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DEVELOPING INFRASTRUCTURE ADAPTATION PATHWAYS TO COMBAT HURRICANE INTENSIFICATION: A COUPLED STORM SIMULATION AND ECONOMIC MODELING FRAMEWORK FOR COASTAL INSTALLATIONS

THESIS

Alexander J. Baldwin, Captain, USAF

AFIT-ENV-MS-21-M-204

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

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Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Alexander J. Baldwin, BS

Captain, USAF

March 2021

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Alexander J. Baldwin, BS

Captain, USAF

Committee Membership:

Major Justin D. Delorit, Ph.D., P.E.
Chair

Dr. Christopher M. Chini, Ph.D., P.E.
Member

Lt Col Steven J. Schuldt, Ph.D., P.E.
Member

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Abstract

Global climate change projections suggest an intensification of extreme weather events, including hurricanes, is expected over the remainder of the century. This intensification will ultimately lead to increased destruction over contemporary losses for coastal U.S. military installations unless infrastructure resiliency and adaptation measures are implemented. To develop actionable adaptation measures, risk analyses of climate-intensified hurricanes can be downscaled to the infrastructure-level, to determine what systems need to be made resilient to future intensities, and at what time horizon adaptation is necessary to mitigate losses. This research examines this through simulation of probabilistic, climate-intensified hurricane events occurring throughout the 21st century at Eglin Air Force Base. Coupling Federal Emergency Management Agency's (FEMA) Hazus hurricane and flood models with climate projections for wind intensity, tidal conditions, and sea-level rise produces an end of century assessment of losses to the installation. Coarse spatial damages emanating from Hazus's wind and storm surge intensity outputs are downscaled to the facility level so that timely climate adaptation triggers can be identified. The facility losses and climate signals are used as inputs for a dynamic adaptation pathway model. The pathway model is used to calculate the expected benefits, risks, and costs associated with adaptation by utilizing various infrastructure investment strategies. This work is the first of its kind to downscale multi-hazard threats from a single extreme weather event to the facility-level and produce actionable facility adaptation recommendations for military installations. Such pathways can be used by planners and engineers to inform campus and installation development and sustainment plans. Development of adaptation pathways with climate uncertainty considerations is vital to reducing coastal bases’ vulnerability to future hurricane events.

For my son, mein ganzer Stolz

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First, I would first like to thank my wife whose constant support enabled me to succeed throughout this program. Putting up with me working from home this past year has not been easy, but you were always patient and understanding. Thank you for being my foundation and the best spouse I could ever have.

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Alexander J. Baldwin

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DEVELOPING INFRASTRUCTURE ADAPTATION PATHWAYS TO COMBAT HURRICANE INTENSIFICATION: A COUPLED STORM SIMULATION AND ECONOMIC MODELING FRAMEWORK FOR COASTAL INSTALLATIONS

I. Introduction

"*Climate change constitutes a serious threat to global security, an immediate risk to our national security, and, make no mistake, it will impact how our military defends our country.*" - President Barack Obama, USCGA Commencement Address, 2015

Background

Throughout its history, the United States Department of Defense (DoD) has monitored, analyzed, and prepared for threats that might be detrimental to national security and ensured the safeguarding of the American people. While these threat analyses have traditionally been kinetically focused, either on near-peer foreign adversaries or terrorist organizations, the United States' greatest threat may not come from opposing militant groups, but perhaps nature itself. In recent history, extreme weather events have caused widespread destruction, financial impact, and severe loss of life in the U.S. (Smith & Katz, 2013; Smith & Matthews, 2015; NHC, 2020). The most impactful and threatening of which have been tropical cyclones (TC) (Smith & Matthews, 2015).

The DoD has positioned many of its installations in coastal areas and has not been spared from these extreme weather events, as multiple TCs have ravaged coastal installations over the last several decades. In 1992 Hurricane Andrew caused such severe destruction to Homestead Air Force Base (AFB) that it was closed as an active-duty installation (Grudo, 2017). In 2005, Keesler AFB experienced storm surges of over 9.1 m (30 ft) from Hurricane Katrina, which resulted in approximately $1 billion in damages (Perry, 2006). Most recently, Tyndall AFB sustained over $3 billion in damages from Hurricane Michael in 2018, and 75% of facilities on the installation needed to be extensively repaired or demolished (Beven et al., 2019; Everstine, 2019).

While TCs have historically been, and are currently, a severe threat to DoD coastal installations, the outlook of future TC conditions is even more alarming. Major TCs, defined as storms categorized as hurricanes, are projected to intensify (Fraza & Elsner, 2014; Villarini & Vecchi, 2013), increase in occurrence frequency (Bacmeister et al., 2016), and undergo rapid intensification before landfall (Emanuel, 2017). These future conditions are expected to be caused by climate change and rising global temperatures (Contento et al., 2019). As a result, future hurricane occurrences are projected to have substantially greater impact on coastal areas, and result in significantly greater damages relative to contemporary events (Elsner et al., 2011; Pilkington & Mahmoud, 2016).

Since 2010 the DoD has identified climate change and extreme weather events as two of the greatest threats to national security and has made initial attempts to incorporate resiliency measures into installation master development and sustainment plans (DoD 2019). However, the results of these cursory efforts have primarily been limited in scope, lacking in implementation guidance, and minimal in effect. The largest contributor to this lack of infrastructure adaptation is that installations do not have experts to determine climate projections and future extreme weather event possibilities or translate these threats into actionable adaptation measures (GAO 2019).

In 2019, Congress was dissatisfied with the DoD's lack of climate and extreme weather adaptation progress and tasked the U.S. Government Accountability Office (GAO) with evaluating the DoD's efforts. The resulting report from this audit highlighted the DoD's need to "*update master planning criteria to assess extreme weather and climate change risks and to incorporate DoD guidance on the use of climate projections into facilities design standards*." (GAO 2019). Through the Strategic Environmental Research and Development Program (SERDP), the DoD crafted a series of Statements of Need for the development of tools and methods to address infrastructure resilience concerning climate change and extreme weather events over the lifetime of infrastructure and assets. The goal of these programs is to provide military and municipal decision-makers with strategies and policies to improve the overall resiliency of DoD's infrastructure in the face of future climate condition uncertainty (SERDP 2019). This thesis is focused on addressing a portion of this need, through the development of a holistic adaptation pathway framework that coastal installation asset managers and planners can use to identify risks, downscale them to an actionable spatiotemporal resolution, and incorporate resilience adaptation measures into installation development and sustainment plans to combat hurricane intensification.

Problem Statement

DoD coastal installations are struggling to adapt existing infrastructure to withstand contemporary and future climate conditions, and extreme weather events (GAO, 2019). This lack of adaptation progress, combined with continued military development along the U.S. coast, puts billions of DoD assets in harm's way from future hurricane event occurrences. If the DoD does not develop and implement effective adaptation measures, future hurricane events may cause unprecedented destruction resulting in severe degradation of mission capabilities, billions in asset recovery and losses, and potentially loss of life. Therefore, this research effort focuses on analyzing the risks associated with future, climate-intensified hurricane events and the development of dynamic adaptation pathways that base-level asset managers and planners can use to improve infrastructure resilience and inform installation master plans.

Research Objectives

This thesis is focused on developing a dynamic infrastructure adaptation pathway framework to reduce the risk that coastal DoD installations face from future, climate-affected hurricane events. To accomplish this, research has been focused on addressing the following objectives:

1. Determine how climate change is expected to affect future hurricane behavior and what risks DoD coastal installations face throughout the 21st century.
2. Apply multi-hazard modeling tools to simulate losses and intensities experienced by coastal installations from climate-intensified hurricanes.

3. Develop infrastructure adaptation pathways to aid DoD decision-makers' and planners' incorporation of actionable resilience measures within installation development plans.

Scope and Approach

To accomplish these research objectives, this thesis follows a scholarly format in which Chapters 3 and 4 are stand-alone, academic publications addressing research objectives 1, 2, and 3. Chapter 2 discusses relevant literature associated with infrastructure resilience and DoD funding decision matrices topics that are not covered in Chapters 3 or 4.

Chapter 3, "Resilient to what? Downscaling multi-hazard, tropical cyclone risk assessments for coastal cities to infrastructure system levels" addresses research objectives 1 and 2 by producing a model-based framework with which climate-intensified hurricane events can be simulated against coastal DoD installations. This framework first identifies how hurricane wind and surge intensities are forecasted to change over the remainder of the century due to climate projections. Specifically, SLR and global temperature parameters are analyzed as they are known to be correlated with hurricane intensities. FEMA Hazus Multi-Hazard (MH) software was used to simulate these climate change parameters, applied to a pre-determined hurricane profile (Appendix), along with tidal conditions, and produce probabilistic, climate-intensified hurricanes at Eglin Air Force Base (Eglin AFB) in the Florida Panhandle. Resultant intensities from the hurricanes are downscaled to infrastructure system-levels to determine how spatiotemporal differences propagate across the installation. This article was presented at the American Geophysical Union's (AGU) 2020 Fall Meeting in December 2020 and is scheduled for submission to the *Earth's Future* for publication consideration in spring 2021.

Chapter 4, "Dynamic adaptation using infrastructure system-level climate signals to inform strategies: an economic-based policy pathway comparison" addresses research objective 3 by developing a dynamic adaptive policy pathway (DAPP) model for Eglin AFB. The results from Chapter 3 are taken and applied to determine three possible adaptive strategies for sample facilities on the installations. These strategies are then combined to develop possible dynamic adaptation pathways that allow decision-makers to balance benefits, risks, and costs to determine implementation options throughout the remainder of the century. While this article is still in draft format, the target publishing journal for submission is Natural Hazards Review, which is managed by the American Society of Civil Engineers (ASCE). The expected timeframe for submission is spring to summer of 2021.

Chapter 5 discusses the research conclusions, contributions, significance, and future recommendations associated with this thesis.

II. Literature Review

Chapter Overview

The purpose of this chapter is to summarize the relevant research associated with infrastructure resiliency and DoD infrastructure decision matrices topics not covered in Chapter 3 or 4. First, definitions and accepted practices of quantifying infrastructure resilience are discussed. Second, DoD infrastructure decision-processes are explained and analyzed to identify existing matrices in which adaptation pathways can be applied. These topics are combined with the results in Chapters 3 and 4 to formulate the conclusions of this thesis discussed in Chapter 5.

Infrastructure Resilience

For the DoD, resilience has been a focus across many mission areas, including infrastructure (DoD Directive 4715.21, 2016). While multiple strategic directives have been issued urging installations to implement resilience measures in facilities and infrastructure systems (AFPD 10-24, 2019; DoD Directive 3020.40, 2016), there lacks any direction on how resilience is formally defined, or 'to what' extremes and levels infrastructure should be made resilient. Within the DoD, resilience has achieved somewhat of a buzzword status over the last decade (Herrera, 2021). While the term can be interpreted and quantified in various ways, there is a need for a standardized, measurable resiliency metric for DoD installations.

The original term for resilience was coined by C. S. Holling as, "…*the measure of the persistence of systems and of their ability to absorb change and disturbance, and still maintain the same relationships between populations or state variables.*" (1973). While Holling's definition applied to ecological systems, it set the foundation for the concept of system resilience that applies to infrastructure. Specifically, when it comes to the maintenance and improvement of critical infrastructure systems, resilience is generally accepted as "*the ability to resist, absorb, recover from or successfully adapt to adversity or a change in condition*" (DHS, 2010). In this context, system resilience can be determined by the amount of impact prevented or absorbed from disruptive events before and after improvements are made (Figure 1).

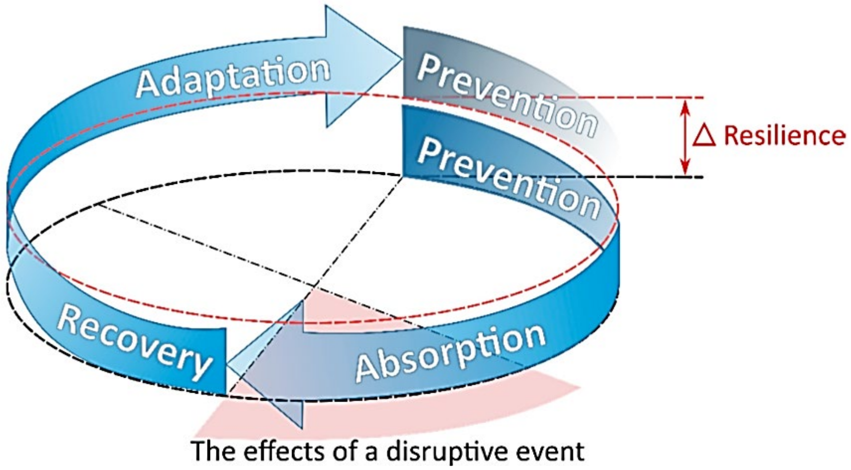


Figure 1. Critical infrastructure resilience cycle (Rehawk et al., 2019)

This concept of measuring system resilience by comparing impact mitigation and avoidance caused by disruptive events or changing conditions has been applied in numerous asset-management research efforts. The first step in the traditional measurement of resilience is determining the risk, which is defined as system vulnerability to some uncertain threat (Panteli et al., 2017). The next step is to implement adaptation-intervention to increase system robustness, targeted at loss or impact mitigation (Alderson et al., 2015, Rehawk et al., 2019). This change in impact is the measure of benefit for the infrastructure investments. However, such benefits may be costly to implement, either initially or through recurring maintenance expenses. Thus, implementing robust system improvements pre-maturely can reduce the overall resilience of infrastructure systems (Rose, 2017). Combining these resilience concepts leads to determining an infrastructure system's resilience being the balance between probabilistic values for un-prevented risk, beneficial loss mitigation, and cost to implement (Franchin & Cavalieri, 2014).

Applying this definition of system resilience to coastal infrastructure facilities allows for resilience metrics to be calculated that can be used to inform policy and development plans. For example, benefits for infrastructure improvements to systems can be determined by measuring the loss avoidance from hurricane events, and the remaining loss potential would be the associated risk. These resilience metrics can then be incorporated with existing infrastructure investment decision processes, and balanced with decision-maker tolerances, to find optimal adaptation measures to implement. Conglomerating sets of adaptation measures across many infrastructure systems creates a risk-based portfolio with which hurricane-protected infrastructure and installations can be achieved.

DoD Infrastructure Decision Processes

Traditionally, the DoD has utilized infrastructure criteria to prioritize sustainment, improvement, and construction expenditures. For the Air Force, these criteria are typically the Plant Replacement Value (PRV), Mission Dependency Index (MDI), and Condition Index (CI) scores tied to a specific infrastructure system, sub-system, or facility. The Air Force Comprehensive Asset Management Program (AFCAMP) currently uses a scoring system based upon existing asset's Probability of Failure (PoF) and Consequence of Failure (CoF) scores to determine infrastructure projects worth funding each fiscal year (AFCEC 2019). An asset's CoF is based primarily on its MDI and PoF is based on its CI score (Figure 2). This ultimately translates such that those assets with greater centrality to Air Force operations and degraded condition are most likely to receive funding in a given fiscal year. However, this does not consider system vulnerability to fail or sustain damage from disruptive events, such as hurricanes.

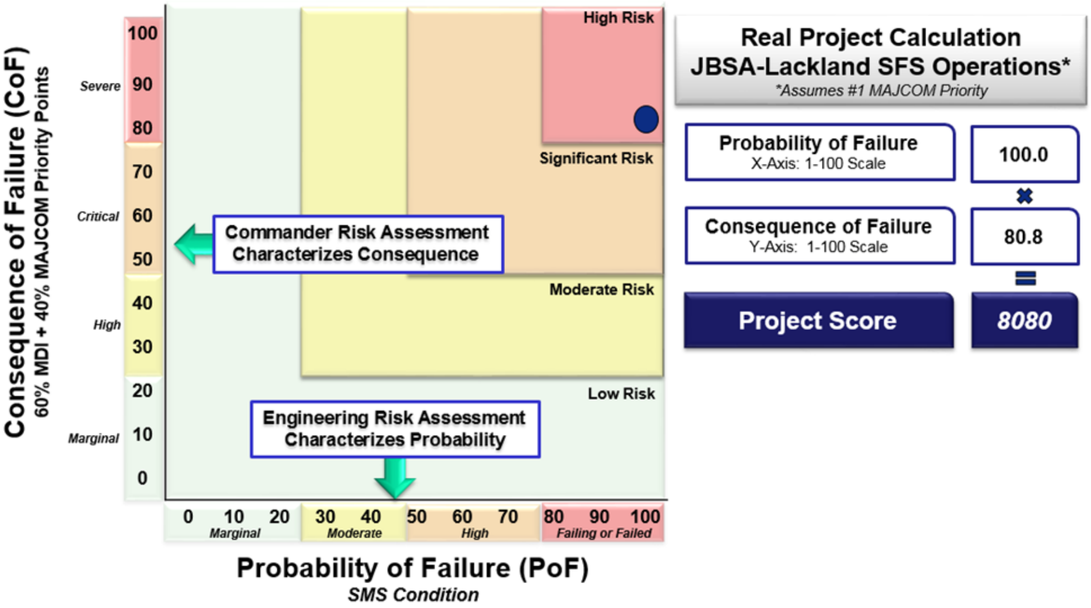
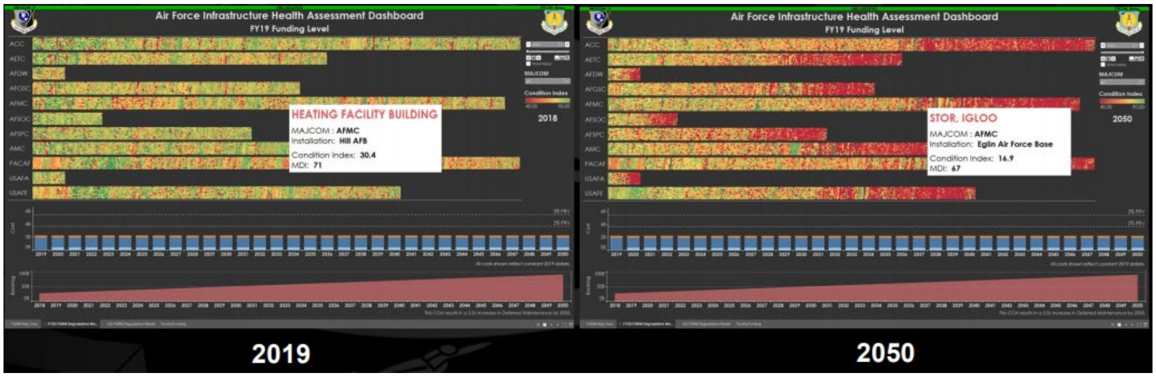


Figure 2: Sample AFCAMP project matrix based upon CoF and PoF (AFCEC, 2019)

Long-term use of this project prioritization methodology is forecasted to have negative impact on the overall condition of Air Force infrastructure. As bases compete for limited infrastructure funding sources, many struggle to maintain their current portfolios that are aging beyond intended service life. An overall Infrastructure Health Assessment (IHA) for the entire Air Force infrastructure portfolio (Figure 3) concluded that one-third of systems will reach failure states, and maintenance backlogs will increase from $25B to $89B by 2050 (Vandeveer, 2019). The IHA is also threat-unaware, meaning it does not consider risks such as hurricane vulnerability for coastal installations. This gap in the Air Force's risk assessment methodology suggests that without proper adaptation measures, infrastructure system failure will occur throughout the century, and certainly beyond what is predicted in the IHA.



MAJCOM : AFMC
Installation: Hill AFB
Condition Index: 30.4
MDI: 71

MAJCOM : AFMC
Installation: Eglin Air Force Base
Condition Index: 16.9
MDI: 67

Figure 3: Air Force forecasted IHA (Vandeveer, 2019)

PoF scores can consider several factors beyond conditions ratings to integrate infrastructure resiliency adaptation into existing funding practices. Non-condition-based projects, for which infrastructure adaptation would be considered, have scoring multipliers that account for cost savings, such as Specific Enterprise Execution Direction (SEED) and Enterprise Objectives (EO). Cost savings is a straight-forward economic analysis of the net benefit that a project provides the Air Force. Though traditionally focused on energy savings, exporting this component to evaluate resilience adaptation projects are possible provided project benefits versus risk factors can be calculated. SEEDs are based upon strategic directions from higher levels to specific base units. Currently, SEEDs are typically used to beddown specific units or missions at installations. However, SEEDs could be created for at-risk coastal installations and spur a ready supply of risk mitigation projects.

EOs are like SEEDs but are not installation-specific. These objectives are strategic enterprise directives that align installations with Air Force master plans and doctrine. The current list of EO categories for project scoring is as follows; 1) mission resiliency in contested environment, 2) nuclear enterprise sustainment and modernization, 3) right-size mission footprint supporting mission and partners, 4) mitigate risk to mission essential functions, 5) mission assurance and redundancy features, 6) lifecycle reduction through partnership, and 7) restore military readiness and while building a more lethal force (AFCEC 2019). Infrastructure resilience could fall within one of the existing EO areas, such as 1 and 4, but applicability would be highly subjective to reviewing official discretion for whether the projects fit the EO directive. If a dedicated Air Force EO was made for infrastructure resiliency to align with the DoD and Congressional directives, then projects that directly reduce vulnerability from extreme weather events would be competitive for funding on the AFCAMP process. This would allow the Air Force to award installations projects that reduce risk, achieve infrastructure adaptation, and correspond with resiliency-focused master development and sustainment plans.

Development of non-condition-based project scoring factors also could provide incentives for bases to implement and adopt adaptation strategies for infrastructure-systems. Since the abstract concept of infrastructure resilience is ill-defined for military installations, there is a lack of buy-in from bases to pursue adaptation (GAO, 2019). Rather, installations are focused on maintaining the infrastructure systems they have with limited funding and labor resources. Therefore, even if resilience projects were conceptualized, most installations would not pursue them due to a lack of incentive to do so, other than strategic directives stating that they ‘should.’ If separate funding resources or additional project scoring prioritization were applied to long-term, resilience-focused projects and installation master plans, then there would be a stronger pull for installations to pursue them (Narayanan et al., 2019). Providing such incentives for coastal bases would help meet DoD and Congressional directives, and implement projects that would be of greatest benefit to reducing future climate and hurricane risks.

Summary and Way Forward

While the existing literature provides components of a framework with which coastal infrastructure resilience could be measured and incorporated into existing Air Force funding practices, there exists a gap for the development of a cohesive approach to producing adaptation pathways that Air Force asset managers can use take action to promote mission assurance through infrastructure resilience. Chapters 3 and 4 address this gap to provide an adaptation framework for coastal installations to use that compares benefits, risks, and costs of adaptation against probabilistic, climate-intensified hurricane events.

III. Scholarly Article 1: Resilient to what? Downscaling multi-hazard, tropical cyclone risk assessments for coastal cities to infrastructure system levels

Abstract

Tropical cyclones have intensified and are expected to continue strengthening throughout the 21st century due to climate change impacts. Storm intensification poses a serious threat to coastal municipalities and infrastructure that are not designed to withstand future wind and storm surge potential. Coupled modeling software has been widely used to replicate extreme weather events and simulate forecasted climate change effects to understand the magnitude of vulnerability coastal regions face. However, these studies are often conducted at too coarse resolutions to provide decision-makers with actionable information for infrastructure-level adaptation. This study addresses this limitation using a coupled modeling approach by simulating climate-intensified hurricane events at Eglin Air Force Base (AFB) along the Florida Panhandle. The study simulates hurricane impacts throughout the 21st century using multi-threat, probabilistic projections of storm surge, sea-level rise, and wind intensification. Hazus Multi-Hazard software is used to simulate hurricanes at four threat horizons for five possible climate change scenarios. Storm intensities are downscaled to the facility-level using geographic information system software to determine the spatiotemporal impact on Eglin AFB's infrastructure. This analysis provides asset managers with likely intensities that buildings will experience and helps determine when and to what extent vulnerable facilities need to be made resilient. Results show Eglin AFB could sustain between $773 million and $1.8 billion (2020 USD) in facility damage by the end of the century. This methodology can be applied to other coastal municipalities, provided adjustments are made to fit regional conditions and extremes, and could be used to inform infrastructure adaptation and development plans.

Plain Language Summary

Extreme weather events, including hurricanes, pose a serious threat to coastal communities. This threat is expected to increase throughout the remainder of the century from storm intensification due to climate change. While previous research has evaluated hurricane threats and climate change intensification, most of these efforts have focused on singular parameters such as wind speeds and sea-level rise at large spatial scales, and for specific timeframes. There is a need to apply multi-threat, coupled models to be used in comprehensive evaluations of extreme weather events' impact on municipalities at the infrastructure-system level. Results from simulating multiple, climate-intensified hurricanes at Eglin Air Force Base show that the installation could sustain between $773 million to $1.8 billion in damages by the end of the century. Analyzing these results at the facility-level allows for adaptation decisions to be made on which buildings need to be protected and what protection levels are needed to reduce losses.

1 Introduction

There is growing global concern over the impact of climate change on tropical cyclones (TCs), and their threat to coastal communities and infrastructure portfolios (Pielke & Pielke, 1997; Mendelsohn et al., 2011; Peduzzi et al., 2012). Hurricanes, TCs with sustained wind speeds greater than 64 kts (74 mph), making landfall in the U.S. have increased in intensity (Fraza & Elsner, 2014), and are expected to continue strengthening, though non-uniformly across space and time throughout the 21st century (Meehl et al. 2000; Elsner et al., 2008; Villarini & Vecchi, 2013). While TC frequency is expected to decrease overall (Walsh et al., 2016), the number of extreme TCs (Category 4 and 5 hurricanes) are expected to increase in occurrence, potentially doubling in frequency by the end of the century (Bacmeister et al., 2016; Bender et al., 2010; Emanuel, 2013). Evidence of this trend can be seen by comparing past hurricane seasons, as damages and fatalities stemming from Atlantic Ocean storm activity in the U.S. have increased dramatically. Sixteen of the top 20 costliest hurricanes on record have occurred since 2000, causing $32.2 trillion (2020 USD) in total damages (NHC, 2020). The historical frequency of TCs has increased as well, with 15 named storms and three major hurricanes occurring on average, each season between 2000 and 2019. This represents a 150% increase in frequency and magnitude compared to 1980-1999 averages (NHC, n.d.-b). The 2020 Atlantic hurricane season alone produced 30 named storms and four major hurricanes, making it the most active Atlantic hurricane season on record (NHC, n.d.-a).

Most coastal communities and organizations, including Department of Defense's (DoD) installations, struggle to adapt asset portfolios to be resilient against TC threats and therefore face substantial risk in terms of infrastructure losses (Contento et al., 2019; Pilkington & Mahmoud, 2016; Woodruff et al., 2018). Loss risk from TCs is compounded by population growth and the attractiveness of infrastructure development in coastal areas, putting more people and assets in harm's way (Crossett et al., 2013; Hauer et al., 2016; Neumann et al., 2015). While the threat has become apparent, there is still a considerable amount of uncertainty in determining the true magnitude of risk that coastal communities face as the population and the built environment change over time. Historically, regional TC climatology or storm-of-record events have driven coastal community risk assessments and infrastructure design codes (Dehring & Halek, 2013; Simmons et al., 2019). As infrastructure adaptation is expensive and socio-politically sensitive, it is easier for decision-makers to gain support for adaptation to events that have already transpired than it is to rely on projections of future possibilities, which are uncertain or unaccepted (Akerlof et al., 2013; Shao et al., 2017).

Reevaluation of design standards is typically reactive and undertaken when the storm-of-record is superseded, as was the case when Miami-Dade standards were implemented after Hurricane Andrew (Simmons et al., 2019). This reactive design practice causes coastal municipalities to be extremely vulnerable as climate change effects cause uncertainty with possible future TC event intensities. While most adaptation efforts have been reactive, some coastal municipalities are beginning to develop adaptation strategies based on climate projections (Shi & Varuzzo, 2020; Xie et al., 2019). However, cities possess little guidance or mandated documents to drive actionable adaptation (Woodruff & Stults, 2016) and regularly postpone implementation to meet short-term budgetary demands (Shi & Varuzzo, 2020). A primary struggle in gaining support for adaptation is the quantifying and understanding of future uncertainties that infrastructure needs to be made resilient against (Kwakkel et al., 2016). Research conducted on uncertainty quantification for coastal regions has underlined this need for adaptation, but these studies are traditionally broad in scope and lack specific implementation recommendations that infrastructure managers require to make informed adaptation decisions (Woodruff & Stults, 2016).

An additional gap in research exists in producing and downscaling multi-hazard, climate intensification-informed damage assessments at the infrastructure-level (Li & Ellingwood, 2006). In the context of TCs, which are multi-hazard by nature (Misuri et al., 2019), an analysis might consider the combined impacts of wind and surge flooding (Li et al., 2012). Combining storm threat criteria can enable a holistic assessment of TC damage potential, so long as the interconnections between threats are designed appropriately (Kappes et al., 2012). Calculating damages from individual parameters, such as wind alone, or simple aggregation of damages ignores the interconnectivity of storm parameters, which can lead to under-estimation of true damage potential or double counting of damages sustained from multiple hazards (Pilkington & Mahmoud, 2016). For example, a wind model combined with a storm surge model may overestimate losses if damage to infrastructure is caused by both parameters (Pei et al., 2018). Conversely, there might be cases where the compound impacts of wind and rain magnify damages not captured by simple aggregation alone (Silva de Abreu et al., 2020). This limitation can be overcome by using coupled modeling processes and simulation tools, such as open-access software like FEMA's Hazus-MH program or coupled estimation frameworks (Barbato et al., 2013) that account for multi-hazard criteria and their interconnectivity. This study explores the use of such modeling software and fills this knowledge gap.

If it is the goal of storm simulation research to answer the question: "What degree must infrastructure be made resilient?", it is natural to expect that new design standards will emerge as an adaptation method. However, it is inefficient to establish a single design standard needed to achieve long-term resilience, as this might lead to overdesign or premature adaptation (Dehring & Halek, 2013). Furthermore, not considering facility importance and condition when applying a uniform building standard will drive excessive expenditures in terms of initial construction and recurring maintenance costs (Simmons et al., 2019). Analyzing storm threats must be done both temporally and spatially to enable effective development of adaptation standards to inform policy (Pei et al., 2014), and determine likely intensities and their timeframe for individual facility damage mitigation (Masoomi et al., 2019). Therefore, modelers must consider various climate change projection scenarios to ensure standards are robust enough for future intensity possibilities. Comparing the severity of damage intensities and probabilities across multiple threat horizons allows for adaptation signals to be identified of when improvements are needed to achieve maximum threat avoidance (Stephens et al., 2018). This concept of using risk signals to trigger adaptation is crucial to adapting infrastructure to changing conditions over time (Haasnoot et al., 2013) and mitigating the threat TCs pose to coastal cities.

Considering the limitations of the aforementioned literature, highlighted by the gap between the coarseness of storm model predictions and the demand for additional granularity in risk assessments, the objective of this research is to analyze the potential effects of climate change on TC activity at the facility level for coastal communities. The results address three questions: 1) How will climate change affect TC strength and risk to coastal communities and infrastructure over time? 2) How can multi-hazard, coupled modeling be used to develop damage estimates and determine the spatial importance of individual threats from intensified storms? 3) How can analyzing storm activity at the infrastructure system level be beneficial in improving coastal resiliency? This study applies a multi-hazard, coupled model at the infrastructure system-level to answer these questions through a case study analysis of Eglin Air Force Base (AFB), located in the Florida Panhandle, which the current infrastructure at the installation is simulated against major probabilistic hurricanes occurring at various threat horizons throughout the 21st century. Hazus software was used to simulate these hurricane events, and spatiotemporal analysis at the facility level was performed to produce the likely intensities that buildings will experience over the remainder of the century. While this research is focused on a specific region, the methodology framework presented here can be applied to other coastal municipalities; provided adjustments are made for regional conditions, extremes, and geospatial infrastructure parameters are known or available.

2 Data and Methods

2.1 Methodology Overview

The multi-hazard modeling approach developed in this work combines existing climate change projections with historical hurricane profile parameters to generate facility-level damage loss estimates for storm occurrence at four threat horizons (2020, 2035, 2065, 2100). These threat horizons are coupled with five different climate projections of increasing severity (Lowest, Low, Moderate, High, Highest). This simulation is accomplished in four parts: 1) production of a multi-threat TC damage framework, calibrated to a previously performed analysis for Eglin; 2) aggregation of climate-intensified hurricane parameters; 3) construction and simulation of intensified hurricane scenarios to produce census tract-level damage estimates; and 4) downscaling of hurricane damage outputs to the facility level through coupling with Eglin AFB's building inventory data. Figure 1 shows the methodological sequence performed for each climate change scenario across the threat horizons, which resulted in 16 simulated storms.

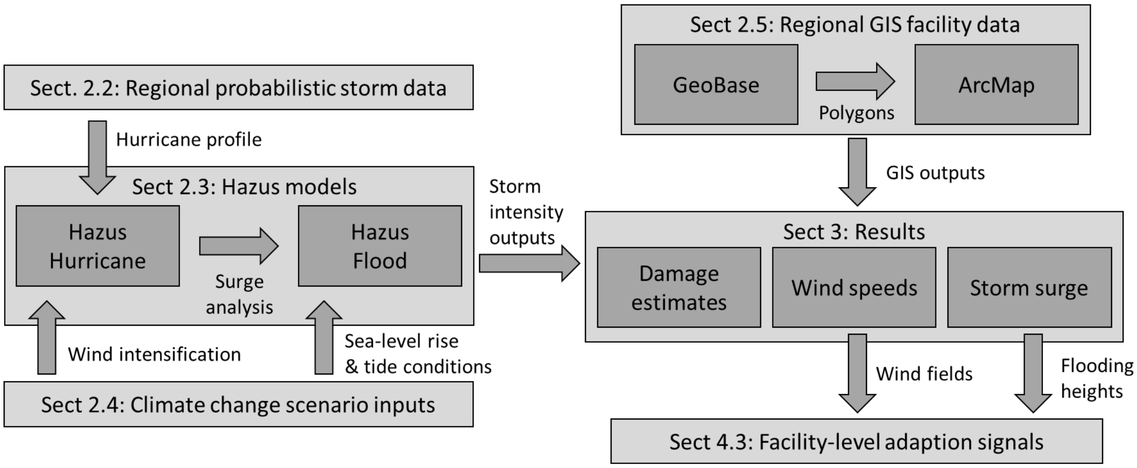


Figure 1. Methodological sequence for threat horizon storm simulations. Labels correspond with methodology sections discussed below.

2.2 Eglin Study Region and Prior Research

Eglin AFB is a major U.S. military installation located in northwestern Florida, bordering the Gulf Coast (Figure 2). The installation is the largest in the Air Force, in terms of size, encompassing over 1,870 km^2 (460,000 acres). It consists of over 3,000 facilities with a total plant replacement cost of $9 billion, supporting 9,500 active-duty military members and their families (DoD, 2018). Elevation for the installation ranges from -0.4 m (-1.3 ft) below mean sea level (MSL) along the shoreline to 28 m (92 ft) above MSL in northern woodland regions. Eglin AFB was selected as the study region of interest due to its proximity to the Gulf of Mexico, which has experienced increased hurricane activity, and its compatibility with coastal communities. Additionally, available data included facility-level datasets and GIS information, enabling the downscaling of damage risk. Lastly, Eglin AFB was the subject of previous hurricane, wind-only threat assessments (Elsner et al., 2011; Scheitlin et al., 2011; Scheitlin & Elsner, 2009). These studies provided the platform for calibration and a hurricane profile that was expanded upon for simulating intensification.

Prior assessments of Eglin AFB's vulnerability to TC activity determined that there is a high likelihood of a 'worst-case' hurricane event occurring by the end of the century as determined by analysis of historical hurricanes occurring within 150 km (93 miles) of Eglin AFB from 1851-2008. This storm, consisting of extreme 100-year return wind speeds, has the potential to cause severe damage to the installation. The total economic impact was estimated to be $664 million (2020 USD) in damage and revenue loss to residential and commercial buildings without considering specific government facilities (Scheitlin et al., 2011). Solely due to increasing sea-surface temperatures (SST), wind damages were estimated to be 36% greater at Eglin AFB by the end of the century (Elsner et al., 2011). These assessments used Hazus-MH hurricane modeling software to simulate storms, translated along a manually defined track, intended to maximize the destructive impact of winds. The model was formulated based on four profile parameters: translation speed, radius to maximum wind, wind speed, and central pressure. The storm made landfall on the western side of Eglin AFB before continuing inland (Scheitlin & Elsner, 2010).

As this previous research shows, wind forces alone pose a significant threat to Eglin AFB, and infrastructure resiliency improvements would reduce this risk. However, the lack of geospatial data on storm intensities makes resiliency adaptation difficult for decision-makers to prioritize infrastructure maintenance and improvements within budgetary limitations. While the analysis of Eglin AFB's vulnerability to hurricane-force winds is extensive, there is room for more robust and comprehensive damage assessments. Specifically, this study focuses on the facility-level and models damage risk stemming from interconnected wind intensities and storm surge inundation simulated through multiple climate change intensified storms. Geospatial analysis of Eglin AFB's impact by both wind intensities and storm surge inundations advances the understanding of holistic threat at the facility-level that the installation faces, allowing for robust decision-making to be done in terms of prioritization and identification of building resiliency adaptation signals.

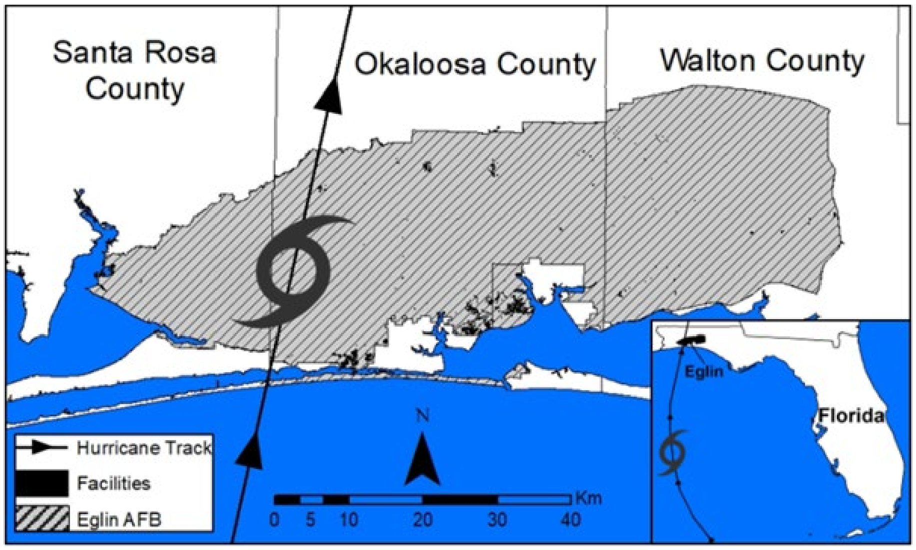


Figure 2. Eglin AFB study region located in the northwestern Florida Panhandle. The simulated hurricane track passes through the Gulf of Mexico before making landfall. The hurricane symbol shown is to illustrate track and is not to scale with the actual storm size.

2.3 Hazus-MH

Hazus is a geographic analysis tool developed by FEMA to simulate and analyze extreme weather event likelihood, impact, and regional recovery for emergency management purposes. While multiple storm simulation models exist, many of these tools are not open-source and may require specialized training to operate. For use and uptake by DoD and coastal community planners, models should be available at low to no cost and produce interpretable and actionable results. Aside from the necessary addition of ArcMap, which is a tool most planners and community engineers have available, Hazus satisfies these requirements. Additionally, training and technical manuals are regularly updated and provided by FEMA, including reach-back support. Hazus can perform detailed modeling of extreme weather events (earthquakes, floods, hurricanes, and tsunamis) and can be coupled with census and topographic data to produce various desired outputs (Pluss et al., 2018). Hazus has been widely used to model extreme weather event intensities and impact simulations (McGrath et al., 2015; Pei et al., 2018), and the results have been found to closely replicate artificial wind tunnel, small scale flooding models, and real-world events (Vickery et al., 2006; Vickery et al., 2009; Elsner et al., 2011). Hazus hurricane and flood modeling software were used in this study to produce the damage loss estimates and storm intensities of both wind fields and storm surge inundation heights at Eglin AFB.

2.3.1 Hurricane Model

Hazus hurricane models can be operated in many modes, simulating manually defined, historical, or probabilistic hurricane events for a region of interest. The region of interest is customizable and can be as small as a single census tract. For Eglin AFB, the hurricane parameters from Scheitlin et al. (2011) were used to calibrate Hazus before expanding the analysis to the multi-hazard domain. The hurricane wind analysis outputs were used to determine wind intensities experienced by each census tract, which then served as inputs for the storm surge analysis, ultimately producing the multi-threat damage estimation. A complete description of the hurricane wind modeling process can be found in the Hazus hurricane technical manual (FEMA, 2018b).

2.3.2 Flood Model

Coastal surge analysis produced by the hurricane models were incorporated into Hazus flood models to produce combined wind and surge intensities, and damage estimates. Regional topographic digital elevation model (DEM) data was first obtained for Eglin AFB from the United States Geological Survey (USGS) National Map at the 1/3 arc-second interval to accomplish the storm surge analysis. Next, a coastal surge analysis consisting of both a surge elevation grid, as determined by the National Oceanic and Atmospheric Administration's (NOAA) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model and a significant wave height grid using a Simulating Waves Nearshore (SWAN) model were run. This surge analysis was performed for each climate change scenario across the threat horizons. Floodplains for each scenario were then delineated from the SLOSH and SWAN models, completing the Hazus surge flooding analysis. Hazus used the analysis results to calculate the combined wind and storm surge loss estimates for each scenario. A complete description of the flooding model process can be found in the Hazus flood technical manual (FEMA, 2018a).

2.4 Climate Change Scenarios

2.4.1 Sea-Level Rise (SLR)

Storm surge is widely accepted as the most lethal and costly aspect of TCs, and estimates suggest it is responsible for 60% of the $36 billion annual economic loss to residential and commercial sectors in the U.S. (CBO, 2019). It is projected that high-tide conditions combined with SLR alone will produce regular flooding events for coastal locations that exceed contemporary storm surge extremes, referred to as recurrent or "nuisance flooding" (Moftakhari et al., 2017; Taherkhani et al., 2020). Scheitlin et al. (2011) omitted the impact of storm surge from damage estimates for Eglin AFB, likely because storm surge has not traditionally been a threat due to its inland geographical location, elevation, and the protection provided by natural barriers. However, it remains unclear whether these attributes will be overcome by intensified storm surge when coupled with climate change-informed expectations for SLR (Hall et al., 2016; Sweet et al., 2017). While the uncertainty associated with regional SLR projections vary, several agencies have produced comprehensive forecast predictions for the remainder of the century, such as NOAA. For DoD's coastal installations, the U.S. Strategic Environmental Research and Development Program (SERDP) evaluates and forecasts

SLR potential at military installations, using a wide variety of climate change models and tools. SERDP's Regionalized Sea Level Change & Extreme Water Level Scenarios tool generates five possible SLR scenarios based on NOAA data and Representative Concentration Pathway (RCP) greenhouse gas accumulation scenarios. Using the SERDP tool for Eglin AFB, the most conservative of these scenarios, labeled 'Lowest,' estimates that SLR will only increase 0.3 m (1 ft) by the end of the century. The most extreme scenario, 'Highest,' predicts SLR could rise as much as 2.3 m (7.5 ft). SLR values were used as inputs in the Hazus models at each threat horizon and accounted for each scenario produced by SERDP.

2.4.2 Tide Conditions

Sea-level rise is not the only hydrologic parameter that affects storm surge inundation. Tidal conditions impact wave behavior, and during a TC can intensify storm surge and produce a 'storm tide.' Storm tide-influenced floods have consistently caused damages exceeding $1 billion (Smith & Katz, 2013) and account for approximately 50% of fatalities during TC events (Rappaport, 2014). To further replicate the worst-case conditions for the simulated storms, high-tide levels were added to SLR estimates at each threat horizon. Previous five-year high-tide averages were taken for the region from the Pensacola, FL monitoring station (Station 8729840), the closest available station to Eglin AFB (NOAA, n.d.). Tide conditions were taken during August through October, which corresponds to the Atlantic's peak hurricane season period. This resulted in an MSL baseline of 0.55 m (1.8 ft).

2.4.3 Wind Strength

The exact effect of climate change on TC wind intensities is not fully understood (Walsh et al., 2016). Several studies have been conducted with respect to evaluating TC intensity change due to singular influences, such as SST and global temperature rise (Bhatia et al., 2018; Fraza & Elsner, 2015; Knutson et al., 2019). Expert opinions on end of century predictions for TC wind intensity are mixed, though the consensus is that major TC wind intensities will be greater than or equal to contemporary values (Cui & Caracoglia, 2016; Fraza et al., 2016; Villarini & Vecchi, 2013). Research performed on evaluating TC maximum intensity in the North Atlantic basin due to SST sensitivity predicted that a 1° C change might result in 10.7-13.6 kts (12.3-15.7 mph) higher wind speeds (Strazzo et al., 2016). Additional forecasts suggest TCs intensity increases of 1-10% for every 2°C global temperature change is likely (Knutson et al., 2019). Combining this range for TC intensity increases with global temperature projections ranging from 1-5°C throughout the end of the century (O'Neill et al., 2016) create a potential range of TC wind intensity increase of 1-30%, which falls within the broad range of wind intensity increase expectations (Bhatia et al., 2018; Strazzo et al., 2016). Wind field multipliers for the 2100 threat horizon intensities were then derived from this range to produce the simulated TC wind strengths at Eglin AFB for the five climate change scenarios. End of the century wind field multiplier values ranged at 5% increments from a 1.05 multiplier for the Lowest scenario, representing a 1°C change, to upwards of 1.25 for the Highest scenario. It is assumed that wind intensity increases will follow an exponential trend throughout the century, like SLR and SST, due to the positive correlation between wind and temperature (Michaels et al., 2006; Strazzo et al., 2013). Wind intensity multiplier values, along with SLR and tide heights, are shown for all climate scenarios and threat horizons in Table 1.

Table 1. Hazus threat horizon wind intensity multiplier and SLR parameters.

	Threat horizon						
	2020	2035		2065		2100	
Climate scenario	MSL (m)	Wind multiplier (%)	SLR (m)	Wind multiplier (%)	SLR (m)	Wind multiplier (%)	SLR (m)
Highest	0.55	1.009	0.40	1.08	0.98	1.25	2.29
High		1.007	0.30	1.06	0.70	1.20	1.68
Moderate		1.005	0.30	1.05	0.49	1.15	1.10
Low		1.004	0.18	1.03	0.30	1.10	0.58
Lowest		1.002	0.18	1.02	0.18	1.05	0.30

Wind fields are not singular values but multiplied to all coordinate points throughout the storm track. Initial sea levels used for surge analysis consisted of SLR values added to the baseline, high-tide MSL.

2.5 GIS Facility Data

GIS data produced by Hazus for the wind field intensities and storm surge inundation heights were overlaid with Eglin facility data in ArcMap to downscale impacts to the facility-level. Eglin facility data was obtained from the Air Force GeoBase GIS database, which contains specific geographic shapefile polygons, including size, importance to Eglin operations, replacement cost, and location. As expected, most facilities (44.6%) are in the main base sector (Figure 3), which is equivalent to a community's downtown. Due to security requirements, three generalized facilities are discussed here to show the effect of simulated hurricane impacts at the facility-level, across the threat horizons. These buildings, referred to as Facility A, B, and C, are purposefully chosen to represent the diversity in functions, replacement costs, and mission importance of facilities within Eglin. Furthermore, each facility was selected from different locations around the installation (Figure 3) to illustrate the geospatial effects of storm intensities within even a relatively small area and how they can inform specific infrastructure adaptation decisions.

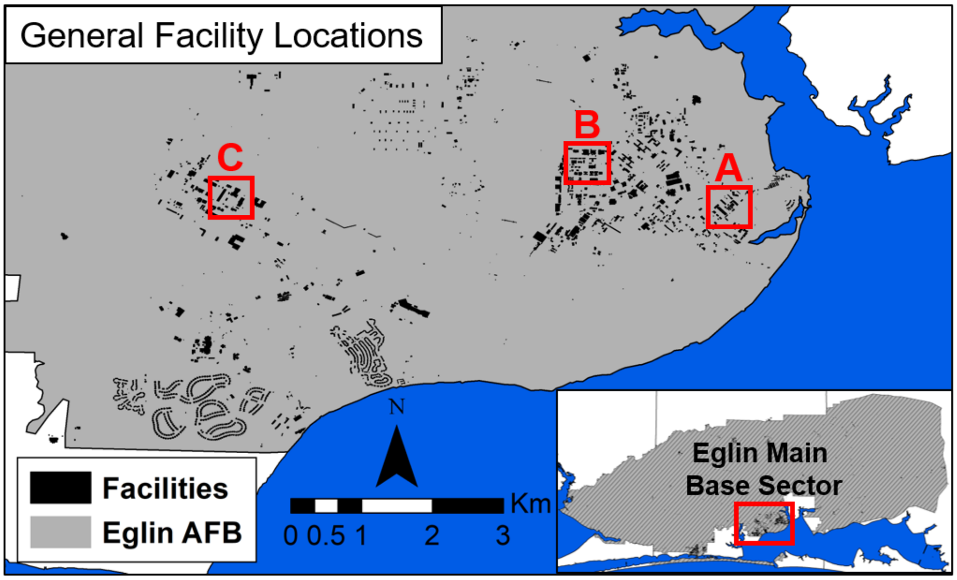


Figure 3. Facility A, B, and C generalized locations on Eglin AFB main base sector. Facility A is a community support/recreation facility of low importance to Eglin AFB, Facility B is an office/administrative facility of moderate importance, and Facility C is an operational facility of high importance.

3 Results

3.1 Wind Intensity

Hazus wind outputs varied due to the variation in climate projections used to inform the wind field multipliers across the threat horizons. For the 2020 baseline storm, the maximum wind speed (v_{max}) was determined to be 113 kts (130 mph) at landfall and decreased to 108 kts (124 mph) as the storm moved inland, making it resemble a Category 3 hurricane. At the 2035 threat horizon, v_{max} was relatively unchanged, though, by 2065, it rose to 118 kts (136 mph), which elevated the hurricane to a Category 4. At 2100, v_{max} rises to 130 kts (149 mph), but the range of intensity potential is the most diverse of the threat horizons, with an interquartile range of 123-136 kts (142-157 mph). Though v_{max} variance increases with each threat horizon, which reflects model and input uncertainty, the general results suggest that the expected TC event would transition from a Category 3 hurricane to a severe Category 4 by the end of the century at the median (Figure 4). Landfall intensities increase consistently; the maximum potential v_{max} at any given threat horizon is less than the 25th percentile value of subsequent threat horizon.

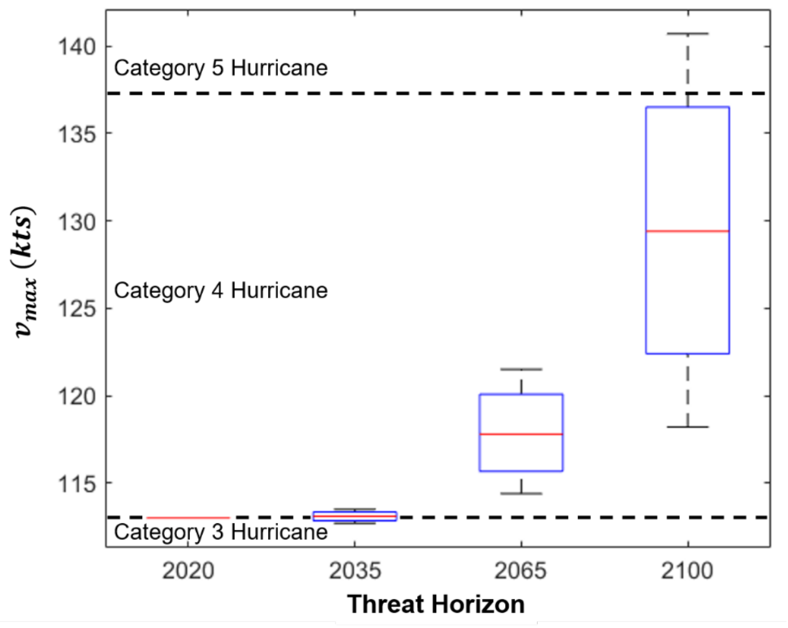


Figure 4. v_{max} inter-quartile ranges produced across the climate change scenarios at each threat horizon. 2020 baseline v_{max} is 113 kts (130 mph) and ranges of v_{max} are 112.8 - 113.6 kts (129.8 - 130.7 mph), 114.4 - 121.5 kts (131.6 – 139.8 mph), and 118.2 - 140.7 kts (136.0 – 161.9 mph) in 2035, 2065, and 2100, respectively.

3.2 Storm Surge

Storm surge inundations produced by the Hazus models show how SLR and tidal conditions affect the number of facilities threatened over the century. As mentioned above, storm surge has not historically been a significant concern for Eglin due to its geographic parameters. For the 2020 hurricane, storm surge produced at high tide is 5.7 m (18.7 ft) for some coastal regions of the base, but these areas are largely uninhabited and result in little to no facility damage. On the main base, where the bulk of buildings are located, storm surge heights were 1.8-2.7 m (6-9 ft) and threatened a small portion of buildings (< 30). As the century progresses, storm surge potential increases across most modeling scenarios (Figure 5). While 2035 scenarios only produce a small (< 0.5 m (1.6 ft)) increase in storm surge heights, the 2065 and 2100 scenarios produced drastically higher inundations. At the 2065 threat horizon, the increase in storm surge to Eglin AFB ranged from 1 m (3.3 ft) in the Lowest scenario to 2.6 m (8.6 ft) in the Highest scenario, threatening 479 - 632 facilities, respectively. For 2100, storm surge increase ranges from 1.6 m (5.3 ft) to 4.9 m (16 ft) between Lowest and Highest scenarios and threatened 530 – 837 facilities, respectively. The total number of facilities for all of Eglin AFB affected by storm surge inundation rises from 419 (12.9% of total facilities) in 2020 to 837 (25.8%) by 2100 for the Highest climate change scenario. This means that the number of surge-affected buildings could double between 2020 and 2100. Surge maps for climate-intensified storms like this can be utilized to identify flooding zones and highlight facilities that are susceptible to future storm surge inundations for adaptation planning.

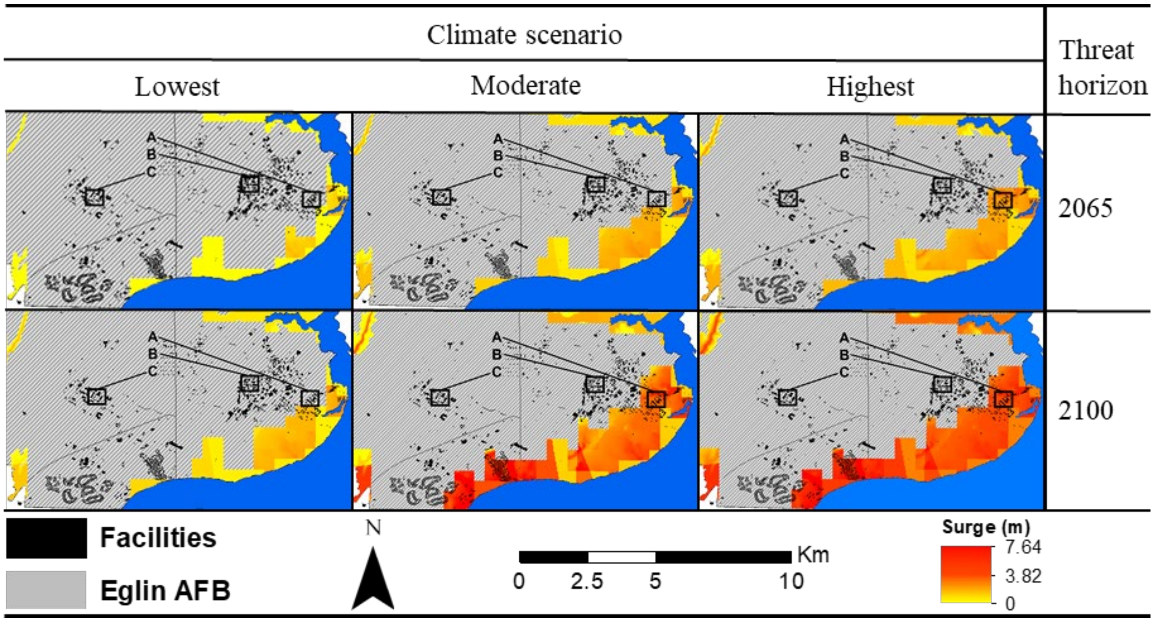


Figure 5. Storm surges increase between 2020 and threat horizon Highest, Moderate, and Lowest climate scenarios for 2065 and 2100. 2035 surges not shown due to insignificant increase (< 0.5 m (1.6 ft)) from 2020 values. The coarse boundaries of storm surge heights are a result of Hazus and more sophisticated flood modeling software could produce higher resolutions.

3.3 Multi-Hazard Damage Estimates

The simulations produced a variety of loss estimates across the threat horizons. Conducting a two-tailed, t-distribution analysis on the outputs illustrates that Eglin AFB faces facility damages of $1.8 billion [($2.45B, $1.16B) = 90% confidence interval (CI)] for a storm occurring by 2100 (Figure 6). This is a 133% increase of potential loss [(216%, 50%), 90% CI] from the $773 million damage potential of the 2020 baseline storm. A comparison of damage by threat shows that wind forces cause the most significant portion of damage. While storm surge, which is influenced by the combination of SLR and tide, is less destructive than wind; it accounts for 35% of storm damage in 2020 and 20% in 2100. The storm simulated is classified as “wind-driven”, which is an artifact of the Scheitlin et al. (2011) hurricane profile development. As such, the escalation in damage from wind compared to surge is not unexpected. Damage loss estimates follow an exponential curve across the threat horizons, which aligns with storm parameter intensification. This means that while increases in loss potential continuously occur throughout the threat horizons, damage potential due to climate change will be comparatively larger as the century progresses. As estimates were only taken at the threat horizons, an exponential fit was used to approximate values between threat horizons.

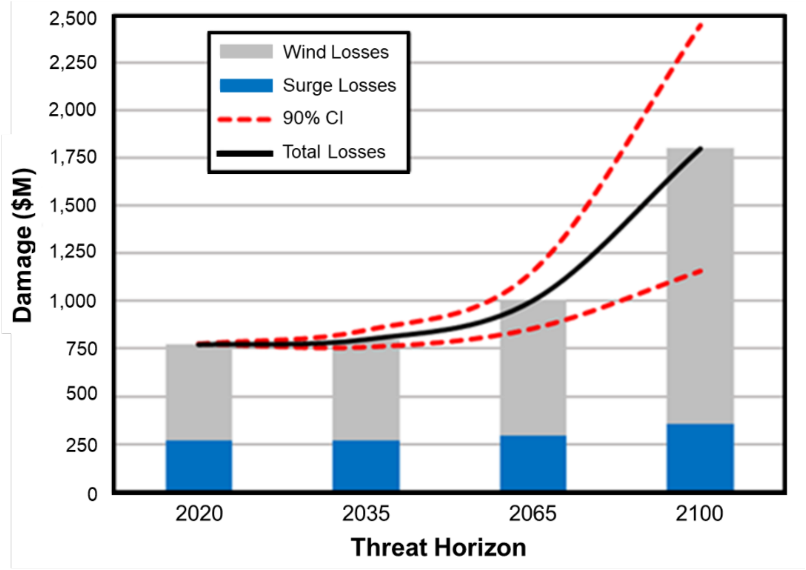


Figure 6. Hazus damage estimations with 90% confidence interval bounds based upon t-distribution statistical analysis. Baseline 2020 losses were estimated to be $773M and threat horizon estimates were $800M + $45M, $1,000M + $150M, and $1,800M + $650M in 2035, 2065, and 2100, respectively. Wind accounts for the most significant proportion of damage to the study region.

3.4 Eglin AFB Facility Impact

As expected, impact at the facility level varies by location and across threat horizons for the simulated hurricanes (Table 2). Facilities A and B experience identical wind intensities across the threat horizons, while Facility C experiences slightly higher intensities. This is due to Facility C being located west of A and B and closer to the storm track. However, Facility A will be exposed to storm surge potential by 2065, whereas Facilities B and C will not be threatened by storm surge, as they are located inland. The use of these climate signals allows for asset managers to make targeted, robust decisions to achieve infrastructure resiliency goals.

Table 2. Threat horizon intensities experienced by Facilities A, B, and C

	Threat horizon								
	2020		2035		2065		2100		
Facility	Wind (kts)	Storm surge (m)	Wind (kts)	Storm surge (m)	Wind (kts)	Storm surge (m)	Wind (kts)	Storm surge (m)	Climate change scenario
A	107	0	108	0	110	0	112	0	Lowest
			108		110	0	118	1.2	Low
			109		112	0	123	2.0	Moderate
			109		113	1.8	130	3.7	High
			109		115	2.9	136	4.6	Highest
B	107	0	108	0	110	0	112	0	Lowest
			108		110		118		Low
			109		112		123		Moderate
			109		113		130		High
			109		115		136		Highest
C	108	0	108	0	111	0	113	0	Lowest
			109		111		118		Low
			109		112		124		Moderate
			109		114		130		High
			110		116		137		Highest

Exposures are not uniform; facilities along the southern coast of Eglin AFB experience substantially higher wind and surge intensities than the main base sector facilities shown here.

4 Discussion

4.1 Fiscal Impact of Storms

The Hazus damage estimates indicate that Eglin AFB's risk to major hurricane events will increase exponentially over time as climate change affects storm intensities.

Wind intensities cause the preponderance of damage, and its significance increases over time. Storm surge, while not as detrimental as wind, will still cause significant damage to facilities. This threat also increases across the threat horizons in an absolute sense, and it should be considered in future resiliency improvement decisions and modeling scenarios. The fiscal threat from the simulated hurricanes to the installation is alarming when considering the damage estimates are based upon contemporary facility replacement costs. After such a widespread natural disaster, construction and material costs are likely to increase as an abundant demand to repair Eglin AFB and surrounding municipal areas strain available resources and labor pools (Chang et al., 2012; Rouhanizadeh & Kermanshachi, 2020). This could lead to a significant increase in recovery costs and timeframe for Eglin, as facilities are brought back to present service levels or adapted states.

Additionally, Hazus produces damage estimates based on available census data of general building stock for Eglin AFB. As was the case with the original threat assessment (Scheitlin et al., 2011), it does not include specific government facility data in its damage calculations. As such, the actual risk to military buildings at Eglin AFB from the simulated hurricanes will be different, and likely larger, than the damage estimates determined by Hazus. In comparison, the census tract general building stock consisted of 11,279 facilities with a $3.6 billion replacement cost. Eglin AFB real property data procured from GeoBase consists of 3,249 military facilities with a $9 billion replacement cost. This translates to a 250% facility replacement cost increase when comparing military facilities to residential and commercial buildings. The interpolation of damage potential to military facilities will not be the same as residential and commercial facilities due to differences in locations and building construction types. Regardless of true damage potential, the difference between military and census building stock datasets indicates that losses to military facilities would be significantly higher, potentially two and a half times greater, than those estimated by Hazus for the census building stock across the threat horizons.

4.2 Future Intensities and Facility Adaptation

As reflected in the increase in damage potential to Eglin AFB, the storm intensities increase on an exponential scale. Wind field projections suggest that future TC events at Eglin AFB will likely produce higher wind speeds than contemporary extremes throughout the century. These winds, combined with SLR and tidal conditions, will likewise result in widespread flooding throughout the region as storm surge inundations increase. In reflection on how coastal communities would adapt to an event occurrence in near-future years (a TC occurring around 2035) design standards and flood protection measures that may have been exceeded will most likely be updated to more stringent design standards (Simmons et al., 2019). While this practice is common and would reduce the risk that an identical TC would have, intensity projections show that such standard would likely again be exceeded if a TC were to occur in subsequent years. Therefore, adopting a singular set of building codes and standards that do not include climate projections and asset service-life will be insufficient in TC threat elimination.

Additionally, designing to worst-case conditions—those occurring at the 2100 maximum extremes—would result in high adaptation costs, both in terms of initial construction and recurring maintenance. To mitigate the climate change-informed threat that TC presents, temporal and spatial analysis of expected storms downscaled to the facility level is needed. This allows decision-makers to make informed decisions based upon risk tolerances and existing limitations. Additionally, preventative adaptation avoids post-event recovery cost escalations that are likely to occur after a major hurricane event, thereby further reducing the cost of recovery for Eglin AFB.

4.3 Geospatial Facility Analysis

Traditionally, building importance or replacement cost logic is used to prioritize maintenance and improvement funding. Such logic puts operational buildings to receive the bulk of funding while lower importance facilities, such as recreation or auxiliary structures, are lower priority and less likely to receive project funding. Using such logic to determine resiliency prioritization would mean that Facility C is the most competitive to receive project funding, followed by Facility B, and lastly Facility A if adaptation measures are pursued. However, the facility climate signals indicate that Facility C risk is comparatively low in terms of intensity increase throughout the century, with v_{max} increasing drastically between 2065 and 2100. Conversely, Facility A is the most vulnerable to storm damage due to the combined threat of wind and storm surge flooding. Using this climate signals highlights when hurricane parameters exceed design standards for the facilities. Based upon this concept, it would be beneficial for Facility A to be made resilient to storm surge by 2035 and have increased wind intensity protection by 2065. Facilities B and C could be made resilient to wind intensities by 2065 and, according to this modeling effort, need not be made resilient to storm surge. This level of analysis can be expanded to all facilities at a coastal region to inform infrastructure sustainment plans and develop project implementation timelines. This allows asset managers to know which facilities should be made resilient and in at what timeframe adaptation is needed against likely storm intensities. Doing so will allow for threatened facilities to be made resilient against future TC potentials at the appropriate time before design standards are exceeded.

4.4 Modeling Limitations

The hurricane parameters and path simulated in this work only represent one possible TC event across the threat horizons. Given the complex and ever-changing nature of TCs, storms can develop various behaviors and the true magnitude of future event parameters may vary from the wind-dominant storms presented here. For this research, rainfall intensities generated by TCs were not considered. Existing research suggests that rainfall is and will continue to be a major factor when coupled with wind intensity and storm surge during TCs. Consistent with other climate variables, rainfall intensification is expected to increase throughout the century (Feldmann et al., 2019). A heavy rainfall-dominated hurricane could generate higher flood levels and cause widespread destruction to buildings at Eglin AFB, possibly to facilities located away from the coastline which are traditionally protected from storm surge.

Such a storm would be similar to Hurricane Harvey, which notably affected Houston, Texas in 2017, with 1000 mm (39 in) of precipitation, causing widespread flooding to the landlocked city (Blake & Zelinsky, 2018). Alternatively, a slower-moving storm would generate prolonged sustained wind fields that could drastically change the damage probability functions for specific facility construction types used in Hazus, resulting in different damage estimations. Additionally, only wind speed and SLR were changed across the threat horizons for the simulated storms. Other storm profile parameters, such as translation speed, radius to maximum wind speed, and pressure were kept constant between all storms. Existing research suggests that this will not be the case and that these parameters will likely change in the future as several are known to be affected by climate change (Liu et al., 2019; Kossin, 2018). A more robust sensitivity analysis would be needed to capture these factors, which is outside the scope of this study.

Additionally, the previously conducted assessment concluded that the simulated storm used represented a probabilistic ‘worst-case’ event for the Eglin region, based upon historical aggregation (Scheitlin et al., 2011). Hurricane activity along the Florida Panhandle has intensified since the 2011 assessment. For example, Hurricane Michael, which made landfall at Tyndall Air Force Base in 2018, only 105 km (65 mi) southeast of Eglin AFB, generated maximum sustained wind speeds exceeding 139 kts (160 mph), and it produced 4.3 m (14 ft) of storm surge above ground level, resulting in $26 billion in damages (Beven et al., 2019). Although Michael could be considered an observed worst-case event for the Florida Panhandle, its conditions were not used here. Rather, the prior research (Scheitlin et al., 2011) simulated storm was kept as a baseline of comparison and expanded upon to highlight the effects that climate change could have on Eglin AFB hurricane risk.

Finally, due to the lack of government facility data, precise damage estimates for military installations cannot be accomplished with Hazus. While replacement cost provides a rough comparison of damage potential, the true risk to Eglin AFB's military infrastructure from hurricane events is not known. It is recommended that future research to military installations threatened by climate change and extreme weather events evaluate damage estimates and impact analysis, both at the base and infrastructure system-level, with military-specific data. The opportunities of such efforts would allow for specific facility improvements to be considered and analyze their practicality through a benefit-cost analysis from various resiliency strategy perspectives. However, this specific data is not currently available for the study region.

5 Conclusion

This research demonstrates a coupled, multi-hazard modeling framework that can be used to develop climate signals for future TCs, downscaled to the facility-level. These signals can inform decision-making regarding which facilities face the greatest threat and prioritize when buildings should be made resilient to future conditions. While the hurricane profile used only represents one type of TC the defined study region could experience, the message is clear: the impact of climate change on storm parameters results in higher intensities and damage potential from future events than contemporary values. Moreover, this increase in TC intensities will likely exceed building codes upon which facilities in coastal regions were constructed, resulting in increased losses and widespread damage. Recent hurricane activity indicates that cities in the U.S. possibly face a far greater threat from major TC events than this or previous research suggests.

To mitigate this increasing threat, coastal municipalities must adopt actionable adaptation methods and strategies into infrastructure sustainment and development plans. Just as there is no singular standard that can be implemented to avoid losses from all possible future TCs, no singular adaptation strategy should be considered. A range of infrastructure adaptation portfolios should be created to allow for alternative resiliency options. These options can be optimized by balancing decision-maker risk tolerances, fiscal availability, and resource limitations factors. Performing infrastructure system-level risk assessments for coastal regions aids in bridging the gap for actionable research provided by climate scientists for coastal asset managers. Such assessments should consider geospatial storm damage parameters, both temporally and spatially, to develop climate signals to provide the greatest reduction of risk through determining appropriate adaptation measures before future intensified TCs are realized. This research can be expanded to other coastal municipalities, provided adjustments are made for specific geographic parameters and regional TC extremes.

IV. Scholarly Article 2: Dynamic adaptation using infrastructure system-level climate signals to inform strategies: an economic-based policy pathway comparison

Abstract

As climate change imposes uncertainty on the frequency and intensity of Atlantic hurricanes, coastal cities struggle to adapt infrastructure portfolio sustainment and development plans. Numerous risk analyses and climate adaptation strategies have been produced for coastal regions, mostly at coarse spatial resolutions. These strategies generally lack the granularity required by asset managers and decision-makers to take adaptive action, and even when action is possible, there is little guidance on implementing adaptive measures. As such, the advancement of coastal infrastructure adaptation to hurricane threats in the U.S. has largely been slow to progress, limited in scope, and minimal in effect. To ensure facility managers are equipped with actionable information, spatial storm damage simulation software must be coupled with facility-level data to ensure risks and adaptation strategies are actionable and can be combined to develop dynamic policy pathways for improved system protection. These strategies and pathways provide a balance between future condition uncertainty and infrastructure adaptation benefit. This concept is applied in a case study analysis of Eglin Air Force Base in northwestern, Florida, using Monte Carlo forecast simulations for a probabilistic, 100-year multi-threat hurricane event occurring over various threat horizons and climate conditions, throughout the next 80 years. Infrastructure adaptation strategies are applied to a sample facility portfolio and combined to develop possible dynamic policy pathways. Results show that the development of such pathways can balance risk, benefit, and implementation cost for infrastructure systems to improve community resilience under future condition uncertainty.

1 Introduction

Major tropical cyclones, categorized as hurricanes, have caused widespread devastation and destruction to coastal regions over the last several decades (Boccard, 2021; Klotzbach et al., 2018). This threat is expected to intensify over the remainder of the century, as climate change amplifies (Fraza et al., 2016; Knutson et al., 2020) and increases the frequency of major categorical hurricanes (Bacmeister et al., 2016). For the U.S., it is expected that future, climate-intensified hurricanes will cause significantly higher economic losses compared to contemporary values (CBO, 2019; Franzke and Czupryna, 2020). To mitigate this growing threat, coastal cities have begun to investigate options to improve infrastructure resilience against climate change (Shi & Varuzzo, 2020) and hurricane risks (NRC, 2014). However, the impacts of these efforts have largely been limited in scope and minimal in effect (Contento et al., 2019; Woodruff et al., 2018).

While multiple adaptation strategies have been developed to combat climate change and specific aspects of hurricanes, such as sea-level rise (SLR) and storm surge (NRC, 2014; Horn, 2015), there exists a gap between climate adaptation research for the needed development of actionable strategies to inform infrastructure improvement and sustainment plans (Woodruff & Stults, 2016). The largest contributor to this lack of actionable guidance is that coastal regions do not fully understand the protection levels that are needed to mitigate losses from future hurricanes given global climate uncertainty (GAO, 2019; Vousdoukas et al., 2018).

Research conducted on predicting future climate conditions is traditionally too coarse spatially to be actionable for asset-managers. While such research may provide a thorough evaluation of possible future conditions, the results are discussed at a broad scale, such as at the city or census tract-level (Hallegatte, 2011; Shi & Varuzzo, 2020) and therefore do not translate into executable sustainment practices. Similarly, research that downscales hazards to the infrastructure system-levels may not consider the risks, benefit, or costs associated with adaptation or lack thereof, under future condition uncertainty (Elsner et al., 2011; Klima et al., 2012; Sichani et al., 2020). A rising asset management practice has been developed to overcome this. Dynamic adaptive policy pathways (DAPPs) are used to balance system sustainment and improvement with future condition uncertainty (Haasnoot et al., 2013). A key concept with DAPPs is the triggering of adaptation measures using climate signals, identified periods when condition uncertainty tips future possibilities past tolerance thresholds and new mitigation action should be taken (Ramm et al., 2018).

Using DAPPs to mitigate climate uncertainty for coastal regions is theoretically beneficial (Lawrence et al., 2019a; Ramm et al., 2018). However, just as developing one set of building standards will not protect infrastructure from all possible future conditions

(Simmons et al., 2019), DAPPs are most beneficial when composed of ensembles of climate scenarios and portfolios of adaptation strategies to inform actionable, risk-centered implementation (Lawrence et al., 2018). This portfolio of adaptation strategies allows for pathways to be shifted as decision-maker tolerances change and climate conditions are realized (Lawrence & Haasnoot, 2017). The benefit of using DAPPs is also constrained by the disruptive event simulations that adaptation strategies are compared against. If only singular threat parameters are considered, such as SLR alone, then the DAPP will be ineffective in addressing multi-hazard scenarios, which hurricanes naturally produce (Misuri et al., 2019), such as SLR and storm-tide or surge. By considering an array of conditions and strategies, infrastructure system-level improvements can be determined with DAPPs on which systems should be made resilient, in what timeframe adaptation is necessary, and to what standards systems need to be adapted so future losses are mitigated (Lawrence, 2019b).

This research explores the development of a DAPP model, for a sample facility portfolio at Eglin Air Force Base (Eglin AFB) in the Florida Panhandle using climate signals derived from a probabilistic, 100-year hurricane event forecasted over the remainder of the century. This forecast is applied to estimate damages and determine costs associated with three example adaptation strategies implemented within four threat horizons: 2020, 2035, 2065, and 2100. These strategies are aggregated into possible policy pathways that can be taken with the expected risk and benefit associated with each. Comparison of pathways at each threat horizon allows for decision-maker tolerances to be considered for coastal infrastructure adaptation, which can be balanced with contemporary funding and resource limitations for execution determination.

2 Data and Methods

2.1 Eglin Air Force Base Study Region and Prior Analysis

Eglin AFB (Figure 1) is a major U.S. military installation located in northwestern Florida along the Gulf Coast, which has experienced increased hurricane activity in recent years (Bruyere et al., 2017). The installation is the largest in the Air Force, by size, encompassing over 1,870 km^2 (460K acres). It consists of over 3,000 facilities with a total replacement value of $9 billion (DoD, 2018). Eglin AFB was selected as the study area of interest due to its similarities with coastal communities and availability of prior research and facility-level data. Eglin AFB's vulnerability to hurricane activity has been studied under one major effort, which determined that there is a high likelihood of a major storm occurring by the end of the century (Scheitlin & Elsner, 2009; Scheitlin et al., 2011). Additional assessments determined the damages sustained from such a storm could increase exponentially as the century progresses due to climate change-induced intensification (Elsner et al., 2011; Baldwin et al., 2021).

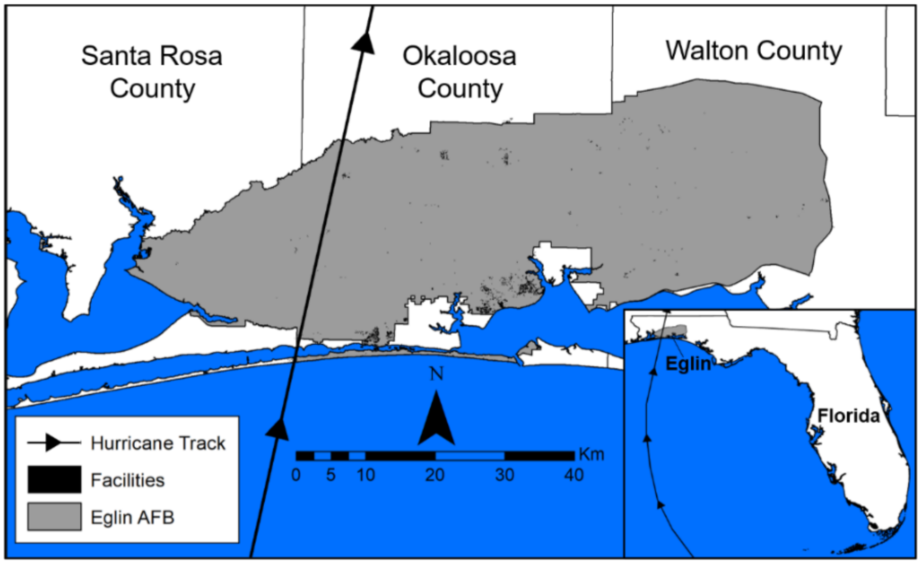


Figure 1: Eglin Air Force Base study region located in the northwestern Florida Panhandle. Hurricane track illustrates the probabilistic storm path as endogenously determined using FEMA Hazus modeling software.

Using these prior assessments provided this research a platform upon which climate signals from a probabilistic hurricane event could be used to develop realistic adaptive policy pathways for a set of sample facilities (Figure 2). These facilities, labeled A, B, and C, represent the types of structures that exist on the installation, and by extension, most coastal communities. The sample facilities' replacement values are approximately \$5, \$3, and \$10 million, respectively.

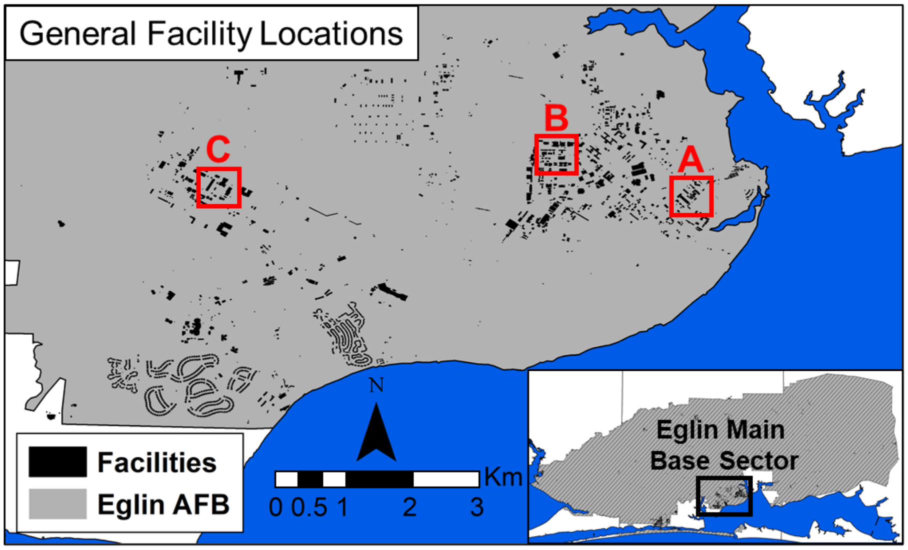


Figure 2: Eglin AFB sample facility portfolio. Boxes are intended to show general facility location. Facility A represents a masonry structure used for recreation and community support purposes, Facility B represents a concrete administrative building, and Facility C represents a large, steel-framed industrial facility.

The climate signals derived for the sample facilities determined the wind speed intensity and coupled SLR and storm surge inundation that is expected under five potential climate scenarios. These scenarios were simulated at the threat horizons using the Federal Emergency Management Agency (FEMA) Hazus multi-hazard modeling software (Baldwin et al., 2021). These five climate scenarios labeled Lowest through Highest, combined climate projections and their expected effect on hurricane wind and surge parameters to determine intensities for the sample facilities (Table 1). Storm surge was simulated using the combined effect of localized SLR and tide conditions, to simulate maximum inundations possible under each scenario. Wind intensity increases were determined using global temperature forecasts and its correlated effect on hurricane wind behavior (Bhatia et al., 2018; Knutson et al., 2019). Based upon these climate signals, adaptation strategies are developed to harden and protect the sample facility portfolio against expected wind and surge intensities.

Table 1: Eglin AFB sample facilities portfolio expected wind and surge intensities under climate-intensification scenarios (Baldwin et al., 2021).

Facility	2020		2035		2065		2100		Climate Scenario
	Wind (kts)	Surge (m)	Wind (kts)	Surge (m)	Wind (kts)	Surge (m)	Wind (kts)	Surge (m)	
A	107	0	108	0	110	0	112	0	Lowest
			108		110	0	118	1.2	Low
			109		112	0	123	2.0	Moderate
			109		113	1.8	130	3.7	High
			109		115	2.9	136	4.6	Highest
B			108	0	110	0	112	0	Lowest
			108		110		118		Low
			109		112		123		Moderate
			109		113		130		High
			109		115		136		Highest
C			108	0	111	0	113	0	Lowest
			109		111		118		Low
			109		112		124		Moderate
			109		114		130		High
			110		116		137		Highest

2.2 Monte Carlo Hurricane Forecast

An occurrence forecast for Eglin AFB using Monte Carlo simulations is performed using the climate-intensified hurricane event, hereafter referred to as Hurricane Hayley. Hurricane Hayley has an annual occurrence probability of one percent (100-year return period). While the work of Scheitlin et al. (2011) considered Hurricane

Hayley to be a ‘worst-case’ event for Eglin AFB, recent Gulf of Mexico hurricane activity suggests that this is not the case (Beven et al., 2019; Bruyere et al., 2017).

This research considered the possibility and impacts Hurricane Hayley potentially occurring by 2100. To determine the probability of occurrence consistent with threat horizons for which wind and surge intensity parameters were estimated, threat horizons 2035, 2065, and 2100 are assessed using the standard exceedance probability equation (Equation 1). Simply if Hayley were to occur in 2035, it would not occur again in 2065 or 2100. For 2020, the probability of occurrence was equal to the annual occurrence probability of one percent.

$$P(H_{TH}) = 1 - (1 - P(Hayley))^{(TH-2020)} \tag{1}$$

where:

$P(H_{TH})$ = occurrence threat horizon probability

P($Hayley$) = annual occurrence probability for Hurricane Hayley ≡ 1%

TH = occurrence threat horizon

Using the wind and surge intensities produced from the climate scenarios, facility damages were estimated using Hazus damage probability curves based upon the sample portfolio’s corresponding structure types (FEMA, 2012a; FEMA 2012b; Scawthorn et al., 2006; Vickery et al., 2006). To determine Hurricane Hayley’s intensity in each Monte Carlo forecast iteration, the climate scenarios were fitted to a normal distribution, corresponding with representative concentration pathways and global warming projections research (Jackson & Jevrejeva, 2016; Watterson, 2008), with the distribution mean equal to the Moderate climate scenario. The climate scenario distribution was then applied to each Hurricane Hayley occurrence in the forecast to calculate the number of climate scenario events that occur within each threat horizon.

2.3 Adaptation Strategies

Using the sample facility portfolio climate signals, three adaptation strategies are developed. These strategies are discussed in detail in the following sections. While this number and type adaptation strategies discussed are not exhaustive, they illustrate possible alternatives, and temporal decision points that provide value differentiation in terms of robustness, the magnitude of protection measures taken (Rehak et al., 2019). These strategies are then aggregated to form multiple policy pathways for the sample facility portfolio. Theoretical reduction in damages sustained with each adaptation strategy is accomplished with the data references used to estimate protection measure costs (FEMA, 2012a; FEMA 2012b; Klima et al., 2012; Unnikrishnan & Barbato, 2016).

2.3.1 Strategy 1: Risk-Acceptance

The first strategy is to take no active measures in improving existing infrastructure. Clearly, it simplest in terms of concept and implementation cost. While the concept may seem illogical, there is justification for its inclusion. First, hurricanes are not inevitable events; there is always a possibility that no storms will occur within a given timeframe, and even if an event were to occur, it is unlikely to be of major severity. A minor category hurricane will likely not exceed design standards for coastal infrastructure and therefore result in minimal impact. Second, infrastructure adaptation to climate-intensified standards is both expensive and socio-politically sensitive (Shao et al., 2017). For certain structures, that may be more inland or protected by human-made and natural defenses, adaptation is unnecessary as the potential for a hurricane occurring that could supersede standards is unlikely. Lastly, this approach provides a baseline, to which ‘do something’ approaches can be compared in terms of costs and benefits. This gambler’s approach, commonly referred to as risk-acceptance (Cha & Ellingwood, 2014), saves money in the short-term and is a path many coastal cities have followed for the last several decades to meet contemporary fiscal demands, based on the aforementioned justification (Shi & Varuzzo, 2020).

2.3.2 Strategy 2: Climate Signal Triggers

This strategy takes the climate signals produced by the previous research (Baldwin et al., 2021) and implements facility wind and surge protection interventions, to counteract likely future intensities, that will supersede current structural building codes. These are permanent protective measures implemented in advance of Hurricane Hayley, dependent upon which threat horizon the strategy is executed by. For wind protection, hardening measures include installing wind shutters on windows and doors, strengthening roofs, increasing tie-downs, and improving roof-wall connections against moderate climate scenario intensities, approximately 126 kts (145 mph). For surge protection, Facility A is expected to be threatened by 2 m (6.6 ft) surge inundation. Surge protection for Facility A is accomplished by wetproofing the facility against 2.13 m (7 ft) surge, which consists of raising utilities and fixtures, reconfiguring electrical and mechanical systems, installing flood openings, proofing of windows and doors, and installing of pumps (FEMA, 2013).

Estimations for facility protection measures were derived from Hazus damage adjustments (FEMA, 2012a; FEMA, 2012b), Florida building code requirements (FBC, 2020), and additional hurricane mitigation research (Klima et al., 2012; Li, 2012; Unnikrishnan & Barbato, 2016), with costs adjusted to the Eglin region and 2020 USD equivalence. Over 30 years at 3% interest, the annualized cost to implement these wind hardening standards for the sample facility portfolio is approximately $50 thousand. The cost of surge protection for Facility A is approximately $1.4 million considered a one-time cost, with minimal increase in annual maintenance. Facility B and C receive no surge protection as they are not expected to be affected at any threat horizon. While these protective measures will significantly reduce the probability of damages experienced by the sample portfolio, they do not eliminate loss possibilities for experienced storm intensities even at or below design standards.

2.3.3 Strategy 3: Maximum Robustness

This strategy protects facilities against maximum intensities, meaning all structures are made resilient to the highest expected wind and surge extremes. Such a strategy resembles the adoption of Miami-Dade County building standards that were developed after Hurricane Andrew (Klima et al., 2012; Simmons et al., 2019). Expected wind intensities to be designed against for this strategy are 139 kts (160 mph). While the most costly and intensive strategy to adopt, it has the greatest damage reduction potential.

The annualized cost to implement and maintain maximum wind hardening standards, over 30 years at 3% interest, for the sample facility portfolio is $65 thousand. Extrapolating the cost to every facility on Eglin AFB, not just the sample portfolio, would cost $215 million per year for the installation. For surge protection, Facility A wetproofing was performed against a flood elevation of 3.7 m (12 ft) and the cost to implement is approximately $1.6 million. Similar to Strategy 2, Facilities B and C receive no surge protection as they are unlikely to be flooded even under the Highest possible climate scenario.

2.4 Dynamic pathway development

Pathways were created using combinations of adaptation strategies to develop a DAPP model for the sample facility portfolio. Each pathway was determined by considering a singular strategy to implement between threat horizons. It is possible to move into more adapted states between subsequent threat horizons along each pathway, i.e., from Strategy 1 to 2 or 3, or from Strategy 2 to 3. By creating this versatile DAPP model, which allows pathways to jump between adaptation strategies, asset-managers and decision-makers have the flexibility to change course as needed or desired.

2.5 Expected Value Calculations

Using engineering economic principles, the expected benefit (E[B]) and expected risk (E[R]) associated with each pathway are determined. The risk associated with each pathway (Equation 2) is determined as the expected possibility of damages from the Hurricane Hayley forecast (Equation 3). This expected damage is determined using the facility damage caused under all climate scenarios in each threat horizon of occurrence (Equation 4). The benefit associated with each pathway is determined as the reduction in damage, i.e., loss avoidance (Equation 5). These values, along with the associated pathway implementation costs, allow for comparisons to be made between individual pathways in the sample facility DAPP.

$$E[R] = \sum_{TH=2035}^{2100} E[D_{TH}] \times P(H_{TH}) \tag{2}$$

$$E[D_{TH}] = \sum_{S=Lowest}^{Highest} D_S \times P(S) \tag{3}$$

$$P(S) = \frac{\#\ climate\ scenario\ category\ occurences}{\#\ Hayley\ occurences\ in\ threat\ horizon\ (H_{TH})} \tag{4}$$

$$E[B] = E[R]_{Strategy\ 1} - E[R] \tag{5}$$

where:

$E[D_{TH}]$ = Expected sample facility damage at TH, based on adaptation strategy selected

D_S = Sample facility damage under climate scenario category

$P(S)$ = Probability of climate scenario category

S = climate scenario category; Lowest, Low, Moderate, High, or Highest

3 Results, Discussion, and Limitations

From the Monte Carlo simulations, 5000 events were produced across the threat horizons. Overall, Hurricane Hayley occurred in 83% of the total scenarios over the remainder of the century. The threat horizons probability of occurrence (P[H_{TH}]) were equal to 1.1%, 13.4%, 31%, and 37.5% for Hurricane Hayley to occur by 2020, 2035, 2065, and 2100, respectively (Figure 3). The climate scenario categories followed a normal distribution, as expected, in each occurrence threat horizon with the largest proportion of Hurricane Hayley events being under Moderate conditions.

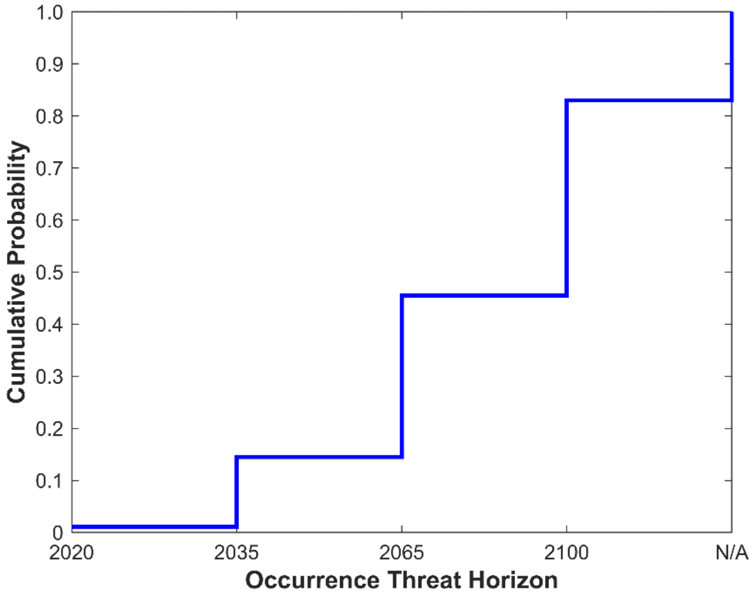
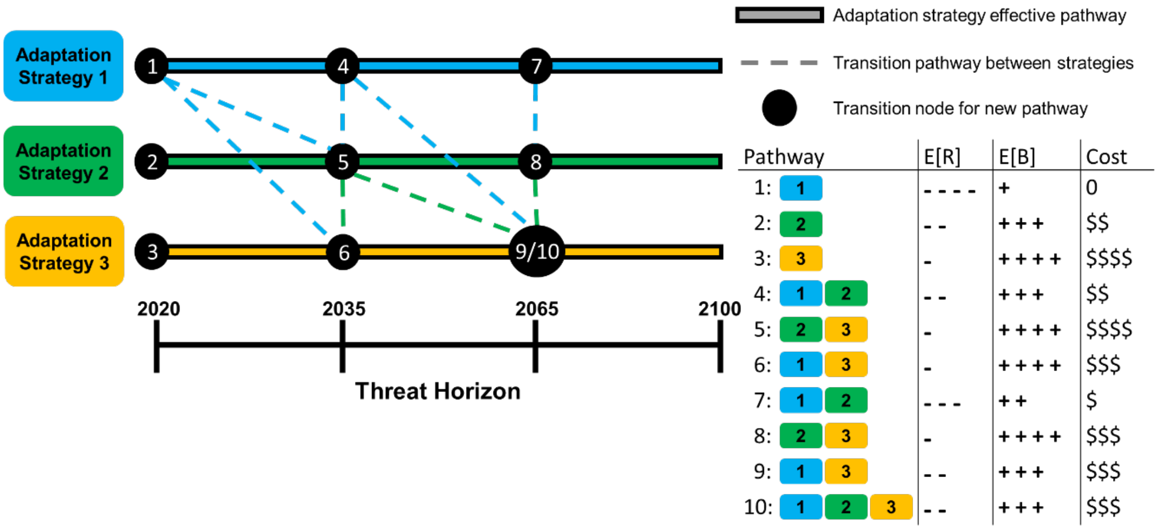


Figure 3: Hurricane Hayley occurrence forecast histogram. N/A represents the probability that Hurricane Hayley does not occur in any simulated threat horizon,

In total, ten possible pathways were created for the DAPP model (Figure 4). For Pathway 1, i.e., Strategy 1 being used throughout all threat horizons, there is the highest amount of E[R] and no implementation cost associated. However, the minor benefit with Pathway 1 comes from the cost avoidance of implementing any adaptation strategy rather than damage avoidance like the other pathways.



Pathway	E[R]	E[B]	Cost
1: 1	- - - -	+	0
2: 2	- -	+ + +	$$
3: 3	-	+ + + +	$$$$
4: 1 2	- -	+ + +	$$
5: 2 3	-	+ + + +	$$$$
6: 1 3	-	+ + + +	$$$
7: 1 2	- - -	+ +	$
8: 2 3	-	+ + + +	$$$
9: 1 3	- -	+ + +	$$$
10: 1 2 3	- -	+ + +	$$$

Figure 4: Eglin AFB sample facility DAPP model with E[R], E[B], and cost comparison

Comparison of the adaptation pathways impact on the damage expectancy for the sample portfolio shows that there is not one overall, superior strategy for every threat horizon. Tradeoffs associated with more robust pathways (Pathways 2-6) are a higher E[B] to E[R] ratio, but a higher cost of implementation. Conversely, pathways that defer adaptation until later in the century (Pathways 7-9) generally have lower E[B] and higher E[R] associated but cost less to implement, as they cover a smaller range of threat horizons. Pathway 10 balances occurrence probability with adaptation strategies and has a moderate E[B], E[R], and cost. In determining which pathway to implement at any given threat horizon, E[B] should be compared with tradeoffs, such as E[R], cost, and other non-economic factors.

While this comparison is economically based, fiscal loss is not the only criteria that could be observed to calculate risk and benefit. For Eglin AFB mission degradation due to facility damage would be of major concern, and therefore protecting facilities that are vital to military operations, such as Facility C, may be of higher importance than less critical buildings, like Facility A, even though there is a lower likelihood of severe damage from future storms. Optimization principles can be applied to weight risk-tolerances of decision-makers to see which strategy is ‘optimal’ (Schuldt et al., 2020). However, such tolerances will change as decision-maker personalities and resource availability or limitations evolve over time (Aengenheyster et al., 2018).

Similarly, the cost associated with each adaptation pathway is dependent upon the parameters upon which the strategies are defined. As such, various factors will impact the true cost of implementation, such as the speed of execution, deferred maintenance practices, or material usage. While this research only considers one hurricane event, to determine a cost-benefit comparison between pathways the entirety of loss avoidance from multiple hurricane probabilities should be considered, such as multiple regional storms of varying intensity. While the cost-benefit relationship will vary for each pathway, it is expected that in general investment in future risk mitigation techniques will yield a positive cost-benefit relationship to be significantly higher than the amount invested, albeit with expected benefits-per-dollar decreasing as more robust mitigation measures are implemented (NIBS, 2018).

Additionally, the Eglin AFB sample facility DAPP model only focuses on a small portion of the installation’s structures. While expanding this analysis to all structures on Eglin AFB structures is preferred and would lead to more comprehensive results, such an analysis is outside the scope of this research effort. This model also only considers four possible threat horizons for years of storm occurrence. Intermediate years were not considered, and as such are not a complete temporal risk analysis for the remainder of the century. It is recommended that future research on comparing infrastructure adaptive policy pathways use expanded hurricane forecast analysis coupled with multiple adaptation strategies to produce more comprehensive dynamic policy pathways. Such improvements on the methodology used here are expected to enhance the theoretical benefit of using infrastructure system-level climate signals to inform DAPPs for coastal municipalities.

4 Summary and Conclusion

While the occurrence and severity of climate-intensified hurricane events are uncertain, it is expected that future storms will produce higher intensities and resultant damages over contemporary values. Additionally, major category hurricanes are expected to occur more frequently for coastal regions and further compound future risks. The inclusion of sound infrastructure adaptation strategies into asset sustainment and maintenance plans is crucial to mitigating this threat. However, such strategies must be implementable. As decision-maker tolerances and resource limitations change over time, it is clear no single infrastructure adaptation strategy may be considered truly optimal over the remainder of the century. The combined use of multiple improvement strategy possibilities along with future condition uncertainty predictions can lead to more beneficial infrastructure adaptation results.

This paper has performed a probabilistic climate-intensified hurricane forecast for a coastal region across varying climate conditions. The resultant intensities experienced at the infrastructure-system level were then evaluated to form adaptation strategies that informed a dynamic adaptive policy pathway model. Decision-makers and asset managers can use this model to balance adaptation pathways expected benefit, future risk, and cost with contemporary limitations as risk-tolerances and climate conditions change over time. The resultant use of such dynamic pathways will ultimately create actionable options to inform coastal infrastructure sustainment and adaptation policies and plans.

V. Conclusions and Recommendations

Conclusions of Research

This thesis focused on using climate-intensified hurricane events to assess infrastructure system-level risks to inform the development of adaptation pathways to improve coastal installation resilience. This was accomplished by addressing three primary research objectives:

1. Determine how climate change is expected to affect future hurricane behavior and what risk DoD coastal installations face throughout the 21st century.
2. Apply multi-hazard modeling tools to simulate losses and intensities experienced by coastal installations from climate-intensified hurricanes.
3. Develop infrastructure adaptation pathways to aid DoD decision-makers' and planners' incorporation of actionable resilience measures within installation master development plans.

The first objective was accomplished by a thorough review of existing literature on expected climate change effects on hurricane parameters, discussed in Chapter 3. Climate change, specifically global temperature and SLR rise, was applied to a baseline hurricane profile (Appendix) to project expected changes throughout the century. The resultant storm intensities produced differed for both wind speeds and storm surge values across multiple climate scenarios. However, the general trend of climate change effects suggests that wind speeds and storm surge intensities produced by major category hurricane events will be exponentially higher than contemporary values as the century progresses. As a result of these strengthened intensities, it is expected that losses sustained by coastal regions will exponentially increase unless adaptation measures are implemented.

The second objective was also accomplished in Chapter 3 by simulating climate-intensified hurricane events on a coastal installation study region, Eglin AFB. FEMA Hazus software was used to simulate 16 climate-intensified hurricanes at the installation. These simulated events consisted of both wind and flooding models to capture the multi-threat nature of hurricanes. The resultant damages sustained by Eglin AFB from the intensified storms drastically increase across the century. The produced intensities from the climate-intensified storms were then downscaled to the facility-level to determine the spatiotemporal variations across the installation. These variations were captured for a sample facility portfolio at Eglin AFB to produce climate signals of when expected storm parameters will supersede design tolerances.

The third objective was accomplished by using the climate signals determine in Chapter 3 to develop possible adaptation strategies that could be aggregated together to form dynamic policy pathways. Such pathways were completed in Chapter 4 for the sample facility portfolio at Eglin AFB. These pathways consisted of combining differing adaptation strategies that coastal installations could implement to mitigate losses. Inclusion of such pathways in installation master development plans allows for decision-makers to balance risk-tolerances and contemporary limitations, such as funding availability. Although the benefit and risk associated with each pathway vary, all adaptive states result in improved loss mitigation over non-adaptive states. Therefore, investment in infrastructure adaptation, even under uncertainty, will result in improved benefits and lowered hurricane risks for Eglin AFB.

Combining these objectives with the literature associated with infrastructure resiliency and DoD decision practices discussed in Chapter 2 creates a possible resiliency project funding process using the adaptation pathway metrics. Including such pathways in coastal installation infrastructure development and sustainment plans allows for long-term project planning to be accomplished for which funding can be budgeted accordingly. Instead of having resilience enhancement projects compete yearly for limited funds, adaptation pathways allow for budgetary consideration to be made throughout the century of when adaptation projects are needed. By comprehensively planning for and budgeting adaptation projects within infrastructure development and sustainment plans, the resilience of coastal infrastructure-systems can be improved even under future climate condition and extreme weather event uncertainty.

Contributions of Research

This thesis effort contributed to the development and advancement of the following areas:

1. Understanding of the holistic risk that coastal installations face from future hurricane events due to climate change effects.
2. Development of a hurricane simulation methodology that asset managers can use to forecast climate condition effects on infrastructure systems.

3. Creation of climate signals for facilities on a coastal installation that identify when adaptation is necessary and to what degree tolerance thresholds will likely be exceeded.
4. An original dynamic adaptation pathway model that can be used to optimize benefits, risks, and costs to inform installation master development and sustainment plans.
5. Identification of a feasible opportunity for incorporating resilience improvements under uncertainty within existing infrastructure DoD funding and decision-making processes.

Significance of Research

The significance of this research is the development of an infrastructure adaptation methodology and framework that Air Force asset managers can apply to localized regions. The use of this framework will allow for base-level asset managers and planners to develop adaptation portfolios for existing infrastructure under uncertain future conditions. This will ultimately help bridge the gap between climate research and actionable adaptation that has limited DoD infrastructure resilience progress. This thesis is novel in its approach as it is the first effort to apply coupled multi-hazard modeling and climate projections tools that are readily available to perform an in-depth analysis of resiliency and adaptation to climate-intensified extreme weather events at a U.S. military installation. This provides the groundwork upon which follow-on research efforts can be conducted, which are already underway at the Air Force Institute of Technology.

Additionally, this thesis produced the development of two peer-reviewed journal articles that are currently in review and a presentation at an international conference thus furthering the academic and military community's understanding of the topics discussed here.

Future Research Recommendations

While the research performed advances the holistic understanding of infrastructure resiliency for coastal installations, additional research areas should be explored to improve the frameworks presented. Future research should explore:

1. Inclusion of additional hurricane events. This thesis simulates one hurricane event, Hurricane Hayley, potentially occurring within the remainder of the century. For more comprehensive risk and resilience assessments, multiple hurricanes of varying magnitude need to be probabilistically simulated throughout the century. Doing so will further illuminate the temporal aspect of when climate-intensified hurricanes will likely occur and exceed facility design standards.
2. Alternative hurricane profiles and hazard-driven events. Hurricane Hayley is predominately a wind-driven event. Future research is needed to examine hurricane profiles with different risk mixtures, such as rain-driven, slower translating, and lower pressure events. Surely, these will alter the damage parameters and intensities experienced by coastal installations. A variety of intensities, storm-profiles, and horizons should be computed to assess risks

more comprehensively for infrastructure and produce robust adaptation pathways.

3. Modeling of comprehensive military-specific facility information for robust adaptation strategy comparison. The research presented here focuses on a few facilities, mostly to simplify the presentation results and as proof of the larger framework’s ability to downscale risks to the facility-level. Additional research is required to perform a comprehensive assessment for installations. Ideally, adaptation portfolios for affected facilities should be developed to create installation-level resilience and vulnerability metrics. Tradeoffs between portfolio executions, i.e., the order in which adaptation projects are completed, must be explored and provided as alternatives for decision-makers.
4. Coupling of existing DoD infrastructure programs with geospatial analysis software for tailored toolsets available to installation asset managers and planners. To fully assess storm-related risks to installations, facilities data must be coupled with the risk maps produced by Hazus. While this process is no longer novel, it is necessary to accomplish future research topic 3.
5. Development of a comprehensive DoD funding strategy that can be utilized by all branches of service. Ultimately, adaptation pathways are demand signals. Without appropriate funding mechanisms providing a corresponding supply signal, installations have little incentive to produce pathways, and likely an even smaller chance of having these projects funded since adaptation

projects may be in direct conflict with service scoring models. Work should focus on developing feasible policy levers, and ideally those that can be integrated into the current project funding methodology.

Exploration of these research areas will improve the adaptation and modeling framework presented in this thesis. Ultimately, such research can lead to improved adaptation pathways for DoD coastal installations to include in infrastructure development and sustainment plans. Continued research on this topic is needed to create dynamic resilience strategies to meet DoD directives and improve the longevity of military installations in an ever-changing global climate.

Appendix: Hurricane Hayley Hazus Deterministic Event Inputs

Baseline 2020 Profile (Schietlin et al., 2011)

Point	Latitude	Longitude	Translation Speed (ft/s)	Radius to Max Winds (mi)	Sustained Wind Speed* (ft/s)	Central Pressure (mbr)	Inland Binary
1	-84.6	23	12.97	21.75	110.06	960.7	0
2	-85.3	23.7	12.30	21.75	122.58	949.8	0
3	-85.9	24.4	12.97	21.75	126.39	946.4	0
4	-86.5	25.2	13.42	21.75	129.52	943.5	0
5	-86.9	26	13.65	21.75	124.37	948.2	0
6	-87.1	26.9	13.65	21.75	117.44	954.4	0
7	-87.2	27.8	14.54	21.75	116.10	955.6	0
8	-87.2	28.6	14.09	21.75	118.11	953.8	0
9	-87	29.5	14.76	21.75	116.99	954.8	0
10	-86.8	30.4	15.21	21.75	106.48	963.6	1
11	-86.6	31.3	17.22	21.75	77.17	985	1
12	-86.3	32.2	28.86	21.75	53.46	998.6	1

2035 Hurricane Hayley Wind Speeds*

Point	Climate Forecast Scenario				
	LL	L	M	H	HH
1	110.26	110.44	110.64	110.83	111.03
2	122.80	123.01	123.23	123.44	123.66
3	126.61	126.83	127.06	127.27	127.50
4	129.75	129.97	130.21	130.43	130.66
5	124.60	124.81	125.03	125.24	125.47
6	117.65	117.85	118.06	118.26	118.47
7	116.31	116.50	116.71	116.91	117.12
8	118.32	118.52	118.74	118.94	119.15
9	117.20	117.40	117.61	117.81	118.02
10	106.67	106.85	107.04	107.22	107.42
11	77.31	77.44	77.58	77.71	77.85
12	53.56	53.65	53.75	53.84	53.93

2065 Hurricane Hayley Wind Speeds*

Point	Climate Forecast Scenario				
	LL	L	M	H	HH
1	111.82	113.58	115.23	116.99	118.75
2	124.55	126.51	128.35	130.31	132.27
3	128.41	130.43	132.33	134.35	136.37
4	131.59	133.66	135.61	137.68	139.75
5	126.36	128.35	130.22	132.21	134.20
6	119.32	121.20	122.96	124.84	126.72
7	117.95	119.81	121.55	123.41	125.27
8	120.00	121.89	123.66	125.55	127.44
9	118.86	120.74	122.49	124.36	126.23
10	108.18	109.89	111.48	113.19	114.89
11	78.41	79.64	80.80	82.04	83.27
12	54.32	55.17	55.98	56.83	57.69

2100 Hurricane Hayley Wind Speeds*

Point	Climate Forecast Scenario				
	LL	L	M	H	HH
1	115.56	121.06	126.57	132.07	137.57
2	128.71	134.84	140.97	147.10	153.23
3	132.71	139.03	145.35	151.66	157.98
4	135.99	142.47	148.95	155.42	161.90
5	130.59	136.81	143.03	149.25	155.47
6	123.31	129.18	135.06	140.93	146.80
7	121.90	127.71	133.51	139.32	145.12
8	124.02	129.92	135.83	141.73	147.64
9	122.84	128.69	134.54	140.39	146.24
10	111.80	117.13	122.45	127.77	133.10
11	81.03	84.89	88.75	92.61	96.47
12	56.14	58.81	61.48	64.16	66.83

Bibliography

Aengenheyster, M., Feng, Q. Y., van der Ploeg, F., and Dijkstra, H. A. (2018). The point of no return for climate action: effects of climate uncertainty and risk tolerance. *Earth System Dynamics*, 9(3), 1085–1095. https://doi.org/10.5194/esd-9-1085-2018

Air Force Policy Directive (AFPD) 10-24. (2019). *Operations: mission assurance.* Washington, DC: U.S. Department of Defense. https://static.e-publishing.af.mil/production/1/af_a3/publication/afpd10-24/afpd10-24.pdf

Air Force Civil Engineer Center (AFCEC). (2019). *FY 21-25 AFCAMP business rules.* San Antonio, TX: Air Force Installation and Mission Support Center.

Akerlof, K., Maibach, E. W., Fitzgerald, D., Cedeno, A. Y., and Neuman, A. (2013). Do people "personally experience" global warming, and if so how, and does it matter? *Global Environmental Change*, 23(1), 81-91. https://doi.org/10.1016/j.gloenvcha.2012.07.006

Alderson, D. L., Brown, G. G., and Carlyle, W. M. (2015). Operational models of infrastructure resilience. *Risk Analysis*, 35, 562-586. https://doi.org/10.1111/risa.12333

Bacmeister, J., Reed, K., Hannay, C., Lawrence, P., Bates, S., Truesdale, J., Rosenbloom, N., and Levy, M. (2016). Projected changes in tropical cyclone activity under future warming scenarios using a high-resolution climate model. *Climate Change,* 146, 547-560. https://doi.org/10.1007/s10584-016-1750-x

Baldwin, A., Chini, C., Schuldt, S., and Delorit, J. (2021). Resilient to what? Downscaling multi-hazard, tropical cyclone risk assessments for coastal cities to infrastructure system levels. *Earth's Future*. Unpublished article.

Barbato, M., Petrini, F., Unnikrishnan, V. U., and Ciampoli, M. (2013). Performance-Based Hurricane Engineering (PBHE) framework. *Structural Safety*, 45, 24-35. https://doi.org/10.1016/j.strusafe.2013.07.002

Beven, J., Berg, R., and Hagen, A. (2019). *Tropical cyclone report: Hurricane Michael (AL142018).* Miami, FL: National Hurricane Center. https://www.nhc.noaa.gov/data/tcr/AL142018_Michael.pdf

Bhatia, K., Vecchi, G., Murakami, H., Underwood, S., and Kossin, J. (2018). Projected response of tropical cyclone intensity and intensification in a global climate model. *Journal of Climate*, 31(20), 8281-8303. https://doi.org/10.1175/JCLI-D-17-0898.1

Blake, E. and Zelinsky, D. (2018). *tropical cyclone report: Hurricane Harvey (AL092017)*. Miami, FL: National Hurricane Center.

Boccard, N. (2021). Analysis of trends in disaster risk. *International Journal of Disaster Risk Reduction,* 53, 101989. https://doi.org/10.1016/j.ijdrr.2020.101989

Bruyere, C. L., Rasmussen, R., Gutmann, E., Done, J., Tye, M., Jaye, A., … Niesel, J. (2017). *Impact of climate change on Gulf of Mexico hurricanes*. Boulder, CO: National Center for Atmospheric Research (NCAR). http://dx.doi.org/10.5065/D6RN36J3

Cha, E. and Ellingwood, B. (2014). Attitudes towards acceptance of risk to buildings from extreme winds, *Structure and Infrastructure Engineering*, 10(6), 697-707. https://doi-org.afit.idm.oclc.org/10.1080/15732479.2012.758642

Chang, Y., Wilkinson, S., Seville E., and Potangaroa, R. (2012) Changes in resource need for post-disaster reconstruction: a longitudinal study in China. *Building Research & Information*, 40(3), 327-336. https://doi.org/10.1080/09613218.2012.684867

Congressional Budget Office (CBO). (2019). *Expected costs of damages from hurricane winds and storm-related flooding.* Washington, DC: Congress of the United States.

Contento, A., Xu, H., and Gardoni, P. (2019). Chapter Two - Risk Analysis for Hurricanes Accounting for the Effects of Climate Change. In E. Bastidas-Arteage and M. G. Stewar (Eds.), Climate Adaptation Engineering (pp. 39-72), Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-816782-3.00002-4

Crossett, K., Ache, B., Pacheco, P., Haber, K. (2013). *National coastal population report: population trends from 1970 to 2020.* Washington, DC: National Oceanic and Atmospheric Administration.

Cui, W. and Caracoglia, L. (2016). Exploring hurricane wind speed along US Atlantic coast in warming climate and effects on predictions of structural damage and intervention costs. *Engineering Structures*, *122*, 209–225. https://doi.org/10.1016/j.engstruct.2016.05.003

Dehring, C. A., and Halek, M. (2013). Coastal building codes and hurricane damage. *Land Economics*, 89(4), 597–613. https://doi.org/10.3368/le.89.4.597

Department of Defense (DoD) Directive 3020.40. (2016). *Mission assurance (MA).* Washington, DC: U.S. Department of Defense. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodd/302040p.pdf?ver=2018-09-11-131221-983

Department of Defense (DoD) Directive 4715.21. (2016). *Climate change adaptation and resilience.* Washington, DC: U.S. Department of Defense. https://dod.defense.gov/Portals/1/Documents/pubs/471521p.pdf

Department of Defense (DoD). (2018). *Base structure report: fiscal year 2018 baseline, a summary of the real property inventory data*. Washington, DC: U.S. Department of Defense.

Department of Defense (DoD). (2019). *Reports on effects of a changing climate to the Department of Defense.* Washington, DC: U.S. Department of Defense. https://media.defense.gov/2019/Jan/29/2002084200/-1/1/1/CLIMATE-CHANGE-REPORT-2019.PDF

Elsner, J., Lewers, S., Malmstadt, J., and Jagger, T. (2011). Estimating *contemporary* and future wind-damage losses from hurricanes affecting Eglin air force base, Florida. *Journal of Applied Meteorology and Climatology*, 50(7), 1514–1526. https://doi.org/10.1175/2011JAMC2658.1

Elsner, J., Kossin, J., and Jagger, T. (2008). The increasing intensity of the strongest tropical cyclones. *Nature,* 455, 92-95. https://doi.org/10.1038/nature07234

Emanuel, K. (2017). Will global warming make hurricane forecasting more difficult? *Bulletin of American Meteorological Society,* 98(3), 495-501. https://doi.org/10.1175/BAMS-D-16-0134.1

Everstine, B. (2019). NOAA upgrades Hurricane Michael to Category 5, the 4th in U.S. history. *The Air Force Magazine*. https://www.airforcemag.com/noaa-upgrades-hurricane-michael-to-category-5-the-4th-in-us-history/

Feldmann, M., Emanuel, K., Shu, L., and Lohmann, U. (2019). Estimation of Atlantic tropical cyclone rainfall frequency in the United States. *Journal of Applied Meteorology & Climatology*, 58, 1853-1867. https://doi.ord/10.1175/JAMC-D-19-0011.1

Federal Emergency Management Agency (FEMA). (2012a). *Multi-hazard loss estimation methodology: flood model technical manual.* Washington, DC: United States Department of Homeland Security. https://www.fema.gov/sites/default/files/2020-09/fema_hazus_flood-model_technical-manual_2.1.pdf

Federal Emergency Management Agency (FEMA). (2012b). *Multi-hazard loss estimation methodology: hurricane model technical manual.* Washington, DC: United States Department of Homeland Security. https://www.fema.gov/sites/default/files/2020-09/fema_hazus_hurricane-model_technical-manual_2.1.pdf

Federal Emergency Management Agency (FEMA). (2013). *Floodproofing non-residential buildings*. Washington, DC: United States Department of Homeland Security. https://www.fema.gov/sites/default/files/2020-07/fema_p-936_floodproofing_non-residential_buiildings_110618pdf.pdf

Federal Emergency Management Agency (FEMA). (2018a). *Hazus flood model user guidance.* Washington, DC: United States Department of Homeland Security. https://www.fema.gov/sites/default/files/2020-09/fema_Hazus_flood_user-guidance_4.2.pdf

Federal Emergency Management Agency (FEMA). (2018b). *Hazus hurricane model user guidance.* Washington, DC: United States Department of Homeland Security. https://www.fema.gov/sites/default/files/2020-09/fema_Hazus_hurricane_user-guidance_4.2.pdf

Florida Building Code (FBC). (2020). *Test protocols for high-velocity hurricane zones* (7th ed.). Retrieved from https://codes.iccsafe.org/content/FLTP2020P1

Franchin, P. and Cavalieri, F. (2015). Probabilistic assessment of civil infrastructure resilience to earthquakes. *Computer-Aided Civil and Infrastructure Engineering*, 30, 583-600. https://doi.org/10.1111/mice.12092

Franzke, C. and Czupryna, M. (2020). Probabilistic assessment and projections of US weather and climate risks and economic damages. *Climatic Change,* 158, 503–515. https://doi.org/10.1007/s10584-019-02558-8

Fraza, E. and Elsner, J. B. (2014). A spatial climatology of North Atlantic hurricane intensity change. *International Journal of Climatology*, 34(9), 2918–2924. https://doi.org/10.1002/joc.3884

Fraza, E. and Elsner, J. B. (2015) A climatological study of the effect of sea-surface temperature on North Atlantic hurricane intensification. *Physical Geography*, 36(5). 395-407. https://doi.org/10.1080/02723646.2015.1066146

Fraza, E., Elsner, J. B., and Jagger, T. H. (2016). A space & time statistical climate model for hurricane intensification in the North Atlantic basin. Advances in Statistical Climatology, Meteorology and Oceanography, 2(2), 105–114. https://doi.org/10.5194/ascmo-2-105-2016

Government Accountability Office (GAO). (2019). *Climate resiliency: DoD needs to assess risk and provide guidance on use of climate projections in installation master plans and facilities designs*. Washington, DC: Congressional Budget Office. https://www.gao.gov/assets/700/699679.pdf

Grudo, G. (2017). When Andrew hammered Homestead. *The Air Force Magazine.* https://www.airforcemag.com/article/when-andrew-hammered-homestead/

Haasnoot, M., Kwakkel, J. H., Walker, W. E., and Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2), 485-498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Hall, J. A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger. (2016). *Regional sea level scenarios for coastal risk management: managing the uncertainty of future sea level change and extreme water levels for Department of Defense coastal sites worldwide*. Washington, DC: U.S. Department of Defense.

Hauer, M., Evans, J., and Mishra, D. (2016). Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, 6. https://doi.org/10.1038/NCLIMATE2961

Herrera, J. G. (2021). *Military installation resilience: what does it mean?* Washington, DC: U.S. Congressional Research Service. https://www.everycrsreport.com/files/2021-01-06_IN11566_e792abaa4080c20af2d4b0ee49f0a9e05604808d.pdf

Holling, C. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4(1), 1-23. https://doi.org/10.1146/annurev.es.04.110173.000245

Horn, D. (2015). Chapter 6 - storm surge warning, mitigation, and adaptation. In J. F. Shroder, J. T. Ellis, and D. J. Sherman (Eds.), *Coastal and marine hazards, risks, and disasters* (pp. 153-180). Elsevier. https://doi.org/10.1016/B978-0-12-396483-0.00006-6

Jackson, L. and Jevrejeva, S. (2016). A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. *Global and Planetary Change*, 146, 179-189. https://doi.org/10.1016/j.gloplacha.2016.10.006

Kappes, M. S., Keiler, M., von Elverfeldt, K., and Glade, T. (2012). Challenges of analyzing multi-hazard risk: a review. *Natural Hazards,* 64(2), 1925-1958. https://doi.org/10.1007/s11069-012-0294-2

Klima, K., Lin, N., Emanuel, K., Morgan, G., and Grossmann, I. (2012). Hurricane modification and adaptation in Miami-Dade County, Florida. *Environmental Science & Technology,* 46(2), 636-642. https://doi.org/10.1021/es202640p

Klotzbach, P., Bowen, S., Pielke, R., and Bell, M. (2018). Continental U.S. hurricane landfall frequency and associated damage: observations and future risks. *Bulletin of the American Meteorological Society,* 99(7), 1359-1376. https://doi.org/10.1175/BAMS-D-17-0184.1

Knutson, T., Camargo, S., Chan, J., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., and Wu, L. (2020). tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, 101(11), 303–322. https://doi.org/10.1175/BAMS-D-18-0194.1

Kossin, J. (2018). A global slowdown of tropical-cyclone translation speed. *Nature,* 558, 104–107. https://doi.org/10.1038/s41586-018-0158-3

Kwakkel, J. H., Walker, W. E., and Haasnoot, M. (2016). Coping with the wickedness of public policy problems: approaches for decision making under deep uncertainty. *Journal of Water Resources Planning and Management*, 142(3). https://doi.org/10.1061/(ASCE)WR.1943-5452.0000626

Lawrence, J. and Haasnoot, M. (2017). What it took to catalyze uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science & Policy*, 68, 47-57. http://dx.doi.org/10.1016/j.envsci.2016.12.003

Lawrence, J., Bell, R., Blackett, P., Stephens, S., and Allan, S. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. *Environmental Science & Policy*, 82, 100-107. https://doi.org/10.1016/j.envsci.2018.01.012

Lawrence, J., Bell, R., and Stroombergen, A. (2019a). A hybrid process to address uncertainty and changing climate risk in coastal areas using dynamic adaptive pathways planning, multi-criteria decision analysis & real options analysis: A New Zealand application. *Sustainability*, 11, 406. https://doi.org/10.3390/su11020406

Lawrence J., Haasnoot M., McKim L., Atapattu D., Campbell G., and Stroombergen A. (2019b). Dynamic adaptive policy pathways (DAPP): from theory to practice. In: Marchau V., Walker W., Bloemen P., Popper S. (Eds.), *Decision making under deep uncertainty*, Springer. https://doi.org/10.1007/978-3-030-05252-2_9

Li, Y. and Ellingwood, B. (2006). Hurricane damage to residential construction in the US: Importance of uncertainty modeling in risk assessment. *Engineering Structures*, 28(7), 1009-1018. https://doi.org/10.1016/j.engstruct.2005.11.005

Li, Y., Van de Lindt, J., Dao, T., Bjarnadottir, S., and Ahuja, A. (2012). Loss analysis for combined wind and surge in hurricanes. *Natural Hazards Review*, 13(1), 1–10. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000058

Liu, M., Vecchi, G., Smith, J., and Knutson, T. (2019). Causes of large projected increases in hurricane precipitation rates with global warming. *npj Climate and Atmospheric Sciences,* 2, 38. https://doi.org/10.1038/s41612-019-0095-3

Masoomi, H., van de Lindt, J., Ameri, M., and Do., T. (2019). Combined wind-wave-surge-hurricane-induced damage prediction for buildings. *Journal of Structural Engineering*, 145(1). https://doi.org/10.1061/1943-541X.0002241

McGrath, H., Stefanakis, E., and Nastev, M. (2015). Sensitivity analysis of flood damage estimates: A case study in Fredericton, New Brunswick. *International Journal of Disaster Risk Reduction*, 14, 379–387. https://doi.org/10.1016/j.ijdrr.2015.09.003

Michaels, P. J., Knappenberger, P. C., and Davis, R. E. (2006). Sea-surface temperatures and tropical cyclones in the Atlantic basin, *Geophysical Research Letters*, 33, L09708. https://doi.org/10.1029/2006GL025757

Meehl, G., Karl, T., Easterling, R., Changnon, S., Pielke, R., Changnon, D., and Zwiers, F. (2000). An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *Bulletin of the American Meteorological Society,* 81(3), 413–416. https://www.jstor.org/stable/26215113

Mendelsohn, R., Emanuel, K., and Chonabayashi, S. (2011). *The impact of climate change on global tropical storm damages*. World Bank Policy Research Working Paper No. 5562. Available at SSRN: https://ssrn.com/abstract=1955106

Misuri, A., Moreno, V. C., Quddus, N., and Cozzani, V. (2019). Lessons learnt from the impact of Hurricane Harvey on the chemical and process industry. *Reliability Engineering & System Safety,* 190, 106521. https://doi.org/10.1016/j.ress.2019.106521

Moftakhari, H., AghaKouchak, A., Sanders, B., and Matthew, R. (2017). Cumulative hazard: the case of nuisance flooding. *Earth's Future*, 5(2), 214-223. https://doi.org/10.1002/2016EF000494

Narayanan, A., Knopman, D., Van Abel, K., Miller, B., Burger, N., Merrill, M., Rothenberg, A., Muggy, L., and Mills, P. (2019). *Valuing Air Force electric power resilience: a framework for mission-level investment prioritization.* Santa Monica, CA: RAND Corporation. https://www.rand.org/content/dam/rand/pubs/research_reports/RR2700/RR2771/RAND_RR2771.pdf

National Hurricane Center (NHC). (2020). *Costliest U.S. tropical cyclones.* Washington, DC: National Oceanic and Atmospheric Administration (NOAA). https://www.ncdc.noaa.gov/billions/dcmi.pdf

National Hurricane Center (NHC). (n.d.-a). 2020 Atlantic Hurricane Season. *National Oceanic and Atmospheric Administration (NOAA).* Retrieved November 12, 2020, from https://www.nhc.noaa.gov/data/tcr/

National Hurricane Center (NHC). (n.d.-b). Tropical Cyclone Climatology. *National Oceanic and Atmospheric Administration (NOAA*) Retrieved November 12, 2020, from https://www.nhc.noaa.gov/climo/#bac

National Institute of Building Sciences (NIBS). (2018). *Developing pre-disaster resilience based on public and private incentivization*. Retrieved from: https://cdn.ymaws.com/www.nibs.org/resource/resmgr/MMC/MMC_ResilienceIncentivesWP.pdf

National Oceanic and Atmospheric Administration (NOAA). (n.d.) Tides and currents: Pensacola, FL. Retrieved October 20, 2020, from https://tidesandcurrents.noaa.gov/stationhome.html?id=8729840

National Research Council (NRC). (2014). *Reducing coastal risk on the East and Gulf Coasts.* Washington, DC: The National Academies Press. https://doi.org/10.17226/18811

Neumann, B., Vafeidis A., Zimmermann J., Nicholls R. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding - a global assessment. PLoS ONE 10(3): https://10.1371/journal.pone.0118571

O'Neill, B., Tebaldi, C., van Vuuren, D., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J., Lowe, J., Meehl, G., Moss, R., Riahi, K., and Sanderson, B. (2016). The scenario model intercomparison project (scenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Panteli, M., Mancarella, P., Trakas, D., Kyriakides, E., and Hatziargyriou, N. (2017). Metrics and quantification of operational and infrastructure resilience in power systems. *IEEE Transactions on Power Systems*, 32(6), 4732-4742. https://ieeexplore.ieee.org/document/7842605

Peduzzi, P., Chatenoux, B., Dao, H., De Bono, A., Herold C., Kossin, J., Mouton, J., and Nordbeck, O. (2012). Global trends in tropical cyclone risk. *Nature Climate Change,* 2, 289–294. https://doi.org/10.1038/nclimate1410

Pei, B., Pang, W., Testik, F., Ravichandran, N., and Liu, F. (2014). Mapping joint hurricane wind and surge hazards for Charleston, South Carolina. *Natural Hazards* 74, 375–403. https://doi.org/10.1007/s11069-014-1185-5

Pei, B., Pang, W., Testik, F., Ravichandran, N., and Liu, F. (2018). Selection of hazard-consistent hurricane scenarios for regional combined hurricane wind and flood loss estimation. *Natural Hazards*, 91(2), 671-696. https://doi.org/10.1007/s11069-017-3149-z

Perry, J. (2006). Keesler Air Force Base: One year after Katrina. *The Air Force Magazine*. https://www.af.mil/News/Article-Display/Article/129983/keesler-air-force-base-one-year-after-katrina/

Pielke, R., Jr., and Pielke, R., Sr. (1997) *Hurricanes: their nature and impacts on society*. John Wiley and Sons.

Pilkington, S. F. and Mahmoud, H. N. (2016). Using artificial neural networks to forecast economic impact of multi-hazard hurricane-based events. *Sustainable and Resilient Infrastructure*, 1(1-2), 63-83. https://doi.org/10.1080/23789689.2016.1179529

Ramm, T., Watson, C., and White, C. (2018). Describing adaptation tipping points in coastal flood risk management. *Computers, Environment, and Urban Systems*, 69, 74-86. https://doi.org/10.1016/j.compenvurbsys.2018.01.002

Ramm, T., Watson, C., and White, C. (2018). Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. *Environmental Science & Policy,* 87, 92-101. https://doi.org/10.1016/j.envsci.2018.06.001

Rappaport, E. (2014). Fatalities in the United States from Atlantic tropical cyclones: new data and interpretation. *Bulletin of the American Meteorological Society,* 95(3), 341–346. https://doi.org/10.1175/BAMS-D-12-00074.1

Rehak, D., Senovsky, P., Hromada, M., and Lovecek, T. (2019). Complex approach to assessing resilience of critical infrastructure elements. *International Journal of Critical Infrastructure Protection,* 25, 125-138. https://doi.org/10.1016/j.ijcip.2019.03.003

Rouhanizadeh, B. and Kermanshachi, S. (2020). Post-disaster reconstruction of transportation infrastructures: lessons learned. *Sustainable Cities and Society,* 63, 102505. https://doi.org/10.1016/j.scs.2020.102505

Rose, A. (2017). Benefit-cost analysis of economic resilience actions. *Oxford research encyclopedia of natural hazard science.* https://oxfordre.com/naturalhazardscience/view/10.1093/acrefore/9780199389407.001.0001/acrefore-9780199389407-e-69

Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C., and Lawrence, M. (2006). HAZUS-MH flood loss estimation methodology II: Damage and loss assessment. *Natural Hazards Review*, 7(2), 72-81. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(72)

Scheitlin, K and Elsner, J. (2010). A track-relative climatology of Eglin Air Force Base hurricanes in a variable climate. *Hurricanes and Climate Change,* Springer, Dordrecht, 217-229. https://doi.org/10.1007/978-90-481-9510-7_13

Scheitlin, K., Elsner, J., Lewers, S., Malmstadt, J., and Jagger, T. (2011). Risk assessment of hurricane winds for Eglin air force base in northwestern Florida, USA. *Theoretical & Applied Climatology*, 105(3), 287–296. https://doi.org/10.1007/s00704-010-0386-4

Schuldt, S., El-Rayes, K., Soylemezoglu, A., and Garfinkle, N. (2020). Minimizing consequences of explosive attacks on remote construction sites. *Journal of Performance of Constructed Facilities*, 34(1). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001354

Strategic Environmental Research and Development Program (SERDP). (2019). *FY 2021 statement of need: research to improve installation infrastructure resiliency progresses, systems, and tool.* Washington, DC: U.S. Department of Defense. https://www.serdp-estcp.org/Funding-Opportunities/SERDPSolicitations/Core-SONs/RCSON-21-C2-Infrastructure-Resiliency

Shao, W., Xian, S., Keim, B.D., Goidel, K., and Lin, N. (2017). Understanding perceptions of changing hurricane strength along the US Gulf coast. *International Journal of Climatology*, 37, 1716-1727. https://doi-org.afit.idm.oclc.org/10.1002/joc.4805

Shi, L., and Varuzzo, A. (2020). Surging seas, rising fiscal stress: exploring municipal fiscal vulnerability to climate change. *Cities,* 100, https://doi.org/10.1016/j.cities.2020.102658

Sichani, M., Anarde, K., Capshaw, K., Padget, J., Meidl, R., Hassanzadeh, P., Loch-Temzelides, T., and Bedient, P. (2020). Hurricane Risk Assessment of Petroleum Infrastructure in a Changing Climate. *Frontiers in Built Environment*, 6, 104. https://doi.org/10.3389/fbuil.2020.00104m

Silva de Abreu, R. V., Pinelli, J. P., Raji, F., and Zisis, I. (2020). Testing and modeling of hurricane wind-driven rain water ingress, propagation, and subsequent interior damage in residential buildings. *Journal of Wind Engineering and Industrial Aerodynamics,* 207, 104427. https://doi.org/10.1016/j.jweia.2020.104427

Simmons, K. M., Czajkowski, J. and Done, J. M. (2019). Building code economic performance under variable wind risk. *Mitigation and Adaptation Strategies for Global Change*, 24, 235–258. https://doi.org/10.1007/s11027-018-9808-x

Smith, A., and Katz, R. (2013). U.S. billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Natural Hazards,* 67(2), 387–410. https://doi.org/10.1007/s11069-013-0566-5

Smith, A. and Matthews, J. (2015). Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates. *Natural Hazards,* 77, 1829–1851. https://doi.org/10.1007/s11069-015-1678-x

Stephens, S., Bell, R., and Lawrence, J. (2018). Developing signals to trigger adaptation to sea level rise. *Environmental Research Letters*, 13(10). https://doi.org/10.1088/1748-9326/aadf96

Strazzo, S., Elsner, J. B., Trepanier, J. C., and Emanuel, K. A. (2013). Frequency, intensity, and sensitivity to sea surface temperature of North Atlantic tropical cyclones in best-track and simulated data. *Journal of Advances in Modeling Earth Systems*, 5, 500– 509. https://doi.org/10.1002/jame.20036

Strazzo, S., Elsner, J. B., LaRow, T. E., Murakami, H., Wehner, M., and Zhao, M. (2016). The influence of model resolution on the simulated sensitivity of North Atlantic tropical cyclone maximum intensity to sea surface temperature. *Journal of Advances in Modeling Earth Systems*, 8, 1037–1054. https://doi.org/10.1002/2016MS000635

Sweet, W., Kopp, R., Weaver, C., Obeysekera, J., Horton, R., Thieler, E., and Zervas, C. (2017). Global and regional sea level rise scenarios for the United States. *NOAA Technical Report NOS CO-OPS,* 83. https://doi.org/10.7289/V5/TR-NOS-COOPS-083

Taherkhani, M., Vitousek, S., Barnard, P., Frazer, N., Anderson, T., and Fletcher, C. (2020). Sea level rise exponentially increases coastal flood frequency. *Scientific Reports,* 10, 6466. https://doi.org/10.1038/s41598-020-62188-4

Unnikrishnan, V. and Barbato, M. (2016). Performance-based comparison of different storm mitigation techniques for residential buildings. *Journal of Structural Engineering*, 142(6). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001469

Vandeveer, M. (2019). *Installation health assessment: Strategic use of big data, predictive modeling, and visualizations in Air Force infrastructure investments.* San Antonio, TX: Air Force Installation and Mission Support Center (AFIMSC). https://stenterprise.org/wp-content/uploads/sites/12/formidable/21/Day1-Morning-RmG-AnalyzingRisks-Vandeveer.pdf

Vickery P., Lin J., Skerlj P., Twisdale L., Young M., and Lavelle, F. (2006). "Hazus-MH hurricane model methodology. II: damage and loss estimation. *Natural Hazards Review*, 7(2), 94-103. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(94)

Villarini, G. and Vecchi, G. (2013). Projected increases in North Atlantic tropical cyclone intensity from CMIP5 models. *Journal of Climate,* 26(10), 3231–3240. https://doi.org/10.1175/JCLI-D-12-00441.1

Vousdoukas, M., Bouziotas, D., Giardino, A., Bouwer, L., Mentaschi, L., Voukouvalas, E., and Feyen, L. (2018). Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. *Natural Hazards and Earth System Sciences,* 18(8), 2127-2142. https://doi.org/10.5194/nhess-18-2127-2018

Walsh, K., McBride, J., Klotzbach, P., Balachandran, S., Camargo, S., Holland, G., Knutson, T., Kossin, J., Lee, T., Sobel, A., and Sugi, M. (2016). Tropical cyclones and climate change. *WIREs Climate Change,* 7, 65–89. https://doi.org/10.1002/wcc.371

Watterson, I. (2008). Calculation of probability density functions for temperature and precipitation change under global warming. *Journal of Geophysical Research*, 113, 12106. https://doi.org/10.1029/2007JD009254

Woodruff, S., Stults, M. (2016). Numerous strategies but limited implementation guidance in US local adaptation plans. *Nature Climate Change*, 6, 796–802. https://doi.org/10.1038/nclimate3012

Woodruff, S., Meerow, S., Stults, M., and Wilkins, C. (2018). Adaptation to resilience planning: alternative pathways to prepare for climate change. *Journal of Planning Education and Research.* https://doi.org/10.1177/0739456X18801057

Xie, D., Zou, Q., Mignone, A., and MacRae, J. (2019). Coastal flooding from wave overtopping and sea level rise adaptation in the northeastern USA. *Coastal Engineering*, 150, 39-58. https://doi.org/10.1016/j.coastaleng.2019.02.001

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14. ABSTRACT

Climate change projections suggest intensification of extreme weather events, including hurricanes, is expected throughout the 21st century. This will lead to increased destruction for coastal military bases unless infrastructure resiliency and adaptation measures are implemented. This research focuses on examining the simulation of probabilistic, climate-intensified hurricane events at Eglin Air Force Base. FEMA Hazus models are combined with climate projections for wind intensity, tide, and sea-level rise to produce an assessment of losses to the installation. Damage estimates and hurricane intensity outputs are downscaled to the facility-level so that climate adaptation signals can be identified. The facility losses and climate signals are used as inputs for a dynamic adaptation pathway model. Utilizing a variety of infrastructure investment strategies, the pathway model is used to calculate the expected benefits, risks, and costs associated with adaptation. Such pathways can be used to inform campus and installation master plans and are vital to reducing coastal bases' vulnerability to future hurricane events.

15. SUBJECT TERMS

Infrastructure, resilience, climate change, hurricanes, adaptation pathways

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