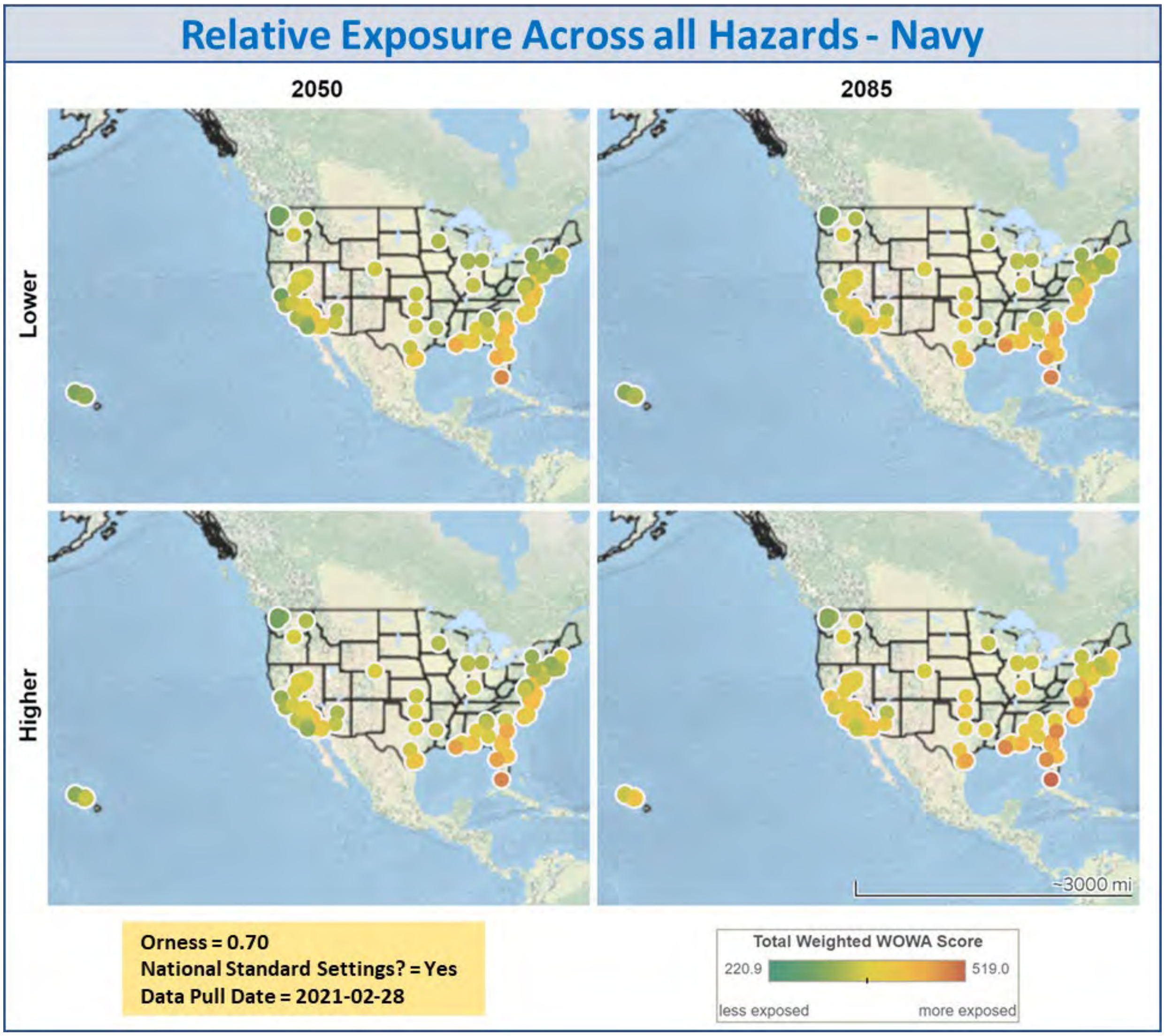


Figure 26. Relative exposure to all hazards across Navy CONUS and HI installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

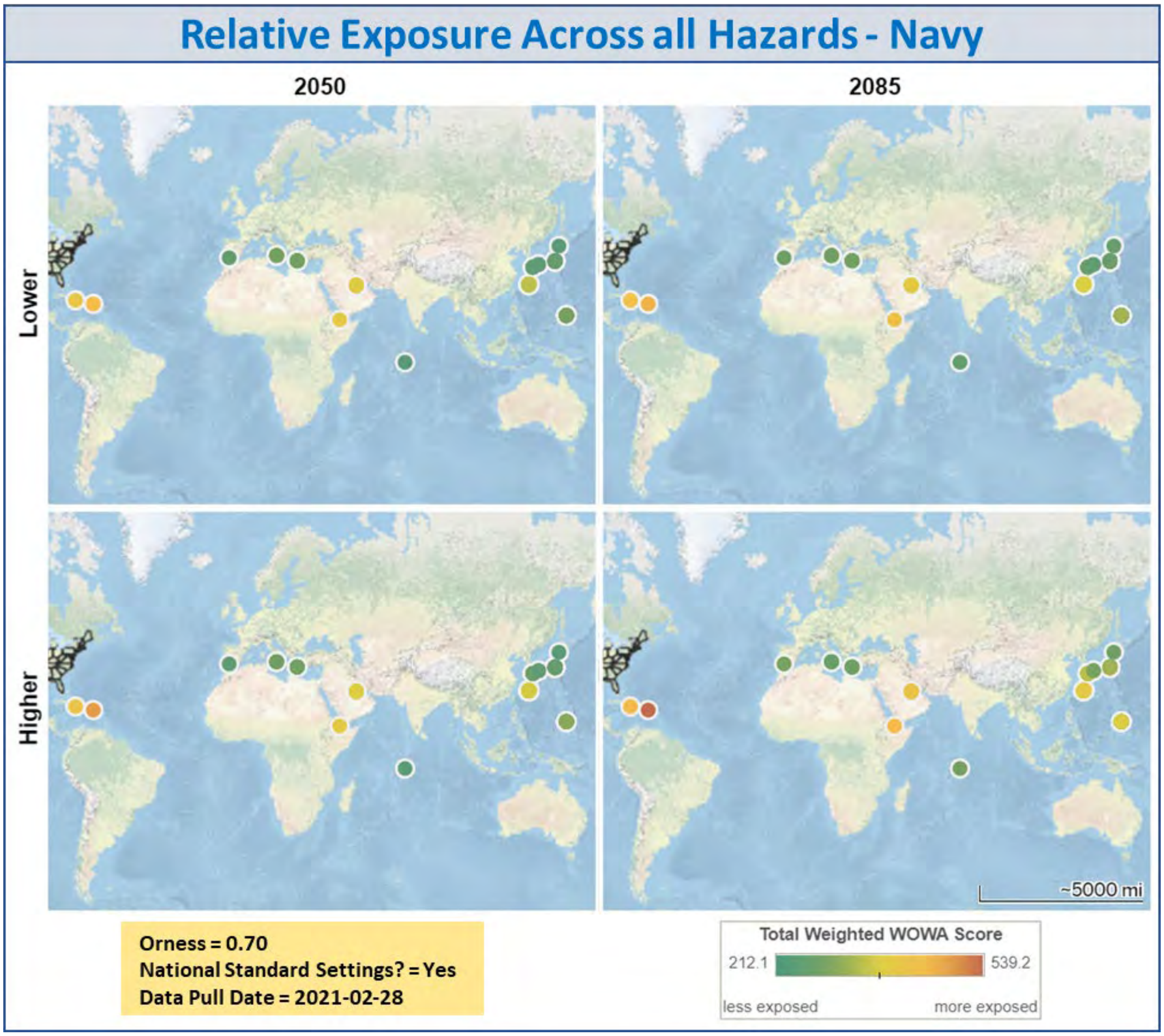


Figure 27. Relative exposure to all hazards across Navy ROW installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

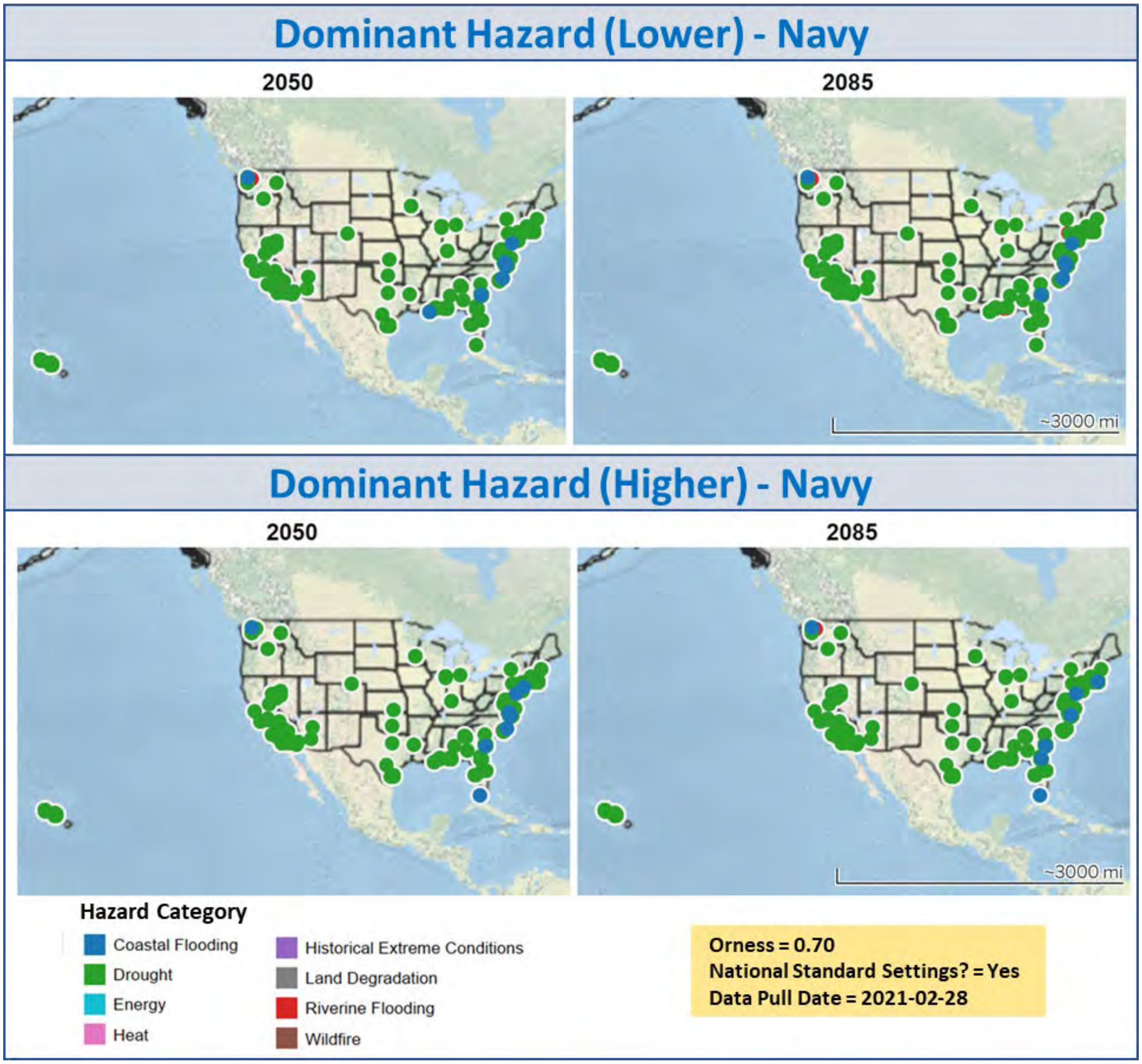


Figure 28. The dominant hazard impact category identified in DCAT for Navy installations in CONUS and HI is drought.

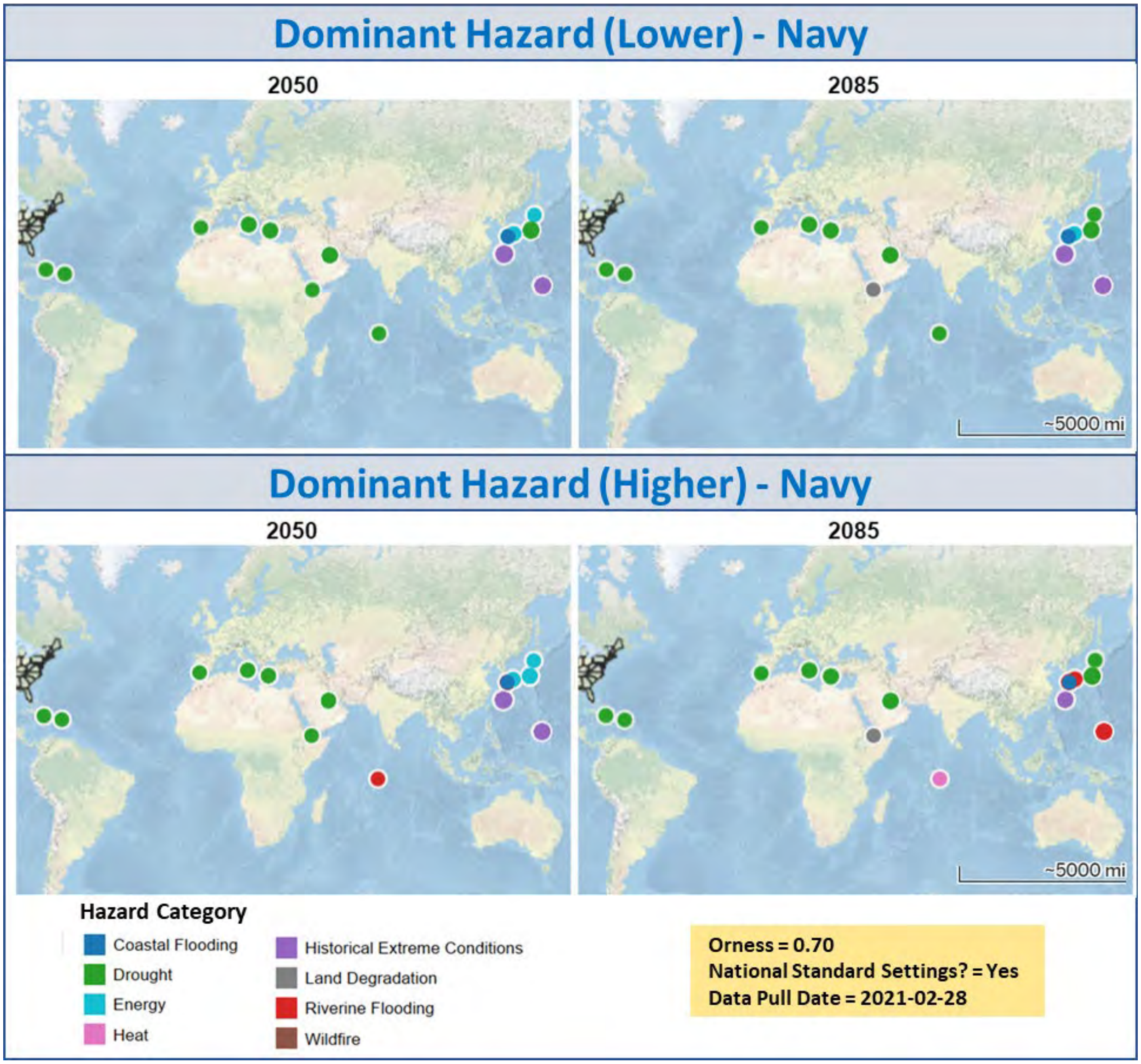


Figure 29. The dominant hazard impact category identified in DCAT for Navy ROW installations is drought.

DEPARTMENT OF THE AIR FORCE OVERVIEW

As with the DoD as a whole, and the Army, exposure to drought is the dominant climate hazard for the Department of the Air Force installations. The Air Force CONUS, AK, and HI installations in the DCAT are abundant in the High Plains, the Southwest, and extreme Southeast, all areas where either long-term aridity or recurring short-term drought are anticipated to increase. These two different sources of drought exposure may require different kinds of adaptation to reduce vulnerability where sensitivity is noted. The exposure to drought also contributes to a step-wise increase in wildfire exposure across all epoch-scenarios for Air Force installations, though less pronounced than for other Departments. Like Navy, ROW Air Force sites in the DCAT have increasing exposure to coastal flooding over time. However, like the Army, many of its ROW installations occur in northern Europe and East Asia, where reductions in heating needs drive down energy demand through time. Air Force exposure is summarized in Figures 30–37.

KEY TAKEAWAYS:

- Air Force CONUS, AK, and HI installation exposure to drought, heat, and land degradation climate hazards are greater for the late century compared to DoD as a whole.
- ROW installations are highly exposed to coastal flooding, riverine flooding, drought, and wildfire.
- Climate exposure is highest for the Southeast, Southwest, and mid-Atlantic Coast in CONUS, AK, HI, and in the Caribbean and South China Sea in the ROW.
- The dominant climate hazard for Air Force installations in CONUS and AK is drought.

TECHNICAL DISCUSSION

Figures 30–32 depict the distribution of aggregated climate hazard exposure and the hazard categories across the selected Air Force installations. These appear quite similar to the results aggregated across the DoD, reflecting the geographic spread of Air Force installations. The high-end WOWA scores (right tail) shown in Figure 11 are also evident in the Air Force installation scores for all epoch-scenario combinations. Air Force installation exposure to drought, heat, and land degradation are greater for the late century higher scenario than for the aggregated results.

Figure 33 compares relative exposure across all hazards for CONUS and AK Air Force installations, broken down by epoch-scenario. In the graphic, color gradients from green to red indicate increasing aggregate climate exposure index (WOWA) scores, with green representing lower scores, yellow representing intermediate scores, and red representing higher scores. The general trend indicates higher WOWA scores for the Southeast, Southwest, and mid-Atlantic Coast. This highlights higher aggregate hazard exposure in these regions. As with DoD as a whole, exposure to drought is the dominant climate hazard for Air Force installations (Figure 33).

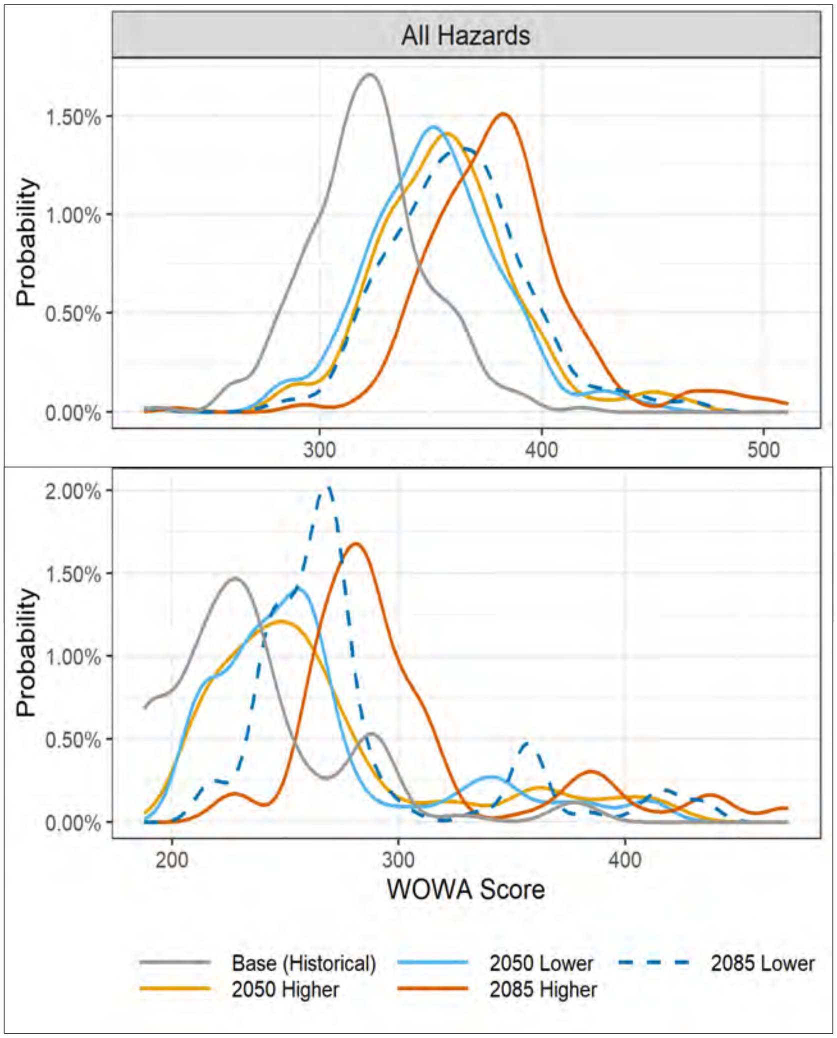


Figure 30. Distribution of aggregated climate hazard exposure (WOWA) scores across Air Force CONUS, AK, HI (top), and ROW (bottom)installations for both epochs and both scenarios for all hazard categories.

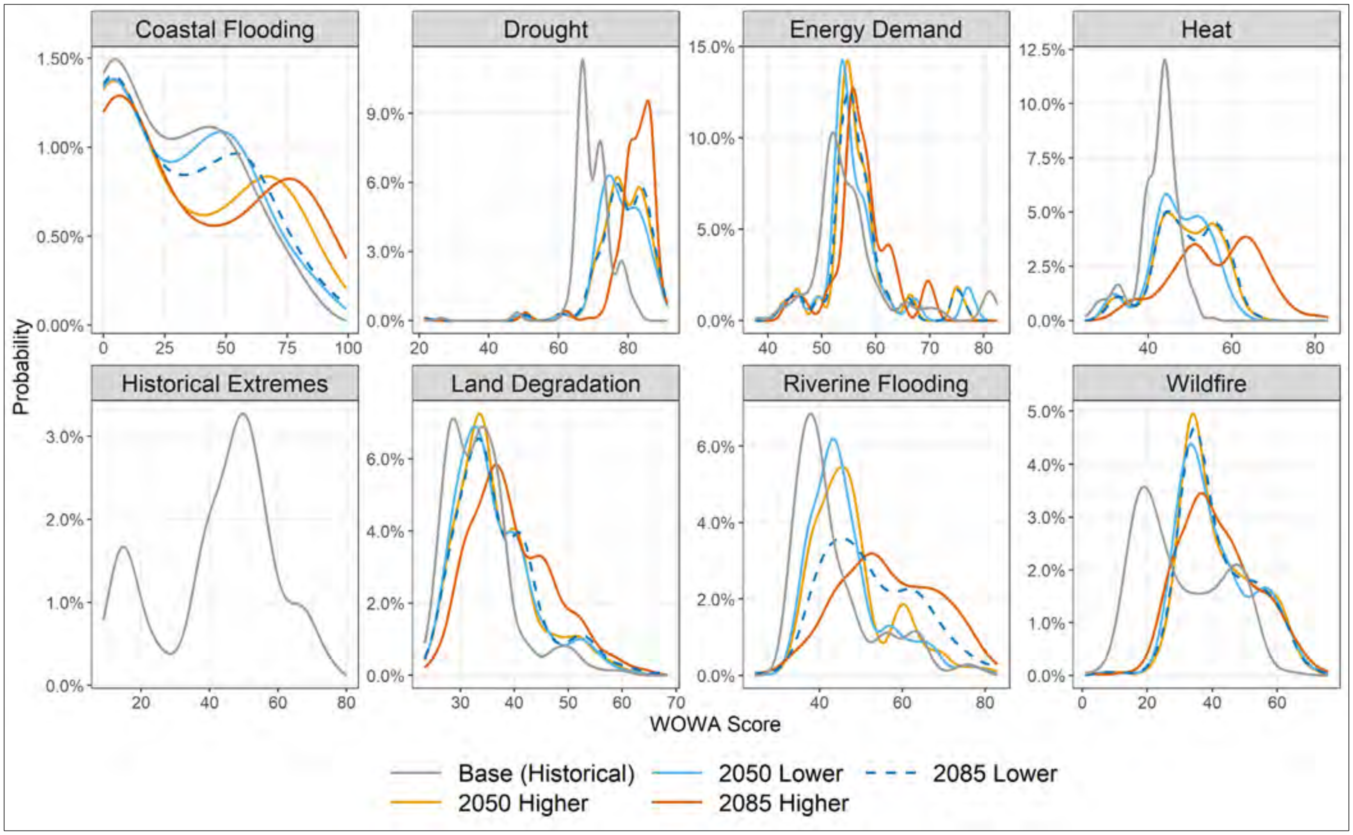


Figure 31. Distribution of climate exposure WOWA scores across Air Force CONUS, AK, and HI installations for each epoch and scenario. Note that the historical extreme conditions hazard is static. Installation exposure increases over time and with higher scenarios, though some increases are more pronounced than others (drought, heat).

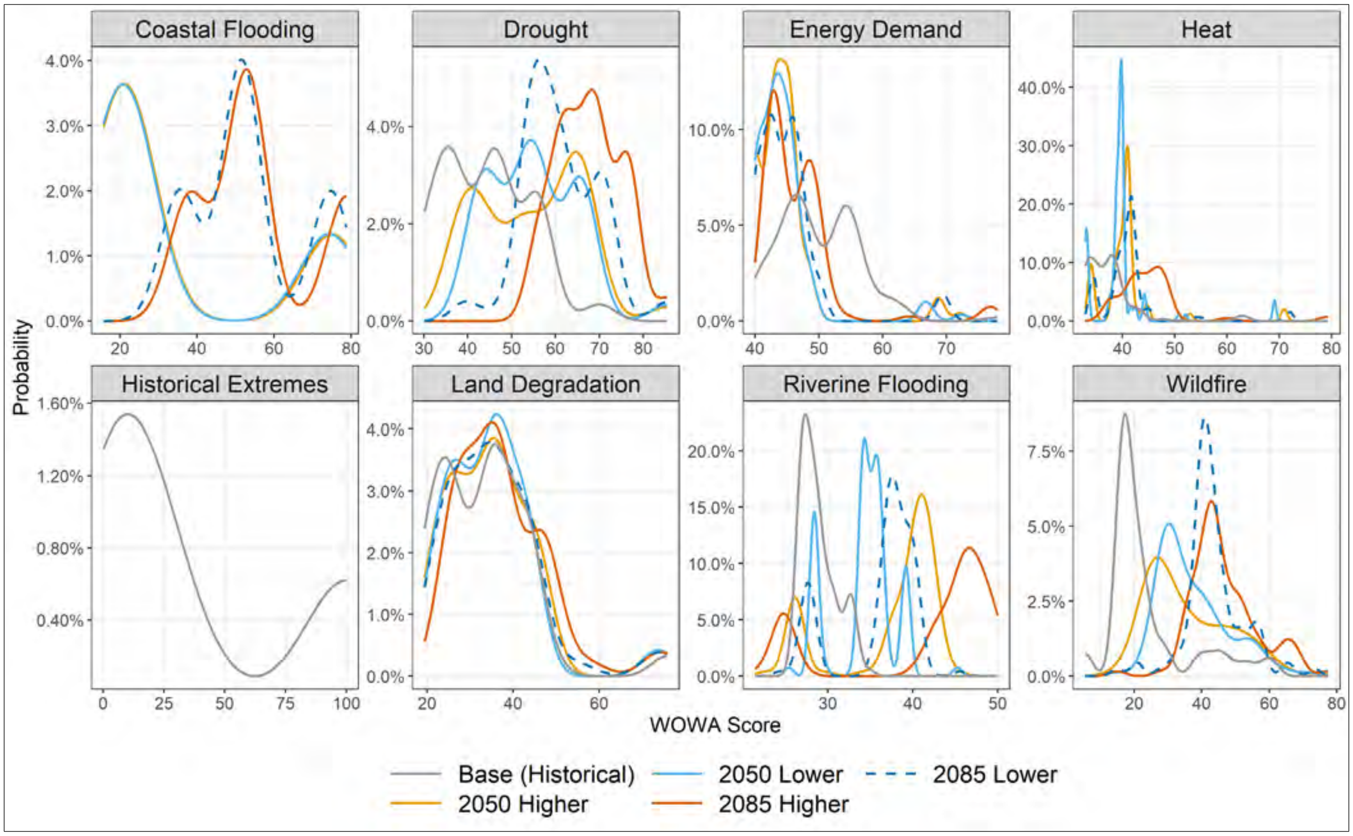


Figure 32. Distribution of climate exposure (WOWA) scores across Air Force ROW installations for each epoch and scenario. Note that the historical extreme conditions hazard is static. The ROW data behave less uniformly than the CONUS, AK, and HI data because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks. For some ROW indicators, the response with time and scenario appears non-uniform because one or another of these regions is responding differently from the rest. Installation exposure to other hazards increases over time and with higher scenarios, though some increases are more pronounced than others (land degradation).

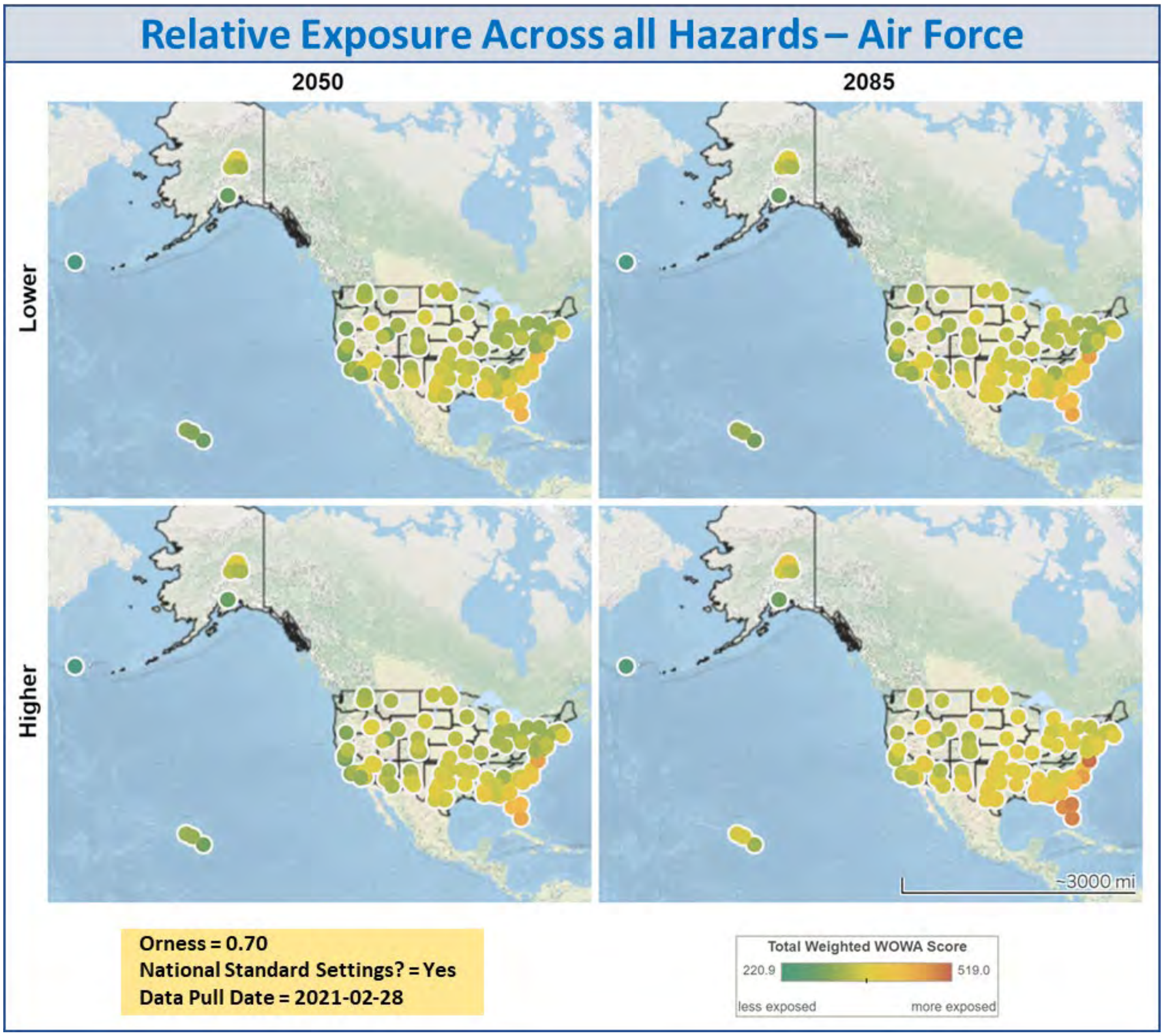


Figure 33. Relative exposure to all hazards across Air Force CONUS, AK, and HI installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

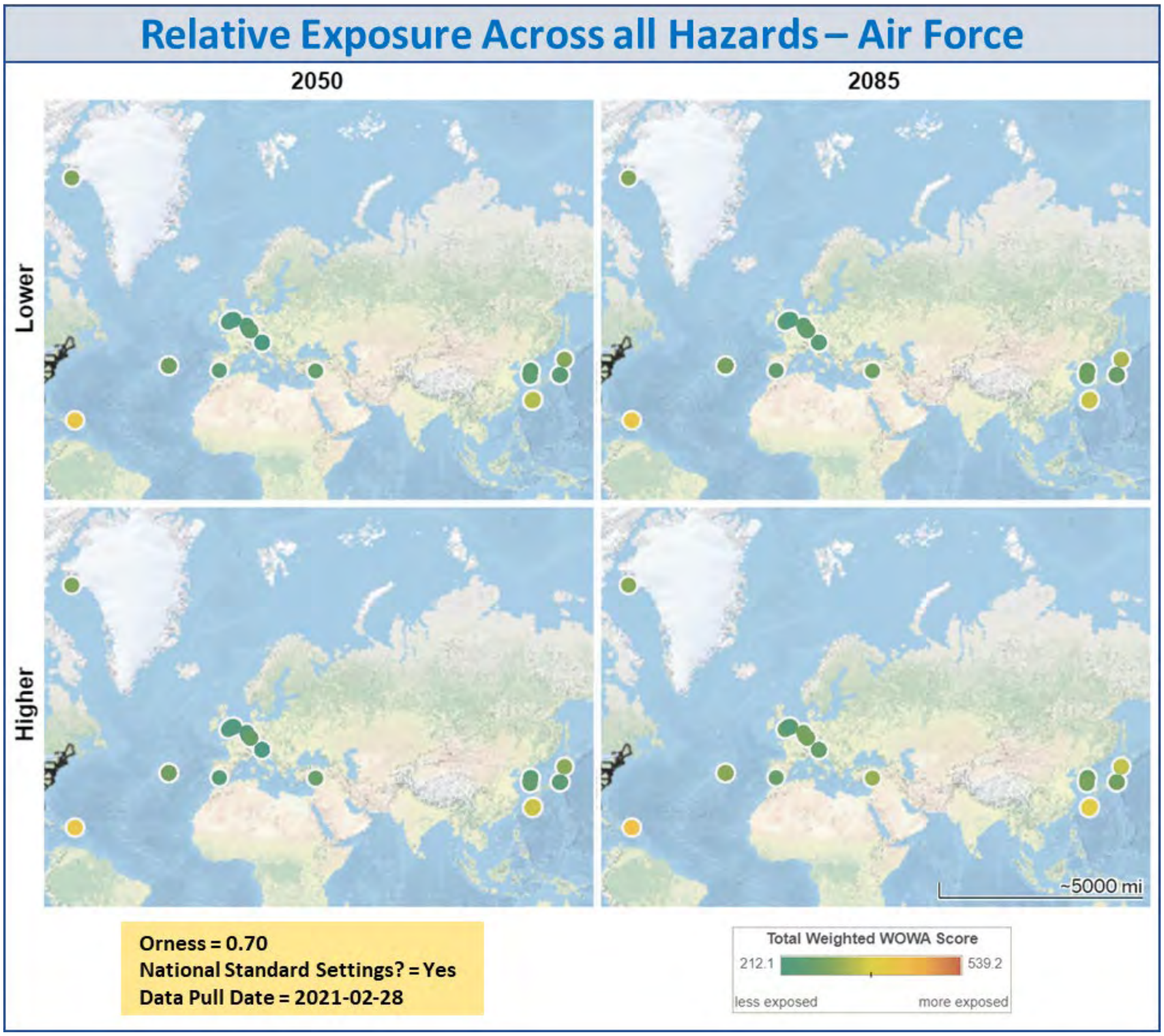


Figure 34. Relative exposure to all hazards across ROW Air Force installations within DCAT for lower emissions scenarios (top) and higher emissions scenarios (bottom). Lower aggregated climate hazard (WOWA) scores indicate less relative exposure (green), while higher scores indicate more exposure (red).

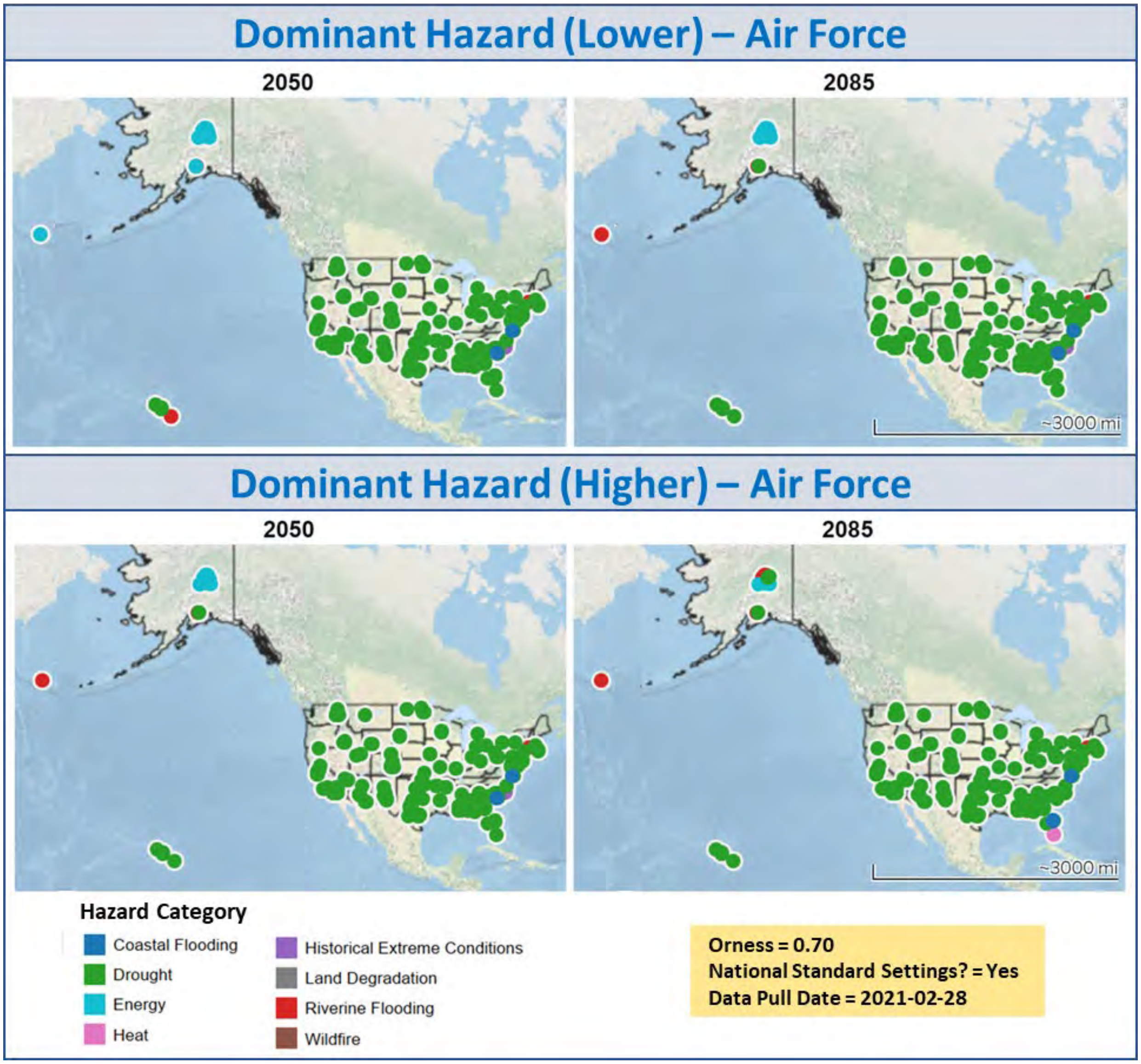


Figure 35. The dominant hazard category identified in DCAT for Air Force CONUS, AK, and HI installations is drought.

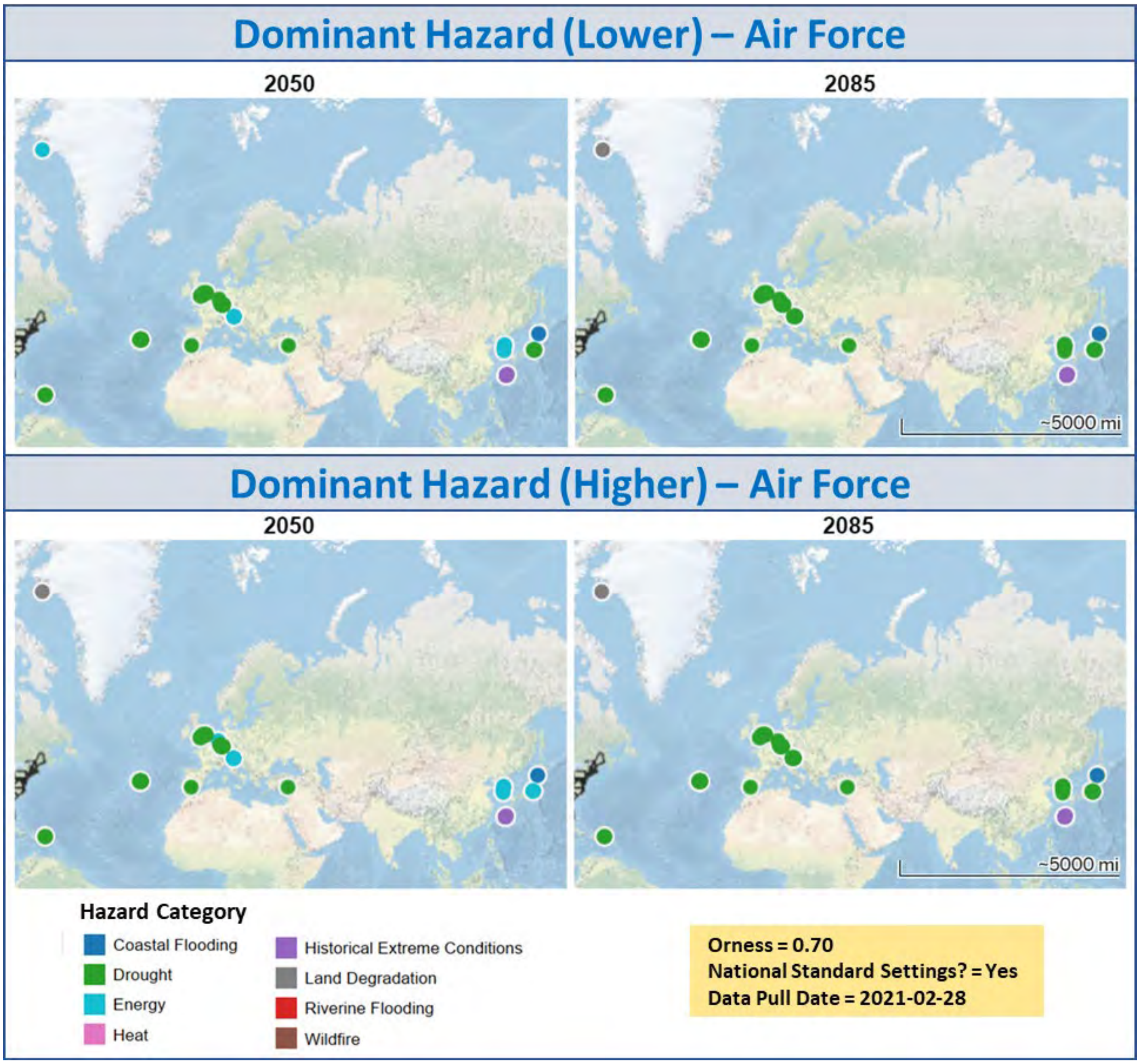


Figure 36. The dominant hazard category identified in DCAT for Air Force ROW installations is drought.

DEEPER DIVE: RISING TEMPERATURES

The higher and lower future scenarios differ due to different underlying assumptions about the rate at which global temperatures are projected to rise. Temperature increases typically increase the magnitude and frequency of extreme events. For example, heat waves, droughts, and deluges all increase with higher temperatures at the expense of more moderate weather conditions. Warmer circumpolar temperatures result in increased ocean temperatures, which accelerates ice sheet melt and contributes to sea-level rise. Generally, greater increases in temperature result in more significant consequences, although the response of the climate system may be non-linear (e.g., accelerating).

KEY TAKEAWAYS:

- Rising temperatures will increase the exposure of all Departments to a wide range of hazards that can directly impact military readiness.
- Rising temperatures are also projected to increase both drought and precipitation quantity and/or intensity.

TECHNICAL DISCUSSION

For DoD installations across CONUS, AK, HI, and ROW, rising temperatures will increase exposure to a wide range of hazards (especially heat-related hazards) that can directly impact military readiness. Climate change is anticipated to increase heat-related health problems, with even small climate changes resulting in increases in illness and death.

Increases in temperature are anticipated to have significant effects on military training and testing, including (1) an increase in the number of "black flag" (suspended outdoor activities) or fire hazard days (limiting live-fire activities), (2) increases in the need for operational health surveillance, (3) higher rates of heat-related mortality and morbidity, and (4) reassessment of weapons system operation and deployment procedures (including changes to soldier readiness due to changes in the availability or timing of days when conditions are suitable).

Higher temperatures may also affect pilot readiness by limiting cockpit time while on the ground and by affecting aircraft lift on takeoff and landing. In addition, higher temperatures significantly increase the opportunity for vector-borne diseases: Higher winter temperatures reduce vector mortality rates in the winter, while higher spring-fall temperatures extend the length of the breeding season, increasing disease reproductive cycles.

Figure 37 shows changes in 5-day maximum temperature across all installations, a measure of heat wave severity. Compared to the base period, most sites will experience heat wave temperatures 10˚F to 15˚F greater in the future than they experience in the base epoch. These temperature increases have many subsequent effects, including increased heat stress for individuals working and recreating outdoors.

Similarly, the number of days in which the National Weather Service (NWS) Heat Index[2] values are projected to equal or exceed 90˚F rapidly increase across the DoD portfolio (Figure 38): By 2050 under both scenarios, most installations are projected to experience significant increases in the number of days with restrictions on outdoor activities).

[2] https://www.weather.gov/safety/heat-index. Heat Index is used in the DCAT because it is not currently possible to accurately calculate some of the inputs to the Wet Bulb Globe Temperature Index using climate model data.

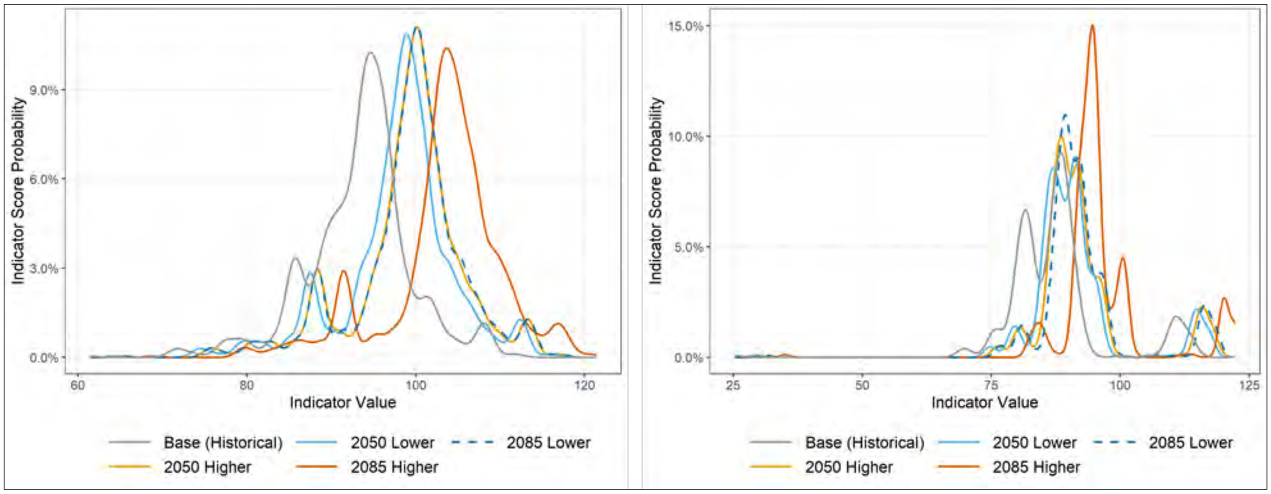


Figure 37. Distribution of 5-day maximum temperature values across CONUS, AK, HI (left), and ROW (right) installations. As in other cases, the values for 2050 higher scenario and 2085 lower scenario are very similar.

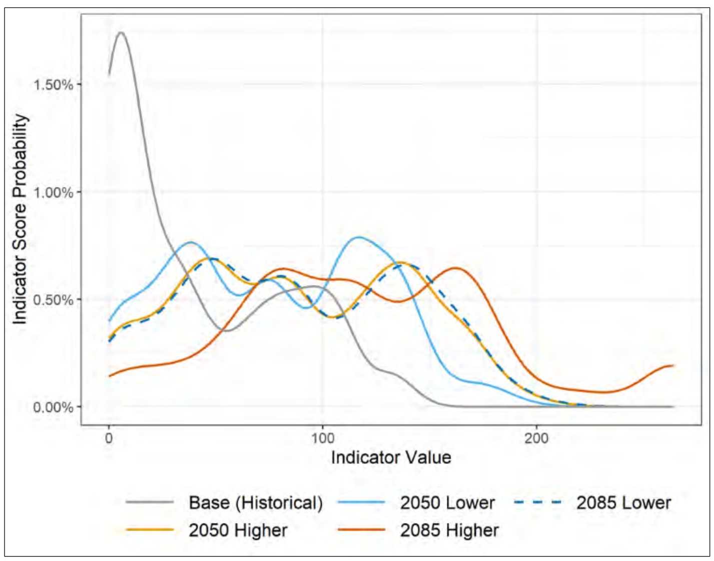


Figure 38. Distribution of days with NWS Heat Index values ≥ 90°F (extreme caution or higher) for a portion of the day across CONUS, AK, and HI installations. Similar to 5-day maximum temperature, the results for 2050 higher scenario and 2085 lower scenario are very similar. High Heat Index days were not calculated for ROW installations due to lack of an authoritative global humidity dataset.

Rising temperatures are also projected to increase precipitation quantity and/or intensity. Across the DoD portfolio, this is demonstrated by changes in precipitation-related hazards, such as maximum 1-day precipitation (Figure 31). Gradually, each epoch-scenario curve shifts to the right, demonstrating that the average maximum 1-day precipitation is likely to increase from under 2 inches to over 2 inches. In addition, as the curves shift to the right, the likelihood of occurrence for more extreme events increases as well. This means that a larger share of installations is more likely to experience 1-day precipitation totals greater than 2.5 and 3 inches. Even small changes in maximum 1-day precipitation can have significant repercussions for the total volume falling across a watershed, potentially leading to large increases to riverine and urban flood risk.

While DoD-wide exposure changes are important to highlight, the DCAT enhances visibility into geospatial exposure variation. For example, in more arid regions, rising temperatures are projected to increase drought risks (e.g., Figure 8), result in more frequent heat waves, and drive increases to fire danger. This occurs because a warmer atmosphere can hold more moisture before reaching saturation.

A warmer atmosphere acts like a bigger sponge, drawing more moisture from the soil and plants at a higher rate via evapotranspiration while at the same time being able to hold more water before reaching saturation and starting to rain. In arid regions, the net result is that as temperatures warm it becomes increasingly rare for there to be enough moisture in the atmosphere to produce rain: Rain events become much rarer, but when rain comes it is very intense. Aridity and multi-year droughts increase along with wildfire risk. Surface water supplies decline. Vegetation cover becomes sparser and the land surface more easily degraded through human activity and during rain events. The U.S. Southwest, for example, is already thought to be in the middle of its first multi-decade temperature-driven drought [Williams et al., 2020].

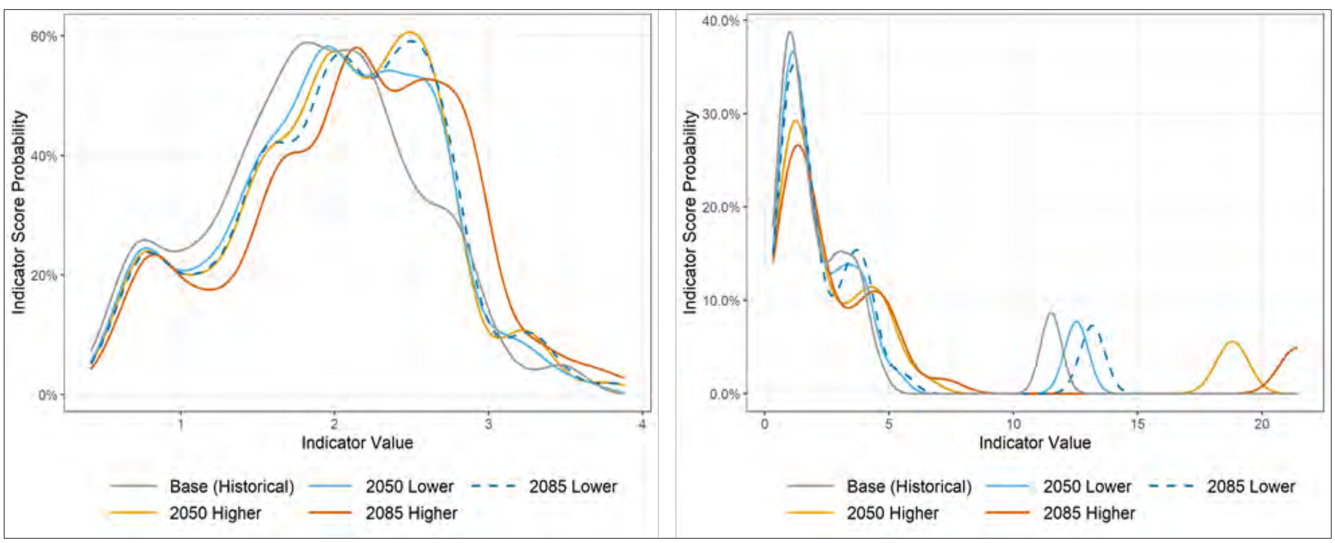


Figure 39. Distribution of maximum 1-day precipitation across CONUS, AK, HI (left), and ROW (right) installations. Similar to 5-day maximum temperature, the results for 2050 higher scenario and 2085 lower scenario are very similar. The ROW data behave less uniformly than the CONUS, AK, and HI data because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks.

Since 2010, there has been an increased emphasis on "flash droughts." Otkin et al. [2018] define flash droughts as droughts that occur with rapid intensification. As an example, they describe the 2012 flash drought, where large areas with near-normal conditions evolved into extreme drought conditions [Swoboda et al., 2002] over a 2-month period. For the DoD, flash droughts pose significant risks and challenges, where acute impacts to water supply and reductions in soil moisture can directly impact DoD installations.

As shown in Figure 32, flash drought frequency increases over time and under higher scenario conditions. Specifically, the flatter curves highlight an increasing range of flash drought risk across the DoD. Though some installations may experience flash droughts at similar rates to rates in the base epoch-scenario, projections indicate that many installations will experience a higher risk of flash draught frequency under all scenarios in the future epochs (with these risks most pronounced for the higher 2085 epoch-scenario).

In more humid regions, there is usually enough soil moisture so that a warmer atmosphere will still be able to reach saturation. In these regions, there is likely to be more energetic storm systems that drop more rain and occur more frequently, contributing to more frequent and larger riverine flood events. In addition, relative humidity will continue to be high, resulting in large increases in high NWS Heat Index days (Figure 30) that pose significant morbidity and mortality risks for troops engaged in outdoor activities. The U.S. Southeast is anticipated to be particularly hard-hit by temperature-driven increases in rainfall and humidity [Carter et al., 2018]. The trend to increasing rainfall in this region is evident in DCAT as well (Figure 41 and 42).

Other impacts of rising temperatures that will uniquely impact Polar Regions were noted by the General Accountability Office (GAO) [GAO, 2014]. These include temperature-related reductions in sea ice and thawing permafrost. These changes will accelerate coastal erosion, reduce accessibility to training ranges as the permafrost thaws, and increase freezing rain events, which may otherwise have fallen as snow.

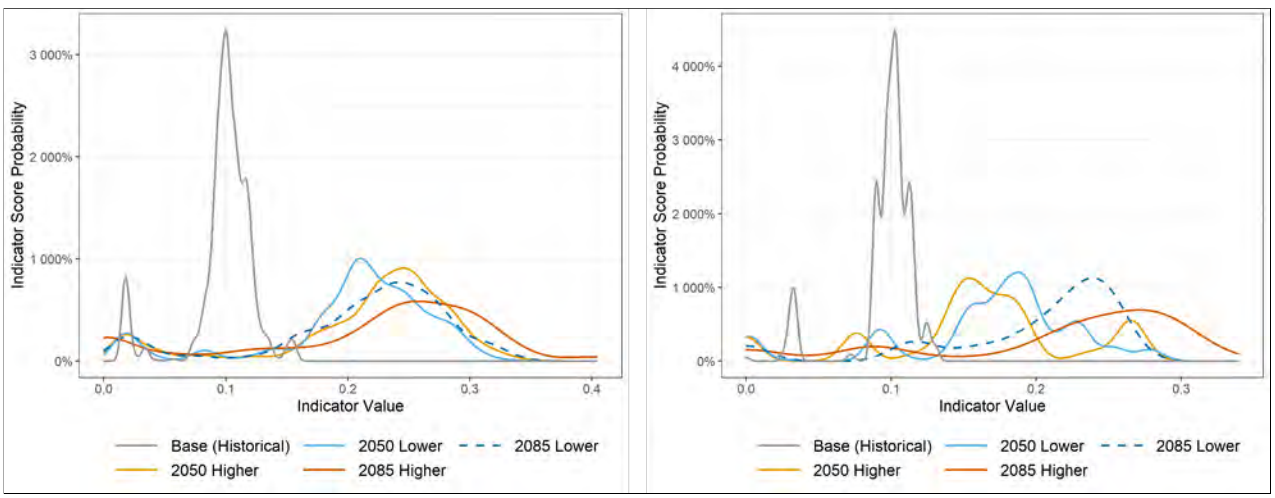


Figure 40. Changing frequency of flash droughts across the DCAT CONUS, AK, HI (left), and ROW (right) installations calculated as the average number of times per year in which rapid-onset drought occurs, characterized by a sharp drop in precipitation over a 3-month period. It is represented using the 1-month Standardized Precipitation Evaporation Index (SPEI). The ROW data behave less uniformly than the CONUS, AK, and HI data because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks.

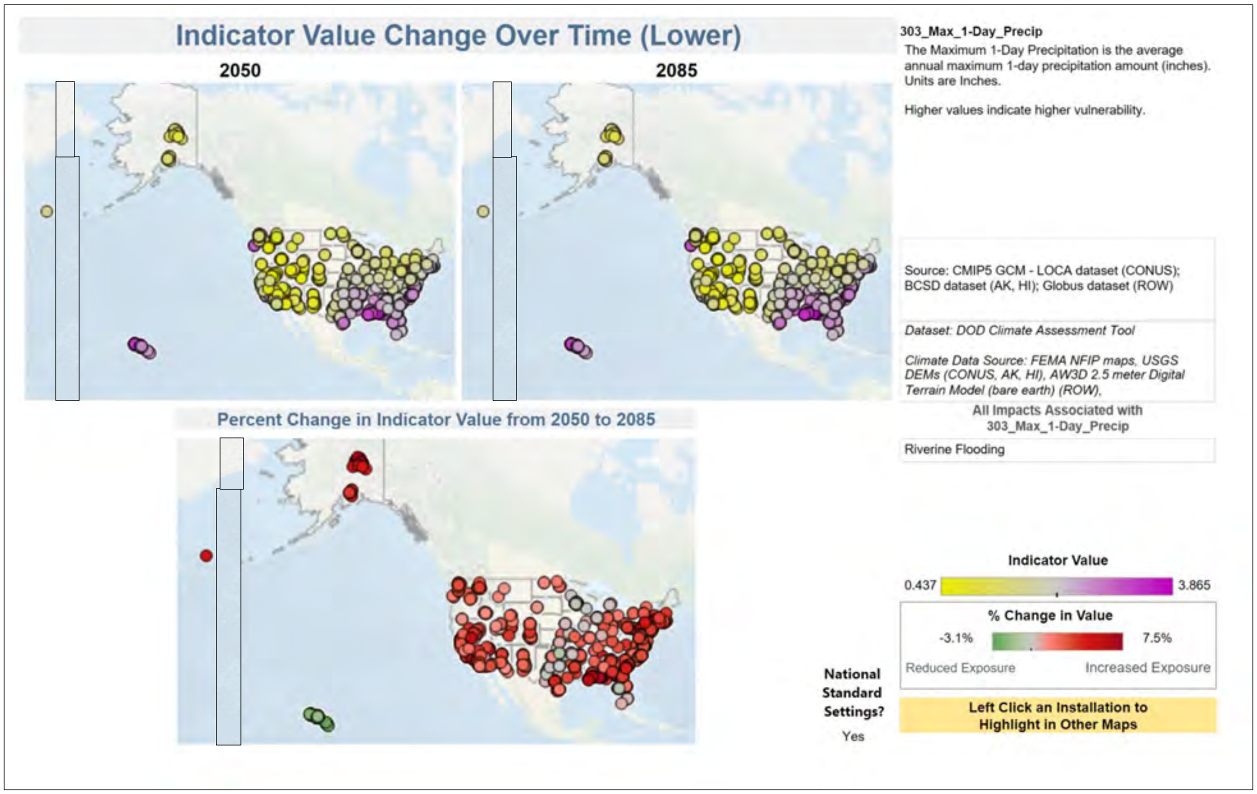


Figure 41. Geospatial depiction of the maximum 1-day precipitation across CONUS, AK, and HI installations as shown in the DCAT.

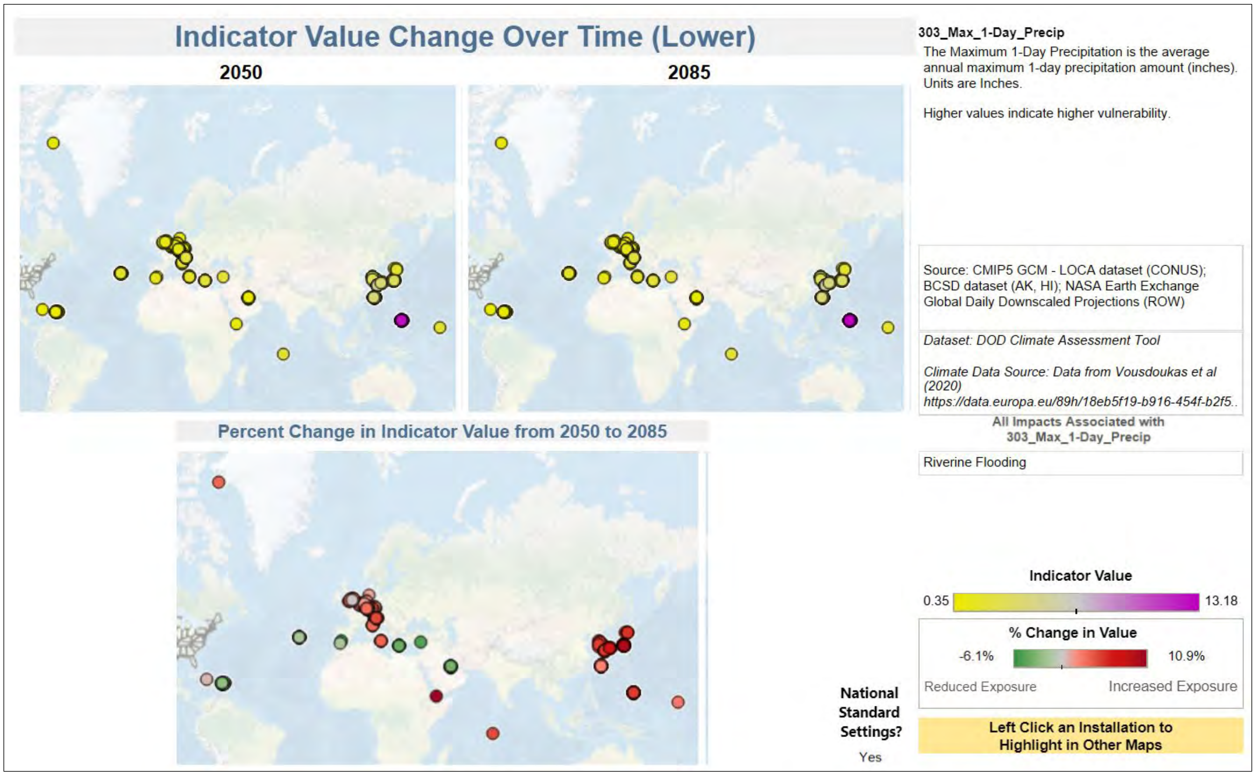


Figure 42. Geospatial depiction of the maximum 1-day precipitation across ROW installations as shown in the DCAT.

DEEPER DIVE: ENERGY DEMAND

Among the requirements of EO 14008, Sec. 211, is the requirement for agencies to include in their draft action plan an assessment of their climate vulnerabilities with respect to installation, building and facility energy efficiency, and to describe steps the agency can take to bolster adaptation and increase resilience in this area.

DoD is already required, under 10 U.S. Code (U.S.C.) § 2911: Energy Policy of the Department of Defense, to develop a comprehensive master plan for the achievement of the energy performance goals of the Department of Defense that considers, among other provisions, opportunities to enhance energy resilience to ensure the Department of Defense has the ability to prepare for and recover from energy disruptions that affect mission assurance on military installations.

Energy resilience is defined by 10 U.S.C. § 101(e)(6) as the ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including mission-essential operations related to readiness, and to execute or rapidly reestablish mission-essential requirements.

It is well-established that climate change will increase the frequency and magnitude of daily maximum temperature extremes (high heat days and heat waves), and decrease cold extremes [Sillman et al., 2013]. It is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st Century over many areas of the globe [IPCC, 2012]. Increases in the frequency of extremes, including heatwaves and droughts, have already been observed in many regions of the world [IPCC, 2019].

As events in Texas in 2021 have shown, extreme events can have significant impacts on local and regional energy supplies by altering peak and cumulative energy demand, and by disrupting power generation and transmission. Climate change can also affect water availability for power generation (hydropower, thermoelectric cooling).

The DCAT assesses exposure to installation energy demand changes using two indicators for peak load (5-day maximum temperature and 5-day minimum temperatures) and two indicators for cumulative energy demand (cooling degree days and heating degree days). The patterns are quite similar across both the CONUS, AK, and HI, and ROW installations (Figures 43 and 44): 5-day maximum temperature, 5-day minimum temperature and cooling degree days increase over time while heating degree days decline. These changes reflect the shift to warmer average and extreme temperatures in all seasons. The changes in the warm extremes are greater than the reductions in the cold extremes.

Geographically, changes in climate factors that affect energy demand at CONUS, AK, and HI installations will be greatest in Alaska and the Northern Plains driven by rapidly warming temperatures in all seasons (all four indicators). In an absolute sense, the highest exposure will be felt in the Southeast and Southwest, where temperatures will be the highest both on average and the extremes.

Among ROW installations, the greatest exposure to changes in energy demand is felt in the dry subtropics (e.g., the Middle East) where 5-day maximum temperatures are likely to exceed 110°F, and days over 95°F are projected to occur more than half the days of the year by 2085. But the greatest impact of changing energy demand may occur in Northern Europe and similar climates where air conditioning and other heat adaptations are uncommon: Recent heatwaves in Europe and Russian claimed tens of thousands of lives in 2003 and 2010 [Robline et al., 2008; Barriopedro et al., 2011]. The large increase in 5-day minimum temperature occurs at Thule Air Base in Greenland, where 5-day minimum temperature average above freezing in the 2085 higher scenario.

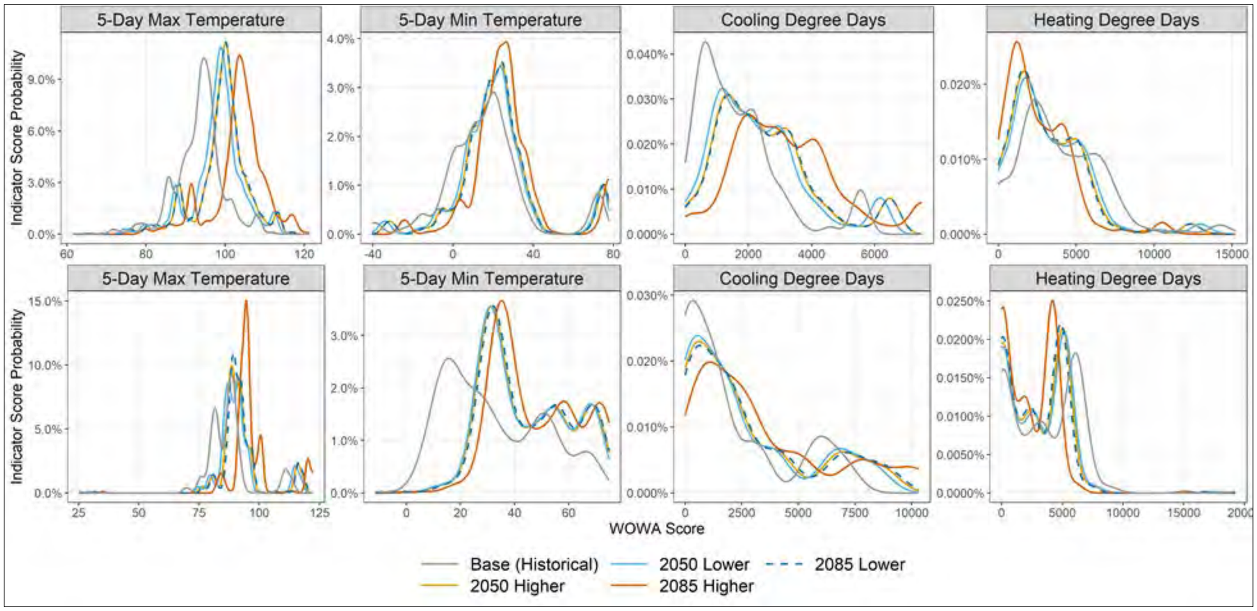


Figure 43. Changes in indicators of energy demand for CONUS, AK, and HI (top), and ROW (bottom) installations. The ROW data behave less uniformly than the CONUS, AK, and HI data for some indicators because most sites are concentrated in the cold, marine climates of Europe, the humid climates of East Asia, or the hot subtropics (Mediterranean and Middle East). Consequently, ROW graphs often exhibit multiple peaks.

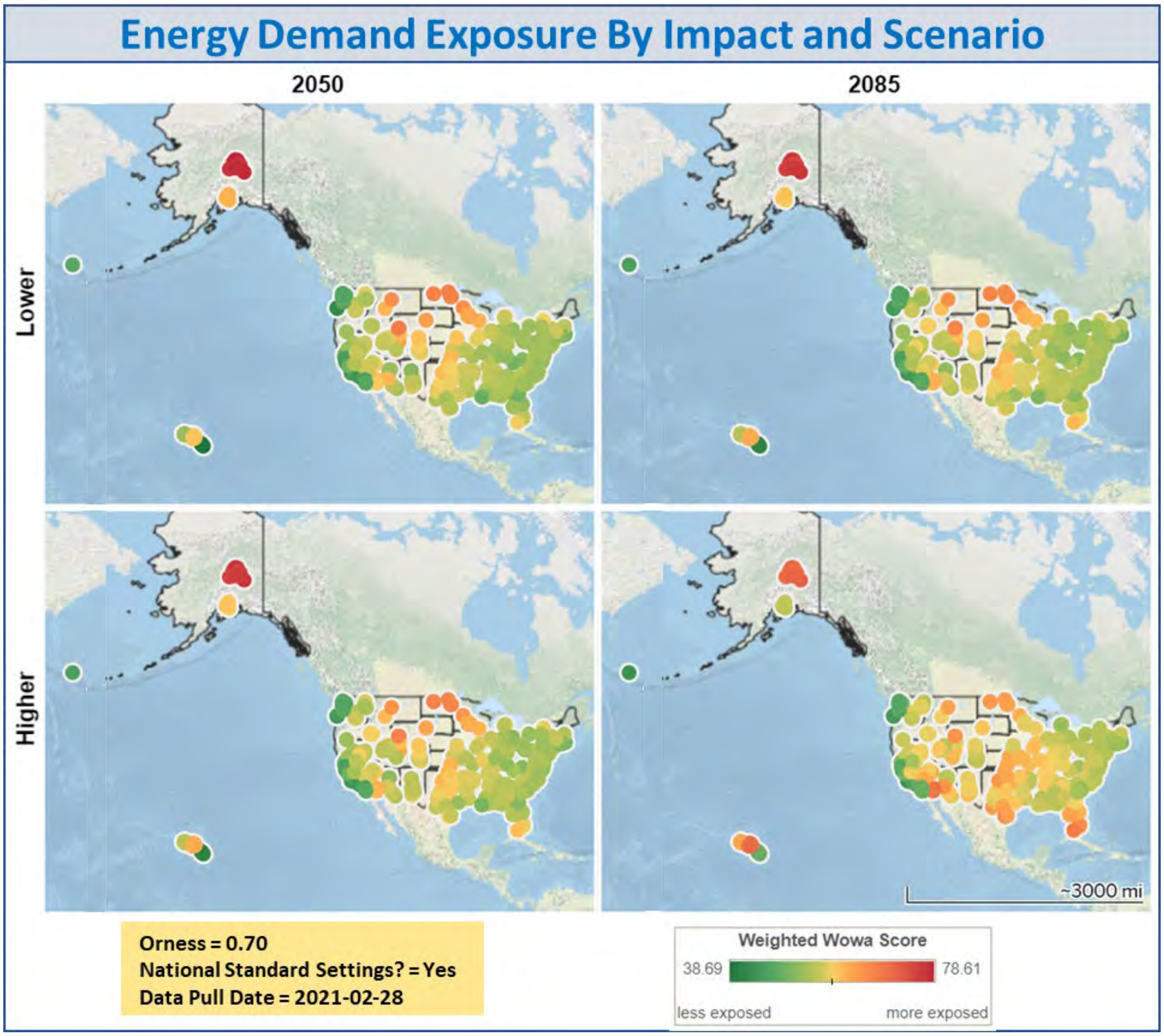


Figure 44. Changing exposure to climate factors that drive energy demand for CONUS, AK, and HI installations.

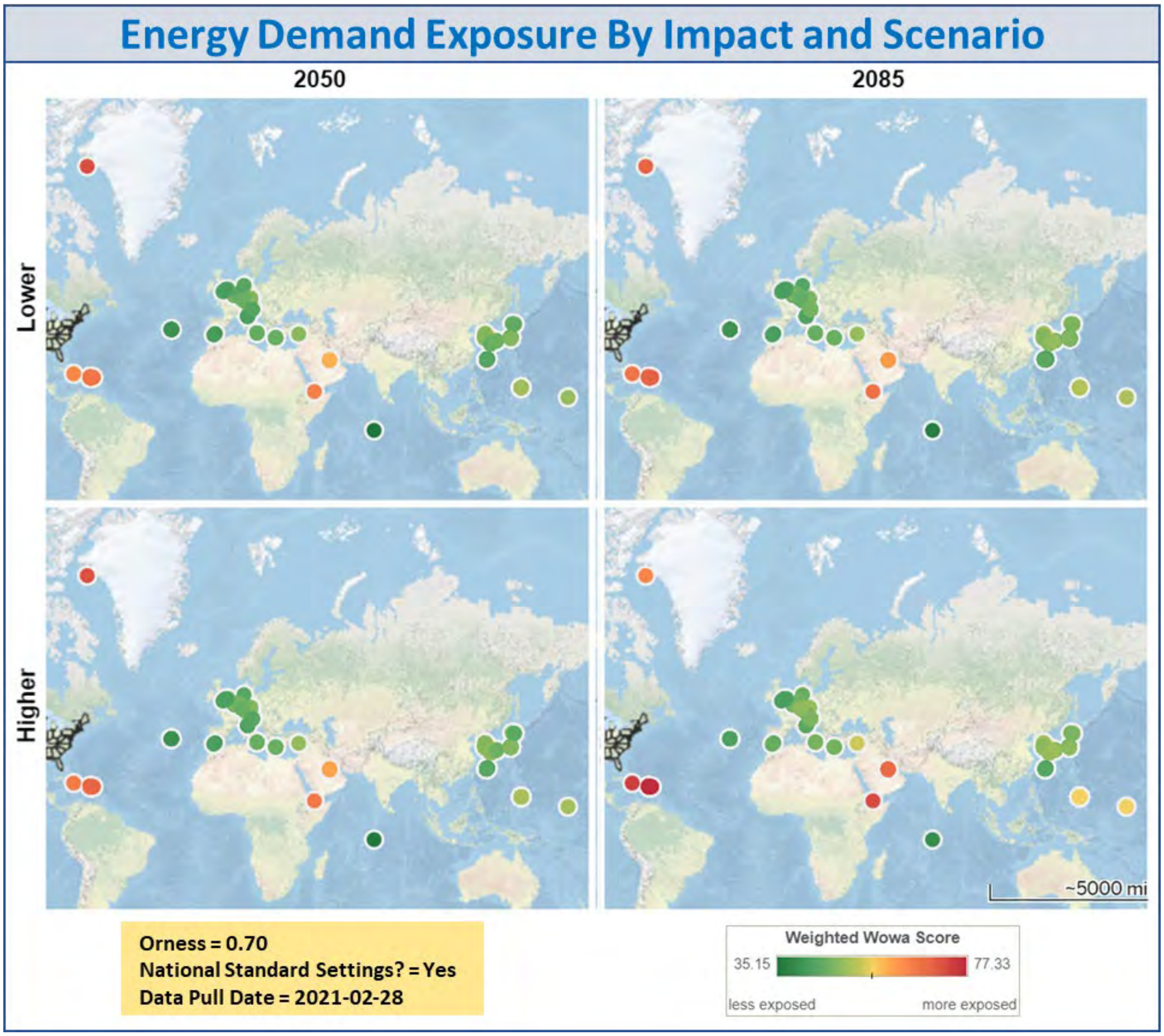


Figure 45. Changing exposure to climate factors that drive energy demand for ROW installations.

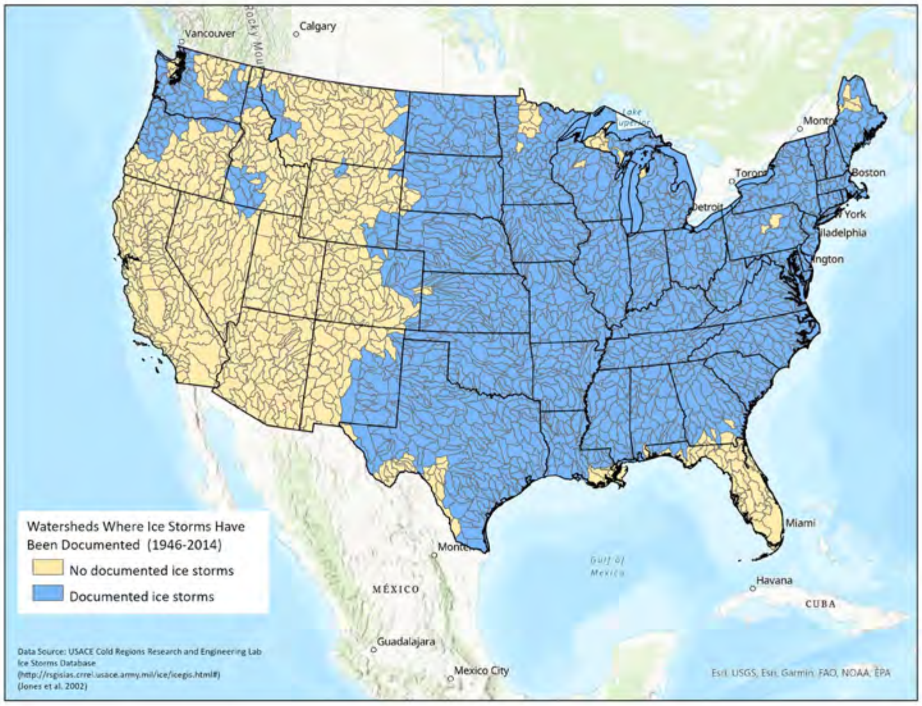
In addition to affecting the demand for energy, climate change may also interrupt energy supplies to installations by reducing generation and transmission efficiency, decreased water available for thermo-electric generation and cooling, and damaging infrastructure (Figure 46).

Technology	Δ air temp.	Δ water temp.	Δ precip.	Δ wind speeds	Δ sea level	Flood	Heat waves	Storms
Nuclear	1	2	-	-	-	3	1	-
Hydropower	-	-	2	-	-	3	-	1
Wind (onshore)	-	-	-	1	-	-	-	1
Wind (offshore)	-	-	-	1	3	-	-	1
Biomass	1	2	-	-	-	3	1	-
Photovoltaic	-	-	-	-	-	-	1	1
Concentrated Solar Power	-	-	-	-	-	1	-	1
Geothermal	-	-	-	-	-	1	-	-
Natural gas	1	2	-	-	-	3	1	-
Coal	1	2	-	-	-	3	1	-
Oil	1	2	-	-	-	3	1	-
Grids	3	-	-	-	-	1	1	3

Key: 3= Severe impact, 2 = Medium impact, 1= Small impact, - = No significant impact

Figure 46. Qualitative assessment of the potential exposure of energy technologies to climate changes [European Commission, 2011].

Although climate models are not able to resolve individual storm events, individual storms can cause extensive damage to generation facilities and transmission lines. Hurricane winds and damaging ice storms are two of the major causes of power outages. Authoritative data for historical events is available for CONUS, AK, and HI. Figure 47 shows locations in CONUS where damaging ice storms have occurred (top, where freezing rain fell and damaged above-ground communications and energy infrastructure) and the annual frequency of damaging hurricane force winds greater than 50 knots (bottom). The Eastern U.S., and particular the coastal Southeast, has high exposure to damages from both sources.



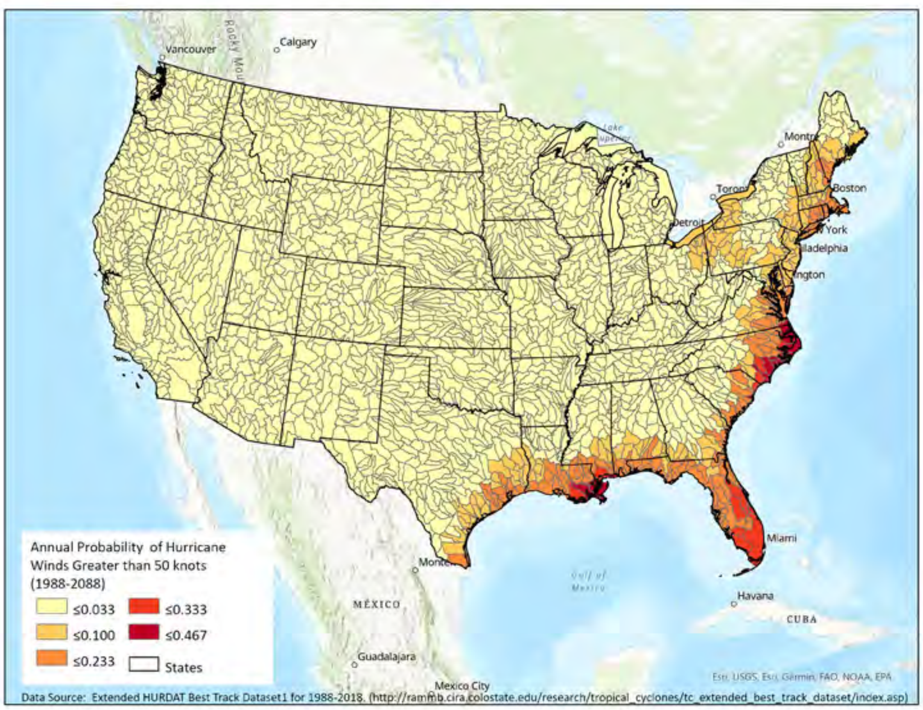


Figure 47. Historical ice storm occurrence (top: blue is a known occurrence; beige indicates no known occurrence) and the frequency with which installations experience hurricane force winds in excess of 50 knots (bottom: value is annual probability) for CONUS watersheds.

COMPARISON TO PREVIOUS ASSESSMENTS

Over the last few years, many studies have attempted to identify both current and future exposure and/or risk of extreme weather events for DoD installations. Of note, there is no consistent predefined list of risk indicators or a predefined method to estimate future risk. As a result, each study may use a unique set of risk indicators and unique methods for estimating current or future risk indicators. In general, these studies tend to be most consistent when the indicators are strongly tied to observed or modeled future temperature and precipitation data.

Perhaps the closest comparison for DCAT is the 2019 DoD Report on Effects of a Changing Climate to the Department of Defense [DoD, 2019], which provided information on relative exposure to selected Army, Air Force, and Navy installations in the present data and in the near future (2035) across a range of hazards (flooding, drought, desertification, wildfires, and thawing). Of the hazards used in this report, three have a strong overlap with hazard categories used by the DCAT. Here, the 2035 estimate from the 2019 DoD report is compared to the DCAT 2050 higher epoch-scenario data for Army and Navy installations.

1. **Army**: Fifteen installations are in both the DoD report and the DCAT. Across these installations, there is strong agreement between installations identified as exposed to recurrent flooding in the DoD report and those identified in the DCAT for having higher than average exposure to riverine flooding in the DCAT.

   Specifically, installations in the DoD report that have both current and future flood exposure have comparatively higher riverine flooding WOWA scores in the DCAT. Furthermore, there is strong agreement for drought risk: both the DoD report and the DCAT highlight the same top four installations. Similarly, the three sites identified with near-term wildfire risk in the DoD report are among the top five sites for wildfire risk in the DCAT. With respect to overall exposure, despite relying on very different metrics, there is agreement on three of the top five installations with greatest future exposure.

2. **Navy**: Eleven installations are in both the DoD report and the DCAT. For all these sites, DoD report indicates current and future flood and drought risk. Similarly, in the DCAT, these sites have higher than average exposure scores for both hazard categories. Of note, the DoD report and the DCAT do not share similar results for installation wildfire risk. As a whole, although the studies have varying results for overall climate exposure across these sites, both identified the same top two Navy installations as those with the greatest exposure.

DCAT findings were also compared to the findings of two Army-specific studies.

1. **Miller et al. [2015]**: In their work, the authors identify 10 Army installations as having extreme water consumption stress in 2050. Of these 10 installations, four were analyzed by DCAT. In the DCAT, three of the four installations have top 5 Army-specific WOWA scores for drought exposure in the 2050 higher epoch-scenario, while also carrying top 20 WOWA scores when compared to the entire DoD installation portfolio.

2. **Lozar et al. [2011]**: In their work the authors identify Army installations at greatest risk from temperature increase by the late 21st Century. A total of 11 installations in this report overlap with Army installations in the DCAT. Of the 11, 10 have higher than average risk to heat exposure. Lozar et al. also identify installations at the greatest risk of precipitation decrease. All five of the identified installations that are in the DCAT have higher than average WOWA scores for exposure to drought. Though there is no correlation between the identified sites in the author's high and very high erosion risk categories and those with higher than average WOWA scores for land degradation, this may not be surprising given the very different underlying measurements.

Though other evaluations were considered, they proved to be more difficult to compare. In 2018, the DoD reported on climate-related risk to DoD infrastructure in its initial Vulnerability Assessment Survey (SLVAS) Report [DoD, 2018]. The survey captured the effects of past events, such as flooding from storm surge, flooding from other sources (e.g., rainfall, snowmelt, ice jams, riverine flooding), extreme temperatures, wind, drought, and wildfire to the asset categories shown in Table 3. To fully compare this analysis to that of DCAT, a more detailed analysis at the installation level would be required to measure agreement for installations affected by single or multiple hazards.

Table 4. Asset categories of facilities, infrastructure, operations, and associated services as used in assessments of sensitivity [DoD, 2018].

Asset Category	Definition
Airfield Operations	An area prepared for the accommodation (including any buildings, installations, and equipment), landing, and takeoff of aircraft.
Training Areas/Ranges/ Facilities	Areas and facilities where training activities take place, whether land, sea, or air.
Piers/Waterfront Services	Pier and/or port complex and associated services that assist and/or provide support to loading, unloading, staging, etc.
Information Systems	Infrastructure, organization, personnel, and components for the collection, processing, storage, transmission, display, dissemination, and disposition of information.
C4ISR	C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) infrastructure (including radar and towers).
Energy Infrastructure	All aspects of generation, transmission, and distribution systems that are essential to power use at installation (e.g., power lines, substations, generators).
Fuel Infrastructure	All aspects of generation, transmission, and distribution systems that are essential to fuel use at installation (e.g., storage tanks, distribution pipelines, fill stands).
Logistics Supply	Storage, inspection, distribution, transport, maintenance (including repair and serviceability), and disposal of materiel as well as the provision of support and services (excluding fuel).
Transportation Infrastructure & Routes	Ground transportation routes and assets; for example, roads, bridges, and terminals (non-airfield or waterfront).
Emergency Services	Assets and capabilities used to provide the support, resources, program implementation, and services that are most likely to be needed to save lives, protect property and the environment, restore essential services and critical infrastructure, and help victims and communities return to normal, when feasible, following domestic incidents. To include emergency operations centers, hospitals, and clinics.
Water/Wastewater Systems	All aspects of pumping, storage, distribution, collection, and treatment systems that are essential to water use and wastewater management at an installation.
HVAC Systems	All aspects of HVAC (heating, ventilation, and air conditioning) systems.
Environmental Restoration Sites	Sites where actions are required or controls are in place to reduce the risk to human health and the environment from past waste disposal operations and hazardous substance releases.
Natural Resources	"All elements of nature and their environments of soil, sediments, air, and water. Those consist of two general types: a) earth resources—nonliving resources such as minerals and soil components; and b) biological resources—living resources such as plants and animals." (Department of Defense Instruction [DoDI] 4715.03, Natural Resources Conservation Program)
Historic/Cultural Resources	Includes historic properties, cultural items, tribal sacred sites, and archaeological resources/artifacts/collections. (DoDI 4715.16)
Housing	Temporary and/or permanent residential structures and barracks.
Headquarters (HQ) Buildings	Structures where senior installation staff conduct their activities.
Personnel Support	Childcare center, school, commissaries, and exchanges.

RESILIENCE CONSIDERATIONS

Resilience measures as used here means measures taken to reduce or avoid the exposure of an installation and its asset categories (Table 3) to the hazards considered in this analysis. Resilience encompasses four key actions: preparing for exposure and disruptions from these hazards, absorbing their impacts while providing essential services and minimizing the consequences of failure, recovering rapidly and wisely to the exposure and disruptions, and adapting or transforming to reduce future vulnerabilities [after USACE, 2017].

OVERVIEW

The planning and implementation of resilience measures for extreme weather and climate change is generally tailored to the value of the assets at risk, the consequences of nonperformance, the spatial, temporal scale of the decision maker, and the lifecycle horizon [Veatch and White, 2019]. These decisions are also subject to constraints (e.g., standards, funding and technological limitations, regulations) and residual risks that change over time (e.g., increasing sea level).

The exposure-sensitivity-adaptive capacity framing used here informs decisions differently at scales appropriate to the decision maker (Figure 3). Understanding relative exposure to climate hazards enables strategic prioritization and resourcing decisions at the DoD and Department scale, while more detailed, installation-level information about future climate hazards, sensitivity, and adaptive capacity supports tactical decision making and informs strategic decisions.

While many decision makers only consider extreme events, effective resilience for DoD installations addresses the range of climate exposure [Pinson et al., 2020] from chronic or frequent hazards such as changes in high tide flooding that permanently inundates land [e.g., Sweet et al., 2014; Moftakhari et al., 2016] to extreme events such as hurricanes. The types of resilience measures appropriate for chronic or frequent events may be smaller in scale and lower in cost than for extreme events. Yet, the accumulated benefits over time can be significant, and may justify a larger investment than if extreme events alone are the basis for resilience planning.

Decision makers should also take into account emergency response and recovery costs when planning resilience measures. These costs include debris removal and cleanup costs for collection, processing, and disposal of debris materials; emergency use of public facilities (e.g., schools, hospitals, libraries, elder care facilities); public services (e.g., police, fire); public utilities disruption to service and users; and infrastructure (e.g., energy, transportation, wastewater, water supply) [USACE, 2015].

Many climate hazard exposure situations could be addressed through a single solution, but the “multiple lines of defense” approach allows for efficient and cost-effective resilience implementation. The multiple lines of defense approach often includes a mix of management, temporary, structural and nature-based, and nonstructural measures in order to deliver performance and resilience over the intended project lifecycle [e.g., Naval Facilities Engineering Command 2017, USACE 2015]. This approach also provides redundancy and robustness to multiple and compound hazards.

To illustrate how resilience measures might be considered for DoD installations, we apply typical hazards included in the DCAT analysis to a representative installation with features typical of the three Departments within DoD. Two cases are presented in Appendix 2: 1) a base case with historical extreme events, and 2) a future condition representative of a lower end-of-century climate scenario or a higher mid-century climate scenario. Each case is accompanied by a figure representing the installation features, locations of hazards, and asset categories affected. Additional information on these categories of resilience measures and costs (where available), can be found in Appendix 3 and Pinson et al. [2020].

ARMY

Identifying the climate hazards to which Army installations are most exposed is the first step in addressing the potential physical harm, security impacts, degradation in readiness, and increased humanitarian deployment needs resulting from global climate change [DA, 2020]. Critical next steps include the determination of sensitivity of exposed installations and the identification and implementation of actions and measures that can be used to increase resilience and therefore reduce the consequences of exposure to climate change (Figure 2).

The DCAT results for the Army indicate that exposure to drought is the dominant climate hazard. The Army installations in the DCAT have a wide geographical spread, with installations in all the areas where either long-term aridity or recurring short-term drought are anticipated to increase. These two different sources of drought exposure may require different kinds of adaptation to reduce vulnerability. Army installations are also located in areas subject to coastal and riverine flooding, heat, wildfire, and land degradation, including permafrost thaw in Alaska.

The planning and implementation of resilience measures for extreme weather and climate change for the Army is governed by the Army Climate Resilience Handbook [Pinson et al., 2020] and applicable Unified Facilities Criteria (UFC) [DoD, 2020b and 2020c]. Standards such as American Society of Civil Engineers (ASCE) 7, Minimum Design Loads for Buildings and Other Structures, and ASCE 24, Flood-Resistant Design and Construction [ASCE, 2017 and 2015] also guide flood risk reduction planning and design. Recent additions addressing climate resilience include ASCE Manual of Practice 140, Climate-Resilient Infrastructure: Adaptive Design and Risk Management [ASCE, 2019].

NAVY

Like Army, identifying the climate hazards to which Navy installations are most exposed is the first step in addressing the potential physical harm, security impacts, degradation in readiness, and increased humanitarian deployment needs resulting from global climate change [e.g., Navy 2020]. Critical next steps include determining the sensitivity of exposed installations and identifying implementing actions and measures that can be used to increase resilience and therefore reduce the consequences of exposure to climate change [Naval Facilities Engineering Command, 2017].

The Navy installations in the DCAT are primarily coastal, and some of these have a high degree of exposure to sea level rise. Many, however, do not have high exposure due to location above the highest projected water surface elevation, location within protected harbors or river mouths, or location in highly developed urban areas. Consequently, the DCAT results for Navy indicate that exposure to drought is the dominant climate hazard across the entire portfolio, with inland installations in the U.S. Southwest or in subtropical ROW locations facing increased exposure to long-term aridity or recurring short-term drought. These two different sources of drought exposure may require different kinds of adaptation to reduce exposure where installations are sensitive to this exposure.

The planning and implementation of resilience measures for extreme weather and climate change for Navy is governed by the Climate Change Planning Handbook [Naval Facilities Engineering Command [2017] and applicable Unified Facilities Criteria [e.g., DoD 2019, 2020b]. Standards such as American Society of Civil Engineers (ASCE) 7, Minimum Design Loads for Buildings and Other Structures, and ASCE 24, Flood Resistant Design and Construction [ASCE, 2017 and 2015] also guide flood risk reduction planning and design.

Recent additions addressing climate resilience include ASCE Manual of Practice 140, Climate-Resilient Infrastructure: Adaptive Design and Risk Management [ASCE, 2019].

AIR FORCE

As for Army and Navy, identifying the climate hazards to which Air Force installations are most exposed is the first step in addressing the potential physical harm, security impacts, degradation in readiness, and increased humanitarian deployment needs resulting from global climate change [e.g. Department of the Air Force 2020]. Critical next steps include the determination of sensitivity of exposed installations and the identification and implementation of actions and measures that can be used to increase resilience and therefore reduce the consequences of exposure to climate change (Figure 2).

The DCAT results for Air Force indicate that exposure to drought is the dominant climate hazard. The Air Force installations in the DCAT are abundant in the U.S. High Plains, the U.S. Southwest, the U.S. Southeast, the Caribbean and subtropical Pacific, all areas where either long-term aridity or recurring short-term drought are anticipated to increase. These two different sources of drought exposure may require different kinds of adaptation to reduce exposure to drought where installations exhibit sensitivity to drought.

The exposure to drought also contributes to an increase in wildfire exposure across all epoch-scenarios for Air Force installations. Wildfire risk is the result of three important variables: protracted dry climate, availability of fuels, and human activity. The importance of fire management is evident not only through the development of a Fire Science Strategy [DoD 2014c], but also by the establishment of the Air Force Wildland Fire Branch (AFWFB) in 2012.

The planning and implementation of resilience measures for extreme weather and climate change for Air Force is governed by Air Force Civil Engineer Severe Weather/Climate Hazard Screening and Risk Assessment Playbook [Department of the Air Force 2020] and applicable Unified Facilities Criteria [e.g., DoD 2019, 2020b]. Standards such as American Society of Civil Engineers (ASCE) 7, Minimum Design Loads for Buildings and Other Structures, and ASCE 24, Flood Resistant Design and Construction [ASCE, 2017 and 2015] also guide flood risk reduction planning and design. Recent additions addressing climate resilience include ASCE Manual of Practice 140, Climate-Resilient Infrastructure: Adaptive Design and Risk Management [ASCE, 2019].

DEEPER DIVE: RIVERINE AND COASTAL FLOOD RISK REDUCTION

Riverine and coastal flood risk reduction begin with knowledge of past exposure, significant trends, nonstationarities that could alter those trends, and projections of future changes (e.g., increasing precipitation, rising sea level) that could impact those changes. Tidally influenced locations may also experience compound flood events with storm surge and precipitation [Zchleischler et al., 2020; Raymond et al., 2020, Wahl et al., 2015]. Coastal flooding results when ocean water inundates land that is not typically inundated during the annual tidal cycle. Coastal flooding is caused by extreme high water events that result from storm surge, waves, and tides that push saltwater inland. Coastal flooding is exacerbated by sea-level rise, which is especially problematic for relatively flat coastal plains where small increases in sea surface elevation allow for large increases in areas flooded.

The DCAT coastal flooding hazard category (Figures 1214 and 15) relies on two indicators of coastal flooding: coastal inundation and coastal erosion (see Appendix 1 for details). The latter is a static indicator, while the former is the percent area of the installation inundated, equivalent to the 1% AEP coastal flood elevation for the base scenario modified for future epochs by the DRSL database lowest and highest sea level scenarios. The DCAT riverine flooding hazard category relies on five indicators. These include percent installation area inundated under the 1% AEP flood elevation, with future flood extent represented by adding 2 ft (for 2050) and 3 ft (for 2085), extreme precipitation days, a flood magnification factor based on the 10% AEP flood, maximum 1-day precipitation, and maximum 5-day precipitation. Appendix 1 contains additional information.

DoD installation flood risk reduction is guided by a number of Unified Facilities Criteria (UFC), both general (e.g., UFC 2-100-01, Installation Master Planning [DoD 2019] and UFC 3-201-01, Civil Engineering [DoD 2020b]) and specific (e.g., UFC 3-260-01, Airfield and Heliport Planning). Navy facilities use the Climate Change Planning Handbook [Naval Facilities Engineering Command (2017]. Air Force relies on the Severe Weather/Climate Hazard Screening and Risk Assessment Playbook [Department of the Air Force 2020], while Army assessments use the Army Climate Resilience Handbook [Pinson et al., 2020; DA 2020a]. Standards such as American Society of Civil Engineers (ASCE) 7, Minimum Design Loads for Buildings and Other Structures, and ASCE 24, Flood Resistant Design and Construction [ASCE, 2017 and 2015] also guide flood risk reduction planning and design. Recent additions addressing climate resilience include ASCE Manual of Practice 140, Climate-Resilient Infrastructure: Adaptive Design and Risk Management [ASCE, 2019].

DoD has undertaken a number of climate-related studies through its Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP). These include general assessments such as the 2013 SERDP Report “Assessing Impacts of Climate Change on Coastal Military Installations: Policy Implications” and the DoD Regional Sea Level (DRSL) Scenarios [Hall et al., 2016], which are housed in a database containing over 1700 locations globally. The DRSL database provides a high-level assessment of projected water surface elevations at 2035, 2065, and 2100, including estimates of extreme water levels for several annual exceedance probability events.

Federal agencies, the private sector, academics, and non-governmental organizations have extensive experience with determining site-specific riverine and coastal flood delineations and resilience measures, now and in the future. SERDP and ESTCP have also sponsored a number of site-specific studies related to climate-impacted coastal and riverine flooding (Table 4). These types of studies can provide detailed information about climate exposure, sensitivity, and adaptive capacity at installations, which can supplement the screening-level information provided in the DCAT. Appendix 3 contains additional information on resilience measures for riverine and coastal flooding, including estimated costs, where available.

Table 5. Examples of SERDP and ESTCP site-specific studies related to climate-impacted coastal and riverine flooding.

Project #	Principal Investigator	Organization	Title	Description
RC19-1389	Simon S.-Y. Wang	Utah State University	Useful Prediction of Climate Extreme Risk for Texas-Oklahoma at 4–6 Years	This project develops a novel combination of large-scale climate diagnostics and storm-scale simulations: (a) examining the climate/ocean controlling factors for the spring rainy season and then applying this understanding to evaluate the multi-year prediction produced by an earth system model and (b) conducting fine-resolution downscaling to add detailed simulations of storm characteristics and to derive extreme-weather metrics that are useful to installation managers.
RC-2336	Jeffrey Donnelly	Woods Hole Oceanographic Institute	Impacts of Changing Climate on Pacific Island-Based Defense Installations	The objective of this project is to provide probabilistic information on potential climate-related threats for DoD installations across the Pacific over the next century, including those that might arise from hydrological changes, sea-level change, and changes in tropical cyclone activity.
RC-2514	Yonas Demissie	Washington State University	Linked Rainfall and Runoff Intensity-Duration-Frequency in the Face of Climate Change and Uncertainty	The primary objective of this project was to revise and update storm and flood intensity-duration-frequency (IDF) relationships (or curves) for selected military installations by considering changes in the past and future storm and flood events, effect of snowmelt, and modeling and data uncertainties.
RC-2515	Anna Wagner	USACE Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory	Changes in Climate and Its Effect on Timing of Snowmelt and Intensity-Duration-Frequency Curves	The objectives are to (1) investigate the timing of and intensity of snow accumulation, snowmelt, and runoff for historical and future climate scenarios at regional and watershed scales and (2) produce current and future IDF runoff curves for the study locations.
RC-2516	Casey Brown	University of Massachusetts, Amherst	Climate-Informed Estimation of Hydrologic Extremes for Robust Adaptation to Non-Stationary Climate	This project looked at the challenges and advances in design of infrastructure for floods under non-stationarity.

Project #	Principal Investigator	Organization	Title	Description
RC-2517	Kenneth Kunkel	North Carolina State University	Incorporation of the Effects of Future Anthropogenically-Forced Climate Change in Intensity-Duration-Frequency Design Values	The overriding objective of this project is to develop a framework for incorporating the potential impact of future climate change into the IDF values of heavy precipitation.
RC-2513	Dennis Lettenmaier	University of California, Los Angeles	Effects of Global Change on Extreme Precipitation and Flooding: New Approaches to IDF and Regional Flood Frequency Estimation	The overarching science/applications question this research will address is how can engineering design criteria associated with extreme precipitation and flooding be adjusted to reflect observed and projected effects of climate change in a manner that is consistent with standards of engineering practice?
RC-2546	Mark Wigmosta	PNNL	Next-Generation Intensity-Duration-Frequency Curves Considering Spatiotemporal Non-Stationarity in Climate, Intense Precipitation Events, and Snowmelt	This project will use physics-based modeling and data analysis to develop and demonstrate a scientifically defensible methodology for creating next-generation IDF curves with direct consideration of intense precipitation events and snowmelt under conditions of climate non-stationarity.
RC-2644	John Marra	NOAA NCEI	Advancing Best Practices for the Analysis of the Vulnerability of Military Installations in the Pacific Basin to Coastal Flooding under a Changing Climate	Advance the practical application of statistical and other analytical techniques that can be used to assess the vulnerability of built and natural environments to the impacts of coastal flooding in a changing climate.
RC-2204	Casey Brown	University of Massachusetts Amherst	Decision-Scaling: A Decision Framework for DoD Climate Risk Assessment and Adaptation Planning	The objective of this project is to develop and evaluate a framework for assessing DoD relevant climate change risks and for incorporating climate information into decision making.
RC-2205	Christopher Castro	University of Arizona	Assessing Climate Change Impacts for DoD Installations in the Southwest United States During the Warm Season	The overarching research objective was to evaluate how warm season extreme weather events in the Southwest will change with respect to occurrence and intensity.

Project #	Principal Investigator	Organization	Title	Description
RC-2334	Curt Storlazzi	USGS Pacific Coastal and Marine Science Center	The Impact of Sea-Level Rise and Climate Change on Department of Defense Installations on Atolls in the Pacific Ocean	The primary goal of this joint investigation was to determine the influence of climate change and sea-level rise on wave-driven flooding and the resulting impacts to infrastructure and freshwater resources on atoll islands.
RC-2335	John Marra	NOAA National Climatic Data Center	Advancing Best Practices for the Formulation of Localized Sea-level Rise/Coastal Inundation Extremes' Scenarios for Military Installations in the Pacific Islands	The objective of this project was to develop guidance that outlines best practices and methodologies that can be used to formulate scenario-dependent probabilistic estimates of future extreme sea levels under a changing climate and apply it to select DoD sites in the Pacific Islands.
RC-2340	Stephen Gingerich	USGS Pacific Islands Water Science Center	Water Resources on Guam: Potential Impacts and Adaptive Response to Climate Change for DoD Installations	(1) Provide basic understanding about water resources for DoD installations on Guam. (2) Assess the resulting effect of sea-level rise and a changing climate on freshwater availability, on the basis of historical information, sea-level rise projections, and global-climate model temperature and rainfall projections.
RC-2709	Simon (Shih-Yu) Wang	Utah State University	Useful Prediction of Climate Extreme Risk for Texas-Oklahoma at 4–6 Years	This limited-scope project tackled the challenge of predicting water-cycle extremes in Texas and Oklahoma as severe as the 2015 and 2016 floods beyond seasonal timescale.

DEEPER DIVE: WILDFIRE RESILIENCE CONSIDERATIONS

Wildfire risk is the result of three important variables: protracted dry climate (drought and flash-drought, discussed in previous sections), availability of fuels, and human activity. Fire risk days refers to the number of days per year in which sufficiently dry conditions occur within a region, with the measure being used taking into account prior precipitation and soil moisture conditions. Extended dry weather conducive to wildfire initiation and spread is considered the most significant contributing factor to wildfire vulnerability.

DoD [2014c] notes that "Fire is a fact of life on a military installation," due in part to training and testing activities that serve as ignition sources, but also because of the vast tracts of land under DoD management. These lands include more than five million acres of forested ecosystems, over seven million acres of sagebrush, over ten million acres of desert, and about one million acres of annual and perennial grasslands [DoD 2014c]. The importance of fire management is evident not only through the development of a Fire Science Strategy [DoD 2014c], but also by the establishment of the Air Force Wildland Fire Branch (AFWFB) in 2012.

Fire science and fire management has been an area of interagency collaboration since the 1990s, when Congress directed the formation of the Joint Fire Science Program between the Department of the Interior (DOI) and the U.S. Department of Agriculture's (USDA) Forest Service (USFS). Similarly, the AFWFB represents collaboration with U.S. Fish and Wildlife Service, Colorado State University, the DOI's Bureau of Land Management, and the University of Montana.

The USDA's Forest Service (USFS) is an authoritative source of information about wildfires, including their prevention, mitigation, and costs. They noted in a 2015 report [USFS, 2015] that the fire season was now on average 78 days longer and burns twice as many acres annually than in 1970 as a result of climate change, often in areas not historically affected by wildfire.

Under increasingly dry conditions, range activities in areas with dense (more than half) wildland vegetation will have increased potential to initiate wildfire compared to developed areas, barren ground, or other disturbed areas outside of the Northeast and Midwest. Naturally ignited wildland fires can cause damages, and at the same time reduce hazardous fuels and the likelihood of future high severity fires while improving the resilience to landscapes, especially those ecosystems adapted to frequent fire [USFS, 2017].

Wildfires may pose a significant risk to military locations [Beavers, 2007, Figure 3] with implications for the timing and type of training activities at a given location [Galbraith, 2011]. Numerous examples of wildfire ignition due to live-fire training during dry conditions exist [e.g., Panzino, 2018; Galbraith, 2011]. Infrastructure may be vulnerable to damage from wildfires that originate on or off an installation, although the clustering of infrastructure within installation for other reasons enhances the defensibility of the space. An additional concern is management of smoke from prescribed and wildland fires both on and off base [Mickler, 2014].

Preparedness and suppression are major features of wildfire mitigation, whereas vegetation and watershed management are critical in post-fire recovery and restoration (USFS, 2015). Management measures to reduce installation fire risk include improved preparedness and recovery through understanding how seasonal risk evolves and knowing which conditions favor wildfire ignition and spread at a particular installation. Table 5 outlines fire risk categories and training restrictions.

Table 6. Fire Danger Categories and Training Restrictions (White et al., 2019).

Fire Danger Condition	Expected Fire Behavior	Training Restrictions	Fire-Fighting Detail Requirements	Derived KBDI*
Green	Fires are difficult to start and do not burn with vigor. Fires can easily be controlled using direct attack.	None	None	0–300
Amber	Fires start easily and may burn quickly through grass and shrub fuels. Fires can be controlled using direct attack, but in some circumstances, may require indirect attack methods.	No aerial flares outside the live-fire training areas Pyrotechnics must be used on roadways, tank trails, or barren areas.	None	300–600
Red	Fires start easily, move quickly, burn intensely, and may be difficult to control.	No pyrotechnics, incendiary munitions, tracers	10-person fire-fighting detail required On-call helicopter required on 20-minute standby	600–750
Black	Fires start very easily and are impossible to control.	No live-fire training No pyrotechnics Non-live-fire training must be authorized by the Senior Mission Commander.	None	750–800
*Keetch-Byram Drought Index (KBDI) is a measure of soil moisture deficit based on mean annual temperature and precipitation. The index has a maximum value of 800, with a value > 600 indicating very dry conditions				

CONCLUSIONS AND NEXT STEPS

Exposure to climate change hazards is not a new problem for DoD installations, but the nature and severity of this problem is changing. The costs and consequences for failing to adapt are increasing, as are the benefits of improved resilience. The DCAT provides an important new capability for assessing and responding to these threats. The DCAT provides screening-level information on exposure to current and projected future climate hazards at 1055 CONUS, AK, and HI. A separate DCAT for the 336 selected DoD installations in the ROW. Using the best available and actionable science, the DCAT allows the user to evaluate climate change exposure hazards across the installation portfolio, across individual Departments and regions, and at individual installations.

The geospatial framework of the DCAT provides Departments and services with a consistent method to evaluate exposure to climate hazards across the portfolio. This enables the user to think strategically about which missions, assets, and resources for which risk can be reduced, or where they might need to be relocated to reduce exposure risk while enhancing security and readiness at the national and global scale.

For the ROW installations, this framework includes hydroclimate variables analogous to those present in the DCAT for CONUS, AK, and HI. A contract was awarded to obtain consistent topographic mapping for the ROW installations, and a method developed to produce riverine and coastal flood extent mapping using comparable techniques. When the flood delineations are competed, the ROW analysis will be conducted. The results for the ROW analysis will be provided in a separate report.

The screening-level DCAT results indicate that:

1. Climate hazard exposure across all installations increases through time for scenarios of both lower and higher warming.
2. Climate hazard exposure is more pronounced for the later epoch (2085) and the scenarios of higher warming.
3. For most hazards, there is close similarity in values between the 2085 lower and 2050 higher conditions.
4. Differences in the degree of exposure to hazards are similar across both scenarios until mid-century, when they diverge.
5. Hazards more directly tied to temperature change (e.g., heat, drought, wildfire) show larger increases in exposure under the 2085 higher scenario than other hazards.
6. Slower increases in exposure with time are evident for other hazards (e.g., coastal flooding, energy demand, land degradation).
7. Drought is the dominant indicator across all epoch-scenarios for DoD and for the individual Departments.
8. There is no epoch-scenario combination under which installation exposure to climate hazards is projected to decrease.

Exposure to climate hazards is broadly similar across the Departments within CONUS, Alaska (AK), and Hawaii (HI). The Air Force installations are often located in areas where long-term aridity or recurring short-term drought are anticipated to increase, driving more wildfire risk. Army installations have a similar pattern of exposure but are more frequently located in areas where exposure to heat, drought, and riverine flooding increase with time. The Navy has a significant exposure to coastal and riverine flooding, but there is great variability: some installations are highly exposed, and some are not. Like other Departments, the Navy’s drought exposure increases stepwise based on the time and scenario.

Across the rest of the world (ROW) installations, the dominant hazard across all the Departments is also drought, and heat is also a common concern. Navy and Air Force ROW installations have large exposure to coastal and riverine flooding, and to land degradation. Army ROW installations in the DCAT, however, are predominantly located in inland urban environments where coastal erosion, coastal inundation, and riverine flood exposure is low.

For all DoD installations, rising temperatures will increase exposure to a wide range of hazards that can directly impact military readiness, including heat-related health problems and adverse effects on military training and testing that may cause changes to soldier readiness due to changes in the availability or timing of days when conditions are suitable.

The information provided by the DCAT is largely in agreement with previous studies with respect to the installations at greatest risk from changes in temperature, precipitation, sea-level rise, and riverine flooding. Unlike previous studies, the DCAT provides a consistent framework for the addition of more installations, additional indicators, and hazard categories. Thus, the user is able to both expand and refine the knowledge available to them as additional data become available.

Identifying the climate hazards to which DoD installations are most exposed is the first step in addressing the potential physical harm, security impacts, degradation in readiness, and increased humanitarian deployment needs resulting from global climate change. Site-specific information can be difficult and expensive to obtain. Fortunately, DoD has undertaken a number of site-specific climate-related studies through its Strategic Environmental Research and Development Program (SERDP, 2013) and the Environmental Security Technology Certification Program (ESTCP).

Assessing the sensitivity of an installation to its climate hazard exposure is the next step. Results from these and similar studies can inform assessments of sensitivity at installations for which DCAT has identified climate hazard exposure. Once sensitivity has been determined, installation managers can begin to identify and plan for actions and measures that can be used to increase resilience and therefore reduce the consequences of exposure to climate change.

Examples are provided through the use of a notional installation with features typical of the three Departments within DoD. Two cases are presented in Appendix 2: a base case with historical extreme events and a future condition representative of a lower end-of-century climate scenario or a higher mid-century climate scenario. Each example includes the impacted asset categories of facilities, infrastructure, operations, and associated services as used in SLVAS [DoD 2018], as well as a list of appropriate resilience measures and their rough-order-of-magnitude costs, based on information contained in Appendix 3.

Climate change exposure and impacts do not stop at the installation boundary. The surrounding communities map provide essential energy, water, transportation, communication, emergency, and other services to the installation. Military and civilian personnel may live in the surrounding communities. Consequently, the climate exposure resilience of the surrounding communities is an essential component of installation resilience. The DoD Office of Local Defense Community Cooperation (https://oldcc.gov/program-overview), formerly known as the Office of Economic Adjustment, provides grants to local communities to undertake investments in public services and infrastructure to support the readiness and resilience of installations.

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APPENDIX 1: DETAILED DESCRIPTION OF CLIMATE HAZARDS CONSIDERED

GENERAL CIRCULATION MODELS

Different model outputs were used in three geospatial subdomains because this project was designed to answer high-level screening questions only, not closely resolved questions about either historical climate or projected future possible climate; therefore, the project used consistent simulation sets within each subdomain. To take best advantage of the already completed, most recent, consistent simulations for each subdomain, different output sets of climatology downscaled at different times in the past using different methods and different sets of GCMs were used. In each case, these are the most complete and consistent model outputs at the finest horizontal grid spacing for each subdomain available at the time of this project's genesis. The GCMs used in the analysis are presented in Table 1-1.

Table 1-1. Climate source data used in the three geospatial regions.

Region	**Source for Temperature and Precipitation**			**Source for Relative Humidity (RH)**	
CONUS	ACCESS1-0 ACCESS1-3 bcc-csm1-1-m bcc-csm1-1 CanESM2 CCSM4 CESM1-BGC CESM1-CAM5 CMCC-CM CMCC-CMS CNRM-CM5	CSIRO-Mk3-6-0 EC-EARTH FGOALS-g2 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GISS-E2-H GISS-E2-R HadGEM2-AO HadGEM2-CC HadGEM2-ES	inmcm4 IPSL-CM5A-LR IPSL-CM5A-MR MIROC5 MIROC-ESM-CHEM MIROC-ESM MPI-ESM-LR MPI-ESM-MR MRI-CGCM3 NorESM1	ACCESS1-0 ACCESS1-3 bcc-csm1-1-m bcc-csm1-1 CanESM2 CCSM4 FGOALS-g2 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GISS-E2-H GISS-E2-R	HadGEM2-AO HadGEM2-CC HadGEM2-ES inmcm4 IPSL-CM5A-LR IPSL-CM5A-MR MIROC5 MIROC-ESM-CHEM MIROC-ESM MRI-CGCM3 NorESM1-M
AK and HI	ACCESS1-3 CanESM2 CCSM4 CSIRO-Mk3-6-0 GFDL-ESM2M	HadGEM2-ES inmcm4 MIROC5 MPI-ESM-MR MRI-CGCM3			
ROW	ACCESS1-0 bcc-csm1-1 CanESM2 CCSM4 CESM1-BGC CNRM-CM5 CSIRO-Mk3-6-0 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M inmcm4	IPSL-CM5A-LR IPSL-CM5A-MR MIROC5 MIROC-ESM-CHEM MIROC-ESM MPI-ESM-LR MPI-ESM-MR MRI-CGCM3 NorESM1-M bnu-esm			

CLIMATE HAZARD CATEGORY: DROUGHT

Drought represents a drier climate condition than is typical for a given location and time of year. It may be the result of a lack of precipitation, a temperature-driven increase in evapotranspiration, or some combination of both factors. These changes may have an acute (sharp and sudden) onset, and may last months to years (sometimes many decades). Droughts may end gradually or suddenly with large precipitation events. The indicators for drought are intended to capture these different facets of drought.

The effects of drought can vary regionally and include reduced water supplies for municipal, industrial, or agricultural purposes; decreased stream flows for navigation and energy generation; decreased water quality; loss of soil moisture and therefore, vegetation stress and die-off; and increased wildfire risk. Because droughts can result in widespread vegetation die-off, the ground surface may be exposed to increased erosion by wind and water (when next it rains).

Drought may affect installation mission and readiness by reducing surface water supply quantity and quality. Drought-induced drying and killing of vegetation can make the land surface vulnerable to erosion when disturbed, potentially limiting vehicle maneuvers, low-level rotary wing flight operations, and other training and testing activities, while also making the landscape more susceptible to wildfire. Droughts are often correlated with clear skies and higher temperatures, increasing the likelihood of heat risk during field activities and escalating energy demand for cooling. Larger WOWA scores for this hazard category indicate greater exposure to the effects of drought. The indicators used to measure drought exposure are shown in Table 1-2.

Table 1-2. Five indicators of drought used to measure the evolution of drought exposure.

Indicator	Importance Weight	Justification
ARIDITY (#105): Aridity is a change in the nature of an installation's climate toward increasingly drier conditions. Increases in aridity indicate essentially permanent reductions in available surface water. It also indicates significant reductions in soil moisture, and therefore changes in vegetation type/density and wildfire risk. Importantly, changes in aridity are not strongly correlated with changes in any of the other drought indicators.	1.5	This indicator is assigned a large weight because it measures a potentially permanent change in water availability at an installation.
MEAN ANNUAL RUNOFF (#108C): Mean annual runoff is the average annual discharge (volume of water) from the entire watershed upstream of an installation for the largest river in this watershed. Changes in this value are symptomatic of increases or reductions in annual surface water supply. Changes in water supply for large rivers may be independent of drought status at an installation.	1.5	This indicator is assigned the same weight as Aridity since reductions in mean annual runoff signal a long-term, permanent reduction in available surface water supplies.

Indicator	Importance Weight	Justification
FLASH DROUGHT FREQUENCY (#101): This measures the change in frequency of droughts that intensify quickly (< 2 months). Increasing flash drought frequency increases risks.	1.4	This indicator is assigned a large weight because it represents an abrupt shift from wet to dry climate that carries with it acute impacts to water supply, reductions in soil moisture, and consequent limitations on training and testing activities.
DROUGHT YEAR FREQUENCY (#102): Drought year frequency is the average percentage of years in which a location is in moderate more extreme drought. It is a measure of year-to-year variability in drought status.	1.2	This indicator is assigned a lower weight because longer term drought is often more predictable than Flash Drought Frequency. These droughts pose a longer-term threat to water supplies, ecosystem health and wildland fire risk and more sustained risk to installation mission and readiness.
CONSECUTIVE DRY DAYS (#106): Consecutive dry days refers to the mean annual maximum number of consecutive days with less than 0.01" (trace) of precipitation. It is a measure of short-term variability in precipitation.	1	Changes in this indicator reflect increasing daily variability in precipitation that may result in minor disruptions to installation activities. This indicator is assigned the smallest weight.

CLIMATE HAZARD CATEGORY: COASTAL FLOODING

Coastal flooding results when ocean water inundates land that is not typically inundated during the annual tidal cycle. Coastal flooding most commonly occurs in response to storm events when on-shore winds push seawater up against the coast (storm surge) and waves, so that the water surface is elevated and salt water is pushed inland. Coastal flooding is exacerbated by sea-level rise, which is especially problematic for relatively flat coastal plains where small increases in sea surface elevation allow for large increases in areas flooded.

Sea-level change is not uniform globally: the elevation at a particular location is influenced by multiple factors, including coastal and sea floor topography, the presence of currents, and whether or not the land surface itself is rising or falling. While in most populated coastal regions, net sea levels are rising relative to coastal elevations, some areas are currently experiencing net sea-level declines. Consequently, projected impacts due to sea-level change must be determined locally to an installation.

Coastal inundation and erosion are threats to installations located along the Nation's shorelines. Projected changes in sea level, coupled with coastal storms, are likely to increase the area subject to damage during storm events. However, Indicators 802 (Hurricane Frequency) and 806 (Hurricane Wind Greater than 50 Knots) provide some historical context for the impacts of large hurricanes (called tropical cyclones or typhoons outside the Atlantic Basin). However, with respect to storm surge, extra-tropical storms (e.g., nor'easters) are also a very significant source of damage and these are not reflected in the hurricane data but are included in tide gauges.

The potential impacts of sea-level change include infrastructure loss or damage, degradation of mission capabilities, loss of training and testing lands, loss of transportation facilities and means, habitat damage, loss of life, and salinization of shallow aquifers. Where sea levels rise, coastal river elevations may also increase, increasing riverine flood risk in coastal areas.

Larger WOWA scores for this hazard category indicate greater exposure to coastal flooding. Two indicators represent coastal flood exposure as shown in Table 1-3.

Table 1-3. Two indicators used to represent coastal flood exposure.

Indicator	Importance Weight	Justification
COASTAL FLOOD EXTENT (#201): Coastal flood extent is the area of inundation given the 1% annual exceedance probability (AEP) coastal flood height. This is a measure of inundation during extreme events. The projected change in relative sea-level data come from the DoD's CARSWG DRSL Database lowest and highest sea level scenarios. A simple bathtub model was used to translate these elevation changes into areas of inundation using a digital elevation model (DEM, topographic map). It is a measure of the amount of potential damage resulting strictly from sea-level rise.	1.5	This indicator is weighted highest. Changes in this indicator reflect permanent changes in area inundated, which could correspond to areas where damages may be high and mitigation measures costly.

COASTAL EROSION (#202): Coastal erosion is a measure of an undeveloped coastline's susceptibility to erosion due to changing sea level and wave action. Coastal erosion is the probability of erosion based on data from the USGS Coastal Vulnerability Index Database. This indicator is static (does not change with time).	1	This indicator is weighted lowest. Coastal erosion is only a significant problem in some areas.

CLIMATE HAZARD CATEGORY: RIVERINE FLOOD RISK

Increases in precipitation, especially increases in the magnitude and/or frequency of extreme precipitation events, are projected in most portions of the U.S. under a warming climate. The most important consequence of excess precipitation is flooding. Flooding can occur when rivers overflow their banks or when precipitation is so heavy that the existing drainage/flood runoff system is overwhelmed. Flooding may be a slow moving disaster, such as the gradual downstream movement of a spring runoff flood peak from mountainous areas under certain conditions, or very rapid, as when extreme quantities of precipitation falling in one area over a relatively short amount of time produces a flash flood. Compound flood events, such as a stalled tropical storm dumping rain on previously saturated ground, can produce floods in areas that have not previously flooded. Development (including impervious surfaces), insufficient stormwater systems, wildfire, and deteriorated flood infrastructure can exacerbate flood risk.

In addition to damaging infrastructure, equipment, materiel, vehicles and aircraft, floodwaters may disrupt access to and from installations; cause utility closure; contribute to land degradation; impact training and testing activities, including use of rangelands; and damage off-base housing and support systems.

Larger WOWA scores for this hazard category indicate greater exposure to riverine flooding. The indicators used to measure riverine flood risk exposure are shown in Table 1-4.

Table 1-4. Five indicators used to represent the changes in riverine flood risk exposure.

Indicator	Importance Weight	Justification
FLOOD EXTENT (RIVERINE) (#301): The current flood extent for the installation boundary is based on Federal Emergency Management Agency (FEMA) National Flood Hazard Layer for the 1% annual exceedance probability (AEP) event, or 2-D hydrologic and hydraulic modeling on a 10 m. digital elevation model where FEMA data are lacking. Projected changes in flood extent were modeled by adding 2 ft (for 2050) and 3 ft (for 2085) freeboard to the current elevation of the 1% AEP event, and mapping the area of inundation that would result. This indicator is a measure of the potential inundation extent during a flood event.	1.5	This indicator is given the highest weight because percent of area in a 1% AEP floodplain is considered the strongest indicator of current and future flood risk. This indicator is a measure of regional flood risk that integrates both direct precipitation and flooding during snowmelt runoff.
EXTREME PRECIPITATION DAYS (#305): This refers to the average annual number of days in which precipitation in the future is projected to exceed the amount that occurred 1% of the days in the historic period. This provides a measure of future increases in precipitation intensity that is relative to current conditions: the definition of an extreme precipitation day will be different in different areas of the U.S. This indicator can be used to assess how frequently heavy precipitation events may disrupt on- and off-base activities, and potentially overwhelm existing flood risk management infrastructure. Larger indicator values equate to increased exposure.	1.4	This indicator is given the next highest weight because it reflects a dual threat. Extreme precipitation events carry two different implications for flood impact: it can influence flood risk at the watershed scale, but also pose an immediate flash flood risk for an installation.

Indicator	Importance Weight	Justification
FLOOD MAGNIFICATION FACTOR (RIVERINE) (#302): Flood magnification factor measures the percent change in flood runoff (daily flow exceeded 10% of the time) in the future compared to the historic period. Values greater than 1 indicate an increase in flood flows in the future while values less than 1 indicate a decrease. Flood factor is calculated for the watershed upstream of the downstream-most point on the installation. Larger numbers indicate increased exposure.	1.3	This indicator is an important measure of how much larger the largest riverine floods may be in the future relative to today. It has important implications for flood risk management. It is rated slightly less in importance than flood extent (riverine) and extreme precipitation days because the information carried in this indicator partially duplicates the information of those two indicators.
MAXIMUM 1-DAY PRECIPITATION (#303): This is the average annual maximum 1-day precipitation total for each epoch-scenario. The intensity of the 1-day event is a particularly good metric for estimating changes in flash and urban flooding exposure. Larger numbers indicate increased exposure.	1	Because this indicator is highly correlated with maximum 5-day precipitation (#304), the weights of both were adjusted down so that local precipitation does not contribute excessively to flood risk compared to other indicators.
MAXIMUM 5-DAY PRECIPITATION (#304): This is the average annual maximum precipitation total for any 5-day period. Unlike 1-day precipitation, this measure is able to take into account the effect of saturated soils on exacerbating flood risk by increasing the share of precipitation that runs off once the soil is saturated. Larger numbers indicate increased exposure.	1	Because this indicator is highly correlated with maximum 1-day precipitation (#303), the weights of both were adjusted down so that local precipitation does not contribute excessively to flood risk compared to other indicators.

CLIMATE HAZARD CATEGORY: HEAT

Rising temperatures pose a direct and measurable risk to human health. Small increases in average temperature can result in significant increases in the frequency of temperature extremes, as well as contribute to increases in precipitation intensity and quantity, reductions in winter snowpack, increases in global mean sea level, increases in evapotranspiration, and changes to other processes. The rate of warming varies by geography, with higher rates of warming in Alaska, the Northwest, the Southwest, and the Northern Great Plains. Warming has been least in the Southeast. Rates of warming may vary by season. The rate of warming in the last decade appears to be accelerating, with the most recent average rate of 0.512°F per decade based on satellite observations.

Heat impacts are important for military readiness for a number of reasons. Climate change is anticipated to increase heat-related health problems, with even small climate changes resulting in increases in illness and death. Increases in temperature are anticipated to have significant effects on military training and testing, including an increase in the number of "black flag" (suspended outdoor activities) or fire hazard days (limiting live-fire activities); increases in the need for operational health surveillance; higher rates of heat-related mortality and morbidity; and reassessment of weapons system operations and deployment (including changes to soldier readiness due to changes in the availability or timing of days when conditions are suitable). Higher temperatures may also affect pilot readiness by limiting time in the cockpit while on the ground and by affecting aircraft lift on takeoff and landing. In addition, higher temperatures significantly increase the opportunity for vector-borne diseases: higher winter temperatures reduce winter vector mortality rates, while higher spring-fall temperatures extend the length of the breeding season, allowing for multiple reproductive cycles.

Larger WOWA scores for this hazard category indicate greater exposure to heat impacts. The five indicators used to measure the evolution of heat exposure are shown in Table 1-5.

Table 1-5. Five indicators used to represent the changes in heat risk exposure.

Indicator	Importance Weight	Justification
HIGH HEAT INDEX DAYS (#405): High humidity levels lower evaporation rates. The National Weather Service Heat Index[3] accounts for the way that temperature and humidity interact to impair thermoregulation. Index values > 91 indicate a threshold where impacts are likely to impact outdoor training and testing activities by limiting the amount of activity, shifting more of that activity to cooler parts of the day, and significantly increasing health risk.	1.7	This indicator is given the highest weight, because direct heat-related morbidity and mortality are significant concerns with direct seasonal impacts on readiness; these are exacerbated by high humidity conditions, which are captured by the Heat Index.
HIGH HEAT DAYS (#403): This is a measure of the gain in heat compared to current high temperatures. It identifies the locally significant, historical high temperature threshold (the high temperature that is exceeded only 1% of the time at a	1.3	This indicator is given the second largest weight because it addresses the magnitude of the most

[3] The DoD standard is the Wet Bulb Globe Temperature, but calculation of this index requires data that is not available from climate models.

given location), and assesses how frequently this threshold will be exceeded in the future.		extreme temperatures, which can damage infrastructure and impede aircraft operations.
5-DAY MAXIMUM TEMPERATURE (#402): This is a measure of absolute gain in maximum temperature. A 5-day window marks a significant impact on training and testing schedules.	1.2	This indicator is given the third largest weight because of the potential impact to training and testing schedules of a sustained high heat event.
DAYS ABOVE 95°F (#401): This is a count of the average number of days where the maximum temperature (daytime high) exceeds 95°F. This threshold is significant because it marks the point at which air temperature is approximately equal to body temperature, which makes it difficult for people to shed heat.	1.1	This measures extremes relative to a common threshold to facilitate comparison across regions. It is given a lower weight in part because there is information overlap between this indicator and others.
FROST DAYS (#404): A frost day is a day in which the minimum temperature gets below freezing (32°F), and therefore infrastructure may be subject to freeze-thaw cycles and some forms of construction need to be suspended.	1	This is given the lowest weight because this risk is anticipated to decline with time as winter temperatures warm, so it contributes less to exposure over time.

CLIMATE HAZARD CATEGORY: ENERGY DEMAND

Rising temperatures are expected to affect both energy demand and supply. Warmer winter temperatures may reduce demand for heating, although cold extremes are anticipated to continue to occur and resulting spikes in demand for energy for heating. Higher summer temperatures are anticipated to drive up energy demand for cooling residential, municipal, industrial, agricultural, and other buildings. This rising demand is anticipated to strain the U.S. energy grid at the same time that transmission is reduced due to reductions in power line transmission and transformer capacities, higher surface water temperatures in waters used to cool power plants and nuclear reactors, reduced renewable and thermo electric energy generating capacity, and at least regional reductions in water available for power generation, including hydropower and biofuels.

The DoD Roadmap identifies two areas of climate change concern related to energy: (1) changing building heating and cooling demand, which impacts installation energy intensity and operation costs and (2) disruption to and competition for reliable energy supplies. Larger WOWA scores for this hazard category indicate greater exposure to increases in energy demand requirements due to rising temperatures. The indicators used to measure energy demand exposure are shown in Table 1-6.

Table 1-6. Four indicators used to measure the changes in energy demand exposure represent the changes in heat risk exposure.

Indicator	Importance Weight	Justification
COOLING DEGREE DAYS (#502): A cooling degree day is the measure of the accumulated time above 65°F, the temperature above which buildings need to be cooled, as the sum of how many degrees above this threshold it gets each day. This indicator is a measure of the average sum of cooling degree days per year for each epoch-scenario. Higher numbers indicate increased exposure.	1.7	This has the largest weight because it represents the change in the total energy demand for cooling, and therefore necessary added energy capacity.
5-DAY MAXIMUM TEMPERATURE (#504): This is a proxy (indirect) measure of peak summertime cooling energy demand. It is the average annual maximum temperature over 5 sequential days for each epoch-scenario. Larger numbers indicate increased exposure.	1.5	This gets the second largest weight because it represents critical peak energy demand during the highest heat events, and shortfalls in this area may result in brownouts/blackouts and spikes in heat-related mortality and morbidity.
HEATING DEGREE DAYS (#501): A heating degree day is the measure of the accumulated time below 65°F, the temperature below which buildings need to be heated, as the sum of how many degrees below this threshold it gets each day. This indicator is a measure of the average sum of heating degree days per year for each epoch-scenario. Higher numbers indicate increased exposure.	1.2	This has a lower weight because the aggregate demand for heating can likely be met with existing capacity in most areas in a warming world.
5-DAY MINIMUM TEMPERATURE (#503): This is a proxy (indirect) measure of peak wintertime heating energy demand. It is the average annual minimum temperature over 5 sequential days for each epoch-scenario. Larger numbers indicate increased exposure.	1	Cold spells and extreme cold are anticipated to continue to occur, but to occur less frequently, and therefore this represents the lowest energy demand risk.

CLIMATE HAZARD CATEGORY: WILDFIRE

Wildfires are uncontrolled fires that originate on or cross onto undeveloped areas, regardless of the cause (human or natural). Wildfires pose a significant and increasing threat to structures and communities intermingled with or immediately adjacent to vegetated areas (termed “wildlands,” which encompass all undeveloped areas including military ranges, grasslands, shrublands, barren lands, woodlands, and forests).

Wildfire may pose a significant risk to military bases, can impact the timing and type of training and testing activities on a given base, and can divert military resources to firefighting activities. There are numerous examples of live-fire activities igniting wildfires during dry conditions with both on- and off-base impacts. Finally, managing smoke from wildfires both on and off base is a significant concern: exposure to smoke outdoors (or even indoors if building air is unfiltered) can cause or exacerbate existing health problems (e.g., asthma, bronchitis, and cardiovascular problems).

Wildfire has three key components: climatological conditions favorable for ignition and spread; the presence of wildland vegetation, especially dense and multi-canopied vegetation; and a natural or human source of ignition. Larger WOWA scores for this hazard category indicate greater exposure to impacts from wildfire. The indicators used to measure wildfire exposure are shown in Table 1-7.

Table 1-7. Four indicators are used to measure the changes in wildfire exposure.

Indicator	Importance Weight	Justification
FIRE SEASON LENGTH (#604): Fire season length is the average annual number of days in which the Keetch-Byram Drought Index (KBDI) is > 600, indicating long-term arid conditions and dry coarse fuels. Vegetation becomes more flammable under prolonged dry conditions. The KBDI captures the accumulated moisture deficit for a given region over the course of a year. Values for the index decrease when precipitation occurs, and increase with number of days since the last precipitation event. An index value of 600 or greater indicates a prolonged period of aridity, which gives time for vegetation and soils to dry out. Consequently, the number of days with KBDI > 600 indicates the share of the year in which vegetation is already very dry and wildfires readily ignite and spread.	1.7	This indicator is given the highest weight because weather conditions that dry fuels and make them prone to ignition and wildfire spread are the most important factor in determining exposure to wildfire risk.
FLASH DROUGHT FREQUENCY (#101): This measures the change in frequency of droughts that intensify quickly (< 2 months). Because of their sudden onset, flash droughts can have very large impacts on agricultural yields, ecosystem health, and wildland fire risk if they occur in the growing season. In addition, for water supply systems with small storage volumes relative to inflow, flash droughts can result in rapid development of critical water shortages. Increasing flash drought frequency increases risks.	1.5	This indicator is given a large weight because it represents an abrupt shift from wet climate that promotes new vegetative growth to a dry climate that carries with it an acute increase in wildfire risk that may impact training and testing activities.

Indicator	Importance Weight	Justification
FUEL ABUNDANCE (#601): Fuel refers to vegetation that is unmanaged (e.g., not irrigated), which responds in concert with weather conditions. Fuel Abundance is the percent area of an installation and a 1-mile buffer around the installation that is in unmanaged wildland vegetation. THIS INDICATOR IS STATIC FOR ALASKA AND HAWAII.	1.3	This indicator is given a low weight because fuels rely on dry conditions to promote the ignition and spread of wildfires.
IGNITION RATE (#602): Humans are a major cause of wildfire ignition when they conduct activities in and close to vegetated areas (e.g., camping, grilling, operating machinery, smoking, burning trash and also military training and testing activities). Ignition rate is the population density in proximity to an installation. Human-caused ignitions are assumed to scale with the density of people in the vicinity of wildland vegetation, and therefore the frequency with which people use that space for recreation and other activities. THIS INDICATOR IS STATIC FOR ALASKA AND HAWAII.	1.1	Humans are only one cause of wildfire ignitions, and that rate varies regionally and is easily modulated through access management on public lands. Consequently, this gets the lowest weight.

CLIMATE HAZARD CATEGORY: LAND DEGRADATION

Land degradation refers to long-term changes in land use, land cover, soil moisture, permafrost, and other processes that result in soil loss, reduced soil fertility, coastal erosion, land subsidence, a reduced ability of the land to support native plants and animals, and reduced agricultural yields. Soil loss in areas that could be classified as arid forms the core of the old definition of desertification. Newer definitions stress the consequences of human activity in causing land degradation under a broader range of climate conditions.

A land’s vulnerability to degradation when disturbed is determined by:

- Rainfall (amount, frequency, duration, and intensity)
- Wind (direction, strength, and frequency of high-intensity winds)
- Evaporation rates, which reduce soil moisture and therefore vegetation cover
- Soil type and topography, which can resist or promote erosion

In the Arctic, increased air temperatures result in increase in soil temperature, leading to significant increases in the depth of annual permafrost thaw or permanent permafrost loss. Wildfire, by destroying vegetation cover, weakening surface soils, and increasing soil direct heating and drying by the Sun, is a significant accelerator of land degradation in many regions.

Land degradation is a significant problem for installations. Many kinds of degradation result in loss of vegetative cover, increasing erosion from extreme precipitation events that can limit off-road transit by military vehicles and personnel. Bare ground, when dry, may become a significant dust source that restricts air and ground travel, fouls machines of all types, penetrates building interiors, and poses health challenges. Soil susceptibility to erosion is at the heart of the issue of land degradation. Soil loss can result from many processes, but chief among these are precipitation intensity (how fast precipitation falls) and land use (how dense the vegetation is and therefore its ability to protect the ground surface from erosion). Both of these variables affect the ability of raindrops to dislodge soil particles, and surface runoff to transport these particles to stream channels.

Wildfire is included under land degradation because of the profound landscape changes that can occur after wildfires if burn conditions are severe enough. In the immediate years post-wildfire, land areas subject to high-intensity burns are susceptible to large, damaging mass-wasting and other erosion events with each rainfall. Susceptibility can last from years to decades. Post-wildfire runoff, often bulked with debris and ash, pose a life-safety risk in excess of what would be expected for a given precipitation event.

Larger WOWA scores for this hazard category indicate greater likelihood of land degradation with a changing climate. The indicators used to measure land degradation exposure are shown in Table 1-8.

Table 1-8. Five indicators are used to measure the changes in land degradation exposure.

Indicator	Importance Weight	Justification
SOIL LOSS (#701): This indicator measures changes in the rate of surface erosion due to changes in precipitation intensity and land use. It is calculated using the Revised Universal Soil Loss Equation (RUSLE). Increases in soil loss not only result in erosion and gully formation of the land surface, but eroded sediment accumulates in stream channels and reservoirs, resulting in reductions in reservoir capacity, changes in the performance of flood risk management infrastructure, and affects to stream habitat.	1.7	This indicator is given the highest weight because it takes into account factors that both enhance erosion and combat erosion. Changes in this indicator show a long-term shift in this balance that indicate long-term, landscape-wide changes in erosion rate with implications for use of a wide range of outdoor landscapes.
FIRE SEASON LENGTH (#604): Fire season length is the average annual number of days in which the KBDI is > 600, indicating long-term arid conditions and dry coarse fuels. Vegetation becomes more flammable under prolonged dry conditions. The KBDI captures the accumulated moisture deficit for a given region over the course of a year. Values for the index decrease when precipitation occurs, and increase with number of days since the last precipitation event. An index value of 600 or greater indicates a prolonged period of aridity, which gives time for vegetation and soils to dry out. Consequently, the number of days with KBDI > 600 indicates the share of the year in which vegetation is already very dry and wildfires readily ignite and spread.	1.5	This indicator is given the next highest value because it is unpredictable in location, time, and severity, but the effects on land surface degradation can be severe and long-lasting.
ARIDITY (#105): Aridity is a change in the nature of an installation's climate toward increasingly drier conditions. Increases in aridity indicate essentially permanent reductions in water supply. It also indicates significant reductions in soil moisture and therefore changes in vegetation type and density and wildfire risk. Importantly, changes in aridity are not strongly correlated with changes in any of the other drought variables.	1.4	This indicator is given a medium weight because a shift to a more arid climate reduces vegetative cover, which increases exposure to erosion, while at the same time slowing the rate at which the land surface recovers from disturbance (such as a military training exercise).

Indicator	Importance Weight	Justification
COASTAL EROSION (#202): Coastal erosion is a measure of a coastline's susceptibility to erosion due to wave action. It is affected primarily by exposure to wave action (largely a function of fetch) and by the nature of the ground at a given location (e.g., sandy vs. rocky). Coastal erosion is the probability of erosion based on data from the USGS Coastal Vulnerability Index Database. It is a measure of potential damage during storm events for more vulnerable coastlines. This indicator is static (does not change with time).	1.2	Coastal erosion is a significant problem in some areas, but the affects may be reduced or eliminated through structural and nonstructural measures. Consequently, this indicator is given a lower weight.
PERMAFROST HAZARD (#702): Permafrost hazard potential is the percent of the installation at significant risk for damage to infrastructure due to permafrost thaw. This indicator reflects the mitigating effects of multiple factors, including soil substrate, on the consequences of permafrost thaw. For example, while fine-sediment deposits may subside or be subject to liquefaction as permafrost thaws, gravelly substrates may retain most or all of their engineering performance characteristics. The former location would have a much higher hazard potential than the later based on this index.	1	While this is a significant hazard for a small number of installations located in the Arctic, it is not a concern for the majority of locations and therefore is given the lowest weight.

CLIMATE HAZARD CATEGORY: HISTORICAL WEATHER EXTREMES

In addition to projected changes in climate variables, the tool includes information on historical extreme weather frequencies and existing wildfire exposure. These datasets provide a background to current exposure to a range of impacts. However, there is insufficient data to understand how this exposure may evolve in the future or in some cases, the method of calculation is very different for the historic condition (e.g., National Integrated Drought Information System [NIDIS] Drought Monitor data). Because most planning processes ask planners to differentiate between existing and future conditions, these indicators were grouped together to facilitate development of the existing conditions assessment portion of the planning processes. Indicators were selected based in part on the availability of nationally consistent, complete, and authoritative data.

Larger WOWA scores for this hazard category indicate greater exposure to these climate variables in the historic period. The indicators used to measure exposure to historical weather extremes are shown in Table 1-9.

Table 1-9. Eight indicators are used to measure exposure to historical weather extremes.

Indicator	Importance Weight	Justification
HURRICANE FREQUENCY (#802): Hurricane frequency is the mean annual probability of being impacted by a hurricane, and is defined as being within 200 km buffer around the hurricane track.	1.7	This indicator is given the highest weight because hurricanes combine widespread high damage and life-safety loss with unpredictability. The results of hurricanes can be substantial disruption to mission and readiness.
HURRICANE MAXIMUM AVERAGE PRECIPITATION (#807): Hurricane maximum average precipitation is the maximum average annual precipitation from hurricane events experienced in any portion of an installation's HUC8 watershed across all storms.	1.5	Hurricane precipitation gets the second highest weight because of high damages and life-safety risk, even for Category 1 and 2 storms, and post-tropical storms.
TORNADO FREQUENCY (#801): Tornado frequency is the average annual probability of a tornado occurring on or in the HUC8 watersheds of an installation.	1.4	Tornadoes are assigned a middle weighting, because although they can result in widespread damage and life safety risk, they have a relatively small footprint.
HURRICANE WIND GREATER THAN 50 KNOTS (#806): Hurricane Wind > 50 knots is the maximum frequency with which any portion of an installation's HUC8 watershed was impacted by hurricane winds greater than 50 knots.	1.4	Similarly, hurricane wind damage causes damage and life safety risk, but for a much narrower area than precipitation.

Indicator	Importance Weight	Justification
WILDLAND URBAN INTERFACE (#805): Wildland Urban Interface (WUI) is the percent of installation classified as wildland-urban interface or intermix, according to the USDA WUI map. For Alaska and Hawaii, WUI was mapped based on the USDA methodology.	1.3	The mix of vegetation and structures is given a lower weight because while it supports wildfires that can cause costly destruction of property, this exposure can be reduced through known measures (e.g., zoning, wildfire codes).
ICE STORM OCCURRENCE (#803): Ice storm occurrence is a presence-absence indicator identifying places in the U.S. where freezing rainstorms have occurred that have significantly impacted above-ground infrastructure.	1.2	This indicator is given a lower weight. Ice storms can cause significant damage to some aboveground infrastructure, such as transmission lines and communications equipment. Ice storms can also inhibit transportation due to hazardous road conditions. Not all locations are subject to ice storms.
ICE JAM OCCURRENCE (#808): Ice jam occurrence is a presence-absence indicator identifying places in the U.S. where ice jams have occurred in an installation's HUC8 watersheds.	1.2	Similarly, while ice jams can increase seasonal flood risk and are unpredictable in time and place, they are also an infrequent, if sometimes significant, cause of damage.
HISTORICAL DROUGHT FREQUENCY (#804): Historical drought frequency is the percent of weeks in the historic period when any part of an installation was categorized as in severe (D2), extreme (D3), or exceptional (D4) drought as determined by the NIDIS historical records.	1.1	Drought is a significant source of damage to agriculture and reductions in water supply. This gets the lowest rate because it is expected that existing water installation water supply infrastructure takes historical drought frequencies into consideration in sizing and operations.

APPENDIX 2: REPRESENTATIVE INSTALLATION RESILIENCE CASE STUDY

Information about exposure to climate hazards does not translate directly to action. As previously discussed, regional to local information about sensitivity must be evaluated to determine whether a particular exposure poses a threat to missions or operations. If so, the next step is to consider potential actions within the constraints and opportunities presented by adaptive capacity. If not, then other priorities may take precedence for action.

We illustrate how the exposure information provided by DCAT now and in the future could feed into the development of resilience measures for a notional installation. This notional installation is not an actual site, but was developed in coordination with representatives of the military departments and includes features that can be found in their installations.

Here we present a graphic that depicts climate hazards addressed in DCAT for the current time, largely impacted by historic extremes, and a future condition illustrative of a late-century lower scenario or mid-century higher scenario. Each graphic includes the installation features, locations of hazards, and a checklist of asset categories affected (Table 3). An accompanying table contains a listing of potential resilience measures appropriate for the features exhibiting sensitivity to the hazards. The table includes cost estimates, where available, based on the resilience measures and costs in Appendix 3.

CURRENT: EXPOSURE TO HISTORIC EXTREMES

The base case is a coastal installation that includes wharves, a harbor, drydock, pier, airfield, bombing range, training areas, and associated facilities and residential areas (Figure 2-1). Observed hazards are indicated by the icons placed on the installation map. These include hurricane, riverine flooding, heat, energy demand, coastal flooding, and land degradation (coastal erosion). Coastal flooding and erosion also impact residential areas along the eastern part of the boundary.

In this example, energy and water resilience measures have already been established for this installation. Generators and solar panels have been located near-critical facilities, including the hospital, headquarters buildings, depot, and the cell tower, to reduce the risk hurricane hazards could interrupt fuel supply. Water storage has been added near the fuel storage and cell tower area. While five asset categories are affected by the existing hazards, as shown in the checkboxes of Figure 2-1, only three asset categories are sensitive to the hazards, as indicated by the italics on Figure 2-1: training areas, ranges, and related facilities; piers and waterfront services; and transportation infrastructure and routes.

Moderate to high adaptive capacity at this point in time can be inferred from the existing energy and water resilience measures as well as additional resilience measures instituted for several of the exposure hazards identified as sensitive in Figure 2-1:

- Shade sheds have been added to the training area to reduce heat-related health risks.
- Retention ponds have been added near facilities to reduce inflow to creeks, thus reducing downstream flooding in the main river that can impact transportation routes.

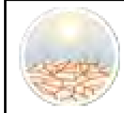
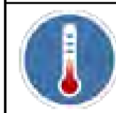
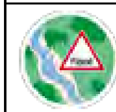
Additional hazards identified include riverine flooding reducing access to roads and coastal flooding that reduces access and reliability of the piers and waterfront services. Coastal erosion is observed along the edge of the wetland and could affect piers and waterfront services. Coastal flooding does not yet impact the community to the east of the installation, though coastal erosion in that area is likely to increase as sea level continues to rise.

CURRENT RESILIENCE MEASURES

This example of resilience planning, selection of measures, and estimation of costs for the sensitive asset categories is based on the screening level information in Appendix 3 as summarized for this base case in Table 2-1. The following assumptions and qualitative assessments:

- Figure 2-1 indicates that at this screening level, riverine and coastal flooding is not widespread, and thus resilience could be achieved with management or temporary measures rather than with high-cost structural measures. Assuming forecasting is sufficient to alert installation staff to the potential for heavy precipitation or hurricanes, temporary measures such as sandbagging or rerouting traffic may be sufficient in the near term.
- Coastal erosion of the wetland could be managed with nature-based or structural features. Because the shoreline erosion at the coastal wetland is in its early stages, monitoring of erosion as part of the installation natural resources management plan could provide insight into appropriate resilience measures. Bulkheads or other hard engineering measures could impact the structure and function of the coastal wetlands, so nature-based and engineered measures are suggested here. Four methods are shown in Table 2-1. We assume here that erosion reduction is desired for more than frequent events, and that monitoring reveals a resilient wetland. Therefore, a living shoreline is a reasonable alternative.
- A look at projected late-century lower scenario or mid-century higher scenario conditions (Figure 2-2) suggests that riverine flood conditions may worsen. In this example, the riverine flooding generally follow the stream channel, and most facilities are not affected significantly differently than in the base case. Therefore, management measures and temporary measures may be sufficient until some point near mid-century.
- Projected coastal flooding at late-century lower scenario or mid-century higher scenario (Figure 2-2) is more widespread in the area of the wharves, suggesting that installation planners consider the need for more permanent coastal flooding resilience measures periodically before mid-century.

Figure 2-1. Climate hazard exposure map for the notional installation.

Hazard	Hazard Name	Asset Categories Affected
	Drought	☐ 1. Airfield Operations ☒ 2. *Training/Areas/Ranges/ Facilities*
	Wildfire	☒ 3. *Piers/Waterfront Services* ☐ 4. Information Systems
	Heat	☐ 5. C4ISR ☐ 6. Energy Infrastructure
	Riverine Flooding	☐ 7. Fuel Infrastructure ☐ 8. Logistics Supply
	Historic Extremes	☒ 9. *Transportation Infrastructure & Routes* ☒ 10. Emergency Services
	Coastal Flooding	☐ 11. Water/Wastewater Systems ☐ 12. HVAC Systems
	Land Degradation	☐ 13. Environmental Restoration Sites ☒ 14. Natural Resources
	Energy Demand	☐ 15. Historic/Cultural Resources ☐ 16. Housing
		☐ 17. HQ Buildings ☐ 18. Personnel Support ☒ 19. Surrounding Community ☐ 20. Other
	TOTAL ASSET CATEGORIES AFFECTED:	**5**

☒ Exposed *Italics* = Sensitive

Table 2-1. Additional resilience measures for base epoch-scenario for the notional installation.

Hazard	Location	Potential Measure	Potential Measure Type	Estimated Cost
Riverine flooding	Roads depot	Hazard mitigation plan	Management, Table 3-1	Negligible, part of installation planning. Should address identified exposures and any sensitivities.
		Flood mapping	Management, Table 3-1	Depends on extent of up-to-date hydrologic and hydraulic mapping and degree of change since previous flood mapping. High-level information in DCAT. Assume here that tributary flooding shown in Figure 10 is not included in FEMA maps. If new facilities are planned or changing conditions are expected, flood mapping should be performed. Cost estimate: $50K.
		Sandbags and sandbag alternatives	Temporary, Table 3-2	Assume 500 ft of road near the base housing requires sandbagging or alternatives to 2 ft high during 1% annual exceedance probability flood to maintain access. Suitable material and labor on-site. Cost estimate: $100 per linear ft per 4 ft vertical = $25K per event.
		Riprap	Structural and Nature-Based, Table 3-3	Consider riprapping 1,000 ft along the south side of the stream passing near the depot, $4,800/linear ft plus appropriate Operation and Maintenance (O&M) per linear ft = $4.8 M plus annual O&M.
		Stormwater drainage improvements	Structural and Nature-Based, Table 3-3	Very site specific. Consider O&M of drainage ditches and clearing any debris. Consider upsizing culverts, which can be very cost-effective if performed during maintenance or after flood event. Include in normal maintenance costs.
		Building/asset elevation	Nonstructural, Table 3-4	Assume two buildings require elevation of 4 ft to maintain required services during flood events through mid-century. Cost estimate = $200,000 per building = $400K.

Hazard	Location	Potential Measure	Potential Measure Type	Estimated Cost
Coastal flooding	Roads Near dry dock Pier access area	Hazard mitigation plan	Management, Table 3-1	Negligible, part of installation planning. Should address identified exposures and any sensitivities.
		Flood mapping	Management, Table 3-1	Depends on extent of up-to-date hydrodynamic modeling and mapping, and degree of change since previous flood mapping. High-level information in DCAT. Assume here that up-to-date coastal mapping from FEMA is available. Include in normal geographic information system (GIS) analyses for installation master planning.
		Sandbags and sandbag alternatives	Temporary, Table 3-2	Assume one side of a half mile length of road near the pier access point and an additional 1,500 ft of wharf require sandbagging or alternatives to 4 ft during 1% annual exceedance probability flood. Suitable material and labor on site. Cost estimate: $100 per linear ft per 4 ft vertical = $414K per event.
		Building/asset elevation	Nonstructural, Table 3-4	Assume one building requires elevation of 8 ft to maintain required services during flood events through mid-century. Cost estimate = $250,000 per building = $250K.

Hazard	Location	Potential Measure	Potential Measure Type	Estimated Cost
Land degradation	Coastal erosion north and south of the pier and near wetland	Wetland restoration	Structural and Nature-Based, Table 3-3	Either one of these four coastal erosion solutions could be suitable for mitigating the coastal erosion at the wetland habitat along 2,500 ft of shoreline x 100 ft inland (5.7 acres), assuming the remainder of the wetland is in good order. This erosion is caused by high frequency events and changing sea level. This solution is less effective for rare events such as hurricanes. Cost estimate: $120,000 plus appropriate annual O&M per acre = $684K plus O&M.
		Living shoreline/riparian vegetation establishment only)[1]	Structural and Nature-Based, Table 3-3	This solution is less effective for rare events such as hurricanes. Cost estimate: $150 plus appropriate annual O&M per linear ft = $375K plus O&M.
		Living shoreline (edging)	Structural and Nature-Based, Table 3-3	This solution can be used either alone (if monitoring reveals a resilient wetland) or in combination with either wetland restoration or living shoreline riparian vegetation, where it can reduce damage and O&M due to its increased effectiveness compared to either alone for rare events such as tropical or extratropical storms. Cost estimate: $1,400 plus appropriate annual O&M per linear ft = $3.5M plus O&M.
		Living shoreline (sills)	Structural and Nature-Based, Table 3-3	This solution can be used either alone (if monitoring reveals a resilient wetland) or in combination with either wetland restoration or living shoreline riparian vegetation, where it can reduce damage and O&M due to its increased effectiveness compared to either alone for rare events such as hurricanes. Cost estimate: either alone for rare events such as hurricanes. Cost estimate: $12,000 plus appropriate annual O&M per linear ft = $30M plus O&M.
			Total Resilience Costs	**$89M plus annual O&M plus $429K per flood event requiring sandbagging.**

[1]Assuming monitoring suggests living shoreline edging can be used to mitigate coastal erosion

FUTURE SCENARIO: CHANGING CONDITIONS IN LATE-CENTURY LOWER SCENARIO OR MID-CENTURY HIGHER SCENARIO

The future late-century lower scenario or mid-century higher scenario installation hazards are shown in Figure 2-2. Observed hazards are indicated by the icons placed on the installation map. These include hurricane, drought, riverine flooding, wildfire, heat, energy demand, coastal flooding, and land degradation (coastal erosion).

Fire risk previously noted near the bombing range has evolved to include actual wildfire damage, along with, or perhaps related to, drought. Riverine flooding and related erosion are now adjacent to the hangars and slightly impacting the closed range. Additional coastal flooding has reduced access to and reliability of pier and wharves. Additional hazards now affect the surrounding community: wildfire damage has spread beyond the northwest of the boundary, threatening regional critical infrastructure (major road, fiber optics cable, and gas line), while coastal flooding and erosion now impact residential areas along the eastern part of the boundary.

Looking into the future, drought risk near the telemetry arrays and munition bunkers could mean increased potential for wildfire in these areas. Riverine flooding adjacent to the aircraft hangars and the depot could increase as a result of regional increases in precipitation. Continued coastal erosion could eventually impact the pier and locally important wetlands.

In this example, 12 asset categories are affected by the existing hazards, as shown in the checkboxes of Figure 2-2, compared to five under the base case. Six asset categories are identified as sensitive to the hazard exposure, as indicated by the italics in Figure 2-2, compared to three under the base case. Newly sensitive asset categories are energy infrastructure, fuel infrastructure, and an environmental restoration site.

FUTURE SCENARIO RESILIENCE MEASURES

This example of resilience planning, selection of measures, and estimation of costs is based on the information in Appendix 3 as summarized for the late-century lower scenario or mid-century higher scenario. The following assumptions are made:

- Resilience measures for the base case shown in Table 2-1 have been put in place. Elevated facilities can withstand additional flooding expected by mid-century.
- The hazard mitigation plan has been updated to account for increased riverine and coastal flooding between the base case and late-century lower scenario or mid-century higher scenario, and has considered the projected hazards at late-century lower scenario or mid-century higher scenario (Table 2-2).
- Design standards for existing facilities meets the International Code Counsel's International Wildland-Urban Interface Code (IWUIC) model code or equivalent. Areas experiencing wildfire are being managed to reduce risks using up-to-date wildfire management methods. Expanded drought areas are being managed to reduce wildfire risk.
- Riverine flood mapping is up to date, and coastal flood mapping includes DRSL intermediate scenario.

- Exposure shown in Figure 2-2 indicates that the coastal erosion measure selected for the wetland is working for the moment. Monitoring is needed to determine whether coastal flooding during extreme events has adversely impacted the wetland structure and function. If so, projected sea-level changes near the end of the century (which can be obtained from the DCAT were this an actual installation) may require adaptation later in the century.
- Community resilience issues including wildfire to the northwest and increased coastal flooding and beach erosion to the south are being addressed in coordination meetings.
- Wildfire management measures instituted include the following:
  - Maintained and trained fire crews experienced in fighting and managing wildfires on base.
  - Managed base vegetation to reduce fire intensity through activities such as controlled burns under favorable conditions and forest thinning.
  - Developed a protocol for deciding when existing fires can be managed with controlled burns vs. when an existing fire requires immediate suppression.
  - With the local community, conducted a risk assessment for infrastructure and facilities in the wildland-urban intermix and interface. Considered incorporating the International Wildland-Urban Interface Code (IWUIC), or comparable requirements into building design and design of the landscape adjacent to the building, including creation and maintenance of a defensible space.
  - With the local community, developed and practiced a plan for evacuating in the event of a large wildfire. Worked with adjacent communities, and county and state emergency officials to develop this plan to ensure consistency between this plan and any county, state, or other governmental hazard plans.

The actions listed above indicate a moderate to high adaptive capacity. Resilience measures (Table 2-2) are required to address sensitive asset categories with the following exposure:

- For large areas of wildland vegetation, create and maintain fire breaks to reduce wildfire spread and provide access for firefighting equipment.
- Additional flooding along the wharves means that temporary measures are no longer suitable, and permanent measures will now be necessary.
- Increases in riverine flooding along the hangars, the closed range, near base housing, and near the depot now require more permanent measures, especially given trends toward more heavy precipitation.

Hazard	Hazard Name	Asset Categories Affected
	Drought	☐ 1. Airfield Operations ☒ 2. *Training/Areas/Ranges/ Facilities* ☒ 3. *Piers/Waterfront Services* ☒ 4. Information Systems ☐ 5. C4ISR ☒ 6. *Energy Infrastructure* ☒ 7. *Fuel Infrastructure* ☒ 8. Logistics Supply ☒ 9. *Transportation Infrastructure & Routes* ☐ 10. Emergency Services ☐ 11. Water/Wastewater Systems ☐ 12. HVAC Systems ☒ 13. *Environmental Restoration Sites* ☒ 14. Natural Resources ☒ 15. Historic/Cultural Resources ☒ 16. Housing ☐ 17. HQ Buildings ☐ 18. Personnel Support ☒ 19. Surrounding Community ☒ 20. Other
	Wildfire	
	Heat	
	Riverine Flooding	
	Historic Extremes	
	Coastal Flooding	
	Land Degradation	
	Energy Demand	
	TOTAL ASSET CATEGORIES AFFECTED:	**12**

☒ Exposed *Italics* = Sensitive

Figure 2-2. Example notional installation exposure map for lower late century (2085) epoch-scenario, or higher mid century (2050) epoch-scenario.

Table 2-2. Additional Resilience Measures for Reducing Vulnerability to Lower Late Century (2085) Epoch-Scenario, or Higher Mid Century (2050) Epoch-Scenario Climate Hazard Exposure for the Notional Installation.

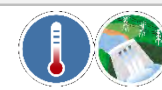
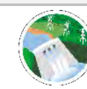
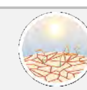
Hazard	Location	Potential Measure	Potential Measure Type	Estimated Cost
Wildfire	Near bombing range Northwest boundary and critical infrastructure (road, fiber optics cable, gas line)	Design Standards: Wildfire	Management, Table 3-1	For large areas of wildland vegetation, create and maintain fire breaks to reduce wildfire spread and provide access for firefighting equipment. Cost estimate: not available. Include annual O&M in facility plan.
Riverine flooding	Roads generally along the installation Riverine flow impinging on closed range and near hangars Pier access area Depot	Sandbags and sandbag alternatives	Temporary, Table 3-2	Assume an additional 1000 ft of roadways near the require sandbagging or alternatives to 2 ft high during 1% annual exceedance probability flood to maintain access. Suitable material and labor on-site. Cost estimate: $100 per linear ft per 4 ft vertical = $50K per event.
		Riprap	Structural and Nature-Based, Table 3-3	750 ft of streambank adjacent to the closed range and an additional 500 ft near the hangars are subject to erosion due to increased riverine flooding. Natural or nature-based measures such as vanes, barbs, J-hooks, and rootwads could be considered. Here, the critical nature of these facilities suggests that riprap would be more appropriate. Cost estimate: $4,800/linear ft plus appropriate O&M per linear ft = $6 M plus O&M.
		Floodwalls	Structural and Nature-Based, Table 3-3	Sandbags no longer sufficient – replace with one-half mile floodwall along roadway near pier access point. Cost estimate: $700K plus appropriate annual O&M per linear foot = $1.8M plus O&M.
		Ring Levee	Nonstructural, Table 3-4	Sandbags no longer effective against river flooding near depot. Replace with ring levee. Cost estimate: $4.8M plus O&M.

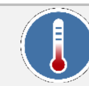
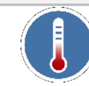
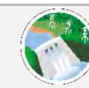
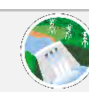
Coastal flooding	Wharves	Sea walls	Structural and Nature-Based, Table 3-3	Sea wall along areas of wharves where flood avoidance is required, estimated 4000 ft in this case, with tieback to high ground. To be supplemented by sandbags. Cost estimate for sea wall, $11,000 plus appropriate annual O&M per linear foot = $44M plus O&M.
	Wharves and near dry dock	Sandbags and sandbag alternatives	Temporary, Table 3-2	Assume 1000 ft of sandbagging at wharves and an additional 500 ft along dry dock require sandbagging or alternatives to 4 ft during 1% annual exceedance probability flood. Suitable material and labor on-site. Cost estimate: $100 per linear ft per 4 ft vertical = $150K per event.
	Wharves	Building/asset elevation	Nonstructural, Table 3-4	Assume two buildings require elevation of 8 ft to maintain required services during flood events through late century. Cost estimate = $250,000 per building = $500K.
Land degradation	Coastal erosion north and south of the pier and near wetland	Wetland restoration	Structural and Nature-Based, Table 3-3	Increased coastal erosion and coastal flooding now through end of century require a combination of wetland restoration and upgrade of living shoreline edging to living shoreline sill to 2500 ft of shoreline x 100 ft inland (5.7 acres), assuming the remainder of the wetland is in good order. Cost estimate for wetland restoration: $120,000 plus appropriate annual O&M per acre = $684K plus O&M.
		Living shoreline (sills)	Structural and Nature-Based, Table 3-3	Upgrade of living shoreline sill to living shoreline edging for 2500 ft of shoreline. Cost estimate: $12,000 plus appropriate annual O&M per linear ft = $30M plus O&M.
			Total Additional Resilience Costs	**$83M plus annual O&M plus $200K per flood event requiring sandbagging.**

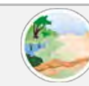
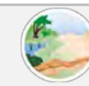
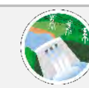
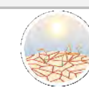
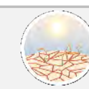
APPENDIX 3: RESILIENCE MEASURES

This appendix provides an overview of resilience measure to provide context. More detailed information about resilience measures can be obtained from a wide variety of sources, including USACE [2015 and 2020], Army [Pinson et al., 2020], Navy[NAVFAC 2017], Air Force [2020], and the studies listed in the deeper dives previously discussed. Management resilience measures are defined as planning, regulatory, information gathering, and behavioral activities that enhance or guide resilience. These measures help prepare for, absorb, recover from, and adapt to the exposure, but do not affect the likelihood of the hazard occurring.

Table 3-1. Management Resilience Measures.

MEASURE[1]	DESCRIPTION	HAZARDS
Audits	Water and energy audits are inspections of infrastructure that evaluate water and energy use, look for waste (such as leaky pipes, lit spaces that do not need to be continuously lit), and identify steps needed to remediate the loss.	
Building Design: Energy Efficiency	Require improvements to the energy efficiency of buildings and infrastructure to reduce energy demand, and therefore, reduce the likelihood of brown-outs and black-outs during heat waves. These improvements could include passive heating and cooling, passive solar design, and increased building spacing (to facilitate nighttime heat dissipation).	
Design Standards: Wildfire	Incorporate information from the International Code Counsel's International Wildland-Urban Interface Code (IWUIC) Model Code (https://codes.iccsafe.org/content/IWUIC2015) or similar into the installation design standard to reduce infrastructure damage due to wildfire. Examples include requiring firebreaks/firescaping, ignition-resistant construction design, noncombustible building materials, and appropriate land use and zoning requirements.	
Diversification of Energy Supply	This is a strategy of having multiple energy supply types and sources contributing to an installation's energy portfolio. Disruptions in one supply source could be compensated for by bringing alternative resources online.	
Education: Drought	For installations where drought is a concern, drought education is essential for compliance with water use restrictions. Such education would focus on water uses issues, but also such drought-related issues as water quality, wildfire, and heat stress.	

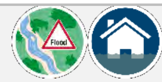
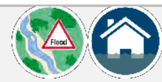
MEASURE[1]	DESCRIPTION	HAZARDS
Education: heat	Improve education around heat-related morbidity and mortality, including recognition of conditions under which outdoor activity should be reduced, identification of signs and symptoms of heat-related illness, and methods for treatment in the field. Additional considerations include increasing acclimatization times for new arrivals on installation during the warmer months, and adjusting the timing of outdoor activities to coincide with cooler portions of the day.	
Emergency response: cooling centers	Designate locations to function as cooling centers during heat waves, as necessary, particularly in locations where air conditioning is not a common feature of buildings.	
Energy metering	Metering allows for tracking of energy use by location and provides essential information needed for energy planning and for the management of energy supplies.	
Evacuation	Evacuation means leaving a residence or facility and relocating to a safer location during a natural disaster. Pre-disaster evacuation planning should account for social vulnerability and other demographic factors, include education on potential disasters, improve personal knowledge of emergency procedures, and increase familiarity with installation emergency management procedures.	
Flood mapping	Use FEMA National Flood Insurance Program flood inundation maps to identify portions of an installation at risk from riverine flooding. Zone accordingly. If NIFP maps are not available for an installation, seek funding to have maps developed to guide engineering decisions.	
Hazard Mitigation Plan	All potential hazards should be addressed in a comprehensive installation hazard mitigation plan. This plan should be coordinated with federal, state, regional, and local government and emergency response entities. Comprehensive interagency practice of this plan should occur annually, and the plan adjusted based on the outcome of these activities and of actual implementation during critical hazard events. This plan should include a risk communication plan, evacuation plans, and an outreach component to make soldiers and civilian employees aware of the hazards and strategies for avoiding or mitigating them.	
Microgrids	Rather than supplying an installation with a single grid, which is vulnerable to disruption, the installation is powered by a series of inter-connected but isolatable microgrids, to increase resilience to energy disruption.	

MEASURE[1]	DESCRIPTION	HAZARDS
Minimize erosion	Use construction sediment management best practices to reduce soil erosion in all disturbed areas and to keep sediment out of waterways.	
Minimize ground disturbance	Ground-disturbing activities should be minimized in areas where soils are loose and unconsolidated, and on steeply slope surfaces to reduce dust and erosion hazards; consider rotating activities to allow the land to recover.	
Permafrost hazard mapping	Map locations on the installation where permafrost hazard exists (where permafrost exists, mean annual ground temperatures are approaching 32°F, and the soil substrate is not gravelly), and adjust development plans to concentrate infrastructure outside these areas, where possible.	
Plan to relocate, repurpose, or adapt buildings	Identify and develop plans for adapting, repurposing, or relocating buildings at risk from flooding due to riverine and coastal inundation. Measures could include elevation of buildings, roads, and utilities; dry and wet flood-proofing; relocation; floodable development; floatable development; and ring walls/levees.	
Third-party financing for energy	The DoD permits installations to make use of a diverse array of third-party financing mechanisms to support energy development and independence on installations.	
Water conservation plan	A water conservation plan sets out long-term goals for water supply management. In addition, such a plan identifies water supply thresholds below which increasingly stringent water restrictions would come into effect.	
Water metering	Metering allows for tracking water use by location and provides essential information needed for water resources planning. All water uses should be metered.	

1 An extensive list of management measures was compiled as part of the USACE North Atlantic Coast Comprehensive Study (2015) and the South Atlantic Coast Study (2020). These resilience measures are included here as appropriate.

Temporary measures reduce the exposure to a hazard and help absorb and recover from exposure to the hazard, but do not affect the likelihood of the hazard occurring.

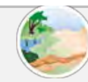
Table 3-2. Temporary Resilience Measures and Estimated Costs.

MEASURE[1]	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT [2]	UNITS
Deployable floodwalls		$11,249–$27,731	Cost/ linear foot
Dry flood-proofing		$31,961–$67,677	Cost/asset (structure)
Wet flood-proofing		$8,603–$20,987	Cost/asset
Sandbag and sandbag alternatives		$100–$300	Cost/linear ft/4 vertical ft

1 Extensive lists of resilience measures compiled as part of the USACE North Atlantic Coast Comprehensive Study (2015) and the South Atlantic Coast Study (SACS, 2020). Resilience measures presented here represent an aggregated list of the categories of measures and corresponding conceptual parametric unit cost estimates from the SACS, unless otherwise stated.
2 Regional factors, such as materials, labor, and fuel, could affect overall costs. The total construction cost estimates must take into account more localized costs of these factors as part of the development of project cost estimates. Please note that the ranges of costs provided considers the variation in regional differences across the USACE South Atlantic Division (SAD) Area of Responsibility (AOR).
3 Sandbags incur cleanup, removal, and disposal costs; reusable methods generally cost less for cleanup, removal, and disposal but require additional storage.

Structural and nature-based measures reduce exposure to a hazard, but do not affect the likelihood of the hazard occurring. These measures help natural and built infrastructure absorb, recover, and adapt to the exposure of the hazard. Most have annual O&M costs in addition to initial investment.

Table 3-3. Structural and Nature-Based Resilience Measure and Estimated Cost.

MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Air-convecting embankment (ACE)	An embankment consisting of large loose rocks placed to foster air movement within the embankment, helping to extract heat from the ground and keep it colder (permafrost areas).		NA	NA
Barrier Island restoration	Construction of a barrier island to shield a coastal area from wave damage.		$243,126–$1,104,307	Cost/acre
Beach fill (initial)	Initial construction or reconstruction of a beach to reduce future erosion by increasing the amount of beach area separating the active shoreline from infrastructure and developed areas.		$1,620–$7,060	Cost/linear foot
Beach fill (renourishment)	The periodic addition of sediment to a beach to replace that lost through erosion in order to sustain beach function.		$1,041–$3,985	Cost/linear foot
Bendway weir	A low level, submerged rock dike angled up stream designed to deflect stream flow away from a riverbank.		NA	NA
Breakwaters	A breakwater is a barrier built out into a body of water to protect a coast or harbor from the force of waves.		$5,533–$22,653	Cost/linear foot
Bulkhead	A wall that prevents erosion of the shoreline due to wave action.		$16,431–$23,354	Cost/linear foot

Drought | Wildfire | Heat | Riverine Flooding | Historic Extremes | Coastal Flooding | Land Degradation | Energy Demand

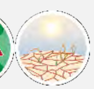
MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Channel relocation	Channel relocation is the dredging of a new channel through a floodplain to divert stream flow away from vulnerable infrastructure.		NA	NA
Discharge gates	Systems that reduce the impact of sea-level rise and tides on gravity draining. Requires storage capacity upstream from gates. Smaller storm surge barriers used to reduce risk to areas with coastal inlets.		NA	NA
Stormwater drainage improvements	Storm water drainage systems are the means by which storm water is transported from one area (typically urban) to another area (typically a river system, ocean, wetland, or retention pond). Increasing capacity and slowing flows are key improvements for such systems.		NA	NA
Dune enhancement (initial)	Dunes provide a barrier to coastal erosion, and if continuous along the coastline, a barrier to coastal inundation.		\$812–\$2,961	Cost/linear foot
Flood barriers, temporary flood	Flood barriers are barriers that can be raised when there is a flood risk, but lowered to permit access when flood risk is absent.		\$5,500	Feet
Floodwalls[3]	An engineered barrier (usually of concrete, masonry, or both) designed to hold back floodwaters.		\$510,350–\$833,572	Cost/linear foot
Groins	A barrier built perpendicular to a shoreline for the purpose of trapping sand moving in longshore currents. This retains the beach at the groin location, which shields coastal development from wave damage.		\$961,643–\$4,521,486	\$/groin unit
Vanes/barbs/ J-hooks	Low profile structures of stone or other material angled upstream, designed to reduce bank erosion by deflecting the river current away from the bankline.		NA	NA

Drought | Wildfire | Heat | Riverine Flooding | Historic Extremes | Coastal Flooding | Land Degradation | Energy Demand

MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Levees & dikes	Compacted earthen structures designed to hold back floodwaters.		$4,032–$6,586	Cost/linear foot
Living shoreline (artificial reefs)	A living shoreline is a protected, stabilized coastal edge made of natural materials such as plants, sand, or rock. Living shorelines grow over time, and provide wildlife habitat.		$83,272–$106,566	Cost/linear foot
Living shoreline/riparian vegetation establishment- (vegetation only)	Creation of a living shoreline only through the addition of vegetation that stabilizes the substrate and reduces wave impact in low wave energy environments.		$19–$1,383	Cost/linear foot
Living shoreline (edging)	Hardening of the toe slope of an existing or vegetated slope to reduce erosion.		$1,400	Cost/linear foot
Living shoreline (sills)	Rocks, cement, or other material placed parallel to existing or vegetated shoreline for the purposes of reducing wave energy and preventing erosion.		$10,011–$13,772	Cost/linear foot
Locks & gates	Locks are structures used to temporarily impound water to for the purpose of raising and lowering boats and other watercraft between stretches of water that are at different elevations. Flood gates are adjustable gates used to control water flow.		$4,311,360,000–$6,956,056,000	Cost/each
Mangrove restoration	Mangroves are a woody plant that grown along the shoreline in the southeastern U.S. They serve to stabilize the shoreline and reduce wave impact.		$1,859–$3,160	Cost/acre

MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Maritime forest restoration	A maritime forest is a coastal wooded habitat found on higher ground than dune areas within range of salt spray. They are typically associated with shoreline estuaries along barrier islands. They may serve to attenuate or dissipate waves and reduce shoreline erosion.		$2,619–$8,781	Cost/acre
Native material and rootwad revetments	Provides toe support for bank revegetation techniques and collects sediment and debris that will enhance bank structure over time. Moves the location of high velocity flows away from the bankline.		NA	NA
Oyster reefs	Oyster reefs are a form of living shoreline treatment used to reduce wave energy and mitigate wave damage and erosion in lower energy environments.		$19–$300	Cost/linear foot
Prevent/delay thawing (Permafrost)	Any of a series of measures such as installing passive convection structures (thermopiles, thermosyphons), ground source heat pumps, and gravel barriers that serve to increase ground heat loss and delay permafrost thaw, therefore reducing the weakening of soils that accelerates loss due to riverine and coastal processes.		NA	NA
Revetment	Revetments are sloping concrete or masonry structures placed on banks or cliffs in such a way as to absorb the energy of incoming water and therefore reduce erosion.		$4,335–$14,113	Cost/linear foot
Riprap	Rock of various sizes used to army banklines and shoreless to absorb the energy of incoming water, and therefore reduce erosion.		$4,800	Feet
Submerged aquatic vegetation (SAV) restoration	Submerged provides extensive near shore habitat, while at the same time providing significant attenuation of wave energy in coastal environments.		$266,448–$864,248	Cost/acre

Drought | Wildfire | Heat | Riverine Flooding | Historic Extremes | Coastal Flooding | Land Degradation | Energy Demand

MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Seawall	Seawalls are concrete or masonry structures placed on banks or cliffs in such a way as to absorb the energy of incoming water and therefore reduce erosion.		$8,370–$15,179	Cost/linear foot
Shade structure	Any structure constructed that allows breaks from the glare of the Sun like an open shed, shade cloths, or umbrella. May be temporary or permanent.		NA	NA
Floodways and side channels (perennial, high flow, oxbows)	An additional feature of a complex channel. During high flows, flow may spill or avulse to a second channel at a low point in the bankline. This is an intermediary step before uniform conveyance across the floodplain, but the side channel also serves to reduce erosive energy in the main channel by reducing main channel flow and flow depth. Side channels can reconnect abandoned floodplain areas.		NA	NA
Spur Dikes	Low profile structures of stone or other material angled upstream, designed to reduce bank erosion by deflecting the water motion away from the bankline.		$7,400	Feet
Stormwater capture and reuse[4]	Stormwater can be captured by a variety of channels, drains, and detention basins. Capturing this water prevents it from reach the stream network where it might increase flood flows and contribute to flood damage. This water can then be added to the water supply system (with treatment) or injected into the local aquifer for long-term storage and later use.	 	$2,000–$440,819	Cost/average stormwater capture (acre-ft/year)
Surge barrier/ closure dam	A surge barrier or closure dam is designed to prevent a storm surge or spring tide from flooding the area behind the barrier, but is open most of the time to enable passage of ship traffic. A surge barrier or closure dam is typically part of a larger system of levees, floodwalls, and other coastal flood risk management structures.		$243,126–$1,104,307	Cost/linear foot

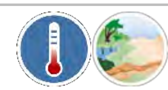
MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Terraces	In coastal and riverine settings, an area of lowered ground designed to accommodate flood waters; in steeply sloping terrain, a series of flat surfaces cut into the slope to slow runoff and reduce hillslope erosion.		NA	NA
Thin layer placement	Thin layer placement is the deposition of dredge material in thin, uniform layers over emergent vegetation or shallow bay bottoms. Benefits wave attenuation and/or dissipation, shoreline erosion, stabilization, and soil retention.		NA	NA
Tidal flats, engineered	Like natural tidal flats, engineered flats are low-gradient, tidally inundated coastal surfaces that allow waves to attenuate before reaching the shoreline, thereby reducing coastal erosion.		$2,069,116–$4,609,313	Cost/each
Vegetative windbreaks	Row of trees or other type of vegetation that provides shelter or protection from the wind. Reduces soil erosion.		NA	NA
Wetland restoration[5]	Restoration of coastal or freshwater wetlands serves a number of functions beyond habitat creation: Wetlands also absorb floodwaters and attenuate erosion.		$112,473–$580,073	Cost/acre

1 Extensive lists of resilience measures compiled as part of the USACE North Atlantic Coast Comprehensive Study (2015) and the South Atlantic Coast Study (SACS, 2020). Resilience measures presented here represent an aggregated list of the categories of measures and corresponding conceptual parametric unit cost estimates from the SACS, unless otherwise stated.
2 Regional factors, such as materials, labor, and fuel, could affect overall costs. The total construction cost estimates must take into account more localized costs of these factors as part of the development of project cost estimates. Please note that the ranges of costs provided considers the variation in regional differences across the USACE South Atlantic Division (SAD) Area of Responsibility (AOR).
3 The concept design identified for the floodwall category consists of a concrete structure. These structures might also require closure structures including stoplogs, miter gates, swing gates, or roller gates, which were not included in the development of the parametric unit cost estimate. A simple steel sheetpile I-wall may be more economical.
4 Stormwater capture and reuse costs are highly variable. Costs included here are from Appendix A of Southern California Water Coalition (2018) Stormwater Capture, 2018 Whitepaper Update, SCWC Stormwater Task Force, April 2018, projects since 2010, in 2017 $.
5 An annual average cost of $120 per foot was used in the SACS Tier 1 evaluation assuming a nominal wetland width (i.e., dimension perpendicular to the shoreline of 200 feet).

Nonstructural measures are measures that reduce the exposure to a hazard, but do not affect the likelihood of the hazard occurring. These measures help infrastructure absorb, recover, and adapt to exposure to the hazard.

Table 3-4. Nonstructural Resilience Measures and Estimated Costs.

MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Building removal and relocation	Removal or relocation of a building or other infrastructure puts it out of reach of floodwaters without altering the frequency of inundation events.		$349,000	Building
Building/asset elevation[3]	Elevating a building or other infrastructure puts it out of reach of floodwaters without altering the frequency of inundation events.		$93,488–$441,708	Cost/asset
Coral reefs	Coral reefs act to reduce or dissipate wave energy, and therefore contribute to reduction in coastal storm damage.		$5,973–$16,383	Cost/linear foot
Dune enhancement (renourishment)	Renourishment is the periodic addition of sediment to dunes to compensate for that lost due to erosion.		$711–$2,448	Cost/linear foot
Elevation (utilities/roads)[3]	Involves raising the infrastructure in place to achieve a reduction in the frequency of inundation during flood events. Elevation can use fill, foundation walls, piers, piles, posts, or columns as appropriate.		NA	NA
Floatable development	Structures that float on the surface of the water or may be floated occasionally during a flood, reducing vulnerability to changing sea level, tides, and some storm surge or wave conditions.		NA	NA

MEASURE[1]	DESCRIPTION	HAZARDS	TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]	UNITS
Floodplain restoration	A floodplain is the area bordering a river that naturally provides space for the retention of flood and rainwater. Restoring floodplains means either partially or fully restoring their functionality as a floodplain post-disturbance.		NA	NA
Reflective roofing	Reflective or light-colored roofing may be installed as way to reduce heat gain in buildings, thereby reducing indoor temperatures and cooling energy demands.		NA	NA
Relocation (utilities/roads)	Involves moving the infrastructure to another location away from flood hazards. Dependable method of protection and provides the benefit of use of the evacuated area.		NA	NA
Relocation/ repurposing (buildings/ facilities)	Moving facilities and buildings from impacted or exposed areas to areas aligned with mission criticality. Repurposing buildings and facilities to house activities with lower mission criticality. Dependable method of protection and provides the benefit of use of the evacuated area building/facility.		NA	NA
Revegetation of slopes/ground covers	Revegetation of slopes is critical for reducing soil erosion; ground cover in all areas reduces rainsplash erosion, land surface heat gain, and evaporative losses.		NA	NA

MEASURE[1]	**DESCRIPTION**	**HAZARDS**	**TOTAL ESTIMATED FIRST COST RANGE PER UNIT[2]**	**UNITS**
Ring walls/ring levees (facility)	A ring wall or ring levee is a wall or levee that encloses a facility, thereby preventing that facility from flood damage when adjacent portions of the floodplain are inundated.		$4,840,000	Facility
Ring walls/ring levees (multi-family housing)	A ring wall or ring levee is a wall or levee that encloses a housing, thereby preventing that housing from flood damage when adjacent portions of the floodplain are inundated.		$3,680,000	Building
Wet flood-proofing	Wet Flood-proofing includes permanent or contingent measures applied to a structure or its contents that prevent or provide resistance to damage from flooding while allowing floodwaters to enter the structure or area.		$8,450–$16,873	Cost/asset (structure)

1 Extensive lists of resilience measures compiled as part of the USACE North Atlantic Coast Comprehensive Study (2015) and the South Atlantic Coast Study (SACS, 2020). Resilience measures presented here represent an aggregated list of the categories of measures and corresponding conceptual parametric unit cost estimates from the SACS, unless otherwise stated.
2 Regional factors, such as materials, labor, and fuel, could affect overall costs. The total construction cost estimates must take into account more localized costs of these factors as part of the development of project cost estimates. Please note that the ranges of costs provided considers the variation in regional differences across the USACE South Atlantic Division (SAD) Area of Responsibility (AOR).
3 The range of costs to elevate structures and roadways can vary considerably. Costs are highly site-specific and vary widely.

APPENDIX 4: DATA USED IN THE DCAT

HYDRO-CLIMATE DATA

The hydro-climate data used in this tool come from several authoritative data sources:

- The hydro-climate inputs for CONUS are the same ones used in the 4th U.S. National Climate Assessment (NCA4) [U.S. Global Change Research Program (USGCRP), 2017, 2018, nca2018.globalchange.gov]. Those CONUS model outputs were first produced for USACE through collaborative work by the USACE Climate Change programs with the developers of the Localized Constructed Analogs (LOCA) empirical-statistical downscaling method [Pierce et al., 2014, doi: 10.1175/JHM-D-14-0082.1]. These outputs were derived from 32 CMIP-5 GCMs downscaled to 0.0625o grids for daily temperature (T) and precipitation (Pr), and separately, from 24 GCMs for relative humidity (RH). All these outputs are served freely at the Green Data Oasis (GDO) site hosted by Lawrence Livermore National Lab [gdo-dcp.ucllnl.org; Maurer, EP, et al., 2014, doi: 10.1175/BAMS-D-13-00126.1]. The National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) post-processed those same LOCA outputs for NCA4 to create indices (e.g., days over 95°F), and USACE has used some of these post-processed values in this evaluation in addition to calculating other new values for this assessment tool.
- The Variable Infiltration Capacity (VIC) hydrologic model was forced with those LOCA outputs to create a consistent portrayal of unregulated and largely uncalibrated areal hydrology across CONUS. VIC is very well established in the climate-changed hydrology community [Liang et al., 1994, doi: 10.1029/94JD00483]; and the areal runoff outputs from these VIC runs are also served freely from GDO. Areal runoff from VIC was routed using mizuRoute [Mizukami et al., 2016, doi: 10.5194/gmd-9-2223-2016].
- Hydro-climate inputs for AK + HI were produced for USACE in collaboration with the National Science Foundation's National Center for Atmospheric Research to develop the first-ever set of current climate mappings and projected futures for those states using compatible state-of-the-science methods comprehensively for each location. For the AK + HI locations, empirical-statistical downscaling was performed using the Bias Corrected Spatial Disaggregation (BCSD) method [Wood et al., 2004, doi: 10.1023/B:CLIM.0000013685.96609.9e], a well-established method for producing future climatologies at scales relevant for surface hydrology. These outputs were derived from 25 CMIP-5 GCMs downscaled to 0.125o grids for monthly T and Pr. The VIC model was used to create the unregulated and largely uncalibrated hydrologic portrayals for these locations; but lack of consistent, tested river routing networks in these locations prevented application of a routing method to channelize the VIC areal outputs. RH was computed using gridded historical observed T through Daymet [Thornton et al., 1997, doi: 10.1016/S0022-1694(96)03128-9]; projected future RH was created using that historical RH and the BCSD-projected future T.
- Global climatologies for non-U.S. ROW locations downscaled from a large set of CMIP-5 models consistently across space were taken from NASA NEX [NASA Earth Exchange Global Daily Downscaled Projections | nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp; facilitated by Will Carrara of the NASA Ames Research Center]. These outputs were derived from 21 CMIP-5 GCMs downscaled to 0.25o using BCSD for daily T and Pr. Accompanying areal hydrologic and routed flows were not available when this project began.

ADDITIONAL DATA

Additional data used in the DCAT are shown in the table below.

Table 4-1. Tool Information.

Data	Source	URL
Land Use/Land Cover	USGS, Multi-Resolution Land Characteristics Consortium	CONUS: https://www.usgs.gov/centers/eros/science/land-cover-projections?qt-science_center_objects=0#qt-science_center_objects [see: Sohl et al. 2016, doi: 10.1080/1747423X.2016.1147619; Sohl et al. 2014, doi: 10.1890/13-1245.1] AK/HI: Multi-Resolution Land Characteristics Consortium National Land Cover Database: Alaska (2016), Hawaii-Oahu (2011), Hawaii-Hawaii (2001), Hawaii-Kauai (2010). https://www.mrlc.gov/data?f%5B0%5D=category%3Aland%20cover ROW: MODIS 0.5 km MODIS-based Global Land Cover Climatology (Broxton et al. 2014) Source: https://archive.usgs.gov/archive/sites/landcover.usgs.gov/global_climatology.html [See Broxton et al., 2014, http://dx.doi.org/10.1175/JAMC-D-13-0270.1]
Population Density	U.S. EPA, U.S. Census	CONUS: US EPA ICLUS Shared Socioeconomic Pathway population estimates (SSP2, 5) Source: https://catalog.data.gov/dataset/iclus-v2-1-1-population-projections AK/HI: U.S. Census 2010 Population, Source: www.census.gov
Soil Erodability	USDA Natural Resources Conservation Service	CONUS: USDA STATSGO 1km gridded dataset, Source: http://websoilsurvey.nrcs.usda.gov/
Topography	USGS, National Science Foundation	For all flood delineations: USGS 30 m DEM, Source: https://prd-tnm.s3.amazonaws.com/index.html?prefix=StagedProducts/Elevation/13/GridFloat/ For soil loss calculation: National Science Foundation Open Topo 90m DEM, Source: www.opentopography.org
Historical Precipitation	NOAA	NOAA Atlas 14 precipitation, Source: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=pa

Data	Source	URL
Wildland-Urban Interface	USDA, U.S. Census	CONUS: 2010 USDA Wildland Urban Interface Map, Source: https://data.nal.usda.gov/dataset/2010-wildland-urban-interface-conterminous-united-states-geospatial-data [See: Martinuzzi et al. 2015, doi: 10.2737/NRS-RMAP-8] AK/HI: Land use/land cover and Population data cited above to map WUI where USDA had not done so.
Sea Level Elevations	DoD Coastal Assessment Regional Scenarios Working Group (CARSWG) DRSL Database	DoD Regionalized Sea-Level Change & Extreme Water Level Scenarios, Source: https://drsl.serdp-estcp.org/ (SERDP, 2013)
Coastal Erosion	USGS, European Commission, Joint Research Centre	CONUS, AK, HI: USGS Coastal Vulnerability Index Database, Source: https://catalog.data.gov/dataset/usgs-map-service-coastal-vulnerability-to-sea-level-rise/resource/824b09f9-8b37-4510-8447-085248fafdf0 ROW: Coastal erosion dataset, Source: http://data.europa.eu/89h/18eb5f19-b916-454f-b2f5-88881931587e [See Vousdoukas et al. 2020, doi: 10.1038/s41558-020-0697-0]
Riverine Flood Extent (interim solution while modeling is completed)	European Union Joint Risk Commission	Source: https://data.jrc.ec.europa.eu/collection/FLOODS [See Alfieri et al., 2014, doi:10.1002/hyp.9947 and Dottori et al. 2016]
Tornadoes	NOAA NCEI (National Centers for Environmental Information)	NOAA NCEI Storm Events Database, Source: ncdc.noaa.gov/stormevents/ftp.jsp
Hurricanes	NOAA	HURDAT2 dataset, Source: nhc.noaa.gov/data/#hurdat International Tropical Cyclone Best Track Dataset, Source: ncdc.noaa.gov/ibtracs Multi-Source Weighted Ensemble Precipitation [See: Beck et al., 2017]
Ice Storms	USACE	USACE Engineer Research and Development Center Cold Regions Research Engineering Lab Ice Storms GIS, Source: rsgisias.crrel.usace.army.mil/ice/icegis.html#

Data	**Source**	**URL**
Historical Droughts	NIDIS (National Integrated Drought Information System)	U.S. Drought Portal, Source: drought.gov/drought/data-maps-tools
Ice Jams	USACE	USACE Engineer Research and Development Center Cold Regions Research Engineering Lab Ice Jam Database Source: icejam.sec.usace.army.mil/ords/f?p=101:7
Permafrost Maps	USGS, European Space Agency	AK: USGS, Source: https://www.sciencebase.gov/catalog/item/5602ab5ae4b03bc34f5448b4 [See: Pastick et al. 2015, doi: 10.1016/j.rse.2015.07.019] Rest of World: European Space Agency GLOB Permafrost, Source: https://doi.pangaea.de/10.1594/PANGAEA.888600 [See: Obu et al. 2018, doi: 10.1594/PANGAEA.888600]
Soil Loss	European Soil Data Center	AK, HI: European Soil Data Centre Global Soil Erosion dataset Source: https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity
Permafrost Hazard		AK, ROW: Permafrost Hazard Index, Source: https://doi.pangaea.de/10.1594/PANGAEA.893881 [See: Hjort et al. 2018, doi: 10.1038/s41467-018-07557-4; Karjalainen et al. 2018, doi:10.1594/PANGAEA.893881]

FRONT COVER PHOTO CREDITS:

Top Left Photo: U.S. Coast Guard photo: Floodwaters accumulate as the Tar River overflows in Greenville, North Carolina. Photo by Coast Guard Petty Officer 3rd Class Corinne Zilnicki, October 12, 2016. https://www.dobbins.afrc.af.mil/News/Article-Display/Article/996078/16-eplos-support-hurricane-matthew-relief-efforts/

Top Right Photo: USDA Photo: Wildfire. Photo by Kari Greer, October 9, 2019. Public domain, obtained from https://media.defense.gov/2019/Oct/09/2002192673/-1/-1/0/191019-D-ZZ999-0001.JPG

Lower Left Photo: Air Force Photo: Damage caused by Hurricane Sandy to the New Jersey Coast. Photo by US. Air Force Master Sergeant Mark C. Olsen, October 30, 2012. https://media.defense.gov/2012/Nov/07/2000098970/-1/-1/0/121030-F-AL508-973.JPG

Bottom Right Photo: U.S. Geological Service photo: Coastal permafrost eroding in Alaska. https://www.globalchange.gov/sites/globalchange/files/permafrost-coastal-erosion-alaska-usgs.jpg

BACK COVER PHOTO CREDITS:

Top Photo: U.S. Air Force Photo: Aerial view of flooding at Offutt Air Base. Photo by Air Force Technical Sergeant Rachelle Blake, March 17, 2019. https://www.af.mil/News/Article-Display/Article/1787869/offutt-afb-battling-flood-waters/

Middle Photo: Patrick Hager, a Savannah District structural engineer, inspects a water crossing that failed due to flooding on Fort Bragg in North Carolina. Photo by Jason Whittaker, Oct. 13, 2016. https://www.sas.usace.army.mil/Media/News-Stories/Article/1004323/engineers-assess-integrity-of-fort-bragg-infrastructure-following-hurricane-mat/

Bottom Photo: U.S. Air Force Photo: Black Forest Fire, Colorado.
Photo by Carol Lawrence, June 11, 2013.
https://www.usafa.af.mil/News/News-Display/Article/428343/local-bases-support-black-forest-fire-efforts/