

FINAL REPORT

Understanding Data Needs for Vulnerability Assessment and Decision Making to Manage Vulnerability of Department of Defense Installations to Climate Change

SERDP Project RC-2206

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Abstract

Objectives—The Department of Defense (DoD) has identified climate change as a risk to its infrastructure and is seeking to develop efficient and effective processes to assess the vulnerability of its assets to this risk. In response to this need, this project developed, piloted, and evaluated an approach for vulnerability assessment keyed to DoD decision-making needs and processes at multiple organizations levels. It also developed and tested methods for use in an overall assessment framework, and it outlined a process for assessments at installations that applies extensive stakeholder involvement, a novel approach to providing climate information (plausible future exposure), a range of existing models and approaches for estimating impacts, and decision-making frameworks.

Technical Approach—Using research literature on climate change vulnerability (theory, definitions, and processes-in-use), this project tested approaches and methods to assess vulnerabilities in case studies at three DoD mid-Atlantic installations that represent three military Services, differing missions, and differing risks from future climate changes: the U.S. Naval Academy, Joint Base Langley-Eustis, and Fort Bragg. It probed for data and potential indicators to establish baseline conditions and installation characteristics, extracted information about the installations' future exposure to climate change from sources including regional climate models, established the significance for missions and operations of future climate impacts, and analyzed the potential for integrating climate risks into short- and long-term DoD decision making. This project developed (1) specialized information on impacts-relevant climate variables and a climate outlook approach to providing climate information; (2) a three-tiered framework for DoD vulnerability assessment; and (3) a process for implementing installation-level assessments that emphasize stakeholder engagement, relevance, and communication and impacts evaluation/modeling paired with qualitative analysis of significance for mission attainment.

Results—The major results were the development of a three-tiered framework for DoD-wide vulnerability assessment, an outline of steps to guide the conduct of installation-level vulnerability assessments, and the identification of three sets of methods that are important for such assessments, as well as research needed on aspects of the assessment process.

The project also produced a climate outlook for the mid-Atlantic region, which was useful in identifying and quantifying climate-change impacts relevant to the installation-level priority systems established through stakeholder engagement processes. The climate outlook provides an overview of climate information relevant to vulnerability assessment of military installations. The analyses in the outlook integrate knowledge of current climate trends from observations with sources of information about possible future climates. The outlook integrates expert judgment about the state of science related to climate phenomena that were identified as important to installations in the region through the project's stakeholder interactions. The information in the outlook can be used with the vulnerability baseline established for an installation to identify potential future impacts of climate change that warrant additional assessment or adaptation planning. The outlook also provides a starting point for building awareness of climate change into extant planning and decision-making processes.

Finally, the project produced insights into impacts modeling approaches/methods and vulnerabilities at each case study location. Specific methods included event history analysis, coastal flooding return period analysis, storm surge modeling, fire risk and ecosystem maintenance, training and flag days, network interdependence analysis, heating and cooling degree days, and decision analysis. Elevation was explored as a proxy for vulnerability to sea level rise and storm surge through the creation of maps that combined elevation data and asset indicators; the web bulb globe temperature, a proxy for outdoor training disruption; and the Keetch-Byram Drought Index, a proxy for fire-prone conditions and disruption of planned controlled burns.

Benefits—Our research supports the following conclusions:

1. Vulnerability assessments provide essential and specialized information needed to determine the susceptibility and consequent risk of climate change to infrastructure assets. The DoD needs such information to successfully and efficiently manage climate risks.
2. Vulnerability should be defined as a function of the characteristics that affect the susceptibility of a site to damage, thus emphasizing sensitivity and adaptive capacity rather than exposure. This definition structures information collection and analysis, and points staff to the dimensions of infrastructure they can prioritize, measure, and manage.
3. A three-tiered assessment approach will increase efficiency and reduce costs while still allowing for detailed analysis where needed. Tier 1 screens all agency sites to set priorities. Tier 2 focuses on more detailed assessments at a smaller number of sites identified as most vulnerable by Tier 1. Tier 3 comprises analysis of adaptation options.
4. An established but flexible process for DoD installation assessments (Tier 2) would provide comparable results and adaptability for varied missions and operations. The case studies suggest a five-step process to meet DoD's needs: (a) frame the assessment, (b) appraise conditions and identify installation vulnerabilities, (c) analyze future climate exposure, (d) estimate/model potential impacts, (e) evaluate significance and next steps, (f) build assessment into ongoing processes, and (g) document and evaluate the process.
5. No "one size fits all" approach is appropriate for stakeholder engagement. Strategies must be tailored to take advantage of the expertise of staff who know how the installation works.
6. Information on future climate change needs to focus on installation- and area-specific variables, drawing on information sources including observations, projections, and scenarios of climate conditions, downscaling, and modeling of hydrology and other related environmental conditions. Projections should be made using diverse quantitative and qualitative methods.
7. The framework and process presented here have promise for future implementation, with (1) continued testing and evaluation of methods (for screening, engagement, priority setting), climate information, indicators and thresholds; (2) assessment of opportunities to integrate climate change considerations into ongoing planning and decision-making

processes; (3) development of training and technical guidance for participants and users of vulnerability assessments; (4) cataloging of available methods and establishing research programs to develop others; and (5) documenting of experience to perform lessons learned analysis.

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Acronyms and Abbreviations

AFB	Air Force Base
CDD	cooling degree day
CI	Condition Index
CMIP3	Coupled Model Intercomparison Project Phase Three
CMIP5	Coupled Model Intercomparison Project Phase Five
DoD	Department of Defense
FVCOM	Finite Volume Coastal Ocean Model
GCM	global climate model
HDD	heating degree day
HVAC	heating, ventilation, and air conditioning
ICEMAP	Installation Complex Encroachment Management Action Plan
IPCC	Intergovernmental Panel on Climate Change
JBLE	Joint Base Langley-Eustis
KBDI	Keetch-Byram Drought Index
MD _b	Interdependency (terminology specific to Mission Dependency Index)
MDI	Mission Dependency Index
MD _w	Intradependency (terminology specific to Mission Dependency Index)
NARCCAP	North American Regional Climate Change Assessment Program
NAVD88	North American Vertical Datum 1988
OSD	Office of the Secretary of Defense
PRV	present replacement value
SERDP	Strategic Environmental Research and Development Program
USNA	U.S. Naval Academy
WBGT	wet bulb globe temperature

Table of Contents

Abstract.....	iii
Acknowledgements.....	vi
Acronyms and Abbreviations	vii
Keywords	xi
Figures.....	xii
Tables	xv
1. Objective and Overview of the Report.....	1
2. Background	2
2.1 Climate change and the Department of Defense	2
2.2 Research to meet the challenge	3
3. Materials and Methods	5
3.1 Case studies to inform a DoD vulnerability assessment framework	5
3.2 Method for describing the state of knowledge of future climate change for the case study sites: The Climate Outlook	12
3.2.1 Context and background.....	12
3.2.2 Domain of mid-Atlantic regional climate change analysis	13
3.2.3 Overview of methods used and organization of the outlook.....	13
3.2.4 Approaches to describe uncertainty in climate information.....	16
3.2.5 Approach to presenting confidence in “key messages”	18
3.2.6 Climate Outlook results and evaluation	19
3.3 Selected methods used in the case study assessments.....	20
3.3.1 Event history analysis.....	20
3.3.2 Coastal flooding return period analysis	21
3.3.3 Storm surge modeling (USNA)	24
3.3.4 Fire risk and ecosystem maintenance (Fort Bragg).....	26
3.3.5 Training and flag days (USNA, JBLE, Fort Bragg).....	27
3.3.6 Network interdependence analysis (USNA)	30
3.3.7 Heating and cooling degree days (USNA, JBLE, Fort Bragg).....	32
3.3.8 Decision analysis (USNA)	33
4. Results and Discussion	35
4.1 Case study results: U.S. Naval Academy, Annapolis, Maryland	36
4.1.1 Baseline: background and establishing priorities	37
4.1.1.1 Background.....	37

4.1.1.2	Setting priorities: Buildings, transportation infrastructure, and outdoor activities.....	39
4.1.2	Buildings and transportation-related infrastructure: Sensitivity, historical exposure, and adaptive capacity	41
4.1.2.1	Sensitivity of infrastructure	42
4.1.2.2	Adaptive capacity related to infrastructure.....	49
4.1.3	Sensitivity, exposures, and adaptive capacity of outdoor activities	50
4.1.3.1	Sensitivity of outdoor activities	50
4.1.3.2	Exposure of outdoor activities	51
4.1.4	Climate change and potential future exposure at USNA.....	53
4.1.4.1	Methods overview for USNA-focused information on future climate	53
4.1.4.2	Summary of projected changes in exposure to flooding and extreme heat	53
4.1.5	Future vulnerability: Integrating baseline sensitivity and adaptive capacity with potential changes in exposure	57
4.1.5.1	Vulnerability to flooding	58
4.1.5.2	Vulnerability to temperature increases	61
4.1.6	Decision making: Current and potential future use of information on climate change and vulnerability	64
4.2	Case study results: Joint Base Langley-Eustis, Hampton, Virginia	68
4.2.1	Baseline: Establishing priorities and identifying current sensitivity, observed exposures, and adaptive capacity	69
4.2.1.1	Setting priorities: Buildings and other built infrastructure	69
4.2.1.2	Buildings and other infrastructure: Sensitivity, historical exposure, and adaptive capacity	70
4.2.1.3	Analysis of observed exposures	75
4.2.1.4	Adaptive capacity related to infrastructure.....	77
4.2.2	Climate change and potential future exposure	78
4.2.2.1	Methods overview for JBLE-focused assessment of future exposure.....	78
4.2.2.2	Projected changes in exposure to flooding and extreme heat.....	78
4.2.3	Future vulnerability: Integrating baseline sensitivity and adaptive capacity with potential changes in exposure	81
4.2.3.1	Vulnerability to flooding: Return period analysis	82
4.2.3.2	Vulnerability to temperature increases	85
4.2.4	Discussion.....	86
4.3	Case study results: Fort Bragg, Fayetteville, North Carolina.....	88
4.3.1	Baseline: Establishing priorities and identifying current sensitivity, observed exposures, and adaptive capacity	88
4.3.2	Climate change and potential future exposure	96

4.3.2.1 Climate change and potential future exposure at Ft. Bragg	96
4.3.3 Future vulnerability: integrating baseline sensitivity and adaptive capacity with potential changes in exposure.....	102
4.3.4 Discussion.....	106
5. Conclusions and Implications for Future Research/Implementation	108
5.1 Does DoD need to conduct climate vulnerability assessments?.....	108
5.2 Core concepts and evolving state of practice	111
5.3 Screening and assessment in a multi-tiered process	113
5.4 Tier 1: Climate vulnerability screening	115
5.5 Tier 2: Installation vulnerability assessments.....	118
5.5.1 Internally or externally led site assessments?.....	119
5.5.2 Draft framework for installation-level vulnerability assessments.....	120
5.6 Tier 3: Adaptation design	127
5.7 A typology of techniques and methods for vulnerability assessment	128
5.7.1 Engagement	131
5.7.1.1 The need for a wide range of engagement methods	133
5.7.1.2 Factors promoting participation.....	133
5.7.1.3 Use of extant sources of information.....	133
5.7.1.4 Challenges in assessing adaptive capacity.....	134
5.7.2 Methods for assessing and communicating potential future climate exposure.....	134
5.7.2.1 Tailoring climate information for impacts modeling	136
5.7.3 Estimating and modeling future impacts	136
5.8 Decision framing for vulnerability assessments	138
5.9 Research needs and gaps	145
5.10 Potential for implementation	147
6. Literature Cited.....	149
Appendix A Climate change outlook for the mid-Atlantic region (In an attachment)	157
Appendix B List of Scientific/Technical Publications	2

Keywords

Vulnerability assessment framework
Vulnerability assessment methods
Climate change
Extreme events
Decision support
Decision analysis
Risk management
Adaptation
Resilience
Adaptive capacity
Baseline sensitivity
Climate exposure
Climate outlook
Uncertainty
Stakeholders
Military installations
Mid-Atlantic
U.S. Navy Academy
Joint Base Langley-Eustis
Fort Bragg

Figures

Figure 1. Dimensions of vulnerability.	9
Figure 2. Map of military installations used as case studies for this project.	13
Figure 3. Observed trend (left) and future change (right) in daily minimum winter temperatures	15
Figure 4. Observed trend (left) and future change (right) in winter precipitation	16
Figure 5. Change in the number of days per year when there is a high risk for forest fires	17
Figure 6. Box plots of the change in domain averaged WBGT and flag day frequency by mid-century from the NARCCAP ensemble	18
Figure 7. Definitions of the different confidence levels	19
Figure 8. Return period and return level analysis at using GIS™	22
Figure 9. Return period analysis at a runway	23
Figure 10. Distribution of storm surge height for historical and future Hurricane Isabel ...	25
Figure 11. Change in number of days when prescribed burning is not recommended (KBDI > 600)	27
Figure 12. WBGT average daily maximum values from 1979 to 2010.....	28
Figure 13. Flag day observations at JBLE and Fort Bragg.....	30
Figure 14. Network representation of the interdependencies between functional areas.....	32
Figure 15. Influence diagram for site expansion and location decisions	34
Figure 16. Original shoreline of the Lower Yard in 1850 at the USNA.....	38
Figure 17. Elevations of USNA areas for evaluating infrastructure exposure to flooding..	39
Figure 18. Network representation of the interdependencies between functional areas using the MDI.....	41
Figure 19. Buildings that are in the upper quartile of the MDI	43
Figure 20. Upper quartile of replacement value and upper quartile of MDI	43
Figure 21. Classifications of flood damages.....	44
Figure 22. Comparison of a sensitive subset of the road network in the Lower Yard.....	46
Figure 23. The number of days each year the USNA experienced flooding.	47
Figure 24. Historical sea level from the Annapolis tide gauge.....	48
Figure 25. Tracks for the hurricanes that caused the two most severe flooding events at the USNA	49
Figure 26. Yearly occurrence of flag days.....	51
Figure 27. Yearly hazardous air quality events in Ann Arundel County, where the USNA is located.....	52
Figure 28. Historical sea level rise extrapolated to 2110 and expected sea level rise in 2055	54

Figure 29. Change in precipitation frequency.....	55
Figure 30. Ensemble mean, seasonal average temperature change	56
Figure 31. Range of uncertainty for the change in average daily mean temperature.	56
Figure 32. Projected trend in the number of 95°F (Tmax >35°C) that occur per year	57
Figure 33. Distribution of storm surge height for historical and future Hurricane Isabel. ...	59
Figure 34. Ensemble mean change (10 NARCCAP simulation ensemble) in the average daily maximum WBGT (°C) for May-September	62
Figure 35. Trends in the daily maximum WBGT (°C) for June, July, and August	62
Figure 36. Expected change in annual occurrence of black, red, yellow, and green flag days.....	63
Figure 37. Influence diagram for facility expansion/location decisions.....	66
Figure 38. Sensitivity of assets evaluated by spatial attributes at JBLE.....	72
Figure 39. Condition assessment metrics can help characterize assets in a vulnerability assessment	73
Figure 40. Return period analysis of facilities with greater than \$15 million PRV	74
Figure 41. Increasing frequency of flooding for the Sewell's Point tide gauge	76
Figure 42. Observed flag day occurrence for Joint Base Langley-Eustis based on analysis of the wet bulb globe temperature	77
Figure 43. Local sea level rise projection to 2100 using the Sewell's Point, Virginia, tide gauge.....	79
Figure 44. Potential for flooding if we superimpose the sea levels from the midpoint of the sea levels projected for 2055	80
Figure 45. Change in precipitation frequency.....	81
Figure 46. Return period analysis at Sewell's Point (across the mouth of the James River from both Langley AFB and Fort Eustis	83
Figure 47. Return period analysis at Sewell's Point (across the mouth of the James River from both Langley AFB and Fort Eustis with sea level rise projections.....	84
Figure 48. Return period analysis of flooding of training ranges at Fort Eustis.....	85
Figure 49. Observed and projected cooling degree days.	86
Figure 50. Red-Cockaded woodpecker nesting sites	91
Figure 51. Annual accumulation of precipitation in the mid-Atlantic region.....	93
Figure 52. Change in very heavy precipitation across the United States.....	93
Figure 53. Fort Bragg cantonment area.	94
Figure 54. Number of days each year when daily maximum temperatures exceed 95°F at Fort Bragg.....	95
Figure 55. Daily mean, maximum, and minimum temperature increases for Fort Bragg at mid-century.....	97
Figure 56. Multi-model or ensemble mean climate changes for three military installations.....	98

Figure 57. The box and whisker plot above shows the spread across the NARCCAP models for projected changes in rainfall for Fort Hood.	99
Figure 58. Multi-model or ensemble mean changes in precipitation for selected military installations.....	100
Figure 59. Percent change in precipitation from 1971-1999 to 2041-2069 for the mid-Atlantic region	101
Figure 60. Number of days per year that are conducive for the formation of severe or significant thunderstorms averaged over the mid-Atlantic region	102
Figure 61. Box and whisker plot representing the range of uncertainty for the change in the number of black, red, yellow, and green flag days expected to occur per year on average at Fort Bragg	104
Figure 62. Projections of changes in mid-century fire risk at Fort Bragg	105
Figure 63. Observed and projected cooling degree days	106
Figure 64. Vulnerability defined as a pre-existing condition based on characteristics of a facility or system.	112
Figure 65. Tiered, multi-criteria framework to vulnerability assessment.....	114
Figure 66. Proposed iterative process to assess vulnerabilities for DoD installations.....	120
Figure 67. Long-, medium-, and short-term elements of planning for DoD infrastructure	1420
Figure 68. Climate change factors, training, and the long-range planning process.....	144

Tables

Table 1. Steps Involved in a Sampling of Vulnerability Assessments	6
Table 2. Fire Risk Index.....	26
Table 3. Flag Thresholds and Impact on Training and Outdoor Activity Source.....	28
Table 4. Categories of Water Heights Defined by the Advanced Hydrologic Prediction Service and Adjusted to the NAVD88 datum	46
Table 5. Air Quality Index Values and Related Concerns.....	52
Table 6. Statistics of Storm Surge under Historical and Future Hurricane Isabel with Sea Level Rises (SLR)	60
Table 7. The Need for Vulnerability Assessments: Translating Exposure into Impact, Consequence, and Adaptive Management	110
Table 8. Methods Used in Draft Vulnerability Assessment Framework	1309

1. Objective and Overview of the Report

This report summarizes the results and conclusions gleaned from one of the four projects awarded by the Strategic Environmental Research and Development Program (SERDP) in response to Statement of Need RCSON-12-02. The overall technical objective of the project is to develop, pilot, and evaluate an approach for vulnerability assessment keyed to Department of Defense (DoD) decision-making needs and processes at both the headquarters and installation level. While other projects focused on developing climate data or testing specific modeling approaches or methods, our project targeted development of an overall assessment framework and a process for evaluating installations that applies extensive stakeholder involvement, a novel approach to providing climate information (likely future exposure), a range of existing models and approaches for estimating impacts, and decision-making frameworks. We used existing methods for projecting impacts or pointed to use of impacts models as a means of identifying specific damages or risks that could affect mission attainment. The case studies tested various methods to develop the overall approach and specific guidance for an installation-level process.

This report describes our research methods, findings, and conclusions. The next section provides an overview of the environmental issue that our research addressed and its importance to DoD and regulatory requirements. Section 3 discusses the method we used to develop the vulnerability assessment framework and process, using our experience at the three case study installations. In addition, it provides brief descriptions of the experiments we performed in the course of the installation-level investigations. The report does not describe all the methods used in detail and instead provides references to the existing methods. We discuss how we applied the methods and what we learned from them about vulnerability assessment and, in some instances, what additional research might be performed to improve the methods or make them provide more useful results in the context of vulnerability assessment. Section 4 describes our three case studies, conducted at the U.S. Naval Academy (USNA), Joint Base Langley-Eustis (JBLE), and Fort Bragg. For each case study, we present results and discuss the implications for our research questions. When restricted data or information was used to conduct the case study, we abstract or generalize the findings. Section 5 presents the conclusions regarding an overall assessment framework and a decision-focused process at high-priority installations and sites. The conclusions include implications for implementing the approach to vulnerability assessments as well as further research that is needed. Section 6 lists the references cited; the appendices provide further technical detail.

2. Background

Climate change will affect all facets of the Department of Defense (DoD), including its ability to complete operations effectively around the world, provide an optimal location for deployment of resources, and train and maintain personnel and resources. Executive orders require Federal agencies to conduct vulnerability assessments for their installations. However, specific guidance on methods is still evolving based on the different frameworks available. This report details the methods, findings, and conclusions from the DoD Strategic Environmental Research and Development Program (SERDP) project, Understanding Data Needs for Vulnerability Assessment and Decision Making to Manage Vulnerability of DoD Installations to Climate Change. We tested diverse methods for conducting vulnerability assessments at three military installations in the mid-Atlantic region of the United States. The objective of the study is to develop, pilot, and evaluate approaches for vulnerability assessment keyed to DoD decision-making needs and processes.

2.1 Climate change and the Department of Defense

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2013) and the Third U.S. National Climate Assessment (Melillo et al. 2014) assess results from a large number of research studies and reports and conclude that impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires, have been observed, are becoming more widespread, and will cause significant challenges in the future. The reports document that many managed and natural systems are vulnerable to potential future conditions. Given the projected rates of climate change over the next century, the potential exists for historically unprecedented impacts.

To address these challenges, U.S. Government agencies are now directed to assess the vulnerability of their operations and facilities to climate change to anticipate and prepare for its impacts. The need for addressing climate change is recognized in two Executive Orders: 13653 (2013), Preparing the United States for the Impacts of Climate Change, and 13693, Planning for Federal Sustainability in the Next Decade (2015). Executive Order 13653 in particular focuses on adaptation (referred to as climate preparedness) and resilience, and highlights the need for addressing climate change for defense purposes. It requires agencies to assess proposed and completed changes to their land- and water-related policies, programs, and regulations in the face of climate change. Executive Order 13693 instructs agencies to ensure that operations and facilities prepare for climate change as part of the requirement to develop, implement, and annually update an integrated Strategic Sustainability Performance Plan and reemphasizes the need to meet planning requirements in Executive Order 13653. In response to the orders, agencies are conducting vulnerability assessments and planning adaptation measures using different approaches.

The task confronting the DoD is enormous. To begin with, the DoD is responsible for 7,000 sites (of which approximately 510 are active installations), 24.9 million acres of land, and many activities and services upon which millions of Americans depend. DoD owns and/or operates more facilities than any other Federal agency (DoD 2015). The Department is the nation's largest employer. Moreover, many of the nation's military installations and assets they depend on

(energy and transportation infrastructure, etc.) are in areas exposed to frequent extreme weather events, such as naval bases located in hurricane-prone zones (Schwartz et al. 2014). As a result of climate change, DoD planners and managers face difficult questions and decisions regarding potential impacts on military resources, services, and readiness. Two recent DoD Quadrennial Defense Reviews (DoD 2010 and DoD 2014) describe two major sets of consequences:

- Climate change will act as a potential threat-multiplier for future conflict (that is, changing where they will need to deploy resources in the future and potentially making it more difficult to do so)
- Without adequate adaptation, climate change will degrade the ability of the Services to meet their missions.

In the 2010 DoD Quadrennial Defense Review, the Office of the Secretary of Defense announced its intention to develop a strategic approach for addressing climate change and energy challenges. The Department has already developed and submitted several adaptation plans to the President's Council on Environmental Quality.

The DoD will continue to train soldiers and new recruits, deploy forces, and build bases across the world. Determining how the configuration of DoD assets will need to change to meet the changing demands of tomorrow—including the constraints of a changing climate—requires developing information on potential impacts and their significance to mission continuity and attainment. This information needs to be provided in a fashion that enables the Department to provide sound stewardship for the Federal government's investment in extant installations and to avoid new investments in facilities that will not be fit for purpose as a result of changing climate conditions.

2.2 Research to meet the challenge

Recognizing the critical importance of assessing the vulnerability of DoD's infrastructure—long-lived assets, both engineered and natural—to climate change impacts, the SERDP issued Statement of Need RCSON-12-02. The Statement of Need focused on five specific needs, four of which addressed broad areas of vulnerability assessment and the importance of connecting weather- and climate-related conditions to decision-making processes. This project responds to these specific needs:

1. Types of weather-related decisions that DoD natural and built infrastructure planners and managers already make, how weather affects those decisions, and the temporal and spatial nature of those decisions.

We tested methods to assess conditions on installations, catalog impacts and damages from past and ongoing climate events, and evaluate what these indicate about vulnerabilities on the installations.

2. Relationship of the currently available output information, and the information projected to be available within the next 5 years, from global climate models (GCMs) and Earth

system models, regional climate models, and derivative products to the extant type of information used by planners and managers to make decisions.

We investigated use of climate information to manage vulnerabilities and planning or implementing responses. We also identified upcoming decisions for which climate change poses a threat and analyzed climate information needs for vulnerability assessment.

3. Opportunities to improve the match between the type of information planners and managers need versus what is potentially available from the global and regional models and derivative information products. Opportunity assessment at regional spatial scales should include appropriate consideration of sources of certainty and uncertainty that address the decisions to be made when applying statistical refinement or other techniques (for example, downscaling) to global model outputs.

We piloted an expert-judgment-based process for preparing a regional “climate change outlook” of data and information relevant to the installations included in our case studies. The outlook focuses on the types of events that have been important in the past and new exposures that could develop as a result of climate change.

5. Development and use of decision-support strategies and analytic methods that support adaptive strategies whose performance is relatively insensitive to poorly characterized uncertainties.

The project was designed to support the applied research and development components of SERDP’s mission by identifying the types of climate information that are used and needed by DoD personnel, exploring methods and assessment frameworks, testing these data and methods in a small number of case studies, and evaluating experience gained.

In sum, the project has produced results that can both inform DoD vulnerability assessment methods and contribute to the broader research literature on approaches for assessing the vulnerability of infrastructure and natural systems to future changes in climate.

3. Materials and Methods

This section focuses on the case study approach we used to answer the five research questions posed in our proposal. Our focus is on the methods we used to test efficiency, accuracy, and feasibility (in a DoD context) of different approaches to vulnerability assessment. To identify different frameworks for assessment, we reviewed the literature on vulnerability assessments and tested promising features of existing processes as well as exploring new approaches. In conducting the case studies, our purpose was not to complete an “assessment” for each installation. Rather, we conducted research as part of the case studies to explore the potential utility of and needs for a variety of data and techniques potentially relevant to an installation assessment process. We emphasized extensive stakeholder involvement, a novel approach to providing climate information (likely future exposure), and methods to project impacts and evaluate their significance for missions. Based on these results, we developed a three-tiered framework that included a screening process, vulnerability assessments at installations prioritized through screening, and more detailed analysis to support adaptation planning and decision making. Most of the research we conducted focused on the middle tier, the installation vulnerability assessments.

Sources of uncertainty in the proposed methods include both the sampling rate and accuracy of the LIDAR data input, which can vary substantially (i.e., both in the horizontal resolution and vertical accuracy). Additional uncertainty arises from the accuracy of the historical record, as well as the distance of the application from the tide gauge. Additional tools are necessary should the user wish to use these methods in areas with poor tide gauge coverage.

This section also provides descriptions of techniques and methods for stakeholder engagement processes, analysis and communication of impacts-relevant climate information, and impacts estimation including statistical analyses, geographical information systems, and a variety of impacts models. These methods require a wide range of environmental, climate, technical, and socioeconomic data drawn from publicly available climate and environmental datasets, installation-specific records, Service-wide information management systems, and surveys.

Specific applications of the methods occurred during the case studies and are described in Section 4 (results). In some cases, this discussion includes description of methods that overlaps with descriptions in this section, in part because there are differences in application across the cases because each case presented unique challenges when it came to tailoring and applying any particular method. In addition, some methodological description is needed in the case study descriptions in order to provide enough information so each case could be read as a “stand alone” document.

3.1 Case studies to inform a DoD vulnerability assessment framework

The first step in our research was to review various vulnerability assessment methods-in-use (including Turner et al., 2003; Schröter et al., 2005; Füssel, 2006, 2007; Yohe and Leichenko, 2010; Glick et al., 2011; DOT, 2012; Csete et al., 2013; Buotte et al., 2014).

In initial efforts, we structured the case studies using common conceptual elements of exposure, sensitivity, and adaptive capacity. However, our approach stressed learning from interactions with stakeholders, data about the installations and their missions, and tools that might be useful within their decision-making processes. Thus, we evolved our conceptual approach and working definition of vulnerability. These changes were not finalized until research at the case study sites was mostly complete and are discussed in conclusion section (Section 5).

In consultation with the Strategic Environmental Research and Development Program (SERDP) office, the military services, and several candidate sites, we selected three major installations in the mid-Atlantic region of the United States as the locations for our research:

- U.S. Naval Academy (USNA) in Annapolis, Maryland
- Joint Base Langley/Eustis (JBLE) in Hampton and Newport News, Virginia
- Fort Bragg in Fayetteville, North Carolina.

Table 1 compares steps for site-specific vulnerability assessments included in three of the foundational analyses.

The approach we developed merges facets of these and other approaches and combines them to facilitate DoD's assessment of fixed infrastructure assets, whether natural (ecosystems for training, lands managed for conservation and renewable energy production, etc.) or built (runways, electricity grids, buildings, etc.). These elements are summarized in a diagram from Polsky, et al. (2007) (see Box 1 and Figure 1), slightly modified here to suggest DoD-specific factors. While we present the assessment process as an ordered sequence of steps, it will likely be necessary to cycle back, repeat some steps, and even change direction as new insights are developed through the process.

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- Fort Bragg in Fayetteville, North Carolina.

Table 1. Steps Involved in a Sampling of Vulnerability Assessments

Schröter et al. (2005)	Füssel (2007)	Csete et al. (2013)
(1) Collaboratively define the study area with stakeholders.	(1) Identify the system of analysis.	(1) Identify a supply typology, that is, sub-divide the sector of interest based on the weather and environmental dependence of the activity of interest.
(2) Get to know the place over time.	(2) Identify the attributes of concern.	(2) Identify exposure indicators, which should capably describe the spatially differentiated exposure of the locations of interest, in addition to the other components of exposure (socio-economic and environmental factors, climate factors, etc.).

¹ In response to a request from Air Force liaison to SERDP, Mr. Daniel Kowalczyk, the investigators explored conducting an additional case study at Dare County Bombing Range. We made a site visit and met with staff at the Air Force portion of the range, as well as reviewed extant reports such as the Integrated Natural Resources Management Plan. In these discussions we learned Dare County Bombing Range staff have been interacting with The Nature Conservancy on a hydrology project to control salt water intrusion that results from wind-driven tidal flows and that could be worsened by sea level rise. The Dare County Bombing Range Integrated Natural Resources Management Plan mentions potential climate-related issues and projects that could improve hydrologic flows. We determined that modeling the coastal inundation processes and sea level rise could provide interesting data and an opportunity to test use of these results in the context of vulnerability assessment. This project was not included in our SERDP budget and additional resources were required to complete it. A supplementary proposal was prepared in response to a request for further information arising from interim reporting but was not acted upon. Therefore, we have decided not to list Dare County Bombing Range as a case study site.

Schröter et al. (2005)	Füssel (2007)	Csete et al. (2013)
(3) Generate hypothesis of system vulnerabilities (and to what).	(3) “Identify the hazard or potential event that might damage or affect the system of analysis and the particular attribute of concern.”	(3) Identify sensitivity indicators, “a characteristic function of the affected system.”
(4) Build causal model(s) of vulnerability.	(4) Identify the temporal reference, which can be either a point in time or period of interest.	(4) Identify indicators of adaptive capacity.
(5) Develop indicators for system vulnerabilities.	(5) “Identify the internal (i.e. from within the system of analysis), external (i.e. outside the system), and cross-scale vulnerability factors.”	(5) Develop vulnerability maps. Vulnerability assessments of this type have tended to focus on larger areas of interest, predominantly regions.
(6) Operationalize the vulnerability model(s).	(6) “Identify the knowledge domain, which includes socio-economic, biophysical or integrated factors.”	<i>Note: Vulnerability assessments of this type have tended to focus on larger areas of interest, predominantly regions.</i>
(7) Project future vulnerability.		
(8) Communicate vulnerability.		

Box 1: Dimensions of Vulnerability

The most frequently used definition of vulnerability is the degree to which a system or exposure unit is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. It comprises:

1. *Exposure to climate change*—the character, magnitude, and rate of climate change and variation to which a system is subjected
2. *Sensitivity*—the extent to which the function or structure of a system—natural or constructed—is impeded by exposure
3. *Adaptive capacity*—the extent to which adjustments are possible that reduce negative impacts

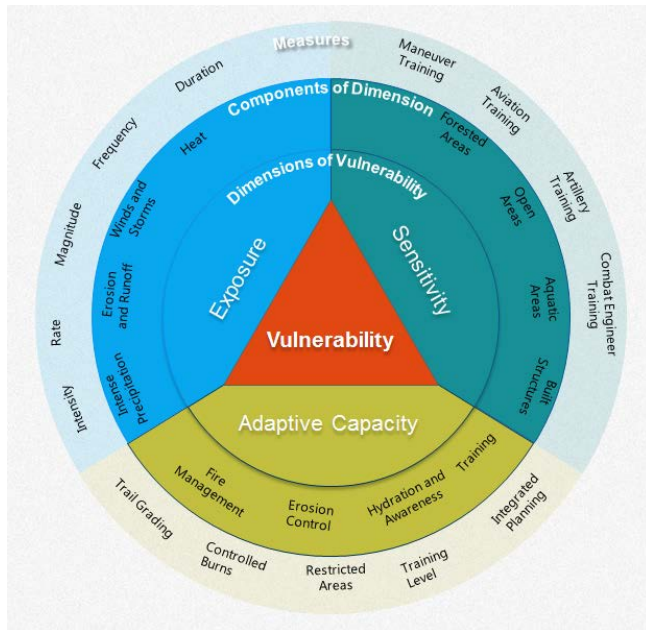


Figure 1. Dimensions of vulnerability / Diagram, modified from Polsky et al. (2007), was the concept used in conducting the case studies. Feedback from case study sites indicated that its focus on exposure (a variable out of the control of installation personnel) distracted from the importance of site-specific conditions in influencing vulnerability.

The selected installations represent a range of missions, including the U.S. Navy's officer development institution, Air Force air training logistics and force protection, and Army's maneuver and training work. The installations also provide a range of facility sizes, coastal and inland locations, types of infrastructure, potential climate stresses, and decision processes.

We structured our research around five key questions:

1. What are the present set of exposures and vulnerabilities of the DoD installation?
2. How do DoD decision makers use available information on extremes and seasonal variability to manage assets and operations? What information could be used but isn't, and what additional information would be useful if it were available?
3. Using insights from a global climate model (GCM), downscaling methodologies, observations, and climate processes research, what information can be provided about the likelihood of potentially significant current climate exposures and future changes in significant climate exposures for the region in which the facilities are located?
4. What are the risks to the selected DoD installations of potential changes in climate, considering installation vulnerability and its consequences for missions or readiness and the likelihood of regionally important changes in climate exposures?
5. How can vulnerability assessments be structured to produce information that has high value for DoD personnel in ranking current and future climate risks and establishing

priorities for implementation of adaptation? How might this information be effectively used in future decision making?

We used the case studies to identify and examine existing vulnerability to climate and extreme weather and review decision processes to clarify future climate information needs and to test various experimental methods.

To answer the research questions, we used the following techniques and methods:

- *Framing and preliminary analysis*—We took a number of preparatory steps to frame our work, set priorities for the research, and gather preliminary information. This included conducting a series of teleconferences, in which we discussed the project and needed participation from site personnel, based on written materials we had sent before the call. We requested and received installation-specific information from some Service-level datasets and used this information to form initial impressions of what issues may be important. We made a presentation on climate change and vulnerability and the project (in person at USNA, via webinar for JBLE and Fort Bragg) and probed for additional data that would be relevant to establishing current exposures, priority systems that are affected by these exposures, and staff level of concern at the site.
- *Information gathering and site visits*—We visited the installations to learn more about specific aspects of the mission activities and supporting infrastructure. We discussed with site personnel the priority infrastructural systems that should be assessed for their vulnerability to climate change. During the site visits we requested data relating to the mission importance of those systems and their condition to assess vulnerability and pertinent to historical damages from events (such as flooding and heat stress) that may change as the climate changes. The visits unfolded differently: at USNA, there were repeated short meetings; at the other installations, we planned and conducted longer visits with specific sessions focused on different issues.
- *Identifying climate-related decision making*—we asked about decisions that incorporate climate or weather factors (such as a decision to implement protective actions or curtail/cancel training) and about decisions that perhaps should include climate information (such as long-range planning) but do not now include it. For one study site, we developed an influence diagram, using an established decision science method. Toward the end of the project, we reviewed established DoD and military service decision processes that influence multiple decisions across many sites to identify leverage points at which climate information should be incorporated.
- *Constructing the vulnerability baseline*—After priorities had been established, we catalogued and assessed the current condition of these assets (for example, transportation facilities, buildings, other infrastructure such as electricity transmission systems, and natural resource infrastructure such as ecosystems used for training) and documented ongoing impacts to infrastructure and training activities (for example, cancellation of training activities due to unfavorable conditions). Our objective was constructing a “vulnerability baseline” for each of the case studies to evaluate the extent to which extreme events and seasonal climate variability have in the past impacted the subject.

Work on establishing the baseline conditions included testing approaches to develop both qualitative analysis and quantitative indicators based on age, location, and engineering characteristics of the installation, the extent of observed impacts from extreme events or extent of departure of seasonal climate normals, and the potential for adaptation.

- *Prioritizing and preparing climate information*—We identified needs for climate information on potential changes in exposure by talking to installation personnel and discussing decision making. This information on needs was used to set priorities for subsequent detailed analysis of impacts-relevant climate variables such as fire risk indicators, measures of heat exposure related to outdoor activities, wind speed, and others. When information needs were identified before site visits, this information was presented during the site visit. Otherwise, the climate information of future climate exposure was used with techniques (both qualitative and quantitative) to estimate potential impacts. As this information was developed, it was assembled into the “Climate Outlook for the Mid-Atlantic” (Appendix A). This approach presents narrative and graphical information about impacts-relevant phenomena important to installations in the region. It is an expert-judgment-based approach that considers a variety of data about future climate.
- *Evaluating future impacts*—We integrated information from the baseline conditions, decision analysis, and Climate Outlook to assess the risks that the identified climate change exposures would present. For one case study site, we modeled the projected impacts of storms such as Hurricane Isabel. For all of the study sites, we provided projected outcomes of climate change factors such as flooding, fire, and heat. We tested a variety of techniques, in some cases using proxy variables such as digital elevation maps (as an indicator of current and future flooding risk), fire risk projections (using a measure of fire-prone conditions), and heat/humidity interference with training (using the wet bulb globe temperature [WBGT]).
- *Presenting experimental results*—We prepared outbriefs of results for the case study sites and revised them in accordance with comments received from site personnel.
- *Drawing up lessons learned*—Not all of these experiments were successful for a variety of reasons (see Section 4). In the final phase of the project, we drew lessons from the case studies, learning from both the successes and failure of techniques we tested. We synthesized across the cases and analyzed the implications for structuring future assessments to support prioritization of adaptation measures, specifically focusing on decision-support strategies and analytic methods for ongoing infrastructure decision-making processes. We developed a three-tiered framework for DoD-wide vulnerability assessment, an outline of steps to guide the conduct of installation-level vulnerability assessments (the middle tier), and identified three sets of methods that are important for such assessments, as well as research needed on aspects of the assessment process. These products of the project are further discussed in Sections 4 and 5.

In the rest of this section, we discuss specific methods and experiments that we undertook in the course of the case studies. We discuss the Climate Outlook, which brings together different sources of future climate projections and focuses the results to enable vulnerability analysis.

Also, we describe nine specific methods that were used in an experimental fashion to test their likely usefulness in assessing vulnerability (we also scoped additional methods or established the relevance of available impacts modeling approaches but did not use them either because the applications were well established or the resources required exceeded those available). Again, the intent is not to present a complete suite of appropriate methods for vulnerability assessment; one research need is to develop and extend other methods.

3.2 Method for describing the state of knowledge of future climate change for the case study sites: The Climate Outlook

Our research included exploring approaches for providing information on future climate exposure that was useful to vulnerability assessments of the installations. A major component of this research was preparing a “Climate Outlook” for the mid-Atlantic region. The purpose of the Climate Outlook is to provide an overview of climate information relevant to vulnerability assessment of military installations. The analyses in the outlook integrate observation-based knowledge of current climate trends with sources of information about possible future climates. The outlook provides an integrated expert judgment about the state of science related to climate phenomena that were identified as important to installations in the region through the project’s stakeholder interactions. The information in the outlook is intended to be used with the vulnerability baseline established for the installations to identify potential future impacts of climate change that warrant additional assessment or adaptation planning. The outlook also provides a starting point for building awareness of climate change into extant planning and decision-making processes. This Climate Outlook builds upon information that appears in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and the Third U.S. National Climate Assessment. However, the outlook is more detailed and includes more local and region-specific sources of information. The entire Climate Outlook for the mid-Atlantic region can be found in Appendix A.

3.2.1 Context and background

The term “climate outlook” has traditionally been used to refer to shorter-term seasonal outlooks of climate (seasonal forecasts). However, the term has been used, as we use it here, to refer to an integration of information about longer-term future climate. In this case, knowledge of historical, observed trends in climate are combined with sources of future climate information. Using an expert-judgment approach, projections for future climate on a regional scale are then projected. Essentially, this is the approach that was used in the IPCC Fourth Assessment Report (Christensen et al., 2007) for regional projections, and was used to some degree in a series of compilations of regional climate information prepared for the Third National Climate Assessment (Melillo et al., 2014). This concept was introduced at several early workshops associated with the National Climate Assessment; for example, at the December 2010 Workshop on Scenarios for National Climate Assessment: Supporting the 2013 National Climate Assessment Report and an Ongoing Assessment Process (NCA, 2011).

3.2.2 Domain of mid-Atlantic regional climate change analysis

While most of the Climate Outlook focuses on the entire mid-Atlantic region, we have also performed case studies to develop specialized information for each of the installations where research was conducted (Figure 2). These installations are highlighted on the map with red dots.



Figure 2. Map of military installations used as case studies for this project / The domain of the mid-Atlantic region used for the Climate Outlook with the locations of the military installations used as case studies for this project.

3.2.3 Overview of methods used and organization of the outlook

As described in Section 3.1 (case study method), direct communication with personnel on each of the military installations was critical for the development of the Climate Outlook for the mid-Atlantic region. Using information collected about each installation, the investigators identified the specific climate exposures and indices that were potentially relevant to a vulnerability assessment. In addition to preparing an overview of knowledge of climate change for the region, analyses of these unique climate impact indices were developed for use on the installations and inclusion in the Climate Outlook.

Here, we provide an overview of the Climate Outlook, highlighting information about the variables studied, methods used, and the key messages of our findings. Detailed results are included in the context of discussion of the case studies conducted at each installation (see Section 4). As discussed below, two unique aspects of the Climate Outlook include our detailed discussion of the uncertainty associated with the climate change results and the inclusion of our expert judgment about the confidence in the key messages.

The Climate Outlook is organized by the climate variables of interest. This includes analysis of basic climate variables such as temperature and precipitation, as well as impacts-relevant variables such as heat stress, potential fire risk, and energy consumption. We also briefly cover potential future sea level rise that will be critical for coastal installations. For each variable, we present the historical climatology, observed trend, and future climate projections.

To examine the historical context of climate change for the mid-Atlantic region, we combine data from multiple sources including in situ surface observations, gridded observed meteorological datasets, and reanalysis. Each dataset has a unique set of advantages. Combining multiple data types improves our confidence in understanding historical climate trends.

Future climate projections are derived from both GCMs (Climate Model Intercomparison Projects 3 and 5 [CMIP3 and CMIP5]) and regional climate models (NARCCAP). In all cases, future projections are for the middle of the 21st century (2041-2070) relative to the current (1971-2000) reference time period. This time period was selected because it is far enough in the future so that distinct signals of climate change are evident, but it is close enough to the current period so that there is some relevance for adaptation needs. The NARCCAP and CMIP3 models follow the IPCC Special Report on Emissions Scenarios “A2” greenhouse gas emissions scenario, while the CMIP5 results follow the Representative Concentration Pathway (RCP) 8.5 trajectory. By the mid-21st century, greenhouse gas concentrations are similar in the two scenarios. By calculating changes in future climate with multiple models forced with comparable greenhouse gas concentrations, we are able to examine the structural uncertainty in future climate associated with different modeling methods and different model configurations. For mid-century, structural uncertainty based on differences in model results is the main source of uncertainty. As we go further out in time, there are larger uncertainties associated with the scenarios of greenhouse gas emissions, aerosols, and land use.

Below we present some of the ways in which we display the observed trends and future climate changes for the mid-Atlantic. For most variables we start by showing their observed trend between 1970 and 2012. Figure 3 (left panel) shows an example of the observed trend in daily minimum temperatures during winter. Daily minimum winter temperatures have experienced a statistically significant increase at the 90% confidence level (shown by hatching) over the past 42 years at every location in our region. Increases range from 0.6 to 3.0°F between 1970 and 2012, with the largest increases found to the north and the smallest increases to the south. Both the NARCCAP ensemble of regional climate models and the combined CMIP3 and CMIP5 global model ensembles project that daily minimum temperatures during winter will also increase by mid-century. In this case, temperature increases range from 3° to 6°F by mid-century. Again, these changes are statistically significant. For variables in which there is considerable agreement across the models about the sign and magnitude of the future change, we focus our results on the ensemble mean results (as shown in Figure 3 [right panel] for daily minimum winter temperatures).

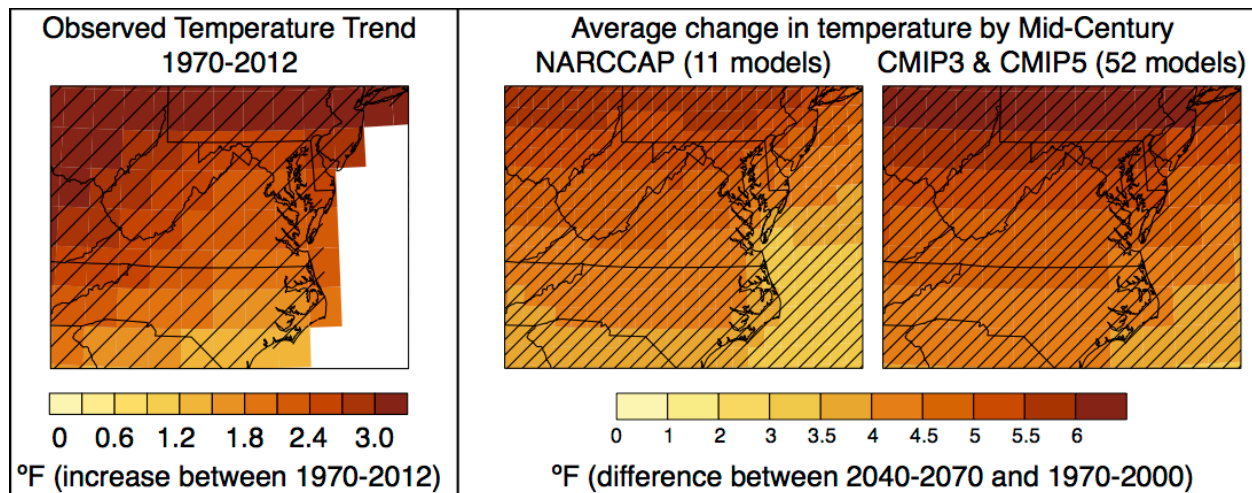


Figure 3. Observed trend (left) and future change (right) in daily minimum winter temperatures / Observed trend is calculated between 1970 and 2012 and is from the Berkeley Earth gridded temperature dataset. Future changes are shown for the NARCCAP ensemble and the combined CMIP3 and CMIP5 ensembles. Future changes are calculated for 2041-2070 relative to the current reference period of 1971-2000.

Figure 4 (left panel) demonstrates that between 1970 and 2010, winter precipitation rates have decreased (increased) in the southern (northern) half of the mid-Atlantic domain. In both cases, values greater than 0.4 are statistically significant at the 90% confidence level. Because precipitation is a much noisier field than temperature, and there is more natural day-to-day variability in precipitation, observed trends are not as robust as for temperature. Extending into the future, we see from the NARCCAP ensemble and the combined CMIP3 and CMIP5 ensembles that winter precipitation is projected to continue to increase over the northern half of the domain. In this figure, the degree of agreement across the model ensemble members is highlighted by the intensity of the colors, with light colors and grey indicating that many of the models disagree on the sign of the change. This is one way we can show the uncertainty about future projections. Appendix A gives a more detailed explanation of observed trends and future changes in precipitation. While the models are in reasonable agreement about future changes in winter precipitation, during summer, the models show much less agreement. While many models indicate precipitation will decrease in the summer over much of the mid-Atlantic region, some show potential increases.

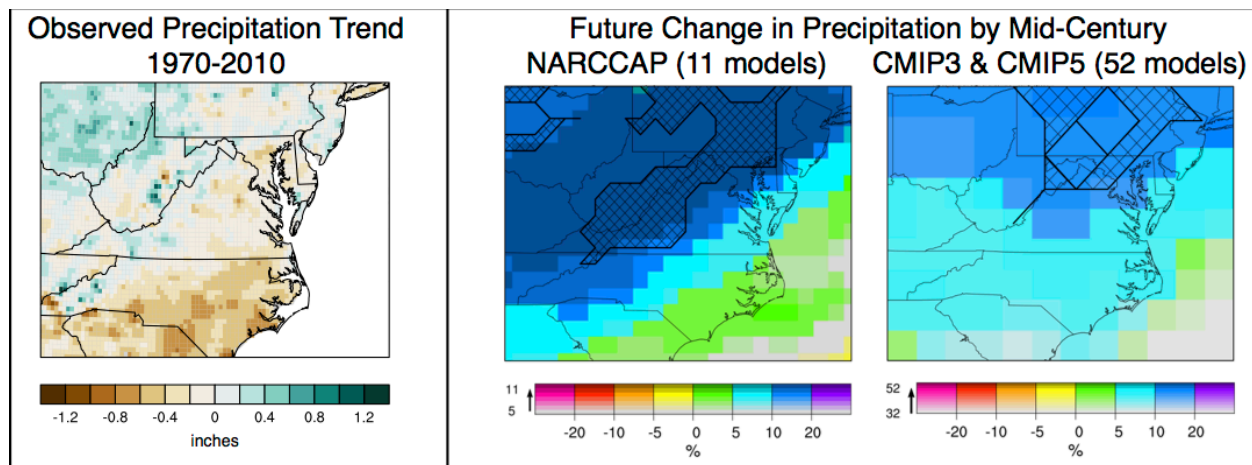


Figure 4. Observed trend (left) and future change (right) in winter precipitation | Observed trend is calculated between 1970 and 2010 from the Maurer dataset. Future changes are shown for the NARCCAP ensemble and the combined CMIP3 and CMIP5 ensembles. Future changes are calculated for 2041-2070 relative to the current reference period of 1971-2000. In the future change plots, the degree of model agreement is indicated by the intensity of the colors, grey indicates low model agreement on the sign of the change. Hatching indicates results are statistically significant.

3.2.4 Approaches to describe uncertainty in climate information

For complex variables and variables where there is less agreement in the climate changes across the models, we show the uncertainty in the future projections in two ways: maps and box plots. To highlight the spatial variability and uncertainty in future changes, we show maps of the median (50th percentile) and the interquartile range (difference between the 25th and 75th percentiles) of the change. For example, in Figure 5, we show the spread in the NARCCAP models for the increase in the average number of days per year with a high risk for forest fires. The Keetch-Byram Drought Index (KBDI) shown in the figure combines accumulated temperature and precipitation throughout the year to predict the potential for extreme fires (Keetch and Byram, 1968). When the KBDI exceeds 600, the risk for forest fire is extreme. As you can see from Figure 5, there is considerable uncertainty across the NARCCAP models about the change in the number of days when KBDI > 600 by mid-century. Some models show increases of 60 day/yr (2 month), while others show increases of only 6-12 day/yr. This result suggests that the risk for more frequent or extreme forest fires is expected to increase, but with uncertainty regarding the magnitude. In this region, where prescribed burning is an important ecosystem management tool, this is a critical result, as it may change how frequently prescribed burns can be performed, and indicates resources for safe fire management may need to be allocated differently in the future.

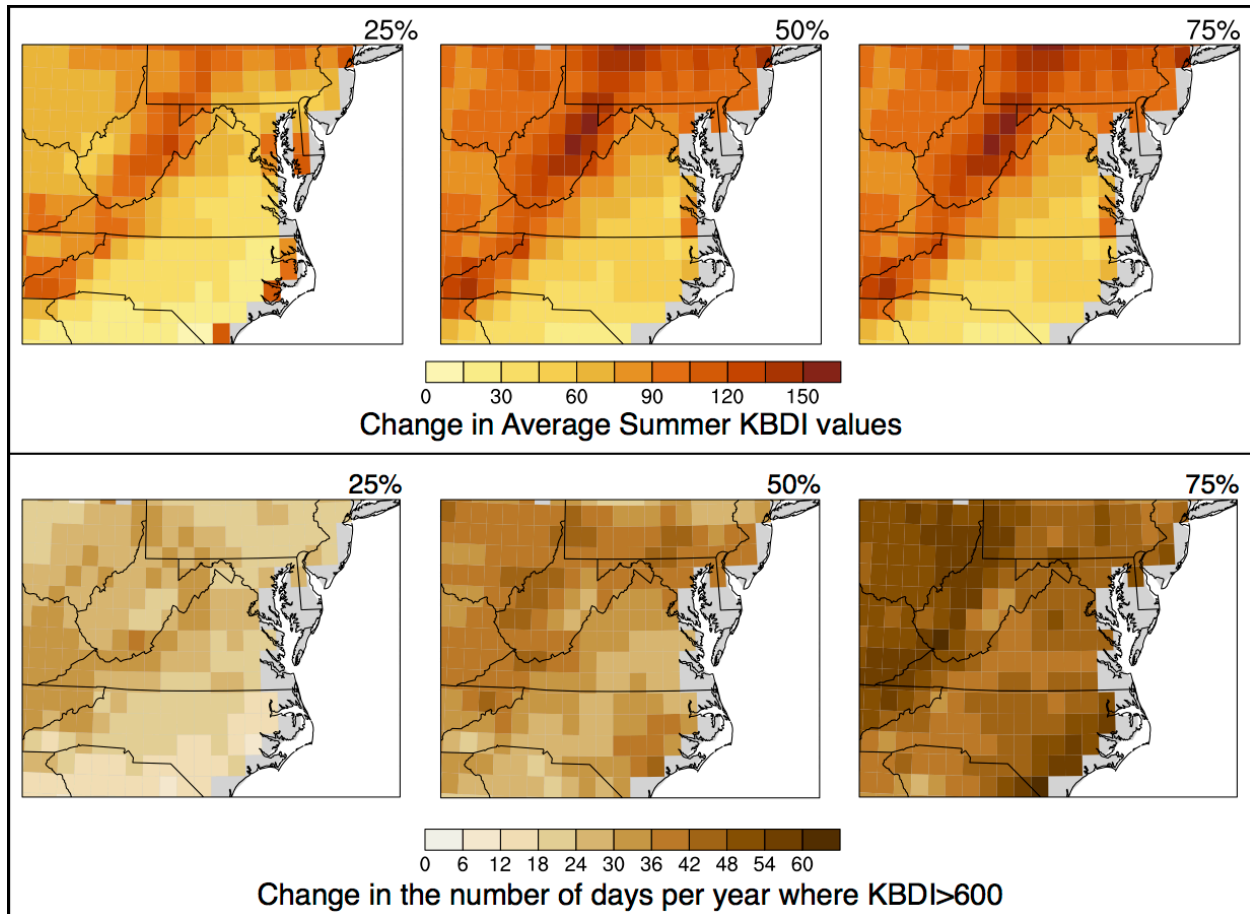


Figure 5. Change in the number of days per year when there is a high risk for forest fires / The graphs show the 25th, 50th (median), and 75th percentiles of the change in the average number of days per year where the KBDI exceeds 600 from NARCCAP. When KBDI > 600, there is the potential for extreme forest fires.

We also display the uncertainty in future climate change through box plots. Figure 6, left panel, shows the spread in future changes of a heat index, the WBGT, commonly used by the military, and the right panel shows the spread in the change of the frequency of heat restriction, or flag day, occurrence due to increases in the WBGT. In both cases, the box plots represent the change averaged over the entire mid-Atlantic region. With box plots we can see, for example, for WBGT, that there is less spread in the annual mean changes than in the summer (June-August) changes. The larger spread for the change in summer WBGT indicates larger model uncertainty. For flag day occurrences, there is considerable spread in the change in the number of black (extreme heat) and green flag (mild heat) days, but little spread in the red and yellow flag day restrictions. We believe this range is in large part a function of model bias (that is, the number of black flag days is too low in the current climate to begin with) and are investigating methods of accounting for this bias. The construction of the WBGT from climate models requires a number of assumptions and empirical calculations, which also limits our confidence in these results.

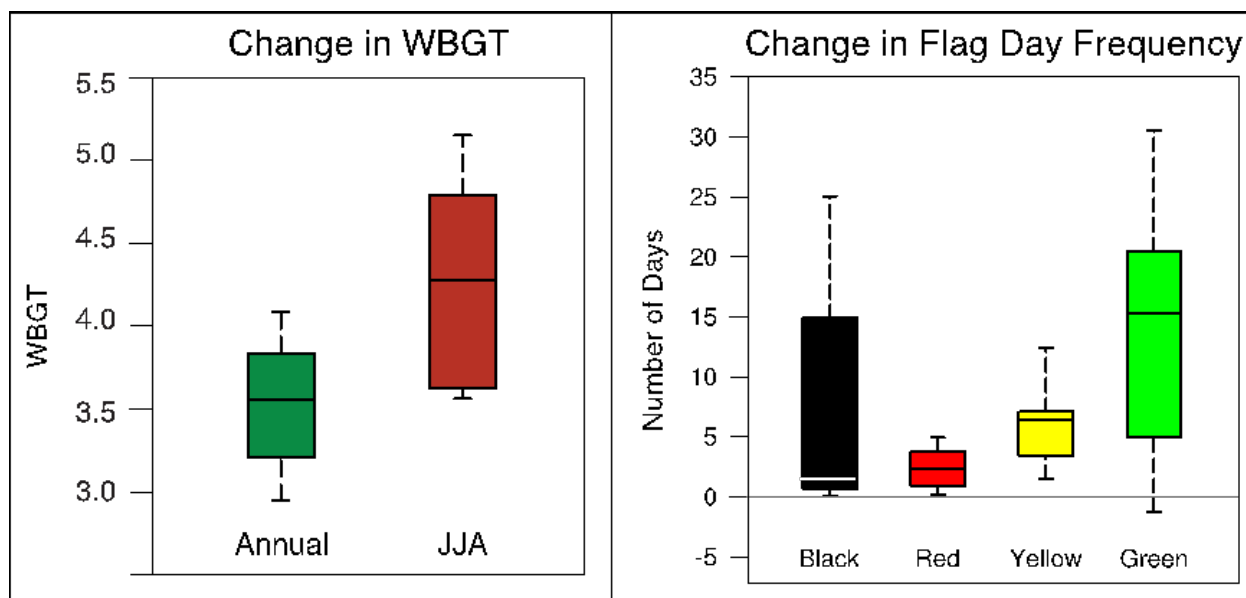


Figure 6. Box plots of the change in domain averaged WBGT and flag day frequency by mid-century from the NARCCAP ensemble / The box is made up of the median (50th percentile) horizontal line within the box, the 25th and 75th percentiles (the horizontal ends of the box), and the maximum and minimum values (smaller horizontal lines extending beyond the upper and lower ends of the box).

3.2.5 Approach to presenting confidence in “key messages”

As part of the Climate Outlook we provide a list of our key messages that highlight the important climate change results for the mid-Atlantic region. We also provide our confidence in the results based on our expert judgment of the supporting evidence (for example, quality of observations, model agreement), confidence in the methods applied, and consistency and physical basis for the results. Our rating system uses Very High, High, Medium and Low confidence values and is outlined in Figure 7. This is followed by example key messages from the Climate Outlook. All key messages covering a number of average conditions and specialized climate impact variables are presented in the outlook in Appendix A.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Figure 7. Definitions of the different confidence levels

- Throughout the 21st century, temperatures will continue to rise (**Very High**). By mid-century, annually averaged temperatures will increase by 3.3-6.0°F (**High**), average winter temperatures will increase by 3.0-5.7°F (**High**), and average summer temperatures by 3.5-6.8°F (**High**)
- Since 1970, the frequency of extremely hot days (daily maximum temperatures >95°F) has increased while the frequency of the number of days that drop below freezing (daily minimum temperatures <32°F) has decreased (**Very High**). These trends will continue into the future (**Very High**)
- The number of days in which the environment is conducive to the formation of severe thunderstorms will increase in the future (**High**)
- The WBGT (indicating heat stress) will increase, particularly during summer (**Very High**). This will result in an increase in the number of heat-related restrictions, following the military work-rest flag day restriction guidelines (**High**).

3.2.6 Climate Outlook results and evaluation

The ways in which information developed as part of the Climate Outlook was applied in the case studies at the installations is described in Section 4. Additional research being conducted to evaluate approaches for communicating results and associated uncertainty is described in Section 5.

3.3 Selected methods used in the case study assessments

We explored different methods to establish baseline information about vulnerability and synthesize it with information about future climate to identify potential future risks to the installations and the missions they support. Methods range from simple, low-cost approaches for estimating how climate change could affect an asset to sophisticated, resource-intensive methods. In some cases they focus on physical proxy variables (for example, using elevation as a proxy of the sensitivity of an asset to flooding) or integrate climate variables from climate model projections to calculate widely used indices of conditions such as fire risk or heat stress. The choice of method used in any particular case was influenced by the importance of the asset and interest of stakeholders, data availability, potential for testing a new approach, and resource requirements. Section 4 provides a more detailed discussion of the results from these and other methods. Section 5 includes conclusions about the range of approaches—from “back of the envelope” estimating techniques to complex integrated models—needed for vulnerability assessments.

3.3.1 Event history analysis

An event history analysis is a longitudinal record of the timing, severity, and impact of events and is an umbrella term for a collection of methods. Event histories are typically collected using surveys of individuals and records. In this study, we tested this method at the USNA to establish baseline climate impacts, specifically on operation and maintenance costs. The relationship between historical climate and operation and maintenance costs is useful in determining the costs of climate change for an installation.

Key research question—What can we learn about the relationship between weather hazards and impacts on the installations that could help us estimate how potential changes in the frequency and/or severity of these hazards could affect operations or mission attainment?

Method description—Build a database of severe weather events and associated costs.

Evaluation—Operations and maintenance departments tend to focus on maintaining the functionality of installations. An event history analysis would require assessment of the root cause of each failure (that is, assign blame to a specific type and severity of climate event). At this point, the data to construct an event history database does not exist and major changes would be required to perform record keeping across installations. Yet by tracking this type of information, it might be possible to develop damage response curves specific to each installation which would allow estimation of the future costs of climate change.

Opportunities for further research—There are opportunities for further research in the most efficient methods for capturing previous impacts associated with weather extremes. This includes developing surveys that query multiple experts that in aggregate fill out an event history database, and using existing databases for collecting information about previous impact of weather extremes.

Suggested reading—

- Box-Steffensmeier JM, and BS Jones. 2004. *Event History Modeling: A Guide for Social Scientists*. Cambridge University Press, Cambridge, UK.
- Steele F. 2005. *Event History Analysis*. NCRM Methods Review Papers NRCM/004, Economic & Social Research Council, National Centre for Research Methods. Available at <http://eprints.ncrm.ac.uk/88/>.

3.3.2 Coastal flooding return period analysis

Global mean sea level rise has resulted in more frequent and severe flooding for many coastal locations. Rising global sea levels not only mean an increasingly severe “extreme” event but also that events previously defined as nuisances are likely to become more frequent. In the United States, nuisance events are becoming more noticeable and widespread along the country’s coastal regions, and are resulting in public inconveniences such as frequent road closures, overwhelmed storm drains, and compromised infrastructure (Sweet et al., 2014). Nuisance events thus can significantly impact budgets and the ability to meet mission through the amount of time and effort needed to address them. As a result of sea level rise, we should expect more frequent interruptions from nuisance events.

*Key research question—*How will sea level rise change the frequency of nuisance events and the severity of extreme events? What do these changes mean for an installation and its infrastructure?

*Method description—*Extreme value statistics provide tools to investigate the tails of probability distributions. One method already widely used in engineering applications is return periods and return levels, which associate a probability of occurrence to particular water levels using historical records. In combination with expected sea level rise estimates, this tool can provide an idea of the future extreme event frequency for a particular location.

To produce the map in Figure 8, we (1) analyzed the historical tide gauge record at Sewell’s Point (chosen because of its proximity and length of record) to calculate the return period and return levels, and (2) displayed the information onto a location using GISTM. To determine the pattern of flooding at a location we use the fill tool, which takes a digital elevation model as an input and calculates the water level necessary to fill each grid cell. In other words, the fill tool takes into account the surrounding topography for each cell. This allowed us to map the data from the tide gauge to the site.

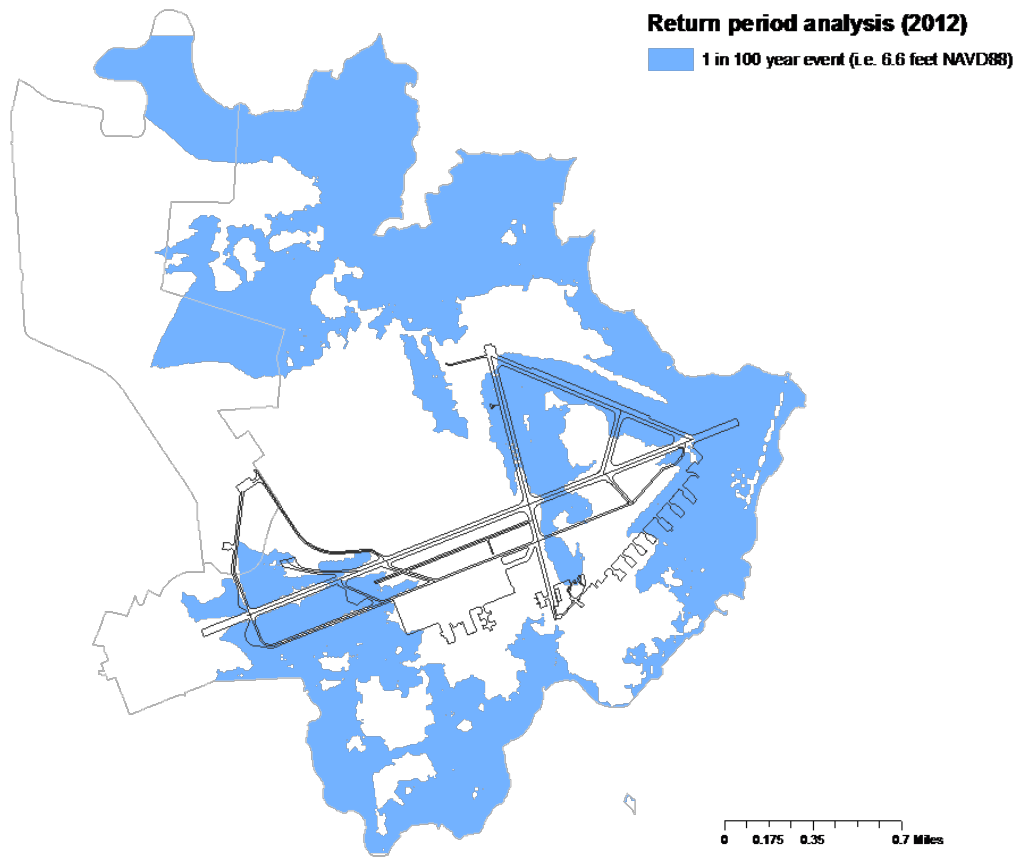


Figure 8. Return period and return level analysis at Langley Air Force Base using GIS™

With this method, we can also look at the patterns of flooding on specific infrastructure. For example, Figure 9 shows the same analysis of return period, but cropped to only show a runway at the same location.

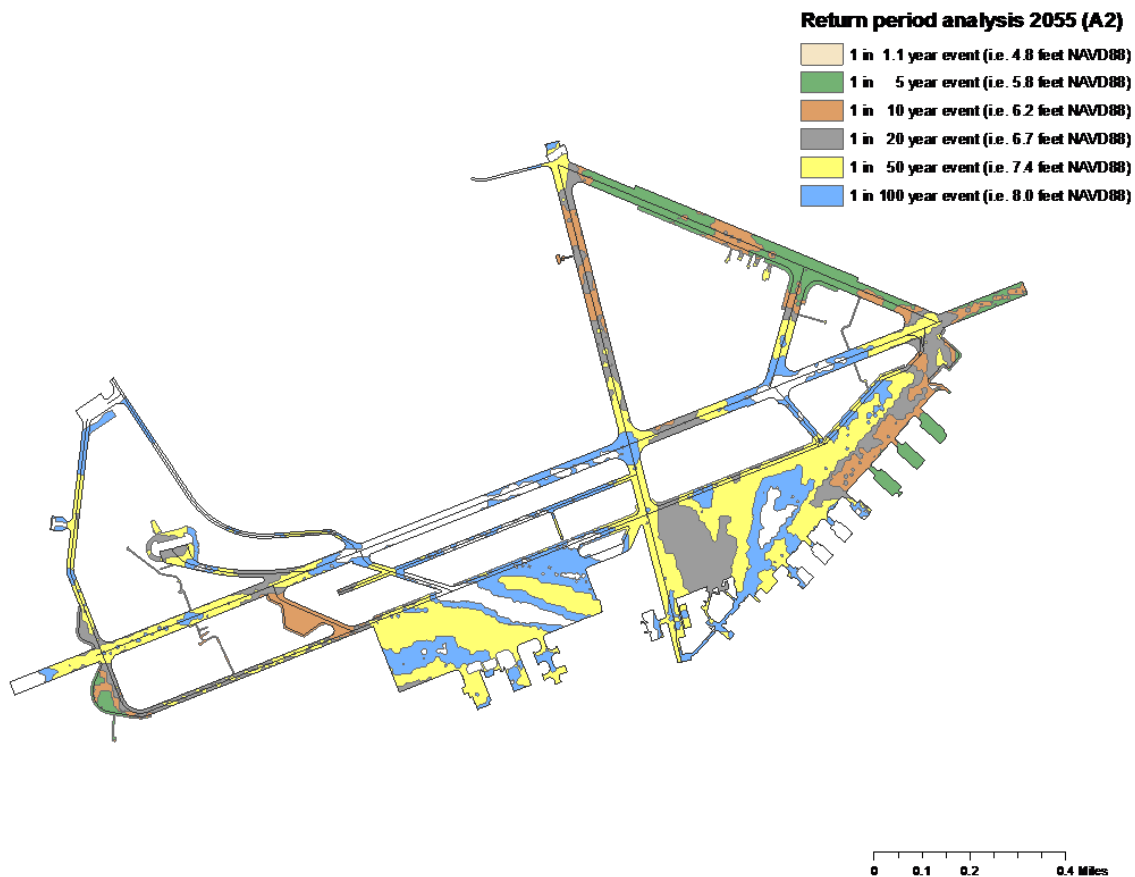


Figure 9. Return period analysis at a runway

Evaluation—Return period analysis can be cost effective compared to other methods such as high-resolution coastal models. However, the results of return period analysis can be non-intuitive and hard to process by decision makers. The images produced contain a wealth of information, but the audience for whom they are useful might be small. Therefore, the choice between this technique and coastal modeling depends on available resources and the target audience.

Opportunities for further research—There are opportunities for research in understanding the changing spatial pattern of flooding under climate scenarios. These insights could influence master planning decisions such as the placement of new key infrastructure assets.

Suggested reading—

- Sweet W, J Park, J Marra, C Zervas, and S Gill. 2014. *Sea Level Rise and Nuisance Flood Frequency Changes around the United States*. National Oceanic and Atmospheric Administration. NOAA Technical Report NOS CO-OPS 073, Washington, D.C.

- Tebaldi C, BH Strauss, and CE Zervas. 2012. "Modelling Sea Level Rise Impacts on Storm Surges along US Coasts." *Environmental Research Letters* 7(1):1-11.

3.3.3 Storm surge modeling (USNA)

Military assets at lower elevations such as those located at the USNA are more exposed to and sensitive to changes in the frequency and intensity of flood-inducing storm events. Hurricane-associated storm intensity and rainfall rates are projected to increase over this century with temperature increases. Absent sufficient adaptation, this could result in impacts including more infrastructure disruptions and changes to compliance with water quality requirements. For military installations and services, such disruptions pose a range of risks, such as required changes to management regimes, relocation of water-intensive activities, master planning adjustments, and infrastructure and facility redesign. Damage and repair costs from extreme weather events alone could be considerable. For example, Hurricane Isabel in 2003 cost the USNA an estimated \$10.6 million in damage and recovery costs for one facility. Given the wide range of possible risks associated with storm event impacts, installation and Service personnel need tools that can help them identify priority areas. One helpful method is a return period analysis. However, the results are sometimes non-intuitive. More generally, it is also often difficult to visualize previous storm impacts. The Finite Volume Coastal Ocean Model (FVCOM) developed by Chen et al. (2003) offers a means to do both of these things by simulating conditions found in several historical storms and generating animated graphics to show the simulations.

Key research question—How will changes in sea level rise affect the impacts of large coastal storm events in the future?

Method description—To explore interactions among sea level rise, storm surge, and coastal flooding at the USNA, we used a storm surge model with high temporal and spatial resolution in several model experiments. This is an alternative model to return period analysis (discussed in Section 3.3.2) for modeling storm surge. The storm surge model used in this study is the unstructured-grid FVCOM. This three-dimensional coastal ocean model fully couples ice-ocean-wave-sediment-ecosystem models with a detailed representation of the land surface, including built features such as flood walls, buildings, or other infrastructure. We included the model results in the discussion of vulnerability because the model could integrate exposure to physical processes associated with flooding and the potential for adaptation through changes in coastal protection. With this model, we explored the effects of sea level rise by simulating the conditions found in several historical storms (for example, Hurricane Isabel) on top of sea level rise. The results of the model show the spatial distribution of water height, which is useful for evaluating the effectiveness of different flood-protection measures. An example of the results can be seen in Figure 10.

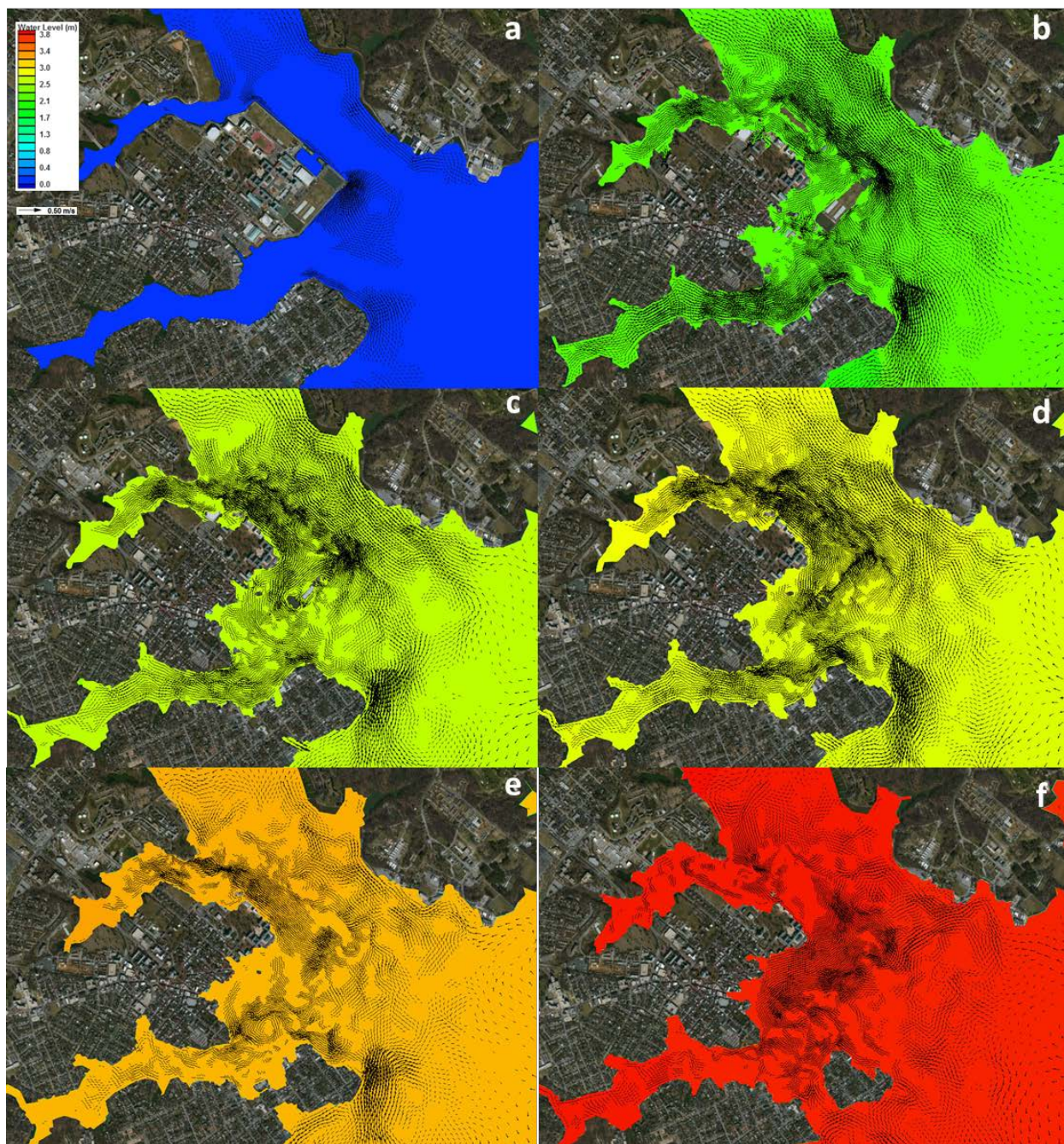


Figure 10. Distribution of storm surge height for historical and future Hurricane Isabel / Several different conditions are portrayed: (a) historical Hurricane Isabel at low tide; (b) historical Hurricane Isabel at peak surge; Hurricane Isabel at peak surge with (c) 1.4 ft (0.42 m) of sea level rise; (d) 2.1 ft (0.64 m) of sea level rise; (e) 3.7 ft (1.12 m) of sea level rise; and (f) 5.7 ft (1.73 m) of sea level rise.

Evaluation—Results showed a range of plausible future exposure scenarios, as well as the extent of flooding that would occur in these scenarios. The animated data products that resulted from this experiment were effective for communicating with stakeholders about the potential impacts of climate change and its potential implications. The model requires more resources than

methods such as return period analysis, which can also be used to model storm surge. This method would be appropriate for cases when more detailed analysis is required and/or desired for stakeholder engagement. Additional research could further develop the approach and explore alternative applications (the project developed a proposal for further testing).

3.3.4 Fire risk and ecosystem maintenance (Fort Bragg)

Fire management is an important operational concern for a number of military installations. Changes in climate could impact not only the likelihood of wildfire but also, and perhaps more importantly, the ability of installations to control fire risk through prescribed burning.

Key research question—How will changes in precipitation, temperature, etc., affect fire risk and fire management efforts at military installations?

Method description—Future fire frequency in the Southeast will depend on how climate change affects precipitation in the region, as well as how forests are managed. One recent study found that while the Southeast may initially see a decline in climatic conditions conducive to fire, an increase in fire sensitivity is projected for inland areas by mid-century and beyond. In particular, more extremely dry periods combined with higher temperatures and more lightning could lead to more intense wildfires, especially if interspersed with wetter years that allow rapid growth of vegetation that provides fuel for fires.

To project changes in temperature and precipitation that are favorable for fires, we use the KBDI to determine future forest fire potential. This index combines rainfall and temperature to estimate how dry forested areas are and their risk for fires, and thus can be used to estimate the change in the number of days it is unsafe to burn. Persistent hot and dry conditions make it dangerous to perform prescribed burns. Prescribed burning is not recommended when KBDI is greater than 600 (see Table 2).

Table 2. Fire Risk Index

Fire Risk	KBDI Threshold	Description
Low	0-200	Soil moisture and large class fuel moistures are high and do not contribute much to fire intensity
Moderate	200-400	Lower litter and duff layers are drying and beginning to contribute to fire intensity
High	400-600	Lower litter and duff layers contribute to fire intensity and will actively burn
Extreme	600-800	Intense, deep burning fires with significant downwind spotting can be expected

This index serves as a proxy for expert judgment and specific knowledge of fuel moisture, but it does not account for wind speeds and ventilation that would likely further restrict the number of burn days. Figure 11 shows an example result from this analysis.

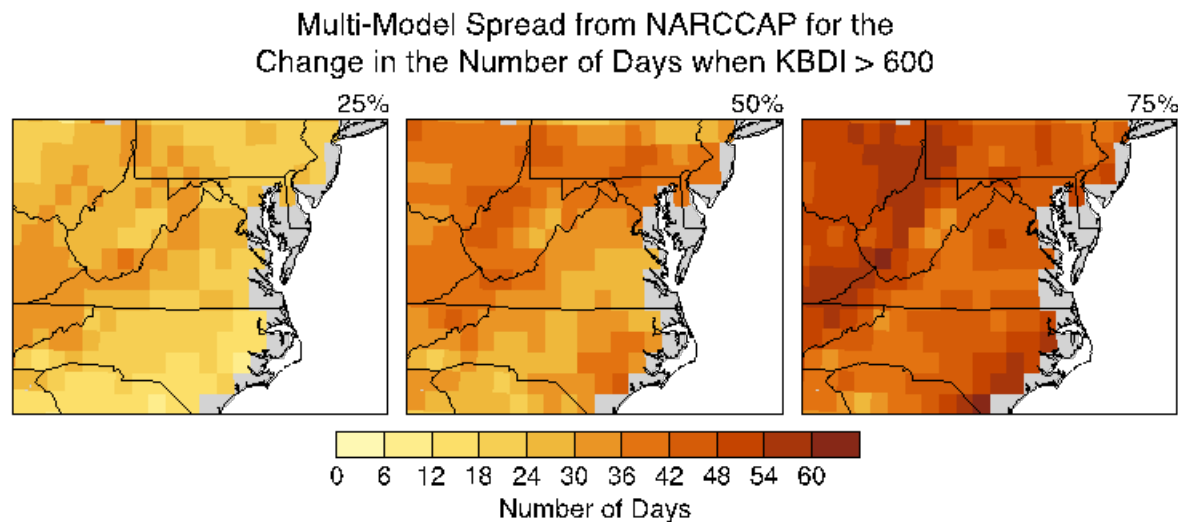


Figure 11. Change in number of days when prescribed burning is not recommended (KBDI > 600)

Evaluation—Fire risk analysis is linked with decision support through a vulnerability assessment framework via two mechanisms: (1) an assessment of regional changes to fire risk as a result of climate change; and (2) direct support to make decisions about future fire management (budget, personnel requirements, etc.).

The number of days unavailable for prescribed burning (especially if these estimates are seasonal) is a variable of use to fire management personnel in costing out prescribed fire budgets. For example, if the length of the prescribed fire season were to go from 4 months to 2 months, then managers could estimate what these changes would mean in terms of hiring or overtime requirements.

Even on an annual basis, indicator variables such as the KBDI provide a macro perspective of changes in the likelihood of a fire during training or fires off base. The indicator provides context for the decision-support environment.

Opportunities for further research—For stakeholders, understanding the changes to annual fire risk is useful but would be more meaningful if changes within seasons could be projected. There are real constraints on the time available for prescribed burning, which is a fire management strategy. If the prescribed burning season were to shrink, it would impact not only fire management costs but potentially the ability to meet mission.

3.3.5 Training and flag days (USNA, JBLE, Fort Bragg)

In extremely hot and humid conditions, the military restricts training and outdoor activity. The military uses the WBGT as an index for expected heat exposure. Unlike other measures of heat stress, the WBGT is designed to include not only the impacts of temperature and humidity,

but also the influence of wind speed and the intensity of the sun. Table 3 presents the heat stress thresholds used to restrict outdoor activity. Increased restrictions could affect future mission attainment by restricting flight support and training time.

Key research question—How might changes in climate conditions affect changes in training and outdoor activity? What are the implications of these changes on achieving training objectives and requirements?

Table 3. Flag Thresholds and Impact on Training and Outdoor Activity

Source: <http://www.med.navy.mil/sites/nhttp/Pages/FlagCondition.aspx>

Flag Category	WBGT Threshold	Activity Restriction
White	Below 80°F	No impact
Green	80-84.9°F	Monitor closely
Yellow	85-87.9°F	Strenuous exercise is curtailed. Additional considerations are made for the first 3 weeks of the Plebe's summer, before acclimatization has occurred
Red	88-89.9°F	Strenuous exercise for anyone without 3 weeks exposure is prohibited
Black	Above 90°F	Outdoor activities prohibited

Figure 12 shows the average annual and summer WBGT values. During summer when temperature, humidity, and surface solar radiation are high, the WBGT reaches potentially dangerous values.

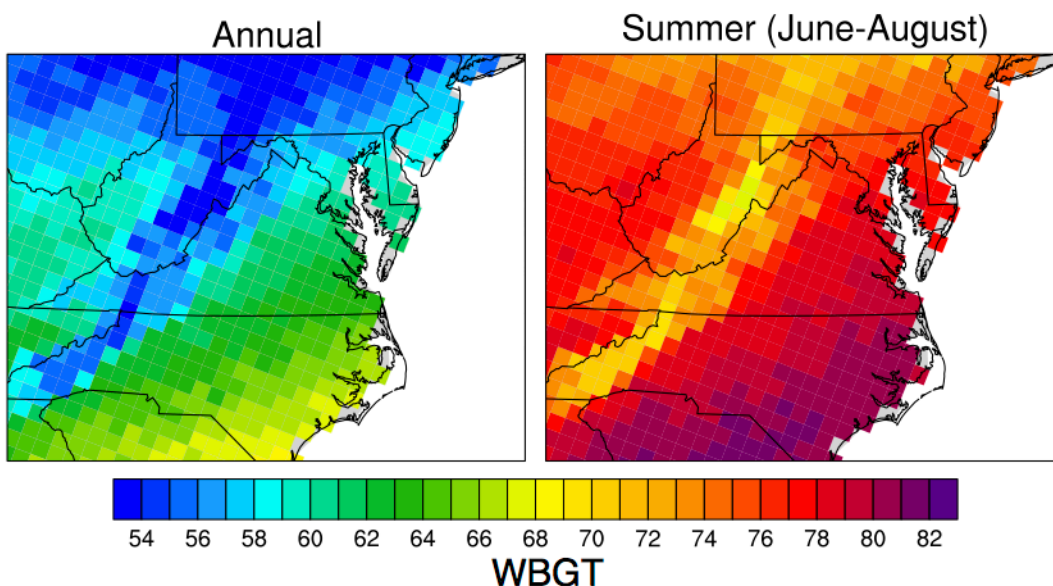


Figure 12. WBGT average daily maximum values from 1979 to 2010 / The figure shows the annual average daily maximum WBGT (left) and average summer (June-August) daily maximum WBGT (right) from NARR, a reanalysis product. The climatology is based on the 1979-2010 time period.

Method description—Although the WBGT is measured at most military installations, the daily values are not saved or archived. The temperature variables used to calculate the WBGT are not standard measurements for most weather stations, nor are they calculated by climate models. To examine heat stress from observations and the climate models, we estimated the WBGT from temperature, humidity, winds, and surface solar radiation.

The time series plots in Figure 13 help illustrate the temporal and spatial variability of the frequency of extreme events in the mid-Atlantic region. The plots show the observed flag day frequency for JBLE and Fort Bragg.

Both time series show considerable year-to-year variability in the frequency of flag days, especially the extreme events (red and black flag days). Also, the figures illustrate how a coastal installation (JBLE), with overall cooler temperatures, experiences fewer extreme heat events than an inland installation (Fort Bragg).

Evaluation—As illustrated in Figure 13, potential future occurrence of flag days can be projected using archived regional climate model output. This can serve as a proxy variable for the challenge that future training program leaders would face in adapting activities to new conditions. Assessing the potential *significance* of changing flag days is challenging because of potential changes to requirements for training and uncertainty about the potential to adapt training programs by shifting the location or time of day for training, or taking other measures.

Suggested reading—

- Department of the Army and Air Force Headquarters. 2003. *Heat Stress Control and Heat Casualty Management*. Technical Bulletin, TB MED 507/AFPAM 48-152(I), Department of the Army and Air Force, Washington, D.C. Available at http://armypubs.army.mil/med/dr_pubs/dr_a/pdf/tbmed507.pdf.
- Navy Medicine, Flag Condition. Available at <http://www.med.navy.mil/sites/nhttp/Pages/FlagCondition.aspx>.

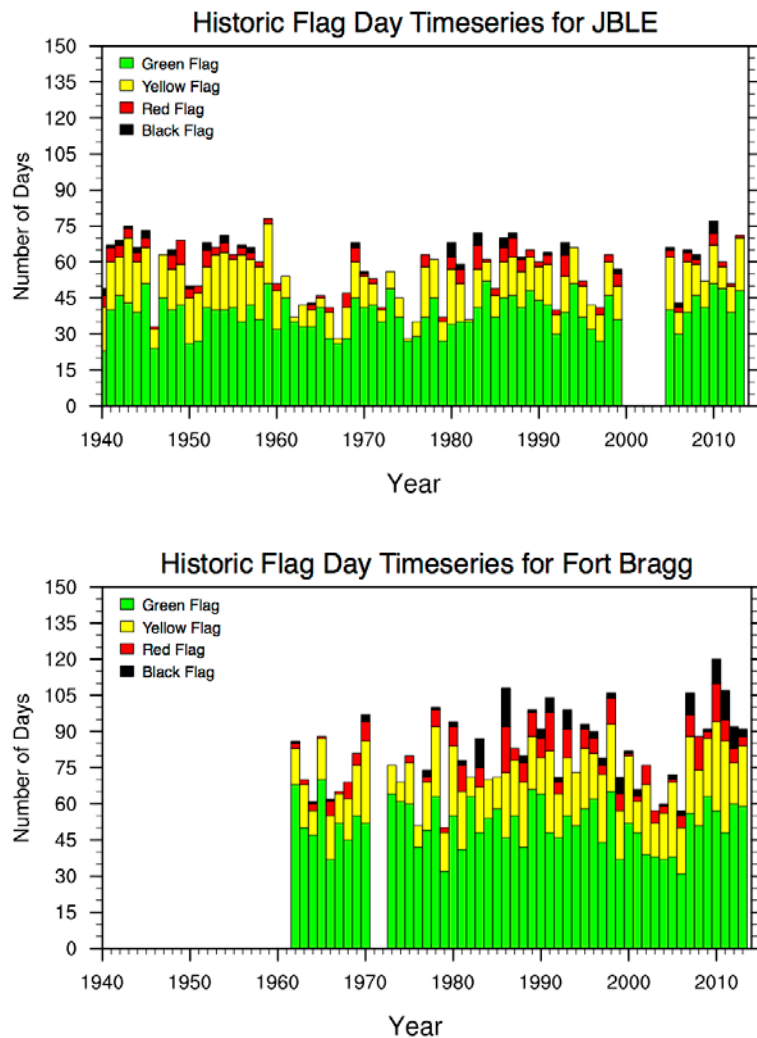


Figure 13. Flag day observations at JBLE and Fort Bragg / The figures show the observed flag day occurrence for JBLE (top) and Fort Bragg (bottom). The WBGT and flag days were estimated from the global summary of the day station observations using temperature, humidity, and surface pressure.

3.3.6 Network interdependence analysis (USNA)

Infrastructure systems often have complex interdependencies that can lead to new vulnerabilities and compound existing ones. These interdependencies can arise within an installation as well as between the installation and the surrounding community.

Key research question—How could interdependencies between infrastructure systems lead to cascading failures?

Method description—To develop insight on how shocks from climate hazards can propagate from one functional area to another (that is, cascading failure), we decomposed the Mission Dependency Index (MDI) and analyzed the MD_b score (that is, the measure of interdependencies

across different classes of infrastructure). Interdependent relationships among infrastructure assets can include the following (Rinaldi et al., 2001):

- *Physical*—A physical reliance on material flow from one infrastructure to another
- *Geographical*—A local environmental event affects components across multiple infrastructures due to physical proximity
- *Cyber*—A reliance of information transfer between infrastructure
- *Logical*—A dependency that exists between infrastructures that does not fall into one of the above categories.

To analyze these dependencies, we construct a weighted, directed network where the nodes of the network were the classes of infrastructure assets at an installation and the edges or links were the dependency relationships as defined by the MD_b score. The direction of the links was determined by the MD_b (that is, Functional Area X depends on Functional Area Y, the direction of the arrow would go X to Y). The representation of this network can be seen in Figure 14. The size of the node is based on the number of functional areas that depend on it (that is, in-degree), and the width of the line indicates the combined weight of the dependency that is derived from combining the MD_b for each dependency from one area to another.

Evaluation—Decomposing the MDI into its principal components requires access to a specialized database, and the method requires network modeling. However, the method is useful for identifying systems that other systems rely heavily on, dependencies which might otherwise seem counterintuitive absent this analysis

Opportunity for further research—There is additional opportunity for researching how the MDI score can be used to gain insights into vulnerability. Specifically, calculating additional measures of network centrality may lead to further insights and understand the propagation of risks across an installation due to interdependencies.

Suggested reading—

- Antelman A, J Dempsey, and B Brodt. 2008. “Mission Dependency Index—A Metric for Determining Infrastructure Criticality.” Chapter in *Infrastructure Reporting and Asset Management*, eds. A Amekudzi and S McNeil, American Society of Civil Engineers, Reston, VA, pp. 141-146.
- Grussing MN, S Gunderson, M Canfield, E Falconer, A Antelman, and SL Hunter. 2010. *Development of the Army Facility Mission Dependency Index for Infrastructure Asset Management*. ERDC/CERL-TR-10-18, Engineer Research and Development Center, Champaign, Illinois.
- Rinaldi SM, JP Peerenboom, and TK Kelly. 2001. “Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies.” *IEEE Control Systems Magazine* 21:11-25.

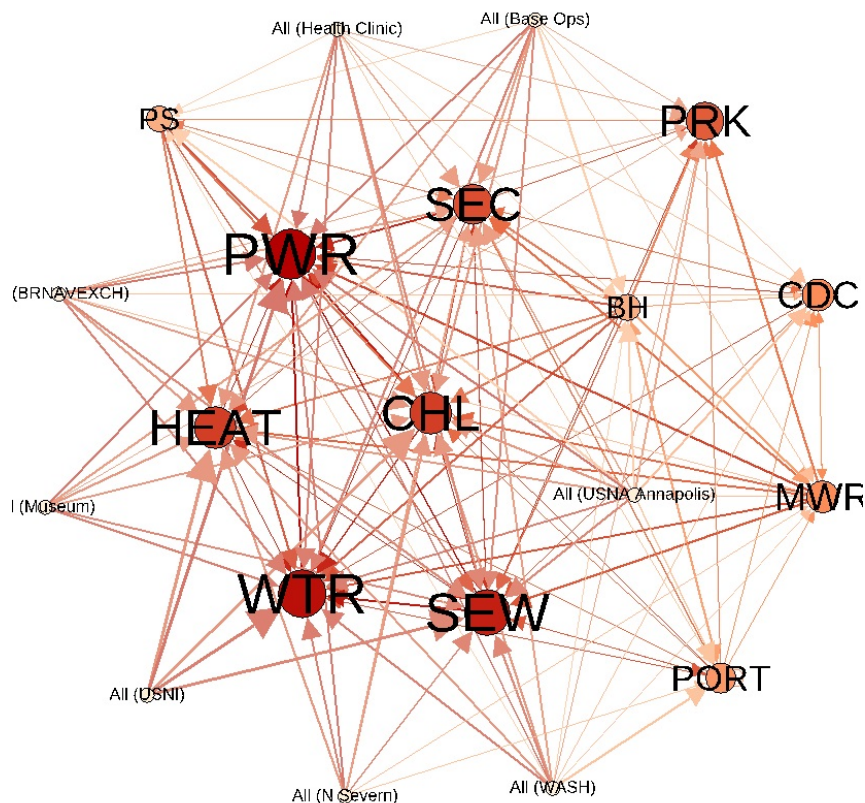


Figure 14. Network representation of the interdependencies between functional areas

3.3.7 Heating and cooling degree days (USNA, JBLE, Fort Bragg)

Heating and cooling degree days are based on the assumption that when the outside temperature is 65°F (a common base temperature used for degree day analysis), the occupants do not need to heat or cool buildings to be comfortable. Heating degree days (HDDs) occur when the daily average temperature is less than 65° (when you would need to heat a building to make it comfortable). Cooling degree days (CDDs) are assumed to occur on days where the daily average temperature is greater than 65°F (when you would need to cool a building to make it comfortable).

Key research question—How would changes in HDDs and CDDs affect building energy costs and infrastructure such as heating and cooling equipment?

Method description—The approach uses climate model projections of daily average temperature to assess potential heating and cooling requirements in the future using standard methods to calculate HDD and CDD. As an example, NARCCAP models project that less energy will go toward heating buildings in winter (HDD are shown to go down), while more energy will go toward cooling buildings in summer (CDD are shown to go up).

Evaluation—Both the CDD and HDD are relatively easy to calculate, and if used with other data (for example, energy use and cost data) can lead to insights on changing operating and

maintenance costs as well as possible changes in cooling and heating capacity requirements. See Filadelfo et al. (2012).

Opportunities for further research—Analysis of HDDs and CDDs calculated with climate analogues may also be a useful method for assessing implications of climate change for future energy use and capacity requirements. See Hallegatte et al. (2007).

Suggested reading—Filadelfo R, J Mintz, D Carvell, and A Marcus. 2012. *Estimating Climate Change Effects on Installation Energy Use*. Technical Report DOP-2012-U-000800-Final, May 2011, Center for Naval Analysis, Arlington, Virginia.

3.3.8 Decision analysis (USNA)

The changing statistics of flooding under future climate change create new vulnerabilities for existing infrastructure in low-lying areas, especially along the U.S. East Coast. Changes in flooding conditions thus pose new challenges for decision making regarding future infrastructure.

Key research question—Can the use of formal decision analytic techniques that incorporate climate vulnerability considerations improve siting decisions for new infrastructure?

Method description—Decision analysis proceeds through a sequence of steps, providing insights for decision makers at each step, including the relative importance of different sources of uncertainty, the robustness of alternatives, accounting for key uncertainties, and the economic value of resolving key uncertainties or finding new alternatives.

A decision analytic structure was developed based on our conversations with site personnel. The first step was to frame the problem by defining alternative choices; identifying the decision objectives; and determining a model that describes the information, uncertainties, and influences affecting the ability to meet those objectives.

The alternatives were defined as (1) staying in currently occupied buildings and upgrading a historic building; (2) obtaining more space within a currently occupied building and renovating it; and (3) constructing a new facility. Preliminary capital cost estimates show that alternatives 1-3 are in order from lowest to highest capital cost. Beyond the capital cost estimates, each alternative needs to be characterized in terms of the full set of objectives that will be considered in the decision-making process. For example,

- USNA personnel indicate alternative (3) not only meets current needs but also allows for growth. What would be the costs of growth with alternatives (1) and (2)?
- What are the costs of the program being distributed across several buildings as opposed to consolidated in one location? Some of these costs could be qualitative, but should be represented explicitly.
- What are the annual maintenance costs for each of the alternatives?

- What are the expected damages due to flooding over the lifetime of the decision for each alternative? These would be location-specific, probability-weighted damages that account for all the buildings/locations involved in each alternative, as well as climate non-stationarity.
- How are these damages expected to change as a function of flood-protection measures that might be implemented at each location?
- What about a new alternative located outside of the USNA Lower Yard (one of three distinct areas of the USNA where most academic buildings are located), where the midshipmen are housed and trained? What would be the savings from avoided flood damages?

To summarize the recommended decision framing for this type of decision, we created the influence diagram shown in Figure 15.

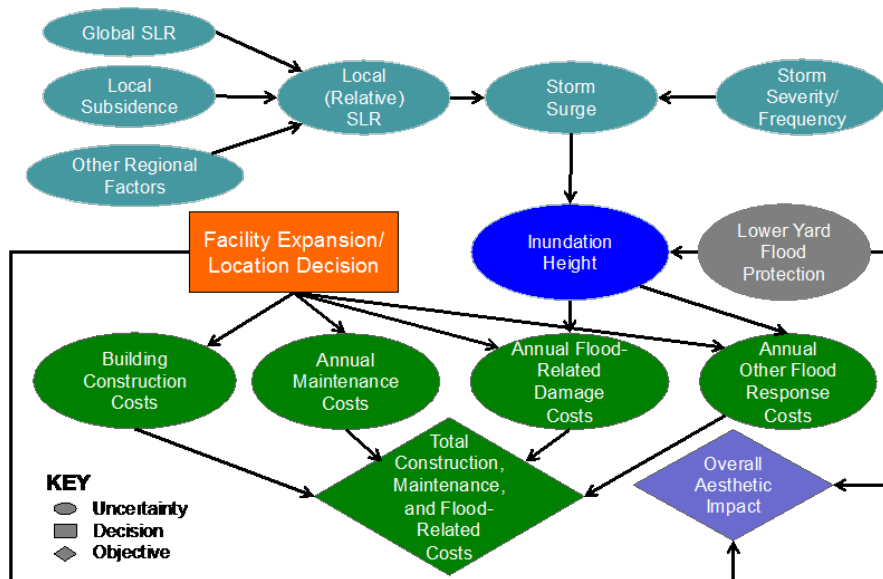


Figure 15. Influence diagram for site expansion and location decisions

Evaluation—Although the influence diagram maps the process for an individual decision, its use for a near-term decision is limited; long-term planning for infrastructure is required, and vulnerability considerations must be included at the beginning of the long-term process, for example, in the Master Plan for the installation. Emphasis should be placed on integrating vulnerability considerations into existing DoD guidance and processes. See Section 5 for a longer discussion of decision framing.

4. Results and Discussion

This section of the report describes the three case studies completed as part of this project. The case study sites are U.S. Naval Academy (USNA), Joint Base Langley-Eustis (JBLE), and Fort Bragg. The case studies enabled us to conduct research on and test methods that could be used in vulnerability assessments. Each case study addresses the first four of our research questions:

1. What are the present set of exposures and vulnerabilities of the DoD installation?
2. How do DoD decision makers use available information on extremes and seasonal variability to manage assets and operations? What information could be used but isn't, and what additional information would be useful if it were available?
3. Using insights from climate models, downscaling methodologies, observations, and climate processes research, what information can be provided about the likelihood of potentially significant current climate exposures and future changes in significant climate exposures for the region in which the facilities are located?
4. What are the risks to the selected DoD installations of potential changes in climate, considering installation vulnerability, its consequences for missions and readiness, and the likelihood of regionally important changes in climate exposures?

The fifth question, regarding development of a framework for vulnerability assessment, is addressed in Section 5, which draws conclusions based on interpretation of the case study results.

The case studies follow the similar outline, each addressing in turn:

- Results related to the baseline condition assessment for priority assets and identifying sensitivity, observed exposures, and adaptive capacity
- Climate change and potential future exposure
- Analysis of future vulnerability that integrates information on baseline sensitivity and adaptive capacity with information on potential future exposures
- Decision making and implications for possible next steps
- Discussion and implications of vulnerability assessment methods.

The results presented are from experiments designed to develop and explore different methods useful to communicating with installation staff about the potential significance of different types of impacts. The results are not intended to present full assessments of vulnerability, as the project was not authorized or funded to conduct such assessments. Not all topics are covered in equal depth, especially related to decision making, as we shifted our approach from decision analysis of individual decisions at installations to analysis of standardized planning, design, and budgeting processes used across installations.

Regarding information on future climate exposure, as described in Section 3.3, climate projections are for the mid-century period: 2041-2069 (with minor variations due to model differences in reporting simulations), and unless otherwise stated, projections are presented against a baseline period of 1971-1999. The projections are derived from global climate models (GCMs) (Climate Model Intercomparison Projects 3 and 5 (CMIP3 and CMIP5) and regional climate models (North American Regional Climate Change Assessment Program or NARCCAP). In our application of methods, we focused on the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) “A2” greenhouse gas emissions scenario to maintain consistency with the forcing used in the NARCCAP inter-comparison. At 2100, this scenario produces a very high level of climate change; for recent decades, it is consistent with observed global emissions (Rahmstorf et al. 2007). For CMIP5 simulations, we referenced model simulations using the RCP 8.5 emission scenario (Moss et al., 2010) which is similar to the SRES A2 scenario in the middle of the century. To estimate the influence of sea level rise on local water levels, we applied the method described in Tebaldi et al. (2012), which implicitly takes into account future thermal expansion, glacial melt, and local effects such as sinking of the land.

Research at the USNA began in Spring 2013 and continued through the end of the calendar year. Research at the JBLE began in Fall 2013 and continued through the Summer 2014. Finally, research at the Fort Bragg began in Fall 2014 and continued through the Summer 2015. The sequential nature of the case studies allowed for many of the lessons learned at one installation to be incorporated and tested at subsequent installations.

4.1 Case study results: U.S. Naval Academy, Annapolis, Maryland

The U.S. States Naval Academy (USNA) was the first installation to be analyzed for vulnerabilities to climate change for this report. In the context of the overall project, the USNA was selected for its importance as the nation’s premier institution for training future naval leaders, its coastal location and exposure to a range of phenomena potentially affected by climate change, and its institutional characteristics including its compact size and infrastructure configuration, which largely consists of academic and office buildings and supporting infrastructure. In addition, its location near the University of Maryland facilitated site visits and interactions between installation personnel and project investigators.

This case study started with a review of current installation characteristics and establishment of priorities. We then examined climate information on a set of priority exposures: (1) flooding as a result of several tropical and extratropical climate events combined with sea level rise (which affects buildings and infrastructure networks) and (2) temperature and related conditions (which affect flag days and outdoor activities, including training). We evaluated trends based on analysis of the historical climate record for the region and the immediate area around the USNA. Next, we examined a broad range of information sources on potential future climate conditions to identify possible changes in these exposures. We used several approaches, including a coastal storm surge model, to examine the potential effects, at the same time assessing the capacity for adaptation based on adjustments to infrastructure or management. The study included the following activities:

1. Developed a stakeholder engagement plan

2. Collected initial data, including documentary research and initial meetings and site visits
3. Scoped and applied methods, prepared climate information, and conducted preliminary analysis of existing vulnerabilities
4. Assessed vulnerabilities under potential future conditions and explored decision analysis for example decisions
5. Presented interim results on baseline vulnerability and discussed additional data needs
6. Prepared an outbrief of initial findings for a briefing at USNA
7. Revised the outbrief document based on staff reactions and questions

We drew conclusions about the overall assessment process and modified some aspects of the approach for the next case study, which was initiated in January 2014.

4.1.1 Baseline: background and establishing priorities

The first question to be answered by our case study was, “What are the current vulnerabilities (sensitivity and adaptive capacity) to the current climate (exposure)?” In this section, we give the background of the USNA and the process by which we set priorities for our discussions with USNA staff and preliminary data analysis. We describe the current sensitivity, exposure, and adaptive capacity; this provides the basis for assessing future exposure to climate change impacts and vulnerability to those impacts.

4.1.1.1 Background

The USNA campus, established in 1845, is located on the banks of the Severn River in Annapolis, Maryland. It is home to more than 4,400 midshipmen, 1,600 staff, 400 officers, and 200 sailors. The campus contains the Lower Yard (188 acre) where the midshipmen are housed and trained, the Upper Yard (161 acre) that provides support functions including a hospital and medical clinic area, and the North Severn area (853 acre) that supports the USNA and a broader community of those associated with the USNA. The Lower Yard is a compact area with dense land use consisting of buildings, monuments, ceremonial areas, and athletic facilities and fields. The North Severn complex includes natural and athletic areas, in addition to support activities. Over the years, space for expansion has been acquired through purchase and pushing the existing land boundaries farther into the Severn River area through land fill projects, especially on the Lower Yard.

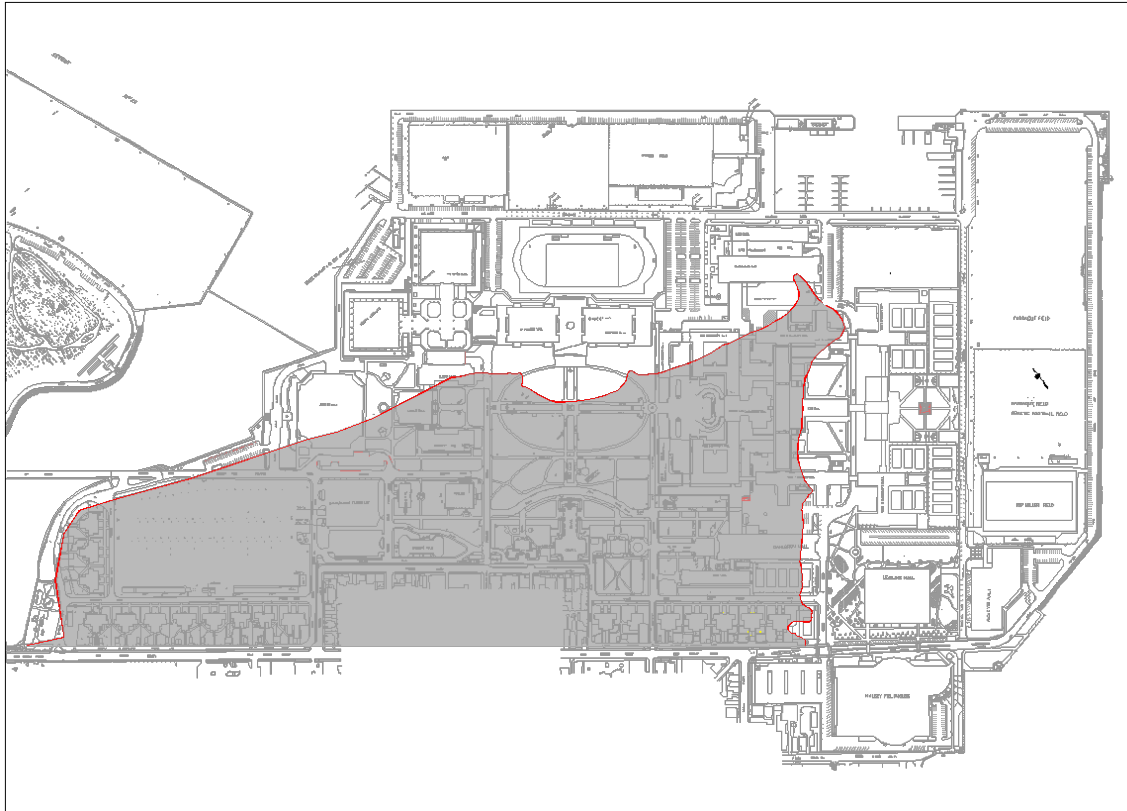


Figure 16. Original shoreline of the Lower Yard in 1850 at the USNA | Source: USNA provided map, 2004.

The USNA's low elevation (Figure 17) renders the campus subject to periodic flooding that is currently addressed through a flood management plan. In September 2003, the USNA sustained substantial damage (estimates range from \$120 to \$150+ million) from Hurricane Isabel, which produced water levels of approximately 7 ft (North American Vertical Datum 1988, NAVD88)—a major flooding event using the categories defined by the Advanced Hydrologic Prediction Service flood stage levels. The flooding damaged 18 buildings.

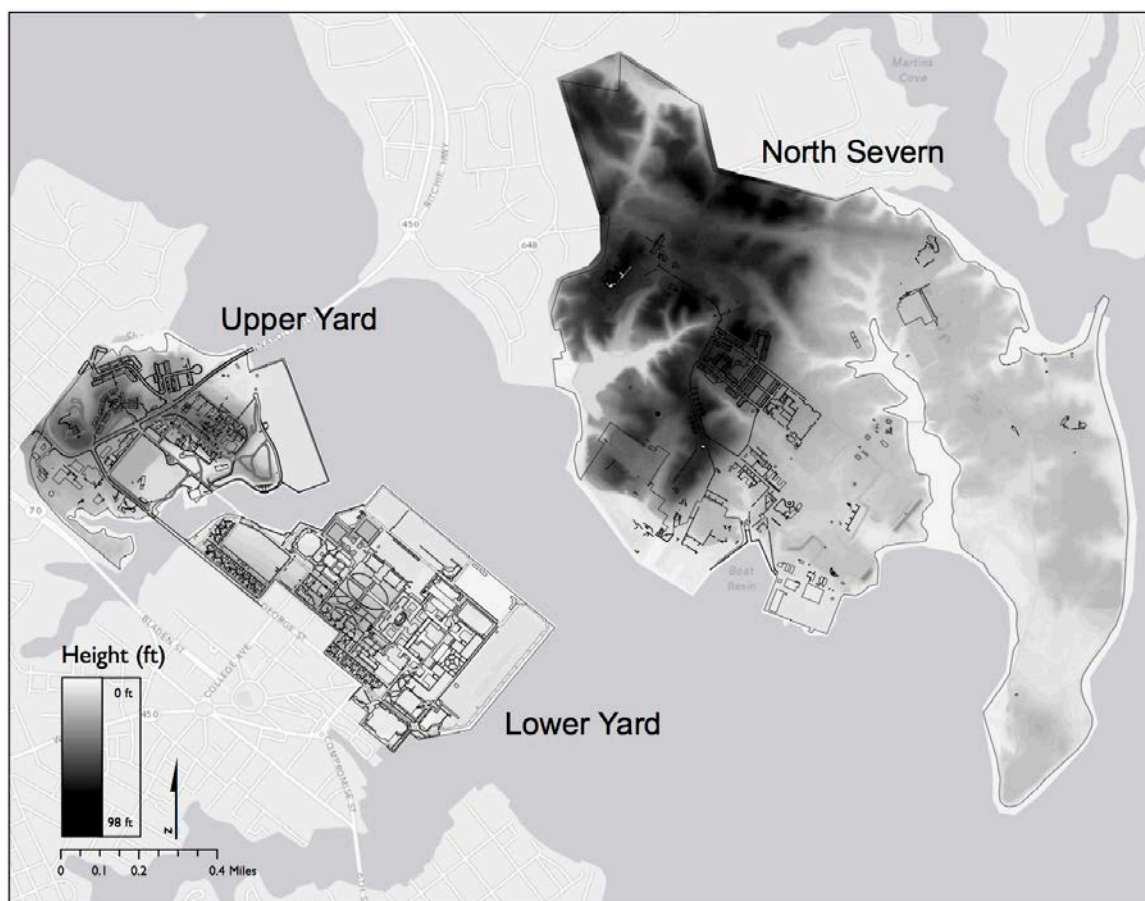


Figure 17. Elevations of USNA areas for evaluating infrastructure exposure to flooding

4.1.1.2 Setting priorities: Buildings, transportation infrastructure, and outdoor activities

Our initial contacts with USNA public works staff and the faculty in oceanography indicated high interest and baseline knowledge; in addition, staff from the Naval Task Force Climate Change indicated their interest in participating in the USNA case study. The stakeholder participants included the Director and staff members of public works (at least two also had responsibilities to Navy headquarters organizations), representatives from Task Force Climate Change, a representative from Annapolis city government, USNA faculty members, a long-range planner, and members of the Joint Global Change Research Institute Environmental Research and Development Program (SERDP) team. A high level of concern was expressed about flooding and sea level rise.

To establish priorities, we explored several sets of approaches. Key input was provided through the interviews with USNA staff, who shared their time to review the details of the impacts of past major exposures and management of ongoing nuisance and minor events.

Building on this information, we tested the use of established metrics that characterize the importance of assets to the fulfillment of the installation's mission, in this case, the Mission Dependence Index (MDI). The MDI is an operational risk-based metric that determines an

infrastructure asset's criticality relative to the installation mission (Antelman et al., 2008). It further describes the impact to a mission if the infrastructure becomes non-operational. Originally developed by the U.S. Navy and U.S. Coast Guard, it is now deployed across the Air Force and National Aeronautics and Space Administration, and has been adapted for managing the U.S. Army's facility assets (Grussing et al., 2010). The MDI links facilities to specific mission elements, and identifies the impact if facilities and infrastructure assets are lost (Grussing et al., 2010). It applies operational risk management techniques to specific assets. MDI relies on the experience and judgment of leaders involved in a mission. It analyzes the following:

- Intradependencies (MDw)—The degree to which a mission depends on infrastructure controlled by the mission itself
- Interdependencies (MDb)—The degree of dependence of a mission on infrastructure or services outside its control.

MDI data pointed to the importance of infrastructure utilities including water, power, heating, and chilled water, and waterfront-related facilities.

To develop insight on how shocks from climate hazards can propagate from one functional area to another (that is, cascading failure), we decomposed the MDI and analyzed it by constructing a weighted, directed network. In Figure 18, the nodes of the network represent the classes of infrastructure assets at the USNA and the edges or links are the dependency relationships as defined by subcomponents of the MDI. Not surprisingly, this analysis demonstrated the high dependence of building systems on the utilities and transportation networks, but also identified the mission importance of the Child Development Center and the potential impact its sudden closure (for example, due to storm conditions or power outages) would have on staff involved in the instructional programs of the Academy.

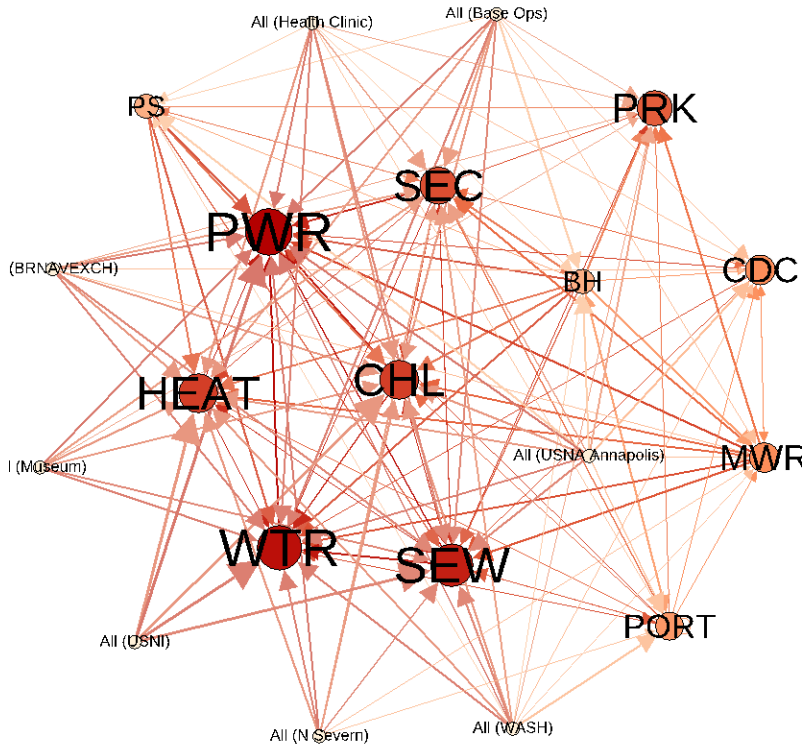


Figure 18. Network representation of the interdependencies between functional areas using the MDI

As a result of this analysis and interviews with decision makers about assets that are currently sensitive to climate hazards, a subset of infrastructure assets—buildings and transportation—was chosen. Although the utilities included a greater number of critical MDI assets and were more central in terms of dependency, the people interviewed considered these assets as more robust and hardened to resist impacts from climate hazards, such as flooding. In contrast, from interviews and analysis of historical damages, buildings and transportation networks are exposed and sensitive to these hazards.

Based primarily on the interview data, outdoor training was also selected because of its importance to the mission of the USNA. All midshipmen participate in athletics, which are a crucial part of the challenging, tightly structured program at the Academy. The daily schedule for students includes company training time and a variety of athletic activities. When plebes arrive, they are gradually conditioned to the rigors of outdoor athletics, including, as needed, conditioning to the high summer temperatures and humidity at the USNA. Outdoor activities are sensitive to a changing climate, for example through the direct effects of elevated air temperature and/or poor air quality on human physiology, and through loss of access to outdoor training facilities as a result of flooding.

4.1.2 Buildings and transportation-related infrastructure: Sensitivity, historical exposure, and adaptive capacity

Buildings and transportation networks at USNA are exposed and sensitive to climate hazards. However, current adaptive capacity is adequate to cope with nuisance flooding.

4.1.2.1 Sensitivity of infrastructure

To assess sensitivity of infrastructure, we explored using (1) information on asset condition, including quantitative condition indicators; (2) past damages from climate events; and (3) a physically based proxy variable, elevation. We briefly discuss each of these approaches and their results at USNA.

We took several approaches using information on asset conditions. One approach we used to assess condition involved examining maintenance logs to identify facilities with deferred maintenance or other deficiencies. In the literature on vulnerability assessment, these factors are sometimes identified as increasing the sensitivity of assets to current and future climate exposures. This approach did not pan out due to difficulties associated with the data as well as challenges in identifying quantitative relationships between these conditions and vulnerability to climate change.

We also explored analysis of the data from condition indicators of individual facilities at USNA. Condition indices are used to monitor soundness and functionality of key assets. These indicators vary across Federal agencies and the DoD Services. Condition assessment metrics are a key tool for both strategic capital planning and prioritization of projects (Booty, 2009). They integrate life-cycle and condition information with facilities management systems. For example, the U.S. Navy's Condition Index evaluates condition based on the system age and remaining useful life. Combined with climate risk information, the Condition Index can provide insight into the sensitivity of assets to climate hazards (for example, Norton et al. [2013]).

In one analysis, we integrated MDI, Condition Index, and elevation data (see discussion below related to use of elevation as a physical proxy of sensitivity) to identify individual buildings that appeared highly sensitive from multiple perspectives. Figure 19 shows the buildings in the Upper and Lower Yards that are important (that is, with an MDI of 85 and higher) and relatively low-scoring on the Condition Index (that is, bottom 50% of all Condition Index scores) with the building color by elevation (that is, represented by flood categories). The buildings that are colored white in Figure 20 are important to the mission, in poor condition compared to other buildings at the USNA, and are located in areas sensitive to flooding.

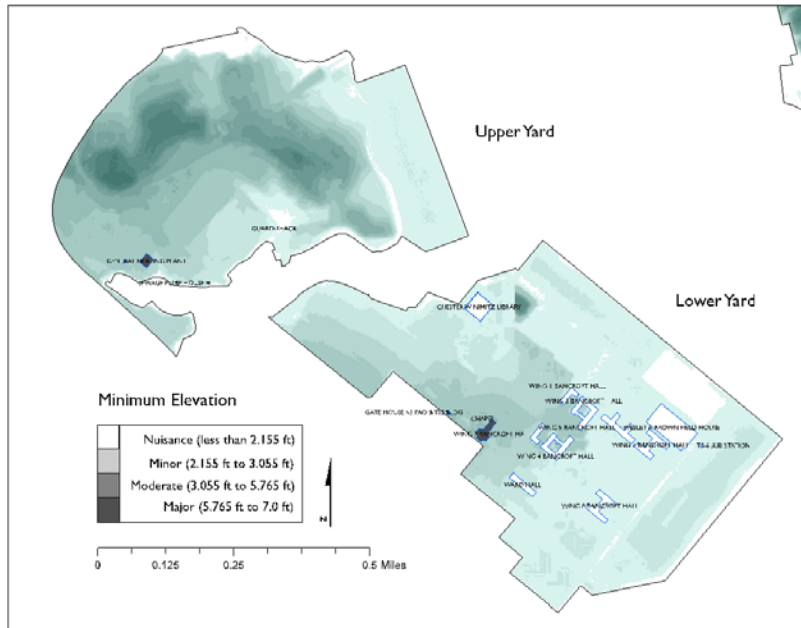


Figure 19. Buildings that are in the upper quartile of the MDI (that is, with an MDI of 85 and higher) and the bottom 50% for Condition Index, with the building color by elevation (darker blue indicates deeper flooding)

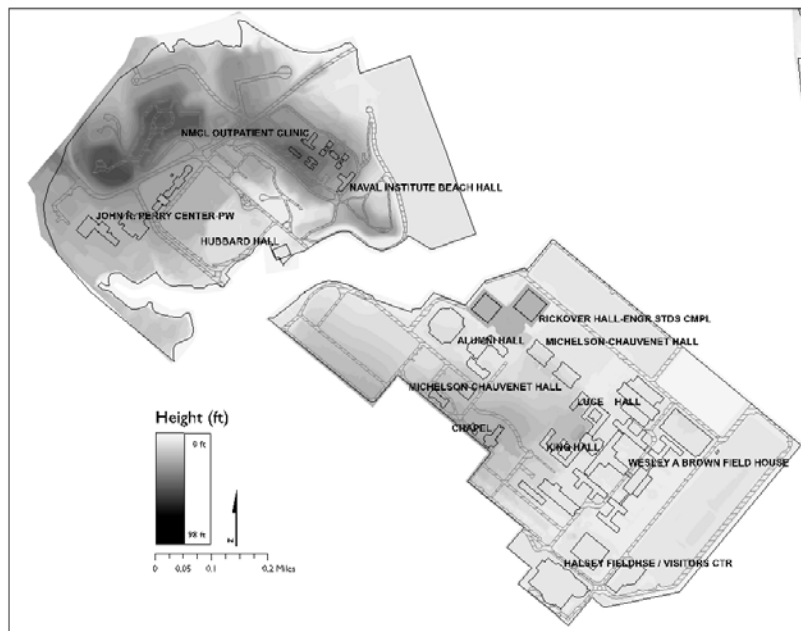


Figure 20. Upper quartile of replacement value and upper quartile of MDI (that is, 85 or higher) with the building color reflecting the elevation (darker color indicates higher elevation)

Damages from recent climate extreme events such as storms, as well as more routine events such as nuisance or minor flooding, can also reveal which assets are more sensitive to future

changes in climate. There are a number of ways that flooding damages can be classified. Figure 21 lists the relationships and definitions of these damages adapted from the *U.S. Army Corps of Engineers Institute for Water Resources* (USACE, 2013). The USNA has experienced the range of damages associated with flooding. At USNA, these have included costs to prepare for an event, closures, direct damages to infrastructure, immediate post-event disaster management/recovery, and repairs.

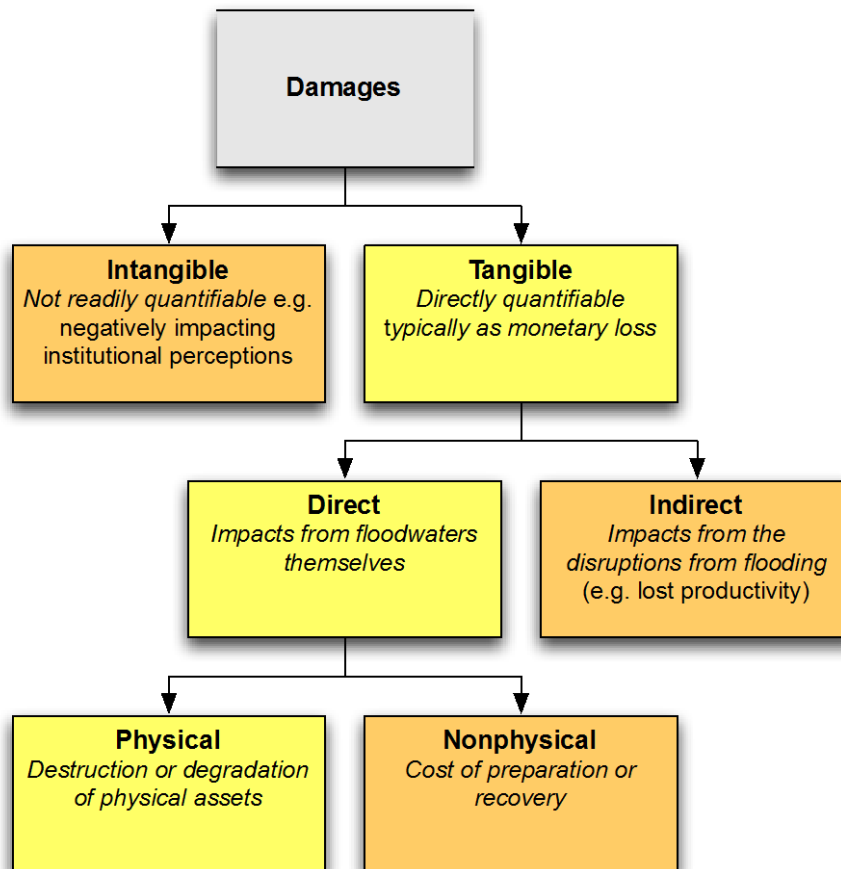


Figure 21. Classifications of flood damages | Adapted from USACE (2013).

We gathered information provided by public works department staff who have long tenures at USNA, from databases, and from other records of preparation, damage, and recovery costs associated with different events. We conducted a number of phone and in-person interviews to identify and collect data and capture staff intuitions on the exposure and sensitivity of the USNA to climate hazards. We identified management systems that tracked maintenance expenses over time, but records proved to be insufficiently detailed to produce data that seemed comparable across events. The approach did provide some basic information, however, as well as detailed records on recovery from Hurricane Isabel in 2003. Our goal with this approach was to construct an events database of extreme event characteristics and associated damages. With access to data

of sufficient resolution, one could develop a set of rudimentary damage functions¹ that relate flood event categories to damages at the USNA by enumerating costs based on information from the site records. In the section of this case study on future vulnerability, we will discuss hypothetical changes in preparedness costs resulting from increased frequency of flooding.

We focused on elevation as a key characteristic and a physically based proxy for sensitivity to damage from flooding of both buildings and transportation infrastructure. For buildings, this approach has limitations due to variation introduced by relocation of assets and building contents over time, and its use is a second best to the approaches described above and is useful for data-limited situations. All other things being equal, lower elevation assets are more sensitive to changes in the frequency and intensity of flood-inducing storm and tidal surge events and are also most at risk from sea level rise. For buildings, analysis of geographical information system data reveals the extent to which major systems are located in areas that create sensitivity to flooding. Many mission-critical academic buildings, residence halls, and athletic fields and facilities are located in the Lower and Upper Yards, often in flood-prone areas. In addition, a hazardous materials storage area was located in the floodplain of the Upper Yard adjacent to a creek at the time this analysis was conducted. The contents of some buildings have been relocated over time, moving expensive and/or critical equipment and assets to higher floors, in some cases in response to prior flooding events. At the time of this analysis, this was not universally the case—some expensive and mission-critical equipment was located in areas sensitive to flooding.

For transportation assets, the road network at the USNA is spread across the Lower Yard, Upper Yard, and North Severn. Approximately 50% of all road area at the Academy is located on the North Severn area with the remaining 50% almost evenly divided between the Upper and Lower Yards. Analysis of road elevation at the USNA across each area revealed that while the lowest road sections are located in the Upper Yard, the area most sensitive to changes in the frequency of flooding is the Lower Yard (see Figure 22). While the Upper Yard contains the road with the overall lowest elevation point, the Lower Yard, where most of the mission-related activities take place, remains the most exposed to flooding in aggregate and the most sensitive to increased flooding. Across the campus, a small percentage of the transportation infrastructure sits below nuisance and minor flood levels (1.1 and 6.6%, respectively). However, approximately 24% of the transportation infrastructure is below the moderate flooding level. Further, the flooding risk is unevenly distributed across the campus as the Lower Yard infrastructure has the most risk.

¹ Depth-damage functions estimate the expected damages associated with different building types and their contents as a function of inundation water depths (FEMA, 2009). In lieu of constructing a set of custom functions, standard functions could be used to estimate damages.

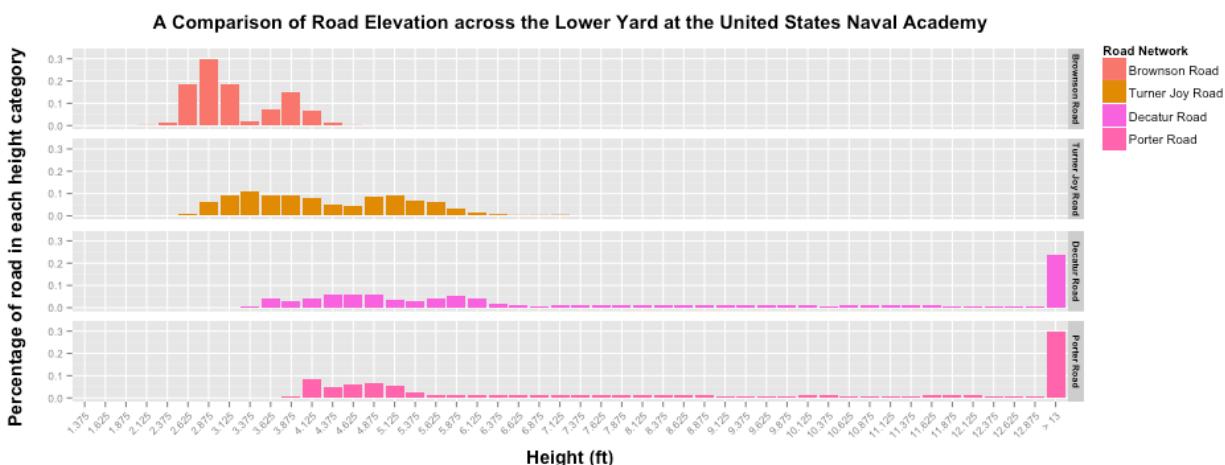


Figure 22. Comparison of a sensitive subset of the road network in the Lower Yard

Analysis of infrastructure-related observed exposures

We focused on coastal flooding and inundation. These have been the most important climate-related events to negatively affect the USNA. Over the past century, the USNA has experienced a number of flooding events. Flood levels in this report are based on deviations from the NAVD88 datum level at the station and refer to the Advanced Hydrologic Prediction Service definitions of flood stage levels (Table 4).

Table 4. Categories of Water Heights Defined by the Advanced Hydrologic Prediction Service and Adjusted to the NAVD88 datum

Category	Water Height (NAVD88)
Nuisance flooding	1.23 ft (0.37 m) to 1.63 ft (0.49 m)
Minor flooding	1.64 ft (0.49 m) to 2.53 ft (0.77 m)
Moderate flooding	2.54 ft (0.77 m) to 5.23 ft (1.59 m)
Major flooding	5.24 ft (1.59 m) or greater

Figure 23 shows the number of days each year where maximum water levels are within one of the flood categories. Due to increasing sea levels, the number of days each year where the USNA experiences some sort of flooding has increased dramatically—by a factor of 10—since 1928. Events that occurred fewer than 10 times a year in the 1930s now occur upwards of 100 times a year. Minor flood stage events have also increased significantly, from 1 to 5 days per

year in the 1930s, to as many as 40 times a year in 2012. While the number of days that experience moderate flooding has increased slightly, the sample size is too small to indicate significant change. Major flood events are rare and have only occurred twice, in 1933 and 2003.

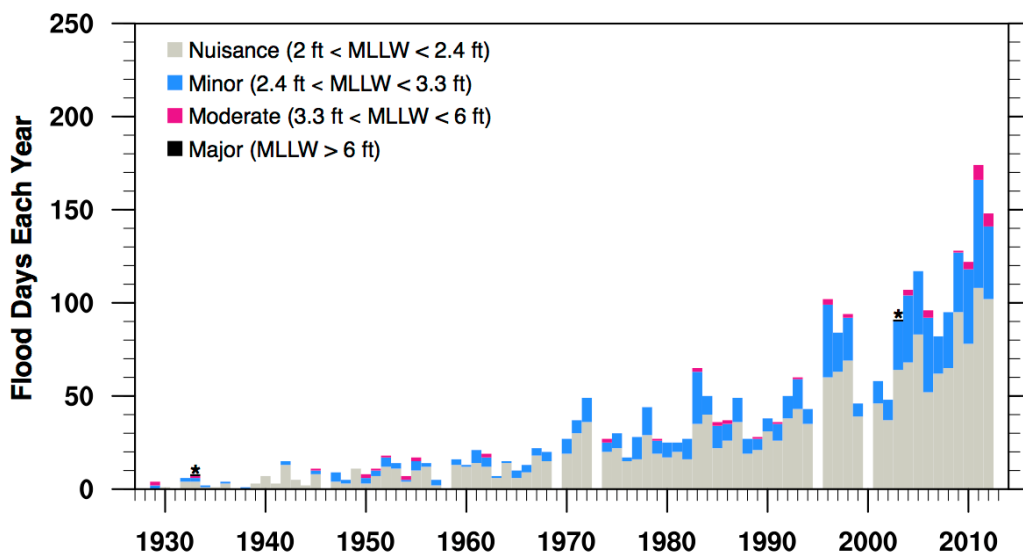


Figure 23. The number of days each year the USNA experienced flooding / Asterisks indicate the years of occurrence for the only two major flood events that have occurred at USNA, 1933 and 2003.

Potential explanations of this increase include land use/cover change that increases impervious surfaces and runoff, changes in storms and processes that contribute to coastal inundation, and increases in sea level. Higher sea levels result from post-glacial rebound, which includes glacial melt water and thermal expansion from increasing ocean temperatures. We begin with sea level and then turn to analysis of storms.

Long-term (1928-present) tide gauge observations (from National Oceanic and Atmospheric Administration station #8575512 located at the USNA) indicate that the area has experienced a 0.138 in./yr or 0.0115 ft/yr (0.0035 m/yr) increase in sea level since the start of the station record in 1928 (Figure 24). Anomalies in the figure are relative to the NAVD88 datum.

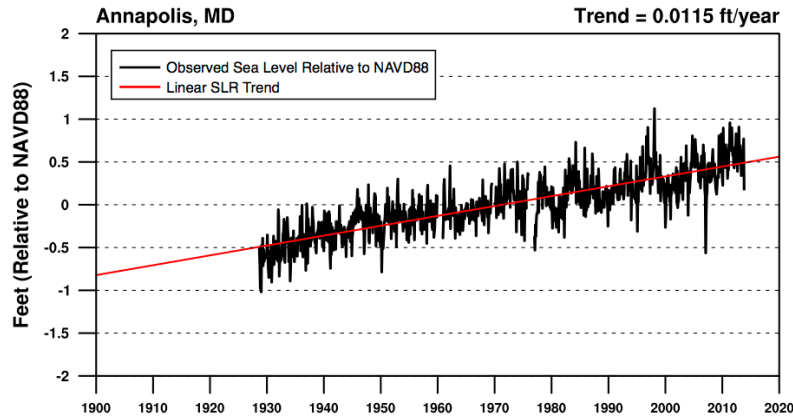


Figure 24. Historical sea level from the Annapolis tide gauge | Values are relative to the NAVD88 datum. A 12-month smoothing has been applied to the raw observed sea level data (black line). Data source: <http://tidesandcurrents.noaa.gov>.

The immediate cause of coastal flooding at USNA is weather systems that produce winds that are southerly (blow from the south to the north) to easterly (blow from east to west). These directions create a fetch and “push” water into the Chesapeake Bay. In theory, any weather event that causes broad southerly to easterly flow over and south of the Chesapeake Bay area can result in high water levels at the USNA; however, we have identified the most common weather events that result in inundation. These events are categorized into tropical and extratropical storms. When hurricanes or tropical cyclones pass to the west of the site (over land), it is likely that they will cause flooding, and the two major flood events to occur at the USNA (Figure 25) were both caused by the passage of hurricanes/tropical cyclones. Extratropical weather patterns cause the majority of floods at the USNA—of 64 minor-to-major flooding events in 1980-1999, 58 were forced by extratropical systems while only 8 were forced by tropical systems. Through analysis of the observational record, we identified four main extratropical weather patterns: lows that track west of the Chesapeake Bay as they travel northward up the coast account for around 60% of these systems, which others are associated with an approaching cold front attached to a low-pressure center near the Great Lakes or in Quebec.

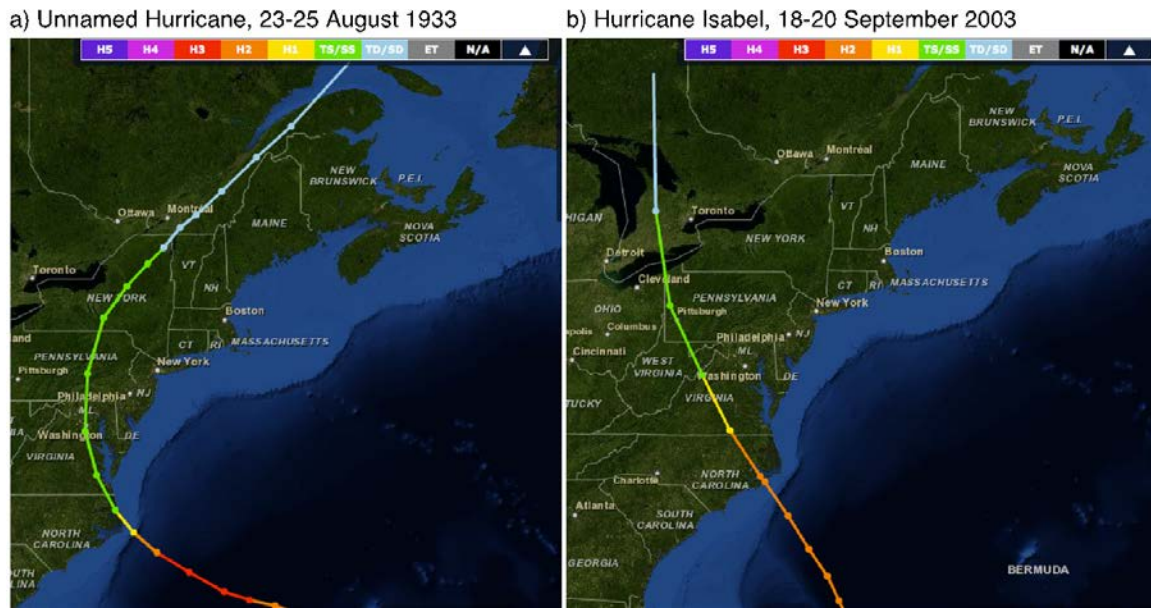


Figure 25. Tracks for the hurricanes that caused the two most severe flooding events at the USNA / Source: National Oceanic and Atmospheric Administration Coastal Services Center, <http://csc.noaa.gov>

4.1.2.2 Adaptive capacity related to infrastructure

Adaptations (adjustments in infrastructure, activities, or management) can reduce vulnerability in a variety of ways including upgrading a facility to higher standards or relocating it. Measuring the effectiveness of different adaptation options is an ongoing research challenge. In evaluating the status of adaptation efforts for infrastructure at USNA, we identified some measures to harden facilities and systems that were undertaken in the wake of Hurricane Isabel. These included implementation of a phased door dam project to provide approximately 4-5 vertical ft (1.21-1.52 m) of protection for buildings that are so outfitted. Door dams are deployed approximately four times per year on average at some locations, but less often (once per year) at others. Deployment of the door dams occurs at different predicted flooding levels for each building, based on that building's elevation. Other buildings are protected by sandbagging. A temporary sea wall can also be deployed between some buildings to create a continuous storm barrier, and balloon plugs have been procured to protect against back flooding through storm drains where needed. We were unable to draw precise conclusions about the effectiveness of recently implemented flood-protection adaptations in terms of reduced damages. Anecdotally, however, deployment of door dams for structures exposed to flooding during storm events; the relocation of heating, ventilation and air conditioning equipment to a less exposed location; and the elevation of sensitive equipment such as electrical substations have reduced vulnerability of the USNA to some climate extremes. In Section 4, we will analyze the adequacy of these measures for adapting to potential future storm surges under conditions of elevated sea level.

Development of quantitative metrics for adaptive capacity (the ability to implement relevant adaptation measures) relevant to infrastructure proved to be a more subjective exercise than anticipated, as adaptation depends not only on physical characteristics of infrastructure and

management practices, but also on considerations such as staff willingness or financial capacity to implement alterations in infrastructure or practice. Adaptive capacity determines whether or not individuals and institutions are able to adjust to changing conditions to reduce damages or take advantage of opportunities. Of the many factors that affect adaptive capacity of infrastructure systems, we identified four that are important for the USNA: preparedness, economic capacity, human capital, and management structure. Preparedness—having well-developed procedures for handling emergencies—is important for reducing damage from storms. Normally, review of the site emergency response plan would indicate what types and magnitudes of climate events were being planned for. Because USNA’s plan was being updated at the time of our case study and could not be provided to us, we were unable to systematically evaluate preparedness. Economic capacity, in this case having access to financial resources for adaptation (through additional funding or budgetary flexibility), was challenging to evaluate because while interview data indicated that budgets for maintenance and capital expansion are tight and there are unmet needs, USNA may well have more financial resources than many less prominent facilities. Access to detailed budget information was also a sensitive issue. Human capital, having a sufficiently trained workforce that is open to considering the need for adaptation, is a strength at USNA, at least as revealed through our interviews and observations that staff are aware of increasing exposure to flooding and the potential for costly damages in the event of a strong storm combined with tidal and other conditions. Finally, in terms of management structure, we noted the public works and other staff were very willing to consider and implement measures to increase resilience. This was offset by lack of decision-making authority over major choices that could affect vulnerability, for example placement of new structures, which were made at other governance levels.

4.1.3 Sensitivity, exposures, and adaptive capacity of outdoor activities

Training and other outdoor activities were identified as a priority during our initial meetings with USNA staff. We identified and interviewed individuals from the Naval Health Clinic Annapolis, and also attempted to contact and interview athletic trainers, without success. We focused on gathering information on the incidence of different flag conditions during the summer months, as well as the implications of these conditions for cancellations or restrictions on training. We also developed and used a physical proxy, calculation of the wet bulb globe temperature (WBGT), using publicly available climate data (a calculation we repeated using data from regional climate models for projection of future conditions and vulnerability).

4.1.3.1 Sensitivity of outdoor activities

Outdoor activities are sensitive to hot and humid conditions, and heat-related injuries are a significant threat to the health and safety of Service members, as well as the attainment of training objectives and operational objectives (AFHSC, 2013). The issue is addressed in policy and instructions from the Commandant of Midshipmen (see Department of the Navy, 2013) intended to prevent injury of midshipmen and students attending summer activities at the USNA campus. The guidance sets forth the procedure for daily monitoring of the WBGT by the Naval Health Clinic Annapolis, which involves automated measurement of temperature, humidity, radiant heat, and air circulation at specified time intervals from roughly May 15 to September 15 each year. Conditions are displayed on the Naval Health Clinic Annapolis website as well as

flagpoles around the campus, and reporting of occurrences of heat stress is required (see Table 3).

The major concern that emerged during our interviews was the potential impact of increases in occurrence of black flag conditions on the summer physical training activities of newly enrolled midshipmen (“plebes”). The physical training program consists of a series of events and ongoing activities intended to introduce plebes to the physical mission of the USNA, including a number of endurance and field exercises. Newly arriving plebes are not acclimatized to the heat and humidity of the region and particularly at the start of the training may not be physically conditioned. The training program guidelines stress minimizing injuries, including those related to heat stress.

We identified the existence of a long-term paper logbook record of WBGT observations at the Naval Health Clinic Annapolis but were not able to access these records during our case study. We also discussed frequency rates of heat-related injuries over time with staff at the health clinic but were unable to identify any records or datasets.

4.1.3.2 Exposure of outdoor activities

The WBGT is a measure of sensitivity for outdoor training at the USNA and used in making decisions about restrictions to outdoor activities. The WBGT is calculated with available station data to estimate the historical time series of flag day occurrence at the USNA (Figure 26). Based on these data, the number of flag days has not changed over the past 70 yr, with black flag days occurring 1-4 times per year, as seen in Figure 26.

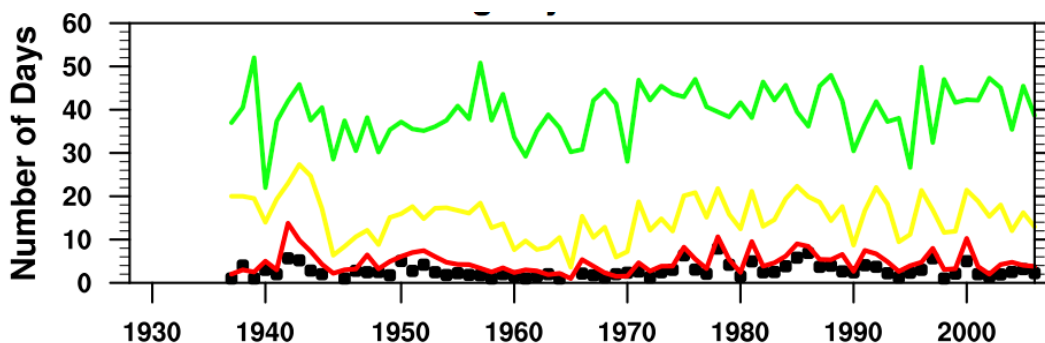


Figure 26. Yearly occurrence of flag days / Green flag days (green line), yellow flag days (yellow line), red flag days (red line), and black flag days (black dots) are shown. The data used show no significant trend over time.

Historically, in the mid-Atlantic region, outdoor activities are also affected by air quality, with high levels of ozone and other pollutants detrimental to the health of sensitive individuals. Thus, we also explored the potential for poor air quality to affect outdoor training. The U.S. Environmental Protection Agency has developed an air quality index for ozone, to highlight when concentrations are dangerous (<http://airnow.gov/index.cfm?action=aqibasics.aqi>). The air quality index thresholds are outlined in Table 5.

Table 5. Air Quality Index Values and Related Concerns

Air quality index values	Levels of health concern	Cautionary statements
0-50	Good	None
51-100	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion outdoors
101-150	Unhealthy for sensitive groups	Active children and adults, and people with lung disease, such as asthma, should reduce prolonged or heavy exertion outdoors
151-200	Unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid prolonged or heavy exertion outdoors. Everyone else, especially children, should reduce prolonged or heavy exertion outdoors
201-300	Very unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid all outdoor exertion. Everyone else, especially children, should avoid prolonged or heavy exertion outdoors
301-500	Hazardous	Everyone should avoid all physical activity outdoors

Source: *Air Quality Guide for Ozone* (http://www3.epa.gov/airnow/ozone/air-quality-guide_ozone_2015.pdf) (EPA, 2015)

Poor air quality caused by elevated concentrations of pollutants is exacerbated by heat. While there is significant year-to-year variability in the number of high ozone concentration days in the data available from the county where the UNSA resides, there are no significant trends for the past 30 years (Figure 27). Through our interviews we determined that poor air quality is not currently a factor in the decision to curtail or prohibit outdoor activities.

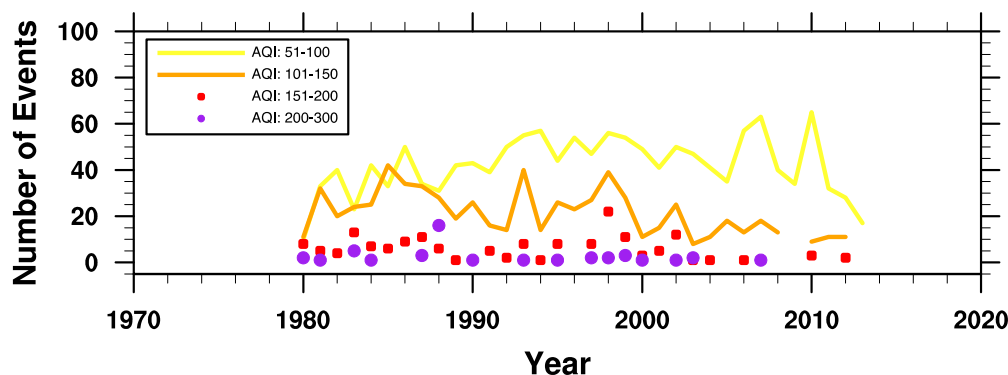


Figure 27. Yearly hazardous air quality events in Ann Arundel County, where the UNSA is located / Data source: <http://www.epa.gov/airdata>

Capacity to cope with current levels of exposure to extreme heat and humidity seem high. There is widespread awareness of the potential for heat stress, especially during the early phases of the Plebe Summer, and guidelines for monitoring and treatment have been issued in the context of an organizational culture in which implementation of measures to minimize injuries is

a priority. Standard measures such as access to water and hydration fluids, regimented rest/drink periods, personal cooling techniques and equipment, and individuals trained and tasked to identify and treat different levels of heat stress are implemented. There is also the potential to move some activities indoors, or to schedule them during early morning or evening hours, when WBGT conditions are more favorable. In the long term, should incidence of WBGT increase (see the next section for analysis of potential future conditions), potential adaptation capacity seems high given the USNA's awareness of the issue.

4.1.4 Climate change and potential future exposure at USNA

Section 3.2 describes the methods used in the project to develop a climate “outlook” for the mid-Atlantic region. This section briefly summarizes the USNA-related content of the Climate Outlook prepared as part of this project (see Appendix A for the full climate outlook) and provides a small amount of general background information needed to understand this section as a standalone case study description.

4.1.4.1 Methods overview for USNA-focused information on future climate

Climate projections for the USNA and the mid-Atlantic region are made using regional climate models because the global models that were run lacked the resolution to represent the Chesapeake Bay and Annapolis was located in a grid box that is an ocean point. Thus, analysis focused on a 13-member ensemble of 31.06 mi (50 km) horizontal resolution regional climate model simulations produced as a part of the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2013). Climate projections are for the mid-century period: 2041-2069 (with minor variations due to model differences), and unless otherwise stated, projections are presented against a baseline period of 1971-1999. The projections are based on the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios “A2” greenhouse gas emissions scenario. At 2100, this scenario produces a very high level of climate change; for recent decades, it is consistent with observed global emissions (Rahmstorf et al. 2007). To estimate the influence of sea level rise on local water levels, we applied the method described in Tebaldi et al. (2012) which implicitly takes into account future thermal expansion, glacial melt, and local effects such as sinking of the land.

4.1.4.2 Summary of projected changes in exposure to flooding and extreme heat

Compared to baseline conditions, the USNA can expect future changes in climate to include more frequent and more severe wind-and-storm-driven flooding, as well as increasing temperatures. We discuss two factors that will contribute to increased flooding: sea level rise and potential increases in extreme precipitation. Finally, we present projections of increased temperatures at USNA and implications for WBGT.

Sea level rise and flooding at USNA

Sea level at the USNA is projected to rise by about 1.6 ft (+/-0.3 ft) (0.48 m +/- 0.09 m) by mid-century (see Figure 28). This will significantly increase the frequency and intensity of coastal flooding. Uncertainty involving the frequency and intensity of the tropical and

extratropical storms that cause the flooding is too high at this point to make a general statement on their projections, but sea level rise will have a large effect on future flooding frequency and intensity regardless.

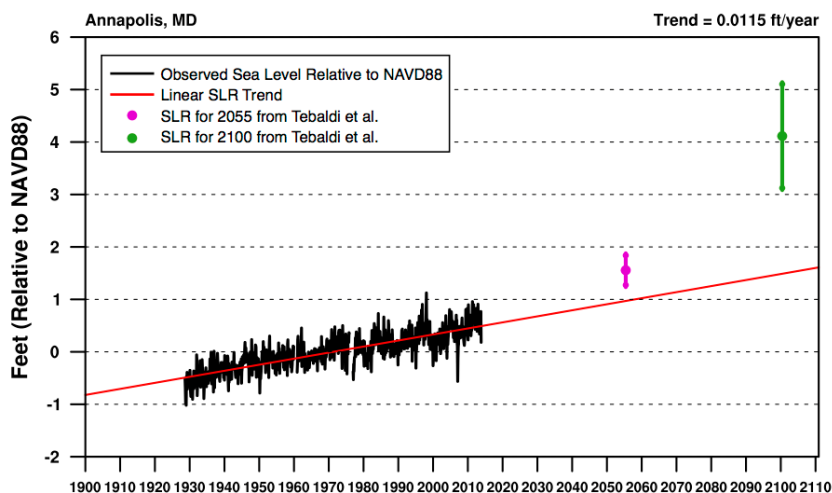


Figure 28. Historical sea level rise extrapolated to 2110 and expected sea level rise in 2055 / Sea level rise extrapolated to 2110 (red line) and expected sea level rise in 2055 using the method in Tebaldi et al. (2012) based on the “A2” scenario.

Heavy precipitation and flooding at USNA

Heavy precipitation, in conjunction with a storm with inundation-producing winds, is a concern because it exacerbates flooding and/or increases flooding potential. (Precipitation alone was not identified as a major concern for the USNA and is discussed in the mid-Atlantic Climate Outlook [Appendix A]). Projected changes in the frequency of intense precipitation ranging from light to very heavy over a 3-hour period are provided in Figure 29 for summer (June-August) and a long cool season (September-April). Almost all flooding events related to extratropical systems occur during the long cool season. In summer, most models indicate a decrease in the frequency of light to moderate rainfall. Heavy rainfall (90th percentile and above) projections are uncertain until the 99.9th percentile, where all but one of the models projects a statistically significant increase in the frequency. The outlier model has a small, insignificant decrease. In the cool season, during the time of most of the extratropical storms that lead to inundation, nearly all of the models agree that very heavy precipitation (95th percentile and above) will significantly increase in frequency. This indicates that precipitation with these storms may be more intense in the future and exacerbate wind-driven inundation to a greater extent.

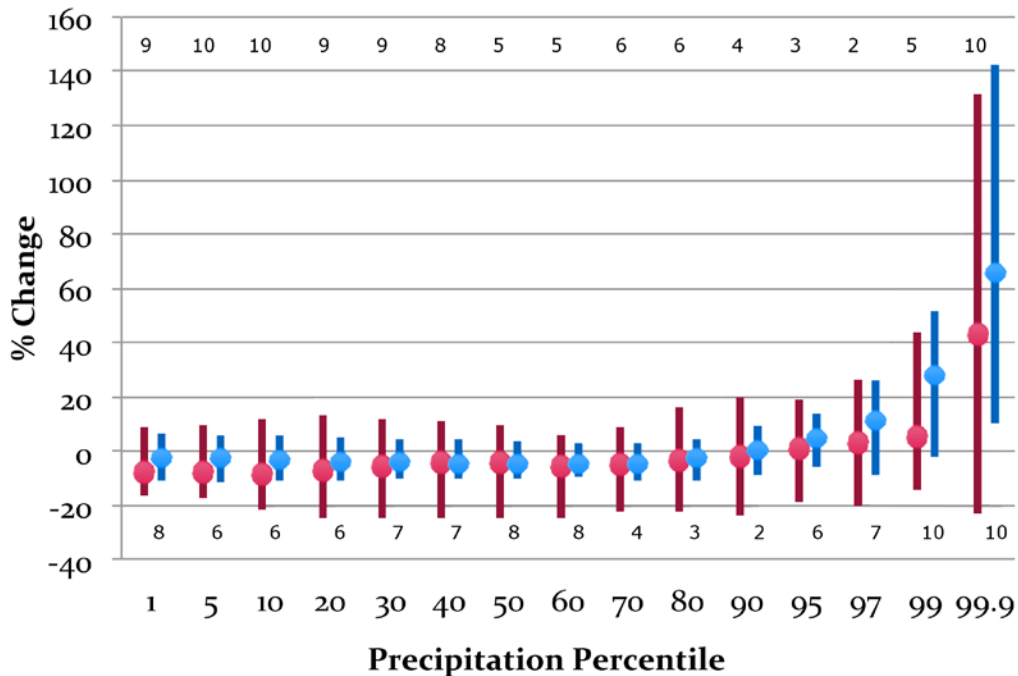


Figure 29. Change in precipitation frequency | Projected change in the frequency of 3-hr average precipitation at low to high intensities for the warm season (June-August) in red and the cool season (September-April) in blue from 11 NARCCAP simulations. The average change across the simulations is indicated by the dot. The range of change projected across the models (minimum change to maximum change) is indicated by the span of the bar. Intensities are given as percentiles (x-axis). Numbers along the top (warm season) and bottom (cool season) indicate the number of models that had a statistically significant change at the given intensity.

Temperature

Temperature-related changes will affect the WBGT readings and potentially the frequency of flag restrictions on outdoor activities. Average temperature is expected to rise 2.7°-6.3° F 1.5°-3.5°C, depending on the season, in the mid-Atlantic region by mid-century, with the greatest increases in the winter. The ensemble mean of the NARCCAP simulations projects an increase in mean temperature ranging from 1.5°C in spring to about 3.5°C in winter across the mid-Atlantic region (see Figure 30). Temperature increases are projected to be the greatest during summer. By mid-century, daily maximum temperatures during summer are projected to increase by 5.6°F in the NARCCAP ensemble and 5.9°F in CMIP5 ensemble. In contrast, multi-model regionally averaged winter daily mean temperatures are projected to increase by 5.1°F in NARCCAP and 5.2°F by CMIP3/CMIP5 ensembles. During the 1971-2000 reference climatology period, the number of days exceeding 95°F ranges from 3-14 days per year on average to the south and East of the Appalachians depending on location. The largest trends in the frequency of 95°F days is found in the southern portion of the region over South Carolina, where there are now 8-12 more days per year that exceed 95°F than there were around 1970. As daily maximum temperatures increase, the average number of days where temperatures exceed 95°F will also increase. While there is uncertainty about the magnitude of the change, the spatial patterns are consistent across a wide range of average temperature increase.

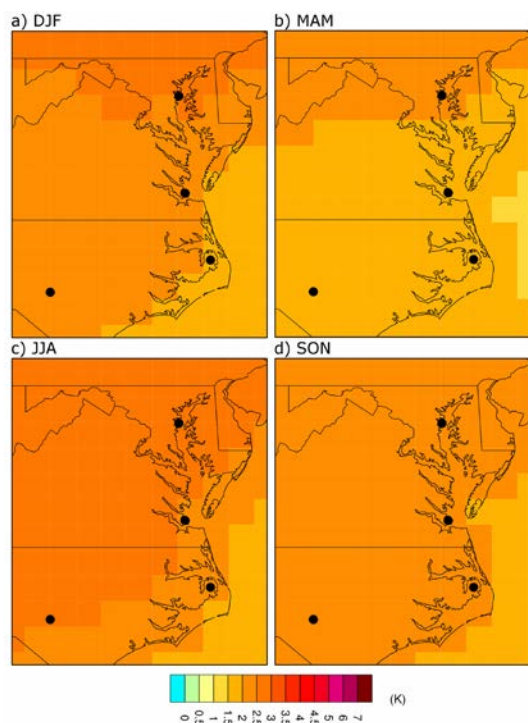


Figure 30. Ensemble mean, seasonal average temperature change / The northern-most black dot indicates the location of the USNA. Temperature change averaged across 12 NARCCAP simulations.

Focusing specifically on an area (62.13 miles by 62.13 miles [100 km by 100 km]) around Annapolis, projections from the NARCCAP simulations suggest an increase in daily mean temperature of approximately 1.8-3.4°C depending on the model and the season (Figure 31).

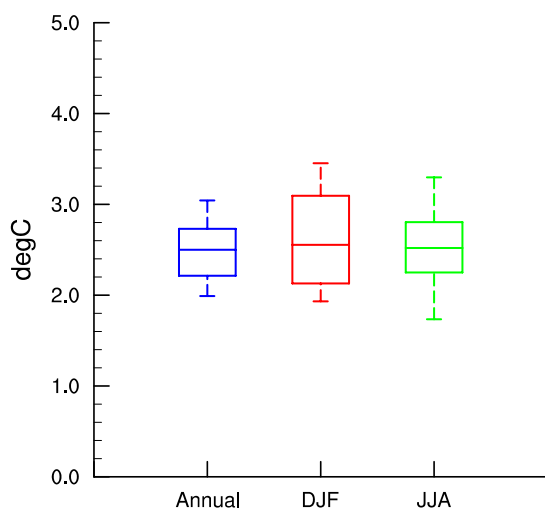


Figure 31. Range of uncertainty for the change in average daily mean temperature / A box and whisker plot representing the range of uncertainty for the change in average daily mean temperature (°C) for the annual mean (blue), December, January, and February (red), and June, July, and August (green) for Annapolis.

Trends in daily maximum temperature and daily minimum temperature are similar to trends in daily mean temperature. Summer trends are larger compared to winter and the annual mean trends. Also, the rate of warming is shown to substantially increase in the future. As the daily maximum temperature increases, the total number of days where temperatures are greater than 95°F (a common benchmark used in climate analysis) increases. On average, Annapolis can expect approximately 22 more extremely hot days per year by 2070. This translates into a 145% increase in the number of days where temperatures exceed 95°F.

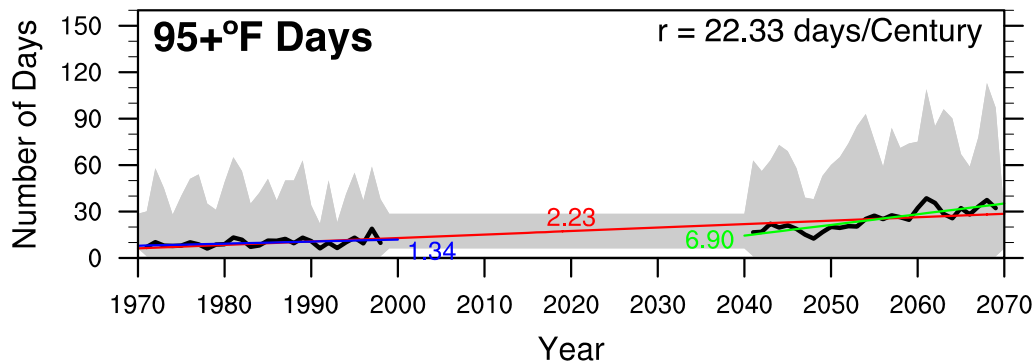


Figure 32. Projected trend in the number of 95°F+ ($T_{max} > 35^{\circ}\text{C}$) that occur per year | The thick black line is the ensemble mean number of freezing days. The grey background represents the spread across the models. The total trend from 1970 to 2070 (red line), the trend from the current climate (blue line), and the trend for the future climate (green line) are also shown. Colored numbers indicate the trend for each line in days/decade. The total trend over the century is shown in the top right of the figure.

4.1.5 Future vulnerability: Integrating baseline sensitivity and adaptive capacity with potential changes in exposure

This section describes several ways in which the project explored future vulnerability by integrating information on sensitive systems and the capacity to adapt them with the analysis of potential changes in exposure due to climate change. As before, we focused this analysis on the implications of flooding and increased temperature. A challenge for vulnerability assessments is to consider not only the ways that exposure may change, but also how relevant societal conditions and infrastructure systems may change as well. For individual sites, master or strategic plans that are developed through processes that consider changes in mission and resulting requirements for installation performance are a good source of information. We considered changes at USNA that could affect future vulnerability that were identified in the USNA master plan (EDAW, 2006) as part of our analysis of the use of information about climate change and vulnerability in decision making.

4.1.5.1 Vulnerability to flooding

We used several experiments to explore the future consequences of interactions among sea level rise, storm surge, and coastal flooding at the USNA.

Modeling coastal storm surge

In one approach we applied a storm surge model with high temporal and spatial resolution, the unstructured-grid Finite Volume Coastal Ocean Model (FVCOM) developed by Chen et al. (2003) to explore the consequences of different magnitudes of storms and tidal processes for flooding on the campus. FVCOM is a three-dimensional coastal ocean model that fully couples ice-ocean-wave-sediment-ecosystem models with detailed representation of the land surface, including built features such as flood walls, buildings, or other infrastructure. Because storm surge and coastal flooding processes are actually driven by extreme events that are at regional scale, the model domain extends from New York State to Georgia at coarse resolution (12.42 mi, 20 km). Higher model grid resolution was specified inside the Chesapeake Bay, especially at the USNA, where horizontal grid resolution is 984.3 ft (300 m) in the Bay and 39.4 ft (12 m) for the USNA campus.

The first experiment modeled a future storm equal in magnitude to Hurricane Isabel coupled with sea level rise to explore how the combined effects of both could affect the USNA. The model was driven by tides at the open boundary and hurricane wind and pressure fields to simulate tidal circulation and storm surge in the Chesapeake Bay and along mid-Atlantic coast. We validated the model using Hurricane Isabel. Good agreement between modeled and observed storm surge induced by Hurricane Isabel indicated that the storm surge model is able to simulate storm surge and coastal flooding processes in the Chesapeake Bay.

We next explored the potential effects of a storm of Hurricane Isabel's magnitude with sea level rise. Model input parameters and open boundary conditions for all future hurricane model runs were kept the same as the historical Hurricane Isabel run. To simulate the effect of sea level rise, we used the approach by Mariotti et al. (2010) to superimpose the sea level rise values on tidal elevations at the open boundaries. Although simulated water surface elevations for the future scenarios show similar trends to the baseline condition with a constant shift by the sea level rise value, differences between the future and historical conditions indicated the effects of sea level rise on the storm surge height are actually nonlinear. The nonlinearity is stronger as sea level rise became higher. Horizontal two-dimensional distributions of peak storm surge and surface velocity for all the scenarios are shown in Figure 33. More area was inundated as future sea level increases from 1.3 ft (0.4 m) to 5.7 ft (1.7 m).

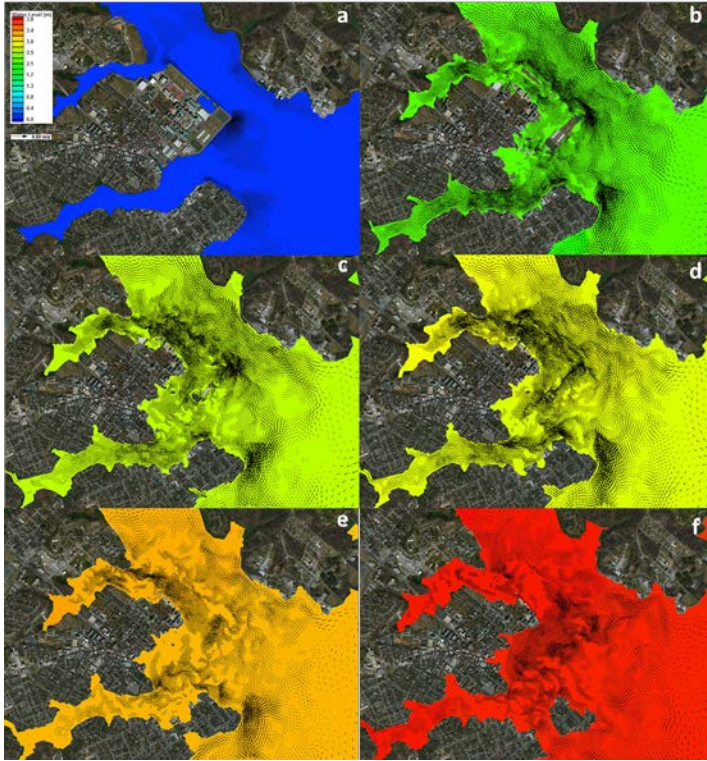


Figure 33. Distribution of storm surge height for historical and future Hurricane Isabel / Several different conditions are portrayed: (a) historical Hurricane Isabel at low tide; (b) historical Hurricane Isabel at peak surge; Hurricane Isabel at peak surge with (c) 1.4 ft (0.42 m) of sea level rise; (d) 2.1 ft (0.64 m) of sea level rise; (e) 3.7 ft (1.12 m) of sea level rise; and (f) 5.7 ft (1.73 m) of sea level rise.

To quantify the effect of sea level rise on storm surge at USNA, statistics of maximum storm surge height, inundated area, and duration for different sea level rise projections were calculated and are provided in Table 6. Maximum storm surge heights for the future hurricane with the sea level rise effect are roughly the same as the sum of the maximum surge height of the baseline condition and the amount of sea level rise. However, the maximum storm surge heights in the future scenarios are not necessarily the same as the baseline condition (Yang et al., 2014). The inundated area increases significantly for the 1.4 ft (0.42 m) sea level rise scenario, up to 24%. The maximum flooding time during storm events increases exponentially as sea level rises.

Table 6. Statistics of Storm Surge under Historical and Future Hurricane Isabel with Sea Level Rises (SLR)

Parameters	Baseline	0.4 m SLR	0.7 m SLR	1.1 m SLR	1.7 m SLR
Max surge height (m)	6.66 ft (2.03 m)	8.03 ft (2.45 m)	9.02 ft (2.75 m)	10.33 ft (3.15 m)	12.27 ft (3.74m)
Max flooding area (m²)	490,682	609,847	643,734	671,722	702,405
Percentage increase (%)		24%	31%	37%	43%
Max flooding time (hr)	11 hr	20 hr	32 hr	58 hr	always
Percentage increase (%)		82%	191%	427%	NA

A final experiment tested the feasibility of forcing FVCOM with regional climate model outputs. This is valuable because it is important to be able to simulate the effects on coastal flooding based on any changes in storm intensity that may occur in addition to changes resulting from sea level rise.

Results demonstrated that the model can be applied to different locations for simulation of storm surge and coastal flooding induced by extreme storm events (such as tropical cyclones and cold front storms), sea level rise, and geomorphologic change including land subsidence. In its application in the Chesapeake Bay, it can be further improved to increase the accuracy of storm surge and tidal predictions through improved geometry and bathymetry of tributaries in the bay, hurricane wind field, grid refinement, and tidal open boundary conditions. FVCOM is not an end user-oriented model in that it requires specialized scientific expertise and resources (data, computational facilities, etc.) to run. The experimental results for the USNA were produced at a cost of approximately \$40K, a cost that could be expected to vary depending on location, whether the model had already been applied in the region, and other factors. While much more expensive than the return period analysis approach described immediately below, this level of expenditure is modest compared to some analyses and may be justified in cases where an installation and its assets have high value or importance.

In addition to using FVCOM, we used several other approaches for investigating the potential implications of increased flooding. In one, we examined potential changes in the frequency of flooding events with sea level rise. Using the methodology in Tebaldi et al. (2012), we created the return period including sea level rise, which demonstrates significant changes to the intensity of flooding events at the Academy. From the historic record, the U.S. Army Corps of Engineers has determined that a one in 100-year event is water heights of approximately 7.8 ft (2.37 m) (NAVD88), which also happens to coincide with the maximum water height at the USNA tide gauge during Hurricane Isabel. By the middle of the century, the water height associated with a one in 100-year flood event will shift to the water height associated with the one in 20-year event. We also explored the time in an average year USNA would experience inundation at three of the four defined flood classes (we did not include the severe flood event category, as this magnitude of flooding has occurred only twice in the history of the USNA). Clearly, the flood defenses as structured are designed for events less severe than events of the

Hurricane Isabel magnitude. Thus far, the flood defenses constructed since Hurricane Isabel have mitigated the potential negative impacts from flooding. However, the costs of deploying the flood defenses are not trivial, and given sea level rise projections, we should expect a larger and larger percentage of USNA resources to be dedicated to flood defenses should the Academy infrastructure continue to exist in its current arrangement.

We also explored the use of depth-damage functions to analyze damages associated with the projected flood depths around major academic and support buildings. We used these results to discuss with USNA staff the potential operational and budgetary implications of increasing deployments of flood defenses. Moreover, existing approaches to flood protection will become less adequate over time, and the USNA will need to revise its adaptation strategies over time to develop more cost-effective approaches. This highlights the importance of not losing sight of a flood wall as an adaptation approach that will need to be carefully reconsidered at some point in the future.

4.1.5.2 Vulnerability to temperature increases

Increases in hot days will directly affect outdoor activities and training, important throughout a midshipman's experience at the Academy. As with temperature, the WBGT is expected to increase in the future. As illustrated in Figure 34, the ensemble mean change of the NARCCAP simulations projects an increase in the May-September daily maximum WBGT of about 2.3°C for the period 2040-2070. Trends for Annapolis from 1970-2070 indicate an average increase of about 3.57°C for the century.

Increases in the daily maximum WBGT will have an impact on the training capacity of the USNA. While the models agree that the WBGT will increase in the future, the impact this increase will have on the number of flag days is less certain. The projections from the NARCCAP models suggest that the number of green flag days may increase by 5-17 days per year, yellow flag days by 1-8 days, red flag days by 1-3 days, and black flag days may increase by 0-27 days per year (Figure 35). Model differences in air temperature, radiation, wind speed, and humidity result in significant uncertainty for the changes in the number of flag days for the models (Figure 36). However, most of the changes in WBGT are driven by changes in temperature.

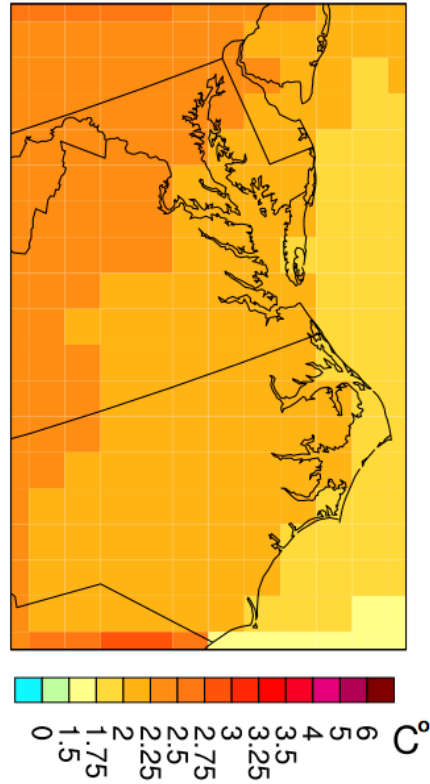


Figure 34. Ensemble mean change (10 NARCCAP simulation ensemble) in the average daily maximum WBGT (°C) for May-September

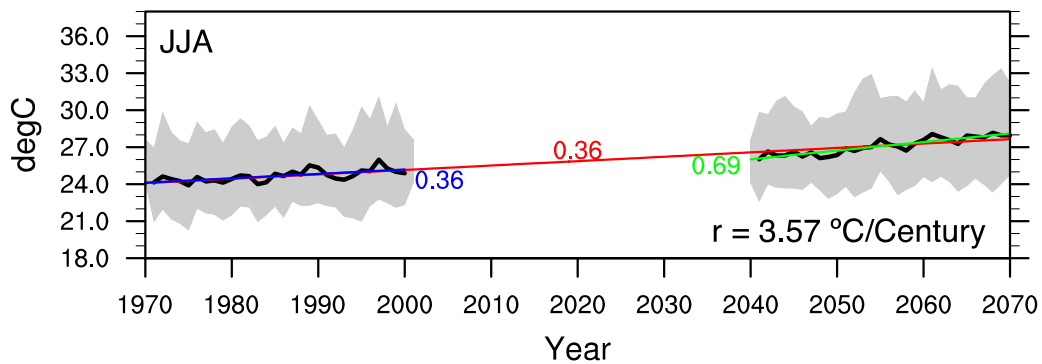


Figure 35. Trends in the daily maximum WBGT (°C) for June, July, and August / The thick black line is the ensemble mean WBGT. The grey background represents the spread across the models. The total trend from 1970 to 2070 (red line), the trend from the current climate (blue line), and the trend for the future climate (green line) are shown. Colored numbers indicate the trend for each line in °C/decade. The total trend over the century is shown in the bottom right of each panel.

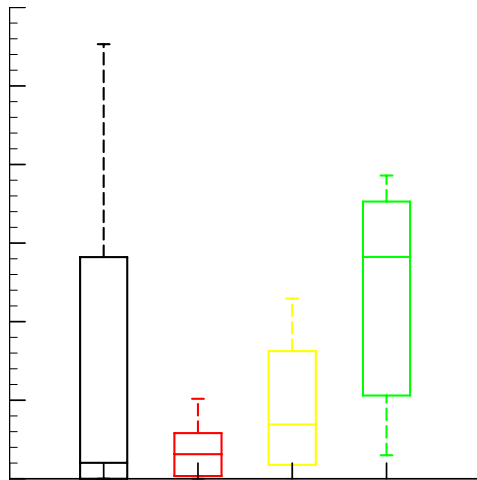


Figure 36. Expected change in annual occurrence of black, red, yellow, and green flag days / A box and whisker plot representing the range of uncertainty for the change in the number of black, red, yellow, and green flag days expected to occur per year on average at USNA.

With regard to air quality, ozone concentrations are strongly influenced by changes in the weather. Tropospheric ozone is created through photochemical reactions involving the chemicals released when we drive our cars. Thus, high ozone concentrations typically correspond with heat waves and droughts—when there is an abundance of sunlight, and very little rain to scrub the atmosphere clean. It is projected that air quality will decline in cities in the future (Confalonieri et al., 2007; EPA, 2009; 74(239) FR 66496-66546). According to the U.S. Environmental Protection Agency, over the United States climate change is expected to produce a 2 to 8 parts per billion increase in ozone levels, exacerbating ozone concentrations on hot, dry days, and lengthening the ozone season. This may mean an increase in the number of poor air quality days per year for USNA. We note, however, that poor air quality is not currently an impediment to outdoor training at USNA, and other trends including increasing use of clean transportation fuels may compensate for the effects of climate change.

Adaptive capacity of outdoor activities to heat

We have no basis for projecting changes in the capacity to adapt to any increased frequency of flag conditions that restrict outdoor activities and did not identify plans to adjust training based on future climatic conditions and increased incidence of flag restrictions. Assuming current practices such as widespread awareness of the potential for heat stress, guidelines for monitoring and treatment, and standard measures continue to be implemented, it seems that capacity to adapt should be sufficient to cope with projected increases in exposure. In addition, there is also the potential to move some activities indoors, or to schedule them during early morning or evening hours, when WBGT conditions are more favorable, should conditions worsen. Monitoring of potential impacts seems likely, given the ongoing measurement and recording process for flag conditions.

4.1.6 **Decision making: Current and potential future use of information on climate change and vulnerability**

We investigated both how decision makers at the site use climate- and weather-related information in making their decisions and what information would be useful for decision making but is not available or not used (especially for future planning). We asked about decisions that include such information or that are in progress or planning phases and that would benefit from climate information such as projections of climate change. We discussed with site personnel different classes of decisions, including choices to deploy protective measures when flooding is a possibility; to invest in existing infrastructure; to improve infrastructure that will prevent or mitigate flooding (for example, removable sea walls and storm drains); and to plan capital investment in major facilities.

Individual managers at USNA take the initiative to incorporate climate- and weather-related information in making infrastructure decisions. Managers actively look for information about potential extreme events from multiple sources and use this information in deciding whether to implement emergency preparedness procedures.

However, development of plans for the future assumes that climate conditions will be the same in the future (climate stationarity) rather than considering the potential for changed conditions. At the time of our research, planning documents did not indicate or incorporate knowledge of likely increases in flooding damage, both from the greater frequency of storms like Hurricane Isabel, and greater damages from such a storm due to sea level rise. Implicitly, planning assumes that the door dams and other adaptations will be sufficient to protect from flooding even at the intensity of a storm like Hurricane Isabel.

Short-to-long-term adaptations and planning

Installation personnel are keenly aware that climate change impacts, especially flooding and rising heat, present real risks for the USNA. In the short term, local decision makers monitor tide forecasts, as well as the WBGT for training activities. Public works personnel monitor tide forecasts and begin preparation in advance of forecasted high water levels.

For the mid-term, as well, planning includes flooding protection that may be related to projected climate change. At the time of this analysis, the Naval Support Activity Annapolis Installation Master Plan (NAVFAC, 2012) included proposed repairs to a number of the sea walls and other protection measures. There were also plans to seal utility tunnels from water intrusion. These preparedness measures would enhance the robustness of the USNA assets up to the moderate flooding category, but would not provide protection against a major flooding category event (for example, at the water height of Hurricane Isabel). There are no plans to adjust outdoor activities to the heat-related impacts of climate change.

In the case of flood-protection planning, assisted by the U.S. Army Corps of Engineers, proposals were developed to provide protection to water heights of 10.8 ft (3.29 m) according to USNA datum, which is 3 ft (0.91 m) above the 100-yr floodplain, and 0.8 ft (0.24 m) above the 500-yr flood elevation (USACE 2006, 2008). These plans assume that climate and sea level are stationary, however. Their robustness to uncertain future conditions would be clearer if evaluated

across a range of potential future scenarios in which changes in climate and sea level are explored.

The decision-making process related to siting new facilities or expanding existing structures is long term, extremely complex, potentially involving many stakeholders in different jurisdictions of the U.S. Navy, other branches of government such as Congress, members of the surrounding community, and even the private sector. The increasing flood risk due to climate change is one of many key issues, including mission criticality, impact on viewsheds, facility age, maintenance requirements and costs, and the costs of building upgrades. As is the case for flood-protection planning, facility-related decisions are primarily premised on the assumption of climate stationarity, as evidenced by the USNA master plan update (EDAW, 2006, p. 2-8).

The team selected two candidate decisions for exploring approaches to incorporate information on future climate and potential impacts into decision making. One was the possible expansion or relocation of an activity (both options involving existing structures) or building a new facility; the other was siting of a new academic building to expand program offerings. The former provided a clear example of the potential to incorporate climate change information into the decision process and was selected for an experiment using formal decision analysis.

Decision analytic methods

We explored analyzing a USNA decision-in-progress to understand where and how the use of information on climate and potential future impacts could help decision makers understand the nature of an asset's or activity's vulnerability and the means to increase resilience, for example, making siting or designing infrastructure decisions that are adaptive to potential climate change impacts.

Using decision analytic methods (Bell et al., 1988), we constructed an influence diagram of the selected decision. An influence diagram may show the relative importance of multiple factors that have different uncertainties, thus improving the likelihood that a specific decision will be robust over various outcomes and the economic value of resolving key uncertainties or discovering new alternatives. We first framed the decision, identifying the objectives and the alternatives under consideration. We then developed a model that describes the important factors in the decision, along with information, uncertainties, and influences that could affect whether or not a particular decision would meet decision makers' objectives.

For the decision on facility/program expansion, the decision context is complex. Considerations include the potential for the program being housed to grow, costs associated with alternatives that spread the program across several buildings, annual maintenance costs, and potential flooding damage costs over the lifetime of the selected alternative. In addition, aesthetic and cultural factors were considered. The expansion alternatives were defined as (1) staying in the currently occupied buildings and performing necessary upgrades to an existing historic building; (2) obtaining more space within a currently occupied building and performing necessary renovations; and (3) building a new facility. Preliminary capital cost estimates prepared using Naval Facilities Engineering Command show, as would be expected, that alternatives 1-3 are in order from lowest to highest capital cost. At the time of this research, the capital cost estimates assumed stationary climate. To consider potential implications of changes

in climate and incidence of flooding, additional information reflecting potential changes in frequency and depth of inundation at different sites would need to be developed and included in revised estimates of added engineering and construction costs for a flood resilient facility plus potential direct costs related to flood protection and recovery. An even broader perspective would consider the potential to begin to fundamentally adapt the USNA to increasing flood risks by beginning to shift activities to less vulnerable portions of the campus, and the related effects of such a move on the considerations described above.

To summarize a decision framing that begins to account for potential future changes in climate and inundation potential, we created the influence diagram shown in Figure 37. Influence diagrams are a graphical way to show the relationships and interdependencies among decisions, uncertainties, and outcomes. Squares represent decisions, ovals to uncertainties, and diamonds to the objectives of the decision. The arrows represent the order of events and resolution of uncertainties over time. Influence diagrams are useful as communication tools, but they can also be implemented as mathematical models employing decision analysis solution techniques.

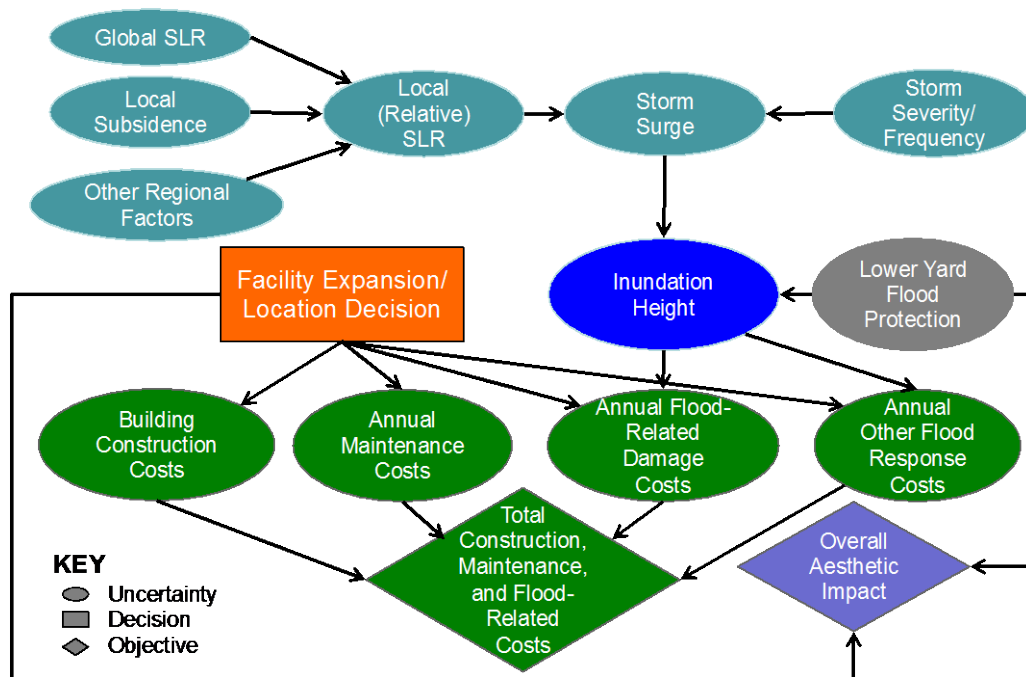


Figure 37. Influence diagram for facility expansion/location decisions

The figure shows the factors decision makers would consider in siting the program: construction and maintenance costs, costs from flooding damages (or other flood response costs), and aesthetic issues. All of these components are potentially uncertain, varying in their uncertainty as a function of the particular location being evaluated. Flood-related costs include both those associated with the building's location, but also those arising from the uncertainty in future inundation heights, which is itself a function of future storm surge uncertainty and any flood-protection measures that may be employed in the Lower Yard.

The top part of the diagram depicts the uncertain factors influencing storm surge. The green diamond represents the total of the quantitative cost factors; the purple diamond represents the

total of any aesthetic impacts associated with flood-protection measures at the building and more broadly in the Lower Yard. The mathematical implementation of the diagram facilitates looking at tradeoffs between the quantitative and qualitative factors.

Refocusing the project's decision-making research: Evaluating widely used planning and budgeting processes to identify opportunities to incorporate climate and vulnerability information

Data were not available to construct a formal decision model and conduct an analysis of the costs and benefits of different options for program expansion at USNA in the context of climate change. The experience of preparing for such an analysis suggests that USNA is confronted with a number of decisions that are potentially affected by climate change, especially as many buildings, roads, and other critical infrastructure are located in flood-prone locations and there is a relatively small amount of land available on the Lower Yard for relocation and buffering. In the absence of policy guidance and training, the inclusion of climate-related information in decisions related to planning and managing USNA to house and train the future Navy officers will rest upon the initiative of individual managers. Here, as at other installations, these individuals would need to be assiduous in seeking out information on the implications of potential impacts from a variety of sources and actively using this information to guide decision making. We realized that rather than approaching the analysis of decision making on an ad hoc basis at the installation level, a better approach might be to focus on identifying opportunities to incorporate climate change and vulnerability information by adjusting more widely applicable planning, budgeting, and management processes. This approach would include exploring what changes in policy, guidance, and training would be necessary to address the challenge of using such information in decision making. We redirected our analysis toward this issue and thus focused subsequent discussions of decision making on the installations to gather information on the nature of decisions that would be potentially affected, and thus the higher-order processes that should be considered by the project. This work is described in Section 5.

Discussion

For the USNA, the research team tested a variety of approaches and developed insights into how to use data about specific areas of the campus to characterize vulnerability to flooding, using both elevation data and model-based projections of sea level, storms, and flooding. The information developed provided evidence of the need to build in consideration of climate change to infrastructure-related decisions (for example, siting and design). Quantifying future heat stress conditions using the WBGT as an indicator also provided information that USNA decision makers could use to plan future activities related to Plebe Summer and other training activities.

The more general lessons from the USNA case study are (1) a more workable vulnerability definition that emphasizes installation characteristics rather than exposure; (2) the realization and identification of differing levels of analysis; and (3) the importance of decision-relevant metrics by converting exposure into impacts and/or significance, considering the vulnerability of USNA infrastructure and activities. This “translation” is needed to enable decisions to relate abstract notions of climate change to installation decisions. The existing literature recommends measuring sensitivity and adaptive capacity, and our efforts to apply a range of methods revealed

that some promising approaches were more problematic than anticipated. Estimating adaptive capacity and establishing climate conditions or thresholds that give rise to impacts were particularly challenging.

In addition, the set of site personnel who can catalyze and facilitate an assessment includes not only those in the Department of Public Works, but also those involved in planning at both the headquarters and installation levels and those who have a high level of concern about climate change and who can champion adaptation measures, whatever their formal roles. At USNA, people in the last category included USNA professors.

Finally, to be useful to decision making, vulnerability assessment must consider potential direct impacts to systems in terms of consequence to missions or other management issues. This includes use of a variety of approaches to estimate or model impacts but also involves discussion of the consequences of impacts and potential adaptations with installation personnel.

4.2 Case study results: Joint Base Langley-Eustis, Hampton, Virginia

Joint Base Langley-Eustis (JBLE) was the second installation case study for this project. JBLE was selected primarily for its importance to the U.S. Air Force training mission, but also its joint management structure involving the U.S. Air Force and U.S. Army (which was assumed to establish a different decision-making environment and hence different information needs than would be the case for an installation located at one site), and its coastal location and the accompanying history of climate-related flooding.

The case study was conducted using an approach similar to that used at the U.S. Naval Academy. We started with an iterative process of interviews with installation and Service-level personnel and review of available documents and data to establish priorities. Using this information, we prioritized analysis of flooding combined with sea level rise (which affects buildings, training areas, ranges, runways and other infrastructure networks) and temperature change (with implications for heating, ventilation, and air conditioning [HVAC] system design and costs, as well as potential ramifications for training and flight operations) using analysis of the historical climate records for the site and region. We used several approaches, including return period analysis and geographic information systems techniques to examine the potential impacts of climate change on base exposure.

This discussion of results is organized around four of the five research questions that motivate this study, those focused on understanding installation baseline vulnerabilities, potential future climate conditions, and future vulnerability and implications for the mission of the JBLE. See Section 5 for a discussion of the implications of the results for a vulnerability assessment framework and methods that can be used by the Department of Defense. The discussion of results is less extensive than for U.S. Naval Academy as we do not cover some aspects of our study process that were discussed in that case.

4.2.1 **Baseline: Establishing priorities and identifying current sensitivity, observed exposures, and adaptive capacity**

This section addresses our first research question focused on baseline conditions at the installation and provides background information and approaches we used to set priorities through discussions with JBLE staff and analysis of preliminary data. We describe current sensitivity, exposure, and adaptive capacity, a description that provides a focus for analysis of future climate exposure and subsequent evaluation of impacts and significance for missions.

Background on JBLE—In 2010, JBLE was created from what previously were two separate military bases: U.S. Army's Fort Eustis and the U.S. Air Force's Langley Air Force Base (AFB). While consolidated into a joint base, the two bases remain geographically separated by almost 17 miles. Fort Eustis is located along the James River; Langley AFB is located at the mouth of the James River where it joins the Chesapeake Bay. Recognizing that Langley AFB and Fort Eustis are now integrated into JBLE, we often refer to them individually because of the different issues and approaches for each location.

Background on Fort Eustis—At Fort Eustis, the primary mission has been transportation training, engineering, and operations. Fort Eustis is home to the 7th Transportation Brigade, which has as a mission to provide logistical support during training and wartime activities to all branches of the service. The fort was established on the banks of the James River in Newport News, Virginia, in 1918. The topography of Fort Eustis includes uplands and lowlands. The installation houses a variety of operational, training, administrative, housing, and supporting functions. One particularly important facility is Third Port, a deep-water port that houses the Army's watercraft fleet and is used to train personnel in cargo logistics and vessel operations. The buildings and infrastructure are mostly located in the upland (cantonment area) while most of the training areas and ranges are located in the lowlands adjacent to the river. While most of Fort Eustis's upland is above the 100-year floodplain, much of the training area has an elevation of only 6 in. (Headquarters Air Force, 2012). An estimated 47.2% (~3,360 acre) of the installation is wetlands. As a result, most of the training area and ranges are vulnerable to periodic flooding and erosion.

Background on Langley AFB—Langley AFB is home to the 633rd Air Base Wing, in addition to several support units. Recently, there has been a significant investment in the resources available to the Intelligence Surveillance and Reconnaissance Wing. The base was established as an Air Service training camp after the United States decided to enter World War I in 1917. The base is situated on low-lying land, which subjects base infrastructure, including the runway, to periodic flooding. It is adjacent to other United States Government (USG) installations (National Aeronautic and Space Administration's Langley Research Center) and privately owned land, which would complicate adaptation that involved relocating infrastructure.

4.2.1.1 **Setting priorities: Buildings and other built infrastructure**

To establish priorities, we explored several sets of techniques. Input was provided by installation personnel during interviews, as well as existing datasets and reports. In particular, the installation complex encroachment management action plan (ICEMAP) (Headquarters Air Force,

2012), a periodic report designed to assist Headquarters Air Force and installation personnel in planning, included a preliminary analysis of climate change in the context of encroachment and sustainment challenges. The report acknowledged the potential threats to the long-term viability of JBLE and highlighted a number of concerns including sea level rise, coastal erosion, invasive species, and more extreme weather conditions resulting in reduced usage days (with impacts on training and readiness) and increased costs. Other studies and resources useful for analysis of climate change vulnerability have also been produced and were consulted in conducting this case study. These studies identify a range of potential issues to include within a vulnerability assessment including several that concern JBLE's dependencies on the community, including transportation systems, electric utilities, and water resources.

4.2.1.2 Buildings and other infrastructure: Sensitivity, historical exposure, and adaptive capacity

On the basis of previous analyses and interviews with installation personnel about assets that are currently sensitive to climate hazards, a subset of infrastructure assets—buildings and the runway—was chosen for further analysis at Langley AFB, while transportation assets, ranges, and training areas were chosen for Fort Eustis. The low elevation at both Langley AFB and Fort Eustis has resulted in a history of periodic flooding and reinforce the importance of these issues.

To evaluate sensitivity of infrastructure, we analyzed (1) past installation damages from climate events (including loss of training), (2) a physically based proxy variable (elevation), (3) information from established metrics on condition and present replacement value (PRV), and (4) several temperature-related issues (impacts on outdoor activities and invasive species). We briefly discuss each of these issues, the approaches, and results.

Past damages from storms to JBLE have been substantial. Hurricane Isabel caused significant damages at both Langley and Fort Eustis. At Langley AFB, storm recovery costs exceeded \$146 million. Hurricane Isabel required the evacuation of 60 F-15 fighter jets and support personnel and the mandatory evacuation of approximately 6,000 personnel living within installation housing (Langley AFB, 2013). Much of Langley AFB, including the historic district and part of the flight line, was submerged by the storm surge that rose to 2.7 m above sea level (Langley AFB, 2013). Other damages included 125 roofs damaged, 200 mechanical rooms flooded, 11 Headquarters Air Combat Command (ACC) facility basements flooded, 101 other assets flooded, and over 800 trees fallen¹. Flooding occurs periodically at Langley and can lead to runway closures and an increase in bird and wildlife aircraft strike hazard (BASH) when debris (including fish) is deposited on the runway and attracts more birds to the area.

At Fort Eustis, recorded damages from Hurricane Isabel were approximately \$3.6 million, resulting from removal and disposal of damaged and fallen trees. The need to store the large amount of debris generated by Hurricane Isabel resulted in the prolonged closure of training areas. According to interviews and email exchanges with Tim Christensen, Chief of the Conservation Branch, substantial additional damage occurred, but descriptions and cost estimates

¹ Hurricane Isabel Storm Damage Briefing for Langley Air Force Base (AFB). PowerPoint presentation, undated. Information provided by Langley Air Force base (January 2014).

were not available. At Third Port, a number of preparedness measures and damages are associated with major storms and lead to increased operating costs and potential loss of functionality during the storm and period of recovery. A variety of medium-size boats are moored in protected areas and smaller vessels are pulled from the water. Past events have resulted in damage to piers and facilities including floating docks and electrical infrastructure. In addition, previous large storms have moved so much sediment as to create a shoaling hazard for large ships.

For both installations, we sought to establish baseline impacts of current climate variability and extreme weather on cancellation of training and loss of access to training areas. Analysis was intended to establish a set of thresholds at which training is cancelled or ranges and training areas are closed, and then to analyze whether the frequency with which these conditions increased over time. A number of factors can influence the ability to conduct flight training at Langley AFB, including air traffic and other encroachments and weather-related events resulting in flooding. In the case of flooding, in addition to primary impacts of flooding suspending use of the runway and potentially causing structural damage, secondary impacts occur when seaweed and fish remain in adjacent areas, attract birds, and increase BASH. Standing water also increases problems associated with rodent and pest control. At Fort Eustis, periodic flooding at the installation closes low elevation ranges and training areas. Typically, Fort Eustis can assume that any named storm will cause flooding at Training Areas 5, 18, 20, 21, and 28. Nor'easters often flood the same areas depending on the storm duration. In the past, flooding and tidal surge has resulted in disruption of training and maintenance of vessels and the port. For big storm events, the larger vessels are sent out to designated areas before they are trapped by the James River Bridge (closes at wind speeds above 50 knots). We obtained digital data on the number of flight cancellations at Langley AFB for a 5-year period. For Fort Eustis, we reviewed a logbook containing information about training area closures, but no digital information was available. In neither case were the reasons for cancellation or closure recorded (these can be related to climate conditions or other encroachments that lead to training restrictions). As a result, we were unable to identify a set of climate thresholds for cancellations and closures and thus were not able to perform trend analysis on weather-related flight training cancellations or the closure of training areas at Fort Eustis.

For a physically based proxy for sensitivity, we used elevation as a key characteristic of infrastructure assets related to their susceptibility to damage from flooding. Lower elevation assets are understandably more sensitive to changes in the frequency and intensity of flood-inducing storm and tidal surge events and are also most at risk from sea level rise. At Fort Eustis, roads located in the lowland areas are particularly vulnerable to periodic flooding. In Figure 38 we illustrate the elevation distribution for particularly vulnerable roads on Fort Eustis. Analysis of road elevation across the installation reveals that Condon Road, Mulberry Island Road, and Range 2 Road have a high percentage of area at relatively low elevation. Given the lack of connectivity in the lower-lying areas of Fort Eustis, the loss of a few roads, either temporarily or longer term, to flooding or flood-related damage can significantly impact the ability to move throughout the area. For some training areas and ranges, damage to the road network would lead directly to their loss of use.

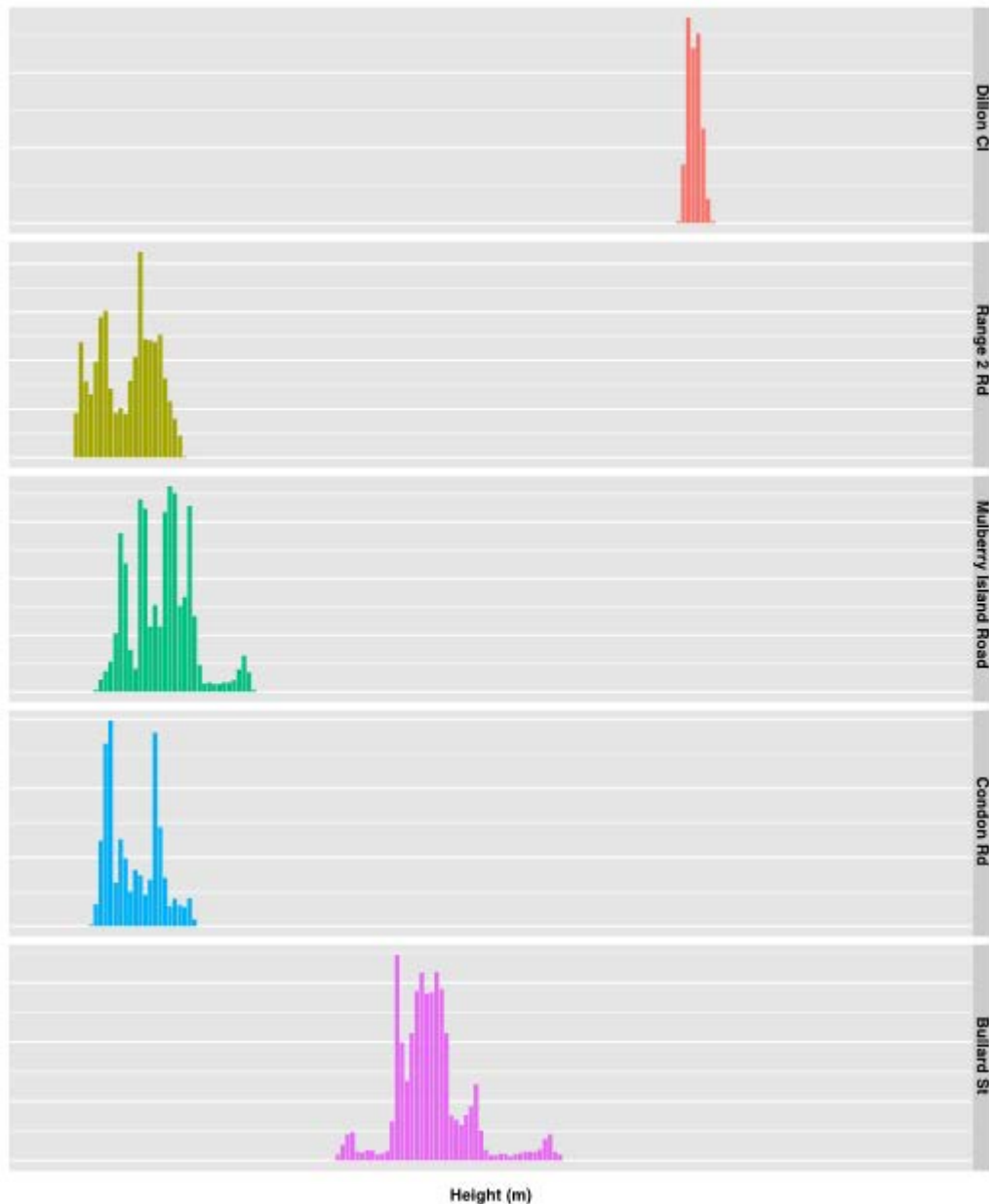


Figure 38. Sensitivity of assets evaluated by spatial attributes at JBLE | The figure shows an analysis of road height elevation to determine the roads at JBLE that are most exposed to flood risk.

In exploring sensitivity at Langley AFB, we combined elevation data with information from established condition and importance indicators. Condition assessment metrics are a key tool for both strategic capital planning and prioritization of projects. They integrate life cycle and condition information with facilities management systems. Combined with climate risk information, these metrics can provide insight into sensitivity of assets to climate hazards. In one analysis, we integrated Mission Dependency Index (MDI) and PRV to identify important and hard-to-replace buildings at Langley AFB. Figure 39 shows the buildings on Langley AFB arranged by the PRV and color coded by MDI. This information was combined with information on elevation and flooding to identify important assets at risk.

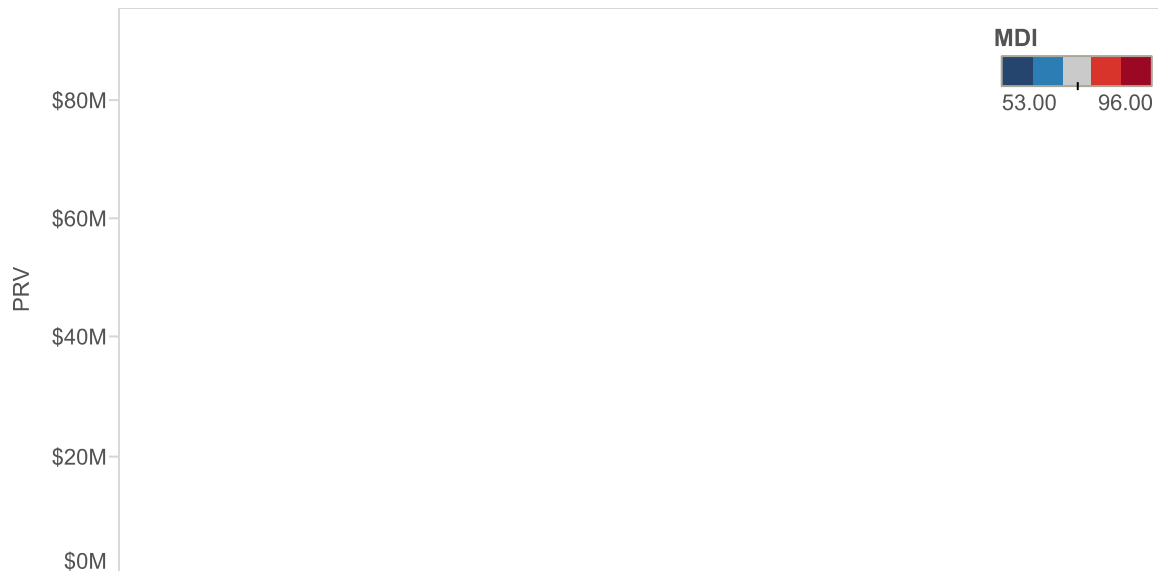


Figure 39. Condition assessment metrics can help characterize assets in a vulnerability assessment / Assets with a present replacement value (PRV) greater than \$15 million and a Mission Dependency Index (MDI) score for those assets at Langley AFB are shown. The reference asset numbers we defined are shown in lieu of showing building names.

Figure 40 identifies assets with PRV greater than \$15 million and shows an analysis of return periods to highlight priority facilities requiring further analysis. The method used to construct the return periods is described in the next section, “Analysis of observed exposures.”

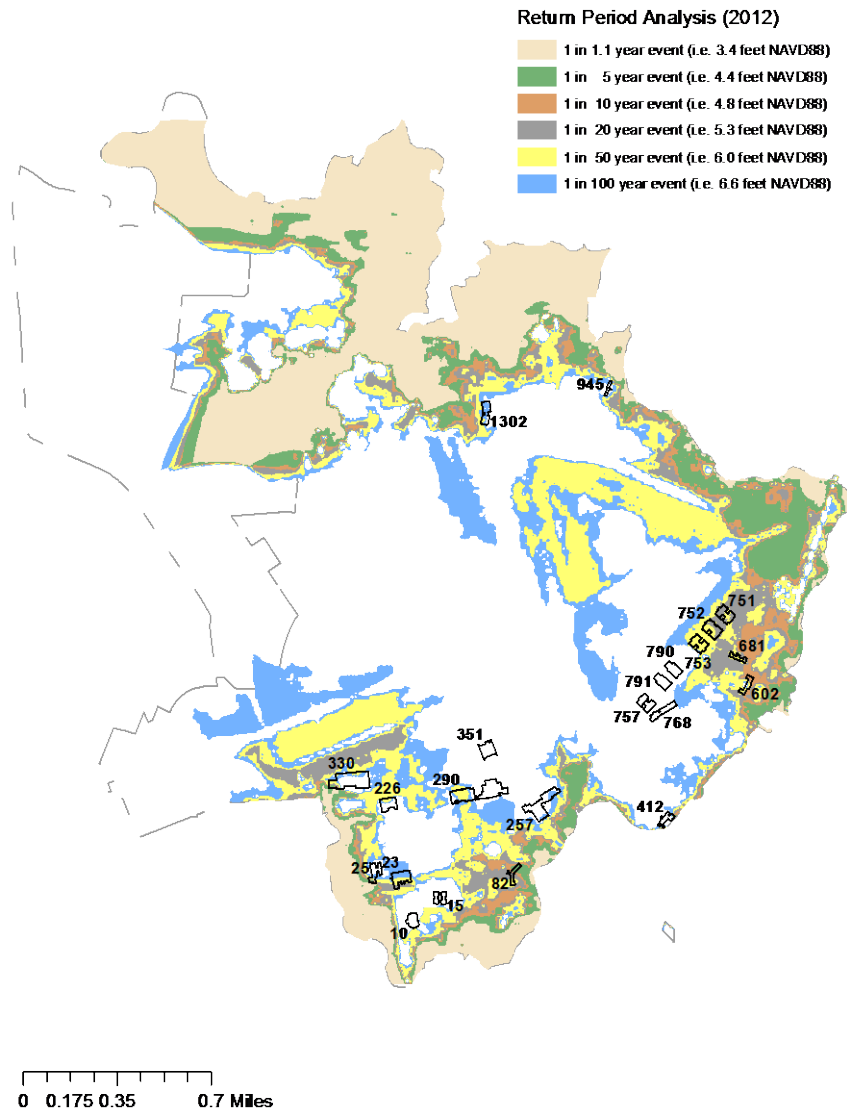


Figure 40. Return period analysis of facilities with greater than \$15 million PRV

Finally, in testing methods to evaluate sensitivity, we note the potential sensitivity of training areas, training, flight support, and HVAC and electrical infrastructure to temperature increases. One concern raised in interviews was that increasing temperatures, combined with other climate factors such as changes in precipitation, could contribute invasive species and pests (including those carrying diseases). Tim Christensen stated that the issue is longer growing seasons that may result in outbreaks of herbivorous insect species (for example, the southern pine beetle complex) that can be destructive to the forests necessary for the training missions of Fort Eustis. Outbreaks would lead to damage of the forests and increased costs for recovery efforts, pesticide applications, and pest management strategies. Another issue identified in interactions with base personnel was that increasing temperatures and a changing climate could contribute to habitat conditions that lead to an increase of key arthropod disease vectors, such as ticks, and mosquitos

(Luber et al. 2014). The 2014 Third National Climate Assessment chapter on the Southeast Region concluded that increasing temperatures have the potential to result in an expanded region with more favorable conditions for transmission of diseases (Carter et al., 2014). There is some evidence that Dengue fever is moving up from Florida. Recently, two ixodid ticks, which are of public health importance, were found at Fort Eustis; none had been found in the past, according to Tim Christensen.

A second issue was the potential for increasing temperatures to affect training at Fort Eustis, as well as on flight support personnel at JBLE. In extremely hot and humid conditions, military regulations call for restrictions in outdoor training and work. The military uses the wet bulb globe temperature (WBGT) as an index for expected heat exposure. Unlike other measures of heat stress, the WBGT combines the impacts of temperature and humidity with the influence of wind speed and the intensity of the sun. During periods when heat stress is likely, measurement stations are established at or near training sites, and restrictions on activity associated with different WBGT thresholds are published and are expected to be observed. Temperature increases associated with climate change would be expected to lead to an increased number of restrictions. The restrictions could affect future mission attainment by restricting flight support, training time, and outdoor work. We attempted to establish installation baselines for both Langley AFB and Fort Eustis. We were not able to obtain data on incidence of heat injuries to soldiers-in-training or flight support personnel, although we believe that such data exist. Changes in frequency of observed WBGTs are discussed in the next section, “Analysis of observed exposures.”

Finally, concerns were raised about energy supply and use, and sizing of HVAC systems. The 2014 Third National Climate Assessment (Melillo et al., 2014) indicates that overall demand for electricity will increase in the summer months, raising costs and straining generation and distribution systems during peak periods. We were unable to obtain baseline data on brownouts or outages, but personnel indicated this was not a major issue at present.

4.2.1.3 Analysis of observed exposures

Sea level rise, in conjunction with subsidence, is the greatest climate change-related threat to both the Langley AFB and Fort Eustis sites. Thus, we included flooding and inundation in analysis of current exposures. Flood levels are based on deviations from the NAVD88 datum level at the station and reference the Advanced Hydrologic Prediction Service, which defines flood stage levels.

Long-term (1927-present) tide gauge observations (from National Oceanic and Atmospheric Administration station #8638610 located at Sewell’s Point, Virginia) indicate that the area has experienced a 0.18 in. (.0046 m)/yr or 0.015 ft (0.0035 m)/yr increase in sea level since the start of the station record in 1927 relative to the NAVD88 datum. Potential explanations of this increase in relative sea level include post-glacial rebound, increasing ocean temperatures and thermal expansion, and glacial melt water.

Figure 41 shows the number of days each year where maximum water levels fall within one of the flood categories. Due to observed increases in relative sea level, the number of days each year where the JBLE experiences some sort of flooding has increased dramatically—by a factor

of 10—since 1928. Events that hardly occurred at all in the 1930s now occur with some regularity, 10-20 times a year. Moderate and major flood categories have occurred only a few times on record.

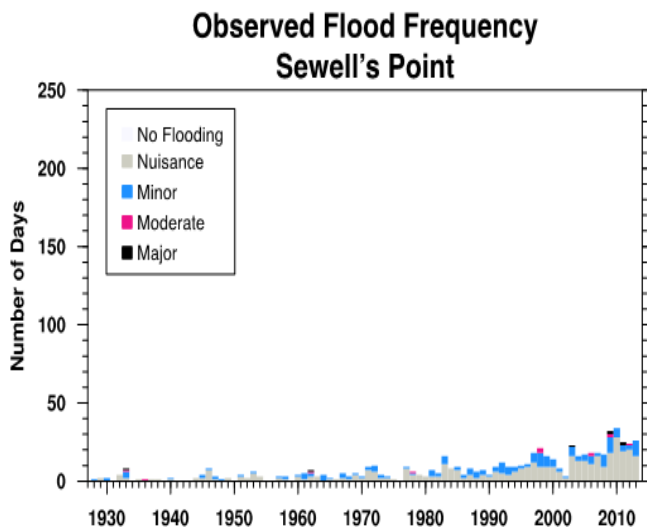


Figure 41. Increasing frequency of flooding for the Sewell's Point tide gauge

Additional factors could also be contributing to the increase in flooding frequency. These factors include land use and cover change that increases impervious surfaces and runoff, and changes in storms and processes that contribute to coastal inundation.

To identify if increasing temperatures were having an impact on outdoor activities, we included an analysis of the historical annual frequency of green, yellow, red, and black flag days using data from a global summary of the daily surface observations obtained by the National Climatic Data Center (<http://www.ncdc.noaa.gov>). We used the data because while the WBGT is measured at most military installations, the daily values are not saved or archived. Figure 42 shows in time series the variability of the frequency of extreme heat and flag day occurrence.

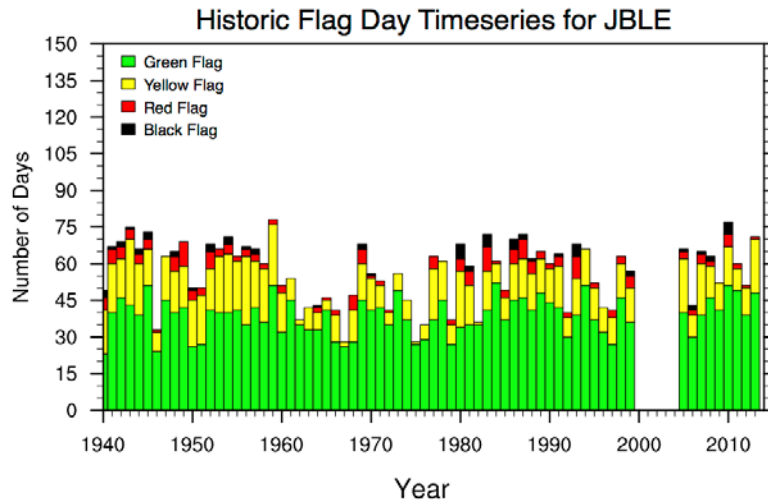


Figure 42. Observed flag day occurrence for Joint Base Langley-Eustis based on analysis of the wet bulb globe temperature | The wet bulb globe temperature and flag days were estimated from the global summary of the day (GSOD) station observations using temperature, humidity, and surface pressure.

4.2.1.4 Adaptive capacity related to infrastructure

Adaptive capacity determines whether or not individuals and institutions are able to adjust to changing conditions to reduce damages or take advantage of opportunities. Adaptive capacity depends not only on physical characteristics of infrastructure and management practices, but also on considerations such as organizational culture, mindset, or financial capacity to implement alterations in infrastructure or practice. Following our experience at the U.S. Naval Academy, measurement of adaptive capacity (the ability to implement relevant adaptation measures) was qualitative. We considered preparedness, ongoing adaptation efforts, human capital, and organizational culture. Input to this analysis included interview data and information from the climate change section of the ICEMAP (Headquarters Air Force, 2012). In sum, this information identified some capacity was in place, but important gaps remain.

Preparedness—having well-developed procedures for handling emergencies—is important for reducing damage from storms. Mutual aid agreements and emergency evacuation and/or response plans were described as being well coordinated with localities. ICEMAP noted that periodic review of preparedness plans to include potential climate change impacts is needed (Headquarters Air Force, 2012). Regarding ongoing efforts to cope with climate variability and extremes, JBLE currently employs a range of erosion control measures—deploying hardened and soft structures (sea walls and dykes, and dunes and vegetation, respectively) in order to prevent flooding—and accommodation measures—allowing flooding to occur in some areas and attempting to work around it. Increasing erosion is highlighted as a future problem, but additional measures did not appear to be planned at the time of the case study research. Potential future measures to address infrastructure impacts included making changes to freeboard standards and elevating components of key systems (HVAC systems and electrical nodes), deploying door dams, and, separating sanitary and storm water handling. Regarding the organizational culture, ICEMAP indicated that JBLE was preparing a climate adaptation strategy

to review current and potential measures more carefully (Headquarters Air Force, 2012). It noted that current adaptation efforts across the installation would benefit from improved coordination and that training for personnel in climate change and managing adaptation is required. Finally, it noted that sea level rise is not yet integrated into long-term planning processes and documents for JBLE. These factors suggest that the organization is beginning to recognize that climate change and sea level rise will require adaptations, but many of the necessary tools to plan and implement needed measures are not yet in place.

4.2.2 Climate change and potential future exposure

Section 3.2.6 describes the methods used in the project to develop a climate “outlook” for the mid-Atlantic region. This section briefly summarizes the JBLE-related content of the Climate Outlook prepared as part of this project (see Appendix A for the full climate outlook) and provides a small amount of general background information needed to understand this section as a standalone case study description.

4.2.2.1 Methods overview for JBLE-focused assessment of future exposure

Climate projections for JBLE and the mid-Atlantic region are made using regional and global climate models, but the focus is on projections from a 13-member ensemble of 31.06 mi (50 km) horizontal resolution regional climate model simulations produced as a part of the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2013). Climate projections are for the mid-century period: 2041-2069 (approximately), and, unless otherwise stated, projections are related to a baseline period of 1971-1999. The projections are based on the Intergovernmental Panel on Climate Change’s Special Report on Emissions Scenarios (SRES) “A2” greenhouse gas emissions scenario (IPCC, 2000), which produces a very high level of climate change at 2100. For recent decades, SRES A2 has been consistent with observed global emissions (Rahmstorf et al., 2007). To approximate the influence of global sea level rise on local water levels, we applied the method described in Tebaldi et al. (2012), which implicitly takes into account future thermal expansion, glacial melt, and local effects such as sinking of the land. We note that Volume II (Reference Book) of the ICEMAP (Volume II, Reference Book) indicates that it “does not address climate change projections themselves ... but rather presents an overview of possible impacts and solutions based on current information and vulnerabilities’ The ICEMAP analysis uses a variety of articles and reports that do not present any consistent view of potential future climate change.

4.2.2.2 Projected changes in exposure to flooding and extreme heat

Compared to current conditions, JBLE can expect future changes in climate to include more frequent and more severe wind- and storm-driven flooding, as well as increasing temperatures. We discuss two factors that will contribute to increased flooding: sea level rise and potential increases in extreme precipitation. Finally, we present projections of increased temperatures at JBLE and implications for WBGT.

Flooding—Sea level at the JBLE is projected to rise by about 1.23 ft (+/-0.3 ft) (0.37 m +/- 0.09 m) by mid-century (Figure 43). By the end of the century, sea levels could be 4 ft(1.22 m)

higher than at present. This will significantly increase the frequency and intensity of coastal flooding. The frequency and intensity of the tropical and extratropical storms that cause the flooding are too uncertain at this point to make a general statement on their projections, but sea level rise will have a large effect on future flooding frequency and intensity regardless.

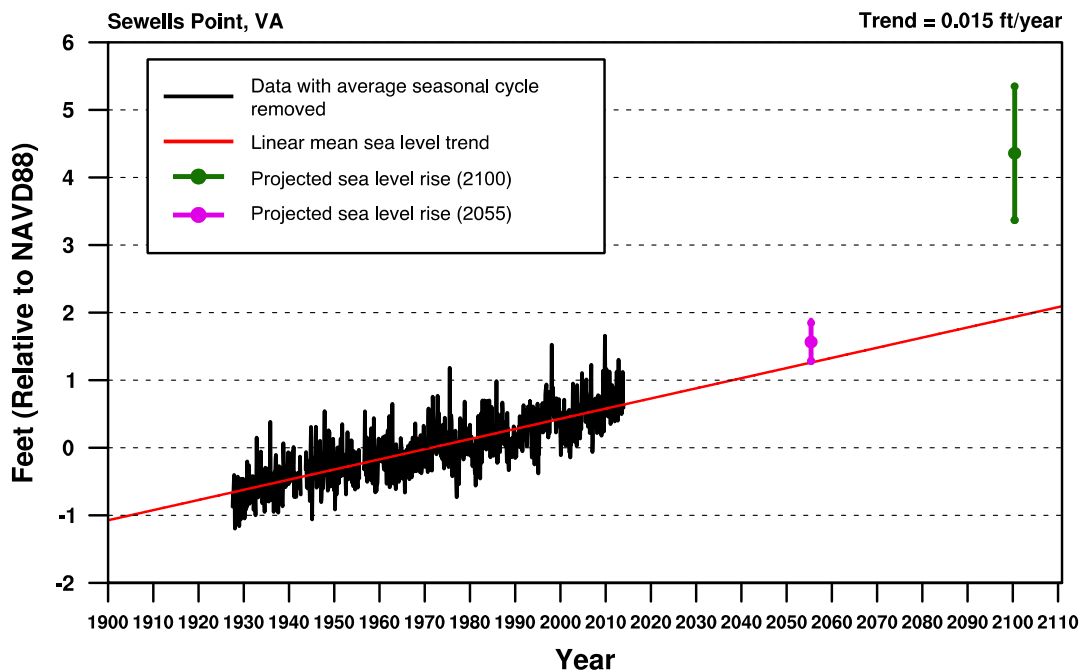


Figure 43. Local sea level rise projection to 2100 using the Sewell's Point, Virginia, tide gauge / The figure compares the historical rate of change of sea level rise (red line), with the expected change in the sea level in 2055 (pink) and 2100 (green) using the Tebaldi method. For 2055 (pink), local sea level rise is projected to be 1.23 +/- 0.28 ft, and for 2100 (green), local sea level rise is projected to be 4.02 +/- 1 ft relative to NAVD88.

In Figure 44, we build on the analysis of the number of days each year where maximum water levels fell within one of the flood categories that is depicted in Figure 431. We perform a thought experiment to explore the potential for future flooding should the observed pattern be repeated, but with different assumptions about the magnitude of relative sea level rise by mid-century. We do not propose this as a projection method, merely an approach for providing input for stakeholder dialogue that makes the potential challenges of managing future inundation more psychologically accessible to managers. Viewing sea level as an isolated factor apart from tides, storm surges, and other factors can lead to underestimation of its potential consequences.

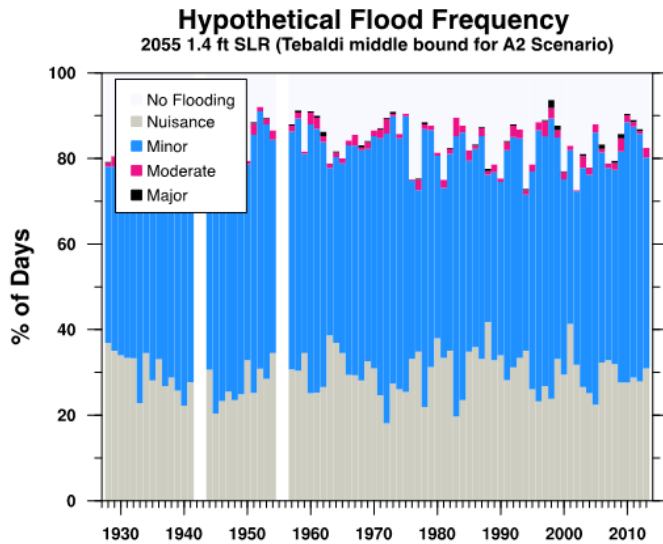


Figure 44. Potential for flooding if we superimpose the sea levels from the midpoint of the sea levels projected for 2055 | This should not be treated as a projection but as a thought experiment based on historical analysis of the number of days each year where maximum water levels fell within one of the flood categories.

Heavy precipitation—In conjunction with a storm associated with inundation-producing winds, heavy precipitation exacerbates flooding and/or increases flooding potential. (Precipitation alone was not identified as a major concern for the JBLE [see Appendix A]). Projected changes in the frequency of intense precipitation, ranging from light to very heavy over a 3-hour period, are provided in Figure 45 for summer (June-August) and a long cool season (September-April). Almost all flooding events related to extratropical systems occur during this long cool season. In summer, most models indicate a decrease in the frequency of light to moderate rainfall. Heavy rainfall (90th percentile and above) projections are uncertain until the 99.9th percentile, where all of the models, except for one, project a statistically significant increase in the frequency. The outlier model has a small, insignificant decrease. In the cool season, during the time of most of the extratropical storms that lead to inundation, nearly all of the models agree that very heavy precipitation (95th percentile and above) will significantly increase in frequency. This indicates that precipitation with these storms may be more intense in the future and exacerbate wind-driven inundation to a greater extent.

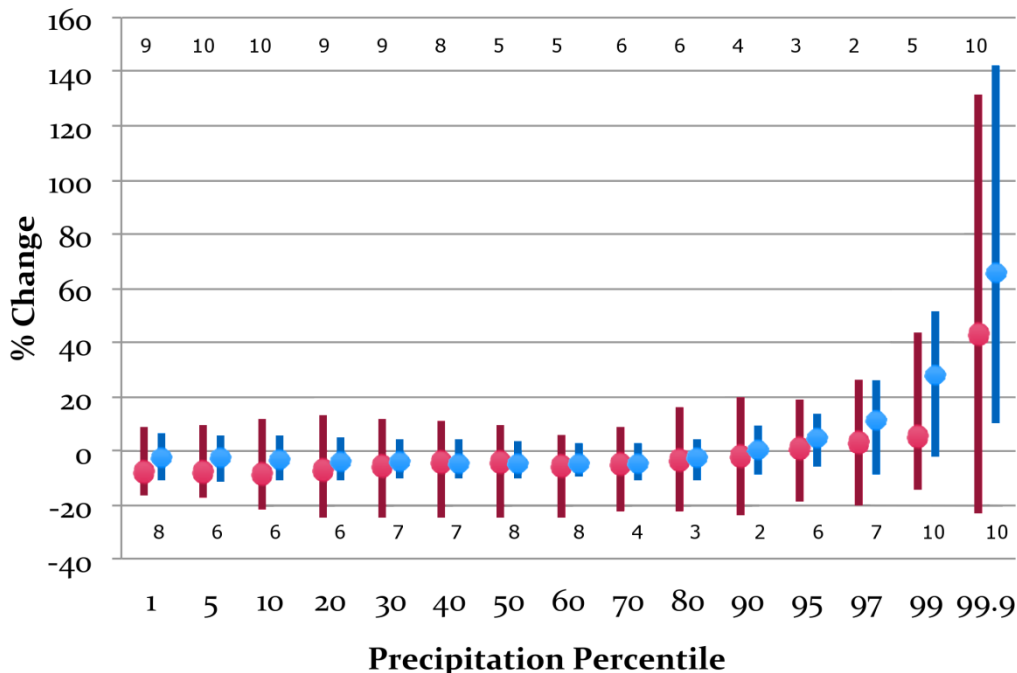


Figure 45. Change in precipitation frequency | Projected change in the frequency of 3-hour average precipitation at low to high intensities for the warm season (June-August) in red and the cool season (September-April) in blue from 11 NARCCAP simulations. The average change across the simulations is indicated by the dot. The range of change projected across the models (minimum change to maximum change) is indicated by the span of the bar. Intensities are given as percentiles (x-axis). Numbers along the top (warm season) and bottom (cool season) indicate the number of models that had a statistically significant change at the given intensity.

Temperature—The Climate Outlook includes regional analysis of changes in WBGT and is not repeated here (see Appendix A).

Temperature-related changes will affect cooling and heating degree days, which will influence the design and operation, as well as the cost, of HVAC systems on the installation. Temperatures across the region are expected to increase as a result of climate change. The average temperature is expected to rise 2.7°-6.3° F (1.5°-3.5°C), depending on the season, in the mid-Atlantic region by mid-century, with the greatest increases during the winter. The ensemble mean of the NARCCAP simulations projects an increase in mean temperature ranging from 1.5°C in spring to about 3.5°C in winter across the mid-Atlantic region (Mearns et al., 2013). Using available observations and projections, heating and cooling degree days can be calculated. We return to this analysis in the next section, “Future vulnerability.”

4.2.3 Future vulnerability: Integrating baseline sensitivity and adaptive capacity with potential changes in exposure

We describe several ways in which the project explored future vulnerability by integrating information on sensitive systems and adaptive capacity with the analysis of potential changes in exposure due to climate change. As before, we focused this analysis on the implications of flooding and increased temperature, as well as addressing the challenge to also consider how

relevant societal conditions and infrastructure systems may change. For individual sites, master plans developed through processes that consider changes in mission and resulting requirements for installation performance are a good source of information.

4.2.3.1 **Vulnerability to flooding: Return period analysis**

Using the methodology in Tebaldi et al. (2012), we created the return period for mid-century flooding, which demonstrates significant changes to the intensity of flooding events at JBLE. At Langley AFB by the middle of the century, much of the runway floods every few years. Only a small portion of the runway does not flood in a 100-year storm event. At Fort Eustis, the airfield and many of the training areas and ranges flood almost every year.

This analysis indicates that the runway area will flood more frequently and for longer periods with sea level rise. The return period analysis suggests that while the runway would only be affected by 50- and 100-year floods (Figure 46), by mid-century, sea level rise sections of the runway could flood with 5-year flood events (Figure 47). The increase in flooding has the potential to increase direct effects (runway closures) and secondary impacts from flooding (pooled water and debris and increased bird and wildlife aircraft strike hazard [BASH]). These would increase disruptions of runway operation, with resulting impacts on training schedules and costs, and at some threshold, consequences for readiness of flight crews. Damage and recovery costs would also increase.

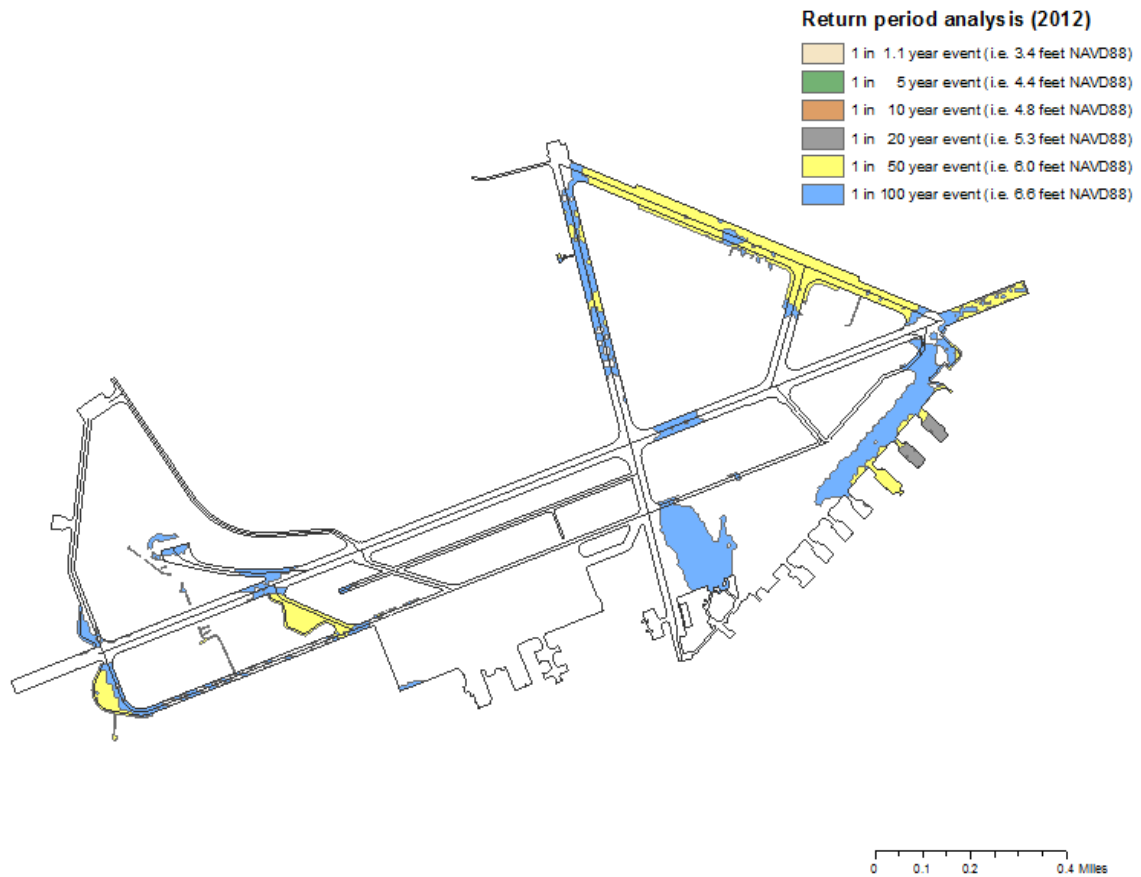


Figure 46. Return period analysis at Sewell's Point (across the mouth of the James River from both Langley AFB and Fort Eustis | To produce the map above, we (1) analyzed the historical tide gauge record at Sewell's Point to calculate the return period, and (2) used a geographic information system fill tool to determine the patterning of flooding at the installation. This allowed us to map the data from the tide gauge to the site.

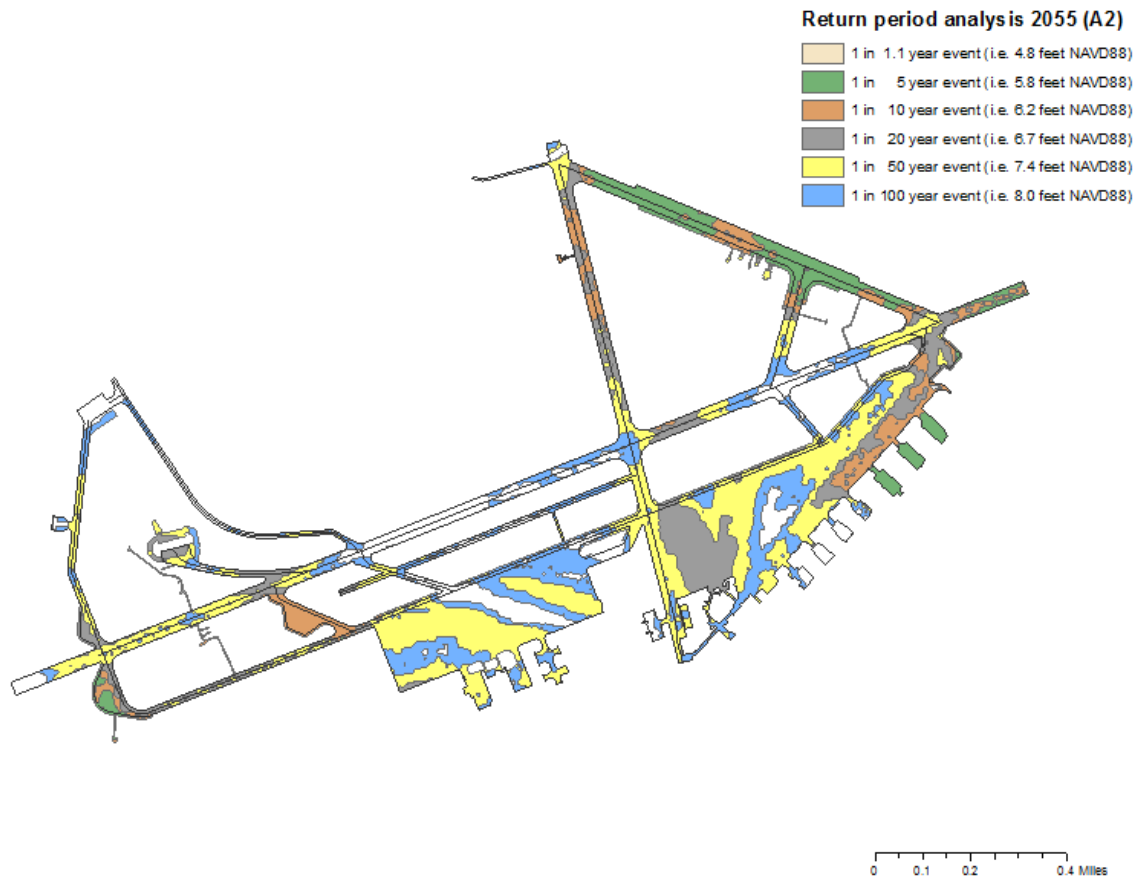


Figure 47. Return period analysis at Sewell's Point (across the mouth of the James River from both Langley AFB and Fort Eustis with sea level rise projections | This figure of the runway was produced using the same method described earlier, but with the addition of sea level rise as projected by the Tebaldi et al. (2012) method for mid-century "A2" high emissions scenario.

Currently, Fort Eustis experiences flooding that affects training areas, the cantonment area, vessels, and Third Port. A return period analysis shows an increase in the frequency of flooding for many of these areas by mid-century. For example, several of the training areas would experience an increase in flooding from 1-year events. For Felker Army Airfield, flooding currently occurs with 5-year events. However, with the sea level rise projected for mid-century, 1-year floods could occur in parts of the base. While most of the ranges currently experience some flooding from 1-year flood events, Ranges 3, 3A, and 4 are well protected from floods. However, by mid-century, these ranges could flood with 50- and 100-year floods. Increases in flood risk may require a re-evaluation of the storm water system. *Figure 48* illustrates a return period analysis using a high emissions scenario (current rate of emissions) and resulting sea level rise as projected by the Tebaldi method (Tebaldi et al., 2012).

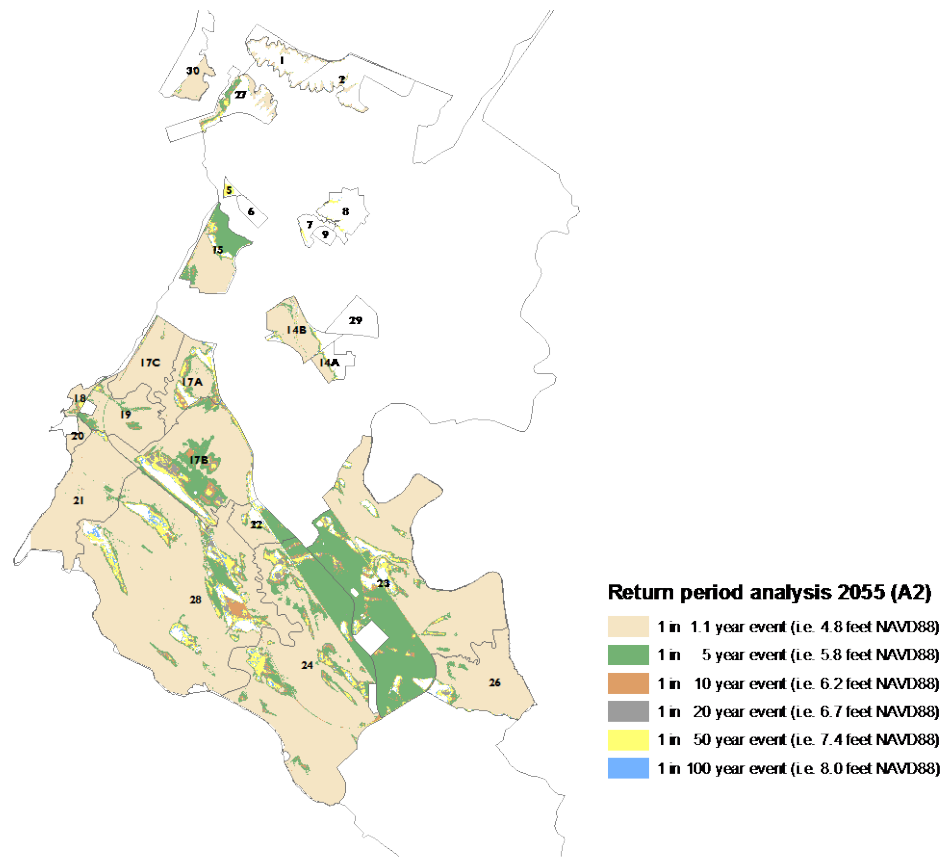


Figure 48. Return period analysis of flooding of training ranges at Fort Eustis using a high emissions scenario (current rate of emissions) and resulting sea level rise as projected by the method described by Tebaldi et al. (2012).

4.2.3.2 Vulnerability to temperature increases

Currently, extreme temperature fluctuation can make it difficult to effectively budget for HVAC operating costs. Projected temperature increases could lead to higher operating costs, particularly for cooling loads for buildings that house data centers. One analysis conducted shows that for the 50th percentile mid-century future, July may have approximately 30% more cooling degree days. Higher temperatures may also stress HVAC systems leading to shorter system lifespans. In addition, changes in extreme temperatures could require new cooling systems installed in areas that are not currently climate controlled to ensure safety of support personnel.

Figure 49 shows the observed and projected cooling degree days. The Third National Climate Assessment (Melillo et al., 2014) evaluation of energy supply and use indicates that demand for electricity will increase, raising costs and straining generation and distribution systems. A similar analysis demonstrates that the number of heating degree days will fall, reducing energy requirements for space conditioning in the winter months. Additional data on energy use at JBLE

would enable costs and benefits of these changes to be calculated. Unfortunately, collection of energy data is insufficient at JBLE to provide the needed information.

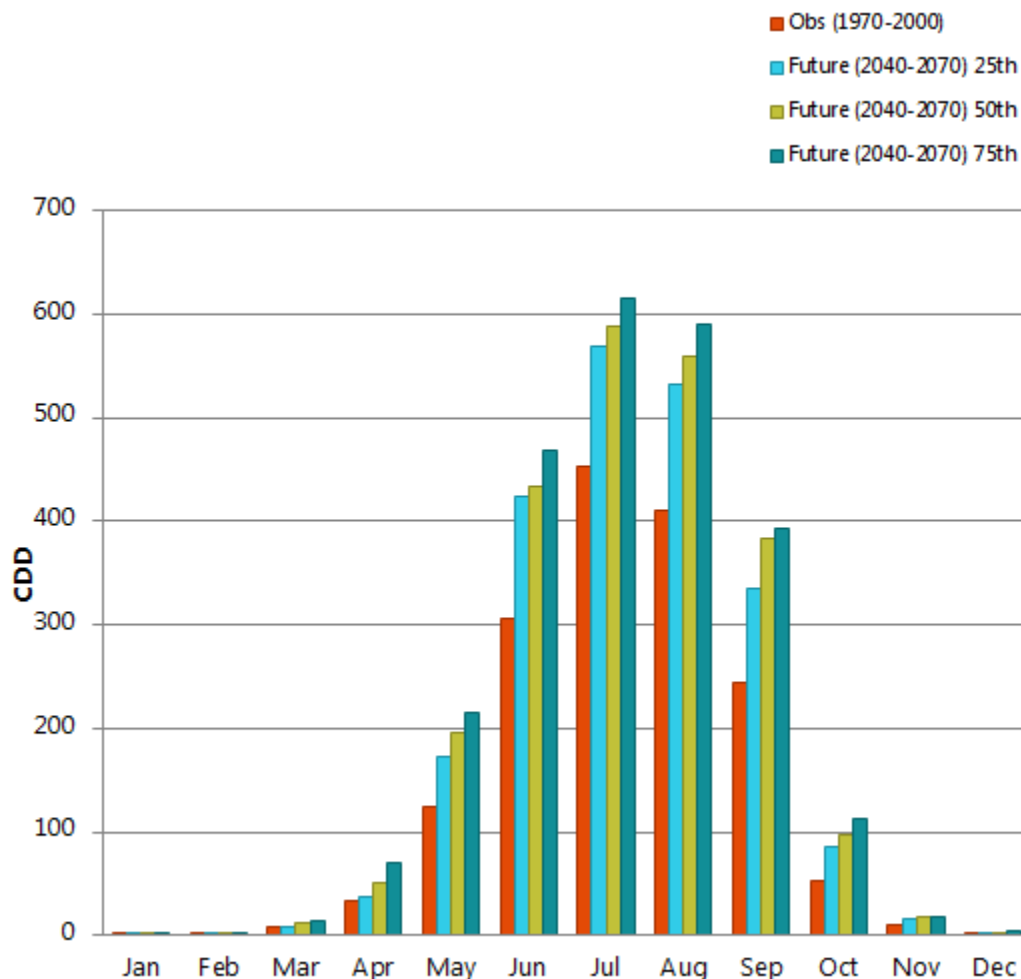


Figure 49. Observed and projected cooling degree days / Cooling degree days are the number of degrees the daily average temperature exceeds 65°F.

4.2.4 Discussion

We tested a variety of approaches for providing information relevant to vulnerability assessment, building on approaches tried in U.S. Naval Academy case study and testing alternatives to those methods. These techniques addressed the need to provide information on baseline conditions (sensitivity of assets, observed exposures, and adaptive capacity), future climate exposures, and implications for future vulnerability and the potential for problems to affect operations, infrastructure, and missions. From a wide range of potential issues that had been identified in previous studies and confirmed through interactions with installation personnel, we narrowed our focus to increases in frequency, depth, and duration of coastal inundation resulting from relative sea level rise and other factors; and changes in average and

extreme temperature and its implications for ecosystems, human health, and energy demand and supply. There were additional issues we could not address, most of which would have required large-scale modeling efforts and substantial community engagement, including water supply interruptions; and impacts of road flooding on staff commuting and transportation systems for crucial supplies.

The specific experiments undertaken as part of the case study offered information on threats to specific areas of the installation and some of the training activities that are essential mission components. The runway area of Langley AFB has been affected by the increasing frequency of flooding; with relative sea level rise, this will increase substantially in the future, with implications for service hours, training, and costs. Projected temperature increases could lead to higher operating costs, although the shorter service and economic life of HVAC systems (when compared to infrastructure such as runways and buildings) provide opportunities for more frequent upgrades that account for evolving scientific information. Fort Eustis currently experiences flooding affecting a number of its training areas and facilities, including Third Port. Analysis indicated future increases in this flooding, which would worsen erosion and other problems. While heat-related flag conditions have not been an issue, temperature increases and related changes have the potential to contribute to habitat conditions that lead to arthropod disease vectors affecting both vegetation and humans.

More generally, the JBLE case study demonstrated the need for methods and models to assess impacts to a wide range of systems, both on base and outside the fence. While some previously conducted research and reports on broader issues such as transportation impacts of flooding were available, in other cases, it was evident that expertise and community engagement were needed to improve understanding of the issues and the potential for climate change induced problems that could threaten assets and mission continuity. Ecosystem impacts and their implications for training area resiliency and the potential introduction of new pests and pathogens is a clear area where deep modeling expertise is needed if an assessment were to provide new value-added information. The case also emphasized the importance of setting priorities and enlisting the participation of departments with necessary expertise and information to focus on the priorities set at the outset. Requests for data and information naturally evolve as one insight or finding leads to another question and focus. Lacking representation from all aspects of the installation that were potentially affected by some of the priority issues created roadblocks and data issues that might have been avoidable. In a number of cases, we ran into issues associated with being an “outside” group looking at installation vulnerabilities in ways that required sensitive information. As a result, some experiments were not seen through to completion. These are issues that could be addressed to some extent through engagement of Headquarters Air Force personnel. They point, however, to the advantages of building capacity for assessment of installation staff over time, and incorporating into existing processes the collection and analysis of information relevant to understanding how vulnerability is changing as a result of both novel climate conditions and installation management decisions. Systematic collection of data relating to direct and indirect damages resulting from weather and climate variability would improve information for management and assessment. Clear examples were flight training cancellations and training area usage data. In addition, improving collection of information on energy use at JBLE would facilitate analysis of both adaptation and mitigation needs and potential.

4.3 Case study results: Fort Bragg, Fayetteville, North Carolina

Fort Bragg was the third and final case study undertaken in the project. Fort Bragg was identified as a promising study site because of the diverse missions it supports and its importance to the U.S. Army. Unlike the first two cases, Fort Bragg is located inland and introduced several different climate change challenges. We built on the approach used at U.S. Naval Academy and Joint Base Langley-Eustis while testing new methods and procedures. A key process difference was that we completed a significant amount of analysis and prepared a draft vulnerability baseline before the site visit.

We began the study by scoping and framing the topics for the assessment to consider through telephone interviews and review of available documentation recommended by installation personnel. During a preparatory webinar, we shared preliminary results, received feedback on topics of interest, and identified focal issues and key individuals needed for the site visit. Following the webinar, we conducted a more comprehensive analysis and prepared a variety of inputs to the site visit. While previous site visits were more introductory, at Fort Bragg we used a structured process to review a draft vulnerability baseline. The site visit occurred over a 2-day period in three stages. On the first day, we engaged the public works department and related personnel and focused on establishing a baseline for infrastructure vulnerability. We met with individuals responsible for managing and scheduling use of ranges and training areas. During these sessions, we walked through interpretation of the preliminary analysis to clarify and update information, prioritize the most pressing issues, and identify data needs and follow-up actions. There were opportunities for staff to raise additional issues and topics. We also presented preliminary climate analyses using local station records, other observational datasets, and regional climate model results to elicit feedback on the additional information needs and identify preferences for communication. On the second day, we conducted a number of parallel meetings to follow up on issues identified in the earlier sessions and discuss next steps. We conducted additional analysis and interviews during subsequent months, and produced an outbrief document to present the findings. We revised the outbrief based on comments from installation personnel, the Office of the Secretary of Defense, and the Strategic Environmental Research and Development Program office, and then drew conclusions about the implications about processes and methods for Department of Defense (DoD) vulnerability assessments.

We present the results by describing the process, baseline vulnerabilities, potential future climate conditions, future vulnerability, and implications for the mission of Fort Bragg. A final section discusses the results and their implications. We defer discussion of vulnerability assessment frameworks and methods to the conclusions section.

4.3.1 **Baseline: Establishing priorities and identifying current sensitivity, observed exposures, and adaptive capacity**

This section provides a general overview of Fort Bragg and describes research conducted to explore baseline conditions, current climate exposures, and adaptive capacity.

Background

Fort Bragg was established in 1918 and is one of the largest military installations in the world, covering more than 250 square miles. It spreads across portions of Cumberland, Harnett, Hoke, and Moore counties and is located outside Fayetteville, North Carolina. Fort Bragg is home to a number of units, including the 82nd Airborne, Joint Special Operations Command, and the U.S. Army Special Operations Command. The installation can be subdivided into the two areas: the cantonment and the training areas. The cantonment area encompasses most of the built infrastructure, and includes the residential and offices spaces. The training ranges include most of the managed natural infrastructure and serve as the staging area for diverse types of training. Along its longest dimension, Fort Bragg stretches approximately 21 miles, from the far eastern side of the installation (which encompasses the cantonment) to the western boundary. The training areas, landing zones, impact areas, and similar areas comprise the majority of the installation from the western edge of the main cantonment to the western edge of the installation. Fort Bragg is located in the Sand Hills ecoregion, which supports a number of endangered species, including five federally protected species:

- American chaffseed
- Michauxs sumac
- Rough-leaved loosestrife
- Saint Francis satyr butterfly
- Red-cockaded woodpecker (Lozar et al. 2011).

The presence of these species necessarily impacts how the Army can manage and operate the base.

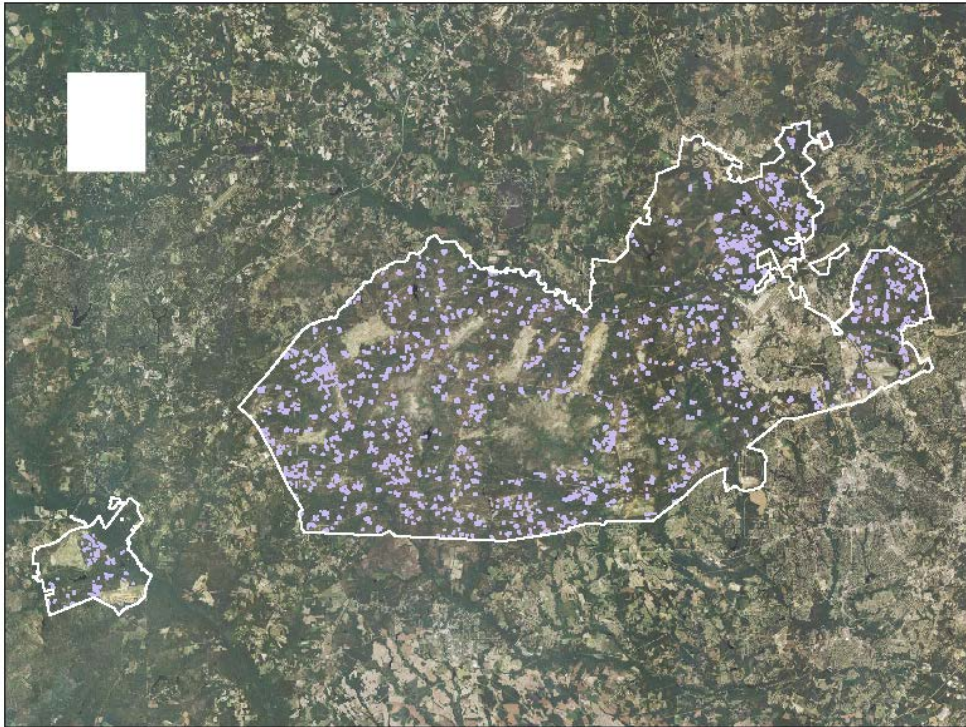
To establish priorities and prepare a draft installation baseline, we conducted interviews both in-person and on the telephone, reviewed available documents, and undertook preliminary spatial analysis. We also consulted several available climate impact studies on Fort Bragg. *Climate Change Impacts on Fort Bragg, NC* (Lozar et al. 2013) focuses on describing potential changes in climate and its implications for ecosystems, endangered species, and erosion. *Anticipating Climate Change Impacts on Army Installations* (Lozar et al. 2011) uses GCM results to forecast potential challenges to habitats, species and erosion at approximately 130 installations in the US. The *Department of Army: High-Level Climate Change Vulnerability Assessment* (Hayden et al. 2013) provide a high-level national scale overview of results of the then recently completed National Climate Assessment regional climate outlooks, including for the Southeast region, and a brief overview of potential impacts. Jenicek et al. 2011 conduct a screening assessment of watershed vulnerability that includes a case study of Ft. Bragg that provides 30-year future scenarios. A key source of information was Fort Bragg's Integrated Natural Resource Management Plan (U.S. Army Fort Bragg, 2011). This report guides management of natural resources and compliance with environmental regulations and is intended to "support the sustained use of training lands by conserving Fort Bragg's natural resources." It provided an

encyclopedic overview of current conditions and challenges. While the report doesn't explicitly reference climate change, it highlights issues that could be complicated by climate change.

Our analysis of the information and data provided to us, and the interviews we conducted, identified both built and natural infrastructure as historically vulnerable to the regional climate. As a result, we identified two sets of priorities and structured the site visit around them: natural infrastructure and training; public works and infrastructure. For each set of issues, we prepared materials for guided discussion of ideas about issues to explore based on the available information, a series of questions to prompt discussion based on their knowledge and experience, and identification of potential next steps and data needs for different types of analysis.

Natural infrastructure and training: Sensitivity, exposures, and adaptive capacity—Fort Bragg's mission depends on the sustainable management of its ecosystems, including a range of forest, swamp, and desert-like ecosystems that provide training areas that replicate conditions likely to be encountered by warfighters. The ecosystems must withstand repeated disturbance from equipment and personnel while being managed in such a way as to ensure safety and meet environmental targets (for example, those related to clean water and endangered species). Changes in climate averages and extremes could increase the challenges and costs of ecosystem management.

We identified a number of potential issues. One potential sensitivity relates to difficulty scheduling training activities, especially during the late spring and summer, "when critical military and ecological events collide" (U.S. Army Fort Bragg, 2011, p. 33) and create a shortfall in training land assets. During the site visit, we explored whether these challenges were related to current climate conditions and weather, and if there were pending decisions to improve the situation that might be affected by climate. We found that some of the effects were from red-cockaded woodpecker's natural cycles, which could limit training activities. The woodpecker has specific habitat requirements; it nests in mature long-leaf pine forests with little to no understory. As shown in Figure 50, there is an extensive distribution of the woodpecker nesting sites across the installation.



*Figure 50. Red-Cockaded woodpecker nesting sites / The blank area indicates missing satellite imagery.
Source: Developed by A. Blohm with satellite imagery and road data from Fort Bragg.*

A second issue we discussed was potential impact of fire risk on controlled burns needed to manage the loblolly pine ecosystem. Fort Bragg responds to approximately 250 actionable fires annually due to the intensity of training activities in woodlands (Fort Bragg 2015). As part of the fire prevention program, the Forestry Branch notifies Range Control when weather conditions present a high risk of wildfires. Use of tracer ammo, pyrotechnics, and incendiaries can be suspended until weather conditions improve. Installation range regulations limit training activities under high risk conditions.

To help reduce wildfire hazard and also improve wildlife habitat, Fort Bragg performs prescribed burns. Prescribed burns are necessary to maintain training areas and RCW habitats. Prescribed burns reduce fuel loads and manage the longleaf pine-wiregrass ecosystem. This practice has improved the condition of training areas and allowed for their continued use. It also benefits habitats for endangered species and other native flora and fauna. In any given year, approximately one-third of the total training area acreage is burned.

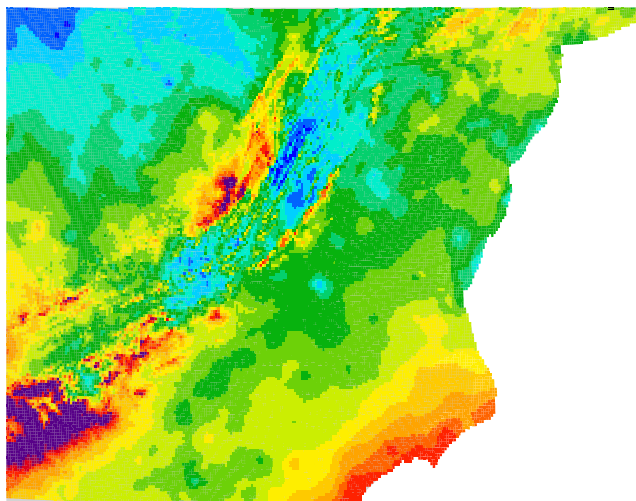
While the practice of prescribed burning is an art as well as a science, there are a number of climate and weather-related factors that must be in place so that prescribed burns can be performed safely. Prescribed burns are sensitive to wind, temperature, fuel load moisture, and humidity conditions. Consistent with these factors, Fort Bragg performs prescribed burns when the following conditions are present:

- Temperatures are below 95°F

- Precipitation occurred recently (so the fuel is not too dry)
- Wind speeds are 4-15 mi/hr
- Sufficient ventilation exists (that is, wind speeds aloft so that smoke can leave the area).

The third issue related to natural resources management identified before the site visit and discussed with staff during the session was erosion. In the context of water quality management and maintaining suitable training areas for air drops and other activities, the Integrated Natural Resource Management Plan identified soil erosion as “Fort Bragg’s most significant long-term environmental issue” (U.S. Army Fort Bragg, 2011, p. 311). During the site visit, natural resources management personnel indicated this conclusion was inaccurate, leading to the biggest surprise of the site visit—which demonstrates the importance of both the advance analysis of existing documents and the site visit itself. Staff described the Integrated Natural Resource Management Plan’s identification of erosion as the major threat to natural systems and assets as outdated: changes to ecosystem management had been made in response to requirements to protect the red-cockaded woodpecker. These involved an extensive program of controlled burns to restore the loblolly pine ecosystem, the bird’s preferred nesting habitat. Over time, controlled burning succeeded in restoring the habitat and in increasing population numbers. Concomitantly, this also improved conditions on the ranges and training lands, with reductions in other problems and better conditions for training. Installation personnel described the woodpecker-motivated prescribed burns as a success story with multiple benefits. Nevertheless, because of Fort Bragg’s sandy soils, topography, and potential for intense rain events, erosion could be a challenge under future changing climate conditions.

This is particularly the case as the area has seen an increase in intense or heavy precipitation over the past several decades. For example, based on surface observations, over the last century, the number of days with rainfall greater than 2 in. has increased by 26-50 days over much of south central North Carolina. According to the Third U.S. National Climate Assessment (Melillo et al., 2014), more intense or heavy precipitation events have increased by 27% in the south east since 1958 (Figure 51). Fort Bragg receives approximately 46 in. of rain each year (Figure 52). Rainfall amounts are relatively constant throughout the year.



Inches 8 60 62

Figure 51. Annual accumulation of precipitation in the mid-Atlantic region (OSU 2015)

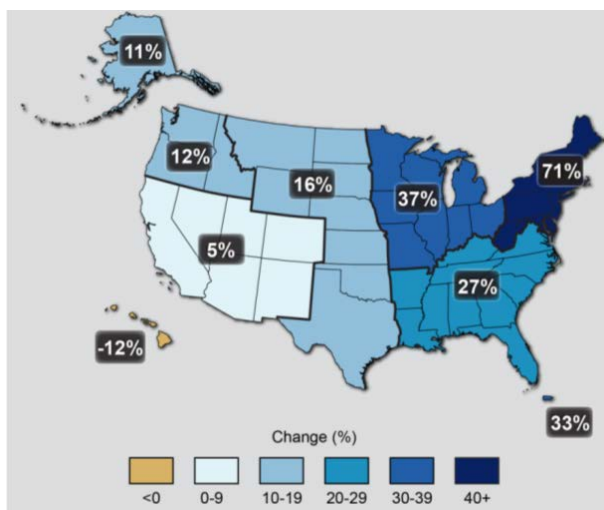


Figure 52. Change in very heavy precipitation across the United States (Melillo et al. 2014)

Finally, we raised a series of questions about the potential direct effects of climate conditions on outdoor training, including wind speeds above thresholds that prevent parachute drops and high temperatures and humidity causing heat injuries and leading to training restrictions. For many of the issues raised above (for example, fire risk, prescribed burns, and erosion), we inquired about the availability of time series records or data, evidence related to the role of extreme weather conditions (for example, precipitation or drought), and questions about the extent to which climate factors are considered in ongoing management or the integrated training area management process to minimize training impacts and restore degraded areas.

Public works and built infrastructure: Sensitivity, exposures, and adaptive capacity—Fort Bragg is larger and more complex than many mid-sized cities, with infrastructure that supports a population of more than 250,000 people (Fort Bragg 2012). Maintaining Fort Bragg’s mission readiness depends on supporting the Commands it houses and maintaining the quality of life of its inhabitants. This, in turn, depends on sound function of basic infrastructure systems (water and energy supply, sanitation and drainage, transport and telecommunication, etc.) and services (security, emergency services, family support, etc.), much of which is in the cantonment area (Figure 53). Climate change has the potential to affect some of these systems and services. During the site visit, we discussed recent findings related to several types of infrastructure from the Third U.S. National Climate Assessment (Melillo et al. 2014) as well as information collected specifically about Fort Bragg.



Figure 53. Fort Bragg cantonment area | Source: Satellite imagery and road data from Fort Bragg.

Traffic congestion and limits to existing transportation infrastructure. It was described as a serious concern were a concern, with “42 of 57 intersections currently assessed as failed or failing in accordance with USDOT [U.S. Department of Transportation] metric” as a result of recent population growth (Fort Bragg 2012). Discussion focused on plans to improve congestion and records that might document flooding, pavement buckling, or other issues on post or in the adjacent community. Despite healthy military construction programs, Fort Bragg still has critical facility needs, especially for transportation and tactical equipment maintenance facilities. Every day, 90,000 vehicles come and go through the gates of Fort Bragg, and congestion is likely to double by 2035 without additional transportation infrastructure investments.

Surface flooding and the adequacy of surface and subsurface drainage given the soil conditions was a concern. Flooding and drainage could intensify the effect of precipitation on erosion and water quality issues associated with the natural infrastructure. Also, flooding and drainage could create vulnerabilities across other infrastructure assets (for example, the road network).

Energy systems planning was the third issue discussed. Available documentation stated that the electric load forecast of some substations would exceed capacity (Parsons, 2010). Also, some portions of the distribution system were rated with poor reliability, high outage rates, and excessive maintenance costs. Our discussion focused on the status of upgrades for electrical supply and heating, ventilation, and air conditioning (HVAC) systems, as well as the potential load implications of increasing summer heat and humidity. During our site visit, personnel suggested that significant upgrades have been made to the system.

Analyses of occurrence of extreme temperatures indicate that the hot days have become more frequent in the summer. Figure 54 shows results from the weather station at Fort Bragg (red bars), and the corresponding grid box from the gridded Berkeley Earth 1°x1° dataset (blue bars). Individual stations often have more extreme values than gridded datasets because information from multiple nearby stations is interpolated and averaged for an individual grid box. As expected, the Berkeley Earth gridded dataset underestimates the frequency of extremely hot and cold days for this one station. Despite this, and despite significant year-to-year variability in the number of extremely hot and cold days, there have been significant trends in these variables over the last several decades.

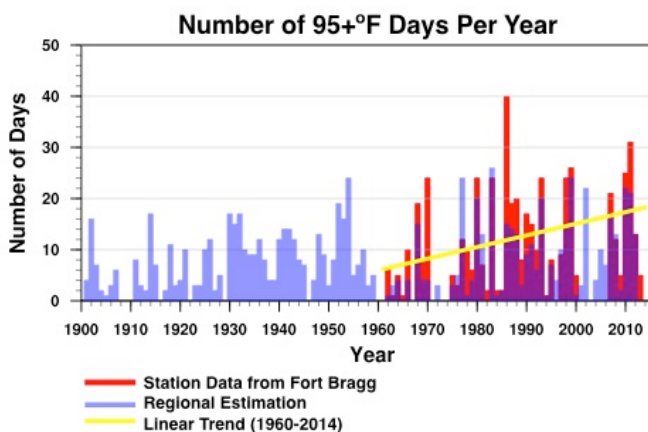


Figure 54. Number of days each year when daily maximum temperatures exceed 95°F at Fort Bragg

The installation's dependency on the Harnett County and Fayetteville water systems was the final issue raised. Both of these systems draw from the same water source (that is, the Cape Fear River). We raised questions about past water restrictions and their consequences, contingency planning, ongoing interactions with the suppliers, and whether or not climate change issues have been considered in planning. Overall, the region's population is growing rapidly—expectations for 2000-2035 are for 62% growth. Major droughts have occurred regularly including 2002 and 2007-2008, which was the all-time worst drought since 1887. Water availability is sensitive to more severe droughts and an increasing population (Griffin et al. 2013). Changes to precipitation and impervious surfaces could lead to decreased river base flows during drought periods. The region immediately surrounding Fort Bragg contains groundwater, but the yields from these aquifers would be small (typically, about 0.25 to 0.5 million gallon/day) (Jenicek et al. 2011). In addition, tapping local aquifers could result in salt water intrusion (Griffin et al. 2013). Fort Bragg currently consumes about 5 million gallon/day, with cooling towers being the leading consumer. In response to growing water demands, Fort Bragg has increased the efficiency of the cooling towers. According to a study by Jenicek et al. (2011), new water-supply contracts with the providers in Fayetteville and Harnett Counties should meet increasing water demand without interruption. In addition, a U.S. Army Engineer Research and Development Study (Jenicek et al. 2009) finds that there is little expected change to river flows. However, this study only looked at total annual stream flows and not changes in the intra-annual stream flows or demand. Further research is needed to examine the implications of climate change on water availability for the region.

4.3.2 Climate change and potential future exposure

Section 3.2 describes the methods used in the project to develop a climate “outlook” for the mid-Atlantic region. This section briefly summarizes the Ft. Bragg-related content of the Climate Outlook prepared as part of this project (see Appendix A for the full climate outlook) and provides a small amount of general background information needed to understand this section as a standalone case study description.

4.3.2.1 Climate change and potential future exposure at Ft. Bragg

Climate projections for Ft. Bragg and the mid-Atlantic region are made using regional climate models because the global models that were run lacked the resolution to represent the Chesapeake Bay and Annapolis was located in a grid box that is an ocean point. Thus, analysis focused on a 13-member ensemble of 31.06 mi (50 km) horizontal resolution regional climate model simulations produced as a part of the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2013). Climate projections are for the mid-century period: 2041-2069 (approximately), and unless otherwise stated, projections are presented against a baseline period of 1971-1999. The projections are based on the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios “A2” greenhouse gas emissions scenario. At 2100, this scenario produces a very high level of climate change; for recent decades, it is consistent with observed global emissions (Rahmstorf et al. 2007).

Fort Bragg has experienced a range of weather-related hazards. This section describes some of the analysis and information regarding potential future conditions conducted for Fort Bragg. As Fort Bragg as the third case study, some of the analysis presented is drawn from the Climate Outlook and compares results across the installations.

Temperature—Projected changes in temperature for the mid-Atlantic region are fairly uniform with most regions showing increases of 4-5°F (2.2-2.6°C) by 2055. While the models show variations in the magnitude of the change in temperature for Fort Bragg, on average, the models project a 4°F (2.2°C) increase in temperature for daily mean, daily maximum, and daily minimum temperatures across all seasons. The uncertainty is largest in winter and summer and smaller in the annual mean (see Figure 55).

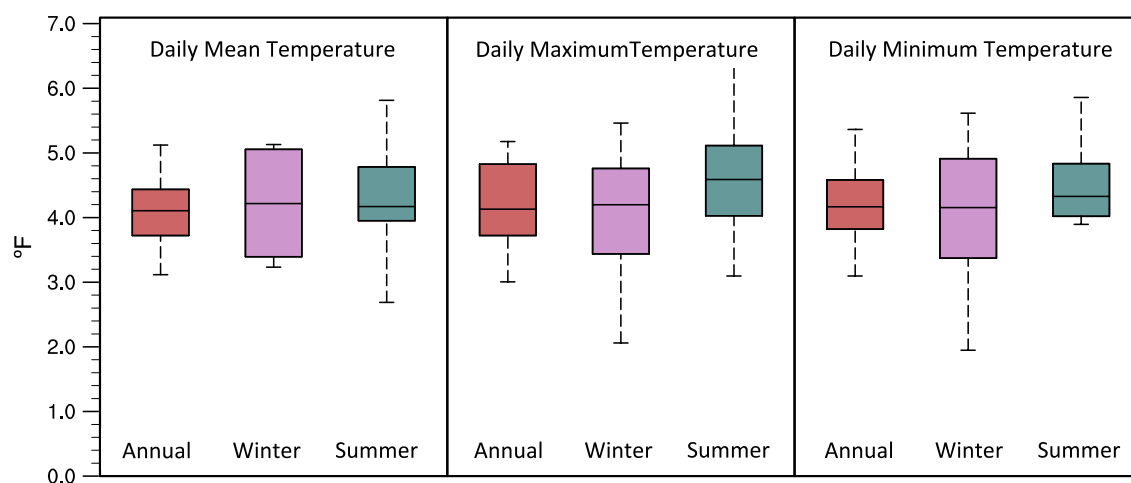


Figure 55. Daily mean, maximum, and minimum temperature increases for Fort Bragg at mid-century / The image was derived from analysis of the North American Regional Climate Change Assessment Program models using a high (“A2”) emissions scenario (similar to current emissions levels).

Figure 56 shows the multi-model or ensemble mean climate changes for all three case study installations. These projections again are based on the North American Regional Climate Change Assessment Program (NARCCAP) models using the same emissions scenarios and are all statistically significant.

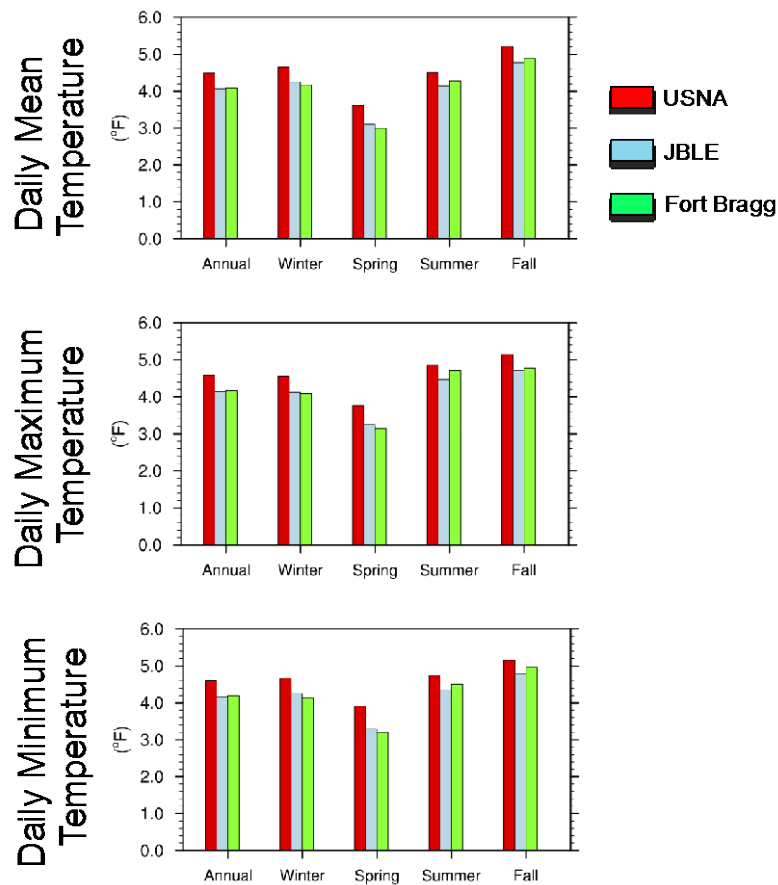


Figure 56. Multi-model or ensemble mean climate changes for three military installations / These projections are from the high-resolution North American Regional Climate Change Assessment Program ensemble. These changes are all statistically significant.

Precipitation—Analysis of the ensemble mean of the NARCCAP suite of regional climate models indicates the number of days when precipitation exceeds 1 in. is also projected to increase by 10-15%. For Fort Bragg, this means an increase from the observed 12.3 day/yr to 13.5-14.1 day/yr by mid-century. The greatest increases in precipitation are found in spring and fall with small changes expected in the winter and summer ($\sim 0\%$). During the summer (June, July, and August) and fall (September, October, and November), the NARCCAP models generally disagree about the sign of the change in rainfall (Figure 57 and Figure 58). There is significant uncertainty about the sign and magnitude of potential changes in precipitation for Fort Bragg with future changes in precipitation less certain than temperature.

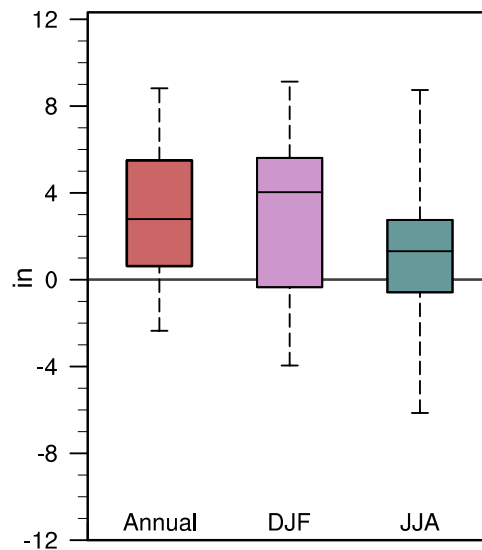


Figure 57. The box and whisker plot above shows the spread across the NARCCAP models for projected changes in rainfall for Fort Hood / DJF=December, January and February; JJA=June, July, and August.

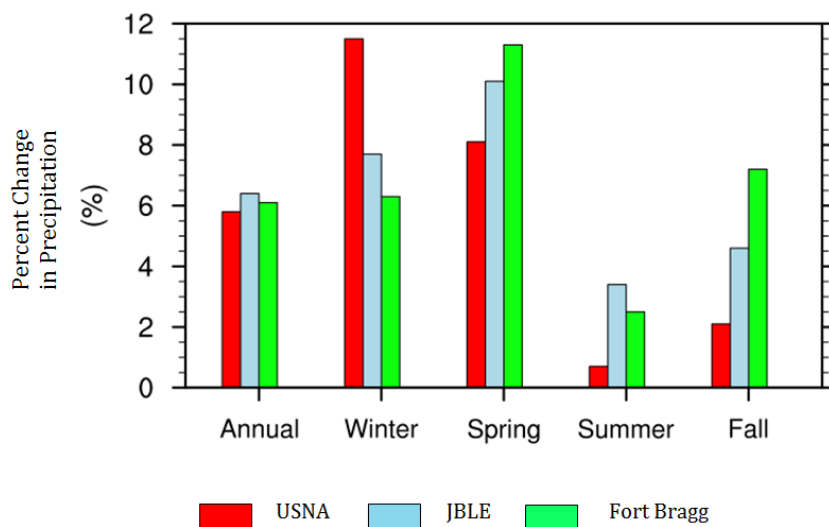


Figure 58. Multi-model or ensemble mean changes in precipitation for selected military installations / These projections are from the high-resolution NARCCAP ensemble.

We have relatively high confidence that even if mean precipitation rates were to decrease, precipitation events that do occur will be more intense. This might mean that it will rain less frequently, but when it does rain, it will be more intense; Figure 59 shows high confidence in projections of rains that are intense. There is strong evidence that higher temperatures and the resulting increase in water vapor in the atmosphere are dominant causes of observed and projected increases in extreme precipitation (Walsh et al. 2014a).

Wind—Modeling surface winds is extremely difficult, and future changes are highly uncertain. Climate models also lack ways to represent strong wind gusts, which typically cause the most damage. Extreme winds are often the result of phenomena such as severe storms which occur on scales that are much smaller than the average grid box of a climate model. Given that our confidence in modeling results of surface wind speeds is low, we provide only a brief description of future changes: The NARCCAP models generally show small decreases in future surface wind speeds over North Carolina. Decreases in surface wind speeds may be favorable for parachute drops, but unfavorable for prescribed burning, as the ventilation of smoke may be inhibited.

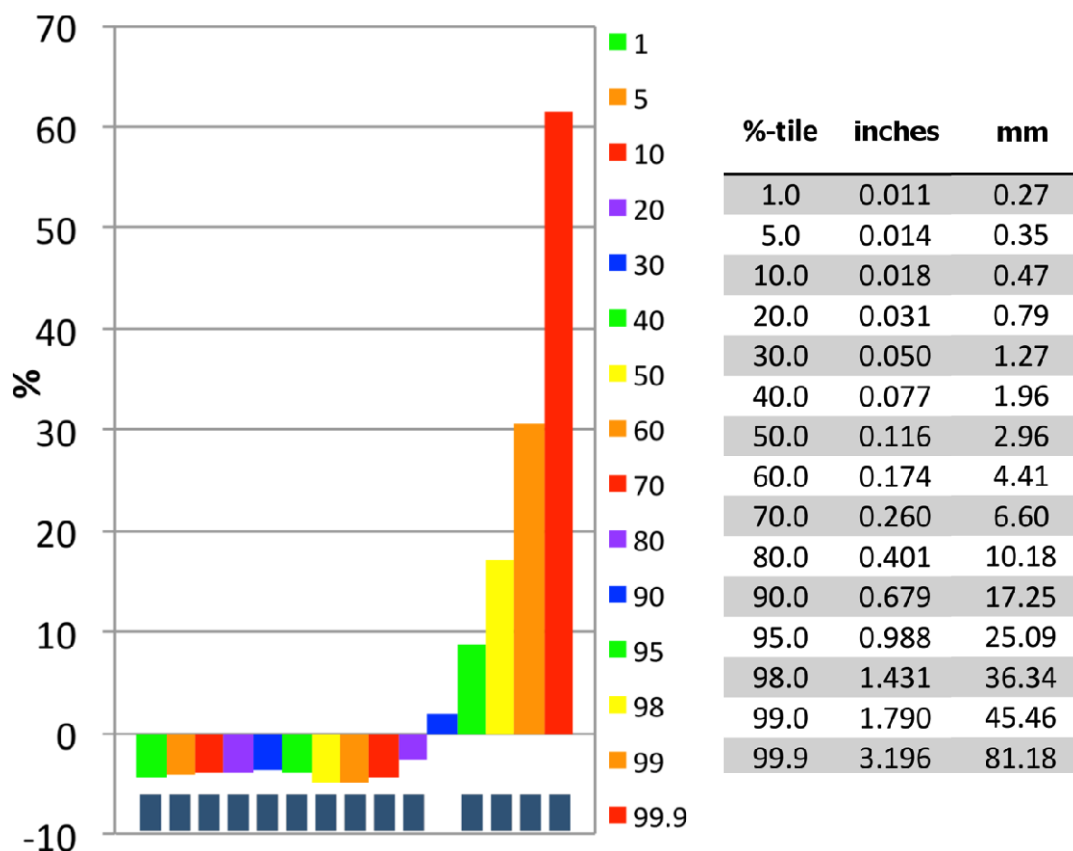


Figure 59. Percent change in precipitation from 1971-1999 to 2041-2069 for the mid-Atlantic region / The percentile value attached to each bin in the legend is the starting point for events within that bin; for example, the blue 90th percentile bin examines the change in the frequency of events with a magnitude greater than or equal to the 90th percentile magnitude and less than the 95th percentile magnitude from the historical climate period. A dark block under a given bin indicates that the change in that bin is statistically significant using a 90% confidence level.

Extreme weather events—Extreme weather may increase at Fort Bragg under future climate conditions. For example, Figure 60 shows the percentage in extreme precipitation increases for the mid-Atlantic region. In addition, the number of days in which the environment (that is, conditions) is conducive to the formation of severe thunderstorms is projected to increase for the mid-Atlantic region in the future. This does not mean that the number of severe storms will go up, but that the environment will be favorable for the formation of severe storms on more days

each year. There are greater uncertainties about how frequently these storms will be triggered in the future. Results suggest that the average number of days that could accommodate severe thunderstorms may increase by approximately 5-9 days, while the number of days that could accommodate significant severe thunderstorms may increase by about 3-8 (Figure 60).

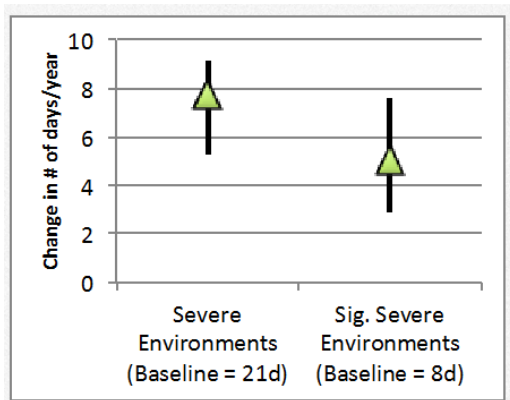


Figure 60. Number of days per year that are conducive for the formation of severe or significant thunderstorms averaged over the mid-Atlantic region / The triangle represents the 50th percentile, while the high and low ends of the bar represents the 25th and 75th percentiles. Climate changes were calculated from the 7 NARCCAP models that had sufficient information. Due to the naturally large variation in the number of these events per year, these results are not statistically significant.

Severe thunderstorms are defined as storms that produce hail that is at least 1 in. in diameter or larger, wind gusts of 58 mi/hr or greater and/or with a tornado. Significant severe thunderstorms are those in which there is hail that is at least 2 in. in diameter, convective wind gusts greater than or equal to 75 mi/hr and/or with a tornado that is at least an EF2/F2 on the damage scale. The methodology used to identify severe weather environments in climate models is complex. It involves calculating the potential energy in the atmosphere that is available for storm (convective available potential energy, CAPE) and the vertical speed within an updraft.

4.3.3 Future vulnerability: integrating baseline sensitivity and adaptive capacity with potential changes in exposure

This section describes several ways in which the project explored future vulnerability by integrating information on sensitive systems and the capacity to adapt them with the analysis of potential changes in exposure due to climate change. A challenge for vulnerability assessments is to consider not only the ways that exposure may change, but also how relevant societal conditions and infrastructure systems may change as well. For installations, a good source of this kind of information includes master or strategic planning documents developed through processes that consider potential changes in mission and resulting requirements for installation performance.

Future vulnerability of natural infrastructure and training to climate change —Although erosion is not currently identified as a challenge by managers and personnel at Fort Bragg, changing patterns and intensity of precipitation under climate change may influence future patterns of

erosion. Intense precipitation could also impact range conditions and scheduling. There is relatively high confidence that even if mean precipitation rates were to decrease, precipitation events that do occur will be more intense. This might mean that it will rain less frequently, but when it does rain, it will be more intense. For example, as previously mentioned, the number of days when precipitation exceeds 1 in. is also projected to increase by 10-15%. There is strong evidence that higher temperatures and the resulting increase in water vapor in the atmosphere are dominant causes of observed and projected increases in extreme precipitation (Walsh et al. 2014).

Future changes in surface wind speeds may influence a number of factors at Fort Bragg including the frequency of parachute drops in training, damage to trees in the rangelands and cantonment, and smoke ventilation during prescribed burns. Increases and decreases in wind speeds have variable effects. For example, decreases in surface wind speeds may be favorable for parachute drops, but unfavorable for prescribed burning, as the ventilation of smoke may be inhibited. Unfortunately, as previously discussed, simulating changes in regional wind patterns is extremely difficult and highly uncertain. Local wind speeds and direction are generally influenced by the complexities associated with topography. Most climate models (even the high-resolution models) are too coarse to represent local topography adequately enough to capture local winds with the correct direction or intensity.

Fort Bragg is sensitive to lightning strikes, which can interrupt training and damage electronic range instrumentation, which has sustained significant damages in past events. As previously discussed, our analysis of climate models suggest that the average number of days that could accommodate severe thunderstorms may increase by approximately 5-9 days, while the number of days that could accommodate significant severe thunderstorms may increase by about 3-8.

Temperature change may increase the number of days with training restrictions use. To appraise vulnerability to temperature increases to outdoor training, we consider the potential increase in wet bulb globe temperature (WBGT) and the associated change in flag days. While climate models do not routinely report the WBGT index, it can be calculated using model output. Across the models, the number of green, yellow, red, and black flag days increase (Figure 61). Using results from a number of the models, the WBGT is projected to increase by 4°F for Fort Bragg, resulting in an increase in black flag days by 3-17 days per year and red flag days by 2-7 days per year, depending on the model. There is significant uncertainty across the models regarding the magnitude of change to the most restrictive heat days (i.e. black flag days). While some models show no or little change in the number of black flag days, many show increases ranging from 3-17 days per year. The most extreme models indicate black flag days may increase by 40 days per year by mid-century. Red flag days are also projected to increase, with most models ranging from 2-6 days per year. These changes imply that Fort Bragg may need to increasingly plan around black flag conditions, which may result in more heat-related restrictions for training. Increases in black flag days could potentially affect future mission attainment by restricting available training time.

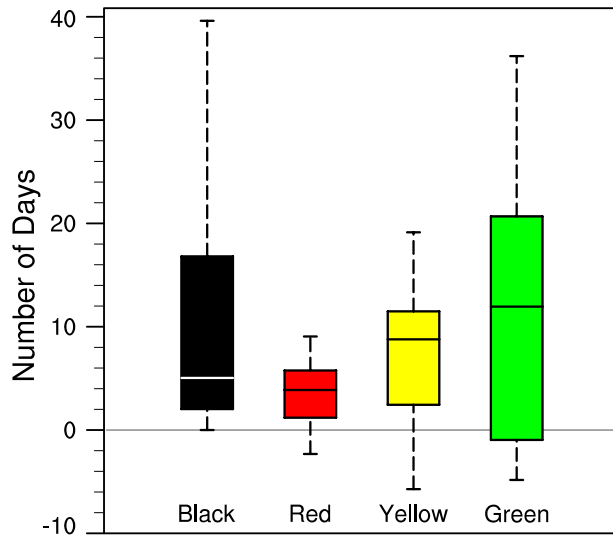


Figure 61. Box and whisker plot representing the range of uncertainty for the change in the number of black, red, yellow, and green flag days expected to occur per year on average at Fort Bragg

As previously discussed, prescribed burns is an essential tool for managing fire risk by reducing fuel loads, maintaining areas open for training, and managing ecosystems such as the longleaf pine ecosystem and red-cockaded woodpecker habitat. Thus a change in the availability of prescribed burn days could affect Fort Bragg's ability to effectively manage the natural infrastructure essential for its mission. The availability of days for prescribed burns is dependent upon temperature, humidity, wind speed aloft, and precipitation patterns. Fort Bragg generally does not conduct prescribed burns (or does so less frequently) from June to September because of high temperatures during these months. Future fire frequency in the Southeast will depend on how climate change affects precipitation in the region, as well as how forests are managed. One recent study found that while the Southeast may initially see a decline in climatic conditions conducive to fire, an increase in fire sensitivity is projected for inland areas by mid-century and beyond. In particular, more extremely dry periods combined with higher temperatures and more lightning could lead to more intense wildfires, especially if interspersed with wetter years that allow rapid growth of vegetation that provides fuel for fires.

Projected temperature and precipitation changes may reduce available days for safe burning at the installation, particularly under current budget constraints on overtime. As was discussed previously, temperatures are projected to increase by approximately 4°F in the region with little change in summer precipitation expected. As temperatures rise, the rate of evaporation and transpiration will increase, causing forests to be drier. Projected changes in precipitation also suggest more time in between rainfall events. This could reduce the number of days when prescribed burns can be conducted safely. When projected temperature and precipitation changes are factored alone, conditions that are favorable for the occurrence and spread of wildfires will become more frequent. We estimate that the number of days each year where the threat of potential wildfire is high (that is, extreme wildfire risk days) will increase by 20-50 days per year by mid-century (see Figure 62). We calculate this change by using the Keetch-Byram Drought Index, which is an index used to determine forest fire potential. This index combines rainfall and temperature to estimate how dry forested areas are and their risk for wild fires. When the index is

high, wild fire risk is high, and prescribed burning is not recommended. This index serves as a proxy for expert judgment and specific knowledge of fuel moisture.

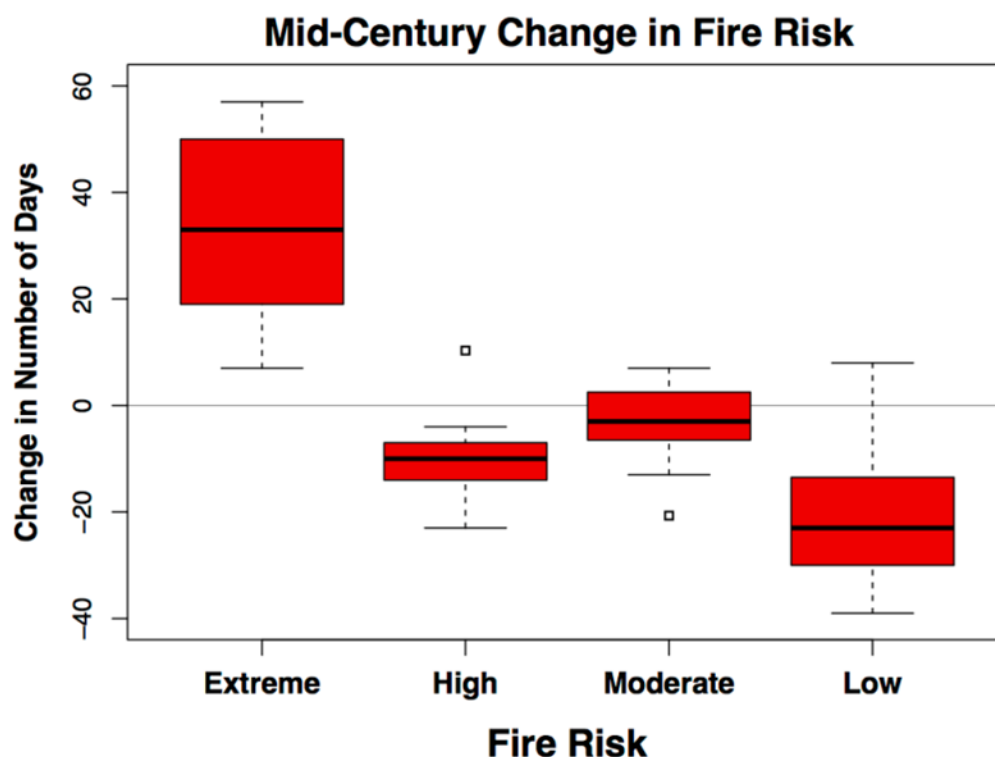


Figure 62. Projections of changes in mid-century fire risk at Fort Bragg / Source: NARCCAP model.

A decrease in available prescribed burn days could affect management of the longleaf pine-wiregrass ecosystem and the red-cockaded woodpecker, as well as leading to heavier fuel loads and a higher fire danger, which would reduce the availability of training areas for certain activities. It would also increase the risk of larger wildfires, which could seriously damage ecosystems and base infrastructure. More study is necessary to determine the likely timing of changes in available burn days. Changes to the available burn days during the period between October and May would negatively impact the ability of installation personnel to manage the fuel loads in training areas.

There are other factors that could affect the management of ecosystems at Fort Bragg and potential to increase training limitations. For example, climate change could increase invasive vegetation, alter the ranges of tree species, and increase the presence of harmful insects. These changes could facilitate or challenge management of natural resources, and likewise serve to increase or decrease training limitations. For example, the red-cockaded woodpecker has specific habitat requirements. Lozar et. al (2013) suggest that climate change might favor a wider spread of longleaf and loblolly pine, the preferred nesting sites of the red-cockaded woodpecker. While this would benefit the woodpecker, there is the potential for an increase in training restrictions due to potential impacts to existing or new threatened or endangered species (for example, changing migration patterns into the area) as temperatures change.

Future vulnerability of public works and infrastructure to climate change—Projected temperature increases could lead to higher operating costs due to potential increases in cooling loads. Annually, cooling degree days (CDDs) are projected to increase by as much as 47-70% for Fort Bragg. CDD are the number of degrees daily average temperature exceeds 65°F. Much of this increase will occur during the hot summer months, potentially resulting in increased energy costs. Future changes were calculated using results from 11 regional climate model simulations based on a high emissions scenario (the 25th, median and 75th percentile changes are represented in Figure 63). The Third U.S. National Climate Assessment (Melillo et al. 2014) evaluation of energy supply and use indicates demands for electricity will increase, potentially raising costs and straining generation and distribution systems. Figure 63 shows the observed and projected CDD.

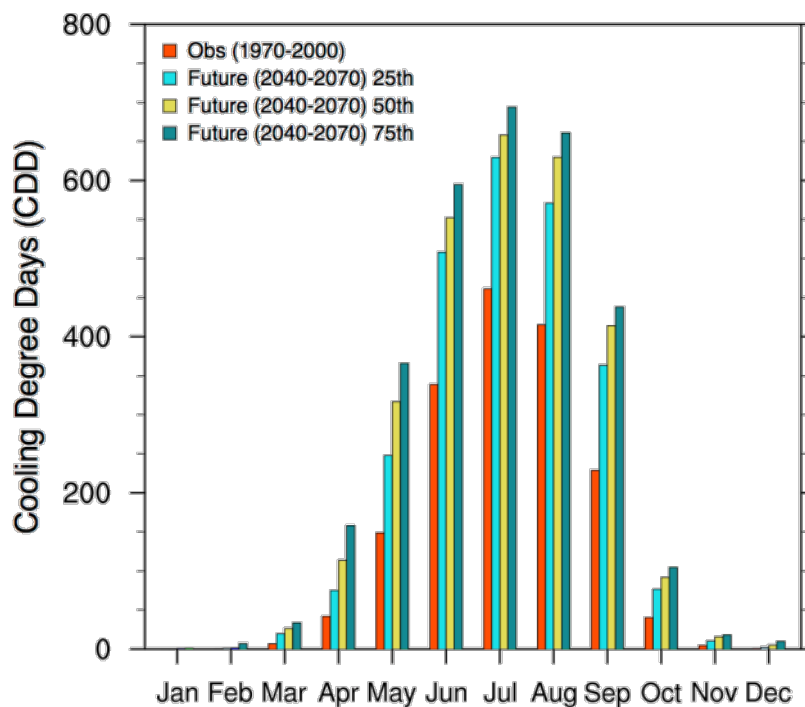


Figure 63. Observed and projected cooling degree days / Cooling degree days are the number of degrees daily average temperature exceeds 65°F.

4.3.4 Discussion

As previously discussed, a key process difference we tested at Fort Bragg was completing a significant amount of analysis prior to a site visit, and holding a webinar to share these interim results. Coupled with the onsite visit, this represented a more structured approach to engagement. We found that this did serve to increase the efficiency of our onsite visit, and get early buy in to the process through the webinar. It further enabled us to take advantage of existing assessments that had been conducted at Fort Bragg. Importantly, this structured engagement enabled us to identify differences between information in existing documentation and that from personnel (for example, the challenges associated with erosion) early in the process. It also assisted us in the early identification of data needs, key stakeholders to engage during the onsite visit, and connect with individuals interested in the project.

We reached a number of conclusions that were helpful to personnel at Army Headquarters regarding the vulnerability of Fort Bragg to climate change. Fort Bragg has adopted sound ecosystem management practices and other infrastructure improvements that have increased its resiliency to future climate change impacts. While the adoption of some of these practices and improvements were motivated by meeting environmental restrictions and targets, they have served to improve Fort Bragg's natural infrastructure. Because of these practices and improvements, and because of its location and associated climate exposures, Fort Bragg is comparatively less vulnerable to climate change than the other two case study installations. To further increase its resilience, existing planning processes should consider the potential effects of climate change. Incorporating climate information into decisions of projects for expanding or recapitalizing buildings or systems could assist in improving estimates of total systems costs, requirements, and reliability. For example, incorporating climate information into decisions related to HVAC system sizing, or potential changes in building energy requirements, could improve resilience and energy demand management strategies. Additionally, quantifying changes in the availability of prescribed burn days on the installation provides information that Fort Bragg administrators could use to plan future activities and budgets.

Several specific areas would benefit from additionally monitoring and study at Fort Bragg in the future. These include the following:

- Impacts on ecosystems and Threatened, Endangered and Species at Risk
- Building energy use changes
- Changes over time in incidence of heat stress or vector-borne diseases
- Impacts on fire management practices
- External network dependencies, especially related to water supply and demand under drought conditions.

There are several opportunities to use existing models and assessments to explore these areas. For example, the Facility Energy Decision System is a building energy efficiency modeling software tool developed by Pacific Northwest National Laboratory that could be used to explore the effect of changing temperatures on building energy use. While outside of the scope of this tier two assessment, it could provide important information for considering different adaptation options for HVAC systems that are robust against future temperature change.

Finally, it will be increasingly important to maintain records of impacts from ongoing weather-related events which could then be integrated into planning and decision processes. For example, identifying the linkage between weather events and impacts on training schedules, operations, maintenance costs, and other factors will provide valuable information for future decision making.

5. Conclusions and Implications for Future Research/Implementation

This section of the report draws conclusions about the characteristics of a three-tiered vulnerability assessment framework based on the case studies conducted at the U.S. Naval Academy (USNA), Joint Base Langley-Eustis (JBLE), and Fort Bragg. The conclusions are mostly focused on issues related to the middle tier of the overall framework—vulnerability assessments conducted at high-priority installations—because our case studies and project were designed to focus on this problem. Before the conclusions about installation-level assessments, we briefly discuss several conceptual and framing topics, including whether vulnerability assessments are needed, what the case study results suggest about basic concepts used to structure information collection, the overall three-tiered framework, and the issue of cross-site vulnerability screening to identify where installation vulnerability assessments are needed. We then turn to our findings related to installation assessments, and following that discussion, conclude the chapter by exploring several cross-cutting issues and priorities for developing methods needed to improve the quality and utility of information produced through vulnerability assessments.

In developing these conclusions, the authors circulated a draft synthesis of results for comments. An online form was developed for readers to provide feedback on specific aspects of the approach, and detailed line-by-line comments were also received on the draft. These conclusions are based on that draft, revised to take account of the input received.

5.1 Does DoD need to conduct climate vulnerability assessments?

The purpose of climate vulnerability assessments is to produce information that improves decisions regarding how to sustain a community, secure capital investments in infrastructure and assets, and/or maintain continuity of key services and missions. Stated this way, many existing processes have this purpose, and personnel may advocate simply adding climate vulnerability to an existing process. After all, depending on their level of detail, climate vulnerability assessments can be time consuming and costly. They can be biased by personal judgments of the consequences of impacts that are projected to arise. Focusing on vulnerability—a “negative”—can discourage managers from revealing potential problems, especially if managers penalize the existence of vulnerabilities as a sign of poor performance. The information produced can miss the mark in terms of its relevance to ongoing management, capital planning, and design cycles and processes.

While all of these things can be true, they can also be true of many processes that consume substantial resources to produce and are currently used in making decisions about infrastructure and facilities across the U.S. Government and civilian society (for example, risk assessments, management systems that evaluate condition and mission dependence). The challenge is to structure an overall framework for climate vulnerability assessments that minimizes the potential downsides and produces information that is relevant to ongoing decision-making processes. To accomplish this, the DoD needs a framework for climate vulnerability assessments that would

- Identify installations and sites that are most at risk

- Evaluate how changes in climate affect mission continuity and protection of existing Federal investments
- Support self-learning in this area by creating opportunities for Department and Service managers to break down information silos and discover and clarify the risks for themselves and those at higher levels of governance

The first purpose is to bring order to the process of identifying places and assets that could be compromised by future climate conditions. An efficient, traceable, and replicable screening process is needed (see Section 5.3). Such a screening process will use information about baseline conditions at installations and sites from existing management systems (to the extent possible), surveys, and other sources in combination with relatively coarse regional (or sectorally-oriented) projections of future climate exposure to identify those sites most at risk. A well-structured screening process will produce comparable information across similar types of installations and sites and allow creation of an ordered list for setting priorities and making best use of resources.

The second purpose is to translate how potential future climate conditions can affect facilities and missions, and to relate these consequences to potential adaptation measures. Translation is needed because information about future climate conditions (for example, temperature, precipitation, or even specific impacts-relevant climate variables such as a fire danger index) alone does not often apply directly to decision-relevant variables without additional analysis. Table 7 illustrates this point, linking climate exposures, potential impacts, significance to management or decision making, and potential adaptive management options. A well-planned process can identify near-term adjustments in policy and ongoing management, although this has been less common than we expected because installations are currently managed to cope with conditions likely to be experienced in the near term.

Thus, to be useful, the process needs to be designed to produce information that matches up with capital planning cycles and decisions with long-term implications (build-out of new or renovated infrastructure; acquisition or decommissioning of bases; siting of training activities and programs; planning of logistical and other systems, etc.) that will be taken within the next decade, a typical planning horizon for such decisions. This observation is consistent with other recent studies that indicate adaptation is occurring more successfully where climate and related information is developed and used in the context of ongoing planning and decision processes (GAO, 2013, 2014). Finally, the process needs some degree of standardization with respect to assumptions and methods so that it produces information that is comparable, facilitating use of the information at higher governance levels where cross-installation decisions are taken.

Table 7. The Need for Climate Vulnerability Assessments: Translating Exposure into Impact, Consequence, and Adaptive Management

Exposure	Impacts (exposure + vulnerability)	Significance for Mission and Operations	Adaptive Management (varies by governance level)
Increased fire risk	Fewer burn days; ecosystem condition; endangered species	Costs; restrictions on training land	Revise scheduling/budget; alter management; add training capacity at other installations
Ecosystem migration (change in flora/fauna ranges)	Threats to protected species; increase in invasive species, pests, disease vectors	Costs; mismatch of training requirements and lands; increase (or decrease) in restrictions	Alter management; redistribute training activities
Increase in days with extreme heat	Outdoor activity and training restrictions; energy system stress	Reduced training throughput; schedule interruptions	Alter training schedule; redistribute training activities
Change in surface wind speed	Flight training, parachute drop cancellations; controlled burn restrictions	Training throughput and readiness; changes in ecosystem maintenance	Alter training regimen; redistribute training activities; change burn patterns
Increase in storms (tropical, sub- and extra-tropical)	Training cancellations; ecosystem disturbance; infrastructure damage	Training, health and safety concerns; increased costs	Increase preparedness; alter maintenance contracts; recapitalize infrastructure; provide backup systems; delay/move training
Increased temperature	Increases in cooling degree days; decreases in heating degree days; ecosystem disturbance	Inadequate heating, ventilation, and air conditioning system design; costs	Alter design standards; revise budget; revise conservation management protocols
Changes in precipitation, runoff, temperature	Flooding, changes in water supply and storm water management; noncompliance with water quality requirements; infrastructure disruption (buildings, transport, etc.)	Use restrictions; supply system adaptation; altered suitability of locations for water-intensive activities; increased compliance costs	Budget for increased costs (cleanup, damage); alter management regimes; relocate water-intensive activities; change to surface/subsurface conveyance systems; adjust master planning, facilities criteria
Coastal flooding	Infrastructure disruption and damage	Costs; health and safety concerns; activity interruptions	Modify service contracts; increase budget; redesign infrastructure; adjust master planning, facilities criteria

The third purpose relates to facilitation of “social-” and “self-” learning within DoD and the military services. Stakeholders who participate in assessments, even in cases where they only provide information on site baseline conditions, are exposed to analysis of trends or changes in observed conditions that may be difficult to perceive directly, as well as to information on the current state of climate science with respect to exposures important to their operations.

Information collection in a climate vulnerability assessment can lead to valuable information exchange, both across management systems at a particular site as well as across governance levels. In our research, this exchange of information clarified that some issues highlighted in existing reports or databases were not in fact problematic, as well as identifying previously undiscovered risks. In cases where stakeholder participation goes beyond this to include participation in methods such as scenario planning, where groups wrestle with how they would respond to projected impacts, participants have the opportunity to more thoroughly consider the consequences they could confront and what they may need to do to prepare. This helps identify certain aspects of current operations and maintenance at the installations that could be modified to better adapt to climate change. It also identifies needs for collection of information about impacts and damages from climate variability and change (for example, closure of training ranges, clean-up costs from floods or storms, reduced expenditures on winter-time heating). This information can include data on occurrence of “thresholds” at which damages or closures occur that can then be used in tailored analysis of climate model data. In some cases, managers may have the leeway to collect this information on their own; in others, a policy decision may be required to add a field to an existing database or system (for example, related to condition or mission importance) that adds a climate condition or factor.

5.2 Core concepts and evolving state of practice

Once the need for DoD vulnerability assessments is established, the next basic question in establishing a framework is what conceptual or logical structure should be used in the assessment. This is not simply an academic question, but rather one that drives information collection and analysis. Our initial literature review (see Section 3.2) identified many vulnerability assessment frameworks. We also acknowledge the relevance of other approaches including risk assessment, and resilience from engineering, ecological, cyber, critical infrastructure, disaster risk management, and other perspectives (for example, IPCC [2012] seeks to integrate climate vulnerability and disaster risk management approaches; Linkov et al., 2014, argue for integration of risk analysis into resilience planning; Larkin et al., 2015 review integration of risk and resilience science within Federal agencies; Bowyer et al., 2015 review methods for developing adaptation strategies that frame the issue as managing climate risk). As vulnerability assessment, adaptation planning, and promotion of climate resilience are incorporated into existing areas of practice such as civil engineering and ecosystems management, it will be important to at least clarify, if not resolve, different definitions ascribed to such terms as “threat,” “vulnerability,” “consequence,” “exposure,” and “resilience.” The focus of this project was not on reconciling differences in definitions or approaches but rather on developing a practical and understandable approach grounded in the literature on climate change vulnerability that has the potential to work within the DoD context. We identify this as an important area for future research that would be advanced by further literature review, analysis, and opportunities for cross-community dialogue.

In the course of the research, we concluded that our definition of vulnerability as arising from exposure, sensitivity, and adaptive capacity (see Section 2) was potentially confusing, particularly the emphasis on climatic variability and extremes. It conveyed to participants that vulnerability assessment could not begin until detailed information about exposure to future climate conditions was provided. We found this to be counter-productive because assessing local

conditions is crucial for understanding the potential significance of climate change for mission attainment and can proceed in parallel with or even before development of information on future climate conditions. In stressing the importance of knowledge of site conditions for establishing a baseline, we found ourselves aligning with Linkov, Larkin, Bowyer, and others who point out it is crucial “to have a sound understanding of how a given system functions in response to changes in both climate and non-climate factors” as a foundation for assessment of vulnerability or resilience (Bowyer et al., 2015).

As illustrated in Figure 64, we suggest revising the conceptual approach used in future facility vulnerability assessments to define *vulnerability* as a function of the characteristics that affect the susceptibility of the site to damage, thus emphasizing sensitivity and adaptive capacity (see Box 1). *Exposure* is still crucial but now distinct from vulnerability and depends on the evolution of the climate system and related environmental conditions. This formulation more clearly distinguishes the baseline characteristics of facilities from the exposures that act upon those vulnerabilities to produce impacts—the resulting damages, injury, or harm (for example, the physical damage to a building, bridge, or training area). The implications for methods development of this change in approach are discussed in Section 5.7.

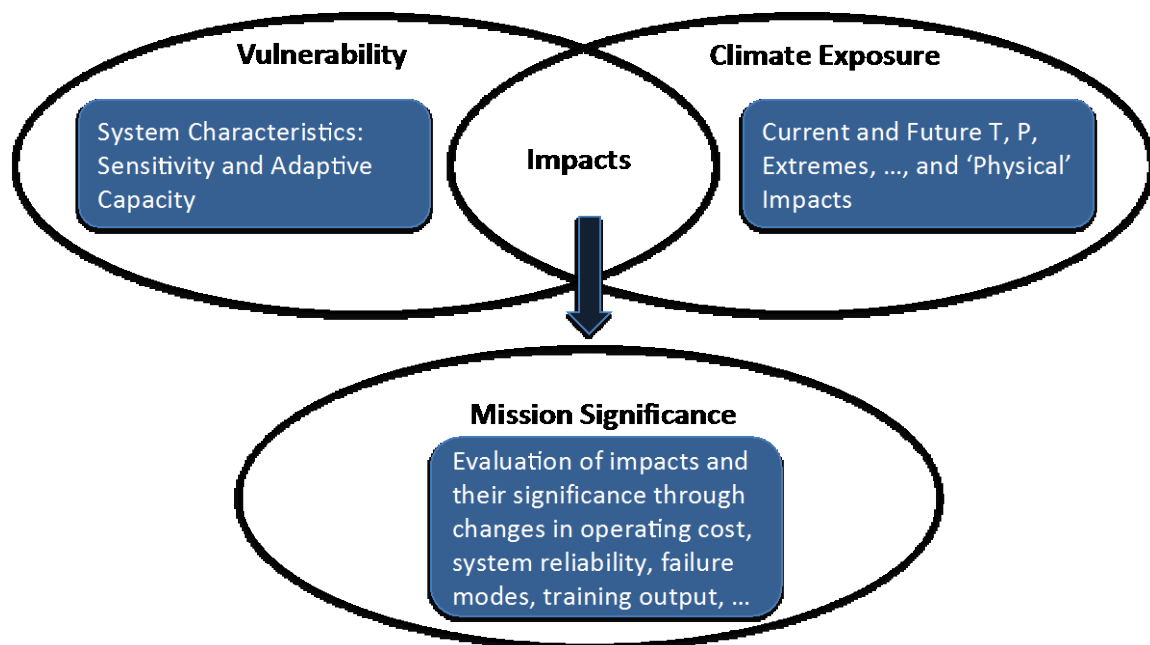


Figure 64. Vulnerability defined as a pre-existing condition based on characteristics of a facility or system / Climate exposures exploit vulnerabilities to produce impacts which affect mission attainment (T = temperature, P=precipitation).

The alterations from our original approach are important for framing and analyzing vulnerability in ways that are more relevant to stakeholders. This altered framework clarifies several important aspects of communication, especially in an environment where "vulnerability" is a charged word and terms such as sustainability and resilience are not, as well as the processes and methods:

- *Emphasizes collecting information on installation characteristics*—Considering vulnerability as a pre-existing condition or property of the facility or infrastructure emphasizes the importance of systematically gathering and analyzing baseline information—information about future climate conditions is not sufficient in itself, as some participants were inclined to think
- *Focuses climate analysis*—Identifying which aspects of a system are vulnerable—and why—helps develop priorities for climate analysis by identifying which specific climate variables or processes are most important
- *Can empower installation personnel*—Emphasizing the importance of site conditions can call attention to the fact that impacts depend on the decisions and stewardship of facility operators and managers, not only on climate factors they cannot control
- *Adds value to impacts modeling*—By explicitly adding a step for assessing “significance” to our conceptual approach, we distinguish “physical impacts” (for example, damage to structures) from their ultimate “significance” for mission attainment (for example, service interruptions, increased costs, lost training capacity). This demonstrates to stakeholders why their engagement in the process is important. Models can be used to project impacts (given site conditions and projected exposures), but stakeholder engagement is needed to explore how impacts affect mission attainment by considering options for coping and recovering from impacts in the immediate aftermath of different levels of impacts, and by reducing vulnerabilities through adaptation. Scenarios, charrettes, and other methods can be very useful in this process.

5.3 Screening and assessment in a multi-tiered process

In Section 5.1, we identified a number of characteristics for a vulnerability assessment framework for DoD. This section of the report briefly describes a multi-tiered approach for vulnerability assessment that could be used to increase efficiency and reduce costs while still allowing for detailed assessment where needed. The framework includes three levels of analysis and is depicted in Figure 65. The bottom tier includes a screening of all agency facilities to set priorities. The middle tier focuses on more detailed assessments at facilities identified as most vulnerable. The top tier comprises analysis of adaptation options using other frameworks currently employed in capital planning, design, and management.

The framework is not intended to be rigidly applied but instead to offer a general flow of analysis of different levels of detail needed to make some of the most important decisions facing DoD in managing its climate risk. The framework will produce a more accurate depiction of vulnerabilities if it builds on existing data and the expertise of site managers. If vulnerability assessments are implemented in synch with budget and planning cycles, they will facilitate investment in facilities and infrastructure that are suited for potential future climate change conditions and impacts and avoid investments in stranded assets that are not fit for purpose. If the framework is implemented in a way that is consistent with the principles of “adaptive management”, managers will be able to build on knowledge developed from prior assessments and adaptations. Adaptive management emphasizes planned, iterative, and sequential evaluation that includes monitoring and learning (NRC, 2009).

We briefly describe the objectives and functions of each tier.

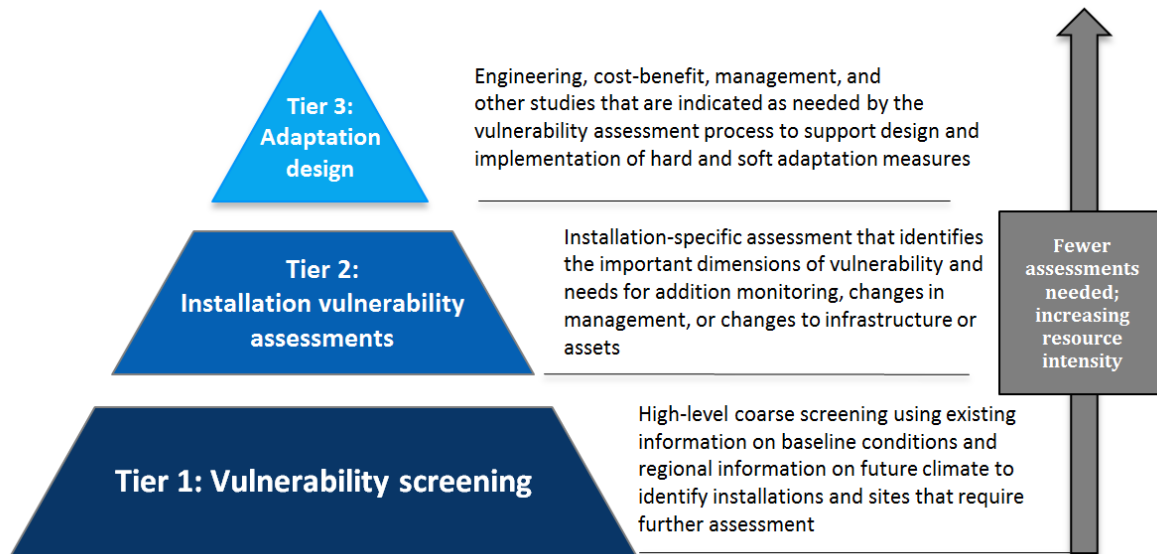


Figure 65. Tiered, multi-criteria framework to vulnerability assessment

Tier 1: Vulnerability screening—In a situation in which financial and other resources are not sufficient to conduct tier 2 assessments at all sites, department- or program-wide comparative analysis of sites can establish priorities for additional vulnerability assessment. Robust prioritization will be based on indicators of vulnerability that are comparable, reflect differences in site baseline conditions, and consider differences in potential future climate change from site to site. As described in Section 4.4, the project (and a related one for the Department of Energy) tested screening approaches that combine site questionnaires and indicators that use existing data on site baseline conditions collected for other purposes. Until existing data and information systems on condition, mission importance, and other factors are modified to collect information related to climate vulnerability, additional information specific to the screening process will need to be collected from site personnel.

Tier 2: Installation vulnerability assessments—For selected sites, potential vulnerabilities are analyzed at a more detailed level of analysis than during the screening process to identify needs for additional monitoring, alterations in management practices, or structural changes. As described in Section 4.5, this tier uses

- Stakeholder engagement to bound the assessment, gather information about baseline conditions, and identify the need for interactions with the broader community
- A variety of approaches for characterizing past and future exposure

- Methods for modeling potential impacts (for example, infrastructure models, geographical information systems, and network models)
- Additional stakeholder engagement to assess consequences and options for adaptive management.

The expert knowledge of site personnel and information from site records and data (including planning documents) are a crucial input, which places a premium on methods for data collection.

Tier 3: Adaptation design and decision making—If the installation vulnerability assessment identifies combinations of vulnerabilities and potential future exposures that threaten mission-important infrastructure or create hazards to safety and welfare, the third tier of the framework is required. The objective of this tier is to incorporate the risks resulting from vulnerability to climate change into ongoing planning and decision processes, for example, during design of already scheduled installation upgrades or expansion. The character of this analysis will vary depending on the nature of the system, location, or activity, as well as the type of potential adaptation being considered. It could include detailed engineering analysis of systems or networks (both onsite and offsite, such as external utility, transportation, or other systems on which the site depends).

The main distinctions across these tiers are the objectives supported and the corresponding level of detail and quality of data required. Tier 1 and 2 each require information about baseline conditions and potential future exposure—simply completing an assessment of current conditions and impacts from ongoing climate variability will not be sufficient to identify whether assets are at risk and the next tier is needed.

5.4 Tier 1: Climate vulnerability screening

Screening level analysis at all DoD installations and sites needs to be efficient and rely on existing information and/or easily collected supplemental information gathered for this purpose. As discussed in Section 5.2, information on site characteristics that create vulnerabilities as well as information on potential future exposures is required. Gathering information about site characteristics can be thought of as developing a vulnerability “baseline” that considers importance, condition, past damages, preparedness, and other factors. It is important to point out that developing a baseline does not constitute a complete screening, as the baseline must be evaluated against possible future climate and related environmental exposures to identify potential problems that warrant additional analysis. Consideration of differences in potential for climate change exposure allows prioritization of those sites that have a higher chance of experiencing problematic climate conditions. Once a screening process establishes priorities for a set of installation vulnerability assessments, it may not be necessary to re-screen for some time, depending on the length of time required to complete the installation assessments. Alternatively, if the screening process is based on an enterprise-level data set, such as a real property data set, it can be iterated more frequently to evaluate changes in relative vulnerability based on the updated information.

Candidate methods for site screening include analyzing existing datasets that track characteristics of the site or installation; questionnaires; interviews; using publicly available

historical exposure data; and indicators that integrate available information to facilitate ranking. Each approach has strengths and weaknesses, and it is likely that no single method will work across DoD's diverse property holdings and facilities. In all cases, tier 1 screening can be designed to help establish priorities for tier 2 screening by gathering information on the contributions of specific systems or assets to an installation's overall vulnerability. Moss et al. (2001) apply sensitivity and uncertainty analysis to evaluate the contribution of different factors to national vulnerability indicators, and the approach used there can be adapted for this scale, as many institutional enterprise data sets compile information at the asset or system level.

Institutional datasets, such as the Mission Dependency Index, Facility Condition Index, and Real Property Assets Database (see for example DoD, 2015), track different aspects of the Department's assets. Some of the information collected can provide insights on characteristics of infrastructure or assets that could indicate whether those assets are vulnerable to potential changes in climate. Because this project focused on testing methods at the installation level, we did not analyze these databases to identify how information extracted from them could be combined to supply information that would assist with vulnerability screening.

In other research, we have worked with datasets from other Federal agencies, and based on that experience, we expect that some valuable information (for example, past damages or preparedness costs related to past storms, droughts, floods or other events) is not tracked in current systems. As discussed below in connection with development of indicators, issues associated with completeness and data quality may also occur, thus making it necessary to supplement information extracted from existing datasets with additional data. Future research and analysis of the use of existing datasets for screening is an important research gap.

Questionnaires can be a useful technique in identifying past impacts, climate exposure thresholds at which damages occur, the effectiveness of current preparedness measures, and upcoming planning or decisions related to long-lived infrastructure that need to be screened for potential climate change vulnerabilities. In work for others, we have explored use of questionnaires, and we note that the Department's Climate Change Adaptation Working Group has administered a questionnaire for screening installations for vulnerability. The literature notes that issues such as recall bias and staff turnover can limit effectiveness and accuracy and must be accounted for, especially related to identifying impacts that resulted from events that occurred in the more distant past. In our experience, we have noted very different responses from staff at similar, co-located facilities, emphasizing the importance of calibrating respondents to these surveys.

Publicly available data on past exposure is often of high quality and sufficient temporal scale to determine how local exposures have evolved over time. This information can be used to help interpret information about past damage and preparedness costs. Data on future exposure for screening purposes can be provided in the form of scenarios, statistical analysis of climate model archives (especially useful if specific impact thresholds can be identified), and narrative descriptions of the current state of scientific understanding of climate changes projected for a region or facility type (for example, coastal installations). This is one of the potential uses of the Climate Outlook developed for this project, although further research would be needed to evaluate the outlook for this purpose.

Integrating diverse types of information on installation vulnerability and future exposure is a distinct challenge. Multivariate indicators are increasingly popular as a tool to rank assets along multiple dimensions. Dashboards, such as those used by the Office of Management and Budget, use indicators to measure progress toward goals. Indicators are highly sensitive to the underlying assumptions of their construction, and the rankings they produce are not necessarily robust due to a variety of issues including data completeness and quality, variable selection, establishing the weights assigned to different variables, and quantification of categorical or non-numeric data. Studies focused on composite indicators have cited approaches and guidance that could address some of these issues; of particular relevance are potential approaches proposed by Balica et al. (2012), Cutter et al. (2010), Munda and Nardo (2005), OECD (2008), and Moss et al. (2001). Some basic good standards for indicators include the following:

- *Choose variables after considering their value as proxies and data quality*—There should be a logical connection between the variables and the facet of vulnerability being considered. Incorporating the views of users and stakeholders provides different points of view on the importance of the variables included in the indicator and also helps the users interpret the results. It is essential to evaluate data availability, quality, and consistency when selecting variables
- *Manage scales and units*—Converting raw data values into comparable scales (using percentages, per capita and density functions, etc.) is necessary to avoid problems inherent when mixing measurement units that span a number of statistical units, ranges, and scales
- *Ensure statistical robustness*—Applying statistical tests to measure multicollinearity and consistency/reliability of composite indicators is another essential practice. For example, statistical reliability analyses can help ensure internal consistency and determine whether the sub-indicators/proxies are sufficient and adequate to describe vulnerability for the group of sites being studied
- *Evaluate weighting schemes*—The issue of assigning weights to the variables included in an indicator needs to reflect both stakeholder and analytic perspectives. Weighting schemes are highly sensitive to underlying assumptions and can skew results, and analysts constructing indicators need to interact with users to ensure the indicator reflects the priorities of decision makers (Esty et al., 2005). Introducing methods to insert expert judgment in or allowing local decision makers to assign weights themselves can also be a useful feature
- *Include capacity for uncertainty characterization*—Capacity to analyze the implications of uncertainty in information about either site conditions (vulnerability) or future exposures is necessary. In particular, Balica et al. (2012) suggests that such capacity is useful for policy and decision makers engaged in risk management in terms of prioritizing investments and formulating adaptation plans
- *Design in transparency*—Transparency in all aspects of an indicator is important so that it is possible to trace changes in scores and relative ranking of installations or assets to particular updates, corrections, or changes in weights assigned to indicator components.

5.5 Tier 2: Installation vulnerability assessments

Vulnerability assessments should only be conducted at high-priority sites identified through some initial screening (as described above, or some equivalent method). Their purpose at DoD installations is to clarify whether potential problems identified in screening are serious enough to warrant further evaluation and action. These assessments analyze how potential changes in climate could lead to consequences that affect continued operations and mission attainment, in a sense converting information about climate change into metrics that are more meaningful for identification of future risks and measures to manage them. Installation-level assessments are not a purely analytic task, although rigorous evaluation and quantitative analysis are required if the information provided to decision makers is to be reliable. Rigor depends on adoption of good practices with respect to engagement, logical structure, organization, accurate measurement and information collection, and sound analysis methods. Vulnerability assessment also requires tapping existing expertise, information, and knowledge at a range of governance levels, including the sites themselves, the Service level (e.g., Army Installation Command, Installation Planning Office (IPO) at HQ Air Combat Command, Naval Facilities Engineering Command, or equivalent), and in some cases, offices within the Office of the Secretary of Defense (OSD) level.

To be most helpful to decision making, assessing vulnerability should be approached as an iterative process in two respects. First, in any given assessment, new information identified in a later step in the process may require circling back and repeating earlier steps, making adjustments and even changing priorities or discarding earlier analysis. This takes advantage of their potential to promote learning and capacity building. Second, vulnerability assessment needs to be integrated into ongoing condition assessment, planning, and budgeting processes. This requires consideration of the types of information that is currently used in planning infrastructure, ranges, or other assets, as well as the timing of these processes. Scoping (step 1 below) can be used to identify opportunities for integrating information from vulnerability assessments into ongoing planning and decision making, and if such openings are identified, the entire process will need to be organized to produce information in ways that meet process requirements. When installation managers realize that simple monitoring or assessment of factors that affect the vulnerability of the sites they steward can be incorporated into ongoing assessment of facility condition, or evaluation of costs and benefits of elements of design of proposed buildings or structures, organizations can become “self-learning” institutions that more effectively adapt to the changing climate and environment that surround and impact them.

Outcomes can include decisions related to monitoring and analysis of conditions and performance of systems identified as vulnerable and exposed, changes in management or use of infrastructure (managed or natural), and planning more significant changes in infrastructure or even location of mission. Being clear about the level of detail of information that is desired by users and can be produced is important. Vulnerability assessments do not typically provide detailed information on specifications or design of systems (for example, constructing a sea wall or modifying subsurface water conveyance systems), although they should identify the need for such planning. We found it is important to set participants’ expectations and to make them aware that detailed engineering, hydrologic, and other studies may be required if the assessment indicates such adaptation measures need to be explored.

5.5.1 Internally or externally led site assessments?

A key issue is who convenes and leads a site assessment: external subject matter experts or site personnel. The choice is not an absolute one but rather a continuum of approaches that provide leadership, participation, and expertise in different ways. Most commonly in an internally led assessment, installation staff assumes convening and leadership functions. Research on these processes indicates that it can be easier to establish a sense of ownership of assessment results and empowerment to act in processes that are internally led. But this need not be the case, especially if an external team executes a well-planned and implemented stakeholder engagement process as a component of the assessment.

It is less common for internally led assessments to be able to draw in all the required expertise from among existing staff. Assessment teams require expertise in planning, organizing, and conducting stakeholder engagements; analysis of site-specific data to evaluate vulnerability of assets (their susceptibility to damage) decomposed into sensitivity and adaptive capacity; identification and preparation of historical trends and projections of relevant climate and related environmental exposures; ability to adapt and employ models of infrastructure and other systems to estimate impacts under different assumptions; and experience in working with stakeholders to evaluate the mission significance of potential impacts. For an assessment to be entirely conducted by an internal team, existing installation personnel would need to have expertise in many of these areas plus access to pre-prepared climate information, impacts models, and stakeholder methods. Based on our experience, expertise existed in varying degrees at installations.

The use of external assessment teams can be resource intensive. Producing an assessment with outside experts to an installation can also be problematic if security issues exist, as is frequently the case at DoD installations. Thus, there are clear incentives to move beyond an externally driven approach. Unfortunately at present, knowledge about how to conduct vulnerability assessments and availability of structured, verified tools and data are limited. Climate projections in their raw form require customized tailoring to be relevant to installation personnel, who will also require training on how best to use projections in a way that appropriately accounts for uncertainty. Training would also need to include sensitization to potential perceptual biases that could result from commitment to current facilities and practices. These are all deficits that can be addressed over time.

Thus, we argue that, for now, DoD should continue to perform vulnerability assessments with external teams of experts involved at some level. This will continue to build experience, contribute to evaluation of methods and approaches, and aid in developing of opportunities to provide training and automated tools. The learning that will take place as a result of the interactions among the external experts and local personnel will help to improve the overall process of conducting vulnerability assessments and make it possible to shift responsibility for ongoing assessment to installation staff as part of extant management and planning processes.

We now turn to presenting a concept for an installation-level process that could provide a useful starting point for planning installation-level assessments. We describe the process so that it can be guided either internally or externally.

5.5.2 Framework for installation-level vulnerability assessments

As discussed in Section 2 and above, we reviewed a wide range of theoretical and applied research on different methods and frameworks. The potential vulnerability assessment process is pictured in

Figure 66 and summarized as a set of five steps or tasks in Box 2.

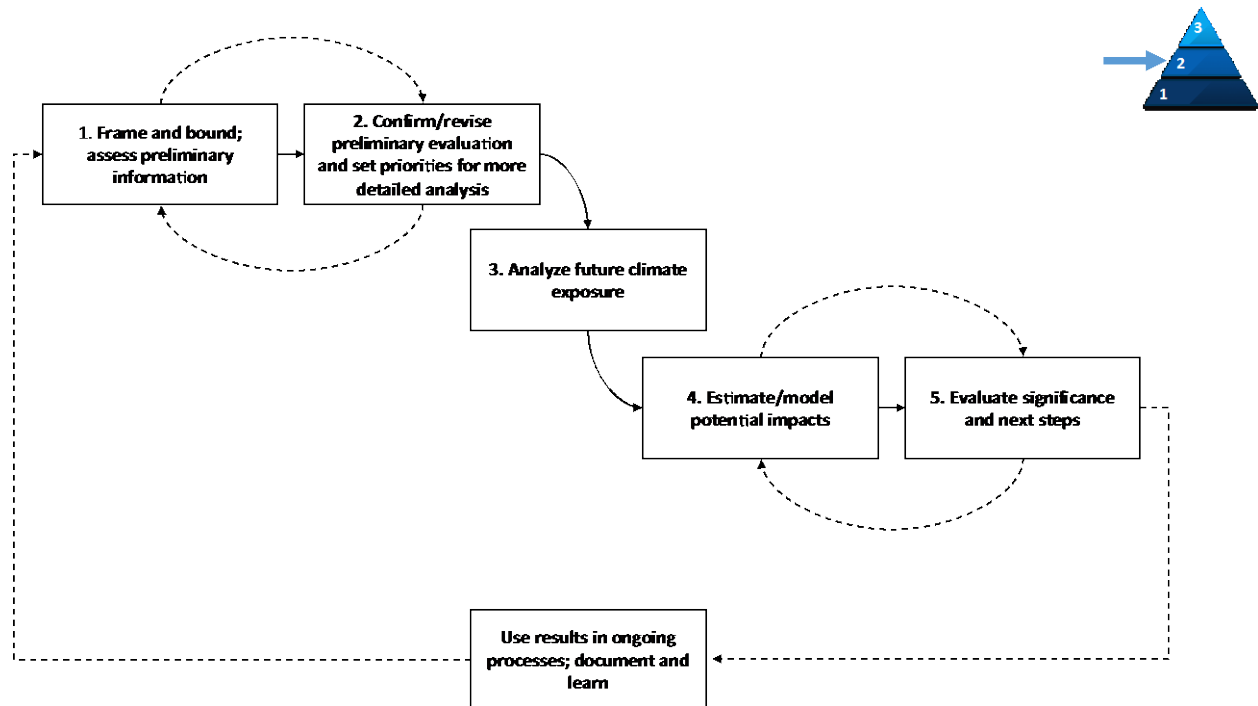


Figure 66. Proposed iterative process to assess vulnerabilities for DoD installations

Box 2: Potential Process for DoD Installation Assessments

1. Frame the assessment: Establish purpose, set system boundaries, and collect/analyze preliminary information
2. Confirm/revise preliminary evaluation and set priorities for more detailed analysis
3. Analyze future climate exposure
4. Estimate/model potential impacts
5. Evaluate significance and next steps

Conduct assessments to support ongoing planning, budgeting, and decision-making processes. Document results to provide a baseline for future assessments.

Step 1: Frame the assessment: Establish purpose, set system boundaries, and collect/analyze preliminary information—Framing the assessment is an iterative process that involves clarifying who will use the results and how, determining what aspects of the installation (and surrounding community) will be included, and analyzing existing information to contribute to making these decisions. Framing also establishes the authority under which the assessment will be conducted, which is necessary to empower (or in some cases require) participation and release of essential information.

Clarifying how an assessment will be used, and by whom, makes it possible to establish information needs and an appropriate level of detail for subsequent analyses. An assessment may be used by installation personnel who intend to incorporate the information in an upcoming master planning or system design process. This would mean that, among other outputs, the assessment would need to produce information about potential damages for planned infrastructure or load requirements for a system. Another potential user group includes individuals at the Service or OSD level who are responsible for providing oversight of the installation. These users might be interested in information about overall operating costs or the ability of an installation to meet training or other targets under different future scenarios. It will likely be the case for any particular assessment that multiple governance levels will be the audience.

Bounding the system is essential because of the complexity of most installations. A large number of natural and built systems are involved in supporting many diverse activities and missions. It is not possible to investigate all aspects of a site. Bounding involves making some basic decisions about which infrastructure or operations will be evaluated, gauging the existing information base, and framing initial questions and ideas about vulnerability for further exploration with installation personnel. Bounding is important for assembling the assessment team, including stakeholders and subject matter experts. Finally, it also enables the team to identify needs for climate information, i.e., which specific variables or processes are important to the priority systems that have been identified.

Deciding whether an assessment includes systems or activities that depend on external service providers and the surrounding community and environment determines whether external

stakeholders need to be involved in the process. Dependencies include provision of required inputs such as electricity, water, sewage treatment, and other basic utilities; agreements regarding operations and “encroachments” that influence operations at the site and that could require modification to those agreements; and, of course, the communities in which the people working at the site live. When dependencies upon external systems are deemed so important that meaningful conclusions cannot be reached without including these external systems, engagement of external stakeholders will be required. This project focused on aspects of the assessment process that involved installation personnel and Service and OSD participants. It does not include conclusions related to approaches for engaging external stakeholders other than to note that involving external groups in an installation vulnerability assessment needs to be embedded within the site’s overall efforts to manage relationships with the community.

Initial collection and analysis of available information need to go hand in hand with initial decisions about framing and bounding the assessment. Having the analysis team adequately “do its homework” at this step sets the stage for a successful assessment. Initial information collection can establish mission dependencies; condition of infrastructure or ecosystems; and current capacity for preventing, managing, or recovering from damages or disruptions. This information can be used in preliminary analyses that employ a variety of statistical, geographical information system, indicator, and other methods that provide a starting point for discussions with managers, planners, and schedulers. It is the foundation for preparation of read-ahead materials or presentations used to kick off the next phase of the process.

Another useful goal of the framing step is to identify upcoming decisions that would benefit from information from the assessment process. Especially important are decisions related to recapitalization and construction of infrastructure; changes in operating margins or conditions; and responses to changing trends in outages, damage, service calls, cancellations, and operating restrictions. Finally, initial information collection can also focus on identifying important previous climate exposures, including notable events such as major storms, as well as changes in frequency or severity of ongoing events such as nuisance or minor flooding.

Information sources include master plans, encroachment plans, other required reports or plans (for example, related to natural resources management on the installation), geographic information system data, mission dependence databases, real property databases, Service records or contracts, summary reports of damages/recovery times/adaptations made from past extreme climate events, vulnerability assessments of external systems, and others.

The techniques used to convene the assessment team, bound the assessment, and gather preliminary information will be influenced by whether the assessment is internally or externally conducted and by the existing mental models and level of interest of installation staff. If personnel perceive that climate conditions are changing in ways that affect the installation (whether those changes are human-induced or the result of natural climate cycles), a wider range of methods that include participatory processes can be used. Otherwise, initial approaches may need to focus on “extracting” information from personnel with knowledge of installation conditions.

Webinars, structured interviews of key personnel, questionnaires, data calls, periodic meetings, and other techniques will enable the assessment team to make decisions about framing and provide producers with opportunities to obtain initial information.

Step 2: Confirm/revise preliminary evaluation and set priorities for more detailed analysis — This step of the process has a number of purposes related to updating and refining understanding of installation baseline conditions and making decisions about the next steps of the assessment process. These purposes include obtaining feedback on preliminary analysis prepared in step 1, more detailed appraisal of conditions, collecting additional information, and agreeing on expected products and next steps. Users often request presentations on potential changes in climate; it can be valuable to present basic information, understand the initial mental models of users regarding climate change, and develop a more precise understanding of what aspects of climate will require further analysis. Interactions at this stage also provide an opportunity for operators and managers of different systems or activities or at different governance levels to exchange information and develop a shared understanding of assessment priorities. The importance of Step 1 preparations in making interactions at this stage successful cannot be overstated.

Information collection at this stage improves understanding of baseline conditions, including changes in infrastructure location or use, current condition (which can differ from that depicted in existing reports or databases), past damages from storms or other climate conditions, management and emergency preparedness measures, and planned future expansion or recapitalization. In our experience (which occurred during site visits), information collected during step 2 was crucial for correcting misimpressions based on existing sources that occasionally reflected conditions that had since been ameliorated by changes in management or infrastructure.

This phase can occur through one or more site visits, if expertise and analysis are provided by an external team, or through a series of meetings over one or more days. The complexity and size of the installation will also be a factor in determining how best to conduct site appraisal. A longer comprehensive session or a sequence of shorter meetings that focus on one aspect of the site at time can be used. Factors that affect how best to organize step 2 discussions include preferences of stakeholders, proximity of the site to researchers and analysts, budget, and other practical factors. See Section 5.7.1 for a more detailed discussion of engagement methods appropriate to different assessment circumstances.

Crucial outcomes are building trust among participants, preparing a draft list of identified vulnerabilities, and agreeing on a number of issues related to subsequent steps including the modeling and analysis that may be required, outputs of the next stages of analysis, and how the outputs will be used in additional engagement processes such as scenario planning or charrettes to assess the significance of potential impacts.

Step 3: Analyze future climate exposure—Steps 1 and 2 have by this point resulted in an improved understanding of baseline conditions, priorities for analysis, and clarification of needs for information about future climate exposures. This step adds the crucial ingredient of providing information about future exposure needed to project potential future impacts. Our case studies

demonstrate the need for climate information that goes beyond the standard climate model outputs of temperature and precipitation and includes phenomena such as fire risk, wind speeds, air quality, runoff, temporary surface flooding, erosion, and changes in tropical/extratropical storm frequency and intensity.

Analysis of exposures needs to employ a wide range of techniques and information sources. It may be necessary to link climate models with hydrological, atmospheric chemistry, storm surge, and other models to provide this information, especially if impacts modeling will be included in the assessment process. Further development of approaches for providing information on specific types of impact-relevant exposures is a research need to be addressed by the climate science community. Additional technical guidance and training are also needed for users, including guidance on needs for and sources of high-resolution climate information and training on the use of scenarios. Information on exposure must capture uncertainty in climate science through various methods, including the use of bounding scenarios and statistical analysis of large climate model ensemble datasets. No one approach for characterizing future exposure will be adequate given the diversity of systems and information needs that installation vulnerability assessments will address.

In Section 3, we introduced one of the methods (a regional climate change outlook) we explored for providing climate information for the purposes of screening and conducting installation vulnerability assessments. The outlook developed for the mid-Atlantic region provides data and interpretive analysis, including confidence levels and discussion of sources of additional information and data. Such interpretation is key, especially considering model and scenario differences and highly varied levels of confidence across variables and regions. Preparation of the outlook entailed use of a variety of techniques to explore some of the climate phenomena that were identified through steps 1 and 2 across the case studies. Continuing to test its use in vulnerability assessments is another research opportunity.

Step 4: Estimate/model potential impacts—Evaluation of potential significance of climate change for missions and infrastructure requires information on how projected changes in exposure will interact with site vulnerabilities to produce impacts on mission-critical infrastructure, systems, and activities. The approach used to develop this information will depend on the level of detail required by users and the type of decision they are confronting—from initiating more careful monitoring to beginning to plan a specific adaptation measure.

Especially in initial rounds of assessment when a primary outcome is scoping potential issues that may require further analysis, expert judgment and qualitative methods are likely to be important. For example, an assessment team may rely on research studies or reports that have already been completed to obtain information on impacts on similar types of assets. They will use scenarios or other information on the future climate to provide overall context about the future and adapt the insights of these previous studies to estimate impacts on their installation. A number of the methods and techniques we developed and tested (as described in Section 2) fit into this category of approaches.

As assessments are repeated at an installation (either as a stand-alone activity or in an adaptive management process, budgeting, or planning cycle), more detailed information may be required. Thus, it may be necessary to explore the impacts of changes in climate (exposures) on

infrastructure or environmental systems using quantitative models. Climate change impacts modeling is still in its early stages (at least when compared to modeling of the Earth system) and is focused on a very wide range of systems including ecosystems, natural resources, energy and water resources, urban infrastructure, and others that provide inputs required for an installation to achieve its missions. Selecting impacts models for use in an assessment depends on the needs of participants and the resources and time available. Approaches include application of geographic information system or large, complex numerical models of natural resources or infrastructure systems at high levels of resolution. For example, to determine whether a change in climate will have significance for the way an installation manages its training lands, analysts may wish to use models that assess potential vegetation using climate scenarios as inputs to assess how ecosystems and species ranges could shift under different scenarios. Assessing implications of climate change for energy systems could involve using building energy demand models to assess changes in peak loads and requirements for distribution systems. Understanding whether surface flooding will increase and lead to more damage to critical infrastructure may benefit from modeling of hydrologic and subsurface water conveyance using climate model data.

Scenarios of future exposure and information from resources such as the Climate Outlook prepared for this project are a necessary source of information for this step. The type of climate information required depends on the methods being employed. Challenges include matching content and level of detail (spatial resolution, time step, types of variables, etc.) and representing uncertainty, either through methods such as adoption of “bounding scenarios” that frame high and low estimates of change, or more formal quantitative methods if impacts modeling is employed. Another challenge related to characterizing potential futures involves projecting changes to the installations, sites, and surrounding communities in addition to changing climate conditions. Change in mission requirements, technology, and infrastructure onsite, as well as shifting demographic conditions (density, location, age structure, etc.) and economic development pathways is relatively certain and will have major impacts on vulnerability, increasing it if climate risks are ignored in making related decisions. The need to identify or develop this sort of information is another argument for building vulnerability assessments into existing capital and master planning cycles that are designed to consider how changes in mission requirements translate to needs for reconfiguration, expansion, or closure of installations.

In Section 5.7, we discuss further research needed to make estimation and modeling of impacts more efficient and appropriate for use in vulnerability assessments. We argue that a systematic approach is needed to catalog and evaluate the use of impacts models in assessing vulnerabilities at various types of installations at different locations across the country.

Step 5: Evaluate significance and next steps—The significance of potential impacts identified by the process up to this point will need to be determined through discussion with stakeholders at the relevant governance levels. This step is closely related to the previous process of estimating and evaluating impacts. We highlight it as a distinct activity to clarify that impacts modeling in and of itself is not sufficient to understand vulnerability and whether future exposures will create risks or problems. An example might be that, having determined that the number of days suitable for controlled burning will fall below requirements to maintain good ecosystem health, engagement with installation and Service-level personnel would be needed to discuss the implications, explore adaptation options, and decide on the next steps. Another example that will likely need to be considered at some coastal installations concerns an increase in frequency of

nuisance or minor flooding events, which will affect maintenance and emergency preparedness costs as well as mission continuity.

This step may assist in answering a number of important questions, including the following:

- At what point in the future would changing occurrence or severity of such events disrupt schedules, increase costs for cleanup, and interrupt training in ways that make current workarounds insufficient?
- What would be the implications of more frequent interruptions of flights or exercises?
- What would make the ecosystem incapable of supporting training—increasingly dry and hot conditions?
- How should the Department “design in” adaptations to sea level rise?
- In short, when will a site be spending more resources on workarounds than is feasible, unless decision makers plan for resilience through adaptation?
- Would it be necessary over time, given projections and a determination that adaptation options were insufficient, for the Service to relocate some training activities to other installations in the longer term?

Choice of methods to use to engage relevant personnel at this stage of the process must be driven by the number of systems and related stakeholders affected and the level of perceived importance of the impacts. Approaches can include one-on-one interactions, focus groups, design charrettes, scenario-building, or any combination of these activities. These activities can add value by pointing to needs for changes that will benefit future mission fulfillment at the site bringing different governance levels together to exchange information and perspectives.

A variety of next steps have been mentioned as outcomes of installation vulnerability assessments, including monitoring, changes in management of existing infrastructure, or moving to the next tier, adaptation design.

Conduct Assessments to Support Ongoing Planning, Budgeting, and Decision-making Processes

Potential climate change impacts can affect many ongoing decisions, both near and long term, but decisions about long-lived capital assets provide the most natural target for decision support. These include decisions related to siting and specifications for buildings, road networks, infrastructure systems such as electricity and water, and natural resources such as training and recreation areas. These decisions require substantial investments, are planned far in advance, and are long lived, which are characteristics that match well with information from vulnerability assessments.

Vulnerability assessments should be planned to provide information used in analyzing and making such decisions. If step 1 (framing) was successful in establishing audience/use and identifying upcoming decisions and relevant decision-making processes, the step will yield information on factors and criteria that site managers, planners, and officials currently use in

making decisions. This includes information related to potential impacts on costs, reliability, encroachments, compliance with health and safety, environmental regulations, and sustainability. Matching results to needs enables program planners, budget analysts, and others to more easily use information produced by the assessment.

See Section 5.8 for additional conclusions about integrating climate vulnerability considerations into decision making.

Document Results to Provide a Baseline for Future Assessments

Careful documentation of assessment results provides a foundation for any subsequent assessments that may be conducted at a site. Having a baseline of prior results facilitates evaluating how conditions are changing as a result of either change in climate conditions or in response to adaptation measures that are implemented. Documentation and evaluation of the process fills another role. Climate vulnerability assessments are still a new activity, and improvements in the efficiency and usefulness of the process are needed. Facilitating revisions to existing frameworks and innovation to develop new approaches—such as self-administered assessments using online decision-support systems—will require agencies to document the processes and results used on different sites in a systematic and comparable fashion. Development of a protocol to evaluate, learn from, and revise assessment processes is in itself an important research task.

Questions related to the effectiveness of methods, participatory and engagement processes, and outcomes need to be developed and answered, for example:

- Were bounding and framing effective in prioritizing without excluding consequential vulnerabilities?
- Did modeling and evaluation of exposure and potential impacts provide information that participants found relevant and useful for understanding the potential significance of changes in climate to their installation's mission attainment?
- Did engagement and communication facilitate learning by participants?
- Was information incorporated into ongoing processes, and if so, were decision outcomes affected?

Possible components of systematic evaluation include careful documentation of the process used in each case, questionnaires and interviews with participants, and data collection to compare projected impacts with those that occurred. It would be advisable to develop a template for documenting and evaluating assessment processes at an interagency level, to facilitate learning and improvements in methods available.

5.6 Tier 3: Adaptation design

For completeness in describing the elements of the tiered framework we introduced in Section 5.3, we briefly discuss the purpose and character of Tier 3. This research project did not

address this element of the framework or test associated methods. Our discussion here is merely intended to distinguish this level of analysis from installation vulnerability assessments (Tier 2) and explain why it is needed (Linkov et al., 2004; USACE 2006).

Tier 3 focuses on a detailed evaluation of various technical or management adaptation options to address specific vulnerabilities identified in the Tier 2 assessment. For example, if the Tier 2 analysis reveals increased vulnerabilities resulting from changes in water height associated with the 100-year flood under a number of scenarios, then this range of flood height increases would be used in conjunction with traditional engineering analysis to evaluate the effectiveness of different floodwall designs and heights. Tier 3 analyses may extend the boundaries to include economic externalities and to focus on detailed scenarios. Tier 3 may develop an integrated adaptive management strategy or determine a range of options for modifying existing built infrastructure, siting of new construction, or developing new maintenance and repair procedures to protect against specific climate change impacts.

Infrastructure is often a critical focus of adaptation design. Buildings and other infrastructure are an obvious category of elements that require substantial investments and planning: infrastructure and associated systems are planned far in advance of construction, long-lived, necessary for the agency missions, and potentially vulnerable to climate change—but, also, potentially resilient in the face of climate change. During adaptation planning, vulnerability to climate change is considered along with other risk factors so that optimal decisions can be made about future capabilities, missions, configurations, and operations. Moreover, decisions about infrastructure are iterative; that is, once a factor (for example, sea level rise) that needs to be considered is included in planning, updates to planning can include updates to the vulnerability assessment. In many cases, incorporating climate risk into ongoing design and planning may require developing “a new paradigm for engineering practice” to account for uncertainties in information about the risks and potential costs of changes to a project (ASCE, 2015).

As planners and managers go through the process of adaptation design, practical considerations including siting, design criteria, and compatibility with other requirements such as sustainability will need to be considered at a detailed, decision-making level. To evaluate feasibility, options, and mission-readiness, planners and designers may conduct detailed engineering studies, analyze existing arrangements (contracts, agreements with utilities or communities, overall configuration of the site, training schedules, etc.) to see if they need to be revised, and look for opportunities to improve both mission capabilities and operations.

5.7 A typology of techniques and methods for vulnerability assessment

In conducting our case studies, synthesizing results, and anticipating approaches needed to conduct future vulnerability assessments, we identified three sets of methods. We offer this typology as a possible approach for cataloging and disseminating methods so that they are more useful and accessible. We note that organizing approaches in this fashion and encouraging a more systematic approach to developing them will improve the methods available. The three categories of methods are as follows:

- *Engagement*—Engage personnel with detailed knowledge of the mission and operation of the sites to (1) provide the information about their condition and characteristics and (2) aid in interpreting the significance of identified impacts for their management tasks
- *Climate exposure*—Prepare tailored information on exposures, drawing on several sources of information including observations, projections, and scenarios of climate conditions, downscaling, and modeling of hydrology and other related environmental conditions
- *Future impacts*—Project impacts using diverse quantitative and qualitative methods.

Different methods will be required for the different tiers (levels of detail) of the assessment framework we describe in this report. Because the focus on this report is on Tier 2, many of the methods described here are most relevant to installation-level assessments. But a well-structured and implemented screening process will need methods in all three categories to evaluate whether installations' conditions will interact with future exposures to create risks that require further assessment, and to produce information that is relevant to those who need to make such decisions.

Table 8 crosswalks the methods to the steps in our draft assessment framework. In the sections that follow, we briefly characterize these methods and suggest resources for further information.

The table demonstrates how the cross-cutting categories of methods (columns in the table) are used throughout the steps of the analysis (rows) described in this paper. For example, the vulnerability assessment team should design engagement methods (such as focus groups or charrettes) to help in reaching a mutual understanding of the requirement for a vulnerability assessment and its use for the site (the first row) and in establishing boundaries for the vulnerability assessment (second row). Also important for bounding the assessment would be using exposure characterization and results from prior impacts analysis (for example, in community or regional area assessments) to determine how wide the boundaries should be—that is, what operations will be affected and how impacts could have indirect as well as direct effects.

Table 8. Methods Used in Draft Vulnerability Assessment Framework

	Engagement Methods	Exposure Characterization Methods	Impacts Analysis and Modeling Methods
Bounding/framing	✓	✓	✓
Confirming initial site and setting priorities	✓		
Tailoring information on exposure		✓	
Estimating impacts		✓	✓
Determining significance and next steps	✓	✓	✓
Supporting ongoing decision making	✓		
Documenting and evaluating	✓	✓	✓

5.7.1 Engagement

These methods are designed to involve stakeholders in the assessment process, through initial and continuing interaction, to determine priority impacts and evaluate their significance for a site. Research has repeatedly shown that agreement among participants in such a process is necessary to produce knowledge recognized as useful to decision makers. This is sometimes characterized as an information problem (for example, Oreskes and Conway, 2011), a communication problem (for example, Moser and Dilling, 2007), a framing problem (for example, Marshall, 2014), an instance of the science-policy gap (for example, Dilling and Lemos, 2011; Rogers and Gullett, 2010), or as a problem inherent in the climate issue (for example, Jamieson, 2014; Rayner and Prins, 2007). Likely all of these factors play a role in the willingness of installation personnel to engage.

Engagement methods must be selected for specific situations. Relevant factors include (1) whether the assessment is internally or externally led; (2) whether climate change is relevant to site personnel (in other words, they see a connection between climate change and the future operation of the site), and, relatedly; (3) whether the potential exists to establish interest and help managers incorporate changing vulnerability to climate change into ongoing site monitoring or decision making. Engagement methods are useful for creating opportunities for stakeholders at any of the governance levels considered in the study (OSD, Service, and site) to collect, exchange, and organize disparate information, and to evaluate the significance of projected

changes for current and future plans. Effective engagement helps create “ownership” of conclusions and can increase the likelihood of follow-up activities.

Data collection methods are needed in all cases, but in some circumstances (when perceived relevance is lacking), extracting data and information may be the primary objective. As described previously, appraising site conditions requires information on current impacts, condition, mission importance, climate observations, thresholds, and upcoming investment decisions.

For the purposes of engaging installation stakeholders, the research literature provides how-to guidance at two levels, and specific tactics are provided by myriad business and organizational experts.

First, the mode of engagement should be considered. Meadow et al. (2015), assessing methods for coproduction of knowledge, use Biggs’ (1989) structure of four modes:

- *Contractual*—Where researchers are testing new technologies or knowledge and stakeholders are primarily passive recipients
- *Consultative*—Where stakeholders and researchers consult to diagnose and solve a problem, but stakeholder views are primarily filtered through a third party
- *Collaborative*—Where stakeholders and researchers directly partner to work on a problem
- *Collegial*—Where the goal is to build local stakeholder capacity to solve problems.

Second, specific approaches for conducting engagement are analyzed by Meadow et al. (2015) include

- Action Research (a collegial mode)
- Transdisciplinarity (a collegial mode)
- Rapid Assessment Process (consultative or collaborative mode)
- Participatory Integrated Assessment (consultative, collaborative, or collegial mode)
- Boundary Organizations (consultative, collaborative, or collegial mode).

Other, related schema can be found in Lim et al. (2005). The intensity of involvement depends upon the length of the task (from a one-time meeting to a continuous collaboration), the context (resource constraints, importance and size of the task, etc.) and the desired mode (collaboration and collegiality demanding more time and commitment than other modes).

At the tactical level, engagement with stakeholders can be via (1) meetings, (2) webinars or other forms of training, (3) data calls and geographic information system maps/discussions, (4) one-on-one interactions, (5) focus groups, (6) design charrettes, (7) scenario-building, (8)

workshops, or (9) any combination of the above. The degree of requested stakeholder effort should be matched to expected degree of influence on decisions or some other incentive, and there is a need to establish roles, competencies, legitimacy, and trust in any engagement process (Cash et al. 2006).

Here, we consolidate some key conclusions about engagement methods based on our experiences with engagement of site personnel.

5.7.1.1 The need for a wide range of engagement methods

Given the potential range of concern, it is essential that those conducting installation-level assessments have access to different types of engagement methods. Where climate change is a priority, these methods can include interactive approaches that encourage information exchange and brainstorming of adaptation options. Where it is not, methods need to focus on extracting site data/information and effective reporting of results. Another engagement challenge is communicating climate science effectively. Especially important are approaches to convey confidence in well-established information and enable participants to work with uncertain future projections. Such methods use scenarios, ranges, probabilistic information, and other approaches.

5.7.1.2 Factors promoting participation

Any of the tiers of vulnerability assessment require a “champion” to ensure that key personnel participate and that results will be used. This leadership can come from a headquarters office or from a person in a position of authority. At the installations, we observed that information collection and salience were greatly affected by the degree to which an accepted authority indicated the importance of participation in the process. Engagement was more successful in collecting information and contributing to learning at installations where operations and maintenance staff held their positions for longer periods. There was more institutional memory of the effects of past extreme events, making it possible to verify and correct information collected from existing reports or databases. Candid participation of personnel can be encouraged by not attributing comments to specific participants. This can be especially important when attempting to identify problems that could make a system more sensitive to climate change, and in evaluating characteristics of adaptive capacity related to leadership or openness to climate change. An additional factor that would promote participation in and use of information from vulnerability assessments is training personnel to understand the assessment process and strengths and weaknesses of resulting information.

5.7.1.3 Use of extant sources of information

For both screening and installation-level assessment research, we attempted to use extant information systems and data on asset condition, mission importance metrics, past damages, planned expansion or recapitalization, and other factors that would provide insight into sensitivity or adaptive capacity, thus reducing the information collection burden on staff. Our experience was that the Department-, Office-, or Service-level databases (for example, mission importance ranking, real property databases) and available reports (for example, installation master plan, Integrated Natural Resources Management Plan) were of limited utility due to

incomplete or inaccurate data. Such data required verification with site personnel. For example, extant reports on conditions at Fort Bragg highlighted considerable erosion problems that could potentially be exacerbated by future extreme weather events. During discussions with personnel at the installation however, we learned that changes in ecosystem management undertaken to protect endangered species had also resulted in reduced fire dangers on training areas.

Records maintained by the public works department and its natural resources management office, health center, and operations center can also be valuable. This information can include training cancellations, number of heat stress incidents, damages arising from specific storms, frequency of deployment of preparedness or response measures, clean-up costs, and the like. In our case studies, we attempted to gather such information and correlate observed damages with meteorological records of routine (but still damaging) incidents or more severe but rare events. Unfortunately, we discovered, at least in our small sample of installations, that while basic information about such impacts was recorded, for example, about the dates on which a training area might be closed, information required to attribute the cause of the impact was not—for example, was the training area closed due to flooding from a combination of high tide and storm surge, or from a temporary encroachment? Some relatively minor changes in procedure could lead to collection of such information, which over time would facilitate improving resilience.

5.7.1.4 Challenges in assessing adaptive capacity

Assessment of adaptive capacity was often challenging. Adaptive capacity depends on many factors that vary in importance from case to case. Availability of financial resources, trained personnel, clear emergency preparedness plans, and other factors can be assessed in a straightforward fashion. Other facets, such as organizational culture, leadership, or informal budgetary flexibility to respond to the unexpected, are more subjective and difficult to assess and verify, and sensitive to discuss.

5.7.2 Methods for assessing and communicating potential future climate exposure

The purpose of this section is to describe approaches needed to analyze and communicate information on climate exposure. We discuss the importance of evaluating methods and tailoring climate information for specific uses.

Many sources of climate information can be useful in vulnerability assessments. We mention a few prominent ones that are components of published assessments or that compile links and information about many other climate information tools. The Third U.S. National Climate Assessment produced and disseminated several climate scenarios and information products (NCA, 2011; Kunkel et al., in press). A series of regional reports and visualizations including more than 700 pages of material and several hundred graphics on past trends and future projections was prepared and made available for the eight National Climate Assessment regions. These, along with other Federal global change data, information, and products can be traced in an open-source, web-based resource called the Global Change Information System (data.globalchange.gov). Projections for the Third U.S. National Climate Assessment used data from global climate models (GCMs), dynamical downscaling (regional climate models with higher resolution than global regions), and statistical downscaling of both observations and GCM

output. In addition, the National Oceanic and Atmospheric Administration and other agencies have collaborated to produce a “U.S. Climate Resilience Toolkit” that includes links to several data sources such as “Climate Explorer,” “Climate Inspector,” and “Climate Wizard.” Evaluation of the quality of scientific information, its appropriateness for the intended uses, and the effectiveness of decision support systems to enable users to apply the information is required.

As described in greater detail in Section 2, to prepare information on exposure for use in our vulnerability assessments, we adopted an approach used in the 2007 Intergovernmental Panel on Climate Change report to evaluate and make qualitative likelihood statements regarding changes in regional-scale precipitation (Christensen et al., 2007). A similar approach was used in the Third U.S. National Climate Assessment to prepare a set of regional climate change descriptions for the eight National Climate Assessment regions. In this study, our objective was to test the regional Climate Outlook approach to evaluate whether a single, common source of information could be developed through interaction with users to provide focused information on future climate exposure for installation-level assessments in the region.

Evaluation of the Climate Outlook is ongoing, but evidence in the literature (PROVIA, 2013) indicates that narrative descriptions of past and future climate conditions are effective at communicating with stakeholders. They make complex, quantitative data easier to understand, can clarify the sources and significance of disagreement in projections across different models or methods, and provide a subjective evaluation of confidence for use of the information in decision making.

As a component of evaluation, this project initiated a study to investigate the effectiveness of expressing uncertain data using choropleth maps to represent future changes in annual mean temperature, contributing empirical evidence on the effectiveness of communicating uncertainty in climate projections. We implemented a basic research design driven by theories from psychology (perception and judgment and decision making) that builds on the results of previous empirical studies on information visualization. Our objective was to see how these communication techniques influence individual choice and confidence. Successful communication of uncertainty should only have a limited impact on choice (unless the uncertainty renders the information useless), and strong impact on confidence. That is, the visual display should allow for choices based on optimizing the appropriate information and give an appropriate sense of confidence one should have in their choice. We used a national online panel to recruit participants and presented them with a hypothetical choice task that required correctly identifying a location based on the data portrayed in the map, and then reporting on their level of confidence in their choice. Initial results are promising (S. Broomell, Personal Communication) and further research is needed.

Finally, we note that while standardized information from the outlook was relevant to some of the issues that arose on the installations, tailored information developed specifically for each site was also needed. This information often used local observational records or focused analysis on interactions between global/regional trends (for example, sea level rise) and local conditions that would create anomalies. If a Climate Outlook for installations in a region (or of a certain type) were viewed as a “living document” and new analyses conducted for individual installations were incorporated and included information on methods, the outlook could become increasingly useful.

5.7.2.1 Tailoring climate information for impacts modeling

The process of assessing vulnerabilities and potential impacts requires the tailoring of climate information into specific impact-relevant climate variables that are not the usual focus of climate model analysis. Example impact-relevant variables identified through interaction with stakeholders at our case study installations included WBGT, heating and cooling degree days, fire potential, changes in the frequency of severe thunderstorms, and surface wind speeds.

Various approaches are available to map the raw climate model output onto changes in the exposure variables of interest. These include techniques such as extreme value statistics (that is, return periods) and indexes, such as the Keetch-Byram Drought Index, which measures fire potential. Different sources of tailored information and analysis methods have different biases, strengths, and weaknesses for application. Weather generators and other approaches such as the “delta method” (in which projected changes are added to observed climate data) are widely used and appropriate for some applications. It is not always the case that the highest spatial resolution models are the best source of information. In some cases, additional models will be required. For example, we used the Finite Volume Community Ocean Model to study coastal estuarine flooding/drying processes.

5.7.3 Estimating and modeling future impacts

Vulnerability assessments require a wide range of methods for analyzing how current and future climate conditions could interact with site vulnerabilities to produce impacts and threaten facilities and mission attainment. As noted above, these methods can vary from qualitative, expert-judgment-based approaches that use results from previous studies and assessments to calibrate effects of potential future climate to high resolution, complex quantitative impacts models. This section introduces the need for an approach for organizing and analyzing the suitability of available methods for impacts analysis in the context of vulnerability assessments for DoD sites (see PROVIA, 2013, for a description of some of the methods relevant for national to community-scale vulnerability assessments; we are not aware of a methods compilation for infrastructure or installation-oriented assessments and recommend that such a compilation be developed as a resource for those conducting assessments).

Analysis of observed impacts involves detecting a change in an impact variable of interest and examining whether there is a statistical relationship with changes in weather or climate. “Impact variables” can vary widely from quasi-climate variables such as heating or cooling degree days and flood return periods to variables related to resources or infrastructure management, such as water reservoir depth, storm damage, electric grid capacity exceedance, or operating costs. In analyzing trends in these variables, it is essential to employ rigorous statistical methods and to consider potential drivers of change beyond climate events, as multiple causative factors can be changing simultaneously.

Projection of impacts focuses on a similar set of variables but adds the complication of using information on potential future climate conditions, from quantitative climate scenarios to more qualitative descriptions of changes in impact-relevant climate exposures. In some cases, quantitative analysis of performance of systems or effects on ecosystems and other “natural assets” will be possible using a variety of impacts models that address sectors such as water

resources, energy supply and use, ecosystem composition and condition, transportation, and training activities. Additional uncertainties on top of those inherent in projecting future climate are involved when adding environmental process (e.g. hydrology) and impact (e.g., damage curves) models to the analysis. These uncertainties result from limited understanding of environmental processes, model incompleteness, uncertain parameterizations, and other factors. Little work has been done on matching the impact model input variable requirements and their spatial and temporal constraints to the available climate information.

Models used in ongoing management and planning can be used to project a wide range of system functions and conditions, for example, runoff and potential flooding, energy demand, and stresses on building or transportation system components. Modeling the impacts of climate change on resource management and infrastructure systems is inherently complex, and, in deciding to undertake impacts modeling, managers should explore application of models already in use, such as the Federal Energy Decision System model, which is used in assessing temperature-sensitive energy loads for different building types (see Scott et al., 2008, for an application focused in interactions of changing climate conditions and energy efficiency programs). Relying on existing system models to evaluate impacts is useful when evaluating the performance of those systems under those climate scenarios. For example, an existing transportation network model may consider how changes in extreme precipitation lead to increased disruptions and travel times.

Many examples of these kinds of methods are found in the literature and in technical reports. For example, Filadelfo et al. (2012) use projected temperature changes to 2040 relative to the 1995-2011 17-year mean to approximate the change in installation energy demand using heating and cooling degree days. The relationship between the degree days and the energy used were based on regression analysis of historical system performance. The authors downscale large regional-scale climate change projections for the immediate areas of several military installations, including Fort Bragg and Naval Air Station Norfolk. Another example is described in Domingo et al. (2010), where a Mike Flood model is developed for a coastal community and then used to simulate flooding from a derived extreme sea level event. Instead of focusing on modeling the impacts themselves, other methods focus on evaluating the anticipated impacts from climate change under different scenarios. For example, Lambert et al. (2011) assess the impacts on transportation infrastructure via a decision model to help prioritize elements of a long-range plan in the area around Hampton Roads, Virginia.

“Decision scaling” methods, described by Brown and Wilby (2012), are approaches that, for a given system performance measure or objective, use a stress test to evaluate the performance of a system under a range of nonclimatic and climatic stresses. They then evaluate climate model information to determine whether hazard thresholds become more frequent and problematic over time. These methods have the potential to preclude climate impact assessments if, for example, a stress test is performed and no risks emerge under a wide range of plausible climates. We tested a diverse set of methods in our research, including the following:

- Statistical analysis of climatology to evaluate the changing spatial pattern of flooding return periods

- Using a coastal storm surge model to evaluate the spatial impact of future storms under different sea level rise projections
- Analysis of the interdependency of systems at a site using network analysis and statistics
- Analysis of changing fire risk to determine how it may impact the availability of burn days necessary to manage an ecosystem
- Evaluation of possible changes in energy use through analysis of changing heating and cooling degree days.

Going forward, it would be beneficial to organize resources for impacts modeling methods at DoD sites along sectoral lines, even though there are important cross-sectoral interdependencies that should be addressed in impact modeling. These sectors could include the following:

- Ecosystems (for example, forests, aquatic, and coastal)
- Water resources
- Energy demand, capacity, and distribution
- Transportation systems
- Waste and wastewater systems
- Information systems
- Human health (for example, effect of heat stress).

A careful review of existing models appropriate for DoD sites is needed to evaluate their compatibility to use as inputs to existing climate model projection information. For example, some hydrological models used for riverine flooding require data inputs that are currently unavailable from climate models. Such a review would provide a starting point for managers and decision makers in understanding the range of tools available to show how future climate change may impact their managed assets.

5.8 **Decision framing for vulnerability assessments**

Among the major objectives of Statement of Need RCSON-12-02 were

- Development of “opportunities to improve the match between the type of information planners and managers need versus what is potentially available from the global and regional models”
- “Development and use of decision-support strategies and analytic methods that support adaptive strategies whose performance is relatively insensitive to poorly characterized uncertainties.”

The case studies and results from this project led to two broad conclusions about DoD information needs and strategies for framing decisions about climate change. First, a framework for conducting different levels and types of vulnerability assessments is an effective approach to develop information needed by planners and managers to assess risks and identify and plan adaptive management strategies to maintain readiness and mission continuity in the face of climate change. Global and regional climate models provide valuable information for understanding the future climate and environmental context for risk management and are essential components of a vulnerability assessment framework. Continuing to improve global and regional models and methods and mapping their output to impacts assessment is important. Policy drivers such as DoD's recently updated floodplain policy and the new Federal Flood Risk Management Standards are indications of the need to focus such improvements on impacts, vulnerability and risk assessments, especially considering that the latter adopts a climate-informed science approach as a preferred option.

The second conclusion is that an effective decision-framing approach for DoD climate risk management is to modify current widely used planning, budgeting, reporting, and decision-making processes to incorporate information about potential impacts and vulnerability to climate change. Vulnerability assessment, decision analysis, risk assessment, and other related approaches will need to be adapted to provide needed information on potential expenditures, benefits, and risks for current decision-making processes. Development of stand-alone decision-support strategies focused on climate change is not an effective way to improve climate risk management.

We will briefly discuss each of the conclusions in the remainder of this section.

Improving the decision relevance of information through climate and impacts modeling— We focused on identifying information needed by installations managers to incorporate climate change considerations into decisions (research question 2). We identified a number of decision variables and factors that directly affect the installation managers. Decision variables include information about costs and performance of installation assets, health and safety, compliance with regulations, and cultural and aesthetic considerations. Climate change introduces the question of whether installation assets will maintain expected cost, performance, and compliance profiles over time. Interactions with installation managers and planners uncovered a wide range of underlying climate-sensitive factors that directly affect these variables, including damages from climate extremes, poor conditions that reduce usage and affect training throughput and hence readiness, exceedance of operating margins of equipment leading to failure or shortened performance life, degradation or migration of ecosystems that affect endangered species or other encroachments, and conditions that lead to heat injuries and training restrictions (see Table 3). These are not variables that are produced by climate models. Information to “translate” climate to decision relevance is required. This information could come from a variety of sources, including records kept at the installations or through other modeling and analytic processes.

When we started this project, we hoped to identify some installation-specific information on the effects of different climate conditions based on the ongoing management expertise of site personnel. We looked for information on climate thresholds that lead to damage, data to correlate changes in climate with changed system performance, records of training cancellations resulting from climate conditions, and other similar variables. Perhaps not surprising to those who work

on the installations, this type of information is not collected. We expect this is to be true of the vast majority of DoD installations and sites, although it can be corrected over time by incorporating information collection into ongoing condition assessments and other record keeping. In particular, identification of thresholds—points at which a system is disrupted or damages increase disproportionately—was often difficult, as damages or disruptions often occurred as a result of multiple conditions, making attribution to specific climate conditions impossible. If thresholds can be identified, analysis can be performed on large ensembles of climate model projections to evaluate whether the probability of exceeding the thresholds changes in the future.

While the lack of this information made it difficult to test several approaches, we fully expected to need a variety of additional techniques to estimate and model how uncertain future climate could affect natural and built infrastructure, outdoor activities, and other factors important to making decisions about installations and their assets.

Decision framing through current planning, budgeting, reporting, and decision-making processes—Given our focus on installation-level assessments, our research on decision framing started by examining how installation personnel make decisions. We examined near-term decisions about climate-related problems such as flooding and emergency preparedness as well as long-term decisions related to design and acquisition of capital assets.

An important conclusion related to decision framing concerns the different challenges associated with providing climate information to support different types of decisions. Supporting near-term decisions, including scheduling, environmental compliance, ecosystem management, and contractual arrangements for maintenance, is more challenging because of a mismatch of time scales. These decisions have a daily-to-yearly character and are naturally more sensitive to weather patterns on annual to interannual time scales. Managers are used to and adept at incorporating information that enables them to deploy procedures for protection and response and believe that on time scales they care about, climate change will not lead them to alter their current approaches. In this sense, they conclude that information about long-term climate change is irrelevant, and as climate changes slowly, they will slowly adapt. In fact, information on long-term vulnerabilities is relevant and should be considered in some near-term decisions. While a range or some other asset may still support mission-critical training while undergoing gradual increases in temperature and decreases in precipitation, at some point, climate impacts will render current management practices ineffective in maintaining needed conditions within acceptable ranges. When will a site or installation be spending more resources on workarounds than on mission activities, unless decision makers plan for resilience through adaptation? Evaluating the potential for this to occur, and how to manage the implications for maintenance and recapitalization of current systems and infrastructure, can reduce the chances of spending scarce resources on facilities that will not be fit for their given purpose with changing climates and environmental conditions. Thus, vulnerability assessments should consider these issues and opportunities for improving near-term decision making. This issue of time scale has been identified in the research literature, most notably in a paper, now updated, on the fit between ecosystems and institutions (Folke et al., 2007).

With respect to long-term decisions, we attempted to apply decision analytic techniques to explore the implications for individual infrastructure-related decisions at each installation. In the

medium and long terms (10-50 years, a span to include the lifetime of the infrastructure), the relevance of climate change impacts on decisions grows steadily. Infrastructure decisions and projects that are to be made or completed at a time scale of a decade and that will be in place for 10 to 50 years should include the results of a vulnerability assessment at installations selected for an assessment. We sought to apply development of decision trees and other decision analytic approaches to evaluate how this information could be integrated into installation-level decisions about infrastructure. These are time- and resource-intensive methods. They require access to information about both official and informal decision-making processes that can be sensitive and difficult to obtain. In addition, there are limitations to some of these techniques in the context of deep uncertainty. We concluded that focusing on individual installation decisions was problematic as a research strategy and, further, that it would not provide an efficient way forward for DoD to improve climate risk decision making.

We turned to an examination of long-term, integrated decision-making processes for DoD infrastructure. Climate changes such as higher temperatures, sea level rise, and increasing storminess and windiness will, for some installations and functions, become factors in how (and if) traditional missions can continue to be carried out, or if new missions can be supported. The usefulness of assessing such climate factors will point to opportunities to mitigate climate change, build resilience to change impacts, and implement adaptation elements. The need to mitigate and adapt may change cost calculations for projects, so it is important to know which projects must have climate information associated with them. Already, for example, the Unified Facilities Criteria (DoD 2012) prohibits infrastructure in floodplains, except for projects certified (that the risk has been accepted) by top management.

Like the uncertainties in future needs for personnel, training, and technologies, the uncertainties in future climate change mean that long-term planning will also need revision as time unfolds. However, the DoD reiterative planning process can incorporate new information and conditions, so that the risk of surprise will be reduced as the long term becomes the short term. The need to determine the risks from climate change leads to the need for long-term planning processes for installations to include vulnerability assessments and to revise those assessments periodically. To investigate where such assessments could be most effective, the project team reviewed current formal processes—those required by DoD and the individual services—to identify useful points of intervention.

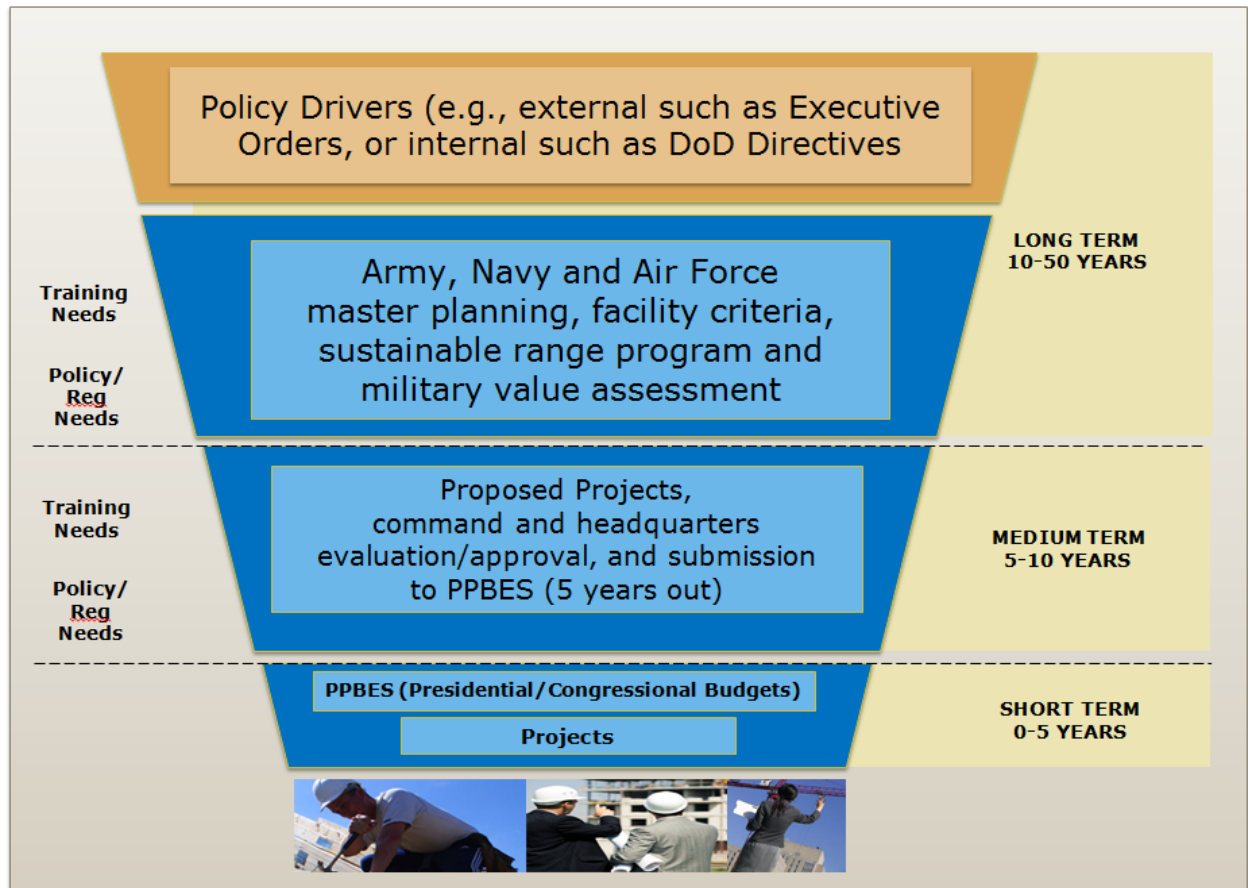


Figure 67 is an overview of how high-level policy covering long-term planning is implemented through military service policy, criteria, and guidance, which in turn guides the development of proposed infrastructure projects in the medium term. When projects enter the short-term planning, programming, budgeting, and evaluation cycle, they should already have climate change considerations built into them. Some managers commented that if projects “in the pipeline” did not already account for climate change, it would be too late to incorporate vulnerability considerations. To ensure that projects address climate change vulnerabilities, planners need to be trained and implementing policy and regulations need to be in place (left-hand side of the figure).

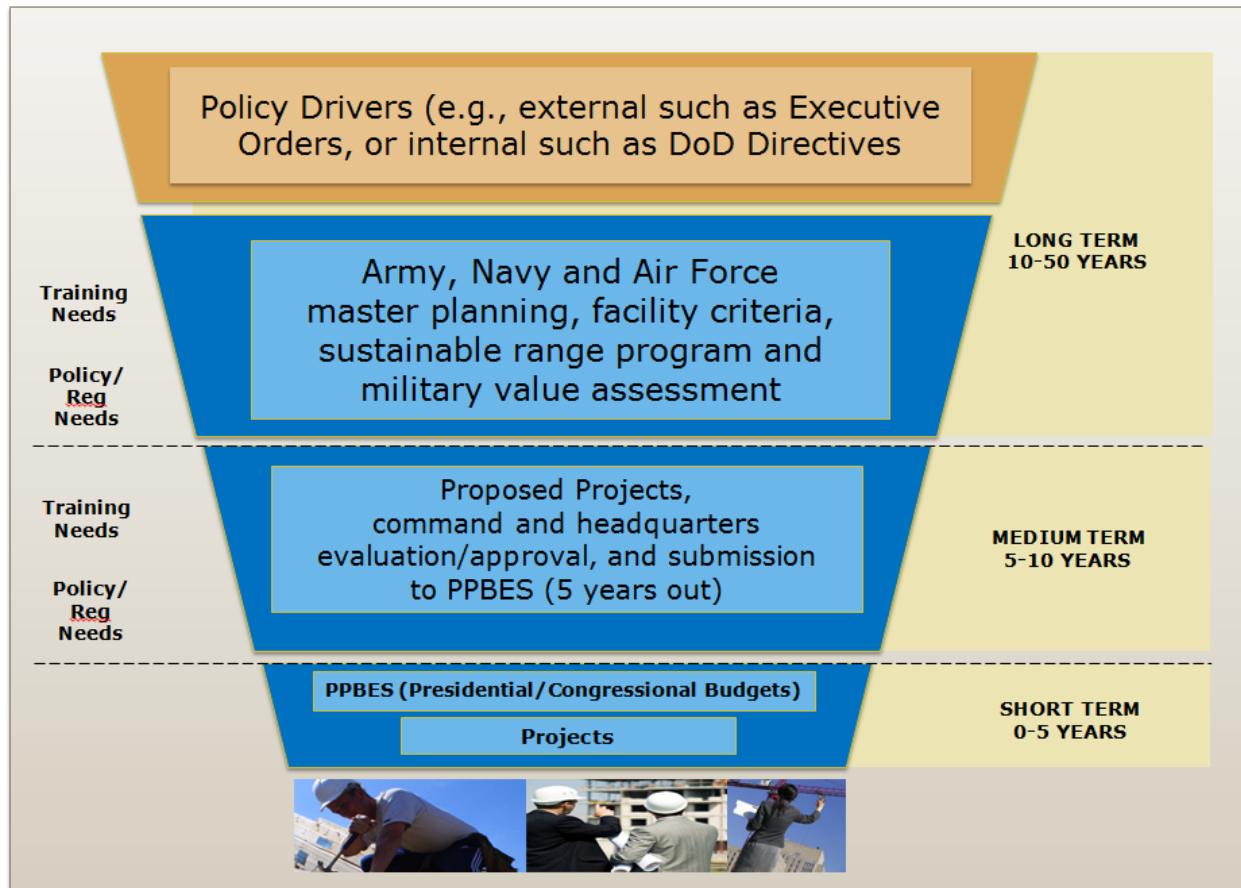


Figure 67. Long-, medium-, and short-term elements of planning for DoD infrastructure / Training, policy, and regulation will be needed to consider vulnerabilities to climate change into this process.

Figure 68 shows a specific example of DoD master planning document locations where climate change information should be incorporated. Extrapolated, this figure identifies the people who are involved in long-term planning and thus should be trained in future climate analysis. There are a number of potentially relevant processes and reports. The DoD mandates infrastructure master planning largely through DoD Instruction 4165.70, *Real Property Management* (DoD, 2005), and *Unified Facilities Criteria: Installation Master Planning* (DoD, 2012b). The Army-specific requirements for master planning are in Army Regulation 210-20, *Real Property Master Planning for Army Installations* (Headquarters Department of Army, 2005). On a parallel and partially integrated track, the services have instituted range sustainability programs based on policy in DoD Directive 3200.15, *Sustaining Access to the Live Training and Test Domain* (DoD, 2013b). The Army's implementing guidance for sustainable ranges is in Army Regulation 350-19, *The Army Sustainable Range Program* (Headquarters Department of Army, 2006), which is currently being updated. Guidance for assessing and managing encroachments to U.S. Air Force installations (limits to activities on installations imposed by legal requirements and conditions around it) are contained in U.S. Air Force Instruction 90-2001 (Ferguson, 2014). In addition, a DoD Directive, *Climate Change Adaptation and Resilience*, is in review. The military value assessments for base realignment and closure activities would also be relevant (see Ewing et al., 2006). We note this analysis is preliminary and, for example, does not yet include the Department of the Navy. Additional research beyond

the scope of this project is needed to evaluate ongoing decision making processes and training needs to identify those where incorporation of information on climate change or vulnerability will be most effective.

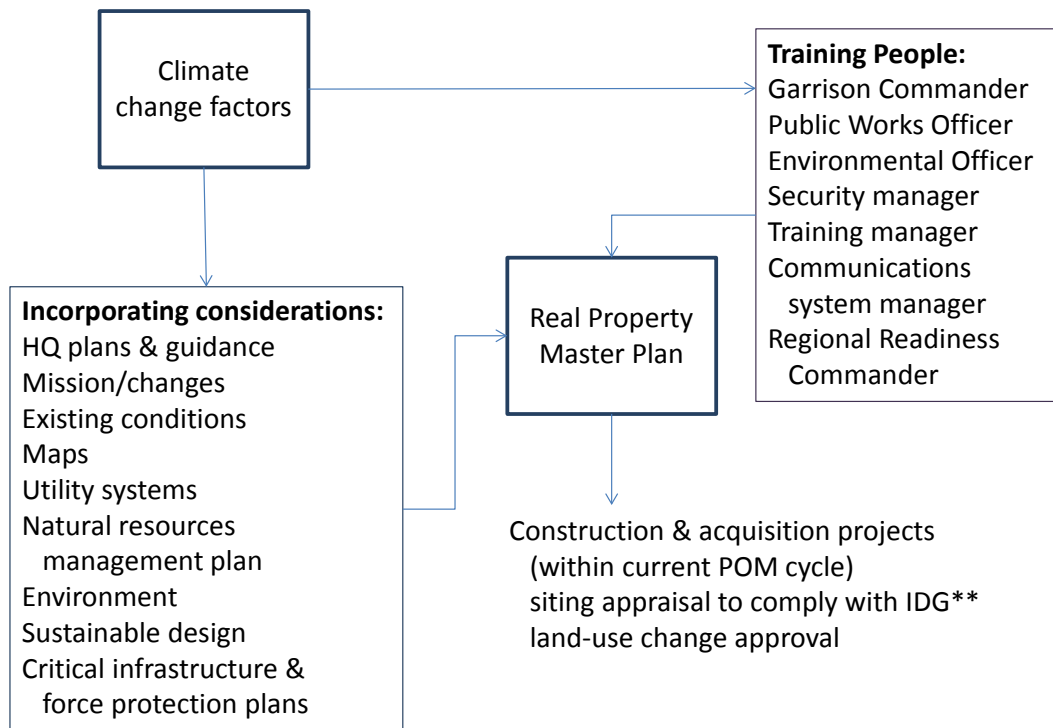


Figure 68. Climate change factors, training, and the long-range planning process / As revealed in vulnerability assessments, climate change factors can enter the long-range planning process through requirements of the master plan (“Incorporating considerations”), facilitated by the knowledge of leaders and planners (“Training people”).

The focal points for this analysis are the installation master plans, because they have a timeframe similar to climate change—a minimum of 10 years, for infrastructure likely to last up to 50 years. The master plans are updated at least every 5 years and include the installation’s vision, given troop and mission requirements, a long-term component that allows planning to fill gaps between requirements and current capabilities, and projects that are intended to fill those gaps. At the level of projects, any climate change considerations (for example, siting, design, and natural resource management) should be incorporated into planning.

Opportunities to incorporate the results of vulnerability assessments into DoD master plans and other long-range plans such as the Integrated Natural Resources Management Plan (for example, see U.S. Army, Fort Bragg, 2011) include the following:

- Facilities and new range siting (for example, to avoid excessive heat gain as the climate warms, impacts of sea level rise, or to avoid floodplain construction)

- Management of training areas and ranges (for example, to adapt habitat, especially vegetation, to new climate conditions). The management of training areas and ranges is outside the purview of the master plan.
- Installation planning standards/facility design criteria (for example, to build in protective features or include stilts to mitigate flood damage). These changes would have to come from Office of the Secretary of Defense. The installation cannot make changes to the design criteria, but they can assess vulnerability against current design standards.
- Energy infrastructure (for example, to avoid outages from flooding or severe storms)
- Transportation (for example, to mitigate heat island effects and avoid flooding on roads and in parking lots)
- Green infrastructure (for example, systems that help manage storm water and heat stress)
- Utilities and communications (for example, water management to cope with long periods of drought)
- Lifecycle costing of projects
- Sustainability planning.

The findings of a vulnerability assessment should be analyzed as part of the decisions indicated in the list above. Moreover, planners could analyze the connections and complementarities between actions taken in consideration of climate change and other requirements, such as energy efficiency, sustainability, and compact development.

Any of the people contributing to or reviewing master plans need to understand how a vulnerability assessment should be conducted and how to apply those findings to long-range master planning. Vulnerability assessment, resilience, and adaptation can be incorporated into the specialized training requirements for long-term planning personnel, and conferences (including keynote presentations) can emphasize the importance of this activity and provide needed information. Officers and civilian staff who develop inputs or who execute the plan include installation commanders, environmental officers, range managers, public works officers and facility managers, infrastructure designers, and those in the Army Corps of Engineers and other specialized organizations who are involved in planning infrastructure projects.

5.9 Research needs and gaps

This project has developed options for a multi-tier framework and process for assessing the climate vulnerability of DoD installations and assets. The framework and process are based on research literature (that does not reflect the specific concerns and issues DoD faces), and the experience of the research team at three installations. The case studies included various missions, operational conditions, knowledge about climate change, and levels of onsite concern. They were not formal vulnerability assessments but rather opportunities to test different strategies and methods that might be used. Operational assessments would require formal direction (or at least

active support) from the chain of command, unfettered access to data, access to ongoing community stakeholder engagement processes, and other supporting conditions that were not in place.

Going forward, the Department needs to significantly deepen its understanding of climate-related vulnerabilities and the risks associated with such vulnerabilities. Learning from actual experiences in conducting formal assessments will be crucial, but should be complemented by other research into communication, alternative methods, etc. Our experience indicates specific needs in the following areas:

- Clarifying and potentially resolving different definitions ascribed to such terms as “threat,” “vulnerability,” “consequence,” “exposure,” and “resilience.” This will be important as vulnerability assessment, adaptation planning, and promotion of climate resilience are incorporated into existing areas of practice such as civil engineering and ecosystems management. This can be accomplished through additional review of ongoing research studies as well as conducting vulnerability assessments at DoD installations
- Identifying and analyzing existing datasets to use variables and potential indicators for screening
- Using questionnaires for screening and for installation-level assessments, with care taken to reduce and account for bias, different levels of experience, and other factors
- Exploring the potential uses of climate change outlooks (exposure) for screening purposes
- Testing the effectiveness of communication forms, such as scenarios, statistical analysis of climate model archives (especially useful if specific impact thresholds can be identified), and narrative descriptions of the current state of scientific understanding of climate changes projected for a region or installation type (coastal installations, etc.)
- Testing of methods for engaging external stakeholders, especially related to ongoing efforts to manage relationships with the community
- Further developing approaches for providing information on specific types of impact-relevant exposures; this needs to be accomplished in partnership with not only those knowledgeable in vulnerability, impacts and adaptation assessment and modeling, but also the climate science community
- Estimating and modeling impacts more efficiently and appropriately for use in vulnerability assessments
- Developing a protocol to evaluate, learn from, and revise assessment processes.

5.10 Potential for implementation

This project met its objective to develop a potential overall framework for DoD to use in understanding and beginning to plan to manage the climate vulnerability of its installations and sites. The framework includes three tiers: screening; conducting vulnerability assessments at a limited number of high-priority installations; and, where needed, evaluating and making decisions about adaptation options. We focused on developing a potential process for conducting assessments at priority installations and tested three sets of methods including stakeholder engagement techniques; analysis and communication of future climate conditions and exposure; and evaluation and modeling of impacts and determination of significance. To obtain comments from OSD and military personnel, we prepared and circulated a draft synthesis of findings that described the framework and process. Based on these comments, we revised the concept as presented in this final report.

The framework and process presented here have promise for future implementation. As described in this report, some specific approaches and methods tested performed well, while others did not work as expected and would require further research and development. Additional steps will be required to move to implementation if the Department finds merit in the approaches described here. These steps include the following:

- Continued testing and evaluation at selected installations and sites
- Additional evaluation of the Climate Outlook
- Developing scenarios and additional sources of climate information for use in assessments
- Continuing to develop and test indicators, questionnaires, and other methods for screening to set assessment priorities
- Assessing ongoing planning and decision-making processes related to investment in facilities to identify what information from climate analysis and vulnerability assessments is needed to build consideration of climate change into these ongoing processes
- Developing training and technical guidance for participants and users of vulnerability assessments, including incorporating climate change vulnerability components into existing training activities and technical guidance
- Cataloging available methods for use in assessments and establishing research programs to continue to improve methods for engagement, exposure analysis, and impacts modeling
- Establishing a template for documenting experience and conducting comparative evaluation of approaches across sites and agencies
- Designing new web-based screening and assessment methods to streamline the process.

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Appendix A

Climate Change Outlook for the Mid-Atlantic Region

Appendix A

Climate change outlook for the mid-Atlantic region (In an attachment)

Appendix B

List of Scientific/Technical Publications

Appendix B

List of Scientific/Technical Publications

- Boesch, DF, LP Atkinson, WC Boicourt, JD Boon, DR Cahoon, RA Dalrymple, T Ezer, BP Horton, ZP Johnson, RE Kopp, M Li, RH Moss, A Parris, CK Sommerfield. 2013. *Updating Maryland's Sea-level Rise Projections*. Special Report of the Scientific and Technical Working Group to the Maryland Climate Change Commission, University of Maryland Center for Environmental Science, Cambridge, Maryland.
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