Climate Resilience and Benefit Cost Analysis: A Handbook for Airports (2019)

DETAILS

160 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-48045-1 | DOI 10.17226/25497

CONTRIBUTORS

GRA, Inc., LMI Government Consulting, RFMarchi Aviation Consulting, AECOM, and CH Planning; Airport Cooperative Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2019. *Climate Resilience and Benefit Cost Analysis: A Handbook for Airports*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25497.

AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP RESEARCH REPORT 199

Climate Resilience and Benefit–Cost Analysis: A Handbook for Airports

GRA, Inc.
Jenkintown, PA

LMI Government Consulting
Tysons, VA

RFMarchi Aviation Consulting
Washington, D.C.

AECOM
Glen Allen, VA

CHPlanning
Philadelphia, PA

Subscriber Categories
Aviation • Economics • Environment

Research sponsored by the Federal Aviation Administration

The National Academies of
SCIENCES · ENGINEERING · MEDICINE
TRB
TRANSPORTATION RESEARCH BOARD
2019

AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). ACRP carries out applied research on problems that are shared by airport operating agencies and not being adequately addressed by existing federal research programs. ACRP is modeled after the successful National Cooperative Highway Research Program (NCHRP) and Transit Cooperative Research Program (TCRP). ACRP undertakes research and other technical activities in various airport subject areas, including design, construction, legal, maintenance, operations, safety, policy, planning, human resources, and administration. ACRP provides a forum where airport operators can cooperatively address common operational problems.

ACRP was authorized in December 2003 as part of the Vision 100—Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), Airlines for America (A4A), and the Airport Consultants Council (ACC) as vital links to the airport community; (2) TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academy of Sciences formally initiating the program.

ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

Research problem statements for ACRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the AOC to formulate the research program by identifying the highest priority projects and defining funding levels and expected products.

Once selected, each ACRP project is assigned to an expert panel appointed by TRB. Panels include experienced practitioners and research specialists; heavy emphasis is placed on including airport professionals, the intended users of the research products. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, ACRP project panels serve voluntarily without compensation.

Primary emphasis is placed on disseminating ACRP results to the intended users of the research: airport operating agencies, service providers, and academic institutions. ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties; industry associations may arrange for workshops, training aids, field visits, webinars, and other activities to ensure that results are implemented by airport industry practitioners.

ACRP RESEARCH REPORT 199

Project 02-78
ISSN 2572-3731 (Print)
ISSN 2572-374X (Online)
ISBN 978-0-309-48045-1
Library of Congress Control Number 2019942236

NOTICE

The research report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the National Academies of Sciences, Engineering, and Medicine.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; or the program sponsors.

The Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; and the sponsors of the Airport Cooperative Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published research reports of the

AIRPORT COOPERATIVE RESEARCH PROGRAM

are available from

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet by going to

http://www.national-academies.org

and then searching for TRB

Printed in the United States of America

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org**.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

CRP STAFF FOR ACRP RESEARCH REPORT 199

Christopher J. Hedges, *Director, Cooperative Research Programs*
Lori L. Sundstrom, *Deputy Director, Cooperative Research Programs*
Marci A. Greenberger, *Manager, Airport Cooperative Research Program*
Lawrence D. Goldstein, *Senior Program Officer*
Anthony P. Avery, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Natalie Barnes, *Associate Director of Publications*
Doug English, *Senior Editor*

ACRP PROJECT 02-78 PANEL
Field of Environment

Mary E. Davis, *Tufts University, Medford, MA* (Chair)
Joshua DeFlorio, *The Port Authority of New York and New Jersey, New York, NY*
Sam A. Mehta, *Gresham, Smith and Partners, Fremont, CA*
Stephanie A. Morgan, *Lewiston-Nez Perce County Regional Airport (LWS), Lewiston, ID*
Kristoffer Russell, *Dallas/Fort Worth International Airport, Prosper, TX*
Jen Wolchansky, *Mead & Hunt, Inc., Denver, CO*
Thomas Cuddy, *FAA Liaison*
Kevin Partowazam, *FAA Liaison*
Melinda Z. Pagliarello, *Airports Council International–North America Liaison*

FOREWORD

By Lawrence D. Goldstein
Staff Officer
Transportation Research Board

ACRP Research Report 199 is a handbook on how to apply benefit–cost analysis tools and techniques to improve decision making affecting resilience of airport infrastructure projects in response to potential long-term impacts of climate change and extreme weather events. This handbook will help practitioners recognize, enhance, and adapt insights and procedures identified from related research currently available or under development affecting both airports and other infrastructure projects.

In particular, the handbook is designed to improve the process by which infrastructure investment strategies are evaluated, with an emphasis on ensuring climate-related resiliency. Procedures for presenting assumptions and results transparently and for implementing the process are also included so that industry users and decision makers can understand and communicate the outcome of the analytical process.

The handbook was developed by a research team led by GRA, Inc., with assistance from RFMarchi Aviation Consulting, LMI Government Consulting, AECOM, and CHPlanning. The methodology presented, which is broadly applicable to any uncertain financial or economic decision being considered by an airport, uses a two-step analytical approach. Step 1 applies a screening analysis using an already-existing ACRP software tool; depending on the outcome of Step 1, Step 2 evaluates risk more systematically and considers potential ways to reduce that risk through specific investments (or operational changes). Step 2 uses forecasts of future climate change that are inherently uncertain and implements a Monte Carlo simulation–based benefit–cost method focusing on identification and analysis of a specific mitigation project designed to reduce or eliminate the potential damages caused by climate change.

Based on data availability, the analytical methods included in the handbook focus on two specific areas of climate change likely to affect airports (although these methods can, in principle, be used more widely): (1) the potential for extreme flooding events resulting from storm surge and sea level rise near coastal airports, and (2) the potential for rising temperatures that require weight restrictions on aircraft takeoffs (or possibly full flight delays) at airports with shorter runways in warm climates or at high elevations. The results available from application of the suggested methodologies do not necessarily make the decision of whether to invest in a mitigation project to combat climate change any easier but, rather, provide a full range of potential outcomes and possibilities for airport planners and managers to consider. Using this methodology, airport decision makers can then determine how much risk from uncertain climate change and extreme weather events they are willing or able to accommodate. Implementation of the methods presented in the handbook can be used to obtain essential quantifiable estimates of those risks, which is of particular value to airport financial professionals.

The handbook is accompanied by a set of Microsoft Excel models to support the decision-making process, a video tutorial, a separate summary document, and an executive briefing to help decision makers understand the process. These separate and supporting products are available on the TRB website by searching for “ACRP Research Report 199” at www.TRB.org.

CONTENTS

1 Summary
1 S.1 Suggested Two-Step Analytical Process
3 S.2 Applying the Process
3 S.3 Summarizing Outcomes from the Analysis
6 S.4 Related Topics

7 **Chapter 1** Introduction
7 1.1 Objectives
7 1.2 Handbook Overview
9 1.3 Why and How Airports Should Assess Climate Change

12 **Chapter 2** Evaluation Methods Under Risk and Uncertainty
13 2.1 Benefit–Cost Analysis and Financial Feasibility Analysis
13 2.2 Using Existing ACRP Resources
14 2.3 Adding Climate Risk to an Analysis
16 2.4 Step 1: Initial Screening Analysis for Assessing Climate Risk
22 2.5 Step 2: Risk-Adjusted Analysis for Assessing Climate Risk
28 2.6 Summary and Next Steps

29 **Chapter 3** State-of-the-Art Climate Measures
29 3.1 Background on Available Climate Data
31 3.2 Climate Stressors

34 **Chapter 4** Potential Airport Impacts
34 4.1 Identifying and Targeting Airport Assets and Infrastructure
36 4.2 Assessing Vulnerability Due to Climate Change Risks
36 4.3 Assessing Criticality

40 **Chapter 5** Responses and Adaptations
40 5.1 Identifying and Targeting Potential Responses
42 5.2 Considering Adaptations Not Involving Infrastructure Investment
43 5.3 Financial Constraints

47 **Chapter 6** Other Relevant Topics for Airports Addressing Climate Change
47 6.1 Defining a Specific Scenario
48 6.2 What Type of Analysis?
50 6.3 Hard-to-Quantify Impacts and Direct Environmental Strategies
51 6.4 Economic Impacts
53 6.5 Option to Delay Investment
53 6.6 Comparing Results Across Different Scenarios

55 **Chapter 7** Case Studies
55 7.1 Introduction
56 7.2 Case Study Overview
59 7.3 Summary of Presentations and Lessons Learned

62 **Chapter 8** Study Limitations and Recommendations for Future Research

64 **Appendix A** Institutional Background: Existing Airport Resources and Plans

77 **Appendix B** Other Climate Risk Evaluation Approaches

79 **Appendix C** Monte Carlo Simulation and Value-at-Risk Analysis

83 **Appendix D** Accessing Available Climate Projections

89 **Appendix E** Microsoft Excel Templates

103 **Appendix F** Climate Risk and Mitigation Numerical Examples

113 **Appendix G** FAA Guidance on Benefit–Cost Analysis

119 **Appendix H** Case Study Details

132 **Appendix I** Potential Climate Change Effects and Illustrative Responses for Airports

137 Bibliography Keyed to Major Topics

140 Glossary

144 References

147 Endnotes

SUMMARY

Climate Resilience and Benefit–Cost Analysis: A Handbook for Airports

The purpose of this handbook is to help airport practitioners assess the benefits, costs, and financial feasibility of infrastructure projects that are designed to improve resilience to the impacts of climate change and extreme weather events. The handbook presents up-to-date methods for conducting benefit–cost and financial feasibility analyses that explicitly recognize risks and uncertainties that are inherent in long-term climate projections and their potential effects on long-lived airport infrastructure. The methodology is also broadly applicable to any uncertain financial or economic matter being considered by airports.

This summary presents some of the features of the analytical methods discussed at greater length later in the handbook. The methods and analyses presented here focus on two specific areas of climate change likely to affect airports: (1) the potential for extreme flooding events due to storm surge and sea level rise near coastal airports, and (2) the potential for rising temperatures that could require weight restrictions on aircraft takeoffs (or that may cause full flight delays) at airports with shorter runways in warm climates or at high elevations. While other aspects of climate change may also affect airports—including, for example, increasing likelihood of localized thunderstorms or air turbulence affecting takeoffs and landings—the methodologies presented in this handbook focus on these two specific areas because specific quantifiable projections are currently available for these climate measures.

S.1 Suggested Two-Step Analytical Process

Exhibit S-1 illustrates a suggested two-step process for dealing with climate change risk. Step 1 screens for potential problems using an existing software tool called Airport Climate Risk Operational Screening (ACROS), which was published as part of *ACRP Report 147: Climate Change Adaptation Planning: Risk Assessment for Airports* (Dewberry et al. 2015). This tool uses climate data published in 2013 to identify potential areas of concern. ACROS leads the user through a process for identifying when airport infrastructure might be vulnerable to climate change (likely to be affected) and whether the infrastructure itself is critical to airport operations (loss of use would be costly to the airport and its users). The projected outcome from the worst-case ACROS data can reveal whether to proceed to Step 2.

To illustrate how Step 1 might work, Exhibit S-2 shows a summary of ACROS climate projections for LaGuardia Airport (LGA). Baseline values for 2013 are shown, along with 25th/median/75th percentile projections for the years 2030 and 2060. Using these data, the airport could focus on the 75th percentile (worst-case) forecast to evaluate whether there are areas to investigate more thoroughly. In this case, sea level rise could expose the airport to flooding.[1]

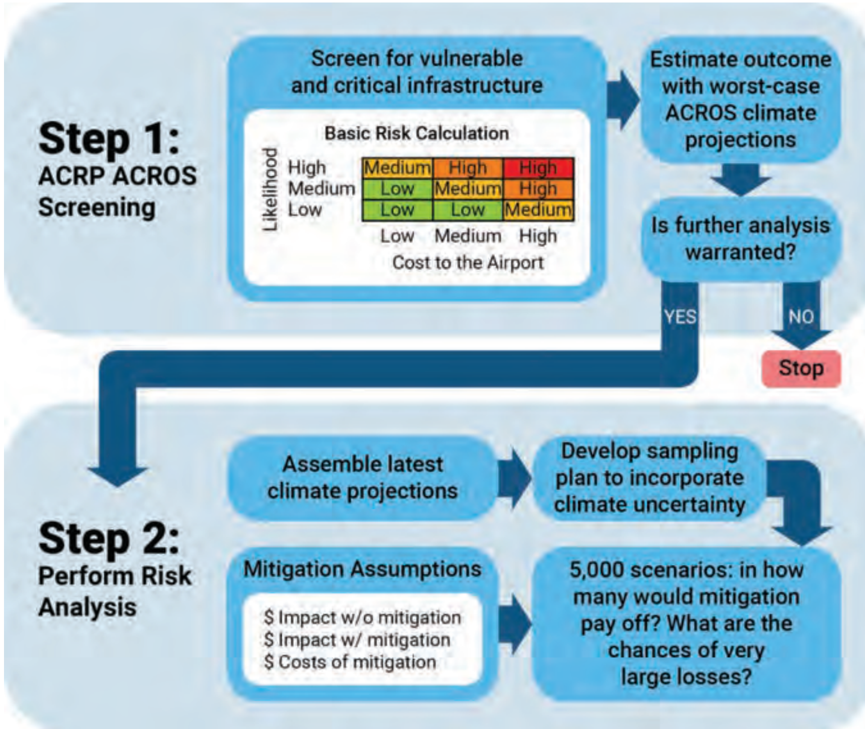


Exhibit S-1. Suggested two-step method for evaluating airport climate risk.

Summary of climate data changes

Summary of Historical Record and Projected Changes (Days/Year)								
Climate Vector	Units	2013	2030			2060		
		Baseline	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
HotDays	days per year	2	3.6	7.2	15	7.3	16.1	34.4
VeryHotDays	days per year	0	0	0.4	1.1	0.1	1.8	5.5
FreezingDays	days per year	17.2	11.8	13.2	14.7	3.7	7.1	11
FrostDays	days per year	74.1	63.6	65.8	67.5	47.7	53.4	57.5
HotNights	days per year	40.1	50.4	54.6	59.3	66	76.2	88.1
HumidDays	days per year	44.9	54.2	57.8	61.9	68.1	77.1	87.4
SnowDays	days per year	4.2	3.2	3.4	3.6	1.8	2.2	2.7
StormDays	days per year	39.5	39.7	41.1	42.8	40	43.6	47.9
HeavyRain1Day	days per year	12.3	12.6	13.1	13.6	13	14.2	15.7
DryDays	days per year	15.3	15.2	15.5	16.2	15	15.8	17.4
SeaLevelRise	days per year	0	1	1	2	1	13	365
CoolingDays	days per year	96	108.6	108.8	109.6	127.4	127.9	150
HeatingDays	days per year	223.9	212.1	213.6	214.1	194.4	198.1	199.4

Summary of Historical Record and Projected Changes (Various Unit)								
Climate Vector	Units	2013	2030			2060		
		Baseline	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
CoolingDegreeDays	yearly accumulation	393.7	485.4	536.2	583.1	622.8	749.9	867.1
HeatingDegreeDays	yearly accumulation	2881.6	2587.7	2672.6	2720.4	2146.9	2359.3	2478.6
HeavyRain5Day	inches	3.5	3.5	3.6	3.8	3.6	3.9	4.1
SeaLevelRise_BaseFloodElevation	feet	13	14	15	15	15	16	17

Source: ACROS from *ACRP Report 147* (Dewberry et al. 2015).

Exhibit S-2. ACROS climate screening for LGA.

Step 2 in the process is to evaluate the risk more systematically by recognizing the uncertainty inherent in climate projections and considering ways to potentially reduce the impacts through investments (or operational changes). Essentially, one wants to know whether it makes sense to address the uncertain climate risk by investing in or changing the airport infrastructure or by changing how the airport operates.

S.2 Applying the Process

An airport could evaluate investing in an enlarged stormwater system to account for increased frequency of storm surge, or it could apply for a Letter of Intent for an Airport Improvement Program (AIP) grant to support a runway extension to offset payload penalties suffered by carriers due to increased frequency of high-temperature days. An analyst working on the stormwater project would want to have estimates of the likelihood that stormwater would rise above the critical elevations of important airport infrastructure. The analyst working on the runway extension would want to know how many days per year temperatures would exceed critical levels that cause airlines to offload payload on long-haul flights. This handbook discusses how these estimates can be extracted from the multiple climate forecasts that are available. It provides greater geographic precision and richer probability estimates than were available in the ACROS software, which was published in 2015.

Because future threats are inherently uncertain, it is important to capture the envelope and likelihood of different outcomes. This can be accomplished by performing a so-called value-at-risk (VaR) analysis. The handbook demonstrates how to take advantage of the variations across different climate projections to capture the range of potential outcomes. For example, in one projection, there could be 3 days forecast to be in excess of 100°F in a future year, while in another projection there could be none. Investment decision making with this kind of uncertainty is best captured in a Monte Carlo framework, where many what-if simulations are considered that randomly sample from the various climate projections to capture the variation in potential outcomes.

This handbook shows how to assemble historic climate data and merge them with a range of climate change forecasts. It discusses how climate forecasts are based on historic data and how to sample the data based on assessments of how accurate the climate models have been historically. Accompanying this handbook are two Microsoft Excel files (one for extreme water rise causing potential flooding events, and the other for high temperatures that may affect weight restrictions on aircraft takeoffs; these Excel files may be found by searching for "*ACRP Research Report 199*" at www.TRB.org) that help the user assemble and use the latest climate data to run Monte Carlo simulations and assess VaR results from risk-adjusted benefit–cost or financial feasibility models. The Excel files sample the climate data randomly over the life of the specified project. A large number of Monte Carlo simulations (5,000) are run, each one counting up the number of days with flood events (at different extreme water levels) or the number of days with payload penalties (at different high ambient temperatures) each year.

S.3 Summarizing Outcomes from the Analysis

Exhibit S-3 illustrates two ways of summarizing potential future climate outcomes based on the simulations. Exhibit S-3a shows forecast changes in water levels for Boston Logan Airport. Reading across any given row, notice that the probabilities of higher water levels increase over time as sea level rises. As shown in the bottom two rows, the median height of the flooding events and the height of the 100-year event (that which occurs with 1% annual

S-3a. Water level events at Boston.

BOS Extreme Water Level Event Probabilities from 5,000 Simulations (RCP 8.5)									
Water Level Rise (ft)	Historical	2025	2035	2045	2055	2065	2075	2085	2095
0-1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1-2	3.88%	0.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2-3	68.46%	45.28%	24.68%	8.84%	1.76%	0.40%	0.12%	0.04%	0.00%
3-4	24.16%	46.46%	60.06%	61.94%	48.16%	28.04%	15.24%	9.52%	4.38%
4-5	2.98%	7.24%	13.34%	24.90%	40.38%	50.00%	47.64%	37.10%	29.00%
5-6	0.40%	0.80%	1.76%	3.66%	8.58%	17.68%	27.32%	34.06%	34.94%
6-7	0.12%	0.12%	0.16%	0.52%	1.02%	3.34%	7.72%	13.76%	19.38%
7-8	0.00%	0.02%	0.00%	0.14%	0.10%	0.48%	1.48%	4.20%	8.66%
8-9	0.00%	0.00%	0.00%	0.00%	0.00%	0.04%	0.44%	1.00%	2.76%
9+	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.04%	0.32%	0.88%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Median (ft)	*2.66*	*3.06*	*3.32*	*3.63*	*4.00*	*4.37*	*4.72*	*5.07*	*5.45*
100-Yr Event (ft)	*4.63*	*4.98*	*5.29*	*5.66*	*6.06*	*6.74*	*7.38*	*8.14*	*8.88*

S-3b. Count of 110°F days at Little Rock.

Sim #	2021	2022	2023	2024	2025	...	2085	2086	2087	2088	2089	2090
1	0	0	0	0	0	...	2	2	0	4	9	11
2	0	2	0	0	2	...	12	12	1	3	19	12
3	0	0	0	0	2	...	1	33	1	10	7	0
4	0	2	0	0	0	...	1	1	9	6	1	15
5	0	0	0	1	2	...	7	2	0	0	0	2
6	0	0	4	0	2	...	0	2	34	0	1	11
7	0	0	0	0	0	...	2	6	4	9	2	17
8	0	2	0	0	0	...	22	2	20	0	0	58
9	0	0	0	0	0	...	2	32	4	8	9	0
10	0	0	0	0	0	...	9	2	4	34	13	10
11	0	0	0	0	0	...	25	1	0	3	3	1
12	0	0	0	0	0	...	17	31	20	0	5	0
13	0	0	4	0	0	...	10	19	0	0	2	6
14	0	0	0	0	0	...	3	1	9	3	0	12
15	0	0	0	0	0	...	0	1	42	9	3	57
16	0	2	0	0	0	...	22	2	1	23	20	0
17	0	0	0	0	0	...	6	2	27	1	2	1
18	0	0	1	0	0	...	9	2	0	1	31	25
19	0	0	0	0	0	...	10	79	0	35	1	10
20	0	0	0	0	0	...	0	6	44	1	9	11
...	...	...	...	...	...	...	...	...	...	...	...	...
5000	0	0	0	0	2	...	10	1	0	9	2	10

Exhibit S-3. Examples of ways to summarize climate risks.

probability) both increase significantly over time. An analyst could use these results to determine when airport infrastructure built to a specific standard would likely be exposed. For example, infrastructure designed to withstand water heights up to 5 ft would be exposed to approximately a 1.7% chance of flooding in the year 2035 according to these projections.[2] If certain long-life infrastructure were being planned today, it would make sense to consider ways to offset these climate risks.

Exhibit S-3b summarizes the results of projections of annual high heat days; this extract shows a count of days per year above 110°F for Little Rock Airport from 2021 to 2090. (Forecasts for other temperatures could be created as well.) An analyst could treat these data as a probability distribution summarizing the chances of temperatures reaching at least this level each year into the future. If 110°F is a level that is important for certain long-haul operations at the airport, it might be worth considering whether a runway extension would make sense to mitigate the implied weight restrictions.

The impacts of the events will vary. The costs of a water rise of 2 ft might threaten some infrastructure, while a 4-ft flood would affect more of the airport. Similarly, only a small number of long-haul flights might be affected when temperatures reach 110°F, while more flights would be affected at higher temperatures. The methods described in this handbook are designed to account for the probabilities of different events.

The effectiveness and life-cycle costs of each mitigation project are also an input in the investment model of the Excel files. For example, a runway extension of 500 ft might reduce all of the payload penalties at 110°F but only half of them at 115°F. The Excel models can be used to quickly assess the impacts of different stormwater adaptations or runway extension lengths based on the probable future need for them; they also provide useful information on the distribution of different but uncertain climate results so that the airport and its users can assess the financial risks they are willing to incur.

To illustrate how this all comes together, Exhibit S-4 summarizes the results of a flood mitigation project evaluation. The blue line in the chart is the range of probable outcomes without mitigation, and the red line is with mitigation. Each line represents 5,000 possible outcomes for the airport—net costs to the airport expressed in net present values. The box

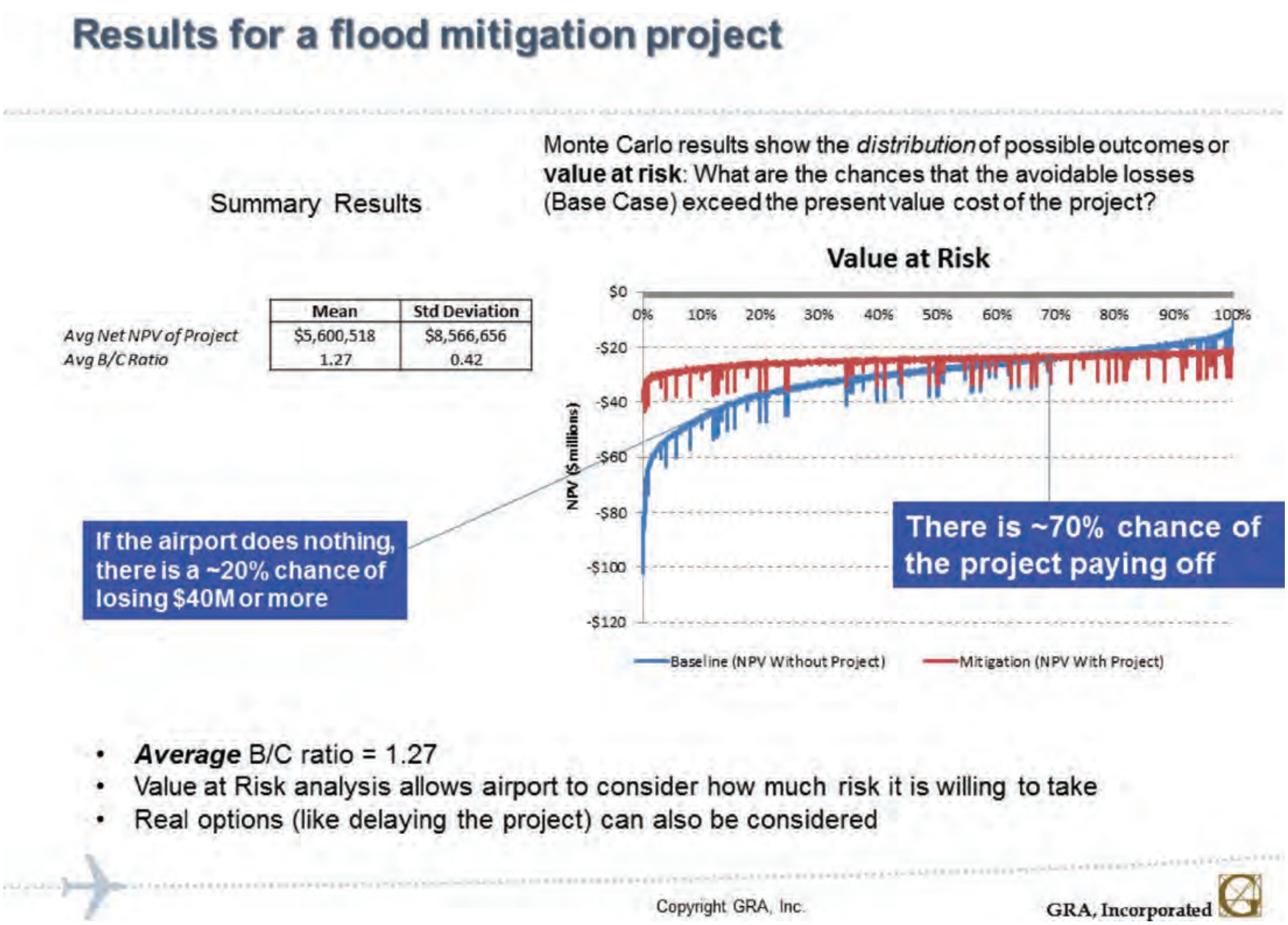


Exhibit S-4. Risk-adjusted evaluation of a climate project.

in the upper left reports the average net present value and benefit–cost ratio for the project. In this example, conventional decision making would suggest that the project is justified and should be pursued (absent capital constraints) since the ratio is greater than one. The graphic on the right represents the results of the VaR analysis and is informative because one can assess the probabilities of the different possible outcomes. For example, it shows that 70% of the time the project would pay off if it were built today, which means that 30% of the time it would not. If the airport does nothing, there is a 20% chance it could lose $40 million or more over the analysis period (expressed in today's dollars). Over the course of the life of the project, an unmitigated 100-year storm would cost the airport over $80 million. (This is the value of the blue line at 1% probability.)

This handbook also describes how to apply the methodology to options such as delaying a project. These findings could be relevant for both financial management and enterprise risk management. To be clear, the results presented in the VaR analysis do not necessarily make the decision on whether to invest in a mitigation project any easier, but the results do provide a full range of potential outcomes and possibilities for management to consider. The decision makers must essentially decide how much risk they are willing to accept.

S.4 Related Topics

In addition to the analytical methods themselves, this handbook discusses other inputs and factors that should be considered when undertaking such analyses of how to respond to climate change challenges. It provides information on classifying relevant airport assets and infrastructure, assessing how vulnerable these assets may be, and identifying feasible responses (including those not involving infrastructure) and financial constraints.

Finally, this handbook includes some discussion of topics that, while not directly related to the methodology, may be relevant considerations for airport analysts. These include direct environmental strategies, how to handle hard-to-quantify impacts, and identifying broader economic impacts beyond the strictly defined project benefits and costs typically used for benefit–cost analysis.

CHAPTER 1

Introduction

1.1 Objectives

The purpose of this handbook is to help airport practitioners assess the benefits, costs, and financial feasibility of infrastructure projects that are designed to improve resilience to the impacts of climate change and extreme weather events. This handbook presents up-to-date methods for conducting benefit–cost and financial feasibility analyses that explicitly recognize risks and uncertainties that are inherent in long-term climate projections and their potential effects on long-lived airport infrastructure.

Topics covered include:

- The types of investment projects that account for climate resilience and that lend themselves to benefit–cost analysis (BCA) or financial feasibility analysis (FFA);
- The components of an FFA or BCA that need to be taken into account; in the case of a BCA, these will include guidelines on incorporating market and nonmarket valuation strategies as well as qualitative/quantitative data and methods;
- Environmental and social benefits and costs as inputs to the analytical process;
- How components of climate risk and uncertainty can be incorporated into the analysis;
- How current project funding options and constraints may affect the analysis; and
- Methods for airports that can be realistically implemented, given the differing levels of resources that may be available.

There is a large amount of literature on climate-related topics relevant to airports. This handbook builds off the existing knowledge base for information on an expansive variety of issues, including:

- Risk and uncertainty planning,
- Airport enterprise risk management,
- Alternative evaluation methods,
- Available climate change data,
- Airport asset vulnerability and criticality assessments, and
- BCA and FFA.

1.2 Handbook Overview

While this handbook provides necessary technical information and instruction, it was important for it to be accessible to high-level decision makers such as airport directors, chief financial officers, and planning executives. Section 1.3 provides a high-level discussion targeted to that audience of why and how airports should assess climate change.

The methods and analyses presented here focus on two specific areas of climate change likely to affect airports: (1) the potential for extreme flooding events due to storm surge and sea level rise (SLR) near coastal airports, and (2) the potential for rising temperatures to require weight restrictions on aircraft takeoffs (or possibly cause full flight delays) at airports in warmer climates. While other aspects of climate change may also affect airports—including, for example, increasing likelihood of localized thunderstorms or air turbulence affecting take-offs and landings—the methodologies presented in this handbook focus on these two areas because specific quantifiable projections are currently available for these climate measures. However, if comparable projections become available for other climate change measures, the basic methodology of the handbook could be adapted to those risks.

Chapter 2 discusses a two-step methodology for analyzing climate risks at a high level. Step 1 shows how an airport could begin to assess climate risks using information from prior ACRP publications; a detailed numerical example using the approach is provided. This approach should be useful to most airports as an initial screening tool, regardless of the level of resources available. Step 1 is a useful way to decide whether further analysis is required in Step 2, which features the methods that are suggested for further analysis of climate risks; these techniques form the core of the handbook for fully analyzing climate risk and uncertainty. The methodology shows how an airport can estimate the vulnerability (likelihood of exposure) of specific infrastructure or operations to flood risk due to extreme water rise or aircraft payload penalties due to increasing exposure to high temperatures. The details of the methodology are implemented in two Microsoft Excel spreadsheet simulation files. (These may be found by searching for "*ACRP Research Report 199*" at www.TRB.org.) Descriptions of the spreadsheet models, including step-by-step instructions for their use, can be found in Appendices E and F.

Chapter 3 provides a description of the climate science literature relevant for airports' exposure to extreme flooding events or high temperatures. This is followed in Chapter 4 with a higher-level discussion of how to identify and classify potential airport impacts based on vulnerability and criticality of airport infrastructure assets. Chapter 5 addresses issues related to how an airport can identify and assess possible mitigation responses or adaptations to expected climate change events. (In the climate science context, the term "mitigation" is typically used specifically for efforts to reduce greenhouse gas (GHG) emissions, while "adaptations" are actions taken to help cope with changing climate conditions. In this handbook, the terms are used interchangeably to refer to projects or actions that airports may undertake to offset the effects of climate change.)

The results from implementing the procedures discussed in these chapters can be used to identify one or more specific infrastructure projects that could be considered to address the risks posed by climate change. Chapter 6 discusses other topics related to defining benefit–cost and financial scenarios and interpreting them correctly.

An important aspect of this project was to test the approach and methods via a series of case studies involving specific airports. The specific goal of these case studies was to introduce an illustrative analysis relevant for each airport that demonstrated the methodology, and then to get feedback and amend the handbook as needed. Chapter 7 provides a detailed description of the case studies undertaken with four different airports—Phoenix (PHX), New Orleans (MSY), Boston (BOS), and Little Rock (LIT). A sample analysis was presented using localized climate data for each airport.

This project necessarily assumed some knowledge of institutional airport realities and involved some rather technical material. Topics related to these issues are in the appendices. Appendix A discusses how making decisions about climate resilience fits into existing airport functions and overall institutional arrangements. Appendix B provides an overview of other climate risk evaluation methods besides those discussed in the main body of this handbook. Appendix C provides a more detailed description of the Monte Carlo and value-at-risk (VaR) methods suggested in Chapter 2 to help analyze the impacts of climate risk and uncertainty. Appendix D presents a detailed description of available climate projections and how they can be accessed and interpreted. Appendix E describes the two Microsoft Excel templates that have been developed in conjunction with this handbook: one can be used to assess potential extreme water events due to expected SLR near coastal airports in the United States, and the other analyzes the incidence of increased high temperatures and their effects on weight restrictions for aircraft takeoffs; both use the methods and analytical approach discussed in the handbook. Appendix F provides two numerical examples using the Excel templates. Appendix G provides technical material relating to FAA guidance on BCA and related topics. Appendix H provides more details of the case studies that are described in Chapter 7. Finally, Appendix I is a reprint of a table of potential climate change effects and illustrative responses for airports from *ACRP Synthesis 33: Airport Climate Adaptation and Resilience* (Baglin 2012).

1.3 Why and How Airports Should Assess Climate Change

The effects of climate change on infrastructure are already being realized, as demonstrated through impacts from increased precipitation and flooding, sea level rise, longer stretches of hot and cold days, and increased frequency and strength of extreme weather events such as hurricanes and tornados. As a result, there has been an emphasis on improving infrastructure to be more resilient and capable of withstanding these events in order to continue normal operations.

Airports are no less subjected to the threats of climate change and are potentially more at risk due to their locations, which are often flat, low-lying areas that may be prone to flooding and storm surge. Additionally, many airports may face an increased risk from rising temperatures that can limit their flight operations. High temperatures reduce air density, which in turn reduces the amount of lift that an aircraft wing can generate. This means that an aircraft must go faster to provide enough lift to take off, and thus it takes more runway to reach the higher speed. If the runway is not long enough, then the only other option is to reduce the aircraft's weight in order to lower its required takeoff speed, which is accomplished by removing payload (passengers and cargo; i.e., imposing a weight restriction).

As the climate changes, these types of incidents are forecast to become more frequent and intense, thereby increasing the risk to facilities and operations. But it is important to understand that there can be wide variances in future projections across different climate forecasts. Dealing with this uncertainty is an important objective of this handbook.

Understanding the risks to airport infrastructure and operations allows decision makers the ability to plan for what can be done to mitigate the effects of climate change. Planning efforts can include assessing possible infrastructure upgrades, continued maintenance for state of good repair, and potential changes to operations, all of which will require funding or financing.

Background: Climate Risk and Impacts of Climate Change

The World Economic Forum lists extreme weather events (e.g., floods and storms) and major natural disasters (e.g., earthquakes, tsunamis, and volcanic eruptions) as two of the top five global risks in terms of likelihood and impact (World Economic Forum 2017). These two categories encompass an enormous breadth of climate events: small and frequent (chronic) to catastrophic (acute), expected to unpredictable, and man-made to entirely out of human control.

A number of sources emphasize the significance of differentiating between extensive or chronic events, which are less severe and more frequent weather events that nonetheless can cause significant damage, and intensive or acute events that happen less often but may cause substantial mortality. While the United Nations' *Global Assessment Report* notes that chronic events are increasing in frequency, economic cost, and mortality (United Nations 2015a), analysts also believe that acute events are much harder to manage or mitigate once they have begun (Shang and Vincelli 2015).

The effects of climate change on transportation infrastructure have already become apparent. According to the federally supported National Climate Assessment:

1. The impacts from sea level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways.
2. Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges.
3. Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.
4. Climate change impacts will increase the total costs to the nation's transportation systems and their users, but these impacts can be reduced through rerouting, mode change, and a wide range of adaptive actions (Schwartz et al. 2014).

The range of impacts of a given event may extend far beyond physical damage to infrastructure. Multiple studies have been conducted to assess the economic consequences due to loss of business, evacuations, and impacts to the workforce, including injuries, psychological trauma, and employee difficulty in getting to work (Bouwer 2013, Santos et al. 2014).

These impacts can be compounded by interdependencies, in which physical infrastructure depends on other systems, especially utilities, which are often damaged by chronic and acute events (Chang et al. 2014). An electricity outage can halt public transit, causing transportation problems. A flood can back up plumbing and sewage systems, leading to secondary effects that the flood itself did not cause. The response to critical climate events also can create financial risks if public (or private) entities take on debt in order to finance infrastructure improvements or rehabilitation (Collier 2015).

All of these impacts are more difficult to quantify or predict than the direct loss in physical infrastructure, but, where possible, they should be accounted for in estimating the value of any investment in climate-resistant infrastructure.

Examples of Assessments of Climate Resiliency

Some airports and other entities have prepared their own reports on climate resilience or undertaken analyses to assess and improve their responses to significant local climate events. Following are some examples of how airports and other entities have assessed the risks from climate change.

A publication entitled *Report of the Heathrow Winter Resilience Enquiry* discussed factors that contributed to a major disruption of operations at London Heathrow Airport (LHR) during the Christmas travel season in 2010 (Heathrow Airport 2011a). The airport closed after it received more than 3.5 in. of new snow on December 18th, and it did not fully recover until December 22nd. At one point, 9,500 passengers were stranded in the terminals.

The report noted that the meteorological record indicates that a 3.5-in. snowfall is expected to occur once every 5 years at LHR. What was unusual was the occurrence of only one snowfall of that magnitude in the previous 22 years, leading the staff to regard such a storm as unlikely.

Although LHR made large investments in upgraded snow removal equipment after the event, most of the report's 14 recommendations were directed at planning, communications, coordination between stakeholders, and other noncapital investments aimed at improving LHR's ability to plan for and execute a resilient response to such an event.

An initiative sponsored by the City of Boston called "Climate Ready Boston" produced a report that presents projections for climate scenarios related to sea level rise, coastal storms, extreme precipitation, and extreme temperatures out to the year 2100 (Climate Ready Boston 2016). This is an initial step in the initiative's primary goal to find solutions for resilient infrastructure and buildings in the coming years. For example, Boston Logan Airport uses the 500-year storm level as the criterion for establishing design criteria to set critical elevations for airport infrastructure.

The Port Authority of New York and New Jersey (PANYNJ) prepared a report that lists effects on bridges, rail, landscaping, mechanical systems, drainage/utility design, and buildings and infrastructure from higher temperatures, increased precipitation, sea level rise, and severe storms (Port Authority of New York and New Jersey 2015). Proposed design improvements for buildings and infrastructure should increase the design flood elevation as a result of sea level rise from severe storms. PANYNJ has also adopted projections into its infrastructure planning guidelines for increased air temperature, precipitation, and sea level rise from the 2020s into the 2100s.

The state of Alaska has estimated the potential costs for upgrades to its public infrastructure that is at risk from climate change, concluding that costs could increase by $3.6 billion to $6.1 billion through 2030 (Larsen et al. 2008). Airports are part of this total, and it is estimated that adapting Alaska's airports to climate change could save 15% over the next few decades. In fact, the study estimated that 24% of the infrastructure costs will be for airports by 2030.

From these examples, it is evident that many airports or governmental units overseeing them have already begun to assess both existing and potential climate change issues. Nevertheless, the key issue of future climate uncertainty and how to incorporate it into analyses and plans has typically not been addressed explicitly. One of the primary goals of this handbook is to provide a how-to guide to allow airport practitioners to do this in a straightforward way.

CHAPTER 2

Evaluation Methods Under Risk and Uncertainty

About This Chapter

Chapter 2 briefly describes the differences between benefit–cost analysis and financial feasibility studies and how climate risk enters into these formal types of analysis to support decision making. Among the important elements discussed are:

- How to conduct an initial screening analysis for climate risk;
- Defining Monte Carlo analysis and why it is important for dealing with analysis of climate risk;
- Defining "value at risk" as a means for supporting decision making by helping to identify levels of risk that an organization is not willing to tolerate.

Many of the technical details required to undertake a full risk-adjusted analysis are in the following appendices:

- Appendix C provides a detailed description of the technical analyses and methods.
- Appendix D describes the available climate projections and how they can be accessed and interpreted.
- Appendix E describes two Microsoft Excel templates that have been developed in conjunction with this handbook: one can be used to assess potential extreme water events due to expected sea level rise near coastal airports in the United States, and the other analyzes the incidence of increased high temperatures and their effects on weight restrictions for aircraft takeoffs. Both use the methods and analytical approach discussed in the handbook.
- Appendix F provides two numerical examples using the Excel templates.

About the Next Chapter

Chapter 3 describes climate change projections and where to obtain them.

While evaluating climate resilience may be a new challenge, it can be incorporated as part of the overall risk management processes that most airports already have. Appendix A describes a generic management structure for assembling a team to analyze the potential impacts and responses to climate change and discusses specific risk management activities that such a team might undertake.

In addition to using existing management processes and structures, airports can also take advantage of existing resources that are directly relevant to the issue of assessing climate change.

These are discussed in the following, before getting into the details of how to actually conduct climate-related risk analyses. It is also important to note that while the present focus is on using the frameworks of FFA and BCA, there are of course other contexts in which climate risks could be assessed and evaluated; some of these are discussed in Appendix B.

A primary goal of this handbook is to demonstrate how components of climate risk and uncertainty can be incorporated into financial feasibility and benefit–cost analyses. Indeed, the prevalence and character of risk and uncertainty in climate forecasts have specific implications for how to address them analytically.

2.1 Benefit–Cost Analysis and Financial Feasibility Analysis

At the outset, it is important to distinguish between a BCA and an FFA. In the context of this handbook, the primary difference between these approaches can be thought of as follows:

- **BCA:** Would society (including all aviation stakeholders) be better off undertaking a proposed project?
- **FFA:** Are the returns from a project adequate for the airport and its users to justify undertaking it? Is there a viable plan to pay for it?

A BCA focuses on whether a proposed project should be undertaken after taking into consideration all relevant benefits and costs to all aviation stakeholders. Such benefits and costs may include items that affect the airport itself, but other entities may be affected as well, including airport users (passengers, airlines, etc.) and the surrounding community. The benefits and costs should be measured in constant (inflation-adjusted) dollars, and those occurring in future years must be discounted using an appropriate discount rate. The results from a BCA are usually presented either in terms of net present value (NPV)—measured as discounted benefits minus discounted costs—or as a benefit–cost ratio—measured as discounted benefits divided by discounted costs.

An FFA focuses on whether a project can be paid for using available sources of funds. It also compares benefits and costs, but it does this by considering only those cash benefits and costs accruing to the airport itself or its users; these may be different from the benefits and costs affecting other aviation stakeholders. These distinctions are discussed in more detail in Sections 2.4 and 6.2. It is important to note that these two approaches answer different questions but are not mutually exclusive, so decision makers could elect to undertake both types of analysis.

2.2 Using Existing ACRP Resources

ACRP has published work on climate change and its effects on airports. In particular, *ACRP Report 147: Climate Change Adaptation Planning: Risk Assessment for Airports* (Dewberry et al. 2015) provides information to help airport practitioners understand the specific impacts climate change may have on their airport, develop adaptation actions, and incorporate those actions into the airport's planning processes.

ACRP Report 147 discusses the climate change risks to practitioners' airports and then considers a variety of mitigation scenarios and examples. Accompanying the report is an electronic assessment tool called Airport Climate Risk Operational Screening (ACROS) that can help airports answer the question, "Within the entire airport, what's most at risk from projected climate change?" The ACROS tool uses a formula to compute an estimated level of risk for assets and operations at the airport. In addition, the tool uses airport-specific climate data for 489 U.S. airports to rank specific risks in order to provide an enterprise-level estimate of the relative risk posed by each asset and operation.

ACRP Report 147 makes a case for climate change adaptation and suggests establishing a stakeholder advisory committee to assist with setting resilience goals and identifying and prioritizing risks. It provides a primer on climate change and uncertainty for airports, provides national climate change projections, and suggests developing adaptations based on the vulnerability of critical assets and refining risk assessments as new, higher-resolution data become available on a 3- to 5-year review cycle.

ACRP Report 160: Addressing Significant Weather Impacts on Airports (ICF International 2016) contains another useful tool. The Airport Weather Advanced Readiness (AWARE) toolkit is designed to raise airport operator awareness about vulnerabilities caused by significant weather events and to help airports develop more robust contingency and recovery plans. The Excel-based AWARE toolkit focuses on events that are "rare but plausible"; that is, events that may have happened in the distant past or in adjacent geographic areas, but are not common event types at the airport itself.

The AWARE toolkit draws on historical weather data relevant to the airport's specific location in order to identify significant weather event types that the airport operators may wish to prepare for. AWARE also contains seven readiness modules that allow users to review best practices for preparing for these different weather events, assess their readiness for the events, and generate customized checklists for preparing for and recovering from them. The seven readiness modules are administration and finance, planning and environment, airfield operations, terminal operations, ground transportation and parking, safety and security, and a consolidated streamlined version of the full toolkit for small airports. The toolkit also contains an impacts tracking module, which is designed to help airports track the costs and other impacts of weather events (e.g., flight delays) over time.

2.3 Adding Climate Risk to an Analysis

It is useful to briefly discuss the distinction between risk and uncertainty. While there is no universal agreement on the distinction, a common approach is to define them in terms of whether a probability of occurrence can be estimated. With risk, the specific outcome that may occur is unknown, but one either knows or can reasonably estimate what the outcome distribution looks like. On the other hand, uncertainty implies that there is little or no knowledge of the outcome distribution itself. For example, a game of chance like roulette involves risk, but one can calculate what the specific odds are for any given outcome. On the other hand, the probability of, say, a terrorist event occurring may be completely unknown, which implies uncertainty. But for present purposes, there is no real advantage to explicitly labelling something as a risk as opposed to an uncertainty. Regardless of what they are called, the goal here is to provide an overview of how to incorporate estimates of risks or uncertainties into a formal analysis.

In practice, the primary risks and uncertainties associated with climate change will typically affect the benefits side of a benefit–cost or financial feasibility analysis. For example, when one is considering a particular infrastructure investment—say, lengthening a runway to allow higher-weight takeoffs during extreme heat—the costs of extending the runway a certain number of feet may be well understood. However, the benefits of the project may be subject to significant uncertainty because even the best climate science projections of future temperature rise cannot predict exactly when or how often such extreme heat events will occur. There is also additional uncertainty regarding actions that might be taken worldwide to reduce generation of GHGs, potentially slowing down and possibly reducing the effects of climate change.

Once again, prior publications can be reviewed to help understand how climate risk and uncertainty can affect these types of analyses. *ACRP Report 76: Addressing Uncertainty about Future Airport Activity Levels in Airport Decision Making* provides a broad treatment of the factors leading to risk and uncertainty in forecasting airport activity levels (Kincaid et al. 2012). While the focus of this report is not on airport activity levels, some of the same proposed methodological approaches can be considered. Some of the material presented in the following is derived from this report.

There have been tremendous advances in quantitative climate change modeling over the past 30 years. While it is not the purpose of this handbook to delve into these models, the results that can be obtained from such models will be discussed in some detail, along with how such results can be incorporated quantitatively into a BCA or FFA. Specifically, projections of surface temperature changes, sea level rise, and increased likelihood of flooding events can be used directly to help quantify the expected benefits of proposed airport infrastructure investments.

There are four key elements to adding climate risk to a BCA or FFA:

- **Accessing climate projections:** What types of climate projections are available, and how can their uncertainty be assessed?
- **Vulnerability:** How likely is it that some or all airport operations will be disrupted by events due to climate change?
- **Criticality:** If the disruptions occur, how expensive would they be?
- **Adaptations:** What can be done (changes in operation or infrastructure), how much will vulnerability and criticality be reduced, and how expensive are the adaptations?

Chapter 3 deals with climate data projections and how to access and analyze them. Chapter 4 addresses the potential impacts on airports, including vulnerability and criticality. Chapter 5 considers airport adaptation strategies, including those not involving infrastructure investments, as well as practical financial constraints that an airport may face. The remainder of this chapter focuses on the suggested methodology for dealing with airport climate risk.

Two steps are suggested to evaluate climate risk at an airport, as shown in Exhibit 2-1.

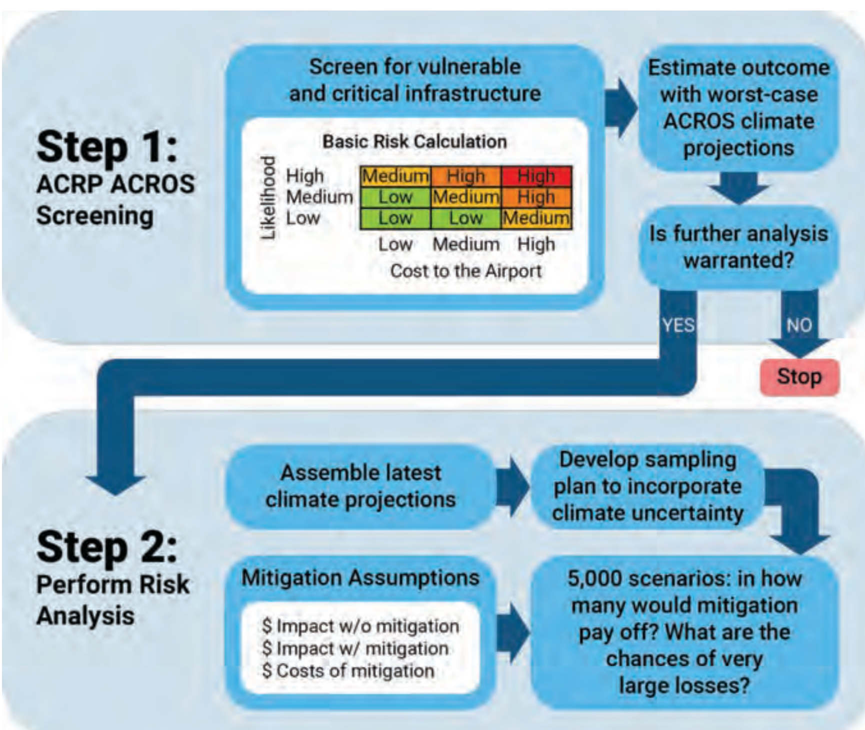


Exhibit 2-1. Suggested two-step method for evaluating airport climate risk.

The first step uses the ACROS tool as a screening device to rule out climate stressors unlikely to affect an airport, at least through 2060 (Dewberry et al. 2015; the ACROS tool can be downloaded at http://www.trb.org/publications/blurbs/173554.aspx). The second step involves more formal climate risk analysis, which is the main subject of this handbook. Both steps are described in the sections that follow.

2.4 Step 1: Initial Screening Analysis for Assessing Climate Risk

In the remainder of this handbook, information on how to deal with climate risk and uncertainty will be presented. It is important to understand that the quantitative methods are built on the same fundamental framework as a conventional BCA or FFA, which describes specific benefits and costs of a proposed project, projects these out over its useful life, and discounts the monetary impacts to estimate a net present value.

However, the basic framework is then extended and modified to treat costs or benefits in a probabilistic way that reflects the uncertainty inherent in future climate change events that may affect an airport. The methods described are straightforward, but in practical terms they may require a fair amount of resources and expertise.

This section provides guidance on using ACROS to screen for climate stressors that may affect a specific airport. Output from this model can also be used to assess uncertain future climate change events within the context of a conventional BCA or FFA that does not rely on the formal probabilistic methods described in this handbook.

A Prior Example

A relevant example of how to use the ACROS model is presented in *ACRP Synthesis 13: Effective Practices for Preparing Airport Improvement Program Benefit–Cost Analysis*, which cites a BCA prepared for Houma-Terrebonne Airport in Louisiana (Landau and Weisbrod 2009). While it pertains to oil spills, the method used can also be applied to climate change events. The project involved strengthening a runway, sections of several taxiways, and the apron in order to handle several new heavy aircraft that would be used by a company specializing in oil-spill mitigation along the Gulf coast. The entire analysis comprised environmental benefits measured as the avoidance of damage resulting from untreated oil spills. The BCA evaluated a range of specific scenarios with different numbers and magnitudes of likely oil-spill events (ranging from two to seven per year and occurring at different distances offshore), and the individual benefit–cost ratios ranged from 0.2 to 4.0.

To support this approach, the analysis cited documentation justifying the specific scenarios selected for analysis, which included an outside oil-spill risk analysis, plus historical data showing the incidence and location of spills over the prior 2 years. Each scenario was evaluated as a conventional BCA with known benefits and costs.

Airports could use this same approach to perform an initial screening analysis of the potential effects of climate change. Under this approach, a few different discrete scenarios would be selected for comparison using a conventional BCA or FFA with specific assumed benefits and costs.

How to Identify Climate Stressors

Airports may be particularly susceptible to climate stressors such as high temperatures above some predefined threshold or increased likelihood of storms and flooding events due to sea level rise. The immediate question, then, becomes one of identifying and justifying specific climate scenarios involving these stressors. In lieu of undertaking the significant effort that may be required to access the latest climate data (as described in Chapter 3), a reasonable first step would be to use the ACROS software tool. ACROS includes projections for different climate stressors at most commercial service airports in the United States. (In ACROS, the stressors are referred to as “vectors.”) As an example, the ACROS forecast for Pensacola Gulf Coast Regional Airport (PNS) is shown in Exhibit 2-2.[3]

Notice that for each stressor/vector, ACROS provides a baseline (the number of days per year where the stressor occurs as of 2013), plus projections for 2030 and 2060. The projection years report median, 25th percentile (low), and 75th percentile (high) estimates. The estimates are based on a limited number of climate forecasting models and employ projections that have since been updated. Nevertheless, they may provide three reasonable scenarios (low, median, and high) for an airport’s operators to assess whether the airport may be significantly affected by any of these stressors. This may be enough information for an analyst to determine if more detailed quantitative analysis of a climate risk is warranted.

Using ACROS as a Screening Tool

ACROS is particularly useful as a screening tool. Potential threats for PNS are easy to identify from Exhibit 2-2. The main threat appears to be high temperatures, where aircraft might have to take payload penalties for longer-haul flights.

Summary of climate data changes

Summary of Historical Record and Projected Changes (Days/Year)

Climate Vector	Units	2013	2030			2060		
		Baseline	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
HotDays	days per year	13.3	23.4	28.6	33.2	38.5	51.6	63.2
VeryHotDays	days per year	0.3	2	4.9	8.1	5.3	12.4	19.8
FreezingDays	days per year	0.1	0	0	0.1	0	0	0.1
FrostDays	days per year	6.4	4.3	4.7	5.4	1.1	2.3	3.9
HotNights	days per year	173	185.8	188.1	191.8	205	210.9	220
HumidDays	days per year	161.8	173.3	177.9	186	190.5	202.2	222.2
SnowDays	days per year	0	0	0	0	0	0	0
StormDays	days per year	78.4	77.3	78.9	80.3	75.6	79.6	83.1
HeavyRain1Day	days per year	11.1	10.7	11.3	11.8	10	11.6	12.9
DryDays	days per year	18.9	19.2	19.6	20.4	19.6	20.7	22.7
SeaLevelRise	days per year	0	0	0	0	0	0	0
CoolingDays	days per year	223.2	234.4	235.3	237.4	251.1	253.4	258.6
HeatingDays	days per year	77.2	67.7	68.9	70	53.3	56.4	59.3

Summary of Historical Record and Projected Changes (Various Unit)

Climate Vector	Units	2013	2030			2060		
		Baseline	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
CoolingDegreeDays	yearly accumulation	1522.5	1735.7	1764.9	1814.6	2055.6	2128.5	2252.8
HeatingDegreeDays	yearly accumulation	576.9	462.4	492.9	519.3	290.8	367	432.9
HeavyRain5Day	inches	4.3	4.3	4.4	4.5	4.3	4.6	4.9
SeaLevelRise_BaseFloodElevation	feet	0	0	0	0	0	0	0

Source: ACROS from *ACRP Report 147* (Dewberry et al. 2015).

Exhibit 2-2. ACROS projections for PNS.

If, in the worst case, the climate stressor would not place a large burden on the airport or its users, then the airport could reasonably conclude that no further analysis needed to be undertaken. For example, ACROS shows that for PNS, up to 19.8 very hot days could occur in 2060. In ACROS, a "very hot day" is defined as temperatures exceeding 100°F. If an analyst knows that PNS users could easily adapt to 100°F temperatures occurring as much as 20 times annually by 2060, then no further action would be needed.

Alternatively, consider a coastal airport. Suppose ACROS showed that in the worst case there were no indications of sea level rise that would threaten the airport by 2060; no further effort might then be required.

If there is some uncertainty about the size of the impact or whether a possible adaptation would pay off in the worst-case scenario, an analyst could undertake a conventional benefit–cost or financial feasibility analysis using the ACROS climate data. An example of such an analysis is provided in the following.

Sample Climate Resilience Analysis Using ACROS

Based on the data shown previously, PNS might decide to analyze whether a certain infrastructure project should be undertaken to mitigate the potential impacts from the projected increase in the number of very hot days (temperatures above 100°F). Up to three specific scenarios could be analyzed:

- **Median:** assume that very hot days increase from 0.3 in 2013 to 4.9 in 2030 and 12.4 in 2060.
- **Low:** assume that very hot days increase to 2.0 in 2030 and 5.3 in 2060.
- **High:** assume that very hot days increase to 8.1 in 2030 and 19.8 in 2060.

Using this framework, a conventional BCA or FFA—assuming that these increases occur with certainty—could be carried out for one or more of these scenarios.[4]

One strategy for performing a screening analysis is to test the proposed project using the most extreme forecast values for climate stressors in the ACROS model. If a project does not pay off at the extreme forecast, the analyst can have some confidence recommending that the project be rejected for the time being and suggest revisiting it during the next planning cycle when more information is available. So, for example, the project might be tabled until the next master planning cycle.

Steps in Creating a BCA (or FFA)

The following presents a sample BCA for PNS of a 1,500-ft runway extension project to mitigate the delays due to very hot days. This is only an illustration and is not meant to represent actual opportunities or risks for PNS.

- **Identify the objective:** The objective of the runway extension would be to avoid current and projected commercial departure delays on days when temperatures exceed 100°F.
- **Define a base case:** The base case is that the airport does not undertake the runway extension project. In this simplified example, it is assumed that afternoon departures between 13:00 and 17:59 would have to be cancelled, thereby imposing delay costs on passengers (as measured by the value of their time) and foregone costs on airlines (as measured by crew costs and aircraft depreciation).
- **Define a scenario case:** Under the scenario case where the runway extension project is undertaken, the analyst would have to project estimated reductions in delays (benefits), which would depend on the number of flights that could avoid delays due to the project; this would be balanced against the costs to invest in, operate, maintain, and rehabilitate the runway extension.[5] To illustrate the process, a fixed growth rate in airport operations over time is assumed, along with a simple assumption that the project would reduce the incidence of cancelled flights (and the corresponding cancellation costs borne by passengers and airlines) by 60%.

- **Identify analysis period:** It is assumed that the runway construction could be completed in a single year (2019) and then would be available for use starting in 2020. It is also assumed that the analysis itself was undertaken in 2017 even though the effects from the mitigation project are not felt until 2020. The effects then run out through 2060—the 40-year life of the runway.
- **Apply decision criteria:**
  - **Benefit–cost ratio ≥ 1:** If the net project benefits (measured as the discounted present value of the reduction in flight cancellations because of the runway extension) exceed the costs (the discounted present value of constructing, maintaining, and operating the runway extension), then the project has merit and the analyst would recommend further analysis of climate risk, along the lines described in Chapter 4 and beyond.
  - **Benefit–cost ratio < 1:** If the costs exceed benefits, the analyst can conclude that the project does not currently have merit because the analysis has assumed the maximum number of very hot days in the ACROS model.[6]

Key parameter assumptions for this example are shown in Exhibit 2-3. All dollar figures are measured in constant (inflation-adjusted) dollars. The BCA is shown in detail in Exhibit 2-4. The calculations for each relevant column are as follows:

1. Annual passenger delay costs shown in Column E are computed as the number of very hot days (B) * daily passengers (D) * average hours of delay per passenger * cost of delay per hour.
2. Airline costs, shown in Column F, are equal to the number of very hot days (B) * daily flights (C) * average block hours per flight * (crew cost per hour + depreciation per hour).[7]
3. Total base case delay costs shown in Column G are the sum of passenger plus airline costs. These are the costs that would be incurred under the base case, where the runway project is not undertaken.
4. As mentioned previously, for this example it is assumed that the runway project reduces the incidence of cancelled flights by 60% starting in 2020. Thus, the scenario case delay costs shown in Column H are 60% below the base-case costs in Column G. Column I simply subtracts Column H from G to represent the delay benefits from undertaking the mitigation project.

Assumptions		Source
Construction cost for 1,500-ft runway extension	$6,562,500	Assumes $175/sq yard for 150-ft wide runway + 75-ft wide taxiway
20-year rehabilitation cost % construction cost	50%	Assumed value
Annual O&M expense % construction cost	3%	Assumed value
Affected Flights:		
Avg daily flights 1300-1759 in 2017	10.3	
Avg block hrs per flight	1.8	Official Airline Guide (OAG) -- PNS departures for May-Sep 2017, 1300-1759 hrs
Avg seatsize	91	
PNS annual departure growth rate	1.1%	FAA TAF Forecast 2016, ITN_AC + ITN_AT ops annual growth rate at PNS, 2017-2045
Passenger Impacts:		
Avg load factor	84.6%	FAA T-100 Domestic Segment report -- PNS load factor for May-Sep 2016
Avg daily pax per flt	77.0	= PNS Avg seatsize * Avg load factor
Avg hrs of delay per passenger	3.0	Assumed value
Passenger delay cost per hr	$44.30	FAA Economic Values, Table 1-1, All Purpose Intercity Air and High Speed Rail
Airline Impacts:		
Crew cost per block hr	$349	FAA Economic Values, Table 4-6, RJ more than 60 Seats
Aircraft depreciation per block hr	$144	

Note: FAA Economic Values document is FAA 2016b.

Exhibit 2-3. Parameters used in conventional sample BCA for PNS.

			Base Case					Mitigation Scenario				
	A	B	C	D	E	F	G	H	I	J	K	L
	PNS MAX Very Hot Days	Interpolated MAX Very Hot Days	Daily Flts Affected per VHot Day	Daily Pax Affected per VHot Day	Annual Passenger Delay Costs	Annual Aircraft Crew plus Depreciation Costs	Base Case: Total VHot Day Delay Costs	Scenario: Total VHot Day Delay Costs	Benefits (Reduction in Delay Costs)	Runway Extension Investment	Annual O&M	Total Annual Costs
2013	0.3	0.3										
2014		0.8										
2015		1.2										
2016		1.7										
2017		2.1	10.3	793	$225,025	$19,517	$244,543	$244,543	$0	$0	$0	$0
2018		2.6	10.4	802	$276,326	$23,966	$300,292	$300,292	$0	$0	$0	$0
2019		3.1	10.5	810	$328,706	$28,510	$357,216	$357,216	$0	$6,562,500	$0	$6,562,500
2020		3.5	10.6	819	$382,185	$33,148	$415,333	$166,133	$249,200		$196,875	$196,875
2021		4.0	10.8	828	$436,778	$37,883	$474,661	$189,864	$284,796		$196,875	$196,875
2022		4.4	10.9	837	$492,504	$42,716	$535,220	$214,088	$321,132		$196,875	$196,875
2023		4.9	11.0	846	$549,381	$47,649	$597,030	$238,812	$358,218		$196,875	$196,875
2024		5.3	11.1	855	$607,428	$52,684	$660,111	$264,045	$396,067		$196,875	$196,875
2025		5.8	11.2	864	$666,662	$57,821	$724,483	$289,793	$434,690		$196,875	$196,875
2026		6.3	11.3	873	$727,103	$63,064	$790,167	$316,067	$474,100		$196,875	$196,875
2027		6.7	11.5	883	$788,771	$68,412	$857,183	$342,873	$514,310		$196,875	$196,875
2028		7.2	11.6	892	$851,683	$73,869	$925,552	$370,221	$555,331		$196,875	$196,875
2029		7.6	11.7	902	$915,861	$79,435	$995,296	$398,118	$597,178		$196,875	$196,875
2030	8.1	8.1	11.8	912	$981,324	$85,113	$1,066,436	$426,575	$639,862		$196,875	$196,875
2031		8.5	12.0	921	$1,039,664	$90,173	$1,129,837	$451,935	$677,902		$196,875	$196,875
2032		8.9	12.1	931	$1,099,148	$95,332	$1,194,480	$477,792	$716,688		$196,875	$196,875
2033		9.3	12.2	941	$1,159,794	$100,592	$1,260,386	$504,154	$756,232		$196,875	$196,875
2034		9.7	12.4	952	$1,221,620	$105,954	$1,327,574	$531,030	$796,545		$196,875	$196,875
2035		10.1	12.5	962	$1,284,645	$111,421	$1,396,065	$558,426	$837,639		$196,875	$196,875
2036		10.4	12.6	972	$1,348,887	$116,993	$1,465,879	$586,352	$879,527		$196,875	$196,875
2037		10.8	12.8	983	$1,414,364	$122,672	$1,537,036	$614,814	$922,222		$196,875	$196,875
2038		11.2	12.9	993	$1,481,098	$128,460	$1,609,557	$643,823	$965,734		$196,875	$196,875
2039		11.6	13.0	1004	$1,549,105	$134,358	$1,683,464	$673,385	$1,010,078		$196,875	$196,875
2040		12.0	13.2	1015	$1,618,408	$140,369	$1,758,777	$703,511	$1,055,266	$3,281,250	$196,875	$3,478,125
2041		12.4	13.3	1026	$1,689,025	$146,494	$1,835,518	$734,207	$1,101,311		$196,875	$196,875
2042		12.8	13.5	1037	$1,760,976	$152,734	$1,913,710	$765,484	$1,148,226		$196,875	$196,875
2043		13.2	13.6	1048	$1,834,283	$159,092	$1,993,375	$797,350	$1,196,025		$196,875	$196,875
2044		13.6	13.8	1059	$1,908,966	$165,570	$2,074,536	$829,814	$1,244,721		$196,875	$196,875
2045		14.0	13.9	1071	$1,985,046	$172,168	$2,157,215	$862,886	$1,294,329		$196,875	$196,875
2046		14.3	14.1	1082	$2,062,545	$178,890	$2,241,436	$896,574	$1,344,861		$196,875	$196,875
2047		14.7	14.2	1094	$2,141,485	$185,737	$2,327,222	$930,889	$1,396,333		$196,875	$196,875
2048		15.1	14.4	1106	$2,221,888	$192,710	$2,414,598	$965,839	$1,448,759		$196,875	$196,875
2049		15.5	14.5	1118	$2,303,775	$199,813	$2,503,587	$1,001,435	$1,502,152		$196,875	$196,875
2050		15.9	14.7	1130	$2,387,170	$207,046	$2,594,215	$1,037,686	$1,556,529		$196,875	$196,875
2051		16.3	14.8	1142	$2,472,095	$214,411	$2,686,507	$1,074,603	$1,611,904		$196,875	$196,875
2052		16.7	15.0	1154	$2,558,575	$221,912	$2,780,487	$1,112,195	$1,668,292		$196,875	$196,875
2053		17.1	15.2	1167	$2,646,632	$229,549	$2,876,181	$1,150,472	$1,725,709		$196,875	$196,875
2054		17.5	15.3	1179	$2,736,290	$237,326	$2,973,616	$1,189,446	$1,784,170		$196,875	$196,875
2055		17.9	15.5	1192	$2,827,575	$245,243	$3,072,818	$1,229,127	$1,843,691		$196,875	$196,875
2056		18.2	15.6	1205	$2,920,510	$253,304	$3,173,813	$1,269,525	$1,904,288		$196,875	$196,875
2057		18.6	15.8	1218	$3,015,120	$261,509	$3,276,630	$1,310,652	$1,965,978		$196,875	$196,875
2058		19.0	16.0	1231	$3,111,431	$269,863	$3,381,294	$1,352,518	$2,028,777		$196,875	$196,875
2059		19.4	16.2	1244	$3,209,469	$278,366	$3,487,835	$1,395,134	$2,092,701		$196,875	$196,875
2060	19.8	19.8	16.3	1258	$3,309,259	$287,021	$3,596,280	$1,438,512	$2,157,768		$196,875	$196,875
						Present Value @7%:	**$13,951,697**	**$6,050,134**	**$7,901,562**			**$8,156,393**

NPV	**-$254,831**
B/C Ratio	**0.97**

Note: PAX = passengers.

Exhibit 2-4. Sample BCA results using ACROS projections for PNS.

5. Construction and annual operation and maintenance (O&M) costs are shown in Columns J and K, respectively, using the assumptions shown in Exhibit 2-3.
6. Total project costs shown in Column L are the sum of Columns J and K.

The relevant discounted present value benefits and costs are shown at the bottom of Columns G, H, I, and L. The overall NPV of the project is simply the difference in present values between Column I (benefits) and Column L (costs). The benefit–cost ratio is the ratio of these two values.

Applying the Decision Criteria

What does this simplified BCA show? The standard decision criterion for a conventional BCA is that if the discounted present value of total benefits exceeds the discounted present value of total costs, then the project has merit. In this case, as shown at the bottom right of Exhibit 2-4, the costs exceed benefits (or equivalently, the benefit–cost ratio is less than 1), and the conclusion is that the proposed runway extension does not make economic sense.

This conclusion is valuable because it is based on the maximum ACROS forecast for very hot days. If all other factors in the analysis are the same, the median or low ACROS forecast for very hot days would show an even lower level of net benefits. Therefore, if the ACROS model forecast is reasonable, one can conclude the project does not make sense now and that it can be reconsidered at a later date, when more or better information on climate change or costs may be available.[8]

It is important to note that if the NPV for the runway project were found to be positive using the maximum ACROS forecast for very hot days, forming a conclusion about its merits would be more difficult. One option would be for the analyst to repeat the process using the median and low ACROS forecasts for very hot days. If the project were found to have merit under all three forecasts, then the analyst would have more confidence concluding that the project had merit. On the other hand, if the project failed assuming the median or low forecast but showed a positive result for the high forecast, perhaps a more formal risk analysis (described in the following sections) would be warranted.

This discussion represents a simplified screening approach to analyzing the potential impacts of climate change. In practice, airports would also need to adequately assess vulnerability (the likelihood of adverse events), criticality (the costs of the adverse events), and adaptation possibilities in order to identify a relevant investment project before actually undertaking a BCA or FFA. Chapters 4 and 5 provide a detailed discussion of these topics.

In sum, one can use the ACROS model to develop standard benefit–cost or financial feasibility analyses of climate mitigation projects. If the projects fail the economic tests at the high ACROS forecast level, one could reasonably conclude that they do not (currently) have merit. However, if the analysis shows a positive result, more formal risk analysis may be warranted.

Differences in Undertaking an FFA

In an FFA, an airport is interested in determining if a proposed project (like the runway extension at PNS) would produce returns (or benefits) to the airport and its users that exceed the costs that the airport and its users pay. Compared to the previous example, the main distinctions between a BCA and an FFA would be:

- **Benefits:** Airports and their direct users (aircraft operators) would be interested in the cash costs of delays and cancellations in the base case and how much they will be reduced in the scenario case. The impacts on passengers would typically not be considered in an FFA.
- **Costs:** Airports would count only the net out-of-pocket costs they or their users would incur to pay for the project; for example, if the airport received an Airport Improvement Program

(AIP) grant that paid for 90% of the runway extension, then in the FFA, the airport would count only 10% of the investment costs.

- **Discount rate:** The airport would use its actual cost of capital (e.g., the interest rate on a recent bond issue).

The remainder of the analysis, including applying the decision criteria, would be identical.

Using ACROS for Sea Level Rise Projections

For airports near coastal areas, the same sort of approach as described previously could be carried out for analysis of future sea level rise using ACROS projections. In this situation, the two key ACROS climate stressors to look at are labelled:

- **Sea level rise:** This refers to the number of days per year where the runway elevation is projected to be inundated by tidal flooding.
- **Sea level rise base flood elevation (BFE):** This refers to the height to which floodwater is anticipated to rise during a 100-year flood event, measured in feet relative to the North American Vertical Datum of 1988 (NAVD88). (See Appendix D for an explanation of the use of a vertical datum in sea level climate analysis.)

Airport operators could identify the critical elevations for each piece of infrastructure and determine if the airport would be exposed in the worst-case sea level rise scenario in ACROS. If there are a number of important facilities exposed, it might then pay to evaluate the benefits and costs of undertaking a mitigation project. The exact climate assumptions and models employed to generate the ACROS projections are not based on the same sea level rise climate data described in Appendix D. Thus, one must be cautious if trying to compare the ACROS projections of sea level rise to the projections described in this handbook.

2.5 Step 2: Risk-Adjusted Analysis for Assessing Climate Risk

The conventional analysis described previously would likely require fewer resources and less effort from the airport than would a risk-adjusted effort, but it would be unlikely to reflect the full range of potential risks faced by the airport.

If, in the worst ACROS case, a climate stressor could impose high net costs on the airport or its users, more analysis beyond ACROS could be warranted. Or it could be the case that the specific climate stressors used in ACROS were not completely relevant for a specific airport—for example, ACROS' definition of 100°F for a "very hot day" may not be relevant for an airport with an 11,000-ft runway that can easily handle takeoffs of large aircraft on long-haul routes. However, it may be that temperatures above, say, 110°F would in fact start to necessitate weight restrictions on certain flights. In these cases, it may be reasonable for the analyst to proceed to Step 2 to obtain more detailed climate data.

Aside from the specifics of climate stressor definitions, another important piece of information not included in ACROS is the likelihood of different future outcomes. What is the distribution of future high temperatures? How likely is it that temperatures will exceed 100°F, 110°F, or 115°F in 2030, 2060, or other years? Or take the case of a coastal airport, where certain pieces of infrastructure would be at risk if flooding exceeded 5 ft while other infrastructure would be exposed at 7 ft. The analyst would want to know the likelihood of these events, recognizing that the probability might increase over time due to sea level rise.

Developing estimates of these kinds of risks is central to good decision making, but ACROS was not designed to provide this kind of information. The primary limitation of using a conventional

BCA or FFA is that the approach does not directly consider the uncertainty of climate change and the risk it imposes on the airport. A more thorough and robust analysis is available through the use of Monte Carlo simulation. This approach involves:

- Defining or assessing probability distributions for one or more variables of interest, such as extreme water levels or high temperatures;
- Using simulation techniques to make a large number of random draws from the distributions to cover the likely range of outcomes;
- Evaluating each draw to obtain a value for the variable of interest (water rise or high temperature); and
- Combining all of the draws to obtain estimates of the expected or most likely values.

Exhibit 2-5 further describes Monte Carlo simulation.

The basic procedure used in Monte Carlo simulation is to draw a random number (by convention between 0 and 1) for each relevant time period of an analysis, with the value determining whether an uncertain climate event occurs in that time period corresponding to its probability.[9]

Consider again the previous example for PNS. In the benefit–cost analysis, it was assumed that the annual counts of very hot days (above 100°F) followed the ACROS projections and increased deterministically from 0.3 in 2013 to 8.1 in 2030 and then to 19.8 in 2060. This could be transformed into a Monte Carlo analysis by repeating the analysis multiple times but using different counts of the very hot days for each repetition in order to reflect the uncertainty inherent in these projections.

Chapter 3 and Appendix D contain detailed information about obtaining future climate projections for the incidence of high temperatures. Suppose one obtained such projections from, say, 10 different climate models, each with its own projection of daily high temperatures occurring in each year from 2020 through 2090. For reasons discussed in Appendix D, the number

Monte Carlo simulation (or the Monte Carlo method) is a computerized simulation technique that makes use of randomization and probability statistics to investigate problems involving uncertainty. Typically, it involves a computer model of a system or project (e.g., air traffic at an airport). The inputs to the model, instead of being fixed numbers or variables, are specified as probability distributions.

For example, rather than traffic growth being set at X% per annum, it may be defined as having a normal (bell-curve) distribution with a mean of X% and a standard deviation of 1.0%. Using computer software, the model is run multiple times, each time randomly sampling from the input distributions, resulting in different outcomes each time. Often, the model will be run thousands or tens of thousands of times (known as iterations), and the results will be collected from each run.

With enough iterations of the model, the output can demonstrate the range of possible outcomes and provide statistical estimates of the probabilities of various outcomes. Depending on the complexity of the model and input distributions assumed, the range of outcomes can be large and not always linear. Expected or most likely values can also be generated.

Monte Carlo can be seen as a powerful what-if or scenario-generating exercise where every possible what-if or scenario is generated (within the confines of the model specification), including interactions between the various input factors. Another way of looking at it is that each iteration of the model represents one possible future for the system being modeled. By running the model thousands of times, the user can view whole sets of possible futures, assess which are most likely to occur, and identify areas of greatest downside or upside.

Monte Carlo is used extensively in a wide range of fields. One of its first applications was in designing the shielding for nuclear reactors at the Los Alamos National Laboratory in the 1940s. (The name *Monte Carlo* was coined as a code name by scientists at the laboratory in reference to the Monte Carlo casino resort.) Monte Carlo simulation has since been used in finance, project planning, engineering studies, traffic modeling, cancer radiation therapy, and telecommunications network design, among many other applications.

Source: *ACRP Report 76* (Kincaid et al. 2012).

Exhibit 2-5. Introduction to Monte Carlo simulation.

of data points to handle a long projection period could be very large. But as shown there, it is relatively straightforward to summarize the data into temperature bins and count the number of days each year temperatures are forecast to be in each bin. Exhibit 2-6 is an extract from such a tabulation of individual forecasts from four geographic locations near an airport.

Each column labelled Hxxx in Exhibit 2-6 is a 2-degree temperature bin, while each row is a forecast from one model for 1 year and one geographic grid point, showing the number of days where the high temperature is at the indicated level.

The further one looks into the future, the wider the dispersion of forecasts would be from the different models. This dispersion represents the inherent risk and uncertainty of climate change. For example, a summary of results for temperatures exceeding a critical level (e.g., 110°F) might look like what is shown in Exhibit 2-7.

To use the data in a risk analysis, one could set up a straightforward sampling plan where, say, drawing a random number between 0 and 0.025 for a given year would mean using the count from Model #1 and Grid_ID #1 (in Exhibit 2-6); a random number between 0.025 and 0.050 would use the count from Model #1, Grid_ID #2, and so forth.

After going through all the relevant years, one will have completed one simulation showing a possible future path for very hot days. The process then could be repeated again and again, thereby generating new simulations representing many different possible futures, and each simulation could be independently evaluated from a benefit–cost perspective.

Suppose 1,000 simulations were performed, representing 1,000 different estimates of benefits and costs. Recalling Exhibit 2-4, the NPVs shown at the bottom of Columns G, H, and I (representing base-case delay costs, scenario case delay costs, and scenario case benefits, respectively) would change in each simulation. Under the assumptions used for the analysis, the present value

MODEL	YEAR	GRID_ID	H100	H102	H104	H106	H108	H110	H112	H114	H116	H118	H120	H122	H124	H126	H128
ACCESS1-0	2020	1	15	16	13	22	29	15	18	1	0	0	0	0	0	0	0
ACCESS1-0	2020	2	18	13	13	23	27	22	13	4	0	0	0	0	0	0	0
ACCESS1-0	2020	3	16	16	12	22	25	19	19	1	0	0	0	0	0	0	0
ACCESS1-0	2020	4	16	14	16	21	28	18	15	2	0	0	0	0	0	0	0
ACCESS1-0	2021	1	24	21	15	21	19	11	7	3	2	0	0	0	0	0	0
ACCESS1-0	2021	2	30	18	18	18	20	12	9	2	2	0	0	0	0	0	0
ACCESS1-0	2021	3	25	16	15	22	21	11	8	3	2	0	0	0	0	0	0
ACCESS1-0	2021	4	32	20	16	20	18	11	8	1	2	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ACCESS1-0	2090	1	7	13	13	7	18	25	28	31	15	5	1	1	1	0	0
ACCESS1-0	2090	2	8	9	14	11	14	24	32	32	13	6	2	2	0	0	0
ACCESS1-0	2090	3	8	11	10	11	17	22	30	32	15	6	1	1	1	0	0
ACCESS1-0	2090	4	11	8	14	8	20	26	32	32	8	6	1	2	0	0	0
ACCESS1-3	2020	1	19	33	32	18	7	10	6	0	0	0	0	0	0	0	0
ACCESS1-3	2020	2	22	32	39	13	10	9	6	1	0	0	0	0	0	0	0
ACCESS1-3	2020	3	20	34	34	15	10	11	5	0	0	0	0	0	0	0	0
ACCESS1-3	2020	4	21	37	37	12	9	11	3	0	0	0	0	0	0	0	0
ACCESS1-3	2021	1	9	22	27	26	19	14	5	2	0	0	0	0	0	0	0
ACCESS1-3	2021	2	14	16	33	22	19	18	5	2	0	0	0	0	0	0	0
ACCESS1-3	2021	3	9	17	29	27	18	14	8	2	0	0	0	0	0	0	0
ACCESS1-3	2021	4	15	20	28	25	18	17	3	2	0	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ACCESS1-3	2090	1	12	15	20	20	37	33	19	15	5	3	1	0	0	0	0
ACCESS1-3	2090	2	12	14	16	23	35	32	30	13	5	1	2	0	0	0	0
ACCESS1-3	2090	3	11	15	18	24	34	35	22	12	6	3	1	0	0	0	0
ACCESS1-3	2090	4	13	16	16	25	34	40	18	12	5	1	2	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Exhibit 2-6. Forecast count of days reaching indicated high temperature.

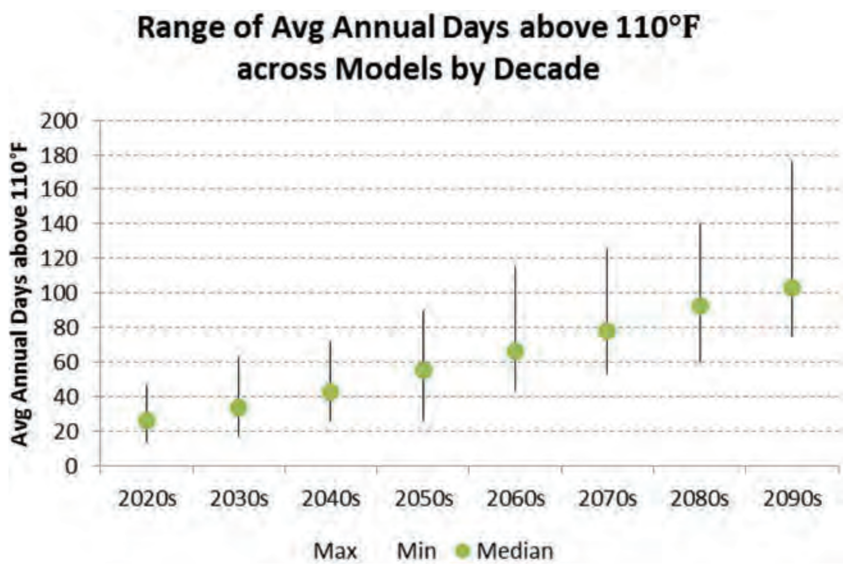


Exhibit 2-7. Forecast range of count of days above 110°F.

of scenario case costs (bottom of Column L) would remain constant because they do not depend on the climate forecasts.

To be clear, Exhibit 2-8 illustrates how the results from 1,000 different simulations could be laid out. Each simulation would relate to a different path for very hot days over time. The baseline outcomes in Column A are the cost of damages that would be incurred over the life of the proposed project if the project were not built (entered as positive numbers). These would be delay (and perhaps other) costs incurred by users due to payload restrictions.

Column B contains the cost of damages incurred if the project were built, while Column C contains the costs of building and operating the project (say, a runway extension). Again, these values would be entered as positive numbers. With this layout of the results, the benefit–cost ratio for each simulation would simply be the reduction in damages (A – B) divided by project cost (C).

An alternative but equivalent way of looking at the results is provided in Column D, which contains the NPV of the project for each simulation, equal to the damage savings (A – B) less the cost of the project (C). The benefit–cost ratio will be greater (lesser) than 1 whenever the

	Baseline (without project)	Scenario (with project)		NPV
	A	B	C	D
Simulation	PV $ of Damages	PV $ of Reduced Damages	PV $ of Project Costs	PV $ of (A – B) – C
1				
2				
…				
…				
…				
1,000				

Exhibit 2-8. Results from 1,000 Monte Carlo simulations.

NPV is greater (lesser) than 0. These 1,000 NPV results then could be sorted and placed in order from highest to lowest. Thus, in some cases the NPV could be positive, while in others it could be negative, the results depending on the overall incidence of very hot days throughout the years for each simulation.

The results could be averaged across all 1,000 simulations, as shown in Exhibit 2-9.[10] In addition, suppose one is interested in how often the project would pay off; one could count the number of simulations (percentage of the time) the project showed a positive result or a negative result. One could also evaluate, say, the worst 1% of outcomes, meaning that the associated results that would occur 1% of the time.

In this example, the average expected NPV is $0.5 million, with a corresponding benefit–cost ratio of 1.07 averaged across all 1,000 simulations. But the range and standard deviations of these measures are large, and without further consideration it would be difficult to draw a definite conclusion about whether the mitigation project should be undertaken based on these results.

VaR Interpretation

As a natural extension, the results from the simulations can be used to look at what is known as "value at risk," which is a concept that originated in the financial industry in the late 1980s but is well suited to assessing the uncertainty associated with future climate change projections. More details about translating Monte Carlo simulation results into a VaR analysis are provided in Appendix C.

For purposes of a VaR analysis, it is appropriate to focus on the net impacts both with and without the project. This is a slightly different way of looking at the NPV results. For convenience, the initial results from the simplified PNS example are summarized here:

- **Baseline net impacts:** –$13.95 million (Column G delay costs from Exhibit 2-4).
- **Scenario net impacts:** –$14.21 million (Column H delay costs + Column L mitigation project costs from Exhibit 2-4).

The impacts are shown as negatives because, under the assumptions of the analysis, the airport or its users would bear these impacts as net damages or costs. If one were to plot these two values on a graph, the scenario impact is more negative than the base-case impact, indicating that the project is not worth pursuing if the count of very hot days were to follow the assumed path shown in Exhibit 2-4.

This could be repeated for each of the Monte Carlo simulations, resulting in a new pair of net impacts under the base case and scenario case. To assess these results across all 1,000 simulations, they can be sorted based on the difference between the two values and then plotted along a percentage scale.

The result is a VaR graph such as the one shown in Exhibit 2-10. The results labelled "baseline" reflect the different possible projected losses that could be incurred by the airport if it chose not

	Average	Min	Max	Standard Deviation
Avg NPV of Project	$0.5 million	–$5.1million	$22.5 million	$4.5 million
Avg B/C Ratio	1.07	0.37	3.75	0.56

Exhibit 2-9 Sample Monte Carlo aggregated results.

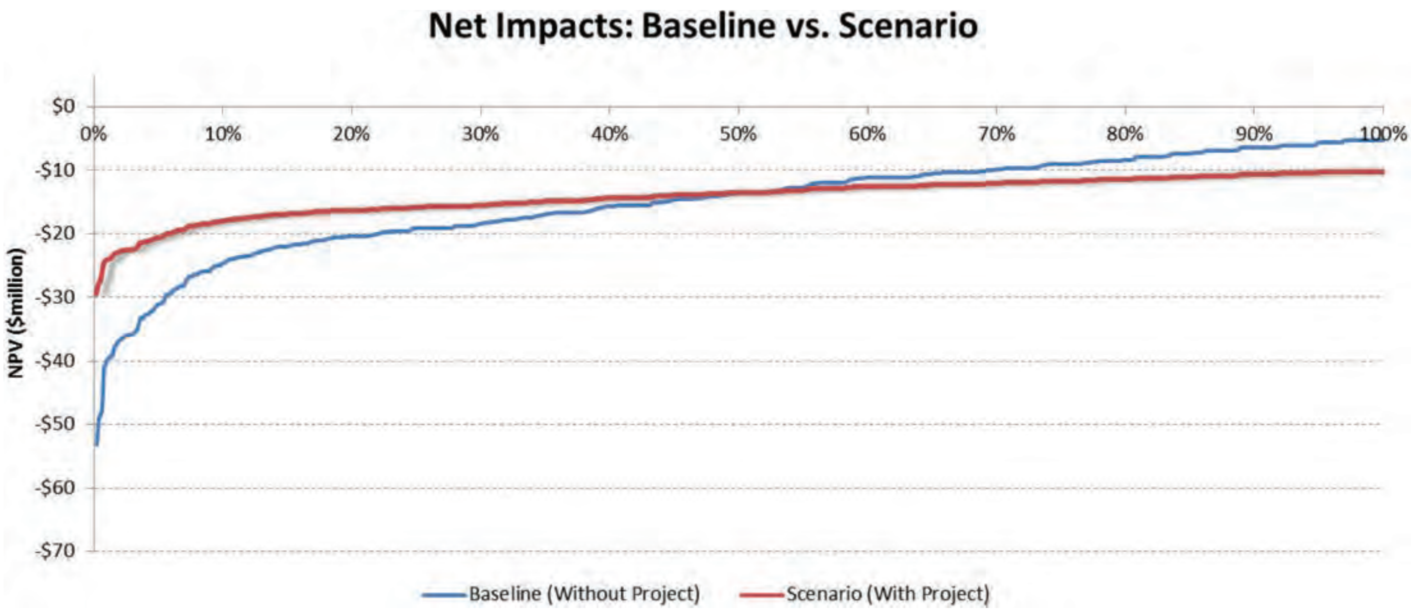


Exhibit 2-10. VaR comparison.

to undertake the proposed project. The alternative is to undertake the project, in which case the airport would face the construction and maintenance costs plus the reduced delay costs; this is represented by the "scenario" line in the chart.

Based on the varying benefit results from the Monte Carlo simulations, the blue line in the chart shows that if the airport does nothing, it faces a 10% chance of incurring damages (in the form of delay costs) of at least around $25 million (where the blue line passes the 10% point on the horizontal axis) and could incur damages of as much as $50 million or more. On the other hand, if it does undertake the mitigation project, it must pay the investment costs (about $8 million from Exhibit 2-4) and will incur any remaining delay impacts; these two factors combined could total as much as about $30 million (left extremity of chart for the red line). But also note that the range of potential net impacts is much larger under the baseline case (from about $5 million–$50 million in damages) than under the scenario case ($10 million–$30 million in damages and project costs). The chart also shows that there is about a 50% chance that the NPV of the project would be positive (indicated by the point at which the two curves intersect).

It is important to properly interpret these results. Facing a 10% chance of incurring damages of at least $25 million means that in 100 of the 1,000 simulations, the present value of damages would be $25 million or worse. Remembering that each simulation represents a set of future outcomes running from 2020 through 2090, these 100 simulations will include many different specific outcomes that vary across the years. In some simulations, there may be a small number of unusually hot years early on, resulting in a few highly valued delays (because they are discounted less when occurring early). In many others, the high temperatures will have been estimated to occur in later years, but they are likely to occur more often, resulting in more lower-valued delays. So it is important to recognize that the 10% chance of damages includes many different potential outcomes; it does not refer to an annual probability of occurrence, but rather the overall likelihood (over the entire analysis period of 2020 through 2090) that the airport's users would face $25 million or more of delay costs (in present value terms) under the base case.

Overall, the VaR analysis provides a different perspective than that from simply focusing on the positive average NPV from Exhibit 2-9. Decision makers at the airport can use the results to help decide between the risky but higher potential payoff of doing nothing and the certain cost of investing in the mitigation project, which reduces but does not completely eliminate the airport's exposure. This is the kind of information decision makers will need to manage climate risk.

2.6 Summary and Next Steps

This chapter has described a two-step process for evaluating climate risk.

- **Step 1: Screening with ACROS:** Assuming the worst ACROS case, is it likely that some airport infrastructure would be vulnerable to one or more climate stressors, and would that be costly to the airport or its users? If the answer is in doubt and there is an adaptation that might make sense, one can use the worst-case ACROS projection to evaluate whether an adaptation would make economic sense (using a conventional benefit–cost or financial feasibility approach).
- **Step 2: Risk-adjusted analysis using Monte Carlo and VaR methods:** When the airport is at risk for large losses or if the ACROS-based analysis is not conclusive, consider undertaking a risk-adjusted analysis to determine how likely it would be for the airport to be affected and whether a potential mitigation project would make sense.

While the approach described here is relatively straightforward, there are a lot of underlying practical and technical topics that must be understood in order to successfully undertake the suggested methodologies. Appendix C provides a more detailed technical description of the Monte Carlo and VaR methodologies, while Chapter 3 and Appendix D provide relevant information on available climate data and projections. In addition, two Microsoft Excel templates have been developed to allow airport analysts to perform their own Monte Carlo and VaR analyses of the effects of future sea level rise and high temperatures. These are described in Appendix E; numerical examples using these templates are shown in Appendix F.

The following chapters provide relevant context and refer the reader to technical material in specific appendices as needed.

CHAPTER 3

State-of-the-Art Climate Measures

About This Chapter

Chapter 3 provides a brief background on available climate projections and measures.

- Section 3.1 describes the different climate scenarios and models that are available for analysis and how to interpret them; technical issues related to accessing, converting, and using specific sea level rise and high-temperature data are provided in Appendix D.
- Section 3.2 describes how existing available software can be used to screen for many other climate stressors in support of Step 1 (screening analysis). (However, note that reliable and detailed forecasts for them may not yet be available to support the kind of risk-adjusted Step 2 analysis described in Section 2.5.)

About the Next Chapter

Chapter 4 discusses identifying and classifying potential airport impacts from climate change.

3.1 Background on Available Climate Data

The first step in performing an analysis of how climate events may affect airports is to understand how they can be measured and what specific data projections are available. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 through a collaboration of the United Nations and the World Meteorological Organization. Since then, the groups associated with the IPCC have produced a series of scientific assessments of the current state of knowledge regarding climate change.

The IPCC's Fourth Assessment Report (AR), known as AR4, uses data and climate projections collected during 2005–2006 from Phase 3 of the Coupled Model Intercomparison Project (CMIP3). IPCC has also produced its Fifth Assessment Report (AR5), which was released in 2015 and is based on more recent climate projections from Phase 5, known as CMIP5 (which itself was released in May 2013). More than 800 authors were involved in writing AR5. The different models considered in both reports are known as general circulation models (GCMs). These models use mathematical equations for a rotating sphere with thermodynamic variables representing energy sources such as radiation and latent heat. These equations are used to simulate the Earth's atmosphere over time, and projections can be made for specific locations (IPCC 2007, IPCC 2014).

AR4 and AR5 both present projections under different future climate scenarios representing different assumptions about the path of GHG emissions reductions. The three AR4 scenarios are named B1, A1B, and A2, while the four AR5 scenarios are named Representative Concentration Pathway (RCP) 2.6, 4.5, 6.0, and 8.5. Generally speaking, B1 and RCP2.6 both represent a low-emissions scenario; A2 and RCP8.5 represent high emissions and involve little or no successful global efforts to mitigate GHGs. The remaining scenarios are between these low- and high-emission scenarios.

To provide an idea of the differences between the more recent AR5 scenarios, global average projections for mean temperature and mean sea level (MSL) rise are shown in Exhibit 3-1 for two future time periods. By comparing the two time periods, one can see that in all cases except for the RCP2.6 temperature estimates, both temperature and mean sea levels are expected to rise more the further into the future one looks. Not surprisingly, it is also the case that the likely range of outcomes becomes wider (less certain). This has important implications in the current context because it suggests that climate impacts will grow over time but with more uncertainty; therefore, decision makers may have to weigh whether to invest in climate resilience projects now or wait until the larger impacts are closer, when perhaps better, more reliable information can be obtained.

It is important to note that it is up to the analyst to decide which scenario to use as the relevant climate assumption. This is extremely important, and choosing between, say, RCP4.5 and RCP8.5 can have significant effects on the projected climate values and, therefore, on the entire analysis. This is particularly true as the scenarios increasingly diverge in later years past the mid-century point.

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range**[c]	**Mean**	***Likely* range**[c]
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range**[d]	**Mean**	***Likely* range**[d]
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Notes:

[a] Based on the CMIP5 ensemble; anomalies calculated with respect to 1986–2005. Using HadCRUT4 and its uncertainty estimate (5–95% confidence interval), the observed warming to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C from 1850–1900, and 0.11 [0.09 to 0.13] °C from 1980–1999, the reference period for projections used in AR4. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period {2.4; 11.2; Tables 12.2 and 12.3}

[b] Based on 21 CMIP5 models; anomalies calculated with respect to 1986–2005. Where CMIP5 results were not available for a particular AOGCM and scenario, they were estimated as explained in Chapter 13, Table 13.5. The contributions from ice sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as largely independent of scenario. This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065 *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for 2081–2100. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near-term (2016–2035) global mean surface temperature change that is lower than the 5–95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. {11.3}

[d] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

Exhibit 3-1. AR5 global warming and MSL rise projections.

For each scenario, there are up to 32 different available models under AR5/CMIP5. Consistent with the overall averages shown in Exhibit 3-1, variations in the projections across different models (even under the same scenario) grow the further out in time one goes. In this regard, it is important to understand that each model makes individual point predictions of various climate measures such as daily maximum temperature and precipitation. It is the variation in the projections across the different models for a given scenario and future date that essentially reveals the uncertainty in those projections. If they are all fairly close to each other, then there is less uncertainty than if they vary substantially. In theory, one could mix projections across models and scenarios when assessing climate risk; in practice, however, it is more common to select a single RCP scenario and then assess variations across models to estimate uncertainty within that scenario.

For practical use, the raw climate projection data must be converted into more relevant measures (called "climate stressors") before they can be used to assess potential impacts on airports. For example, if an airport is concerned that its runway takeoffs may be affected when temperatures get too high, then the climate projections for daily maximum temperature could be used to compute the number of days each year when it would exceed some threshold value. Obviously, there are many different climate stressors that could be computed; which ones are relevant will vary airport by airport depending on location, infrastructure vulnerability, adaptation options, and so forth.

3.2 Climate Stressors

A good place to start evaluating possible climate impacts on an airport is the spreadsheet-based toolkit called the Vulnerability Assessment Scoring Tool (VAST) developed by the U.S. Department of Transportation (U.S. DOT).[11] This resource describes different climate measures such as high temperatures or storm surges that may be expected to increase due to climate change; potential data sources are also cited. The toolkit was developed to help state DOTs, metropolitan planning organizations, and other entities implement an indicator-based vulnerability screen. Exhibit 3-2 is taken from VAST and describes different measures that may be expected to vary in the future due to climate change; potential data sources are also cited. However, note that in some cases there may be limited forecast projections available.

Another option would be to use the ACROS software tool from *ACRP Report 147* (Dewberry et al. 2015). The tool allows the user to look up airport-specific CMIP5 climate projections (based on RCP8.5) that have already been converted into various climate stressor measures. Projections are provided for a base year (2010), and two future years (2030 and 2060). Depending on availability at the time the software was developed, the estimates are based on projections from four to seven different climate models, and the range of results shown include the median, 25th percentile, and 75th percentile values. A confidence rating is also included for each measure based on the robustness of the models and agreement between them. A listing of available climate stressors (called "vectors" in the ACROS software) and their associated confidence levels is reprinted from the report in Exhibit 3-3.

The ACROS tool provides a valuable initial screening mechanism, allowing airports to get a quick assessment of how various localized climate measures may be expected to change over the coming 40 years. As described in Chapter 2, airports actually may be able to rely on data from ACROS to perform conventional analyses with specific scenario assumptions rather than undertake Monte Carlo analyses involving explicit treatment of climate event uncertainties and probabilities.

32 Climate Resilience and Benefit–Cost Analysis: A Handbook for Airports

Stressor Type	Measure	Potential Data Sources
Temperature	Total Number of Days per Year above/below a Threshold Temperature	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool)
	Longest Number of Consecutive Days per Year above/below a Threshold Temperature	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool)
	Number of Freeze-Thaw Cycles per Year	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Annual Maximum or Minimum Temperature	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Regional climate projections -- National Climate Assessment or FHWA Climate Change Effects Typology • Local university
	Annual Mean Temperature	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Regional climate projections -- National Climate Assessment or FHWA Climate Change Effects Typology • Local university
Precipitation	Amount of Rain associated with 100-year 24-hour Storm	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Number of Consecutive Days with Precipitation	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Total Seasonal Precipitation	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Total Annual Precipitation	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Peak Discharge	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Flow Velocity	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
	Discharge Volume	• Climate model outputs (e.g., DOT CMIP Climate Data Processing Tool) • Local university
Sea Level Rise	Modeled SLR Inundation Depth	GIS Sea Level Rise model
	USGS Coastal Vulnerability Index	http://pubs.usgs.gov/of/2004/1020/html/cvi.htm
Storm Surge	Modeled Surge Inundation Depth	• ADCIRC model • STWAVE - STeady State spectral WAVE model • USGS Coastal Change Hazards: Hurricanes and Extreme Storms web viewer • NOAA Sea, Lake and Overland Surge from Hurricanes (SLOSH) model (http://www.nhc.noaa.gov/surge/slosh.php)
	Presence in FEMA Coastal Flood Zone	https://msc.fema.gov/webapp/wcs/stores/servlet/FemaWelcomeView?storeId=10001&catalogId=10001&langId=-1

Source: U.S. DOT, https://toolkit.climate.gov/tool/vulnerability-assessment-scoring-tool-vast.

Exhibit 3-2. VAST climate stressors.

CLIMATE VECTOR	DESCRIPTION	CONFIDENCE
Hot Days	High temperature ≥ 90°F	HIGH
Very Hot Days	High temperature ≥ 100°F	HIGH
Freezing Days	High temperature ≤ 32°F	HIGH
Frost Days	Low temperature ≤ 32°F	HIGH
Heating Day	Mean temperature ≤ 65°F	HIGH
Cooling Day	Mean temperature ≥ 65°F	HIGH
Cooling Degree Days	Departure of mean temperature ≥ 65°F	HIGH
Heating Degree Days	Departure of mean temperature ≤ 65°F	HIGH
Hot Nights	Low temperature ≥ 68°F	HIGH
Humid Days	Mean dew point temperature ≥ 65°F	HIGH
Snow Days	Snow accumulation ≥ 2 in.	MEDIUM
Storm Days	Thunderstorm rainfall ≥ 0.15 in.	LOW
Heavy Rain (1 day)	Daily rainfall ≥ 0.8 in.	LOW
Heavy Rain (5 day)	Total 5-day rainfall	MEDIUM
Dry Days	Consecutive days of rainfall ≤ 0.03 in.	MEDIUM
Sea Level Rise	Daily runway flooding (National Flight Data Center elevation)	HIGH
Sea Level Rise – Base Flood Elevation (BFE)	Relatively infrequent but substantial flooding	HIGH
Wind*	Prevailing wind direction and speed	NONE
Fog*	Visibility ≤ 0.25 miles	NONE

**Vector was investigated, but not included in the ACROS tool due to lack of confidence in existing models.*

Source: *ACRP Report 147* (Dewberry et al. 2015).

Exhibit 3-3. ACROS climate vectors.

A primary objective of this handbook is to present methodologies for evaluating two specific types of climate events that may be particularly relevant for airports:

- The increasing occurrence of high temperatures that may force airlines to impose weight restrictions on takeoffs or (in extreme cases) cancel flights entirely.
- The impact of future sea level rise on the likelihood of flooding events causing disruption to airport operations or damage to infrastructure.

The focus is on these specific forms of climate impacts not only because of their obvious relevance for airports but also because of their data availability in forms that can be reasonably incorporated into probabilistic scenarios via the Monte Carlo methodology. A detailed description of how to access and use the latest available climate data derived from the CMIP5 projections for these types of events is given in Appendix D.

CHAPTER 4

Potential Airport Impacts

About This Chapter

Chapter 4 presents a general discussion of potential airport impacts from climate change. It is meant to provide useful context for identifying and assessing relevant airport assets and their level of vulnerability to potential climate change impacts. Key topics discussed include:

- Identifying relevant airport assets and infrastructure that may be affected,
- Assessing how vulnerable these assets and infrastructure may be, and
- Assessing criticality—how partial or complete failure of an asset may affect the airport.

Note to Readers

Chapter 2 described some of the primary impacts of sea level rise and high temperatures on airports. If the reader is primarily interested in the methodologies presented in Chapters 2, 3, and associated Appendices C and D in order to explore the analytics of a risk-adjusted sea level rise or high-temperature analysis, consider skipping to Chapter 7, which describes the results of four case studies.

About the Next Chapter

Chapter 5 discusses potential responses, adaptations, or mitigation strategies that an airport may undertake in response to climate threats.

In addition to obtaining projections of the increased likelihood of high temperatures, precipitation, or flooding, a central issue to address is how to identify and measure potential impacts on airport assets, infrastructure, and operations. Here, already existing resources can be used to describe how to accomplish this task.

4.1 Identifying and Targeting Airport Assets and Infrastructure

Before assessing potential impacts of projected climate change stressors, one must first identify the relevant assets or infrastructure operations that may be affected. Again, the ACROS software (Dewberry et al. 2015) can be used to provide a good starting point. It identifies a global list of 33 potential physical assets and 10 potential operational components (each categorized into one of 10 service categories) that could in principle be affected by climate change. These assets and operational components are shown in Exhibit 4-1. An individual airport could begin the process of identifying relevant assets and operations by starting with this list and culling or adding to it as necessary.

Another valuable resource is *ACRP Report 69: Asset and Infrastructure Management for Airports* (GHD, Inc. 2012), which essentially applies the same enterprise-wide approach to asset management that *ACRP Report 74* and *ACRP Report 116* (Marsh Risk Consulting 2012; Price

SERVICE CATEGORY	ASSETS	OPERATIONAL COMPONENTS
Aircraft / GSE	Ground Service Equipment	Aircraft Performance Demand and Capacity
Airfield / Airspace	Navigational Aids Runways, Taxiways, and Holding Areas	
Commercial Passenger Terminal Facilities	Apron Commercial Passenger Terminal Facilities Curbside Amenities Gates Gates (Passenger Boarding Bridges)	
General Aviation Facilities	Aircraft Parking Aprons Flight Schools and Pilot Shops General Aviation Terminal Facilities Hangars Loading and Unloading Equipment / Operation Tie-Down Areas Transient Aircraft Parking Apron Areas	
Cargo	Air Cargo Buildings Apron Loading and Unloading Equipment / Operation	
Ground Access, Circulation, and Parking	Access Roads Parking Facilities Rail (Internal to the Airport, e.g., Monorail)	
Support Facilities	Aircraft Fuel Storage / Fueling Airline Maintenance Facilities Airport Administrative Areas FAA Facilities (Air Traffic Control Tower) Flight Kitchens Weather Reporting Facilities	Aircraft Rescue and Fire Fighting (ARFF)
Utilities	On-Site Electrical Infrastructure Sanitary Sewer Stormwater Drainage Water Distribution Systems	Communications
Environmental and Safety		Bird and Wildlife Hazard Management Environmental (Noise, Air Quality, Water Quality and Quantity) Snow and Ice Control (De-Icing)
Other	Regional Infrastructure Parks	Construction Activities Grounds and Landscaping Personnel and Passengers

Source: *ACRP Report 147* (Dewberry et al. 2015).

Exhibit 4-1. ACROS assets and operational components.

2014; see discussion in Appendix A) provide for risk management. It describes a formal structured approach to managing assets across an organization, including development of an asset register that puts assets into a hierarchy and ranks them according to various measures such as current condition, effective life, cost of renewal, and probability and consequences of failure.

4.2 Assessing Vulnerability Due to Climate Change Risks

Once the relevant assets and operations have been identified, the next step is to assess the potential vulnerability of the assets so that one can ultimately identify those most in need of attention and further analysis. Vulnerability in this context depends not only on its susceptibility to failure from a climate change event but also on the likelihood of that event occurring. With this in mind, the ACROS or VAST software described in Chapter 3 could be used to aid in the process of evaluating vulnerability.

One of the modules in ACROS provides, using a simple three-point scale, an assessment of the vulnerability of various assets for a given airport. While default values are supplied, it is strongly suggested that users modify the values based on specific conditions at their airport.

The VAST spreadsheet provides an alternative but somewhat similar framework where users can list their assets and calculate a vulnerability score for each. It is up to the user to identify relevant assets and then assign scores to individual indicators belonging to each of the following three vulnerability components:

- **Exposure:** whether an asset will experience a given climate stressor,
- **Sensitivity:** whether and to what extent an asset will be damaged or disrupted due to exposure, and
- **Adaptive capacity:** how well the system at large can mitigate damage or disruption.

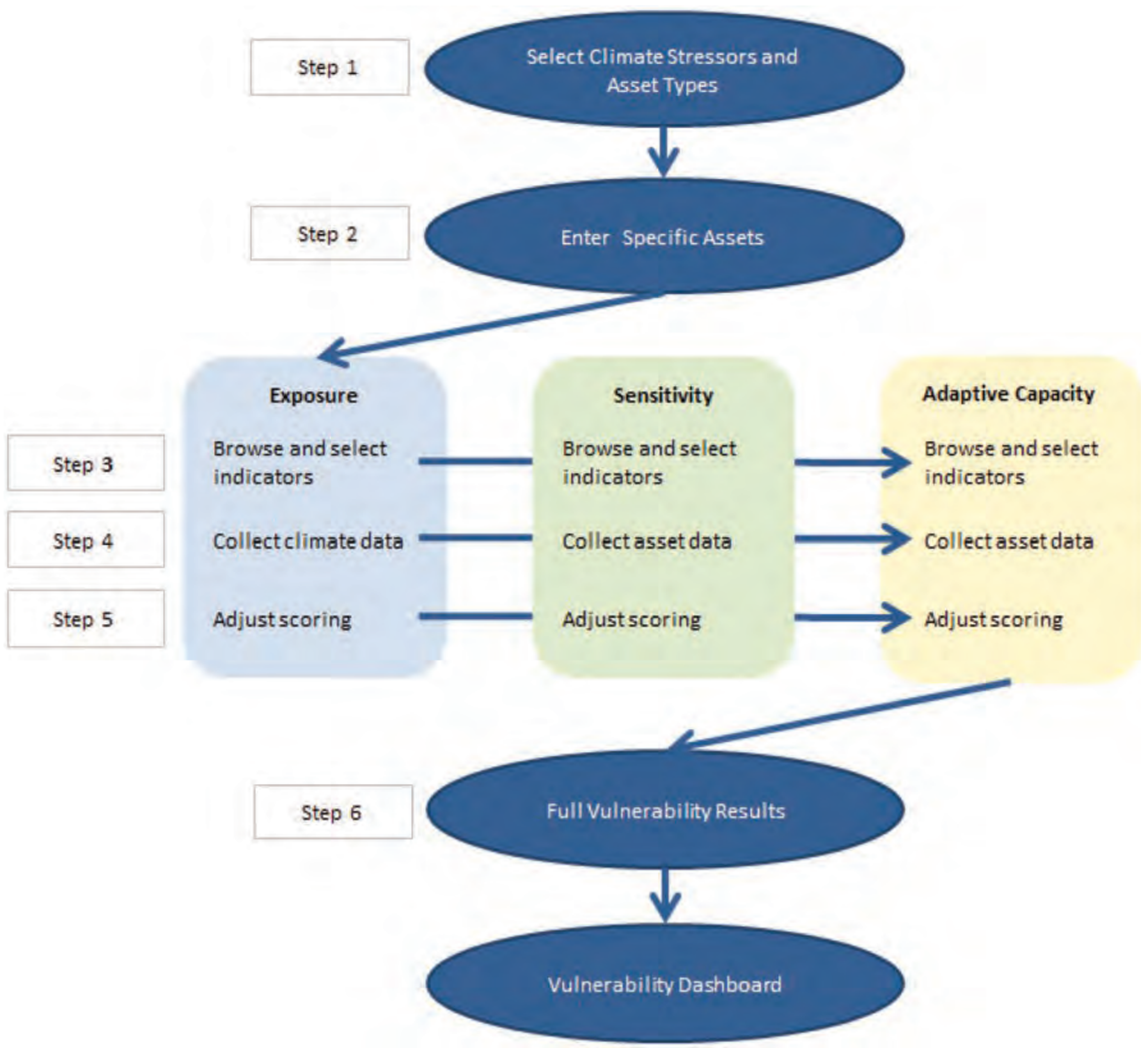
The model computes a weighted average of the indicator scores for each component and then a weighted average across the components to generate a single vulnerability score for each asset. The assets then can be ranked in terms of their vulnerability scores. Exhibit 4-2 is reprinted from the VAST User Guide and provides a visual description of how the tool works.

4.3 Assessing Criticality

Criticality refers to the consequences of failure of an asset for the operation of the airport. Once again, the ACROS software could be used as a starting point, where a three-point scale would be used to rank the level of criticality for each asset. Or using a more structured approach, one could assess criticality with reference to *ACRP Report 69* (described earlier), using an asset register where multiple dimensions of criticality related to the asset can be considered.

Another useful way to begin to screen assets for potential criticality is to consider their placement in FAA's existing BCA guidance (FAA, Office of Aviation Policy and Plans 1999) on benefit categories. The FAA guidance document lists a fairly large number of airport infrastructure projects and identifies the typical types of benefits associated with each. By reviewing the list of potential benefits associated with a particular asset, one can begin to judge its likely criticality to the airport. The relevant table is reprinted as Exhibit 4-3.

By carefully reviewing these benefit categories, the resilience team may gain valuable insight to help them screen their assets to identify those most critical to the airport before actually trying to estimate their potential financial impacts.



Source: U.S. DOT 2015, Figure 2.

Exhibit 4-2. VAST approach diagram.

Finally, airport managers may assess criticality in terms of how interruption in the availability of infrastructure would have financial impacts on the airport or its users. Most airports have a financial planning model that is used to develop annual budgets and airport user fees. For example, if a runway is vulnerable to flooding, then the analyst might assess what it would cost the airport if the resulting reduction in capacity affected delays, cancellations, user fees, and concession revenues. Such interruptions may also have adverse effects on commercial operators; if the interruptions are likely to become more frequent, users may be willing to pay for resilience projects. In many cases, an airport's experience with past interruptions can provide valuable information to help estimate future impacts of climate change. Chapter 2 further discusses who should be involved in these activities and their roles.

Other considerations that may affect the screening process are discussed in Chapter 5.

PROJECT TYPE	TYPICAL BENEFIT TYPE
AIRSIDE **Airside Capacity Projects**	
• New or extended runway, taxiway, apron, or hold pad	• Reduced aircraft, passenger, and cargo delay during normal airport operations • Reduced aircraft, passenger, and cargo delay during reconstruction of other airport facilities • Greater schedule predictability: - Aircraft operator able to make more efficient use of equipment and personnel - Passenger able to take later flight and arrive at destination on time • Improved efficiency of traffic flows (reduced vectoring and taxiing distances) • Reduced aircraft operating costs and passenger travel times due to airport's ability to accommodate faster, larger, and/or more efficient aircraft • Bringing pre-existing infrastructure into compliance with FAA safety and security standards • Safety improvements • Noise abatement • Reduction of aircraft emissions
• Reconstruction of runway, taxiway, apron, or hold pad	• Lower facility maintenance costs • Avoided loss of capacity benefits associated with facility failure
• Acquisition of airside equipment to support capacity objectives (navigational aids, snow removal and maintenance equipment)	• Reduced aircraft, passenger, and cargo delay during normal airport operations • Greater schedule predictability • Improved safety • Lower facility maintenance costs
Airside Safety, Security, and Design Standards Projects	
• Installation of signage and lighting • Expansion of runway safety areas • Removal of obstructions from existing approaches • Fencing • Acquisition of rescue and fire-fighting equipment	• Compliance with FAR and Advisory Circular safety, security, and design standards is mandatory and not subject to BCA. Compliance must be done in most cost-effective manner acceptable to FAA.
Airside Environmental Projects	
• Noise mitigation for pre-existing infrastructure (noise insulation, structure removal) • Fuel and chemical containment for pre-existing infrastructure	• Compliance with FAA environmental order is mandatory and not subject to BCA. Compliance must be done in most cost-effective manner acceptable to FAA.

Exhibit 4-3. FAA benefits of airport projects.

AIRPORT TERMINAL BUILDING (ATB) **ATB Capacity Projects**	
• Reconstruction, expansion, and/or modernization of ATBs (excluding concession areas which are not eligible for AIP funding)	• Reduced aircraft, passenger, cargo, and meeter/greeter delay (attributable to more gates and faster passenger transfers to connecting flights) • Improved passenger schedule predictability (ability to allow less time for potential delays at ATB) • More efficient traffic flows (shortened pedestrian traffic distances) • Improved passenger comfort • Lower ATB operating and maintenance costs
• Baggage Handling Systems	• Reduced passenger and cargo delay • More efficient baggage distribution • Lower operating and maintenance costs
ATB Security Projects	
• Passenger, baggage, and freight security systems	• Compliance with FAA standards--not subject to BCA if primary objective of project
• Security fencing and gates	• Compliance with FAA standards--not subject to BCA if primary objective of project
Inter-Terminal Transportation	
• Fixed rail • Bus	• Reduced aircraft, passenger, and cargo delay (attributable to faster passenger transfers to connecting flights) • Improved passenger comfort • Lower operating and maintenance costs
LANDSIDE **Landside Access Projects**	
• Airport access roads • Passenger pick-up/drop-off areas • Transit areas	• Reduced passenger, cargo, and airport and airline employee delay in getting to airport • Improved schedule predictability (ability to leave later for airport and arrive on time for check in) • Lower operating and maintenance costs • Improved safety • Reduced automobile emissions

Source: FAA, Office of Aviation Policy and Plans, 1999.

Exhibit 4-3. (Continued).

CHAPTER 5

Responses and Adaptations

About This Chapter

Chapter 5 describes how to identify and classify potential airport responses and adaptations that may be available to address climate change impacts. Key topics discussed include:

- Identifying feasible responses,
- Considering potential responses not involving infrastructure, and
- Financial constraints affecting potential adaptations.

About the Next Chapter

Chapter 6 discusses various topics that may be of interest to airports addressing climate change.

5.1 Identifying and Targeting Potential Responses

Once the relevant assets have been identified and screened for both vulnerability and criticality, the next step is to identify potential adaptation options for climate resilience and then to prioritize those options that are available to the airport. Setting these priorities may involve both qualitative and quantitative evaluations.

Once again, the ACROS software from *ACRP Report 147* (Dewberry et al. 2015) may be of use here. For any selected airport, a report can be produced that ties climate stressors to specific airport assets along with user-supplied vulnerability and criticality scores and then lists a number of potential adaptation options. By necessity, these adaptations are generic in nature and not necessarily feasible or relevant for the selected airport. Nevertheless, the report can be a useful starting point from which the resilience team can assess what sorts of potential adaptations should be considered. An example for LaGuardia Airport (LGA) is shown in Exhibit 5-1.

Another potential resource is *ACRP Synthesis 33*, which provides a case example review of the likely effects of climate change on airports and the adaptation responses available to them (Baglin 2012). It uses a series of eight case examples at airports from Alaska to the Gulf Coast to illustrate the increases in risk from coastal flooding/sea level rise, increased winter storm activity/intensity, increased drought frequency/severity, and increased tornado frequency. Each case example describes the airport's process of identifying the increased risk and its approach

SERVICE:					ASSET/OPERATION:
Commercial Passenger Terminal Facilities					**Curbside Amenities**
Impact Risk	***Criticality***	***Vulnerability***	***Climate Vectors***	***Impacts***	***Adaptation Options***
🔴	3	2	HumidDays HeavyRain1Day	Building Moisture Damage; Mold	• Schedule More Frequent Inspections • Improve Building Envelope (Fenestration, Roofing Materials, Cladding Material, Vapor Barriers / Retarders, etc.)
🔵	3	2	SeaLevelRise	External Facility Damage Due to Flooding	• Improve Building Envelope (Incorporate Flood-Resistant Structural Elements) • Install Flood Barriers • Elevate Critical Equipment • Elevate Structure • Develop IROP Protocols
🔴	3	1	HotDays HotNights HumidDays	Increased Level of Insect Activity	• Modify The Effective Lighting Color Temperature and Improve Insect Intrusion Prevention Design Solutions.
🔵	3	2	StormDays HeavyRain1Day SeaLevelRise	Flooding	• Increase Water Removal Capacity • Improve Building Envelope (Incorporate Flood-Resistant Structural Elements) • Install Flood Barriers • Elevate Critical Equipment • Elevate Structure • Develop IROP Protocols

Note: Red indicates high risk; blue indicates low risk.
Source: *ACRP Report 147* (Dewberry et al. 2015).

Exhibit 5-1. ACROS adaptation options for terminal facilities at LGA.

to increasing resiliency. What is of particular value is a matrix that combines specific climate measures, affected airport assets, airport impacts, and illustrative responses into a single table. This table is reprinted in Appendix I.

In addition, airports may want to support efforts to combat climate change—for example, by reducing their own carbon emissions. FAA has supported some of these efforts through its Sustainable Master Plan Pilot Program, which provided funding for airports to develop their own sustainability plans. *ACRP Synthesis 66: Lessons Learned from Airport Sustainability Plans* provides a review focused on smaller airports, showing that many airports undertook initiatives geared toward reducing carbon emissions (both at the airport and for passengers accessing the airport), encouraging recycling, planting trees, and moving toward increased use of renewable fuel (Martin-Nagle and Klauber 2016).

Airports may also elect to participate in the Voluntary Airport Low Emissions (VALE) program, which encourages sponsors to implement clean technology projects that improve air quality. VALE projects can be funded using passenger facility charges (PFCs) or AIP grants and are available to commercial service airports located in areas that are in nonattainment of National Ambient Air Quality Standards.

Ultimately, decision makers will want to identify adaptations that are physically and operationally feasible. In other words, some adaptations may be prohibitively expensive or beyond the potential scope of the airport itself. For example, an airport by itself may not be able to create barriers to sea level rise unless nearby communities also participate.

Based on best practices in the transportation industry (see, for example, Wall and Meyer 2013), it is often recommended that alternative adaptation approaches be evaluated from the perspective of phased investments that maintain a desired level of resilience as the climate changes and as more information is obtained about those changes. This is intended to avoid planning adaptation measures in a single set of actions taken at one time. Instead, a sequence of planning actions should each be evaluated before the next action is taken; this can also inform the design of the next planning action.

A critical element of this approach is quantitative estimation of particular climate risks through time for specific types of assets. This approach can reduce the difficulty of selecting among different adaptation approaches for the following reasons:

- It is specific to particular types of risks of damage or loss;
- It enables ranking of these damages or losses by their magnitude, timing, probability, and level of uncertainty;
- It reduces the complexity of the planning process by making use of this ranking and by shortening the time horizon to be considered by individual phases of sequential planning; and
- It allocates resources more effectively since specific damages and losses can be more easily linked to elements of adaptation plans.

To the extent that adaptation to climate change may include changes in operations (including emergency operations), it will be important that the suggested adaptations be accurately incorporated into safety management systems, emergency preparedness documents, and processes (including snow desks and other airport operations systems) so that the benefits of these suggested changes can be realized.

5.2 Considering Adaptations Not Involving Infrastructure Investment

The list of potential adaptations may include not just infrastructure investments or operational changes but also the following types of options:

- Pursue early preparatory action to mitigate the risk,
- Engage in partnerships with other entities to mitigate the risk, and
- Purchase insurance against the risk.

While the focus of this handbook is on quantitative analyses that will typically involve an infrastructure investment, a brief discussion of these alternative adaptation options is presented in the following.

Preparatory Action

Early preparation and integrating risk management into infrastructure planning can be effective risk management practices. Examples include integrating flood mapping into infrastructure planning, creating building codes based on the specific climate risks to a given region, and undertaking information campaigns to inform the public about climate risks (Atreya and Kunreuther 2016). Such practices can be much less costly than damage control after an event, and it has been suggested that entities consider not only physical infrastructure but also safety concerns and financial preparedness in their planning processes (Collier 2015). Analysts also have recommended that planners consider not only the short-term response time immediately after an event but also the longer-term recovery time once physical systems are back in order (Czajkowski 2016).

Partnerships

Community partnerships may also have a role in mitigating risk, and networks between different entities within a community can allow for information sharing, collective risk mitigation, and collaborative rebuilding after an event. Collaboration within an institution is also important: stakeholders interacting with different aspects of a given firm often have insight into the impacts of extreme weather events on their element that may not be obvious from the top (Chang et al. 2014).

Public–private partnerships, in which institutions work with local governments, can create disaster procedures and risk-mitigation strategies that are effective for the specific risks facing a given region. Risk managers can look to public–private partnerships not just for help in creating risk-mitigation plans but also for innovative ideas in disaster risk financing (Golnaraghi et al. 2016).

A report published by the United Nations goes further in suggesting partnerships between private institutions, public actors, and actors of the financial system in order to ensure risk sharing and social protection (United Nations 2015b). It points out that partnerships across a society also helps mitigate what it refers to as "downstream" costs: the way that one firm's or organization's inadequate preparation can negatively affect other aspects of a community, such as overall economic stability, social welfare, and environmental sustainability. The report also suggests ensuring that every actor related to a risk bears some share of the benefits and costs so that all stakeholders have an interest in risk mitigation.

Finally as noted previously, adequately addressing climate risk may involve cooperation across jurisdictions and outside of airport boundaries. For example, the potential for increased flooding of nearby road systems may reduce the public's access to an airport, making it infeasible for the airport to operate. Close coordination of stormwater projects across jurisdictions may mitigate some of this risk.

Insurance

Rather than undertake an expensive infrastructure investment, one alternative is to purchase insurance. This would most commonly take the form of some sort of catastrophic loss insurance to cover the cost of an extreme climate event such as a hurricane or flooding.

ACRP Synthesis 30 reviews current practices by airports for predicting and managing risk (Rakich et al. 2011). It notes that medium- and large-hub airports often employ whole risk management teams and use robust risk analysis regularly, while smaller airports often have only a part-time risk manager and are less likely to include risk analysis in their operations. While the synthesis does not provide formal guidance on purchasing insurance specifically related to potential climate risks, it does provide a useful overview of the airport risk manager's role, different types of insurance coverage used by airports, insurance buying practices, and options for choosing deductibles and limits.

Extreme climate events present some unique concerns for insurance providers and policyholders. As noted in Golnaraghi et al. (2016), there is generally a lack of historical data on extreme climate events, and such disasters are usually highly unpredictable; this results in difficulty establishing appropriate prices. Insurance markets generally assume that losses are independent of one another, but climate-based risks are often correlated, further complicating the process (Golnaraghi et al. 2016). Thus, some have argued for public–private partnerships in the area of insurance (Kunreuther and Michel-Kerjan 2016).

5.3 Financial Constraints

This section explores the impediments faced by airport authorities, in light of current guidance for funding capital improvement projects, in justifying operational strategies and infrastructure projects geared toward climate change. Such projects may face several challenges in making the case for implementation, including:

- High up-front costs of strengthening the assets,
- Uncertainty regarding the severity/magnitude of climate change,
- Unknown frequency of climate change/extreme weather events, and
- Uncertainty in the timing of climate change that could lead to relatively long payback periods compared to other investment projects.

These challenges (or aspects) are discussed in relation to current federal guidance, and suggestions are made on where these challenges may be overcome in the context of the guidance.

Airport development can be financed from several sources, including federal and state grants-in-aids, private financing or third-party development, passenger facility charges, customer facility charges, a variety of bonds, and local funds. These funding options may have an impact on the implementation feasibility of potential investment projects.

In general, among the challenges in making the case for a financial return on investment assessment or a BCA is that the up-front costs of hardening the asset (mitigating, adapting, or adding extra surge capacity in the case of a new asset) may result in greater capacity or building to a higher engineering standard than is needed for a typical day. This is because the airport incurs the capital and operating costs for capacity that is not fully used on a daily basis.

In addition, the disruption cost to individual airlines or the broad network of air travelers will not likely directly affect the airport's financial performance unless the disruption becomes so common that airlines begin to seek other airports. As different airports will be affected by climate change differently, the costs of making climate change investments will similarly vary, meaning that passing some or all of these costs on to users could alter the competitive landscape. In many cases, airports will be contemplating capital investments to avoid future operating costs.

Moreover, securing funding post-event can remain challenging. Current federal disaster funding does not contemplate climate threats/impacts or steps for adaptation (except migrating out of a floodplain) as part of its eligibility criteria.

Airport Improvement Program Requirements

Of course, virtually all airports in the United States are aware of the FAA's AIP. This program provides grants to public agencies for airport planning and development projects. The AIP Handbook provides detailed guidance from the FAA on policy and procedures used in the administration of the program (FAA 2014a).

The handbook describes the differences between maintenance, rehabilitation, reconstruction, and replacement projects and their eligibility criteria. In general, maintenance projects are not eligible, but rehabilitation, reconstruction, and replacement projects are, assuming they are also justified. Many climate resiliency projects are likely to fall under rehabilitation that restores functionality, as opposed to reconstruction that brings the asset back to its original functionality. Per Table 3-8 of the AIP Handbook, a rehabilitation project generally would require the assumption of a 10-year useful life, while a reconstruction project would use a 20-year useful life. So if climate resiliency projects are categorized under rehabilitation, then a useful life of 10 years may limit an airport's ability to make the case for a resiliency investment. Even reconstruction's 20-year useful life may limit the ability to show an adequate return on investment for many types of climate change projects.

To be a justified project, there are three tests that a project must pass: whether the project advances an AIP policy, whether there is an actual need within the next 5 years, and whether the project scope is appropriate. In general, a climate resiliency project would be justified under at least two of the three tests—such projects advance the AIP policy of preserving airport infrastructure, and the scope of the project would only include necessary elements to achieve appropriate protection. For a climate resiliency project, the challenging aspect in this context may be demonstrating the actual need, given it can be difficult to justify need within the next 5 years. While climate change is imminent and its effects are already being experienced, it could be asserted that an event warranting the project may not reasonably be expected to occur within 5 years.

Another important point to understand is that in order to receive AIP funding, many projects may be required to undergo a formal BCA. Yet it is often the case that the BCA itself will occur before a project's funding is planned in detail; in such cases, the airport sponsor and FAA must jointly agree on a reasonable amount of AIP funding given the information available. Interested readers may wish to review *ACRP Synthesis 13*, which describes effective practices for preparing BCAs for AIP applications (Landau and Weisbrod 2009).

Certain other constraints and requirements documented in the AIP Handbook (FAA 2014a) may also be relevant. Table 3-11 of the handbook contains a specific list of eligible off-airport projects. While drainage and utilities projects may be legitimate adaptation responses to climate resiliency in many situations, the off-airport list only identifies as eligible for funding outfall drainage ditches and relocation of utilities that are airport obstructions.

The FAA guidance document on BCA, discussed in Appendix G, includes an extensive list of project types that are not eligible for funding. This list includes some projects that may pertain to climate adaptation activities. For example, aircraft deicing buildings, which are not eligible, may become more necessary in colder climates that, in the future, could expect to experience more icy conditions. Another prohibited project currently listed is maintenance or service facilities and repeated obstruction removal, which may be critical in adapting to climate change. One takeaway here is that the lists of eligible or prohibited projects outlined in the current AIP Handbook may warrant revision in light of climate change resiliency projects that will be necessary in coming years.

Finally, it should be noted that several of the advisory circulars (ACs) providing guidance for airport design have been updated in the past several years (FAA 2014b, FAA 2014c, FAA 2016a). In general, the use of these ACs is not mandatory; however, the use of the standards is mandatory for all projects funded under AIP or with revenue from the PFC program. Since climate and weather affect the performance of building materials and the useful life of infrastructure, airports may need to rehabilitate their infrastructure to be more resilient following the newly updated guidance on design and construction.

Other Financing Options

ACRP Synthesis 1 provides a comprehensive review of financing options and revenue sources that may be available to airports (Nichol 2007). This synthesis is particularly relevant for financial feasibility analyses and includes discussion of the following:

- Proceeds from bonds and other debt:
  - General obligation and general airport revenue bonds,
  - Bonds backed by PFCs or customer facility charges,
  - Bonds back by future AIP or state grants, and
  - Special facility bonds.
- Other financial instruments:
  - Bond or grant anticipation notes,
  - Pooled credit programs, and
  - Capital leases.
- State and local grants and financial support.
- Self-financing via retained airport revenues.

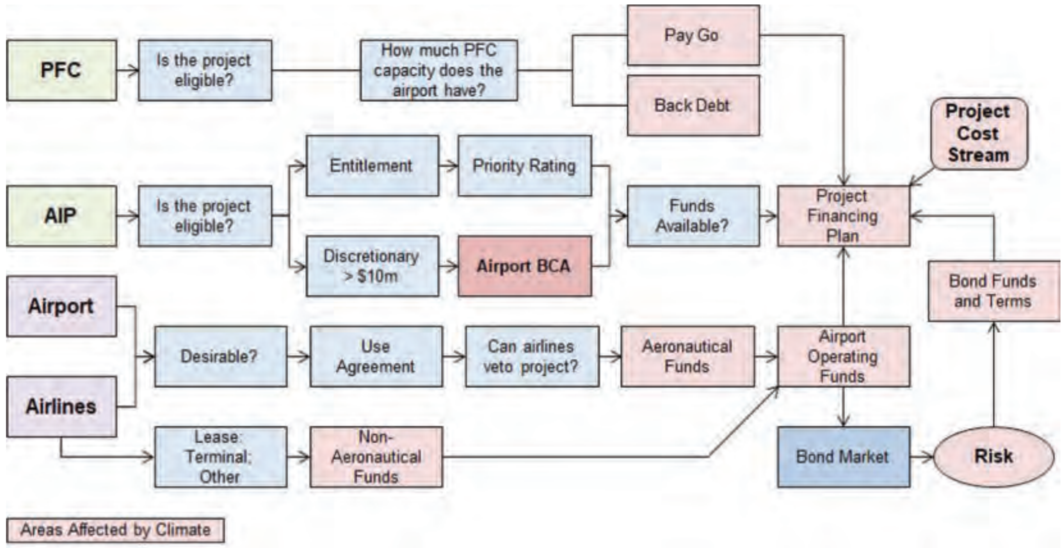


Exhibit 5-2. Effect of climate change on sources and uses of funds and airport project financing plans.

Exhibit 5-2 shows the typical sources of airport funds for new projects. Many projects will mix PFC and AIP funds with internally generated revenues and proceeds of bonds to pay for infrastructure projects. Each funding source may be affected by climate impacts at the critical junctures (shown in red). For example:

- PFC collections would be interrupted if an airport were temporarily closed due to a climate event,
- Some otherwise viable projects may be found to have a benefit–cost ratio of less than 1 once climate impacts are accounted for, which would render them ineligible for discretionary AIP funding,
- Both aeronautical and non-aeronautical revenue streams could be interrupted by an adverse climate event,
- Project costs may increase substantially to adapt to climate risk and uncertainty, and
- The risk perceptions in the bond market for airport projects may change, which could affect the availability of bond funds or the terms and interest rate that would have to be paid.

CHAPTER 6

Other Relevant Topics for Airports Addressing Climate Change

About This Chapter

Chapter 6 discusses a variety of topics that may be of interest to airports addressing climate change. The topics covered include:

- Defining a specific scenario,
- Benefit–cost versus financial feasibility analysis,
- Addressing hard-to-quantify impacts and direct environmental strategies,
- Addressing economic impacts not covered in a BCA,
- Considering the option to delay an investment, and
- Comparing results across different scenarios.

About the Next Chapter

Chapter 7 describes the case studies undertaken with individual airports to assess the usefulness of the approach and methodologies presented in this handbook to analyze risk-adjusted climate scenarios.

After completing all of the preparatory work described in Chapters 3, 4, and 5, the resilience team can get to the task of actually performing a risk analysis. Beyond the calculation methodologies described in Chapter 2, this chapter delves into specific topics related to financial feasibility and benefit–cost analyses in the context of risks and uncertainties associated with climate change.

6.1 Defining a Specific Scenario

As with any analysis involving forecasts, both financial feasibility and benefit–cost studies may be subject to a fair amount of uncertainty, particularly for large projects where costs may be spread over many years into the future. But on top of this, the additional uncertainty related to climate projections can have a major impact on such studies. Specifically, climate uncertainty may well influence the choice of which specific alternative to select for further analysis. For example, deciding whether a proposed retaining wall should be built 5 ft or 10 ft tall may depend on an airport's assessment of the relative likelihood of flooding under both scenarios. Depending on the specifics, it may be that both projects need to be analyzed (whether in terms of financial feasibility or benefit–cost) in order to properly assess which project can or should be undertaken.

With this caveat in mind, the resilience team ultimately will have to decide on one or more specific scenarios to consider for detailed analysis. The scenario(s) should be completely defined in terms of relevant climate measures to be used, which assets may be affected, what specific adaptations or responses are to be evaluated, and which specific cost and benefit elements are to be included.

6.2 What Type of Analysis?

As was stated in Chapter 2, BCAs and FFAs can use the same overall methodological techniques, but they differ in their treatment of which benefits and costs are included in the analysis and how benefits and costs are defined.

For a BCA, all stakeholder benefits and costs directly attributable to the investment project under consideration must be considered. Who receives the benefits, or who incurs the costs—whether it be the airport itself, airport users, the aviation public at large, or other entities—is immaterial. Benefits and costs may include direct monetary gains or losses, nonmonetary effects (e.g., reductions in passenger travel time), or gains and losses related to environmental impacts.

On the other hand, an FFA evaluates an investment project based only on the cash benefits and costs accruing to the airport itself. Such accruals may not reflect net stakeholder impacts at all, even though they affect the airport's finances. For example, cash benefits to the airport such as higher user fees or PFCs are not a benefit from society's point of view (since they must be paid for by someone else—they are a transfer). The focus of an FFA is on whether the airport can earn a return on the proposed investment and fund it; thus, the sources of funds and terms of repayment (if any) are critical components of the analysis.

Both BCAs and FFAs account for the costs of mitigation. However, there are important differences in how costs are treated. A BCA includes the opportunity cost of the project (net of what the airport would do otherwise). Opportunity costs might include an imputed cost for the use of airport land and any subsidy for the use of a resource. A BCA also excludes depreciation (except for the purpose of calculating salvage value), interest, and principal payments. Finally, a BCA is usually expressed in constant dollars and uses a discount rate meant to reflect either constant dollar private or public returns (depending on the application). An FFA will usually treat these items using standard accounting concepts that reflect cash flows in each time period, depreciation, financings, and the airport's cost of capital.

Again, a BCA assessment answers the question of whether the proposed investment is a good one from society's standpoint; the assessment may include a variety of benefits and costs that are external to the airport itself; a financial feasibility assessment simply addresses whether the project is fundable. It is certainly possible that there are projects with total social, environmental, safety, and efficiency benefits that outweigh their costs but that are not financially feasible.

Exhibit 6-1 illustrates how the composition of variables considered could vary between the two types of assessments. The list of variables is illustrative and does not capture every possible impact type.

Because an FFA considers only the costs incurred by the airport itself, costs such as airline operating costs or passenger delay costs typically would not be included. One exception would involve cases where commercial operators express a willingness to pay for an improvement because of the benefits they might gain; in these cases, the airport would pledge user fee revenues to repay the investments.

Candidate Variable	Include in BCA	Include in FFA
Airport operating costs avoided	✓	✓
Airport safety (accident costs avoided)	✓	✓
Airline operating costs avoided	✓	
Passenger injury or delay costs	✓	
Profit and loss depreciation expenses		✓
Airport user fees		✓

Exhibit 6-1. Illustrative cost and benefit categories for BCAs and FFAs.

Conversely, because a BCA considers only net societal costs, an up-front capital expenditure would be included fully in the year it was expended, but depreciation expenses associated with that expenditure (which might appear over time on an airport's income statement) would not be included in a BCA.

As discussed previously, an FFA brings a different set of criteria and objectives to the fore compared to a BCA. Financial feasibility studies are designed to demonstrate whether a proposed infrastructure investment can be paid for using available sources of funds, which may come from user fees, various government agencies, borrowing, or other sources. If borrowing is part of the equation, then the analysis must show that the airport has the ability to meet principal and interest payments.

The FAA provides guidance relating to financial feasibility. Of particular importance is FAA AC 150/5070-6B, Change 2, which requires that each airport master plan include an achievable financial plan to support the implementation schedule for future capital projects (FAA 2015a). Sections 1202–1204 describe the various sources of funds and how the airport's capital improvement program (CIP) can be shown to be financially feasible.

In a financial analysis, an interruption of operations at the airport or part of it would result in lost revenues and potentially unplanned expenditures to make repairs and rehabilitate infrastructure. The airport would look at avoiding the loss of:

- Aeronautical revenue: airline rents, usage fees, and charges including terminal rents, landing fees, and other charges (e.g., jet bridges);
- Non-aeronautical revenue: concession rents and profit sharing, parking and airport access fees, and rental car operations; and
- PFCs collected.

From this discussion, it should be apparent that FFAs may often ignore some of the most significant impacts that may result from certain types of climate change. For example, increases in the likelihood of extreme heat may lead an airport to consider a runway extension project. While the construction and maintenance costs incurred by the airport from such a project would be captured in an FFA, it would likely ignore the benefits accruing to passengers (which would be in the form of avoided delay costs). It might also ignore the avoided cost benefits accruing to cargo users or airlines, although it might include them if these airport users were willing to, for example, pay increased landing fees to avoid delays caused by extreme heat.

Consider another example, such as the increased likelihood of flooding due to storm surge, which causes the airport to consider a project that improves its drainage infrastructure. Here it is quite likely that the airport itself would realize benefits (in the form of avoided costs of flooded terminal buildings or other infrastructure). But it is still likely that there also would be economic benefits accruing to passengers, airlines, or others that might not be accounted for in a financial feasibility analysis.

6.3 Hard-to-Quantify Impacts and Direct Environmental Strategies

As stated previously, the types of impacts associated with different types of climate change suggest that the benefits to making climate resilient infrastructure investments may often be difficult to quantify from a technical standpoint. For example, if climate change would increasingly cause aircraft to be weight-restricted on hot days, it is not necessarily a simple task to estimate the financial impact on carriers or passengers. The actual impact would likely depend on a variety of factors that may be difficult to pin down, including the specific flights affected, the projected flight schedule and alternatives available for the time period in question, how long the high temperatures last each day, downstream or cascading delay impacts that occur elsewhere because of delays at the subject airport, and whether cargo (which may be scheduled for overnight delivery) could be off-loaded. Analysts should be aware that such delay impacts are quite typical for FAA BCAs. The FAA is looking only for reasonableness, not perfection, in such estimates, and sensitivity analysis may be used to assess how changing the assumptions/values may affect the estimates.

The FAA addresses the issue in a broader context by identifying specific, hard-to-quantify benefits that cannot easily be evaluated in dollar terms. These are:

- Impacts on system-wide flight delay (both passenger and freight),
- Effects on airline passenger comfort or convenience, and
- Non-aviation related impacts that represent true macroeconomic or productivity gains or losses (FAA 1999b, p. 58).

The first of these items would appear to be most relevant for disruptions related to climate events, and the FAA has added a section to its Economic Values document (FAA 2016b) that specifically addresses how to value these delays. The recommended approach involves use of what the FAA calls a "delay propagation multiplier" (FAA 2016b), which is essentially a measure of the change in system-wide delay as a result of a unit change in delay at a particular airport. For example, the recommended multiplier for LaGuardia Airport is 1.53 (as of September 2016), meaning that a 1-min delay at LaGuardia would lead to 1.53 min of delay system-wide. Analysts can use such system-wide delay estimates in BCAs as appropriate.

In the present context, it may also be important to identify other potential hard-to-quantify impacts associated with climate resilience. Specific examples are:

- Stranded capacity if long-term climate trends induce future growth to move away from locations with existing capacity toward other locations that are not fully prepared for expanded travel volumes,
- The rate at which climate change accelerates the depreciation of existing airport assets,
- Increased risk of bird strikes on takeoffs associated with the greater incidence of standing water, and
- Potential harm to nearby watersheds when flooding carries pollutants.

For those items that cannot be reasonably quantified, one suggestion is to consider assigning them an ordinal ranking that reflects the magnitude of their likely impacts on the airport. This ranking could be used either for further evaluation purposes or to allocate limited resources. Even though such rankings may not be formally incorporated into a BCA, they may be useful in enabling decision makers to make a decision on a project with a benefit–cost ratio near or just below 1 or when comparing two alternative projects with similar ratios.

In addition, as mentioned earlier, airports may also want to consider investments that directly combat climate change by reducing their own carbon emissions. Again, it may not be a simple matter to evaluate the environmental benefits of undertaking such an investment. One approach would be to use the economic concept of "willingness to pay." There have been multiple studies that have attempted to estimate how much (in dollar terms) people may be willing to pay for specific climate mitigation reductions. An interagency working group established by the federal government published estimates valuing such reductions at about $21 per metric ton of CO_2 (Interagency Working Group on Social Cost of Carbon 2010). In principle, such valuations could be used in a BCA (again assuming that the relevant quantities could be reasonably estimated).

6.4 Economic Impacts

While not the focus of this project, the subject of economic impacts may be an important issue for decision makers. Many airports will have access to an economic impact study that outlines the contributions of the facility to the local economy measured in terms of output, jobs, payroll, and tax contributions. Many states now produce periodic estimates of the economic impacts of their airport systems, and larger airports often undertake such studies as part of their effort to maintain local support for aviation in the area.

In the following discussion, it is assumed that airports already have access to and are familiar with economic impact studies. For those less familiar with the methodologies, the FAA has published a guidance document that provides a very useful overview (Butler and Kiernan 1992). *ACRP Synthesis 7* outlines modern approaches to these studies (Karlsson et al. 2008).

An airport might choose to undertake a new economic impact study for a major mitigation project designed to offset the effects of climate, or it might rely on the data and the economic model from an existing study to project these impacts. Typically such a study would attempt to assess how many jobs, how much income and tax revenue, and how much total output would be created in the local area as a result of the project.

ACRP Synthesis 7 suggests that, via use of an input–output model (or other related approach), the impact study would distinguish three types of impacts:

- Direct impacts: Result from spending in the local area by visitors who arrive by air, as well as spending in the local area for goods and services by airport tenants;
- Indirect impacts: The estimated flow of dollars generated from the supply of materials, goods, and services attributable to the airport by off-airport entities;
- Induced impacts: The multiplier effect of "re-spending" the dollars generated through direct and indirect activities. Spending resulting from direct and indirect activities is spent again by the recipient employees and local businesses (Karlsson et al. 2008, p. 6).

It is important to distinguish between the life-cycle cost of the project (construction and operations and maintenance) and the consequences[12] of the project (the jobs, income, and output it produces in the local economy). For example, a runway extension might make it possible for airlines to extend service to long-haul international destinations that otherwise would not be feasible or economically attractive because of exposure to high temperatures. The runway project would have life-cycle costs (to build and operate the runway extension) and consequences (new nonstop service to international destinations that bring in many new visitors and new spending to the community). Both costs and longer-term consequences of the projects are counted as economic impacts because they produce jobs, income, taxes, and output for the local community.

Continuing with the example, the runway extension would create the following impacts as the airport incurred costs to build and operate the project:

- Direct impacts: Employment for construction and operations, which in turn would add income to the local community and would increase the regional output of construction services;
- Indirect impacts: Other key inputs (e.g., sand, concrete, equipment rentals, construction management) would be also be purchased within the community;
- Induced impacts: Some of the income created in the direct and indirect impacts would be re-spent in the local community.

The same project could also have long-term consequences for the community if it were truly the case that (at least some) international service was not economically feasible due to increased exposure to high temperatures. Over time the project would produce:

- Direct impacts: jobs, income, and output at the airport due to incremental activity;
- Indirect impacts: local purchases by international travelers;
- Induced impacts: additional re-spending of local income within the community.

Among these long-term effects, the indirect impacts would likely be the most consequential because international travelers generally stay longer and spend more than domestic travelers.

Defining Consequences Correctly

The FAA guidance document suggests that the analyst take care in attributing consequences to a project:

> Strictly speaking, direct impacts should represent economic activities that would not have occurred in the absence of the airport. If it were determined that, without the airport, some onsite employees would be doing comparable work elsewhere in the region without displacing other workers, their employment should not be part of the airport's contribution to local economic activity. . . . Like direct impacts, indirect impacts should theoretically represent economic activities that would not have occurred in the absence of the airport. For this reason, it would be desirable to distinguish between tourists (and other visitors) who would not have traveled to the region if there were no airport and those who would have come anyway by some other form of transportation. Only the former are really relevant for the estimation of indirect impacts (Butler and Kiernan 1992, pp. 15–16).

In the context of the runway extension example, it would be important to know whether the project was the key determinant in undertaking or keeping long-haul service (without it there would be no service) or instead if airlines might otherwise undertake the service but incur delay or cancellation costs on very hot days. If the former were the case, then all economic impacts would be properly attributed to the extension to offset very hot days. If the latter were the case, then the economic impacts could be defined as:

(impacts from life-cycle costs) + R $*$ (impacts from project consequences)

where R is the risk of delays or cancellations at the airport.[13]

The best way for an analyst to know how to attribute the consequences of a project would be to examine its financial feasibility. If airlines were willing to pay for all or part of the extension (depending on the way it is financed), then the feasibility study would likely include a forecast that examined the likelihood of long-haul service with and without the project. A benefit–cost study would also make this distinction.

Distinguishing Economic Impacts from Benefit–Cost and Financial Feasibility

As noted previously, both costs and longer-term consequences of the projects are counted as economic impacts because they produce jobs, income, taxes, and output for the local community.

In contrast, a benefit–cost study compares benefits to costs and provides information about whether the project makes economic sense from a national perspective. The benefits of the runway extension project would be defined primarily as passenger (and cargo) time savings, while costs would be defined as the life-cycle costs of the extension. If the discounted present value of benefits exceed costs, the project would have economic merit.

An FFA is designed to examine whether a project can be financed and produce an acceptable return; it has a narrower focus than a BCA. It would define costs in the same way as a BCA, but it would define returns to the airport (e.g., concession earnings, PFC revenue, incremental net rents, and incremental landing fees) as the main benefits. When airlines are willing to pay more in landing fees and rents to gain the runway extension (net of the other incremental airport cash flows), the project would make financial sense.

6.5 Option to Delay Investment

Another important topic to address is that of optionality and timing. Many climate resilience projects will have very long-lived analysis periods. In these circumstances, it is appropriate to examine the option of delaying the projects or only partially funding them with the anticipation that the project planning will be finalized or adjusted in the future depending on the circumstances and the availability of better information on actual risks and exposures.

In principle, the option to delay a decision on an infrastructure investment project can be evaluated in a straightforward manner. For a BCA, this could be handled by specifying an alternative scenario where the investment is delayed X years out into the future, meaning that the benefits stream would also be delayed. Again, one could use Monte Carlo simulations, and the discounted benefit–cost ratios of the simulations from the alternative scenario would then be compared to those of the current scenario.

FAA guidance in fact recommends that benefits and costs be evaluated for a period of at least 5 years beyond the expected project life for precisely this reason—it allows direct comparison of NPVs under a scenario starting in year X versus year X + 5 with the same number of project years (FAA 1999b, p. 22).

For an FFA, the decision may rely on a somewhat more informal process. The results of such an analysis may indicate that the proposed project may be a close call in terms of funding, and if the likely climate risks faced by the airport are thought to be fairly limited over the short term but increasing over the long term, then it may well make sense to delay the project and reassess in a few years.

6.6 Comparing Results Across Different Scenarios

As noted in the FAA's BCA guidance (FAA 1999b; discussed in Appendix G), it may not be possible to determine the best way to proceed until a full range of investment alternatives are identified and evaluated. FAA cautions against airports excluding potential alternatives just because of a predisposed preference toward a favored one. If it has in fact been decided to consider multiple alternatives, then each one should be self-contained (i.e., any identified incremental benefits and costs should be unambiguously attributable to it).

In such a situation, the analysis should be structured so that the evaluation period is the same across all alternatives.[14] Having done so, the question then becomes how to compare results across scenarios. While a simple comparison of NPVs (or benefit–cost ratios) may be possible, the FAA also explicitly recognizes that the final recommendation arising out of a BCA should also consider possible impacts from hard-to-quantify benefits (and costs) and sensitivity of results to uncertainty (FAA 1999b, p. 90). The Monte Carlo method described in Chapter 2 can be used to directly assess comparative NPVs and how sensitive they are to estimates of climate uncertainty (as measured through different climate models). Combined with consideration of any hard-to-quantify impacts, the approach described in this handbook is well suited to the goal of assessing the potential impacts of uncertain future climate events on airport investment projects.

Recall that the VaR interpretation of the Monte Carlo simulations expresses the probability of an airport (or its users) incurring at least a certain amount of damages due to climate events. Through mitigation, some of this risk can be reduced or even eliminated. But the project with the highest NPV may not be the one that leaves the airport with a tolerable amount of unmitigated risk. For example, if project X has the highest NPV, but its VaR chart indicates that the airport has a 25% chance of an unmitigated risk that could bankrupt it, the airport would be well advised to revisit alternatives that provide more comfortable risk profiles.

CHAPTER 7

Case Studies

7.1 Introduction

Case studies for this project featured four local airport sponsors. The interactions with the airports were accomplished through a series of airport-specific webinars and follow-up teleconferences. Airports had expressed concerns about the extent of staff resources that might be required to participate in the project, and the webinars provided a cost-effective way to interact with a more limited effort from airport staff than a series of site visits.

The primary goal of these discussions was to introduce an illustrative case study for each airport demonstrating the methodology described in the project handbook to help airports evaluate the potential impacts of climate change. The project team presented example scenarios of specific climate risks faced by each airport using the most recent and localized climate data.

In the case studies, the risk and uncertainty faced by each airport was modeled using a Monte Carlo simulation implemented in an Excel spreadsheet. In the model's base case, the airport would do nothing and face the full risk of climate change in the future. In the scenario case, the airport would invest in a mitigation investment that would result in a reduction or elimination of the climate risk.

It must be noted that the mitigation investments were chosen only for the purpose of demonstrating the analysis tools developed in this project. The airports were less interested in discussing actual or potential projects and more interested in the climate data and methodology. As a result, neither the type of mitigation nor its feasibility was formally considered as potential capital improvements for the airports in question; they only served as examples for the benefit–cost and financial feasibility analyses.

However, it is important to point out that actual climate data projections were obtained for each airport. Thus, while the project mitigations are purely illustrative, the climate data shown in each case represent actual estimates of potential future climate outcomes. It is also important to emphasize that, in all cases, the climate projections used were those from RCP8.5 (recall Exhibit 3-1), which represents a high-emissions scenario for future climate change.

Two of the case studies involved BCAs suitable for airport letter-of-intent (LOI) funding applications to the FAA; these studies were conducted for runway extensions designed to offset the impacts of high temperatures on commercial aircraft operations. Because the majority of benefits from runway extensions would be enjoyed by passengers and operators, it made sense to follow FAA guidance on appropriate benefit–cost methods, adjusted to account for climate risk as described in the following.

FFA was applied for two cases involving increased exposure to flooding and storm surge. In these cases, airport infrastructure was catalogued for exposure, depending on the forecast extreme water level. The higher the water level, the greater the number of infrastructure components that would be exposed. While operators and passengers could be affected by service interruptions in the event that critical infrastructure was inundated, the FFA focused on whether the airport could justify investing in mitigations solely based on the expected costs avoided.

7.2 Case Study Overview

It was desirable to have case studies of large, medium, and small hubs in order to assess whether there were variations in the levels of awareness of potential climate problems and how the airports were dealing with them. Originally the project team was planning to apply the latest climate data to Monte Carlo models for two of the case studies, with the other two being treated using only data from the ACROS model from *ACRP Report 147* (Dewberry et al. 2015). However, it became apparent that the airports were interested in the Monte Carlo process, so Excel-based models using the latest climate data were developed for each case study.

Agreement was reached with four airports:

- Large-hub airports (2)
  - Phoenix: Case study of the effects of higher temperatures on cancellations and payload/range limitations potentially mitigated by a runway extension. The case study was based on cancellation experience in the summer of 2017 when regional jet flights were cancelled during the midday period because temperatures reached 118°F.
  - Boston: Case study of the exposure to storm surge due to sea level rise, potentially mitigated through a variety of investments, including raising floor levels and building protective infrastructure.
- Medium-hub airports (1)
  - New Orleans: Case study of the exposure to storm surge due to sea level rise. MSY is just 3.7 ft above sea level and has a perimeter dike to limit damage from storm surge. Although the airfield did not flood during hurricane Katrina, the facilities suffered extensive wind and water damage. The airport is also nearing completion of a new replacement terminal. Potential mitigations are similar to those considered in the Boston case study.
- Small-hub airports (1)
  - Little Rock: Case study of the effects of higher temperatures on cancellations and payload/range limitations. LIT has an 8,200-ft runway, and payload range penalties for missions in excess of about 1,000 miles begin when temperatures exceed 100°F. A runway extension could potentially eliminate the problem.

Information Request

Participants were asked to provide information on how their airport was organized to deal with climate change. There were two primary areas of interest:

- The first focus area was on the organizational process implemented at the airport to deal with climate change and potential adaptation strategies. The project team wanted to understand the people involved, both internally and externally. Particular attention was paid to the expertise of the individuals on the core team and whether specialists had been retained to deal with complicated issues related to climate change as well as economic and financial analysis under uncertainties. The research team also wanted to understand how the airport had engaged with the public on these matters and how airport operators made decisions on adaptation strategies.
- The second area of focus was on understanding how the airport was identifying its vulnerability to climate change risk and how it was determining what infrastructure might be critically affected in the future. The research team was interested in the data and tools being used by the

airport operators in making these determinations and, in particular, whether they were using the ACROS tool and the latest data available from the National Oceanic and Atmospheric Administration (NOAA) to assess climate risk.

A brief summary of findings is shown in Exhibit 7-1; more details on the interactions with each airport are provided in Appendix H. In general, it was found that airports facing immediate climate-related impacts (PHX, BOS, and MSY) had taken steps to address the problems. The problems at LIT are likely to be faced further in the future and the airport is smaller, so it appropriately has fewer staff dedicated to these kinds of issues.

Development of Workshop Materials

For the case studies, the project team developed an Excel program employing the latest available climate data for each airport to conduct a VaR analysis. Based on the Excel model, a

	PHX	BOS	MSY	LIT
Senior climate change person	Sustainability coordinator	Climate mitigation and resiliency manager	Cross functional	Cross functional
Reports to	Cross-functional team*	Assistant director – capital programs and environmental management	Cross functional	Director properties, planning, and development
Climate risk evaluated in house or by consultants	Primarily consultants	Primarily consultants	Primarily consultants	Depends on airlines to evaluate payload penalties
Airport access to climate data	Via consultants	Mass DOT partnership with Woods Hole Group, with Climate Ready Boston information as a supplement	Via consultants	Via consultants
Investments in climate mitigation	Cross-functional team*	Capital programs and environmental affairs responsible for 5-year capital improvement program, subject to chief executive officer and board approval	Extreme water events accounted for in the new North Terminal project	None to date
Existing operational mitigations	Hold times when temps rise above thresholds; safety measures for on-ramp staff	Arrangements to deploy flooding/storm surge/tidal surge countermeasures based on forecasts	Yes for flooding	None to date, but concerned about payload penalties effect on air service development to West Coast and New York
Communications with public regarding climate change	Just fact checking articles; otherwise airlines take the lead	Participates in various community programs such as Climate Ready Boston and periodic public awareness events such as a drill on flood abatement deployment	Extensive public discussion of new terminal, which is in the 100-year flood plain (per final supplemental environmental assessment of the project)	Leaves this to the airlines

*Operations, public safety and security (includes fire, police, first responders), facilities maintenance, design and construction services (for any changes to building specs, etc.), and risk management and financial management division.

Exhibit 7-1. Summary of findings.

PowerPoint presentation was prepared for the WebEx conference with each airport. The presentations began with a common set of introductory slides and then moved on to the specific case study for the airport. Once the PowerPoint presentation was completed, the study team presented the Excel simulation model.

Airport participants were encouraged to ask questions and comment on the materials throughout the WebEx conference. All the airports participated actively in the case study process. Follow-up calls and emails were placed to obtain missing information.

Quantifying Risks and Uncertainty

Two types of climate risks were analyzed in detail in the case studies, using the following information sources and operational assumptions:

- Very high temperature days (in excess of 100°F): Localized projections of 31 different climate models from RCP8.5 scenario[15] for the four closest points to the subject airports (PHX and LIT); projections are from 2020 to 2090. Counts of high-temperature days in each year were randomly drawn from the available models. A set of predictions from 2020 to 2090 represent a single simulation, and a total of 5,000 simulations were conducted.
- Sea level rise and storm surge: NOAA historical extreme water level (EWL) and relative sea level (RSL) rise projections linked to RCP8.5 (MSY and BOS); projections are from 2020 to 2100. Outcomes for each year were based on a random draw from localized historical exceedance probability functions developed by NOAA plus a random draw from localized sea level rise projections. The result was a single prediction of the height of an extreme water event each year.[16] A set of predictions from 2020 through 2100 represent a single simulation, and a total of 5,000 simulations were conducted.

In all cases, a climate event in any year could potentially trigger costs (to the airport, operators, or passengers). In each of the 5,000 simulations, these costs were discounted and added up.

Base Case

The results of the simulations were used to consider the VaR to the airport if no mitigation were undertaken.

- In the case of flood risks at BOS and MSY, while it is common to base mitigation investments on the risk of a 100-year event (one with an annual probability of 1%), the VaR analysis provides more complete information by considering the entire range of potential outcomes on the expected loss to the airport and its users. The impact of a 100-year event is essentially embedded within the simulations and would be identified as the 50th (99th percentile out of 5,000) most costly loss generated from the simulations.
- In the case of PHX and LIT, the VaR analysis provides more complete information on the number of days each year where temperatures exceed critical levels; the data are presented in 2-degree increments. This would allow the airport to assess how often some aircraft types on scheduled missions would face payload penalties at, say, 110°F versus 114°F, and how often flights might have to be cancelled at very high temperatures (in excess of 118°F or 126°F).

Scenario Case

The same process was repeated for possible mitigation strategies. First, the effectiveness of the mitigation was defined: Would it eliminate the risk entirely by preventing flooding or averting cancellations and payload penalties due to high temperatures, or would it only be effective in some cases? Then the life-cycle costs of the mitigation were defined.

Applying the same climate risk profiles to the mitigation scenario generated 5,000 outcomes defined as net life-cycle costs (avoided risk minus the life-cycle costs of mitigation). These costs were then compared to the base case (without mitigation). By counting the instances where the net life-cycle costs of the mitigation were lower than the costs without mitigation, one could readily determine how often a mitigation project would pay off.

The mitigation investments considered were fairly generic. The participating airports indicated a preference for focusing on the detailed modeling methodologies and providing comments, but they were not prepared to commit time or resources to the development or endorsement of specific mitigation investment possibilities. Therefore, the main focus of the presentations was on the methodology itself. The example mitigations were chosen only to facilitate the demonstration of the methodology and do not represent any plans of the participating airports.

Benefit–Cost Versus Financial Feasibility Analysis

It is worth noting that the two high-temperature cases involved runway extensions and were presented as benefit–cost studies suitable for an FAA LOI application. This made sense in these cases because a large portion of the benefits were attributed to averted passenger delay costs.

In the case of the two flood mitigation projects, the cases were presented as financial feasibility exercises because more of the costs of flooding would be incurred by the airport making repairs to damaged infrastructure.

7.3 Summary of Presentations and Lessons Learned

A tabular summary of the presentations and sample analysis for each airport is shown in Exhibit 7-2. A summary of the lessons learned is presented in the following.

- Overall, the airport participants had no problem following the methodology for conducting the VaR analysis using the latest climate data.
- All airports appeared to be familiar with the potential threats from climate change.
- PHX and BOS had active programs in place that were evaluating climate risk.
- LIT depended on airline input on potential payload issues and was mostly concerned about the increased frequency of payload penalties affecting its attractiveness for longer-haul service to the East and West Coasts.
- MSY was in the middle of a new terminal project and indicated that the threat of sea level rise had been and would continue to be central to its planning.
- It was apparent that, in the case of sea level rise and flood threats, airports would benefit by linking flood maps with the probabilities that are produced in the VaR analysis. This would help engineers and decision makers visualize the threats to specific infrastructure.
- In the case of high-temperature days, PHX correctly noted that payload penalties in the form of weight restrictions could become an issue at much lower temperatures than the very high values that caused full flight cancellations in 2017. This was addressed directly in the Excel template for high temperatures.
- It became apparent during the case studies that, while ACROS is useful as a screening tool and as a way to classify infrastructure that is vulnerable and critical, the ACROS reports do not produce climate data (temperature or flood risk) that are precise enough to conduct benefit–cost or financial feasibility analyses. Different temperatures and levels of extreme water rise affect different operations and infrastructure. Having the full range or outcomes linked to probabilities allows the analyst to evaluate climate risks appropriately.

	PHX	MSY	BOS	LIT
Date	April 26, 2018	April 27, 2018	May 7, 2018	May 10, 2018
Format	WebEx	WebEx	WebEx	WebEx
Climate risk	Very high temperature days	Extreme water level events due to sea level rise	Extreme water level events due to sea level rise	Very high temperature days
Impacts investigated	Increased exposure to full flight cancellations when temperatures exceed 118°F	Increased exposure to extreme water events (flooding) due to sea level rise	Increased exposure to extreme water events (flooding) due to sea level rise	Increased exposure to passenger payload penalties when temperatures exceed 100°F
Stage 1: ACROS screening	Large increase in days where temperature exceeds 100°F (temp fixed in ACROS software)	Flooding 365 days a year by 2030	No flooding through 2060 but an increase in BFE	Large increase in days where temperature exceeds 100°F (temp fixed in ACROS software)
Stage 2: Need for detailed modeling	ACROS data not detailed enough to model critical temperatures for specific aircraft at PHX: 118°F and 126°F	ACROS data do not differentiate among sea level rise events	ACROS data do not cover the 100-year or 500-year event threat that BOS uses in planning	ACROS not detailed enough to model payload restrictions that may occur at different temperatures for different aircraft
Climate data used	Localized projections of daily high temperatures for four points within 4 miles of PHX, 2020–2090	NOAA historic local extreme water return period data for Louisiana coast, plus six NOAA future coastal scenarios tied to circulation model probabilities, 2020–2100	NOAA historic local extreme water return period data for Boston coast, plus six NOAA future coastal scenarios tied to circulation model probabilities, 2020–2100	Localized projections of daily high temperatures for four points within 4 miles of LIT, 2020–2090
Circulation scenario	RCP8.5	RCP8.5	RCP8.5	RCP8.5
Number of climate models	31	6	6	31
Sampling plan	Random draw among models for each year of each simulation	Random draw among models using interpolations based on RCP probabilities	Random draw among models using interpolations based on RCP probabilities	Random draw among models for each year of each simulation
Monte Carlo simulations	5,000	5,000	5,000	5,000
Summary of climate risk	Increase in median days above 118°F from near zero at time of this report to over 20 by the 2080s, with variances across simulations	Median annual sea level rise event increases from 1.6 ft historically to 6.2 ft by 2095; wide variations in outcomes	Median annual sea level rise event increases from 2.6 ft historically to 5.5 ft by 2095; wide variations in outcomes	Increase in median days above 100°F with variances across simulations
Type of analysis	FAA benefit–cost study	Financial analysis	Financial analysis	FAA benefit–cost study

Exhibit 7-2. Summary of case study sample analysis.

	PHX	MSY	BOS	LIT
Modeled impact of climate risk	Using FAA critical values, evaluate cost of cancelled regional jet flights when temperatures reach 118°F and cancelled standard jet flights above 126°F	Evaluate net benefit of reducing the impacts of extreme water events using generic cost values for differing water levels	Evaluate net benefit of reducing the impacts of extreme water events using generic cost values for differing water levels	Using FAA critical values, evaluate delay costs to passengers bumped from flights to current and potential new destinations due to payload restrictions
Modeled mitigation	Runway extension with discounted life-cycle cost of $30 million	Flood mitigation project with discounted life-cycle cost of $20 million	Flood mitigation project with discounted life-cycle cost of $20 million	Runway extension with discounted life-cycle cost of $30 million
Impact of mitigation	Elimination of flight cancellations	Eliminate flooding for extreme water events up to 5 ft and reduce impact of higher events 80%	Eliminate flooding for extreme water events up to 5 ft and reduce impact of higher events 80%	Elimination of payload restrictions for domestic flights
Analysis results	Project has negative expected NPV and pays off only 15% of the time; 3% chance of $35 million loss if not built, but project could pay off with a higher probability with delayed implementation 10–20 years out.	Project has positive expected NPV and pays off 70% of the time; 20% chance the airport would lose $40 million or more if the project were not built; results based on a 3% discount rate.	Projects has positive expected NPV but pays off only 35% of the time; 10% chance the airport would lose $40 million or more if the project were not built; results based on 3% discount rate.	Project has a negative expected NPV and pays off only 7% of the time.

Exhibit 7-2. (Continued).

CHAPTER 8

Study Limitations and Recommendations for Future Research

This handbook presents airport practitioners and decision makers, who may face significant adverse impacts from uncertain future climate change events, a methodology that can be used with currently available climate projections to simulate a full range of potential future outcomes.

While the methodology itself is sound, as with any quantitative analysis, the outputs will only be as good as the inputs used. Climate science is progressing rapidly, and new and better climate models are constantly being developed and updated.

Consequently, future research could be conducted using the latest projections as they become available, and it is suggested that analysts who want to use up-to-date climate forecasts should keep abreast of the latest CMIP5 projections available from the IPCC, which is the UN-sponsored entity charged with assessing scientific, technical, and socioeconomic information concerning climate change.

The analysis and methodologies presented focus on two specific aspects of climate change likely to affect airports: sea level rise and rising temperatures. While these impacts are readily measurable, other potential impacts of climate change may also be relevant for certain airports—for example, the increased occurrence of localized thunderstorms or air turbulence. Research could focus on advances in climate science to assess whether and how accurately these (or other) types of localized events could be forecast as the science improves.

At a more detailed level, there are important aspects of the sea level rise and high-temperature analyses presented here and in the accompanying Microsoft Excel files that could be improved if better data become available.

In the case of sea level rise, the modeling is based on estimates of historical flooding probabilities and future sea level rise that may not be particularly accurate for a given airport. By necessity, the estimated historical probabilities often rely on small numbers of actual flooding events and so may be subject to significant change as new events occur. Additionally, the future sea level rise estimates used in the Monte Carlo simulations rely heavily on a single table of probabilities for global mean sea level rise produced in a NOAA technical report (Exhibit D-4 in Appendix D). The climate science supporting the probabilities shown there is changing rapidly. Moreover, in order to employ the suggested methodology, one must interpolate between these probabilities; thus, the projections themselves may be subject to uncertainty across a wide range of outcomes. Again, as better or more complete estimates of sea level rise become available, better predictions from the Monte Carlo simulation methodology could be obtained.

In addition, the flood modeling as presented is limited because it cannot take account of any variations in terrain that may exist between the reporting stations and the airport itself. Nor can it account for any existing mitigations (such as levies or stormwater systems) that may be operational. However, knowledgeable users of the software can overcome these shortcomings by adjusting their critical infrastructure elevations to take account of existing mitigations.

Similarly, in the case of high temperatures, one expects that future research will be able to use better and more accurate localized forecasts. Specifically, the localized constructed analogs (LOCAs) referenced in Appendix D are themselves the result of a specific statistical downscaling technique that potentially could be improved in the future. Finally, the weight restriction calculations used in the Excel file for high temperatures are estimates only; analysts may want to confirm performance parameters with aircraft manufacturers when evaluating actual payload penalties.

Overall, the use of better and more current localized data projections would be extremely valuable for future research efforts relating to potential climate change impacts on airports. It should also be noted that the Monte Carlo simulation technique could be more broadly applicable to other factors that affect airport risk assessments if these factors can be characterized probabilistically.

APPENDIX A

Institutional Background: Existing Airport Resources and Plans

Evaluating climate resilience at airports can best be thought of as part of the overall risk management processes that most airports already have. This appendix describes a generic management structure for assembling a team to analyze the potential impacts and responses to climate change and discusses specific risk management activities that such a team might undertake. A discussion of enterprise risk management (ERM) is also provided.

Who Should Be Involved

One of the first things to consider in the resilience analysis process is who should be involved; these participants would make up a resilience team that could be tasked with oversight, analysis, and other related activities. It is essential early on to determine key internal and external contributors to the process. The list of internal participants shown in Exhibit A-1 is taken from *ACRP Report 147* (Dewberry et al. 2015). Participants should be selected based on their ability to contribute to the planning process and their role either in making decisions or driving consensus toward decisions. Note that larger airports are more likely to have individuals or even whole departments devoted to the areas of expertise listed under the internal group in the exhibit. For example, many large airports have environmental sustainability departments and undertake sophisticated risk management analyses. Smaller airports may not have this expertise internally, and in many cases they may not have the financial resources to hire outside expertise. By necessity, their team of contributors may be smaller and more limited than what is listed here.

It is likely that the people participating in a BCA or FFA would be a mix of the internal and external constituents listed in the exhibit. In addition to selecting specific individuals, it is important to decide on specific roles and responsibilities. One way of handling this is to segregate personnel into a core team and an oversight team. The core team is the group that would be tasked with developing and presenting work products and would likely include a risk assessment group charged with identifying an airport's vulnerability to climate change problems and how critical that vulnerability is to the continued operation of the airport. The oversight team would be responsible for reviewing outputs and would be part of the process for communicating with outside stakeholders and building consensus for resilience adaptation strategies recommended by the core team; the strategies could include operational changes and investments in new infrastructure.

With respect to dialog and outreach (both internally and externally), there are a wide variety of communication channels that may be used. Exhibit A-2 provides a good starting point for airports looking to expand these types of activities.

If a solid resilience team has been assembled and specific communication and awareness goals have been identified, then internal and external stakeholders will be in a position

Internal Departments/Personnel	External Stakeholders/Personnel
Executive management Planning Environmental sustainability/resilience Risk management/legal Finance Engineering O&M Emergency operations	Airlines and general aviation airport operators Airport tenants FAA representatives Local government and media Academic and research institutions Nearby residents Business partners and suppliers Climate experts BCA/finance consultants

Source: Derived from *ACRP Report 147* (Dewberry et al. 2015).

Exhibit A-1. Who should be involved in the resilience team.

to receive the results and react to them in a timely and orderly fashion. In many cases, the ability to successfully communicate with external stakeholders (such as airport users, local government, and the public) is often the most critical determinant of whether an airport can actually follow through with recommended investments in resilient infrastructure. It will be important that appropriate documents and work products be accessible, particularly to non-expert stakeholders.

While this suggested structure is straightforward, primary decision makers at a given airport must decide how best to address infrastructure needs in the context of climate resilience. Many airports, even large ones, may choose to select climate experts to help them assess the risk and uncertainties related to climate change and the airports' exposure to them. Some airports will also choose to involve financial consultants or benefit–cost consultants, depending on how sophisticated the analysis is likely to become. Finally, it is always important to include

- Public relations and online presence:
  - Annual publications
  - Press events and releases
  - Marketing partnerships
  - Airport website, including an updated news section
  - Airport-specific apps
  - Social media, including live chat
- Internal and external communications:
  - Conferences, trade fairs
  - Expert talks and discussions
  - Work meetings, employee surveys, performance reviews
  - Passenger surveys
  - Terminal services
  - Community outreach, including noise commissions and regional partnerships

Source: Adapted from *Munich Airport: Integrated Report 2015*.

Exhibit A-2. Communicating with stakeholders.

participants from the FAA and members of the public as well as airlines, other operators, and airport tenants as part of an oversight group.

Resilience Team Activities

After consideration of who should be involved, the next issue to address is what tasks these participants should be undertaking. Exhibit A-3 lists 10 representative categories of activities, the first seven of which are drawn from *ACRP Report 147*.

The airport will need to set resilience goals; this means identifying some overarching objectives for assessing how to deal with climate change. From an operational standpoint, such objectives may include items such as:

- Avoiding flight delays and schedule disruptions,
- Avoiding disruptions or failures to airport emergency systems and processes,
- Avoiding partial or complete closure of the airport, and
- Limiting revenue loss.

Reaching some of these objectives may require investments, while reaching others may require changes in operating procedures or airport design standards.

The resilience team also should set some goals related to communication and awareness. This is relevant both internally (across departments) and externally. By involving team members from different departments or groups, the team can identify and address potential climate risks on an airport-wide system basis. In addition, the ability to successfully communicate with external stakeholders is often the most critical determinant of whether an airport can actually follow through with recommended investments in resilient infrastructure.

Part of the communication process will involve creating appropriate documents and work products and ensuring that they are disseminated to the relevant parties. It will be important that these outputs be accessible to non-experts, despite the complexities of dealing with climate change in a quantitative way.

It is likely that the resilience team will need to coordinate across different airport organizations. For example, if the resilience team recommends changes in operations (including emergency operations), it will be important that the suggested adaptations be accurately incorporated into existing safety management systems, emergency preparedness documents, snow and ice control plans, and other airport operations systems, so that the benefits of these suggested changes can be realized.

1	Set resilience goals
2	Communicate goals
3	Identify audience
4	Identify vulnerable and critical infrastructure
5	Quantify risk and assess uncertainty
6	Identify potential adaptations
7	Prioritize options: qualitative and quantitative methods
8	Perform FFA or BCA
9	Communicate results to stakeholders
10	Monitor, review, and update

Source: Adapted from *ACRP Report 147* (Dewberry et al. 2015).

Exhibit A-3. Proposed activities of the core and oversight teams.

Once the structure and goals of the resilience team are set up, attention can turn to the main information presented in this handbook:

- How to define and measure aspects of climate change that may be relevant to the airport,
- How to assess potential airport impacts, including identifying and targeting airport assets and infrastructure and assessing vulnerability and criticality, and
- How an FFA or a BCA is used to identify and quantitatively assess possible responses or adaptations to accomplish the operational goals identified by the team.

In carrying out these activities, there should be a process for monitoring, reviewing, and updating information as it becomes available to be incorporated into either an FFA or BCA. For example, CIPs often take years to implement, and as new information becomes available on the exposure of airports to climate change risk, this information should be incorporated into the CIP analysis and communicated to relevant stakeholders.

Incorporating Existing Plans and Systems

Most airports already have well-developed processes for meeting FAA requirements, including master planning, AIP requirements, and emergency planning. In addition, numerous existing publications from the FAA, ACRP, and specific airport entities that have already undertaken resiliency efforts offer valuable information so that airports are not starting from scratch when developing new plans or projects related to climate resilience. The following builds on information developed and presented in *ACRP Report 147* (Dewberry et al. 2015).

Exhibit A-4 summarizes existing planning initiatives to comply with FAA requirements and identifies how they are or could be used by airports to address climate resiliency projects. A detailed description of each initiative is in the following sections.

National Plan of Integrated Airport Systems

The National Plan of Integrated Airport Systems (NPIAS) is a report issued to Congress identifying the national airport system and the projects that are eligible for AIP funding over 5 years. The most recent report, which was issued in 2015, covers 3,340 existing and proposed airports across the nation and estimates a need of $32.4 billion in infrastructure development projects for 2017–2021. The report notes that the FAA is working to address the potential effects of climate change and the resources required to enable the airport system to withstand its effects, but the costs of climate change resilience are not included in the current cost estimates (FAA 2015b).

Airport Emergency Plans

All certified airports (CFR Part 139) should develop and implement an airport emergency plan (AEP) following AC 150-2500-31c guidance (FAA 2009) to ensure the safety of and emergency services for the airport and the community in which the airport is located. An airport emergency is defined as any occasion or instance, natural or man-made, that warrants action to save lives and protect property and public health; this includes natural disasters such as hurricanes, tornados, and flooding, all of which are predicted to occur as a result of climate change. The guidance presents the process to prepare for a natural event as well as the steps to assess the damage and to clean and repair key airport facilities. Also, it establishes the need for offering sheltering facilities capable of withstanding strong winds and rain.

Current Management Structure	Purpose	Currently, Is Climate Resiliency Addressed? If Yes, How? If Not, How Could It Be Adapted?
Airport Emergency Plans (AEPs)	Present process for natural disaster preparedness and steps to assess damage	There is no mechanism to track expenses related to natural disaster preparedness or to assess the efficacy of disaster response/mitigation. AEPs could be adapted to formulate formal budget codes/mechanisms to track expenses and compare the preparation for natural disaster events to the severity of outcomes.
Airports Capital Improvement Plan (ACIP)	Presents process through which capital projects are approved, funded, and implemented	The national priority rating (NPR) system provides an opportunity for climate resiliency projects to be incorporated formally in infrastructure project prioritization. NPR formula coefficients could be adapted to accommodate climate resiliency projects.
Airport master plans	Provide guidance to achieve short-, mid-, and long-term needs	Climate resiliency aspects may be considered but are not required under multiple sections in an airport master plan.
National Environmental Policy Act (NEPA) compliance	Establishes policies and regulations for environmental analyses	Discussion about how a proposed project could be affected by climate conditions needs to be included under the environmental consequences section. No thresholds for climate impacts have been confirmed. FAA recognizes guidance will change.
National Plan of Integrated Airport Systems (NPIAS)	Identifies projects that are eligible for AIP funding over 5 years	Resilience project costs are not included in the latest NPIAS. The FAA could calculate climate change project costs to be added into NPIAS.
Sustainability plans	Guide development to meet environmental, social, and economic goals	Within sustainability plans, most airports have undertaken initiatives to reduce their own carbon emissions. Some projects may directly address climate resiliency (e.g., pavement maintenance, stormwater management, and equipment purchases geared toward improving airport operations' response to extreme events).
Safety Management Systems (SMS)	Determines risk management practices and procedures	Material on applicability and scaling of risk analysis is relevant to climate change aspects, and the list of purchases to support resiliency for climate change could be revisited to incorporate more of them.

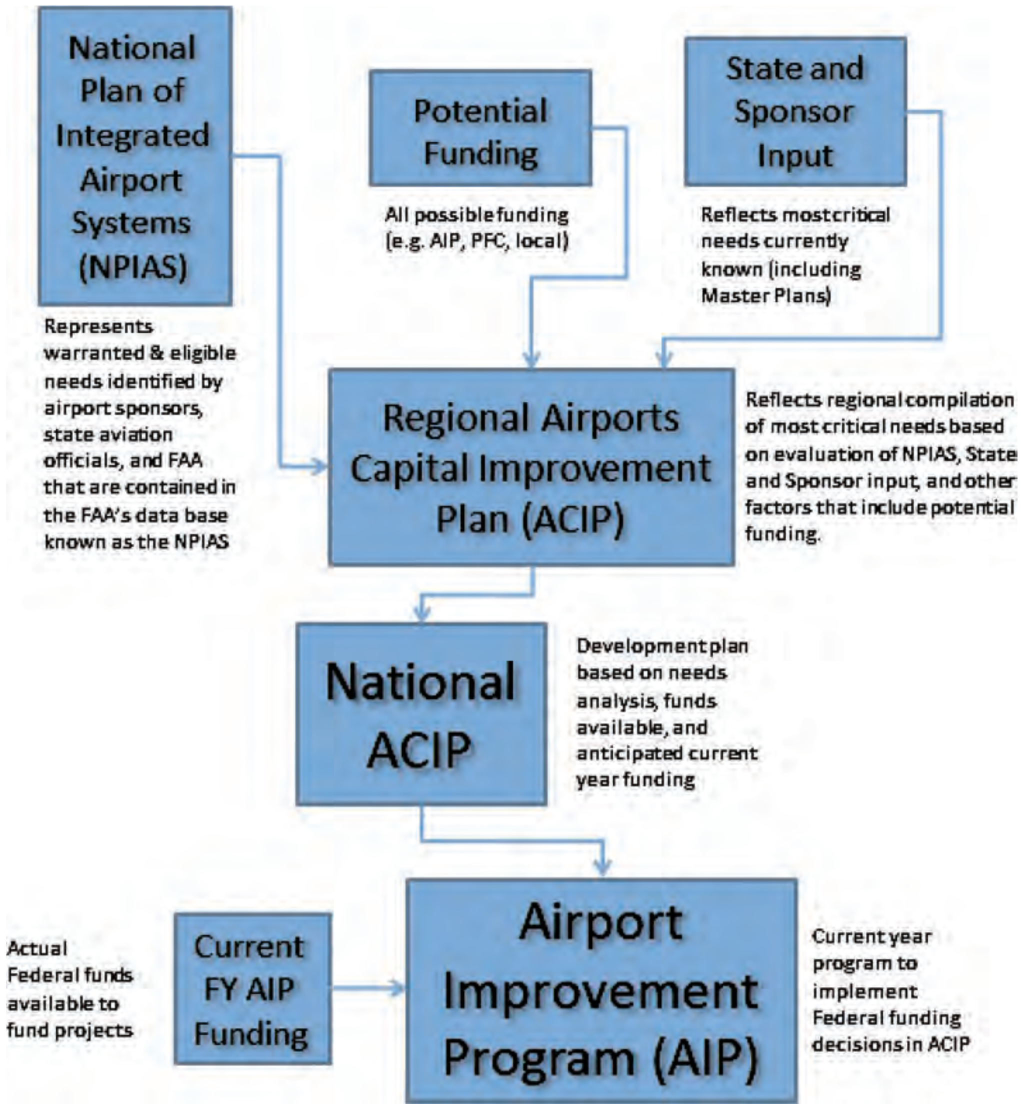
Exhibit A-4. How climate resiliency is addressed in current airport planning processes.

Having an AEP in place with detailed cost estimates in case of an emergency is useful when highlighting the costs incurred and avoided in a BCA. Additionally, the AEP may help to develop a budget system to track actual expenses for preparedness and recovery after the natural disaster.

Airports Capital Improvement Plan

The process for a capital project to be approved, funded, and constructed begins with the project sponsor referring to the FAA guidance (FAA 2000) on Airports Capital Improvement Plans (ACIPs). The ACIP formula process is briefly described here and is represented by the flowchart in Exhibit A-5.

Considering the NPIAS, all potential funding sources, and state and sponsor input, each FAA Regional Airports Office[17] compiles and submits a 3-year ACIP to the Airports Program Implementation Branch (APP-520). The regional ACIP is then reviewed, including any required BCA. Based on previous guidance (from 1999), BCAs were required for airport capacity projects that sought $5 million or more in AIP discretionary funds, but this



Source: Adapted from FAA Order 5100.39A, Appendix 1 (FAA 2000).

Exhibit A-5. The ACIP process.

minimum threshold has since been increased to $10 million (2015). However, the FAA's AIP BCA policy has been modified, and certain exemptions have been made. Based on modified policy, rehabilitation and reconstruction projects with no increase to an airport's original functionality do not require a BCA, even if the sponsor is seeking funds above the minimum threshold (FAA 1999a).

The FAA's APP-520 implementation branch creates national priority rating (NPR) thresholds, and a list of candidate projects is assembled. The NPR thresholds aid in categorizing airport projects, consistent with FAA goals and development needs. Regions may then adjust their submitted lists, and APP-520 then creates budgets for the regional offices. Based on the budget from the APP-520 implementation branch, the region develops its recommendations for funding. The Office of the Associate Administrator for Airports (ARP-1) selects and approves the projects for implementation from the regional recommendations, and projects that are not recommended are considered if there is carryover funding. Finally, the ARP-1 office evaluates the national system and submits an annual report.

The NPR system provides an opportunity for climate resiliency projects to be incorporated formally into the prioritization process. The NPR formula is:

$$NPR = 0.25P * (A + 1.4P + C + 1.2T)$$

where

A = Airport code,
P = Purpose,
C = Component, and
T = Type.

The equation measures how closely the proposed project aligns with agency goals and objectives; the NPR values closest to 100 represent projects that are the most consistent with FAA goals. Points are given for each of the variables A, P, C, and T, ranging from 1 to 10. Appendix 5 of FAA Order 5100.39A summarizes assigned point values for the various ACIP work codes as applicable to the formula (FAA 2000).

Although the NPR formula does not specifically name climate resiliency projects as eligible, many of the key categories would accommodate investments addressing climate change. The airport code (A) would not be affected by a project type because it refers to the size of the airport. By contrast, climate resiliency projects may fall under the following existing codes:

- Purpose (P): Reconstruction (RE, 8 pts), safety/security (SA, 10 pts), and environment (EN, 8 pts);
- Component (C): Land (LA, 7 pts), and other (OT, 7 pts); and
- Type (T): Construction (CO, 10 pts), improvements (IM, 8 pts), miscellaneous (MS, 5 pts), and mitigation (MT, 6 pts).

Projects geared toward addressing accelerated depreciation of infrastructure due to climate change events could fall under the aforementioned codes. Overall, the equation coefficients and individual point values currently assigned favor climate resiliency projects, enabling prioritization of such projects in the planning process.

Furthermore, the guidance notes that "it is anticipated that, based on future experience, the individual point values and equation coefficients (k1-k5) may be adjusted slightly to reflect modified national goals" (FAA 2000). Consequently, adjusting the "k" coefficients affecting the project purpose (P), component (C), or type (T) or creating new codes and associated point values within P, C, and T categories could further prioritize climate resiliency projects.

ACRP Report 120: Airport Capital Improvements: A Business Planning and Decision-Making Approach (Karlsson et al. 2014) addresses the challenge of obtaining reliable cost estimates for planning airport capital improvements. Future capital program costs often are defined during planning processes that lack the project details that only become available as designs progress and reliable construction cost estimates can be made. The quality of a BCA or FFA is limited by the quality of cost estimates available at the time the analysis is prepared. The report provides a thorough discussion of the factors affecting reliable cost estimates for capital planning when uncertainty is high. It reviews the basic principles of cost estimating for airport projects, summarizes best practices, and develops a parametric cost estimating technique based on historic costs for eight types of airport construction projects that are correlated through multiple regression analysis. The resulting cost model is implemented as an Excel spreadsheet tool, called the Airport Capital Cost Estimation (ACCE) tool. ACCE is offered to develop initial cost estimates for planning purposes. It provides user customizable inputs and geographic adjustments for regional construction cost differences, and it produces low, high, and best cost estimates. The tool allows what-if analysis and produces a printed report of all the input data and assumptions.

Airport Master Plans

An airport master plan is intended to serve as a guide for development to meet future demand in the near-, mid-, and long-term. The scale of such a plan varies depending on the size of the airport, its function, and its challenges. AC 150/5070-6B lists and describes the elements that should be included in an airport master plan (FAA 2015a). Currently, climate resiliency projects may be considered, but are not required, in the following sections of an airport master plan:

- **Environmental considerations:** It is noted that planners should try to achieve a balance between the man-made and natural environments.
- **Existing conditions:** Planners should identify historical weather conditions and areas that are potential hazards to aircraft such as flood control zones.
- **Aviation forecasts:** Under "other factors," changing attitudes toward the environmental impacts of aviation are noted as potentially affecting demand. In addition, it may be expected that extreme weather events and changing climates can also affect forecasted demand.
- **Facility requirements:** The emerging trends section includes a greater focus on sustainability, under which climate resiliency infrastructure projects may be included.

A BCA should be conducted as part of the master plan, if possible, for projects enhancing airport capacity and seeking $10 million or more in discretionary AIP funds or applying for a Letter of Intent (FAA 2015a).

Therefore, the effects and planned mitigation for climate change may fall under multiple sections in an airport master plan. This demonstrates the wide-ranging impact that climate change will have on airports and the importance of considering the effects over the near-, mid-, and long-term.

FAA Policy for National Environmental Policy Act Compliance

To be considered for AIP/federal funding, a project must complete various environmental analyses to satisfy the requirements of the National Environmental Policy Act (NEPA). FAA Order 1050.1F (FAA 2015c) outlines policies and procedures for compliance with NEPA and implementing regulations issued by the President's Council of Environmental Quality. FAA Order 1050.1F includes 16 environmental impact categories, and climate change is one of them.

The FAA's 1050.1F Desk Reference (FAA 2015d) complements FAA Order 1050.1F by summarizing all applicable special purpose laws in one location for quick reference. The 1050.1F Desk Reference provides the most up-to-date methodology for examining impacts associated with climate change. In regard to the NEPA review process, "discussion of a proposed project's potential climate impacts" is to be included in a separate section of the NEPA document, distinct from air quality (FAA 2015d). Currently, no significance thresholds for climate impacts have been established. Evaluation is tied to assessment of a proposed project's GHG emissions. For FAA NEPA reviews, discussion on climate impacts could be qualitative but may also include quantitative data (based on estimated project emissions).

Per FAA NEPA guidance, discussion of "the extent to which a proposed project could be affected by future climate conditions" (FAA 2015d) is to be included under the environmental consequences section. An example could include a description of a project area's ability to sustain impacts caused by climate change. Considerations to adapt to forecasted climate change conditions are to be described as part of the NEPA document.

Given the complexity of climate change factors and impacts, no direct linkage of a particular project to climatological changes is given in the current guidance. The FAA acknowledges that the guidance will evolve as research on climate change matures.

Sustainability Plans

ACRP Synthesis 10: Airport Sustainability Practices discussed the newly emerging topic of sustainability for airports (Berry et al. 2008). The report used a literature review and several surveys of U.S. and non-U.S. airports to identify practices that would ensure:

- Protection of the environment, including conservation of natural resources,
- Social progress that recognizes the needs of all stakeholders, and
- Maintenance of stable and high levels of economic growth and employment.

The findings led to the currently accepted definition of sustainability as supporting future growth that considers the goals of the triple-bottom line of environmental, social, and economic progress.

Regarding overall sustainability performance, respondents from non-U.S. airports and large U.S. airports rated their airports' performance higher than those from small and medium-sized U.S. airports. Respondents identified regulation and airport policy as key drivers for the implementation of sustainability practices. For the future, they cited stakeholder concerns and global concerns such as climate change.

A review of the airport sustainability plans in *ACRP Synthesis 66: Lessons Learned from Airport Sustainability Plans*, which includes a number of airports that received funding under the Sustainable Master Plan Program, shows that many airports acknowledge the potential effects of climate change but are only actively monitoring the projections of sea level rise, temperature increases, and increased precipitation (Martin-Nagle and Klauber 2015). Within sustainability plans, most airports have undertaken initiatives to reduce carbon emissions, both at the airport and for passengers accessing the airport, through encouraging recycling, planting trees, moving toward using renewable fuel, and exploring ways to reduce emissions from airplanes. A few projects may contribute more directly to the effects of climate change on infrastructure, such as aggressive pavement maintenance that extends its useful life, development of a strategy for managing stormwater runoff, and purchases of equipment to improve airport operations' response to extreme events.

For example, the Massachusetts Port Authority (Massport) developed a sustainability plan where Logan Airport set a goal of enhancing 25% of its critical assets or resources with resiliency measures over the following 5 years and achieving 100% within a decade. This would allow for the airport to better withstand the effects of climate change. In addition, Massport developed a list of 34 short-term initiatives across six categories for implementation that would help with achieving its sustainability goals. Of the six categories, the category of resiliency had the most actionable initiatives that would result in airport capital projects to protect against climate change, including purchasing and maintaining flood-proofing measures (Massport 2015).

While important efforts toward a more sustainable airport and global environment are being made, these efforts largely fall short of capital improvements to the airport infrastructure that would mitigate the effects of climate change.

Safety Management Systems

A safety management system (SMS) is a set of risk management practices and procedures used to ensure a formal approach to system safety. FAA Order 5200.11 spells out SMS standards used by the FAA to enable adaptation to changes and continuously improve airport safety

(FAA 2014d). There are four components to an SMS: safety policy, safety risk management (SRM), safety assurance, and safety promotion.

SRM is a formalized approach to making sound safety decisions. Based on well-documented data, SRM identifies and examines hazards early on and helps with developing effective risk-mitigation strategies. SRM applies to ARP-produced airport standards and project-specific approvals that could affect aviation safety. Chapter 4 of FAA Order 5200.11 outlines standards and approvals that are applicable by SRM (FAA 2014d).

Appendix C of FAA Order 5200.11 summarizes safety assessment tables by hazard severity classification, likelihood definitions, and a risk matrix. Appendix B of FAA Order 5200.11 summarizes airport project approvals that typically do not require safety assessments. Item 2 in this list includes “purchase of mobile vehicles and equipment,” both of which may be necessary purchases for preparing for and recovering from weather events (FAA 2014d). This list may need to be revisited to include other purchases to support resiliency for climate change.

While FAA regulations on SMSs had not yet been finalized at the time of its publication, *ACRP Report 131: A Guidebook for Safety Risk Management at Airports* (Neubauer et al. 2015) is a good primer on the treatment of safety risk. While the risks associated with BCAs and FFAs are programmatic and financial in nature, this guidebook on the treatment of physical risk provides an excellent introduction.

Conclusions

Airports do not have to start with a blank slate when beginning to plan and assess adaptations to climate change. Several key points to be drawn from the previous discussion are:

- The needs identified for 2017–2021 in the NPIAS do not currently reflect climate change, but it is acknowledged that the cost of climate change resilience is under development.
- Current guidance does not address climate change directly, but it can be modified or adapted to include capital investment projects for resiliency within the current framework.
- The NPR system could accommodate airport projects with a resilience component.
- Estimates for rehabilitation costs incurred and avoided could be calculated using the guidance listed in an airport emergency plan; these are important components of a BCA.
- A budget tracking system could be developed to help understand past emergency costs incurred; this would be helpful in the event of a future emergency.
- Per FAA NEPA guidance, climate change is one of the environmental impact categories. However, no thresholds for climate impacts have been confirmed. FAA recognizes guidance will change.
- Most initiatives within sustainability plans are geared toward reducing infrastructure’s impact on the environment, such as through carbon emissions, with a few projects contributing more directly to the effects of climate change on infrastructure.

Enterprise Risk Management

Larger airports may already take a structured approach to managing risk exposures. ERM is a formal, coordinated approach to identifying and evaluating risks across an entire organization. *ACRP Report 74: Application of Enterprise Risk Management at Airports* discusses the implementation of ERM processes relevant for airports, including the development and ongoing use of a “risk register” that captures and describes risks and opportunities as they are identified together with risk accountabilities, actions, and review and completion dates (Marsh Risk Consulting 2012). A central feature of the risk register is identifying the probability of adverse events and their potential financial consequences for the airport. ERM may be a logical approach to evaluate climate risks.

ACRP Report 116: Guidebook for Successfully Assessing and Managing Risks for Airport Capital and Maintenance Projects provides details on the creation and consistent updating of a risk register, the qualitative evaluation of risk (probability and impact), the quantification of risk probabilities, and appropriate responses (Price 2014). One of the main features of this report is a discussion of how airport personnel, including risk managers, may develop estimates of the costs of risky outcomes, which has direct application here in the context of financial feasibility and benefit–cost analyses. Finally, the report provides suggestions on scaling risk management efforts to the size of the project, with detailed quantification reserved for very large projects and lesser efforts for smaller ones. An overview of these topics is presented here, but interested readers should refer to these ACRP reports for more detailed information.

By analyzing potential risks and developing proactive response plans, an airport can use ERM to reduce volatility and protect its balance sheet from unexpected losses. While different airports will have different operating environments, governance structures, and organizational cultures, an ERM framework will contain certain common fundamental elements.

First, there should be clear guidance on governance and infrastructure. ERM policies should describe concisely why and how risk management will be implemented across the entire airport organization, and the ERM framework should include explicit consideration of the following items:

- Goals—for example, minimizing the likelihood and impact of risks occurring. (In the context of climate change, airports obviously cannot control the weather, but they may be able to mitigate the impacts.)
- Statement of how much risk the airport is willing to accept in different areas—for example, enable main passenger terminal to remain open in the event of a Category X hurricane, or enable the stormwater management system to withstand a 100-year flood event.
- Step-by-step description of the ERM process.
- Outline of roles and responsibilities.
- Description of performance monitoring—how the ERM framework will be monitored and evaluated.

Second, the ERM system should identify and prioritize risks and opportunities. The first step here should be to create and categorize a risk register, which is an inventory or list of all identified risks to the organization. For example, *ACRP Report 74* suggests the register might include the following categories:

- Strategic,
- Operational,
- Financial,
- Human capital,
- Safety,
- Legal/regulatory,
- Technology, and
- Hazards (Marsh Risk Consulting 2012).

Using this sample structure, climate change risks would likely fit into the hazards category (along with, for example, pandemics, terrorism, and fires/explosions) A good ERM system should be able to handle climate change risks within an existing framework.

Once the risks have been identified, each item should be assessed in terms of impact (often referred to in terms of "criticality") and likelihood (often referred to in terms of "vulnerability"). Exhibits A-6 and A-7 are reprinted from *ACRP Report 74* and show examples of risk assessment criteria for both impact and likelihood.

Level	Description	Financial Impact	Reputation
1	Nominal impact	<1% of budget	Public concern limited to a few complaints to the airport
2	Low	1% to 5% of budget	Minor adverse local/public/media attention and complaints
3	Moderate	5% to 10% of budget	Adverse long-term regional/short-term national media/public attention
4	High	10% to 15% of budget	Adverse long-term national media/public attention
5	Very high	>15% of budget	Prolonged internal, regional, and national condemnation

Source: *ACRP Report 74* (Marsh Risk Consulting 2012).

Exhibit A-6. Example impact assessment criteria.

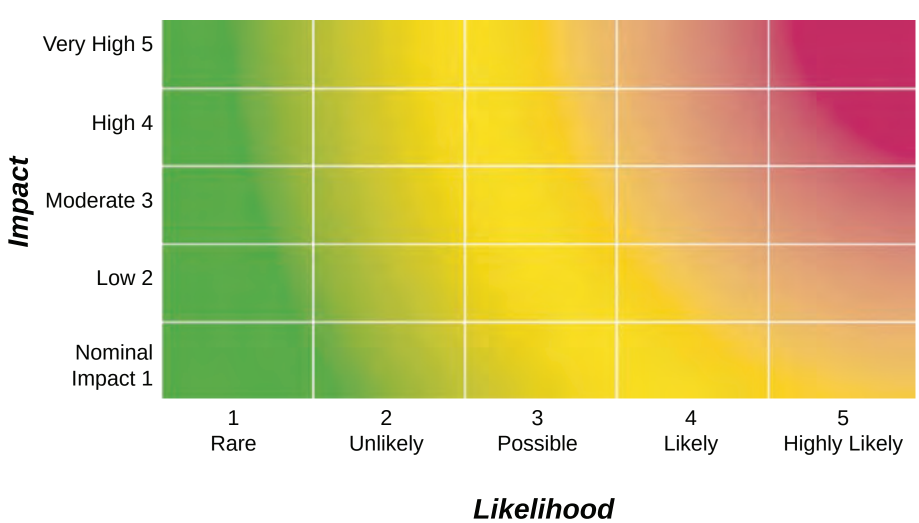
Level	Description	Frequency
1	Rare	< Once in 10 years
2	Unlikely	Once in 10 years
3	Possible	Once every 5 years
4	Likely	Once a year
5	Highly likely	> Once a month

Source: *ACRP Report 74* (Marsh Risk Consulting 2012).

Exhibit A-7. Example likelihood assessment criteria.

Impact and likelihood assessments can then be combined to generate a heat map, such as shown in Exhibit A-8, which visualizes the relative risks due to impact and likelihood and allows decision makers to prioritize them. This is a well-known method that the FAA has in many cases accepted for use—for example, in the SRM practices delineated in FAA Order 5200.11 (FAA 2014d).

For each identified risk, the ERM system should indicate how current measures are assessed to determine whether they effectively mitigate the risk to the required level. Focus then would be given to those risks that require additional controls or responses. As noted in *ACRP Report 74*, it is likely that not every risk can or should be mitigated (Marsh Risk Consulting 2012). Instead,



Source: *ACRP Report 74* (Marsh Risk Consulting 2012).

Exhibit A-8. Heat map example.

the benefits of mitigation (in the form of reduced impact or reduced likelihood) should be assessed against the costs, which may be substantial if, for example, a major upgrade or replacement of infrastructure is involved. Other sections of this handbook provide further discussion of this question, including how to assess costs and (in the case of a formal BCA) benefits and what other adaptation responses may be relevant for a given identified risk.

The ERM framework should also have a monitoring and reporting system in place, and a plan should be in place to guide implementation. Where possible, the framework should be aligned with existing airport processes, including strategic planning, budgeting, and safety management systems, to avoid duplication and maximize efficiency. Finally, the ERM framework should be reviewed periodically against defined performance metrics to ensure that current best practices are being followed and to update and improve as opportunities occur.

APPENDIX B

Other Climate Risk Evaluation Approaches

There are various alternative approaches that airports could consider to assess resilience to climate risks, but they all come with some important caveats. [Czajkowski (2016) outlines a few different risk modeling methods and describes some concerns with each method, finding that overall impacts are often still difficult to estimate and are poorly understood within the field of risk management.] One particularly important issue relates to indirect costs, which are often much more difficult to assess than the costs of physical damage, making overall risk evaluation a complex task involving substantial uncertainty (Litterman 2011).

There have been multiple studies on how behavioral heuristics can affect the way airport planners evaluate the risk to their airports from climate events. Most common of these behavioral heuristics are the availability heuristic, in which planners overestimate the likelihood of events that have taken place recently, and myopic planning, in which planners only pay attention to those risks that seem likely to happen in the near future. Other heuristics that may negatively influence understandings of risk are the way a risk is described (we evaluate more accurately when we understand a risk better), confirmation bias (stronger tendency to believe or work with facts that fit preexisting beliefs), and belief persistence (the difficulty involved in changing one's mind) (Czajkowski 2016; Morrow 2009).

As previously mentioned, many of the impacts of climate events are unknown, and often the same event can lead to a variety of different impacts depending on time and location. The wide variety of effects of a given climate event and the unknown future effects of climate change are two main causes of uncertainty within climate risk modeling.

Heathrow Airport developed and applied a comprehensive methodology to assess climate risks for specific airport assets (Heathrow Airport 2011b). This study considered assets owned by Heathrow Airport Limited and involved a comprehensive risk assessment of climate-related risks to the direct and indirect operations of Heathrow. The approach incorporated climate modeling, a literature review, and consultation with internal and external partners.

The International Civil Aviation Organization (ICAO) issued a report on climate risk that contained descriptions of climate change adaptation and resilience for both the aviation industry generally and for airports specifically (ICAO 2016). As part of the report, Norway's civil aviation authority described a systematic risk assessment, of all of its airports, that included connected navigation systems and surface access to the airports. A simplified version of the Heathrow methodology was used as a starting point (ICAO 2016).

A number of analysts have emphasized that risk analysis can and should be applied to more than just traditional physical infrastructure investments. For example, it has been suggested that society should invest in several different types of capital aside from physical infrastructure in order to become resilient, including financial capital (diversified income, secure wealth), human capital (workforce skills), social capital (effective governance), and natural capital (resilient land and water resources) (Michel-Kerjan 2015). A paper from the Wharton School at the University of Pennsylvania recommends that for each of these types of capital, a firm or government should evaluate the "four Rs": robustness, redundancy, resourcefulness, and rapidity (Wharton Risk Management and Decision Processes Center 2015).

APPENDIX C

Monte Carlo Simulation and Value-at-Risk Analysis

Chapter 2 provided an initial discussion of Monte Carlo simulation techniques and associated VaR analysis. Where appropriate, much of that material is repeated here, along with more detailed discussion, to ensure that a complete description of the techniques is accessible in one place.

Monte Carlo Analysis

In the context of climate change, the uncertainty surrounding future climate events can often be characterized in terms of the percentage chance (or probability) of an event occurring. For example, one may have estimates that there is currently a 2% probability of a significant flood event, and this percentage will increase evenly by 0.1% per year over the next 30 years. This is enough information to perform a Monte Carlo simulation. The basic idea would be to draw a random number (by convention, between 0 and 1) for each year, with the value determining whether a storm surge event occurs in that year based on its probability. For example, a random number between 0 and 0.02 would indicate that the flood event occurs, while any number drawn higher than that would indicate no flood event. After going through all 30 years, one would have completed one simulation showing a possible future path for such flood events. This process then could be repeated multiple times (drawing new random numbers each time), thereby generating many different simulations representing possible future events.

Another possibility is that, rather than having estimates of a percentage probability of a single event occurring, one instead has projections of, say, maximum daily temperatures from a number of different climate models. If temperatures exceed some threshold, flight departures at the airport may be disrupted for certain aircraft types given the length of the runway. Here the range of variation and uncertainty depends not only on which future year one is looking at, but also which model is being used. The idea in this case would be to sample from the different models, yielding projections of the number of days that exceed the temperature threshold. If there were 10 different models, then one could assign Model #1 to the interval 0.0–0.1 for sampling purposes, Model #2 to the interval 0.1–0.2, and so on. Again, by repeating the random draws many times, the result will be multiple iterations that show many possible future outcomes for the number of times that daily high temperature exceeds the threshold.

But how does this all fit into a BCA or FFA? Consider the following simplified example: suppose an airport is considering building a runway extension to handle the extra takeoff length required on days when the temperature exceeds 110°F. As with any BCA, the goal is to evaluate the present value of benefits and costs over time. Presumably, the costs of the runway extension can be accurately projected (say $X) based on construction and maintenance estimates.

The harder part is to identify and quantify the benefits. For simplicity, suppose that without the runway extension, carriers will experience schedule delays or weight restrictions estimated to cost $Y per day if the temperature exceeds 110°F. With the extension, flights can operate normally without any service disruptions.

The suggested approach would be to run Monte Carlo simulations of the maximum daily temperature projections from the different available climate models. Suppose the analyst decides to do 5,000 simulations over a 30-year analysis period. So for Simulation #1, it may turn out that the Year 1 projection is for 5 days in excess of 110°F; in Year 2, there are 12 such days, and so on. After going through all 30 years, one can then compute the base-case damages that would occur without the project; the scenario damages (if any) that would occur with the project; and the construction, maintenance, and operation costs of the project. From these numbers, one can also compute the NPV of the project and a benefit–cost ratio.

The entire process would be repeated 5,000 times,[18] each time generating a new set of results that will vary depending on the number and timing of high-temperature days in the future. Some of the runs will have much lower than average high-temperature days; others will be just the opposite. But collectively, the results should accurately reflect the range and likelihood of high temperatures as projected across all the different climate models.

One could then compute a mean value and standard deviation across the 5,000 NPVs or benefit–cost ratios. This is valuable information for decision makers and provides estimates of not only the average expected NPV or benefit–cost ratio but also the likely range of outcomes as measured by the standard deviation.

Note that the Monte Carlo simulation approach could be used just as well in a financial feasibility study, the only difference being the inclusion or exclusion of certain benefits or costs, depending on whether they accrue to the airport itself. (This topic is discussed further in Chapter 7.)

At this point, it is important to note that using a probabilistic benefits approach as described here is not the method that the FAA is accustomed to when assessing requests for AIP funding. Rather, as noted in *ACRP Synthesis 13*, its general approach is that a benefit either will or will not be realized with certainty, and therefore will or will not be included in a BCA (Landau and Weisbrod 2009). However, as was shown previously, there are cases where the FAA accepts BCAs where benefits are estimated over multiple scenarios reflecting different assumptions about uncertain future events.

Moreover, the FAA's BCA guidance document explicitly addresses the issue of uncertainty and suggests that Monte Carlo methods (what it calls probabilistic or stochastic models) may be used to "generate quickly hundreds or thousands of scenarios based on the specified probability distributions of uncertain variables" (FAA 1999b, p. 89).

In essence, the Monte Carlo simulation approach described here is a formal method for considering multiple scenarios; it can be thought of as a robust way of handling uncertainty about future events that may or may not occur. Given the uncertainty inherent in long-term climate predictions and the fact that when a given climate event will occur is likely to be highly uncertain, a probabilistic approach really is the only reasonable and valid way to account for climate risks. No single, certain alternative provides a realistic estimate of the likely benefits from an investment designed to enhance climate resilience.

Value at Risk

As a natural extension, one can also use the results from the simulations to look at VaR, which is a concept that originated in the financial industry in the late 1980s. The idea was to estimate the likelihood of a financial firm's maximum loss during a relatively short period of time. Because these financial institutions managed large and highly diverse portfolios, it was often difficult to fully understand all of the risks they were exposed to.

A sample VaR for the portfolio of a large financial institution might show that it has a 1% chance of losing $100 million or more in a day given its portfolio and the historic price movements in the underlying individual stocks and bonds. In conventional usage, one would say that the company's 1% VaR is $100 million. This is a useful metric because it gives managers and regulators a way to assess how much capital a firm should have on hand to cover maximum daily losses. The Securities and Exchange Commission instituted capital requirements for financial firms in 1980 sufficient to cover, with 95% confidence, the losses that might be incurred during the time it would take to liquidate a securities firm (30 days) (Holton 2002).

One important difference between VaR as applied to climate risk and that applied to conventional financial risk is that the relevant time periods involving climate change are decades long. However, the information VaR provides to managers is similar: it provides a means for deciding how much risk the enterprise is willing to accept, in this case through the distribution of potential losses from climate change.

In the present context, the output from a Monte Carlo BCA can be transformed into a VaR analysis in a straightforward way. Recall from earlier discussion that a traditional BCA compares benefits of the project (measured as the discounted present value of the dollar reduction in damages) to the costs of the mitigation project (including construction, maintenance, and operation). For purposes of a VaR analysis, rather than focusing on the benefit–cost ratio of a project, one can look at the results in a slightly different way and consider the net impacts for both the base case and the scenario.

For the base case, net impacts are simply the present value of the dollar damages incurred if the project is not undertaken. For the scenario, net impacts are the present value of the remaining damages not mitigated by the project plus the present value of the investment costs (including construction, maintenance, and any other relevant costs) for the project. For VaR purposes, each of these impacts will be represented as negative dollar quantities.

One could then plot these two quantities on a graph; if the scenario value is more negative than the base-case value, this indicates that the project did not pay off. This would be repeated for each Monte Carlo simulation, resulting in a new pair of net impacts under the base case and scenario. To assess these results across all the simulations, they can be sorted based on the difference between the two values and then plotted along a percentage scale. The result is a VaR graph such as the one shown in Exhibit C-1.

Based on the varying benefit results from the Monte Carlo simulations, the blue line in the chart shows that if the airport does nothing, it faces a 10% chance of incurring damages (in the form of delay costs) of at least around $25 million (where the blue line passes the 10% point on the horizontal axis) and could incur damages of more than $50 million. On the other hand, if it does undertake the mitigation project, it must pay the investment costs and incur any remaining delay impacts; these two factors combined could total as much as about $30 million (left extremity of chart for the red line). But also note that the range of potential net impacts is much larger under the baseline case (from about $5 million–$50 million in damages) than under the scenario case ($10 million–$30 million in damages and project costs). The chart also shows that there is about a 50% chance that the NPV of the project would be positive (indicated by the point at which the two curves intersect).

It is important to properly interpret the meaning of these results. Facing a 10% chance of incurring damages of at least $25 million means that in 10% of the simulations, the present value of damages was $25 million or worse. Remembering that each simulation represents a set of future outcomes running from 2020 through 2090, these will include many different specific outcomes that vary across the years. In some simulations, there may be a small number of unusually hot years early on, resulting in a few highly valued delays (because they are discounted less when occurring early). In many others, the high temperatures will have been estimated to occur in later years, but they are likely to occur more often, resulting in more lower-valued

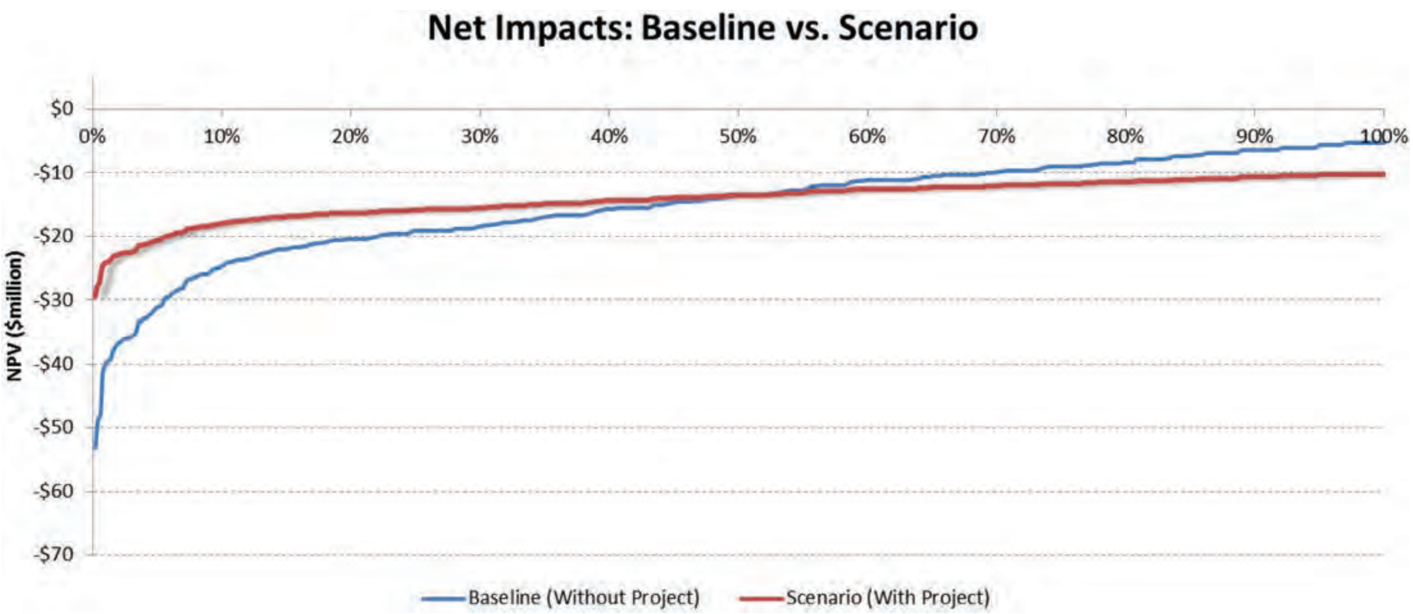


Exhibit C-1. Value-at-risk comparison.

delays. So it is important to recognize that the 10% chance of damages includes many different potential outcomes; it does not refer to an annual probability of occurrence, but rather the overall likelihood (over the entire analysis period) that the airport's users would face $25 million or more of delay costs (in present value terms) under the base case.

This provides a different perspective from simply focusing on the average NPV or average benefit–cost ratio from the simulations. The airport can use the results to help it decide between the risky, but higher potential payoff of doing nothing, and the certain cost of investing in the mitigation project that reduces but does not completely eliminate its exposure. If desired, the results could also be displayed in alternate ways—for example, by highlighting the worst or best possible results (shown at the extreme left or right for the baseline and scenario cases in Exhibit C-1), or by presenting results for every decile (e.g., the benefit–cost ratio at 10% likelihood, 20% likelihood, and so on).

Outside Examples

Several examples exist of using VaR as a means to assess the global impacts of climate risk. One analysis estimates that the expected "climate value at risk" of global financial assets today is 1.8%, assuming a "business-as-usual" global emissions path (Dietz 2016). Taking a representative estimate of global financial assets, this amounts to around $2.5 trillion. Using a similar methodology, the Economist Intelligence Unit (2015) estimates that expected climate VaR would be about $7 trillion, assuming private investor discount rates, but $43 trillion using lower government discount rates.

There also have been various studies of VaR applied to specific assets and locations. One such study described the use of VaR to test the viability of drought derivatives or hedges that had been proposed for financial markets as a means for farmers (and others) to offset some of the risks of climate change in Switzerland (Torriani 2008). Another developed climate VaR estimates with respect to the production and income for coffee production in Veracruz, Mexico (Estrada et al. 2012). Finally, a VaR analysis was used as part of a risk assessment of sea level rise due to climate change for 19 large European coastal cities (Abadie et al. 2016).

APPENDIX D

Accessing Available Climate Projections

CMIP climate projections have been published and periodically updated over the past several years. Many of the projections are available on an annual or even daily basis for many years into the future. The U.S. DOT has developed the CMIP Climate Data Processing Tool, which can process climate model outputs from CMIP3 and CMIP5 into relevant statistics for transportation planners. (The tool and user guide can be downloaded at https://www.fhwa.dot.gov/environment/?sustainability/resilience/adaptation_framework/modules/?index.cfm?moduleid=4#tools.) Specifically, the tool is designed to analyze data that can be downloaded from the U.S. Bureau of Reclamation's downscaled CMIP3 and CMIP5 Climate and Hydrology Projections website (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections).

Readers who are considering doing their own in-house data gathering and analysis could download this tool and access the website as directed in the user guide in order to access relevant climate data for their given airport location. The user guide provides step-by-step instructions for downloading, processing, and interpreting available climate projections. Both CMIP3 and CMIP5 can provide daily projections of a variety of climate measures, including minimum and maximum surface air temperatures, precipitation rates (mm/day), and humidity, and both provide projections that have been downscaled to a spatial resolution of 1/8 degree (which in the continental United States translates to a rectangular cell grid approximately 7.5 miles on each side).

While the more recent CMIP5 projections have not been tested as thoroughly as CMIP3, CMIP5 is widely considered to be the best available science presently, and it has two key advantages. First, it provides continuous daily projections from the present out to 2099, compared to CMIP3, which has projections only for the years 2046–2065 and 2081–2099. Second, some of the CMIP5 data have been further downscaled to a finer resolution in order to provide better risk exposure estimates in a localized area.

LOCA is a statistical downscaling technique that uses history to add improved fine-scale detail to global climate models. LOCA has been applied to 32 global climate models under Scenarios RCP4.5 and RCP8.5 from the CMIP5 archive; it currently provides estimates of maximum daily temperature and daily precipitation at a spatial resolution of 1/16th degree (a rectangular area of less than 4 miles on each side), covering North America from central Mexico through Southern Canada.[19] Aside from the finer resolution, the LOCA technique is thought to result in better estimates of extreme climate days, particularly estimates of precipitation. The LOCA website has links to download sites containing the latest LOCA data.

It is important to note that the ACROS high-temperature projections described in Chapter 3 (suggested for use in an initial screening analysis) were prepared before LOCA-based data became available, so the projections may differ. Thus, one must be cautious if trying to compare the ACROS projections of high temperatures to the projections described here.

Data Collection Strategies for High Temperatures

One of the primary objectives of this handbook is to present a methodology for evaluating the increasing occurrence of high temperatures that may force airlines to impose weight restrictions on takeoffs (or in extreme cases, cancel flights entirely). It is currently possible to obtain LOCA-based high-temperature projections at specific locations across the United States out to the year 2099.

Exactly how much data needs to be collected will vary. For purposes of analyzing the impact of high temperatures on takeoffs, the projection of daily maximums is important because each day that temperatures exceed some threshold value may necessitate a weight restriction. In addition, there are three other factors that will affect the actual data collection:

- Selection of nearby geographical grid points relevant for the airport: Climate science best practices suggest use of at least four adjacent LOCA-based grid points near the airport.
- Relevant time horizon: It may be sufficient to focus on a time horizon that goes to the end of the expected life of an airport's runway(s); however, the analyst may also wish to consider longer time frames to get a more general view of the potential long-term effects of increasing temperatures.
- Number of climate models: Unless specific information dictates otherwise, it is suggested that projections be obtained from all 32 available climate models. As noted in Chapter 4, each model makes individual point predictions, and it is the variation in the predictions across the different models for a given scenario and future date that reveals the uncertainty in those projections.

As an example, if data projections for 2020 through 2099 were obtained from all 32 models for four grid points, the total number of high-temperature observations would be 365 days × 80 years × 4 grid points × 32 models = 3,737,600. While this is a large number, it could be reduced significantly by grouping the actual maximum temperatures into a small number of categories that represent the *count* of the number of times in a given year that the high temperature is at the indicated level. Thus, the data could be organized to look something like what is shown in Exhibit D-1.

MODEL	YEAR	GRID_ID	H100	H102	H104	H106	H108	H110	H112	H114	H116	H118	H120	H122	H124	H126	H128
ACCESS1-0	2020	1	15	16	13	22	29	15	18	1	0	0	0	0	0	0	0
ACCESS1-0	2020	2	18	13	13	23	27	22	13	4	0	0	0	0	0	0	0
ACCESS1-0	2020	3	16	16	12	22	25	19	19	1	0	0	0	0	0	0	0
ACCESS1-0	2020	4	16	14	16	21	28	18	15	2	0	0	0	0	0	0	0
ACCESS1-0	2021	1	24	21	15	21	19	11	7	3	2	0	0	0	0	0	0
ACCESS1-0	2021	2	30	18	18	18	20	12	9	2	2	0	0	0	0	0	0
ACCESS1-0	2021	3	25	16	15	22	21	11	8	3	2	0	0	0	0	0	0
ACCESS1-0	2021	4	32	20	16	20	18	11	8	1	2	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ACCESS1-0	2090	1	7	13	13	7	18	25	28	31	15	5	1	1	1	0	0
ACCESS1-0	2090	2	8	9	14	11	14	24	32	32	13	6	2	2	0	0	0
ACCESS1-0	2090	3	8	11	10	11	17	22	30	32	15	6	1	1	1	0	0
ACCESS1-0	2090	4	11	8	14	8	20	26	32	32	8	6	1	2	0	0	0
ACCESS1-3	2020	1	19	33	32	18	7	10	6	0	0	0	0	0	0	0	0
ACCESS1-3	2020	2	22	32	39	13	10	9	6	1	0	0	0	0	0	0	0
ACCESS1-3	2020	3	20	34	34	15	10	11	5	0	0	0	0	0	0	0	0
ACCESS1-3	2020	4	21	37	37	12	9	11	3	0	0	0	0	0	0	0	0
ACCESS1-3	2021	1	9	22	27	26	19	14	5	2	0	0	0	0	0	0	0
ACCESS1-3	2021	2	14	16	33	22	19	18	5	2	0	0	0	0	0	0	0
ACCESS1-3	2021	3	9	17	29	27	18	14	8	2	0	0	0	0	0	0	0
ACCESS1-3	2021	4	15	20	28	25	18	17	3	2	0	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ACCESS1-3	2090	1	12	15	20	20	37	33	19	15	5	3	1	0	0	0	0
ACCESS1-3	2090	2	12	14	16	23	35	32	30	13	5	1	2	0	0	0	0
ACCESS1-3	2090	3	11	15	18	24	34	35	22	12	6	3	1	0	0	0	0
ACCESS1-3	2090	4	13	16	16	25	34	40	18	12	5	1	2	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Exhibit D-1. High-temperature data.

Each row represents a unique model/year/grid-point combination, and the "H" columns represent counts of annual days at or above the indicated (Fahrenheit) temperature but below the next column's temperature. For example, the row for the model named ACCESS1-0/Year 2020/Grid_ID 4 projects that there will be 16 days with daily high temperatures between 100°F–102°F, 14 days between 102°F–104°F, and so forth. Summarizing the data in these 2-degree increments between 100 and 128 drastically cuts down on the number of total data points but still retains a full range of high temperatures that should be relevant for purposes of estimating weight restrictions at airports across the entire United States.[20]

This specific data organization is used directly in the Excel-based high-temperature template that was developed as part of this project and is described in detail in Appendix E. One could use such a data set as part of a Monte Carlo simulation analysis (discussed in Appendix C) that would reflect the uncertainty of the incidence of high temperatures projected across the different climate models.

Check for Potential Bias Correction

It is important to recognize that a given model's historical accuracy for a specific location may be systematically off (i.e., biased) even though the model does well overall. In this case, climate science best practices suggest that one should test to see whether some sort of bias correction is needed before sampling from the available model projections. For daily maximum temperature, for example, while one would not expect the daily projections from a GCM model to match actual daily temperatures, one would want to check for any systematic differences in the range or distribution of such temperatures over a representative time period—say, 10 to 20 years.

So one could gather actual historical data of daily maximum temperatures for the location of interest over, say, 20 years, plus corresponding projected temperatures from a given model. One approach that has been used in the climate science field is to order both sets of data from low to high, place them into 20 5-percentile bins, and then compute the mean of each bin. The absolute difference between the model mean and the observed historical mean in each corresponding bin (measured in degrees) could then be used as a bias correction factor for the model; this would account for any systematic variations in both the distribution and range (spread) of temperatures. In practice, however, one would also have to account for the likelihood that the overall temperature range itself could rise over the very long term. One way to implement the correction factors in such a situation would be to separate the relevant future years into successive 20-year cohorts (to match the length of the historical test period), compute 5-percentile bins for each, and then apply the relevant bias correction factor to the projections in each bin.

Sampling and Weighting Strategies

Depending on the nature of the available data projections, there are different sampling strategies one could use. For the present case where there are multiple models providing different projections of future high temperatures, one could randomly select a single model for each separate simulation and use its projections for every year out to the end of the analysis period. This approach essentially assumes that the number of unique possible future outcomes is limited to the number of different models available. If one is drawing from a large number of models, then this may well be a reasonable strategy. However, if the collection of models includes some that are considered outliers (i.e., very different from other models), then it also means that the range of results may be quite sensitive to these outlier models.

To dampen the influence of such models yet not exclude them completely, another possibility would be to randomly select (for each simulation) a model for each year of the analysis period. This will tend to reduce the influence of outlier models because it is unlikely they would be randomly selected year after year within a given simulation draw; at the same time, this will also likely increase the year-to-year variability within a simulation since the draws are coming from different models.

A third possibility would be to combine the projections across models to compute a multi-model mean and fit a statistical distribution from which one could take simulation draws. One issue here is that the mean is likely changing over time (as temperatures increase), so one could in principle fit a separate distribution for each year. Short of that, one could aggregate over, say, each 10-year period and fit a single distribution for each decade to cut down on the computational burden (see, for example, Coffel et al. 2017).

Whichever sampling strategy is chosen, one might also want to consider implementing a weighting strategy so that better models are given more weight (and therefore a higher probability of being sampled) than lesser ones. Sanderson et al. (2016) provide a weighting assessment for the 32 climate models mentioned previously; a modified version of these weights is used in the numerical examples provided in Appendix F, as well as in the Excel-based template for high temperatures.

Data for Sea Level Rise

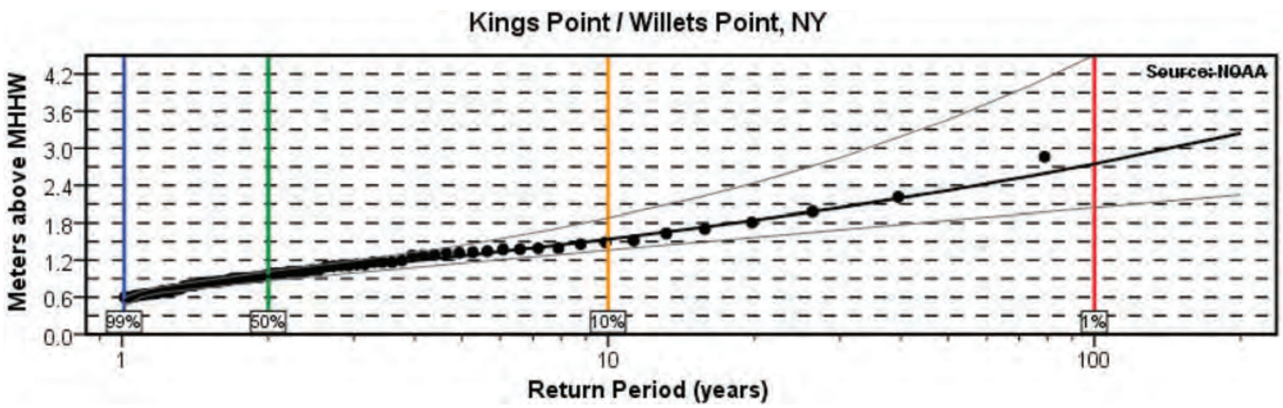
CMIP5 projections also are available for sea level rise. But the nature of the projections is very different than the daily high temperatures from multiple models discussed previously. Specifically, further analysis is required to translate projections into the likelihood of flooding risks at specific locations. One can combine estimates of the likelihood of extreme water events based on historical data with estimates of future sea level rise in order to obtain projections of future extreme water events.

Fortunately, analyses published by NOAA are directly relevant and can be used for these purposes. First, NOAA has undertaken an extensive analysis of historical extreme water levels (EWLs) in the United States at 112 long-term stations of the National Water Level Observation Network operated by the Center for Operational Oceanographic Products and Services (CO-OPS) (Zervas 2013). The data are analyzed to quantify probabilities of exceedance and the return periods (average length of time between exceedances of a given water level). NOAA uses a statistical model to characterize the distribution of EWL values, resulting in the estimation of an "exceedance probability curve" as a function of the return period (Zervas 2013).

For example, the exceedance probability curve for the station at Kings Point/Willets Point in New York is shown in Exhibit D-2. This is the station closest to LaGuardia Airport, which is about 6 miles to the southwest.

Reading off the graph at, say, the 10-year return period shows a water level of about 1.5 meters. This means that, based on the historical data, this location would expect an extreme water event of at least 1.5 meters approximately every 10 years; the 10-year return period translates into a 10% probability on an annual basis. It is important to note that the water level is relative to the mean higher high water (MHHW) vertical datum established by CO-OPS, which is the average height of the diurnal high tide recorded at the station each day.[21]

There are three parameters used to define the curve for each station; these parameters are contained in Appendix I, Table A of the Zervas report. Following Gilleland and Katz (2016), the specific formula[22] for finding the extreme water level is given as a function of these parameters



Source: Zervas 2013.

Exhibit D-2. Exceedance probability curve for Kings Point/Willets Point, NY.

plus the desired annual probability of occurrence. For example, using the parameters for Kings Point/Willets Point and setting p = 0.10 (implying a return period of 10 years) gives a result of 1.539, which is exactly consistent with what is shown graphically in Exhibit D-2.

Note that the exceedance curve provides exactly the type of information needed to conduct a Monte Carlo simulation of annual water levels. For example, if one were considering a time period of, say, 50 years, for each year a random number could be drawn between 0 and 1 representing the annual probability of occurrence, and then the implied extreme water level could be computed from the curve. In accordance with the curve, in many years there would be relatively low water levels (around 1 meter), while in other years there might be higher levels (up to about 3 meters at the extreme).

As described, the estimated exceedance curve for each location is based entirely on historical data. But sea levels generally are expected to rise in the future, which presumably would affect these local flood events. To address this, NOAA has also modeled projected changes in local sea level rise (Sweet et al. 2017). An accompanying data file shows projections for almost 2,000 different coastal locations worldwide.[23] There are six different scenarios considered for future sea level change, identified by the overall projected global mean sea level (GMSL) rise by 2100:

- Low (GMSL = 0.3 meters),
- Intermediate-low (0.5 meters),
- Intermediate (1.0 meters),
- Intermediate-high (1.5 meters),
- High (2.0 meters), and
- Extreme (2.5 meters).

Local projections are given at 10-year intervals out to 2100 for each scenario. For example, the projected RSL rise for Willets Point in New York is shown in Exhibit D-3.[24]

How likely is each of these scenarios? Recalling the earlier discussion of RCP global climate scenarios, these GMSL scenarios have been estimated to have the exceedance probabilities under three of the four available RCP scenarios (as shown in Exhibit D-4).[25] Thus one can select an RCP scenario and match the listed probabilities to the local RSL projections shown in Exhibit D-3. For example, under RCP8.5, the intermediate GMSL (or higher) scenario is estimated to occur 17% of the time.

Increases in local sea level will shift extreme water levels upward by the same amount, assuming no change in local tidal magnitudes in the future. Under this assumption, if the intermediate

GMSL Scenario	RSL in 2020 (cm)	RSL in 2030 (cm)	RSL in 2040 (cm)	RSL in 2050 (cm)	RSL in 2060 (cm)	RSL in 2070 (cm)	RSL in 2080 (cm)	RSL in 2090 (cm)	RSL in 2100 (cm)
Low	5	9	14	19	24	29	32	36	38
Intermediate-low	6	12	18	24	31	37	42	47	51
Intermediate	9	19	29	41	54	69	85	102	118
Intermediate-high	12	26	40	57	77	100	126	153	182
High	16	32	52	77	108	139	173	217	262
Extreme	14	35	61	90	129	169	215	270	326

Source: Sweet et al. 2017.

Exhibit D-3. Projected RSL rise for Willets Point, NY.

GMSL rise Scenario	RCP2.6	RCP4.5	RCP8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

Source: Sweet et al. 2017, Table 4.

Exhibit D-4. GMSL scenario probabilities.

GMSL rise scenario were to occur, then in 2050, the local relative sea level rise for Willets Point would be projected as 41 cm (from Exhibit D-3), and one could then add this increment directly to whatever extreme water level projection were shown from the curve in Exhibit D-2.[26]

As suggested earlier, the nature of the uncertainty associated with these projected flood events is different from the uncertainty related to the high temperature projections described previously. The latter's uncertainty comes directly from the variance in 32 different climate models' projections of daily high temperatures. In contrast, the uncertainty in the sea level rise projections comes from probabilistic estimates of extreme water events as reflected in exceedance probability curves combined with six different projections of the likelihood of localized sea level rise.

The specific methodology outlined previously for estimating future localized flood risks was implemented in the Excel-based extreme water template developed as part of this project. As described in Appendix C, one can make random draws as part of a Monte Carlo simulation that will reflect the uncertainty of the incidence of future extreme water events implied by the exceedance probability curves combined with projected future sea level rise.

Finally, it is important to note that, while the ACROS SLR projections described in Chapter 3 (suggested for use in an initial screening analysis) assume RCP8.5, they are in fact based on older projections than the more up-to-date 2017 NOAA estimates cited previously. Thus, one must be cautious if trying to compare the ACROS projections of SLR to the projections described here.

APPENDIX E

Microsoft Excel Templates

The project team constructed Microsoft Excel–based simulation templates that can be used by individual airport personnel to conduct their own Monte Carlo–based BCAs of climate change. The team developed two separate templates: one for sea level rise, and one for high temperatures. The scope and availability of localized data are different between the two, as are the implications of unknown future climate change; each is discussed in the following. The Excel templates may be found by searching for "*ACRP Research Report 199*" at www.TRB.org.

Template for RSL Rise

The Excel template for potential climate change events reflecting sea level rise includes localized historical estimates of the likelihood of EWL events plus projections of RSL for U.S. coastal areas that are near 153 different airports. Both the historical and projected estimates are based on published analyses from NOAA.

The template file is composed of four separate Excel sheets:

- Overview. This sheet provides a quick-start section plus a high-level overview of how the model embedded in the template works.
- Data Tables. This sheet contains all of the base input data collected from NOAA, plus information about each of the 153 airports.
- User Selections. This sheet is where the user can select the airport of interest and enter various assumptions regarding the global emissions scenario to be used, the costs that would be incurred for a specific mitigation investment, and the dollar damages that would be incurred both with and without the investment.
- Results. This sheet presents the results of 5,000 Monte Carlo simulations based on the user selections.

Data Tables

At the outset, it is important to note that the user does not have to input any information in the Data Tables sheet and may skip directly to the User Selections sheet if desired. However, the Data Tables sheet does contain critical inputs that are needed for analysis.

The first part of the Data Tables sheet contains information on the 153 airports. For each airport, the nearest EWL and RSL stations are identified along with their distances from the airport. The relevant data for a partial sample of the airports are shown in Exhibit E-1.

This is followed by a table showing relevant data for the EWL stations, including the estimated parameters that are used to produce historical exceedance probabilities of extreme

REGION	LOCID	CITY	STATE	NLAT	NLONG	ELEVATION	EWLID	EWLDIST	RSLID	RSLDIST
SO	JKA	GULF SHORES	AL	30.28964	-87.67178	17.1	8735180	24.20	1005952725	17.77
WP	NTD	POINT MUGU	CA	34.11927	-119.11958	13.0	9411270	24.30	1013	24.26
WP	OAK	OAKLAND	CA	37.71869	-122.22166	9.4	9414750	5.56	437	5.55
WP	PAO	PALO ALTO	CA	37.46111	-122.11506	6.8	9414750	23.68	1005252375	21.26
WP	SAN	SAN DIEGO	CA	32.73356	-117.18967	16.8	9410170	1.72	158	1.99
WP	SBA	SANTA BARBARA	CA	34.42619	-119.84149	13.4	9411270	23.34	2126	8.70
WP	SFO	SAN FRANCISCO INTERNATIONAL AIRPORT	CA	37.61881	-122.37542	13.1	9414750	11.39	1005252375	10.67
NE	BDR	BRIDGEPORT	CT	41.16347	-73.12617	8.5	8467150	2.98	1068	2.83
NE	GON	GROTON	CT	41.33006	-72.04514	9.1	8461490	2.77	429	3.11
SO	APF	NAPLES	FL	26.15244	-81.77564	8.2	8725110	2.49	1107	2.63

Exhibit E-1. SLR template airport data.

water events at the indicated location. A sample is shown in Exhibit E-2. For those interested, details on exactly how the probabilities are calculated using these parameters are discussed in Appendix D.

The next table lists the GMSL rise scenario probabilities estimated for three of the four latest emissions scenarios currently used by climate scientists. This table is reproduced as Exhibit E-3.

As described earlier, after the user selects one of the emissions scenarios, the Excel model will generate random draws by interpolating between the GMSL rise scenarios. Combining random draws from the EWL probabilities with those from the GMSL rise scenarios results in probabilistic localized projections of the height of future EWL events.

STATION	NAME	STATE	NLAT	NLONG	LOC	SCALE	SHAPE
8410140	EASTPORT	MAINE	44.903	-66.985	1.044	0.094	0.000
8413320	BAR HARBOR	MAINE	44.392	-68.205	0.754	0.092	-0.008
8418150	PORTLAND	MAINE	43.657	-70.247	0.714	0.103	0.038
8419870	SEAVEY ISLAND	MAINE	43.080	-70.742	0.637	0.120	-0.035
8443970	BOSTON	MASSACHUSETTS	42.355	-71.052	0.764	0.133	0.019
8447930	WOODS HOLE	MASSACHUSETTS	41.523	-70.672	0.565	0.161	0.240
8449130	NANTUCKET ISLAND	MASSACHUSETTS	41.285	-70.097	0.504	0.125	0.052
8452660	NEWPORT	RHODE ISLAND	41.505	-71.327	0.582	0.131	0.290
8454000	PROVIDENCE	RHODE ISLAND	41.807	-71.402	0.720	0.190	0.323
8461490	NEW LONDON	CONNECTICUT	41.355	-72.087	0.618	0.188	0.158

Source: https://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_067a.pdf.

Exhibit E-2. Historical EWL parameters.

GMSL Rise Scenario	2.6	4.5	8.5
0.3 Low	94.00%	98.00%	100.00%
0.5 Intermediate-Low	49.00%	73.00%	96.00%
1.0 Intermediate	2.00%	3.00%	17.00%
1.5 Intermediate-High	0.40%	0.50%	1.30%
2.0 High	0.10%	0.10%	0.30%
2.5 Extreme	0.05%	0.05%	0.10%

Source: https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

Exhibit E-3. GMSL scenario probabilities.

Finally, there is a data table of the localized RSL rise projections. A sample is shown in Exhibit E-4; these projections are given in centimeters. The decadal projections go out to 2100 (and beyond) even though the exhibit only shows the results to 2060. Note that there are six different projections for each site, corresponding to the GMSL rise scenarios shown in Exhibit E-3.

User Selections

On the User Selections sheet, the user selects the airport of interest, an emissions scenario, the costs of a possible mitigation project, and the dollar damages incurred by different-sized flooding events with and without the project.

An example of the top of the sheet is shown in Exhibit E-5. After selecting a specific airport in the indicated cell, the sheet will show the published elevation of the airport and its lowest runway relative to MSL and MHHW. It is important to emphasize that all of the results shown in the file are relative to MHHW (see the discussion in Appendix D for more information). Information about the closest EWL and RSL stations is presented, and the user can click to see a map of their locations relative to the airport. Implied water levels of 1-, 10-, 50-, and 100-year events based on historical data are also shown.

It is important to note that the EWL and RSL stations used as data points do not necessarily coincide exactly with the airport locations. Thus, users should review the distances and inspect the available map to assess whether the data collected from the listed stations can reasonably be used to project extreme water events at the airport being analyzed.

The user also selects the emissions scenario to be used. As seen in Exhibit E-5, explanatory text is provided to help the user understand the possible scenario selections. For presentation purposes here, New Orleans (MSY) airport is selected for analysis.

The second part of the User Selections sheet, shown in Exhibit E-6, allows the user to enter assumptions about the mitigation project, costs, and potential damage impacts from flooding. The user can specify the time horizon for the analysis, discount rate, and construction, maintenance, and rehab costs for the mitigation project. Damage costs are also entered here; by design, these are specified generically as dollars per event for different-sized flooding events. Note that it is quite possible that the proposed project may offer only partial protection against flooding; this can be analyzed by entering non-zero damage amounts in the "With Project" column.

Again, explanatory text is provided to help the user with the various options.

SITE	PSMSL_ID	NLAT	NLONG	SCENARIO	RSL2000	RSL2010	RSL2020	RSL2030	RSL2040	RSL2050	RSL2060
SAN FRANCISCO	10	37.81	-122.47	0.3 - MED	0	3	6	10	13	17	21
SAN FRANCISCO	10	37.81	-122.47	0.5 - MED	0	3	8	12	17	22	28
SAN FRANCISCO	10	37.81	-122.47	1.0 - MED	0	5	10	17	25	36	47
SAN FRANCISCO	10	37.81	-122.47	1.5 - MED	0	7	13	22	34	51	69
SAN FRANCISCO	10	37.81	-122.47	2.0 - MED	0	8	16	28	46	70	97
SAN FRANCISCO	10	37.81	-122.47	2.5 - MED	0	8	18	32	54	83	118
NEW YORK	12	40.70	-74.01	0.3 - MED	0	5	11	15	20	25	31
NEW YORK	12	40.70	-74.01	0.5 - MED	0	6	13	19	25	31	39
NEW YORK	12	40.70	-74.01	1.0 - MED	0	9	19	29	39	51	65
NEW YORK	12	40.70	-74.01	1.5 - MED	0	12	25	39	53	71	92
NEW YORK	12	40.70	-74.01	2.0 - MED	0	14	31	48	67	92	124
NEW YORK	12	40.70	-74.01	2.5 - MED	0	14	29	50	76	105	144

Exhibit E-4. Projected RSL data.

User should select or enter values in blue shaded boxes only							
State_Locid	LA_MSY						
Name	LOUIS ARMSTRONG NEW ORLEANS INTERNATIONAL						
	Relative to MSL	*Relative to MHHW*					
Airport Elevation (ft)	3.7	3.2					
Lowest Runway Elevation (ft)	-2.4	-2.9					
Historical extreme water levels (EWL) based on:			*EWL Curve Parameters*			*Implied Water Levels above MHHW baseline based on historical data (ft)*	
EWL_Station	GRAND ISLE		Location	0.433		100-yr event	6.33
EWL_Distance (miles)	53.58		Scale	0.168		50-yr event	5.16
			Shape	0.261		10-yr event	3.11
						1.01-yr event	0.73
Projected relative sea levels (RSL) based on:							
RSL_Station	grid_29.5_269.5		Click here for map				
RSL_Distance (miles)	37.00						
RCP_Scenario	8.5		RCP stands for Representative Concentration Pathway:				
			There are 4 different RCP scenarios, each with different assumptions about the future path of global emissions reductions.				
			Sea level rise projections for 3 of the 4 scenarios are available for this ACRP project analysis of extreme water levels.				
			RCP 2.6 represents a "low emissions" scenario where significant global efforts are made to curb emissions.				
			RCP 8.5 represents a "high emissions" scenario and assumes little or no successful global efforts to mitigate greenhouse gases.				
			RCP 4.5 represents an intermediate case.				

Exhibit E-5. RSL user selections 1.

		Notes
Analysis_Start_Yr	2020	Discounted benefit-cost calculations reflect time horizon between Analysis_Start_Yr and Analysis_End_Yr
Analysis_End_Yr	2099	Maximum time horizon is 2020 - 2099.
Discount_Rate	3.0%	Traditional FAA guidance (based on Office of Management and Budget directives) suggests using a 7% real discount rate for standard investment projects.
		But see discussion in Handbook for possible use of a lower rate that may be appropriate for climate resilience projects with a long time horizon.
Mitigation_Project_Type	Simplified	Simplified Mitigation Project assumes upfront construction costs, then constant annual maintenance or rehab costs according to schedule below.
Project_Start_Yr	2020	To enter user-specified costs year-by-year instead: Click Here
Mitigation_Start_Yr	2021	
		Project_Start_Yr signifies first year of construction; this can be after Analysis_Start_Yr if considering a delayed project start.
		Mitigation_Start_Yr signifies first year of damage mitigation.
Simplified Mitigation Project Costs		
Construction_Cost	$5,000,000	If using Simplified Mitigation Project:
Annual_Maint_Cost	$500,000	-- Construction_Cost is spread evenly between Project_Start_Yr and Mitigation_Start_Yr.
Rehab_Interval_Yrs	25	-- Final Rehab_Cost before end of analysis time horizon is prorated.
Rehab_Cost	$2,000,000	

Flooding Event Damage Costs

EWL (ft)	Without Project	With Project
0-1	$0	$0
1-2	$0	$0
2-3	$100,000	$0
3-4	$500,000	$0
4-5	$1,000,000	$0
5-6	$1,000,000	$200,000
6-7	$5,000,000	$1,000,000
7-8	$10,000,000	$2,000,000
8-9	$10,000,000	$2,000,000
9+	$10,000,000	$2,000,000

Note: For any given EWL, costs should reflect impacts net of freeboard (if any).

Exhibit E-6. RSL user selections 2.

Results

Once all of the selections have been made, the user can navigate to the Results sheet and click the "Recalculate All Results" button to generate predictions from 5,000 Monte Carlo simulations.[27] Or if interested just in the water event probabilities (exclusive of the NPV calculations from the mitigation project), one can click the button at the top of the sheet to recalculate just those results immediately below. Shown in Exhibit E-7, the results reflect the uncertainty inherent in the projections of future flooding events.

The table at the top displays the simulated probability of EWL events of different heights; the first column of probabilities reflects historical data only, while the remaining columns show how those probabilities change over time due to sea level rise. Just below, the user may also enter a desired height level to assess the cumulative likelihood of an extreme water event at or above that height over the indicated years. This information may be particularly useful to airports when they assess the risk to specific pieces of infrastructure; this is discussed in more detail in the next section.

The bottom part of the sheet shows the average of the NPV and benefit–cost ratio from the 5,000 Monte Carlo simulations followed by charts displaying the VaR results. The chart on

Recalculate Water Event Probabilities

MSY Extreme Water Level Event Probabilities from 5,000 Simulations (RCP 8.5)

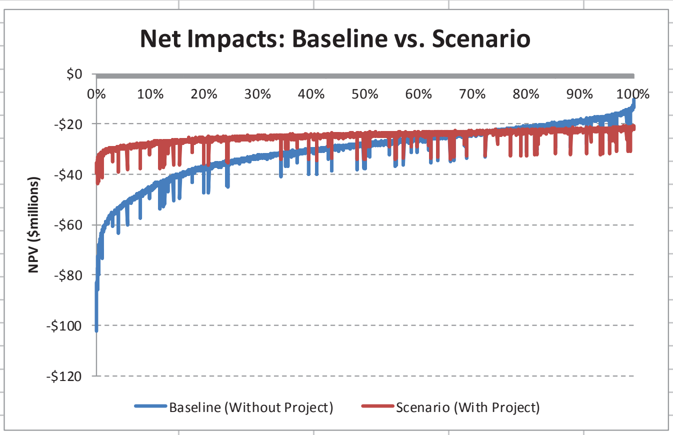
Water Level Rise above MHHW (ft)	Historical	2025	2035	2045	2055	2065	2075	2085	2095
0-1	9.66%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1-2	58.18%	30.80%	4.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2-3	20.62%	46.74%	56.22%	29.88%	4.68%	0.22%	0.00%	0.00%	0.00%
3-4	6.78%	14.38%	26.12%	45.72%	50.08%	25.88%	6.82%	0.84%	0.04%
4-5	2.76%	4.36%	8.00%	16.20%	29.96%	44.86%	41.32%	22.38%	8.52%
5-6	0.80%	1.72%	3.04%	4.64%	9.54%	18.36%	31.78%	38.96%	31.08%
6-7	0.44%	1.00%	1.18%	1.66%	3.10%	6.62%	12.24%	21.64%	31.34%
7-8	0.24%	0.36%	0.70%	0.74%	1.42%	1.92%	4.22%	9.80%	16.00%
8-9	0.18%	0.22%	0.20%	0.32%	0.66%	0.90%	2.16%	3.40%	7.60%
9+	0.34%	0.42%	0.48%	0.84%	0.56%	1.24%	1.46%	2.98%	5.42%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Median (ft)	*1.62*	*2.31*	*2.80*	*3.32*	*3.91*	*4.46*	*5.05*	*5.66*	*6.27*
100-Yr Event (ft)	*6.41*	*6.99*	*7.38*	*8.40*	*8.43*	*9.25*	*9.66*	*10.41*	*11.37*

Cumulative Probability of Inundation above MHHW (from 2020)

Height Above MHHW (ft)	2025	2035	2045	2055	2065	2075	2085	2095
8.0	3.35%	9.27%	17.00%	26.33%	37.58%	52.57%	71.02%	89.66%

Recalculate All Results

	Mean	Std Deviation
Avg NPV of Project	$5,600,518	$8,566,656
Avg B/C Ratio	1.27	0.42



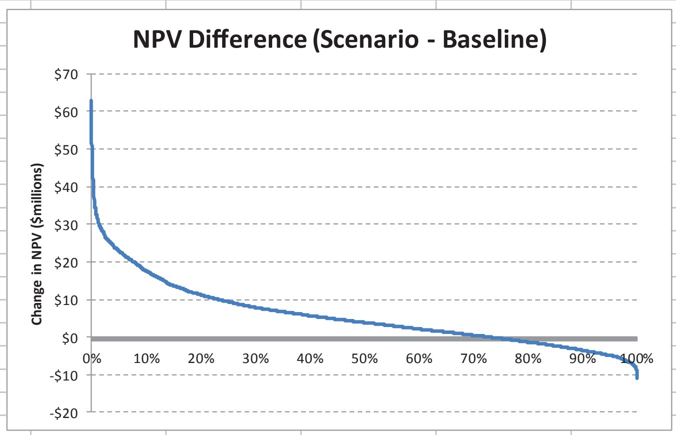


Exhibit E-7. Sea level rise results.

the left shows the estimated net impacts with and without the mitigation project.[28] In the example shown previously, one can see that without undertaking the proposed mitigation project, there is almost a 20% chance that the airport could be exposed to damages in excess of $40 million. With the project, that chance is reduced to under 1%.

The chart on the right shows just the net difference in NPV between the scenario and baseline cases, in this example indicating a range of anywhere between about +$60 million to –$10 million for the net impacts of investing in the proposed mitigation project. Overall, the chances of the project paying off (i.e., where the net impacts of undertaking the project are greater than the net impacts of not doing so, or equivalently, where the benefit–cost ratio of the project is greater than 1) is close to 75%. (Although not shown in the exhibit, the template also shows a table of results for the right-hand chart, indicating the actual NPV difference at 5% increments.)

Overall, the template should be useful to users by allowing them to quickly assess different possible mitigation strategies to combat sea level rise. As one considers the future, the probability of higher extreme weather events increases, which exposes more and more of the airport's infrastructure. The analyst may consider the cost to repair infrastructure that is inundated (including costs of services interrupted) versus the cost to mitigate. As higher extreme water events become more likely, certain potential mitigation projects may become economically attractive.

Further Use of the Climate Projections to Assess Current Infrastructure

Independent of the mitigation project VaR results, airports may be interested in assessing what the climate projections imply for their existing infrastructure that may have been designed to specific standards. For example, many airports utilize design standards based on adding 1 to 3 ft of freeboard to the 100-year (1%) storm projection. The last row in the top table of Exhibit E-7 shows how projected 100-year stormwater levels are expected to change over time (relative to MHHW). These figures could be compared to elevation data for the lowest critical level of each piece of infrastructure at the airport.

Related to this, the section in the exhibit labelled "Cumulative Probability of Inundation" can be used to assess the likelihood that specific pieces of infrastructure would remain safe. For example, if a particular asset has been designed to withstand inundations up to, say, 8 ft above MHHW, then by entering that value into the shaded cell on the left labelled "Height Above MHHW," the results will show the cumulative probability that an event at or above 8 ft would occur by the indicated years based on the 5,000 simulations.

To take this a step further, an airport could develop a complete inventory of relevant assets and their corresponding critical elevation levels and then assess the likelihood of inundation by entering those levels into the shaded cell on the left of the sheet. The resulting table might look something like that shown in Exhibit E-8.[29]

This provides a useful summary of the increasing vulnerability of infrastructure to extreme water events over time if no intervening mitigations are undertaken. One could also assess the reduction in inundation probabilities of a single asset at different levels of additional elevation. Again, this could be accomplished simply by entering the relevant elevation levels into the shaded cell in the template. For example, focusing on the TSA building, one could create a table like that shown in Exhibit E-9. Presenting the projections in this format could make it easier to discuss options with senior management.

			Cumulative Probability of Inundation (from 2020)					
Infrastructure	Critical Elevation (Relative to MHHW)	End of Useful Life	2025	2035	2045	2055	2065	2075
TSA building	8.0	2045	3.4%	9.3%	17.0%			
Fire station	10.0	2050	1.6%	3.8%	7.4%	11.3%		
Utility tunnel	12.0	2055	0.8%	1.9%	3.8%	5.8%		
Terminal	15.0	2070	0.4%	1.0%	1.8%	2.5%	3.4%	4.6%

Exhibit E-8. Vulnerability of infrastructure over time.

Critical Elevation	Cumulative Probability of Inundation 2025	2035	2045
8.0 (Current)	3.4%	9.3%	17.0%
9.0	2.3%	6.1%	11.3%
10.0	1.6%	3.8%	7.4%
11.0	1.1%	2.7%	5.2%
12.0	0.8%	1.9%	3.8%

Exhibit E-9. Effect of alternative mitigations on vulnerability of the TSA building.

Template for Maximum Daily Temperatures

The look and feel of the Excel template for potential climate change events reflecting high temperatures is similar to that for sea level rise. But unlike the latter, there is no centralized collection of high-temperature projections for multiple airports that can be gathered into a single file. Here it is up to the user to retrieve temperature projections for a specific emissions scenario and for the specific airport of interest.

In addition, this template focuses specifically on aircraft weight restrictions that may be incurred due to high temperatures and how these may be mitigated with a specific runway extension project.[30] This is very different from the SLR template where the mitigation project is generic and defined only as it relates to varying extreme water height projections.

Also in contrast to the sea level rise projections that represent six specific GMSL scenarios at 10-year intervals, the data for high temperatures at any given location come in the form of *daily* projections for more than 80 years (out to 2099) across many different climate models.

Adding to the data burden is the fact that best practices in the climate science field suggest that data be collected for at least four geographically adjacent grid points near the location of interest. Thus, the task of retrieving daily high-temperature data and summarizing them in a useful way for analysis is non-trivial and may well require the use of outside professional help.[31]

The process of determining the weight restriction that might occur for a specific flight depends on many variables, including aircraft type, takeoff weight, runway length, elevation, and temperature. Normally, one would have to do many manual calculations by reading off aircraft payload/range and takeoff weight/runway charts published by manufacturers in order to estimate the potential weight restriction for any particular flight. (The FAA has published an advisory circular outlining how to determine minimum required runway takeoff length.[32])

However, the template implements the results of a published analysis that allows for direct lookups of estimated weight restrictions that would apply for a number of popular aircraft types used for long-haul flying and for a given elevation, runway length, and temperature (Coffel et al. 2017).[33] This allows the Excel template to be a useful tool where the incidence and impact of weight restrictions on specific flights can be assessed automatically once the user enters the high-temperature projections along with information on elevation and runway length.

The template file is composed of five separate Excel sheets:

- **Overview:** This sheet provides a Quick Start section plus a high-level overview of how the model embedded in the template works.
- **Weather Data:** This sheet contains a summarized version of the high-temperature data that the user must retrieve, along with a list of weather models used and model weights.
- **Aircraft Data:** This sheet contains the weight restriction lookup information mentioned previously for specific aircraft types.

- **User Selections:** This sheet is where the user inputs the airport elevation and runway length, details about which specific routes and aircraft types may be candidates for weight restrictions if temperatures get high enough, the costs that would be incurred for the proposed runway extension, and the delay costs that would be incurred for passengers that must be removed from a flight if it is weight restricted.
- **Results:** This sheet presents the results of 5,000 Monte Carlo simulations based on the user selections.

Weather Data

The Excel template assumes that the relevant data for daily high temperatures at any given airport for a specific emissions scenario can be retrieved and summarized to look like that shown in Exhibit E-10. (Instructions are provided in the template file.) Again, it is up to the user to gather and paste in this data.

The data shown here is for PHX airport. Each row represents a unique model/year/grid-point combination, and the "H" columns represent counts of annual days at or above the indicated Fahrenheit temperature but below the next column's temperature. For example, the row for the model named ACCESS1-0/Year 2020/Grid_ID 4 projects that there will be 16 days with daily high temperatures between 100° and 102°; 14 between 102° and 104°, and so forth. Summarizing the data in these 2-degree increments between 100° and 128° drastically cuts down on the number of total data points but still retains a full range of high temperatures that should be relevant for purposes of estimating weight restrictions at airports across the United States.

The Weather Data sheet also contains a list of the 32 climate models and their analysis weights.[34] Higher weights are given to those models that have historically provided better predictions, and

MODEL	YEAR	GRID_ID	H100	H102	H104	H106	H108	H110	H112	H114	H116	H118	H120	H122	H124	H126	H128
ACCESS1-0	2020	1	15	16	13	22	29	15	18	1	0	0	0	0	0	0	0
ACCESS1-0	2020	2	18	13	13	23	27	22	13	4	0	0	0	0	0	0	0
ACCESS1-0	2020	3	16	16	12	22	25	19	19	1	0	0	0	0	0	0	0
ACCESS1-0	2020	4	16	14	16	21	28	18	15	2	0	0	0	0	0	0	0
ACCESS1-0	2021	1	24	21	15	21	19	11	7	3	2	0	0	0	0	0	0
ACCESS1-0	2021	2	30	18	18	18	20	12	9	2	2	0	0	0	0	0	0
ACCESS1-0	2021	3	25	16	15	22	21	11	8	3	2	0	0	0	0	0	0
ACCESS1-0	2021	4	32	20	16	20	18	11	8	1	2	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ACCESS1-0	2090	1	7	13	13	7	18	25	28	31	15	5	1	1	1	0	0
ACCESS1-0	2090	2	8	9	14	11	14	24	32	32	13	6	2	2	0	0	0
ACCESS1-0	2090	3	8	11	10	11	17	22	30	32	15	6	1	1	1	0	0
ACCESS1-0	2090	4	11	8	14	8	20	26	32	32	8	6	1	2	0	0	0
ACCESS1-3	2020	1	19	33	32	18	7	10	6	0	0	0	0	0	0	0	0
ACCESS1-3	2020	2	22	32	39	13	10	9	6	1	0	0	0	0	0	0	0
ACCESS1-3	2020	3	20	34	34	15	10	11	5	0	0	0	0	0	0	0	0
ACCESS1-3	2020	4	21	37	37	12	9	11	3	0	0	0	0	0	0	0	0
ACCESS1-3	2021	1	9	22	27	26	19	14	5	2	0	0	0	0	0	0	0
ACCESS1-3	2021	2	14	16	33	22	19	18	5	2	0	0	0	0	0	0	0
ACCESS1-3	2021	3	9	17	29	27	18	14	8	2	0	0	0	0	0	0	0
ACCESS1-3	2021	4	15	20	28	25	18	17	3	2	0	0	0	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
ACCESS1-3	2090	1	12	15	20	20	37	33	19	15	5	3	1	0	0	0	0
ACCESS1-3	2090	2	12	14	16	23	35	32	30	13	5	1	2	0	0	0	0
ACCESS1-3	2090	3	11	15	18	24	34	35	22	12	6	3	1	0	0	0	0
ACCESS1-3	2090	4	13	16	16	25	34	40	18	12	5	1	2	0	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Exhibit E-10. High-temperature data.

the sampling method directly accounts for the weights by adjusting the probability of being sampled in each year of the Monte Carlo simulations.[35]

Aircraft Data

As mentioned previously, the Aircraft Data sheet contains a lookup table where the weight restriction for a given aircraft type can be estimated given the airport elevation, runway length, and temperature. Basic assumptions for aircraft takeoff weights and fuel consumption are also contained in this sheet.

An important practical inference from the weight restriction data table is that net improvement in allowed takeoff weight from a longer runway does not vary much based on temperature. In other words, for a given aircraft type, if moving from a 7,000-ft runway to a 9,000-ft runway increases the allowed takeoff weight by, say, 15,000 lbs when the temperature is 100°F, then the improvement at 110°F will also be around 15,000 lbs (or until the structural maximum takeoff weight of the aircraft is reached). For example, Exhibit E-11 shows the change in required weight restriction for the Boeing 737-800. This implies that the uncertainty of future temperature increases will not likely have large effects on the BCA of a proposed runway extension—the net impact of a 2,000-ft extension will be approximately the same regardless of the future path of high temperatures (assuming the restriction is binding to begin with).

A related implication from the data is that the increase in allowed takeoff weight as a function of temperature is very gradual. From Exhibit E-11, one can see that the weight restriction for the 7,000-ft runway increases gradually and steadily from 24,000 lbs at 100°F to 35,000 lbs at 116°F. This implies that, whatever the runway length is, the weight impacts (and corresponding costs due to delay for passengers who cannot be accommodated) will change only modestly, leading to relatively flat NPV curves that make up the VaR analysis. This will be the case under both the baseline and the scenario cases.

User Selections

On the User Selections sheet, the user first inputs the airport elevation, baseline runway length, and runway length after the extension project is completed. This is followed by a section where the user may enter specific routes and aircraft types in order to have the model estimate the implied weight restrictions at different temperatures.

Exhibit E-12 shows the part of the User Selections sheet where this information is entered. Again, explanatory text is provided to help the user understand the possible selections. The estimated required weight restrictions at different temperature levels are shown to the right of where the specific flight information is entered.[36] In this example, information on three new long-haul routes not currently served from PHX is considered.

Weight Restriction (000 lb) from Maximum Takeoff Weight for 737-800 Aircraft at 2000-Ft Elevation

	Temp (°C)	38	39	40	41	42	43	44	45	46	47
Runway Length	Temp (°F)	100.4	102.2	104.0	105.8	107.6	109.4	111.2	113.0	114.8	116.6
7000		24	26	27	28	30	31	32	33	35	35
9000		11	12	14	15	17	18	19	21	22	23
Change		**13**	**14**	**13**	**13**	**13**	**13**	**13**	**12**	**13**	**12**

Exhibit E-11. Impact of runway length on weight restrictions.

User should select or enter values in blue shaded boxes only

When finished making selections and/or changing values, press the Refresh Current Sheet button.

Baseline represents current status; Scenario represents runway extension to mitigate weight restrictions.

Elevation	1135	ft	Valid elevation range is 0-4000 ft; latter is the maximum elevation for which model can automatically estimate weight restrictions.
Rwylength_Baseline	11500	ft	Valid runway length range is 4000-16000 ft.
Rwylength_Scenario	14500	ft	

Refresh Current Sheet

Enter routes and distances (measured in nautical miles) below to analyze weight restrictions.
Select aircraft from drop-down list; for aircraft types not listed, go to next section, where you must enter weight restrictions manually.
Weekly Departures should represent # of weekly flights scheduled during peak temperature times in Analysis Start Year.

The estimates of required weight restrictions shown here are based on standard assumptions and averages that may not be appropriate for a specific route flown by a particular carrier with their own equipment specifications.
The reported weight restrictions are derived by comparing estimated allowed takeoff weight (based on elevation, runway length and temperature) vs. required takeoff weight for the route and passenger counts entered.
Inaccurate results may occur if you specify routes that are beyond the practical range of the aircraft selected, or if you enter passenger counts beyond the seatsize capacity. Guidelines are shown below:

	Max Range (nm)	Typical U.S.	Maximum Seatsize
A320	3300	160	186
B737-800	3000	158	189
787-8	7000	235	300
777-300	7000	317	500

							Weight Restriction (000 lb) per Flight at Indicated Temperatures (°F)									
	Route	**Distance (nm)**	**Eqpt**	**Passengers per**	**Weekly Departure**		100-101	102-103	104-105	106-107	108-109	110-111	112-113	114-115	116-117	118-119
1	PHX-BOG	2728	737-800	130	7	Baseline	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.9	3.4	4.9
						Scenario	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PHX-LHR	4570	787-8	195	7	Baseline	3.5	7.5	15.0	19.0	23.0	26.6	30.6	33.6	34.9	36.2
						Scenario	0.0	0.0	0.0	0.0	2.6	7.2	11.2	14.2	18.2	21.7
3	PHX-NRT	4999	777-300	260	7	Baseline	29.6	35.1	46.1	51.6	57.1	63.1	68.1	74.1	79.7	85.7
						Scenario	0.0	5.1	15.7	21.7	27.7	32.7	38.7	44.7	50.1	56.1

Exhibit E-12. High-temperature user selections 1.

The second part of the User Selections sheet is shown in Exhibit E-13; it is similar to the corresponding section of the RSL template and allows the user to enter assumptions about the mitigation project, costs, and potential damage impacts from weight restrictions (measured as passenger delays). The user can specify the time horizon for the analysis, discount rate, and construction, maintenance, and rehab costs for the runway extension project.

In addition, the user may select whether or not to use model weights when sampling, and whether to sample from the same model across all years of a given simulation or from a different model each year. (Remember that a set of predictions across all years of interest represents a single simulation, and there are 5,000 simulations.) Again, explanatory text is provided to help the user with the various options.

It is important to note that the template considers only a narrow definition of negative impacts due to the weight restrictions—namely, delay costs to passengers; no net impacts on airlines or the airport itself are considered. But a broader analysis that accounts for impacts beyond simple passenger delay costs could be undertaken using the same overall format and approach shown here.

Results

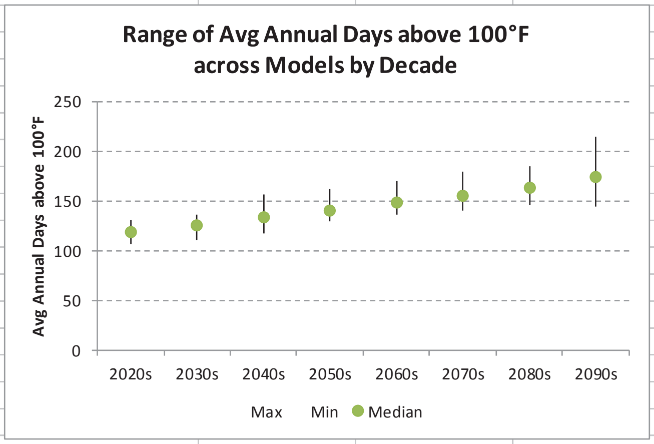
Once all of the selections have been made, the user can navigate to the Results sheet and click the Recalculate button to generate predictions from 5,000 Monte Carlo simulations. Sample results are shown in Exhibit E-14. The charts at the top display the uncertainty in high temperatures across the available climate models. Not surprisingly, the uncertainty grows in later years. The middle portion of the sheet shows the average of the net NPV and benefit–cost ratios from the Monte Carlo simulations, while the charts below display the VaR results. The chart on the left shows the net impacts with and without the mitigation project, while the one on the right shows the difference in NPV between the scenario and baseline cases.

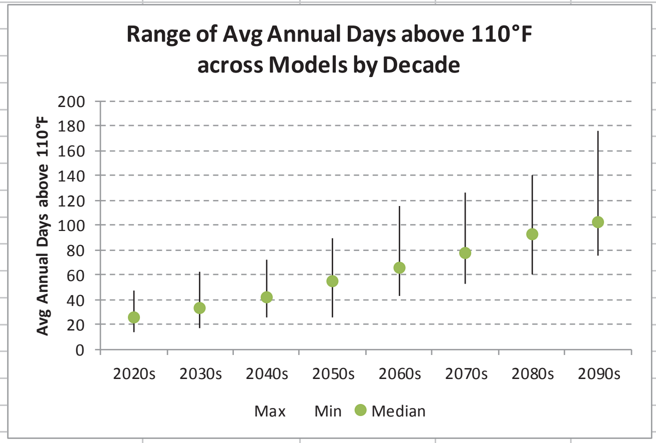
The sample results shown here are consistent with the previous discussion. While high temperatures may certainly have a large impact on the passengers affected by weight restrictions (the net damages shown on the left chart, which reflect delay costs to passengers, reach as high as $60 million under the baseline case), the uncertainty of when those high temperatures will occur has only a modest effect on the net impact of a given runway extension. The chart shows that the runway extension never pays off under the current assumptions, and the net impacts do not vary much across the simulations. The chart on the right shows that NPV difference between the baseline and scenario cases ranges between about $15 million and $20 million (consistent with the very small standard deviation in the benefit–cost ratio).

If this sort of result holds up in an actual airport analysis, it suggests that decision makers could focus more on whether weight restrictions are likely to be an issue in the first place and the appropriate size and cost of a runway extension, and less on how the BCA results may be affected by climate change uncertainty.

Analysis_Start_Yr	2020	Discounted benefit-cost calculations reflect time horizon between Analysis_Start_Yr and Analysis_End_Yr.
Analysis_End_Yr	2060	Maximum time horizon is 2020 - 2099, but actual limits depend on the years covered by the Weather Data.
		User may wish to consider a time horizon matching the expected/remaining life of current or new assets.
Discount_Rate	3.0%	Traditional FAA guidance (based on Office of Management and Budget directives) suggests using a 7% real discount rate for standard investment projects.
		But see discussion in Handbook for possible use of a lower rate that may be appropriate for climate resilience projects with a long time horizon.
Mitigation_Project_Type	Simplified	Simplified Mitigation Project assumes upfront construction costs, then constant annual maintenance or rehab costs according to schedule below.
Project_Start_Yr	2020	To enter user-specified costs year-by-year instead: Click Here
Mitigation_Start_Yr	2021	
		Project_Start_Yr signifies first year of construction; this can be after Analysis_Start_Yr if considering a delayed project start.
		Mitigation_Start_Yr signifies first year of damage mitigation.
Simplified Mitigation Project Costs		
Construction_Cost	$40,000,000	If using Simplified Mitigation Project:
Annual_Maint_Cost	$1,000,000	-- Construction_Cost is spread evenly between Project_Start_Yr and Mitigation_Start_Yr.
Rehab_Interval_Yrs	25	-- Final Rehab_Cost before end of analysis time horizon is prorated.
Rehab_Cost	$10,000,000	
Damage Parameters		
Avg_PaxPayload	220	Avg payload per passenger in lbs
Avg_PaxDelay	2.0	Avg hours of delay for passengers on impacted flights
Hourly_DelayCost	$44.30	Passenger delay cost per hr
Sampling_Method	One Model per Year	One Model per Simulation -- same model is used for all years of a single simulation (rem 5,000 total simulations)
		One Model per Year -- different model is used for each year of a single simulation (reduces influence of outlier models)
Use_Model_Weights	Yes	Select Yes to use model weights listed in Weather Data sheet; No to use equal weighting across whatever models are in Weather Data.

Exhibit E-13. High-temperature user selections 2.

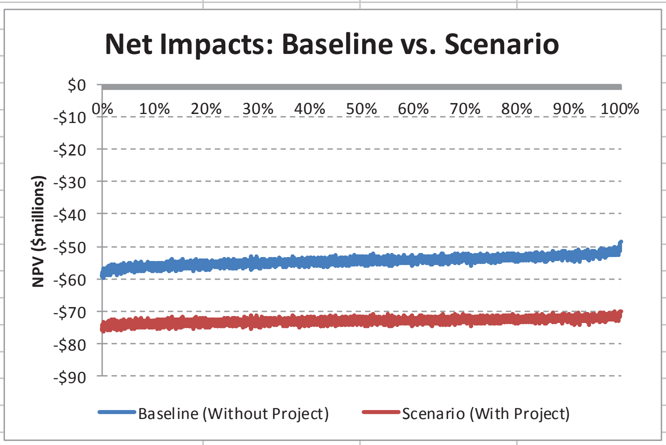




After making sure you have refreshed other sheets, click Recalculate button for results:

Recalculate

	Mean	Std Deviation
Avg NPV of Project	-$18,458,050	$662,973
Avg B/C Ratio	0.64	0.01



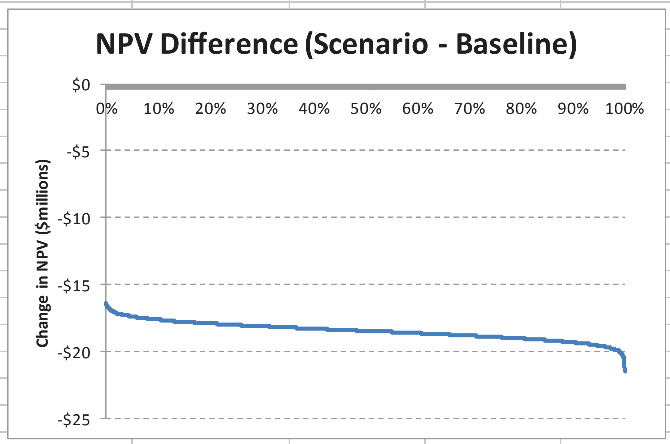


Exhibit E-14. High-temperature results.

APPENDIX F

Climate Risk and Mitigation Numerical Examples

Two numerical examples are presented here using the Excel templates described in Appendix E. Simulation results are presented for airports in Myrtle Beach (for the relative sea level rise example) and Phoenix (for the high-temperature weight restriction example). It is important to emphasize that these examples are used only to describe how the methodologies embedded in the templates can be utilized. They are not meant to be accurate descriptions of potential mitigation projects that might be undertaken.

Numerical Example for Myrtle Beach International Airport

Myrtle Beach International Airport (MYR) is located south of the city of Myrtle Beach, about 2 miles west of the Atlantic coastline. Unfortunately, the ACROS software does not provide any projections related to sea level rise for MYR, so an initial screening analysis is not possible.

The Excel template for relative sea level rise can be used to undertake an analysis of potential extreme water level events for MYR. As a first step, the airport can be selected on the User Selections sheet, shown in Exhibit F-1.

As seen in the exhibit, the airport elevation is listed as 24.5 ft above MSL, with its lowest runway being 9.0 ft above MSL. These elevations translate to 21.6 ft and 6.1 ft, respectively, above MHHW, which is the relevant vertical datum measure used in the template. In this example, RCP8.5 (the high-emissions scenario) is selected as the relevant forecast for future SLR.

The next step is to specify a potential mitigation project for analysis on the User Selections sheet. But before doing so, one can examine the projected probabilities for flooding events of different heights at MYR under RCP8.5. The first table at the top of the Results sheet presents these results (shown in Exhibit F-2) along with corresponding projected heights for the median event from the simulations as well as the height of the projected 100-year (i.e., top 1%) event.

The results shown in Exhibit F-2 do not depend on any specific mitigation project assumptions; they reflect only the flood event probabilities implied by RCP8.5, taking into account global SLR, the expected localized effects, and the history of extreme water events for MYR. As expected, the probabilities of higher water level events increase gradually over time.

Interestingly, the heights of the expected 100-year event are projected to rise from a historical average of 3.15 ft to about 6 ft by 2075, the latter being just above the lowest runway height shown in Exhibit F-1. These results might suggest that the airport may not be in much danger for runway flooding until that time; however, it is important to note that the software cannot take account of any variations in terrain that may exist between the reporting stations and the airport itself, nor can it account for any existing mitigations (such as levies or stormwater systems) that may be operational.

State_Locid	SC_MYR	
Name	MYRTLE BEACH INTERNATIONAL	
	Relative to MSL	*Relative to MHHW*
Airport Elevation (ft)	24.5	21.6
Lowest Runway Elevation (ft)	9.0	6.1
Historical extreme water levels (EWL) based on:		
EWL_Station	SPRINGMAID PIER	
EWL_Distance (miles)	1.81	
Projected relative sea levels (RSL) based on:		
RSL_Station	SPRINGMAID PIER	
RSL_Distance (miles)	1.45	
RCP_Scenario	8.5	

Exhibit F-1. RSL template information for MYR.

Given this background, Exhibit F-3 shows the mitigation assumptions selected for this example. By design, the mitigation costs and damages with and without the project are defined in a generic way, allowing users to consider specific amounts that would be relevant for however they decide to define the mitigation project.

The time horizon for this project is assumed to run from 2020 through 2060. The project takes 1 year for construction, starting in 2020, then mitigation benefits begin to accrue the following year. Initial construction costs are $4 million, with annual maintenance costs of $200,000, plus a rehab cost of $1 million after 20 years. The damage costs listed in the exhibit imply complete mitigation for flooding events of less than 5 ft, and 80% mitigation for events higher than that.

Using these assumptions, the template carries out 5,000 Monte Carlo simulations. The results shown in Exhibit F-4 indicate that the project has a very low average benefit–cost ratio and virtually never pays off. This is not surprising given the very low probabilities for flooding events in the early years, as shown in Exhibit F-2.

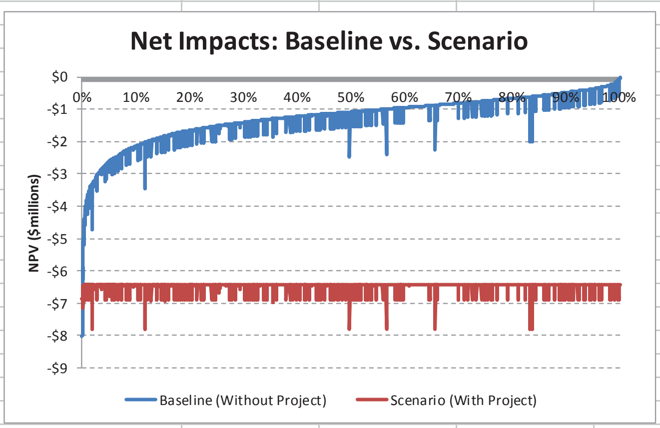
MYR Extreme Water Level Event Probabilities from 5,000 Simulations (RCP 8.5)									
Water Level Rise above MHHW (ft)	Historical	2025	2035	2045	2055	2065	2075	2085	2095
0-1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1-2	52.10%	11.46%	1.38%	0.08%	0.00%	0.00%	0.00%	0.00%	0.00%
2-3	46.34%	82.16%	81.60%	61.40%	31.78%	11.64%	3.44%	1.00%	0.44%
3-4	1.54%	6.22%	16.62%	36.76%	61.10%	66.66%	53.78%	35.32%	23.18%
4-5	0.02%	0.16%	0.40%	1.70%	6.88%	19.38%	33.76%	45.10%	42.80%
5-6	0.00%	0.00%	0.00%	0.06%	0.24%	2.14%	7.88%	13.12%	21.80%
6-7	0.00%	0.00%	0.00%	0.00%	0.00%	0.14%	0.92%	4.56%	7.92%
7-8	0.00%	0.00%	0.00%	0.00%	0.00%	0.04%	0.20%	0.66%	3.16%
8-9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.14%	0.36%
9+	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.10%	0.34%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Median (ft)	*1.98*	*2.35*	*2.61*	*2.87*	*3.19*	*3.54*	*3.90*	*4.25*	*4.61*
100-Yr Event (ft)	*3.15*	*3.49*	*3.79*	*4.10*	*4.59*	*5.27*	*6.06*	*6.93*	*7.67*

Exhibit F-2. Event probabilities for MYR.

Analysis_Start_Yr	2020	
Analysis_End_Yr	2060	
Discount_Rate	7.0%	
Mitigation_Project_Type	Simplified	
Project_Start_Yr	2020	
Mitigation_Start_Yr	2021	
Simplified Mitigation Project Costs		
Construction_Cost	$4,000,000	
Annual_Maint_Cost	$200,000	
Rehab_Interval_Yrs	20	
Rehab_Cost	$1,000,000	
Flooding Event Damage Costs		
EWL above MHHW (ft)	Without Project	With Project
0-1	$0	$0
1-2	$0	$0
2-3	$0	$0
3-4	$500,000	$0
4-5	$1,500,000	$0
5-6	$2,500,000	$500,000
6-7	$5,000,000	$1,000,000
7-8	$10,000,000	$2,000,000
8-9	$10,000,000	$2,000,000
9+	$10,000,000	$2,000,000

Exhibit F-3. Assumed user inputs for MYR.

	Mean	Std Deviation
Avg NPV of Project	-$5,185,165	$732,004
Avg B/C Ratio	0.19	0.11



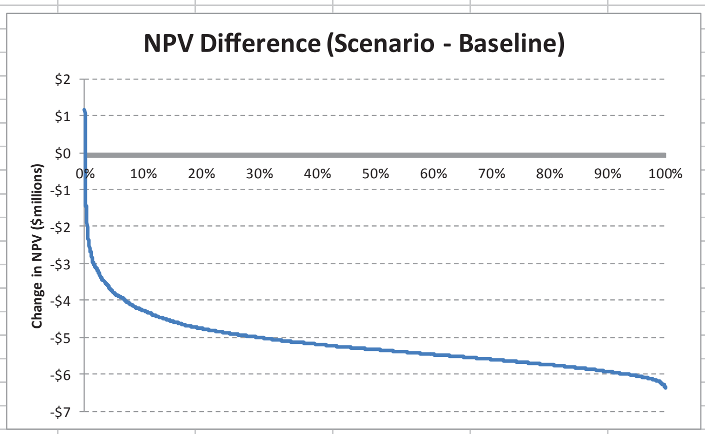


Exhibit F-4. BCA and VaR results for MYR 2020 project.

	Mean	Std Deviation
Avg NPV of Project	-$1,690,116	$2,730,672
Avg B/C Ratio	0.74	0.43

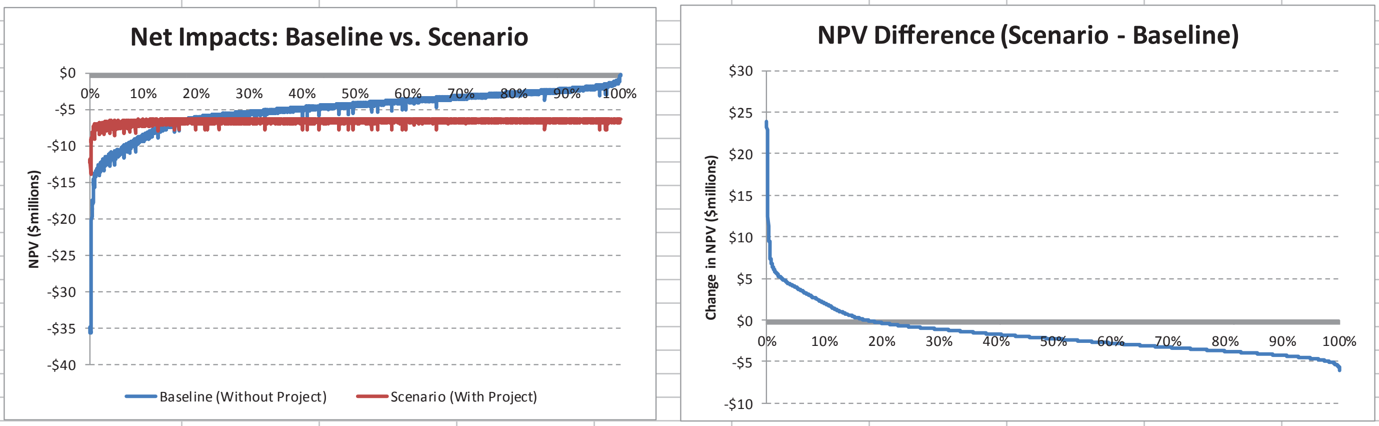


Exhibit F-5. BCA and VaR results for MYR 2040 project.

The template makes it easy to do what-if comparisons. For example, one could see the effect of delaying the project for 20 years (e.g., starting the project in 2040 and moving the analysis time horizon to 2040 through 2080). These results are shown in Exhibit F-5. The results improve substantially, but the chances of the project paying off are still low at around 17%. Obviously, a viable option might be to wait several years and then undertake a revised analysis when the chances of extreme events are closer in time and when newer and more reliable data for the time period of interest are likely to be available.

The impact of the discount rate can also be investigated easily. The choice of discount rate can have a significant effect on the results. Exhibit F-6 shows the results when combining the 20-year project delay with a 3% discount rate. Now the results show an average benefit–cost ratio well above 1. However, the VaR results show that the probability of

	Mean	Std Deviation
Avg NPV of Project	$2,112,055	$6,169,306
Avg B/C Ratio	1.24	0.70

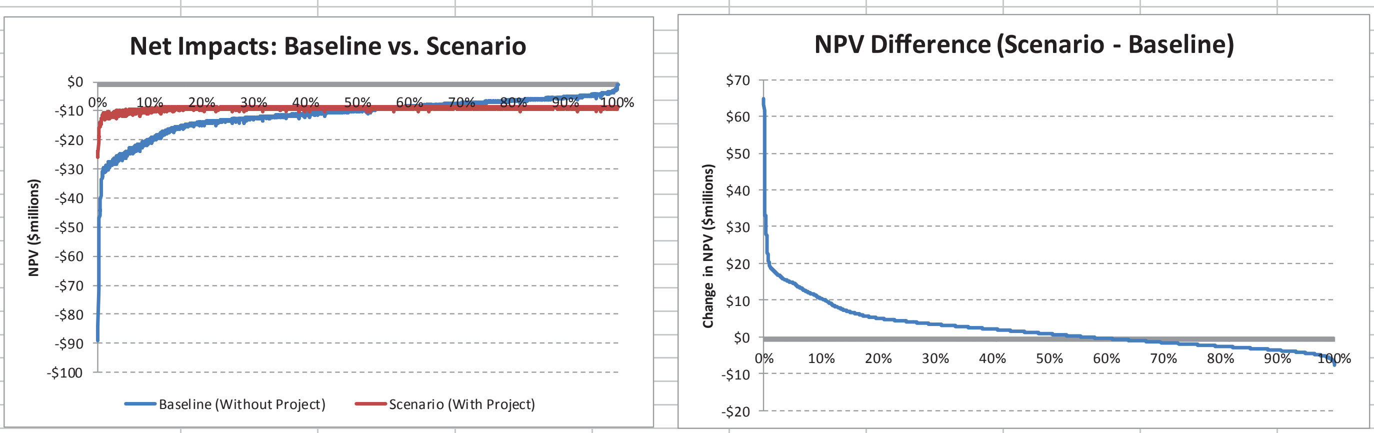


Exhibit F-6. BCA and VaR results for MYR 2040 project with 3% discount rate.

a positive payoff from the project is still relatively low (about 56%), so decision makers must consider whether they would be willing to accept the risk of not undertaking the project.

All of the results presented have been for illustrative purposes only. However, they show how the template may be used to undertake a Monte Carlo analysis in a straightforward way and how different assumptions can have significant impacts on the reported results.

Numerical Example for PHX

PHX is a major hub for American Airlines, and it plays an important role in the national aviation system. Phoenix of course has a very warm climate, and it is expected to get warmer over the coming decades. As a first step in assessing how future climate change may affect the airport, one can look at the ACROS climate projections for PHX, shown in Exhibit F-7.

The incidence of hot days (defined as maximum temperatures at or above 90°F) and very hot days (temperatures above 100°F) is expected to increase fairly significantly by 2060. One potentially important impact of high temperatures at airports is that they increase the required runway distance for takeoffs and reduce climbing performance. Whether a specific operation will be affected depends on the actual temperature, airport elevation, length of the runway, aircraft load, and aircraft being used.

In principle, an airline could have multiple options available during hot weather. For example, it could be able to remove some weight from the aircraft, which would lower its minimum takeoff length requirements. This could involve removing passengers (or cargo) from the flight. But if the temperature gets high enough, it may simply choose to cancel the flight altogether.

This is a real-world issue at PHX, which has seen heat-related disruptions to operations in the past. For example, extreme heat in June 2017 caused American to cancel more than 40 flights as temperatures reached close to 120°F:

> A statement from the airline suggested that the maximum operating temperature for a number of aircraft (127°F for an Airbus, 126°F for a Boeing, and 118°F for a Bombardier CRJ regional aircraft) had been reached, or was expected to be reached later in the day (Samuelson 2017).

Summary of climate data changes

Summary of Historical Record and Projected Changes (Days/Year)								
		2013	2030			2060		
Climate Vector	Units	Baseline	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
HotDays	days per year	114	124	126.3	127.6	138.9	144.7	148
VeryHotDays	days per year	47.6	56.7	58.8	61.4	70.4	75.7	82.2
FreezingDays	days per year	0.2	0	0	0.1	0	0	0
FrostDays	days per year	24.3	14.2	18.5	21.8	1.2	10.4	18.2
HotNights	days per year	95.7	105.5	110	115	120.2	131.4	143.8
HumidDays	days per year	10.2	11.6	13.7	16.7	13.6	18.9	26.5
SnowDays	days per year	0.4	0	0.1	0.2	0	0	0
StormDays	days per year	14.8	13.8	14.3	14.7	12.3	13.6	14.5
HeavyRain1Day	days per year	1.8	1.8	1.9	1.9	1.8	2	2.1
DryDays	days per year	81.4	81.7	83.7	86.6	82.1	87.3	94.3
SeaLevelRise	days per year	0	0	0	0	0	0	0
CoolingDays	days per year	257.4	268.2	268.7	269.3	284.4	285.6	287.1
HeatingDays	days per year	63.1	50.8	51.1	51.3	32.2	33	33.6

Exhibit F-7. ACROS climate stressor forecast for PHX.

For PHX, it is clear that projections for temperatures well above the "very hot days" definition identified in the ACROS projections would be needed to assess the potential impact on aircraft operations at the airport. Using methods described in Chapter 4, the project team obtained LOCA-downscaled projections of daily maximum temperatures for the RCP8.5 climate scenario from 32 different GCM models and four grid points surrounding PHX for the period 2020 through 2089 in order to more fully examine the potential impact of extreme temperatures.

The Excel high-temperature template is used for the following example. The temperature projections from RCP8.5 were converted and copied into the Excel template as described in Appendix E and following the specific instructions contained in the template itself.

For this example, it was assumed that the airport wished to investigate if and to what degree there might be weight restrictions that could affect certain long-haul routes for which they were trying to gain new service. The relevant information is in the shaded areas at the top of the User Selections sheet, as shown in Exhibit F-8.

As shown in the exhibit, the project being considered would extend the runway from its current 11,500 ft to 14,500 ft. Three long-haul routes (each using a different aircraft type) were specified, along with estimated passengers and number of weekly departures. The results under the Weight Restriction columns show the impact of lengthening the runway in terms of pounds of required weight reduction per flight. The implied counts of affected passengers are shown at the bottom, assuming that departures grow at a 2% annual rate.

The next step is to specify the relevant time period for the analysis and costs of the runway extension on the User Selections sheet. But before doing so, one can examine the range of projected high temperatures from the different models. The charts at the top of the Results sheet present these results, shown in Exhibit F-9. The results shown in the exhibit do not depend on any specific mitigation project assumptions; they reflect only the high-temperature projections from the different climate models implied by RCP8.5. As expected, both the counts and uncertainties of high temperatures increase gradually over time. The increased variation across the models is not surprising—it reflects the real uncertainty in climate projections many years out. By sampling from all of the models in the analysis, the results will reflect this range of variation.[37]

The proposed mitigation project for this example is an extension for Runway 08/26, which runs on the north side of the terminal complex. It is constrained by the airport property boundary, the airport Skytrain transit system, and South 44th St. with associated bridge structures and access drives. Beyond those features, there is relatively undeveloped land extending to Route 143 located about 3,600 ft east of the end of Runway 08.

For purposes of this example, it was assumed that an extension of Runway 08 to the east by 3,000 ft would be possible. In reality, such an extension might not be feasible since it could well involve the need for property acquisition (depending on whether the airport holds title to the affected land) and either relocating or depressing and bridging over the Skytrain system and South 44th St. In addition, it is possible that additional obstruction removal would be required to maintain obstacle clearance requirements. Also, even if it were physically feasible, there could be other obvious policy or legal reasons why such a project could not be undertaken. Given this background, Exhibit F-10 shows the project assumptions selected for this example.

The time horizon for this project was assumed to be from 2020 through 2070. The project would take 1 year for construction, starting in 2020, and then mitigation benefits would begin to accrue the following year. Initial construction costs would be $40 million, with annual maintenance costs of $1,000,000, plus a rehab cost of $10 million after 25 years. Avg_PaxPayload at the bottom of Exhibit F-10 is the average weight in pounds per passenger; Avg_PaxDelay is the assumed average delay in hours that must be incurred by a passenger who is weight-restricted off of a flight; Hourly_DelayCost is the FAA-recommended value of time for commercial airline passengers.

Elevation	1135	ft	Valid elevation range is 0-4000 ft; latter is the maximum elevation for which model can automatically estimate weight restrictions.
Rwylength_Baseline	11500	ft	Valid runway length range is 4000-16000 ft.
Rwylength_Scenario	14500	ft	

Refresh Current Sheet

	Route	Distance (nm)	Eqpt	Passengers per Flight	Weekly Departures		Weight Restriction (000 lb) per Flight at Indicated Temperatures (°F)									
							100-101	102-103	104-105	106-107	108-109	110-111	112-113	114-115	116-117	118-119
1	PHX-BOG	2728	737-800	130	7	Baseline	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.9	3.4	4.9
						Scenario	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PHX-LHR	4570	787-8	195	7	Baseline	3.5	7.5	15.0	19.0	23.0	26.6	30.6	33.6	34.9	36.2
						Scenario	0.0	0.0	0.0	0.0	2.6	7.2	11.2	14.2	18.2	21.7
3	PHX-NRT	4999	777-300	260	7	Baseline	29.6	35.1	46.1	51.6	57.1	63.1	68.1	74.1	79.7	85.7
						Scenario	0.0	5.1	15.7	21.7	27.7	32.7	38.7	44.7	50.1	56.1

Total Daily Passengers Affected:

Paxdaily_Baseline	124.6	160.7	230.8	266.3	302.4	338.5	373.9	413.7	445.0	478.5
Paxdaily_Scenario	0.0	19.4	59.2	81.9	114.3	150.4	188.1	222.1	257.7	293.8

Exhibit F-8. High-temperature template information for PHX.

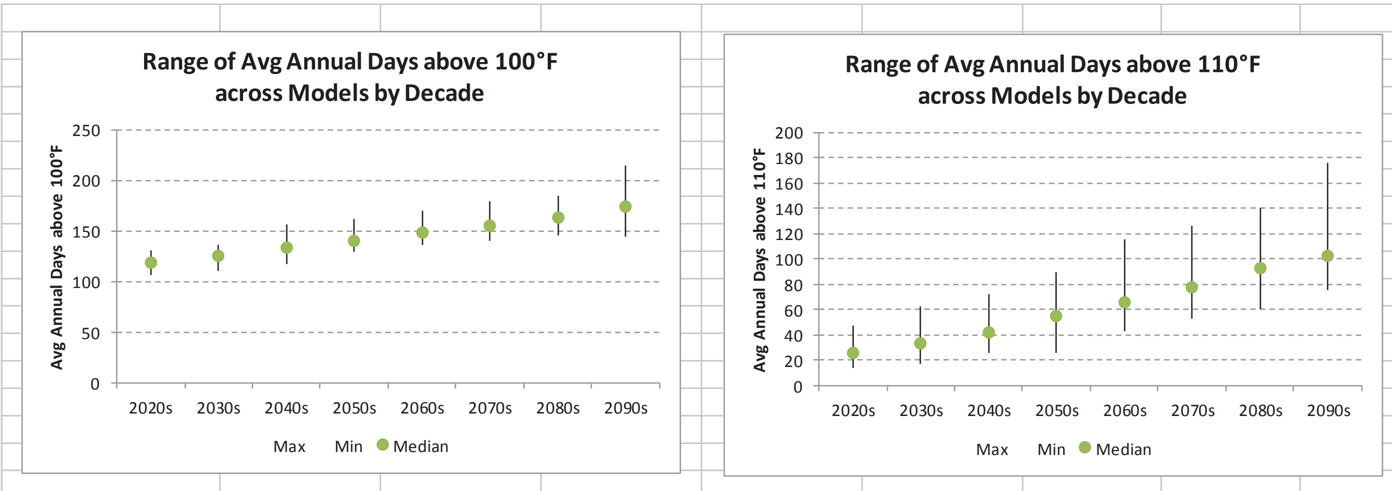


Exhibit F-9. Range of incidence of projected high temperatures for PHX.

Analysis_Start_Yr	2020
Analysis_End_Yr	2070
Discount_Rate	7.0%
Mitigation_Project_Type	Simplified
Project_Start_Yr	2020
Mitigation_Start_Yr	2021
Simplified Mitigation Project Costs	
Construction_Cost	$40,000,000
Annual_Maint_Cost	$1,000,000
Rehab_Interval_Yrs	25
Rehab_Cost	$10,000,000
Damage Parameters	
Avg_PaxPayload	220
Avg_PaxDelay	2.0
Hourly_DelayCost	$44.30

Exhibit F-10. Assumed user inputs for PHX.

	Mean	Std Deviation
Avg NPV of Project	-$18,458,050	$662,973
Avg B/C Ratio	0.64	0.01

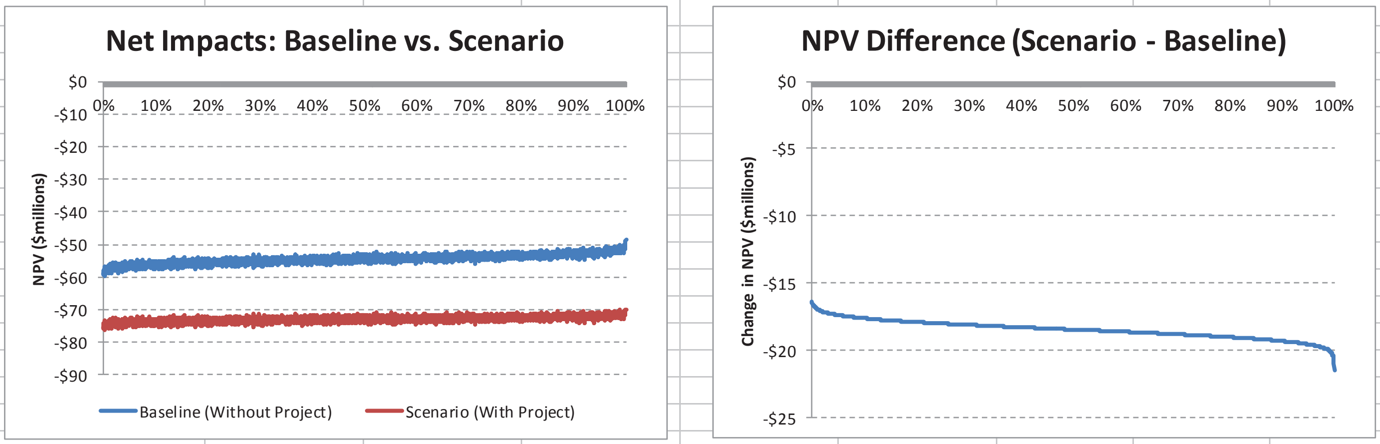


Exhibit F-11. BCA and VaR results for PHX project.

Using these assumptions, the template carries out 5,000 Monte Carlo simulations. The results shown in Exhibit F-11 indicate that the project has a very low average benefit–cost ratio and never pays off. Both net impact curves in the VaR chart on the left are relatively flat, which is consistent with the discussion in Appendix D that both curves will typically change only modestly based on temperature variations.

Again, the template makes it easy to do what-if comparisons. The impacts of changing the discount rate from 7% to 3% are shown in Exhibit F-12. Now the results show an average benefit–cost ratio well above 1, again showing the dramatic impact that choice of discount rate can have on the analysis.

	Mean	Std Deviation
Avg NPV of Project	$9,510,258	$1,281,451
Avg B/C Ratio	1.14	0.02

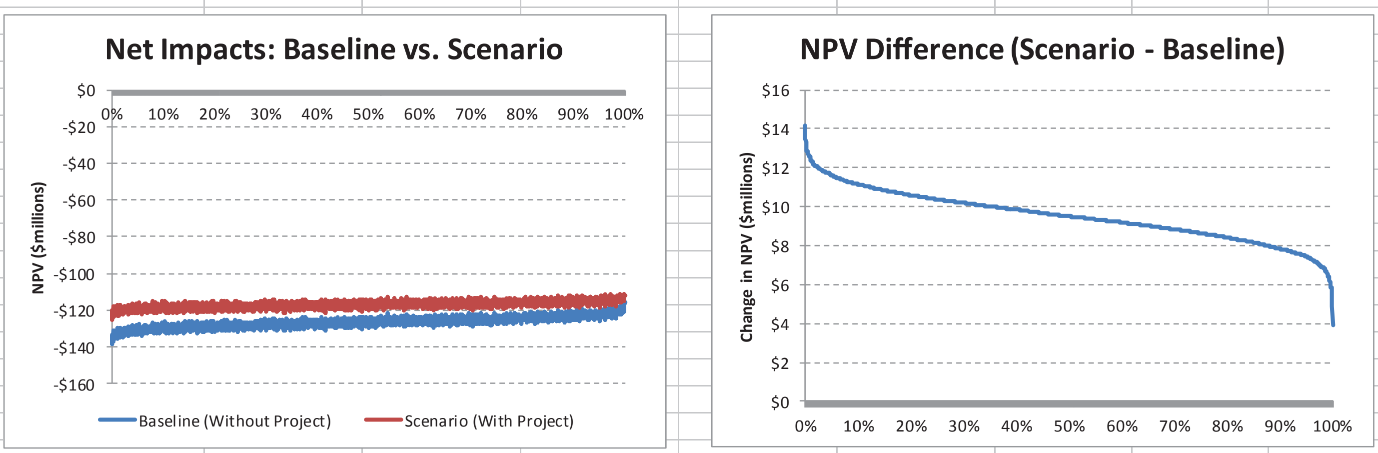


Exhibit F-12. BCA and VaR results for PHX project with 3% discount rate.

	Mean	Std Deviation
Avg NPV of Project	$9,414,641	$4,237,418
Avg B/C Ratio	1.14	0.06

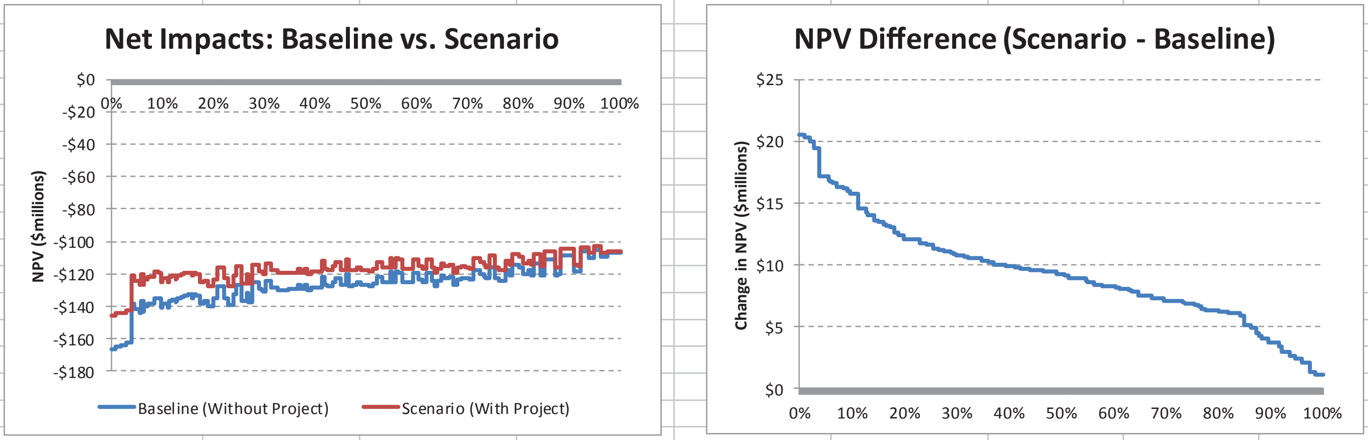


Exhibit F-13. BCA and VaR results for PHX project with 3% discount rate and alternate sampling strategy.

One can also see the effect of changing the sampling strategy. Both sets of results shown previously use the one-model-per-year strategy, where a different model is used for each year of each simulation. One could select the one-model-per-simulation strategy instead, where the same model is used for all years of any single simulation. These results (also assuming a 3% discount rate) are shown in Exhibit F-13.

The alternate sampling strategy has very modest effects on the average NPV and benefit–cost ratios, but it does increase the overall variability in results, as shown by the increased standard deviations, the more variable NPV curves in the VaR chart on the left, and the overall range of NPV differences in the chart on the right.

APPENDIX G

FAA Guidance on Benefit–Cost Analysis

The federal government has published general guidelines for conducting benefit–cost and cost-effectiveness analyses for federal programs under Office of Management and Budget (OMB) Circular No. A-94 (U.S. Office of Management and Budget 1992). This document serves as a checklist to ensure that all relevant elements of a proper BCA (or cost-effectiveness analysis) have been addressed. It also provides specific guidance on discount rates that are to be used in evaluating programs where benefits and costs are distributed over time. (Appendix C of this circular is updated annually and provides current discount rates for cost-effectiveness, lease purchase, and related analyses.) The guidelines in this document are directly relevant to the current study because airports seeking to obtain AIP funds for investment projects must be in compliance with the guidelines.

Circular A-94 contains specific guidance on a number of topics relevant to a public investment project, including:

- Identifying and measuring benefits and costs,
- Treatment of inflation (real or nominal values),
- Discount rates,
- Treatment of uncertainty, including expected values and sensitivity analysis,
- Incidence and distributional effects (i.e., who is affected), and
- Special guidance for public investment analysis.

The FAA's BCA guidance document (FAA 1999b) is consistent with OMB Circular A-94 and is tailored to airport investment projects under AIP. The explicit purpose of this document is to "provide clear and thorough guidance to airport sponsors on the conduct of project-level benefit–cost analysis (BCA) for capacity-related airport projects" (FAA 1999b, p. 1). The FAA takes a broad view of what qualifies as a "capacity project," which is determined via concurrence with FAA's Office of Airport Planning and Programming. The FAA identifies capacity projects as "development items that improve an airport or system of airports for the primary purpose of accommodating more passengers, cargo, aircraft operations or based aircraft" (FAA 2000). Currently, it is FAA policy that a BCA is required if the sponsor is requesting more than $10 million in discretionary funding over the life of the project, although the FAA may require a BCA for smaller projects as appropriate. As such, it is quite likely that most large climate adaptation investments being considered would require a formal BCA.

The FAA document provides comprehensive guidance on how to perform a BCA and includes instructions for the following:

- Defining project objectives,
- Specifying assumptions,
- Identifying the base case,

- Identifying and screening reasonable investment alternatives,
- Determining the appropriate evaluation period,
- Establishing reasonable level of effort,
- Identifying, quantifying, and evaluating benefits and costs,
- Comparing benefits and costs of alternatives,
- Performing a sensitivity analysis, and
- Making recommendations (FAA 1999b).

Certain elements of the guidance contained in OMB Circular A-94 and the FAA's BCA guidance document are particularly relevant in the context of analyzing climate change effects, and these are discussed in the following.

Description of the Project

Defining the project base case and scenario case(s) correctly is important to developing technically correct BCAs. To do this, decision makers should be able to answer the following questions:

1. What is the primary objective of the proposed project?

   As noted in the FAA guidance document, the objective should be identified in the context of specific problems or needs at the airport (FAA 1999b). It is important not to mistake the objective with the proposed plans for meeting that objective. In the present case, there are several types of objectives that could arise in light of climate change risks and uncertainties:
   - Mitigate delays or closures,
   - Mitigate damage to existing infrastructure and property,
   - Improve efficiency of airport operations, and
   - Improve airport safety and security.

   Correctly identifying the objective makes it easier to identify the base and scenario cases as well as the benefits and costs of the adaptation.
2. What is the best way to project the future airport environment?

   The benefit–cost estimates of most airport projects will depend on the assumptions made about the future airport environment. The most important component of these assumptions is typically the projected growth in airport activity. However, in the present context, another important component is the exposure of specific airport infrastructure to climate risk. Answering this question requires working through the processes described in prior chapters, identifying likely climate stressors, listing vulnerable and critical exposures, quantifying potential impacts, and identifying potential adaptations and responses.
3. How should the base case be specified?

   The base case is a reference point representing what is expected to occur if the proposed project is not undertaken. It is important to correctly identify the base case. In particular, it is almost never correct to identify the base case as a do-nothing course of action. Assuming such a static base case will almost certainly lead to an overstatement of the net benefits of a proposed project. This is particularly true in the case of climate resilience analyses, where the relevant time period for analyzing benefits and costs may be quite long.

   As noted in the FAA BCA guidance document, the base case "must assume optimal use of existing and planned airport infrastructure . . . ; it must also incorporate reasonable expectations of corrective actions by airport managers, users, and air traffic managers" (FAA 1999b) to mitigate identified airport problems or needs in the absence of a proposed project. In the present context, it will be important to identify existing or proposed adaptations (in operations or infrastructure) that should be included in the base case.

4. How should the scenario case be specified?

   In its broadest form, the scenario case represents a range of one or more alternatives that could be undertaken to achieve the objective(s) identified by the sponsor. As written in the FAA guidance document, "a valid BCA must have at least one alternative identified for each possible course of action. Each alternative must be a reasonable, well-founded, and self-contained investment option" (FAA 1999b). Of course, it is important to keep in mind that the alternative(s) for the scenario case selected for analysis should be a product of the screening and other potential constraints described in Chapter 6.

   Even if it seems clear that one particular alternative is the only reasonable way to proceed, the sponsor should not automatically exclude other possibilities. In the present context, relevant alternatives may be to delay the proposed investment for a certain length of time or to delay the decision itself about whether to make the investment.

Appropriate Evaluation Period

As has already been discussed, the latest science suggests that climate change is likely to continue well into the foreseeable future, and it will become more pronounced the further out one goes. Some relevant climate measures for localized areas are available out to the year 2099. This suggests that a long evaluation period may be appropriate when analyzing a specific project meant to mitigate the effects of climate change.

However, this may be at odds with FAA convention. The FAA's BCA guidance identifies three different evaluation periods:

- Requirement life. The period over which the benefits of the project will be greater than the costs. The guidance states that "from a practical point of view, requirement lives should not exceed 30 years" (FAA 1999b).
- Physical life. The period over which the asset can be expected to last physically.
- Economic life. The period over which the asset can be expected to meet the requirements for which it was acquired in a cost-effective manner. By definition, economic life is less than or equal to both requirement life and physical life (FAA 1999b).

The guidance states that investment projects are usually evaluated over their economic lives. By implication, this suggests that the relevant time period for analysis should always be less than 30 years. In fact, the guidance specifically states that the "FAA generally uses an economic life span of 20 years beyond the completion of construction for major airport infrastructure projects" (FAA 1999b).

However, the guidance also states that "longer life spans may be used if justified" (FAA 1999b). It is suggested here that investment projects designed to mitigate climate impacts are exactly the types of projects where a longer evaluation period may be justified since the largest climate impacts may well occur many years into the future. From a practical viewpoint, one important implication of using a long evaluation period is that the infrastructure being proposed may have to be replaced (at the end of its economic life) one or more times. In principle this can be directly handled in a BCA by specifying additional construction/rebuilding costs at appropriate points in the future.

It should be noted that FAA guidance also recommends that the selected evaluation period be augmented by "at least" 5 years to accommodate the need to evaluate optimal timing of investment alternatives (FAA 1999b). This fits in neatly with the timing options discussed previously.

Level of Effort

The FAA explicitly recognizes that the appropriate level of effort for a BCA may depend on many factors, and it suggests that the effort should be tailored to factors such as magnitude and complexity of the project, number of practical alternatives, availability of data, and sensitivity of benefits and costs to assumptions.

In addition, FAA guidance recognizes that practical considerations include the availability of time and budget; this is obviously a major concern for many smaller airports with limited resources. However, the guidance also states that "while lack of budget or time may constrain the scope of a BCA, they cannot be used to justify an inadequate analysis where circumstances clearly indicate a need for more information" (FAA 1999b). In any event, airport sponsors should consult early with the FAA regarding appropriate levels of effort.

As described earlier, it may be advantageous for entities with limited resources to consider a conventional BCA approach involving a few alternative scenarios with differing specified climate event assumptions. The discussion in Chapter 2 on conducting an initial screening analysis is particularly relevant. Those with more expertise or a larger budget could also consider the Monte Carlo simulation approach.

The FAA has also published a document providing useful guidance and information tailored to smaller airports (FAA 2013). It covers topics such as forecasting future demand and aircraft operations, consideration of nearby airports as potential next-best alternatives, and identification of relevant benefits and costs. In addition, the document explicitly discusses the case where a full BCA cannot be completed due to budgetary or other constraints and identifies the minimum amount of information that can be provided to the FAA.[38] This process is further discussed in the context of a less formal analysis when a full-blown BCA is not required (for example, during master planning or while vetting alternative projects).

The document also refers to a "BCA Lite" analysis (FAA 2013), which may be relevant in the form of a cost-effectiveness study for many typical airport rehabilitation projects. As noted in the FAA's BCA guidance document, the primary benefit associated with a rehabilitation project typically would reflect the impact on the airport if the facility were allowed to fail completely (FAA 1999b). In most cases, the FAA expects that it will not be beneficial to allow a major airside facility to fail, so the concern focuses more on the most cost-effective way to complete the rehabilitation. A BCA Lite cost-effectiveness analysis typically would not be relevant for assessing the impacts of uncertain climate change because it focuses entirely on the direct costs of undertaking a project without formal consideration of the benefits.

Measurement of Benefits and Costs

The impacts of climate change—whether they be chronic (increased daily surface temperatures) or acute (increased likelihood of flooding events)—will typically be measured on the benefits side of a BCA in the form of avoided costs due to airport delay, closure, or other related significant impacts.

Many of these impacts will not accrue directly to the airport. As such, they may be considered "social" impacts, reflecting costs to aviation stakeholders at large. In the case of a partial or complete airport closure due to, say, a storm surge, the relevant list of benefits from avoiding such an event might include any or all of the following avoided costs:

- Aircraft, passenger, or cargo delay;
- Airport and aircraft damage;

- Airport cleanup/restitution costs;
- Costs due to personal injury or death; and
- Loss of local business activity.

Some of these impact categories reflect social costs not incurred directly by the airport itself. Regardless of what specific entities are affected, determining a method of measuring them can be difficult. For example, it is not necessarily an easy matter to estimate how many hours of delay would be caused by surface temperatures rising above some specified threshold. Generically, temperatures above the threshold would cause an aircraft's minimum required takeoff speed to exceed what is possible on the available runway, and the operator would have to either cancel the flight or remove passengers or cargo to decrease its weight and thus lower its required takeoff speed. Such weight restrictions are fairly common in some locations, obviously depending on local temperatures and the specifics of the aircraft involved.

While the specifics of quantifying the expected incidence and impact of high temperatures on aircraft performance are well beyond the scope of this handbook, some recent work has been done on this exact subject using CMIP5 projections (see Coffel and Horton 2015; Coffel et al. 2017). While limited to an analysis of four large U.S. airports (Phoenix, Denver, LaGuardia, and Washington-National), the results suggest significant increases in the incidence of high temperatures causing either a 10,000-lb or 15,000-lb weight restriction for a Boeing 737-800 aircraft. Combined with projections of scheduled aircraft activity, such impacts could be translated into passenger or cargo values in order to estimate total delay quantities and dollar values for a given threshold temperature occurrence in a given year.

Generally speaking, if the quantities can be reasonably estimated, then in many cases their overall valuation in dollar terms can be projected using FAA guidelines. Unit valuations are available directly from the FAA's Economic Values publication (FAA 2016b), which is updated periodically and includes recommended values for passenger time, life and injury costs, aircraft capacity and utilization factors, aircraft operating costs, replacement and restoration costs of damaged aircraft, and labor cost factors.

On the investment cost side, FAA guidance also provides valuable information related to life-cycle costing. Interested readers should consult the FAA BCA guidance document for details on topics such as planning and research and development costs, investment costs, operations and maintenance costs, and termination costs.

Appropriate Discount Rate

A particularly important factor to consider in a BCA is the appropriate discount rate for the project. The FAA has traditionally followed OMB guidance on this subject. There are two alternative rationales for discounting. One is investment-based, which says that the rate should reflect the prevailing rate of capital productivity [i.e., the opportunity cost (or pretax average return) of capital]. Under Circular A-94 (U.S. Office of Management and Budget 1992), OMB has set this rate at 7% in real terms (net of inflation), and that is the rate that is conventionally used in most BCAs considered by the FAA.

An alternative rationale for discounting is consumption-based, which reflects the rate at which society is willing to trade consumption today for future consumption (this is sometimes called the social rate of time preference). A reasonable approximation of this rate is the real rate of return on long-term government debt. Over the past 50 years or so this rate has averaged under 3%.

If there were no tax or other distortions, then in principle the consumption-based discount rate would equal the investment-based rate. However, there are many practical reasons why the two might diverge.[39] In 2003, OMB issued additional guidance via Circular A-4 suggesting that for projects involving regulatory analysis, separate estimates should be presented using both 7% and 3% real discount rates (U.S. Office of Management and Budget 2003).

Note that use of a 7% discount rate in the present context implies that the increasing effects of climate change felt many years into the future would not likely have significant present value impacts. For example, discounting a $1 million impact occurring 50 years from now by 7% annually would result in a present value impact of under $34,000. By contrast, discounting at 3% gives a present value impact of about $228,000. While OMB has not issued formal updates to its 7% guideline, it is suggested that airport sponsors proposing to undertake climate resilience investments with a long time horizon discuss this issue with the FAA.

A separate though related topic concerns whether the use of a declining discount rate might be preferred for projects with long time horizons. In particular, it is difficult to know for sure what the average or median return on investment might be many years into the future. In general, it can be shown that using a single mean discount rate will lead to a lower net present value of a given cash flow compared to using values above and below the mean that are considered equally likely; the effect is magnified the longer is the time horizon. This suggests that use of a declining discount rate may be economically justified for projects with very long-term impacts (Arrow et al. 2012).

APPENDIX H

Case Study Details

Four airports agreed to participate in illustrative case studies demonstrating the methodology described in this handbook to help airports evaluate the potential impacts of climate change. The project team presented example scenarios of specific climate risks faced by each airport using the most recent and localized climate data. This appendix provides further details on the interactions with each airport. It is important to emphasize that while the project mitigations are purely illustrative, the climate data shown in each case represent actual current estimates of potential future climate outcomes. It is also important to emphasize that, in all cases, the climate projections used were those from RCP8.5, which represents a high-emissions scenario for future climate change.

New Orleans

Historical experience and current climate projections indicate that MSY is at significant risk of flooding. After introducing the ACROS tool to the airport team, the summary results from that software were presented, as shown in Exhibit H-1. The results show that flood risk for the airport will occur every day of the year by 2030, regardless of the climate model employed. ACROS shows an increase of 2 ft in BFE, which would have implications for protecting existing infrastructure through the use of dikes or raising infrastructure to offset flood risks.

Following the methodology suggested previously, ACROS screening indicated that further analysis was warranted.

A slide from the MSY presentation, shown in Exhibit H-2, provides a general introduction to historic EWL and projections of future RSL rise. NOAA is the source for both data series. The example in the slide is taken from data for Kings Point/Willets Point, New York, a tidal station near LaGuardia Airport. The top graph is the historic probability of water levels above mean high tide; for example, this area could expect a 1.5-m extreme water event every 10 years. Therefore, the annual probability of such an event is 1 in 10. The bottom table on the right shows local sea level rise predictions (expressed in centimeters) for the Kings Point station based on six different forecast GMSL rise scenarios (low to extreme). The probabilities of these outcomes are linked to three global emissions scenarios used by climate scientists—RCP2.4, 4.5, and 8.5, as shown in the bottom left table. For example, under RCP8.5, the probability of the King's Point Intermediate scenario sea level rise of 41 cm is 17% in 2050.

As described in Appendix D, after selecting one of the RCP scenarios, one can generate a random draw of future sea level rise by interpolating between the GMSL rise scenarios and

Step 1: ACROS Screening Analysis

- ACROS flood risk for MSY for 2013, 2030 and 2060

Summary of Historical Record and Projected Changes (Days/Year)								
Climate Vector	Units	2013	2030			2060		
		Baseline	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
SeaLevelRise	days per year	0	365	365	365	365	365	365
SeaLevelRise_Base Flood Elevation	feet	-2	-2	-1	-1	-1	-1	0

- Projections provide limited usefulness for MSY specifically since they project runway inundation (sea level higher than runway elevation) for every day of the year by 2030
- There is a projected increase in Base Flood Elevation of two feet in the worst case scenario
- But the projected high annual counts suggest further investigation is warranted

7 April 25, 2018 Copyright GRA, Inc. GRA, Incorporated

Exhibit H-1. ACROS results for MSY.

between the 10-year intervals for the localized projections. Combining that draw with a random draw from the historical EWL graph results in a probabilistic localized projection of the height of a future EWL event in any given year.

Exhibit H-3 shows the results of 5,000 Monte Carlo simulations for the localized projection of EWL events for MSY.[40] The top-most table shows both the historical probabilities and the projected mean annual outcomes for the future at 10-year intervals. The bottom part of the exhibit shows the assumptions for a generic mitigation project. The left side reports the assumed investment and operations and maintenance costs (including periodic restoration) and the right side reports the assumed costs to the airport of each extreme event with and without the mitigation project. (These cost assumptions are completely generic and not based on any real data.)

These values can be considered in relation to the conventional use of the 100-year storm as a metric for establishing building standards. Many localities and airports use the 100-year storm (based only on historical data) to set elevations for new building and for remediation of existing infrastructure, typically adding 1 to 3 ft of freeboard to the expected flood level to generically account for sea level rise. As shown in the Exhibit H-3, the 100-year event for MSY grows from about 6.4 ft based on historical data to well over 11 ft by 2095. These results show that using a conventional assumption of 3 ft of freeboard for infrastructure assets would provide a good chance of protection through at least 2065.

Exhibit H-4 illustrates how the probability projections and cost data are combined to get results in the Monte Carlo model; each row is one of 5,000 simulations, with the columns being

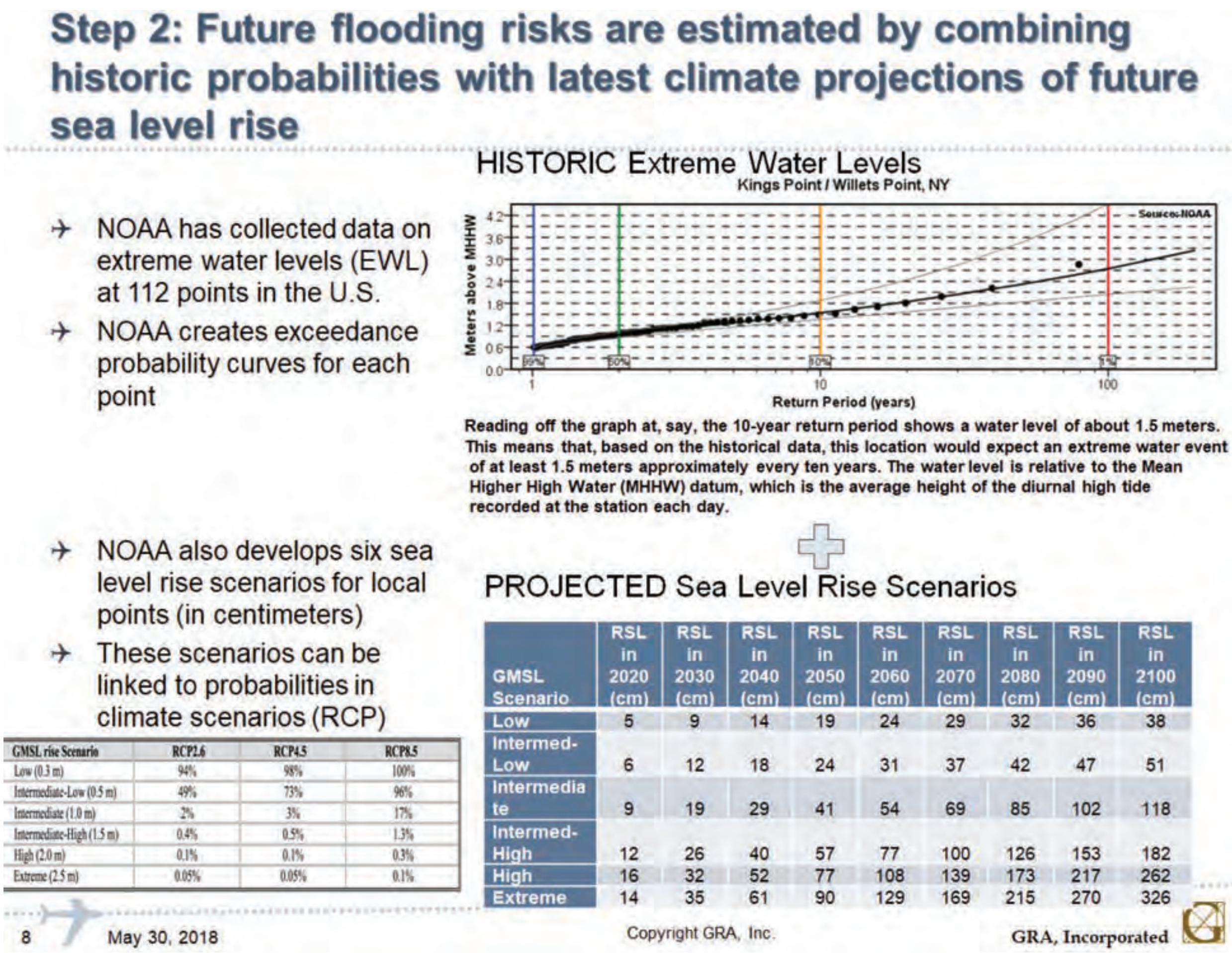


Exhibit H-2. Historical and future projections of extreme water events.

each year from 2020 to 2099. In this instance, the numbers shown in the table are the cost to the airport of extreme water events with the mitigation project. The implicit assumption in the simulations is that the generic mitigation project does not fully eliminate the costs of all flood events. Notice that the costs increase over time as the probability of more extreme events increases.

The main findings of the sample analysis are presented in Exhibit H-5, as expressed in a VaR graphic. The blue line is the range of probable outcomes without mitigation, and the red line is with mitigation. Each curve is composed of 5,000 possible outcomes for the airport (net costs to the airport expressed in NPVs). The box on the left side of the exhibit reports the average NPV and benefit–cost ratio for the project. In this generic example (using actual climate data), conventional decision making would suggest that the project is justified and should be pursued (absent capital constraints).

The graphic is informative because it shows the distribution of potential outcomes based on the Monte Carlo simulations. It shows that 70% of the time, the project would pay off (benefit–cost ratio greater than 1), but if the airport does nothing, there is a 20% chance it would lose $40 million or more over the analysis period (expressed in today's dollars). These findings could be relevant for both financial management and risk planning.

Participant Feedback

The airport participants appreciated the level of detail that went into the analysis and suggested that the approach could have some value as an adjunct to their consideration of future

Extreme Water Events at MSY could cause damage and flight disruptions

- Select a future climate change scenario. Use the probabilities from the historic data + the probabilities from the projected climate change scenario to create 5000 simulations of future extreme water events for MSY (from 2020 thru 2100); this results in a distribution of outcomes

MSY Extreme Water Level Event Probabilities from 5,000 Simulations (RCP 8.5)

Water Level Rise (ft)	Historical	2025	2035	2045	2055	2065	2075	2085	2095
0-1	9.66%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1-2	58.18%	30.80%	4.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2-3	20.62%	46.74%	56.22%	29.88%	4.68%	0.22%	0.00%	0.00%	0.00%
3-4	6.78%	14.38%	26.12%	45.72%	50.08%	25.88%	6.82%	0.84%	0.04%
4-5	2.76%	4.36%	8.00%	16.20%	29.96%	44.86%	41.32%	22.38%	8.52%
5-6	0.80%	1.72%	3.04%	4.64%	9.54%	18.36%	31.78%	38.96%	31.08%
6-7	0.44%	1.00%	1.18%	1.66%	3.10%	6.62%	12.24%	21.64%	31.34%
7-8	0.24%	0.36%	0.70%	0.74%	1.42%	1.92%	4.22%	9.80%	16.00%
8-9	0.18%	0.22%	0.20%	0.32%	0.66%	0.90%	2.16%	3.40%	7.60%
9+	0.34%	0.42%	0.48%	0.84%	0.56%	1.24%	1.46%	2.98%	5.42%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Median (ft)	*1.62*	*2.31*	*2.80*	*3.32*	*3.91*	*4.46*	*5.05*	*5.66*	*6.27*
100-Yr Event	*6.41*	*6.99*	*7.38*	*8.40*	*8.43*	*9.25*	*9.66*	*10.41*	*11.37*

- Develop estimates of the costs per event when water rises to each level
- Develop estimates of the costs to mitigate
  - Example: $5M project with annual maintenance cost of $0.5M; rehab in 25 years for $2M

Flooding Event Damage Costs

EWL (ft)	Without Project	With Project
0-1	$0	$0
1-2	$0	$0
2-3	$100,000	$0
3-4	$500,000	$0
4-5	$1,000,000	$0
5-6	$1,000,000	$200,000
6-7	$5,000,000	$1,000,000
7-8	$10,000,000	$2,000,000
8-9	$10,000,000	$2,000,000
9+	$10,000,000	$2,000,000

9 May 3, 2018 Copyright GRA, Inc. GRA, Incorporated

Exhibit H-3. Simulation summary and cost assumptions for MSY.

flood elevation maps. They stated that it could also be useful in master planning. While the airport representatives were focused on stormwater management at that time, they commented that the methodology could be useful in the analysis of any projects with long life spans such as runways, parking garages, terminals, and levees. They were also aware that the specific localized sea level projections used in the sample analysis might not be accurate for MSY due to their remote geographic location.

Boston

Similar to MSY, Logan Airport in Boston may be threatened by flooding from sea level rise or storm surge. The ACROS screen for BOS shows no expected days of flooding from sea level rise. However, ACROS does show an increase in base flood elevation, which could threaten some BOS infrastructure or access routes.

Exhibit H-6 shows the localized projection of the probability of extreme water events for the airport, using the same data sources and methodology described for MSY.[41] The exhibit also presents the same $5 million generic project to mitigate the effects of climate change.

5000 Monte Carlo Simulations

→ Example: Damages Caused by Flooding with Mitigation Project

Annual Costs to Airport with Mitigation

Scenario	2020	2021	2022	2023	...	2097	2098	2099
1	$0	$200,000	$0	$0	...	$200,000	$200,000	$200,000
2	$500,000	$0	$0	$0	...	$1,000,000	$200,000	$200,000
3	$0	$1,000,000	$0	$0	...	$200,000	$200,000	$1,000,000
4	$100,000	$0	$0	$0	...	$0	$1,000,000	$2,000,000
5	$0	$0	$0	$0	...	$1,000,000	$1,000,000	$0
6	$100,000	$0	$0	$0	...	$1,000,000	$1,000,000	$1,000,000
7	$500,000	$0	$0	$0	...	$200,000	$1,000,000	$200,000
8	$0	$0	$1,000,000	$200,000	...	$1,000,000	$1,000,000	$1,000,000
9	$0	$0	$0	$0	...	$200,000	$1,000,000	$2,000,000
10	$100,000	$0	$0	$0	...	$2,000,000	$2,000,000	$2,000,000
					...			
4998	$0	$0	$0	$0	...	$2,000,000	$1,000,000	$1,000,000
4999	$0	$0	$200,000	$0	...	$2,000,000	$2,000,000	$2,000,000
5000	$100,000	$0	$0	$0	...	$2,000,000	$2,000,000	$2,000,000

10 April 25, 2018 Copyright GRA, Inc. GRA, Incorporated

Exhibit H-4. Monte Carlo simulations for MSY.

It is interesting to compare the climate simulation results with more traditional analysis based on 100-year events. The 100-year event for BOS represents an EWL of about 4.6 ft based on historical data, and it grows to nearly 9 ft by 2095. These results show that using a conventional assumption of 3 ft of freeboard for infrastructure assets would provide a good chance of protection through at least 2075.

Exhibit H-7 shows the results of the VaR analysis for the generic mitigation project. The mean project shows marginal net benefits with a benefit–cost ratio of 1.02. However, the project would pay off only 35% of the time. There is a 10% chance of the airport losing at least $40 million (NPV).

Participant Feedback

BOS was already doing its own modeling of flood risks using the Boston Harbor Flood Model. It used that model to provide estimates for the Massport Flood Proofing Design Guide, which uses a 500-year event (probability 0.2%) and the "intermediate-high" GMSL rise scenario as baselines. Given this background, airport representatives had no trouble understanding the methodology and the added benefit of sampling across different uncertain future outcomes. They appreciated the fact that the Excel model allows the user to select from among different emissions scenarios. They also suggested that in addition to analyzing new mitigation projects, the methodology could also be used to summarize risk in terms of the probability of occurrence over the remaining life of existing assets.

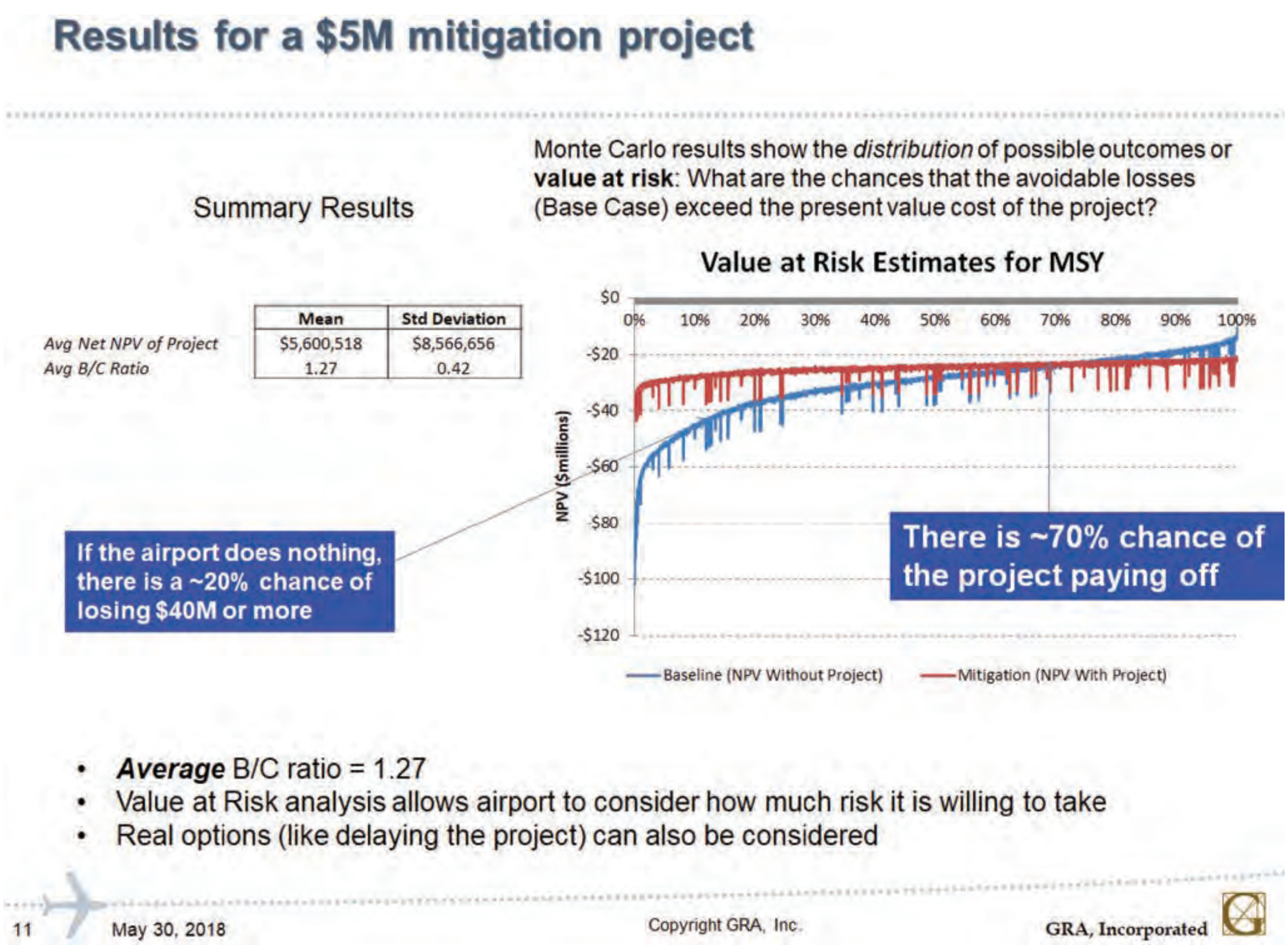


Exhibit H-5. Sample VaR results for MSY.

Although the presentation did not directly discuss the potential use of inundation maps, the Boston participants suggested that linking such maps to flooding occurrence probabilities could be useful for their own internal illustration purposes. They also thought that a high-level handbook would be useful for upper management.

Phoenix

One of the important climate issues faced by PHX is increased frequency of very high ambient temperature days. In the summer of 2017, there were about 50 regional jet operations that were cancelled when temperatures breached 118°F. Standard narrow-body jets would face similar cancellation issues at about 126°F (Wang 2017).

The case study presented to the airport examined the number of days the airport would face extreme temperatures in the future (118°F for regional jets and 126°F for standard jets). For the purposes of the case study, in the base case it was assumed that flights would be delayed by an average of 3 hours during the middle part of the day. The mitigation project analyzed was a runway extension that would completely eliminate these delays.

It is important to note that this is a simplified analysis where flights are delayed due to very high temperatures. A more realistic analysis would assess the impact of weight restrictions (which could begin to occur at much lower temperatures), where flights are not actually delayed

Extreme Water Events at BOS could cause damage and flight disruptions

- Select a future climate change scenario. Use the probabilities from the historic data + the probabilities from the projected climate change scenario to create 5000 simulations of future extreme water events for BOS (from 2020 thru 2100); this results in a distribution of outcomes

BOS Extreme Water Level Event Probabilities from 5,000 Simulations (RCP 8.5)									
Water Level Rise (ft)	Historical	2025	2035	2045	2055	2065	2075	2085	2095
0-1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1-2	3.88%	0.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2-3	68.46%	45.28%	24.68%	8.84%	1.76%	0.40%	0.12%	0.04%	0.00%
3-4	24.16%	46.46%	60.06%	61.94%	48.16%	28.04%	15.24%	9.52%	4.38%
4-5	2.98%	7.24%	13.34%	24.90%	40.38%	50.00%	47.64%	37.10%	29.00%
5-6	0.40%	0.80%	1.76%	3.66%	8.58%	17.68%	27.32%	34.06%	34.94%
6-7	0.12%	0.12%	0.16%	0.52%	1.02%	3.34%	7.72%	13.76%	19.38%
7-8	0.00%	0.02%	0.00%	0.14%	0.10%	0.48%	1.48%	4.20%	8.66%
8-9	0.00%	0.00%	0.00%	0.00%	0.00%	0.04%	0.44%	1.00%	2.76%
9+	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.04%	0.32%	0.88%
TOTAL	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Median (ft)	*2.66*	*3.06*	*3.32*	*3.63*	*4.00*	*4.37*	*4.72*	*5.07*	*5.45*
100-Yr Event	*4.63*	*4.98*	*5.29*	*5.66*	*6.06*	*6.74*	*7.38*	*8.14*	*8.88*

- Develop estimates of the costs per event when water rises to each level

- Develop estimates of the costs to mitigate
  - Example: $5M project with annual maintenance cost of $0.5M; rehab in 25 years for $2M

Flooding Event Damage Costs		
EWL (ft)	Without Project	With Project
0-1	$0	$0
1-2	$0	$0
2-3	$100,000	$0
3-4	$500,000	$0
4-5	$1,000,000	$0
5-6	$1,000,000	$200,000
6-7	$5,000,000	$1,000,000
7-8	$10,000,000	$2,000,000
8-9	$10,000,000	$2,000,000
9+	$10,000,000	$2,000,000

10 May 3, 2018 Copyright GRA, Inc. GRA, Incorporated

Exhibit H-6. Simulation summary and cost assumptions for BOS.

but are forced to offload passengers in order to take off. The Excel template developed for high temperatures directly addresses these impacts rather than assuming flight delays.

The ACROS model shows an appreciable increase in hot days (90°F or more) and very hot days (100°F or more). Using ACROS as a screening tool suggests that the airport needs to prepare for increased frequency of such days, but the information is not precise enough to examine the problems that aircraft with current technology may face when temperatures exceed 118°F.

The more detailed VaR evaluation for PHX uses the high-emissions RCP8.5 climate scenario. For each of the 5,000 simulations run for PHX, and for each year between 2020 and 2089, the model randomly selects from one of 31 different climate models, each of which makes daily projections of high temperatures throughout the selected period. For each year, one can simply count up how many days the selected model forecasts in excess of 118°F and 126°F.

Exhibit H-8 summarizes the range of outcomes for 118°F days by decade. The dots in the graph show the median number of days each year. The lines represent the range of average number of annual days (by decade) produced by the Monte Carlo simulations. Notice that the uncertainty increases significantly the further into the future one looks.

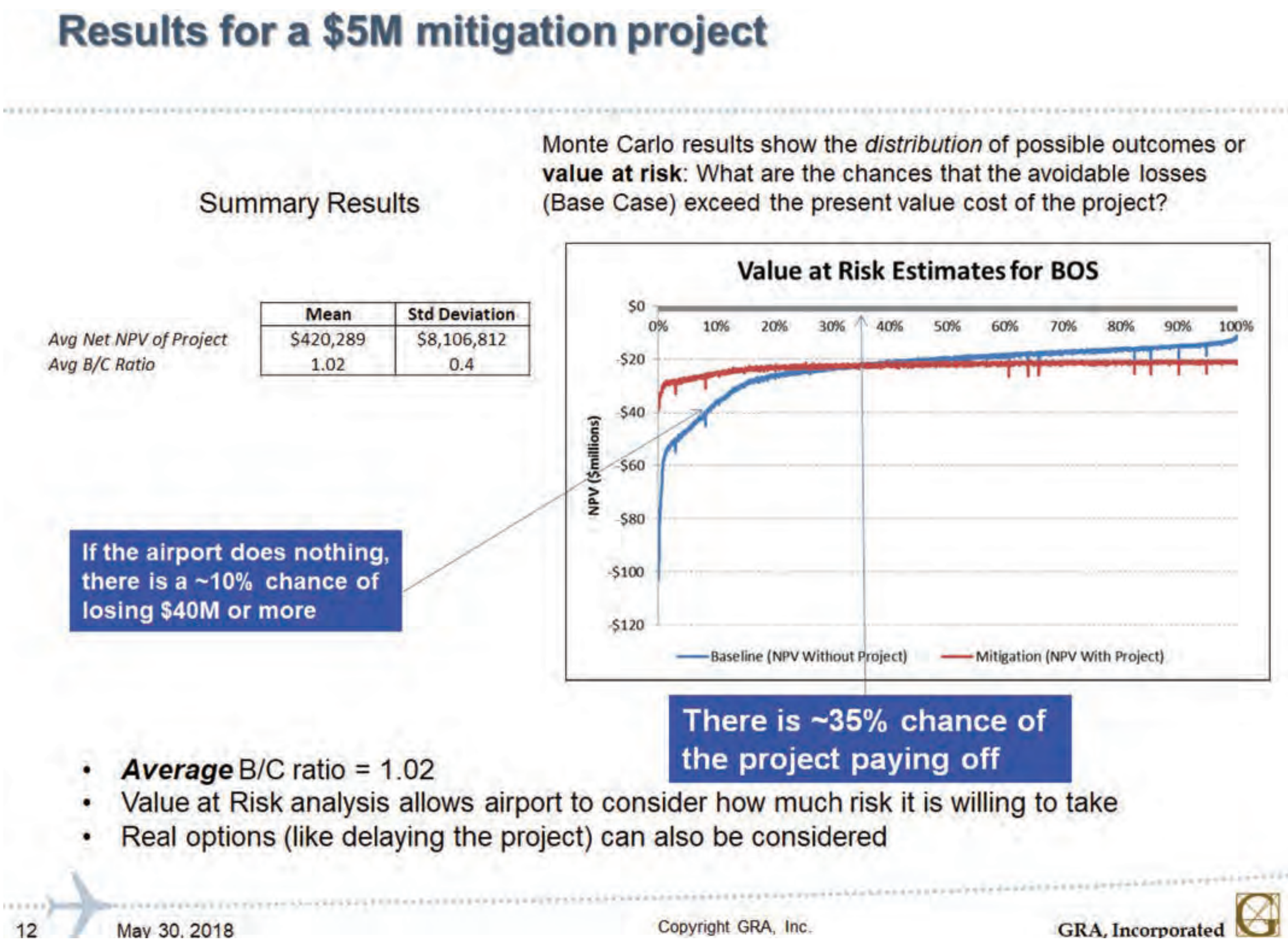


Exhibit H-7. Sample VaR results for BOS.

It was assumed that the airport would be developing a benefit–cost study to support an LOI application for an AIP grant to extend its longest runway. The main purpose of the extension would be to prevent the cancellation/rescheduling of flights on days with very high temperatures.[42] The life-cycle costs (discounted present value) of the extension were assumed to be $30 million. In the base case, each time temperatures reached 118°F, regional jet flights during the middle of the day incurred 3-hour delays. Standard jets experienced the same delays at 126°F. The FAA's airport benefit–cost guidance methodology (FAA 1999b) and its Economic Values for FAA Investment and Regulatory Decisions (FAA 2016b) were used to value passenger delays, operator crew costs, and depreciation (the latter due to the aircraft not being productively used for 3 hours). Exhibit H-9 summarizes the assumptions used in the analysis example.

The results of the VaR analysis are shown in Exhibit H-10. In this instance, the NPV of the project is negative (–$5.1 million), with only a 15% chance of being positive. There is a 3% chance that passengers and operators would lose $35 million (NPV) over the analysis period.

Participant Feedback

PHX personnel appreciated the level of detail that went into the methodology and thought the Monte Carlo analysis made sense and was well organized. However, they suggested that material presented to senior management would have to focus much less on the modeling and more on the primary takeaways from the summary results. There also appeared to be some sense that due

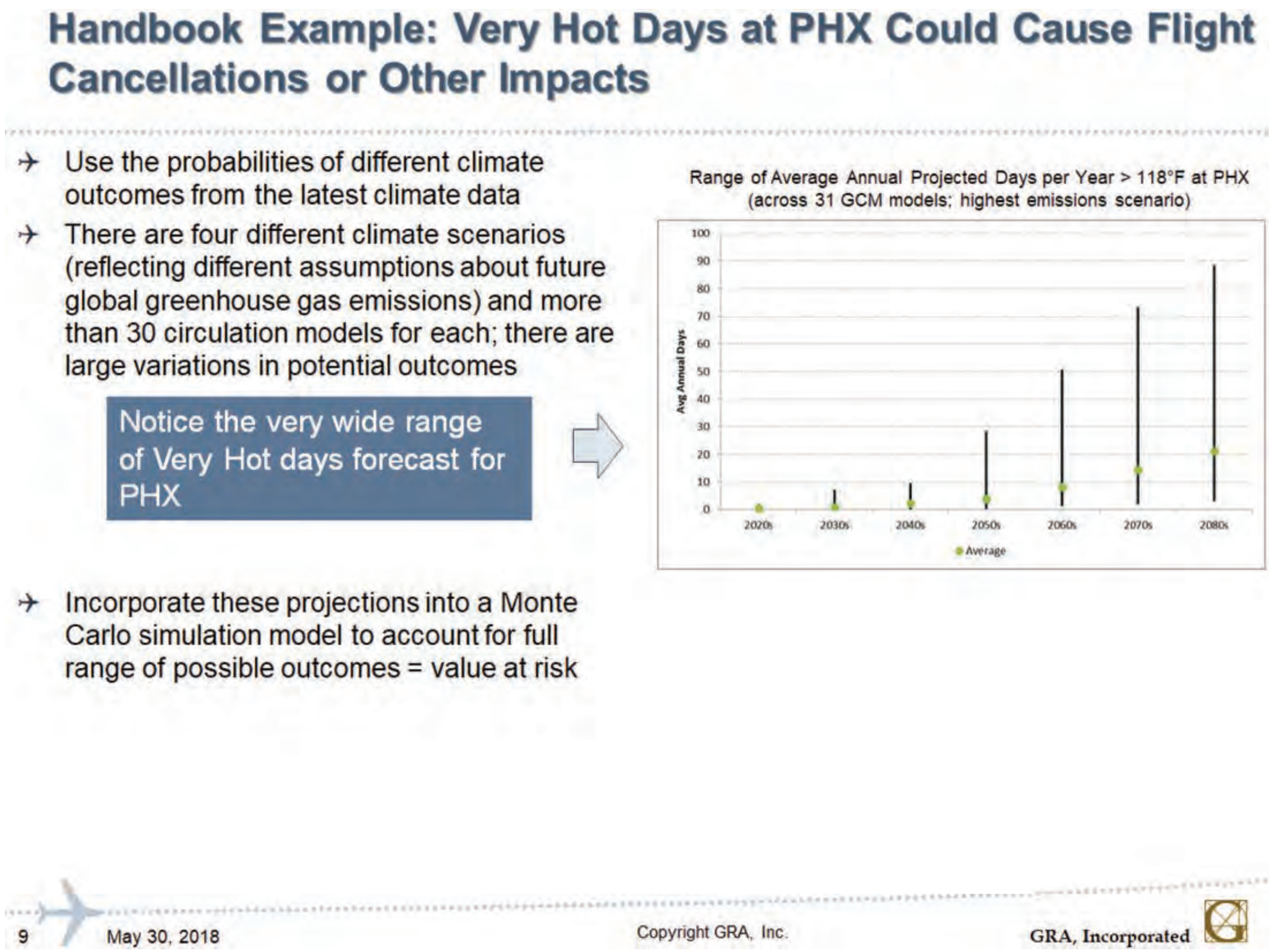


Exhibit H-8. High-temperature projections at PHX.

to the highly uncertain nature of future climate change, one would have to be careful not to put too much stock in the results from any one analysis.

As for the specific analysis, airport representatives correctly noted that there will be payload/range restrictions that would become relevant at much lower temperatures than the very high ones used in the example. They also noted that high temperatures are also detrimental to asphalt taxiways and ramps and to personnel working outside (which PHX is already addressing).

Little Rock

LIT has an 8,200-ft runway. Its longest commercial flight at the time of writing was to Los Angeles, but it had aspirations for longer flights. The airport indicated that it would be concerned if airlines faced frequent payload penalties for service to these destinations due to increasing high temperatures.

The case study presented to the airport examined the potential impact of payload restrictions when daily high temperatures exceeded 100°F. The ACROS model shows a substantial increase in very hot days (more than 100°F) by 2060 for LIT. Thus, a more precise analysis for a possible runway extension could be warranted.

Assumptions								**Source**
Construction cost for 2,500-ft runway extension $21,875,000								Assumes $350/sq yard for 150-ft wide runway + 75-ft wide taxiway
20-year rehabilitation cost % construction cost	50%							Assumed value
Annual O&M expense % construction cost	3%							Assumed value
Affected Flights:	**320**	**321**	**738**	**739**	**CR7**	**CR9**	**E75**	**Source**
Threshold Temperature (°F)		126			118			
Avg daily flights 1300-1759 in 2017	20.2	24.9	42.0	6.3	22.5	24.7	5.9	Official Airline Guide (OAG) -- based on May-Sep 2017, 1300-1759 hrs
Avg block hrs per flight	2.6	2.7	3.0	2.7	1.4	1.4	2.1	
Avg seatsize	170	187	158	175	63	84	75	
Passenger Impacts:								
Avg load factor	83.0%	83.2%	81.0%	85.2%	86.4%	75.4%	84.8%	FAA T-100 Domestic Segment report -- PHX load factors by eqpt type for May-Sep 2016
Avg daily pax per flt	*141.1*	*155.6*	*128.0*	*149.1*	*54.4*	*63.3*	*63.6*	= Avg seatsize * Avg load factor
Avg hrs of delay per passenger	3.0	3.0	3.0	3.0	3.0	3.0	3.0	Assumed value
Passenger delay cost per hr	$44.30	$44.30	$44.30	$44.30	$44.30	$44.30	$44.30	FAA Economic Values, Table 1-1, All Purpose Intercity Air and High Speed Rail
Total passenger delay cost at threshold in 2017	*$378,794*	*$514,860*	*$714,359*	*$124,837*	*$162,765*	*$207,909*	*$49,869*	= Avg daily flights in 2017 * pax per flt * hrs of delay per pax * delay cost per hr
Total Passenger Impacts at threshold in 2017		*$1,608,013*			*$545,380*			
Airline Impacts:								
Crew cost per block hr	$777	$777	$724	$777	$349	$349	$349	FAA Economic Values, Table 4-6
Aircraft depreciation per block hr	$352	$352	$221	$352	$144	$144	$144	
PHX delay propagation multiplier	1.49	1.49	1.49	1.49	1.49	1.49	1.49	FAA Economic Values, Table 10-1
Total airline cost at threshold in 2017	$88,350	$113,095	$177,414	$28,614	$23,139	$25,401	$9,101	= Avg daily flights in 2017 * block hrs per flt * (crew costs + depreciation per block hr) * delay propagation multiplier
Total Airline Impacts at threshold in 2017		*$378,859*			*$86,256*			
Total Daily Impacts at threshold in 2017		***$1,986,872***			***$631,636***			
PHX annual departure growth rate, 2017-2045	2.1%							FAA TAF Forecast 2016, ITN_AC ops avg annual growth rate at PHX, 2017-2045
PHX annual departure growth rate, 2045-2079	1.0%							Assumed value

Exhibit H-9. BCA assumptions for PHX.

Based on estimates from Airbus A320 and Boeing 737-800 aircraft performance charts, Exhibit H-11 shows estimated payload penalties in terms of passengers who would not be able to fly when temperatures breach 100°F or 110°F.

It is important to note that these estimates of passenger reductions do not take into account the possibility that an airline might be able to offload cargo, which would reduce the number of passengers affected. In addition, these are manual, informal projections based on visual approximations taken from the aircraft performance charts, and they assume 100% load factors.[43]

The presentation assumed that LIT was developing a benefit–cost study to support an LOI application for an AIP grant to extend its runway. It was assumed that passengers would be delayed by an average of 6 hours if not able to fly due to weight restrictions.[44] Unit costs to passengers are the same as those assumed for PHX. The mitigation project being analyzed was a runway extension costing $30 million.

The sampling of the 31 climate models used in the PHX analysis (assuming emission scenario RCP8.5) was repeated for LIT. The temperature projections are illustrated in Exhibit H-12, which shows the range of forecasts (by decade) for annual days at LIT exceeding 110°F. Again, the uncertainty increases the further into the future one looks.

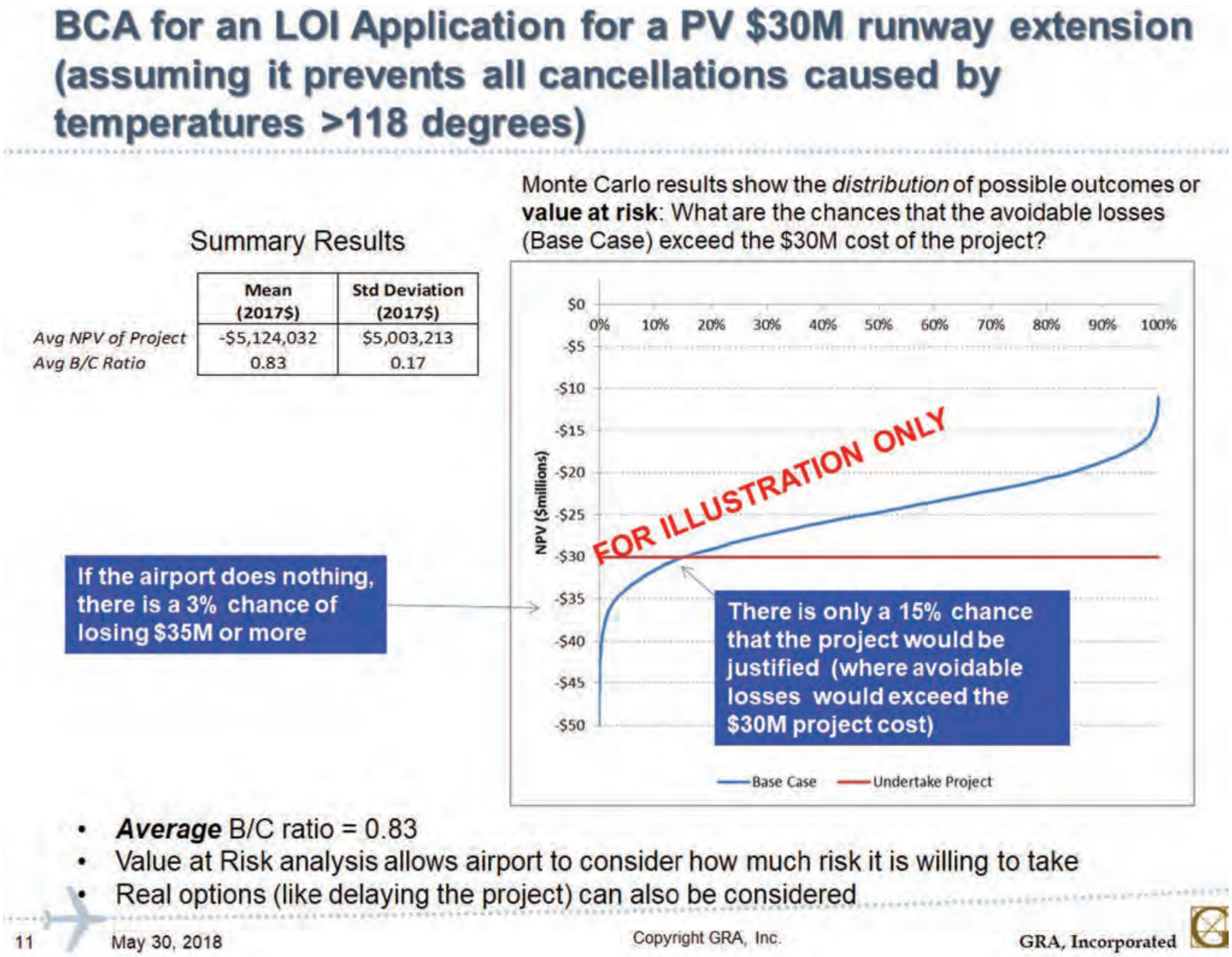


Exhibit H-10. Sample VaR results for PHX.

Exhibit H-13 shows the results of the VaR analysis. The benefit–cost study showed negative mean results (–$1.8 million NPV and benefit–cost ratio of 0.91). There is only about a 7% chance of the project paying off if it were built today. Large losses for passengers appear to be unlikely, even in the worst cases, if nothing is done (base case).

Participant Feedback

Although the participants from LIT were not familiar with ACROS, they found the summary projections informative and potentially indicative of a future issue regarding payload restrictions. They specifically viewed payload penalties as an issue for air service development efforts involving service to other airports.

Based on their engineering backgrounds, the participants found the logic of the Monte Carlo VaR analysis easy to follow and agreed that it might be useful to apply this type of analysis to justify AIP funding. They did noted that the wide variance in outcomes is similar in nature to the uncertainties of enplanement scenarios used in master planning.

As a general matter, the airport personnel offered that they typically would depend on the airlines to identify needed infrastructure improvements to support long-haul flights.

			Passengers Removed per Flight			
			100°F day		110°F day	
Airport	Served Today	Distance (nm)	A320	737-8	A320	737-8
LAS	Yes	1122		10		16
LAX	Yes	1298	10		16	
LGA	No	943		3		
BOS	No	1095		9		14
SFO	No	1467		24		44
SEA	No	1552		28		51

Note: LAS = McCarran International Airport, LAX = Los Angeles International Airport; LGA = LaGuardia Airport; SFO = San Francisco International Airport; SEA = Seattle–Tacoma International Airport.

Exhibit H-11. Estimated passenger payload restrictions at LIT.

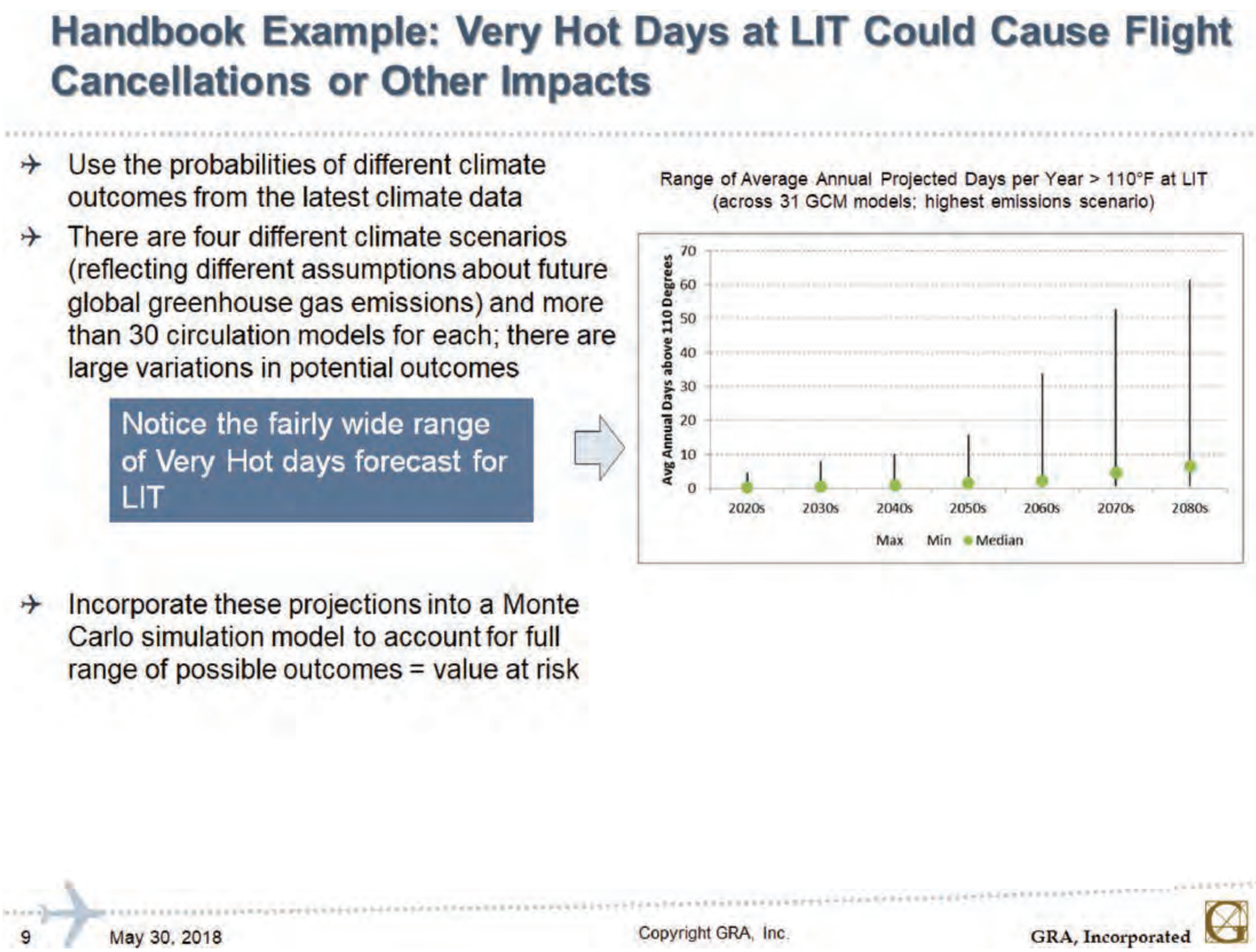


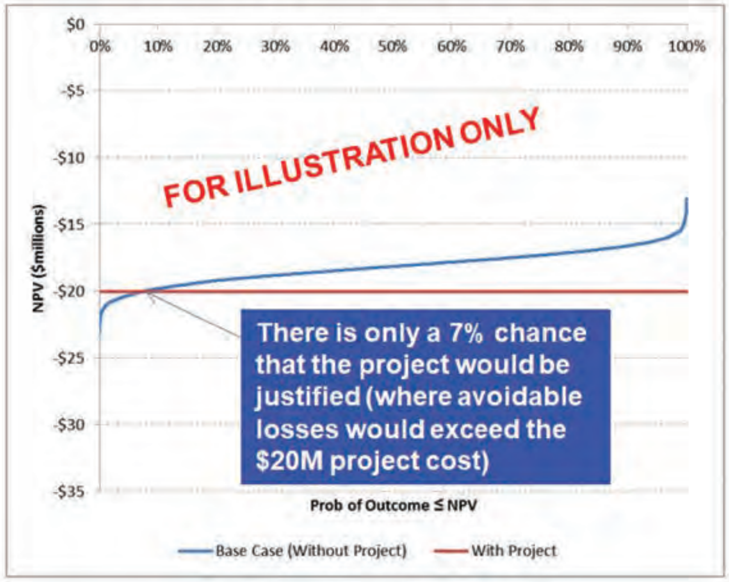
Exhibit H-12. High-temperature projections at LIT.

BCA for an LOI Application for a PV $20M runway extension (assuming it prevents all weight restrictions caused by temperatures >100 degrees)

Summary Results

	Mean (2017$)	Std Deviation (2017$)
Avg NPV of Project	-$1,849,171	$1,241,971
Avg B/C Ratio	0.91	0.06

Monte Carlo results show the *distribution* of possible outcomes or **value at risk**: What are the chances that the avoidable losses (Base Case) exceed the $20M cost of the project?



- ***Average*** B/C ratio = 0.91
- Value at Risk analysis allows airport to consider how much risk it is willing to take
- Real options (like delaying the project) can also be considered

12 May 30, 2018 Copyright GRA, Inc. GRA, Incorporated

Exhibit H-13. Sample VaR results for LIT.

APPENDIX I

Potential Climate Change Effects and Illustrative Responses for Airports

ACRP Synthesis 33: Airport Climate Adaptation and Resilience (Baglin 2012) provides a series of airport case examples to illustrate increases in risk due to a variety of different climate events. The following table, which is reprinted from that report, provides a compact summary of climate changes, affected airport assets, airport impacts, and potential responses.

Potential Climate Change Effects and Illustrative Responses for Airports

Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Temperature Change	More hot days	Take-off	Hotter days, when combined with moisture, can reduce airplane performance, increasing the runway length needed for take-off and climbing ability, particularly at high altitudes and/or hot weather airports (Peterson et al. 2008; Love et al. 2010; Shein 2008)	Delays and cancellations due to need to limit daytime flights (Peterson et al. 2008; TRB 2008; Shein 2008) Limits on payload (TRB 2008; Shein 2008) Use of greater thrust, leading to more noise (Burbidge et al. 2011), increased fuel use and greenhouse gas emissions (*Evaluating the Risk Assessment* . . . 2011) Reduced ability of certain airports to take certain aircraft (*Evaluating the Risk Assessment* . . . 2011)		Alternate or new routes or schedules (Shein 2008) Improved engine design (CCSP 2008) Longer runways (Schwartz 2011; Klin et al. 2011; Stewart et al. 2011)

Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Temperature Change	More hot days	Airfield, access roads, vehicles	Pavement buckling (e.g., concrete expansion while remaining rigid) (Peterson et al. 2008) Loss of non-concrete pavement integrity (e.g., tarmac melt) (TRB 2008) Heat-related weathering of fleet, including tires (TRB 2008)	Decreased utility of pavement (Peterson et al. 2008) Increase in foreign object damage on airfield; e.g., from weathered tires (*Evaluating the Risk Assessment* . . . 2011)	Pavement damage	Load restrictions for certain pavement (CCSP 2008; Peterson et al. 2008) At 40–100 years in the future, better maintenance strategies (Meyer 2008) Replace road and bridge expansion joints (Schwartz 2011) At 40–100 years in the future, possible significant impact on pavement and structural design; need for new materials; better maintenance strategies (Meyer 2008) Research new materials (Schwartz 2011)
Temperature Change	More hot days	Utility systems (energy, water, fuel, etc.)	Increase in temperature will increase demand in energy; e.g., for air conditioning and for water needed to cool air conditioning systems (in the terminal, airplanes, etc.) (TRB 2008) (Stewart et al. 2011) Reduced lifespan of air conditioning equipment due to increased use (*Evaluating the Risk Assessment* . . . 2011) Flashpoint of aviation fuel exceeded on hot days (*Evaluating the Risk Assessment* . . . 2011)	Increased utility consumption and attendant costs (Stewart et al. 2011) Possible impacts of fuel ignition on emergency services and safety (*Evaluating the Risk Assessment* . . . 2011)	Increased risk to IT failure stemming from increased risk of power failure from pressure on the system (Stewart et al. 2011)	Modification to infrastructure (Cranfield 2011) by, for example, ensuring availability of Fixed Electrical Ground Power on aircraft stands for air conditioning (Gatwick Airport Limited 2011) Research possible impacts on emergency services and safety (*Evaluating the Risk Assessment* . . . 2011)
Temperature Change	More hot days	Human resources	Heat illness (Peterson et al. 2008; *Evaluating the Risk Assessment* . . . 2011)	Limitation on outdoor maintenance and services (Peterson et al. 2008) Increase health issue, especially for vulnerable groups (*Evaluating the Risk Assessment* . . . 2011)		More nighttime construction (Schwartz 2011) Infrastructure capability assessment of heating and cooling needs (Birmingham Airport 2011)
Temperature Change	More hot days	Air	Increased heat causes increased levels of ozone, and other air quality issues (EPA 2009; *Evaluating the Risk Assessment* . . . 2011)	Regulatory compliance issues (Klin et al. 2011)		Conduct monitoring of conditions (*TRB Special Report 299* 2009)

(continued on next page)

Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Temperature Change	More hot days	Airfield, airstrips, access roads	Decrease in sea ice, making Arctic shoreline vulnerable to erosion (GAO 2003)		Erosion or subsidence of coastal airstrips and access roads in the Arctic (GAO 2003)	Dikes or levees to protect vulnerable coastal communities (Schwartz 2011) Move at-risk communities (Schwartz 2011)
Temperature Change	Fewer cold days	Airfields, airstrips, access roads	Permafrost thaw (Peterson et al. 2008)		Subsidence and other disruption to foundations (TRB 2008)	Identify areas with accelerated permafrost thaw (Schwartz 2011) Reinforcement or relocation (GAO 2003) Design changes in colder regions (Meyer 2008)
Temperature Change	Fewer cold days	Airfield, access road, all surfaces	Decrease in frozen precipitation (Peterson et al. 2008)	Improved safety (Peterson 2008 et al.; TRB 2008)		Increase in air routes in northern regions (Love et al. 2010)
Temperature Change	Fewer cold days	All	More mix in precipitation, with shift from snow to ice (Peterson et al. 2008)		Changes in snow and ice removal costs and environmental impacts from salt and chemicals (TRB 2008)	Possible reduction in de-icing facilities (TRB 2008)
Temperature Change	More hot days Fewer cold days Increase in extreme temperature days (greater amplitude, hot or cold)	Airport operations	Under increased warming and/or in combination with other climate change impacts (e.g., inundation), and increase in human migration away from areas severely affected by climate change	Operational issues associated with large, migrating, human populations, including increase in passenger traffic, public health concerns, and other issues (Stewart et al. 2011)		Incorporate the potential of climate change events into the existing systems of planning for irregular operations (Stewart et al. 2011) Change in wildlife populations may call for changes in landscaping, maintenance practices (Klin et al. 2011)
			Changes in vector borne and contagious diseases increase likelihood of epidemics and pandemics (*Evaluating the Risk Assessment* . . . 2011) Drought and increased or decreased water availability and/or earlier springs, later in falls may change ecosystems and wildlife, including migration (Stewart et al. 2011).	Issues associated with increases in migrating wildlife or ecosystem shifts, including increases in invasive species and endangered species at airports (Klin et al. 2011; *Evaluating the Risk Assessment* . . . 2011), including more bird strikes and associated costs of prevention (*Evaluating the Risk Assessment* . . . 2011) and changing health and safety issues for staff (*Evaluating the Risk Assessment* . . . 2011)		

Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Temperature Change	More hot days Fewer cold days Increase in extreme temperature days (greater amplitude, hot or cold) Changes in season duration	Entire facility and its operations	Systemic changes in demand and delays such as increases in hotter days and fewer cold days, changes tourism destinations (Burbidge et al. 2011)	Delays and other knock-on effects of systemic changes and increased irregular operations (Stewart et al. 2011) Decrease in capacity demands in some locations, increases in others due to tourism shifts (Burbidge et al. 2011)		Incorporate the potential of climate change events into the existing systems of planning for irregular operations (Stewart et al. 2011)
Seasonal Change	Temperature swings above and below freezing		Changes to freeze-thaw cycle of road subsurface: earlier in spring, later in fall (Peterson et al. 2008) Early appearance of ground heaves with earlier arrival of spring (Peterson et al. 2008)	Damage to underground utilities leading to pollution and compliance issues (*Evaluating the Risk Assessment* . . . 2011)	Damage to roads (Peterson et al. 2008) Fracture risk to underground utilities (*Evaluating the Risk Assessment* . . . 2011)	New management regime in weight limitations for certain pavement types (Peterson et al. 2008) Where there are shorter winters but longer thaw seasons, the timeframe for load restrictions may have to expand (Peterson et al. 2008) Shorter season for using ice roads in northern climates (Peterson et al. 2008)
Precipitation Changes	Increase in heavy precipitation events	Airfield, roads, bridges, stormwater drainage system	Flooding, standing water (Peterson et al. 2008; *Evaluating the Risk Assessment* . . . 2011)	Flight delays; passenger and employee access issues; implications for emergency evacuation planning, facility maintenance; and safety management (TRB 2008) Increase in surface water leads to potential contamination of surface water from de-icing fluids (*Evaluating the Risk Assessment* . . . 2011)	Road submersion; (Peterson et al. 2008) Scouring around bridges, roads, buried pipelines (Peterson et al. 2008) Damage to runway or other infrastructure (TRB 2008)	Protect existing and vulnerable structures; e.g., bridge piers (Schwartz 2011) Update hydrological storm frequency curves (Schwartz 2011) Over next 30–40 years, more targeted maintenance (Meyer 2008) Better land use planning in flood plains (Schwartz 2011) Over next 30–40 years, effect on pavement and drainage design. (Meyer 2008)
					Damage to pavement drainage systems (TRB 2008) Flood damage to aircraft navigation systems and instrument landing systems (*Evaluating the Risk Assessment* . . . 2011)	More probabilistic approaches to design floods (Meyer 2008). At 40–100 years in the future, impact on designs for foundations, drainage systems and culverts; effect on design of materials and pavement subgrade (Meyer 2008)

(continued on next page)

Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Precipitation Changes	Increase in heavy precipitation events	Operations	Fog	Delays due to reduced visibility (*Evaluating the Risk Assessment* . . . 2011) often at 7:00 a.m. slowing down flight operations (Peterson et al. 2008) Restrictions on airside maintenance (*Evaluating the Risk Assessment* . . . 2011)		Shift to instrument flight rules from visual flight rules (Klin et al. 2011) Changes in aircraft separation (Klin et al. 2011)
Precipitation Changes	Increase in heavy precipitation events		Increase in convective weather	Generally, increase in delays due to re-routing to avoid convective weather (thunderstorm) (McCarthy and Budd 2010) and changes in flight levels to avoid turbulence or convective weather (McCarthy and Budd 2010)	Destruction or disabling of navigation aid instruments (TRB 2008)	Consider review of airspace management and related systems (Burbidge et al. 2011)
Precipitation Changes	Drought	All	In combination with increased heat, wild fires (TRB 2008; *Evaluating the Risk Assessment* . . . 2011) Possibility of water restrictions (*Evaluating the Risk Assessment* . . . 2011)	Less visibility (Peterson et al. 2008; TRB 2008), slowing down flight operations (Peterson et al. 2008)	Smoke effects on aircraft engines (Stewart et al. 2011)	Incorporate the potential of climate change events into the existing systems of planning for irregular operations (Stewart et al. 2011)
Sea Level Rise	Rising water levels in coastal areas and rivers (Meyer 2011)	All or part of airport	In combination with incremental warming (NRC 2011), causing glacial melt coastal erosion and threat of inundation	Closures of airports, including major ones, on coasts (TRB 2008)	Damage to airports not designed or sited taking into consideration sea level rise	Protect infrastructure with dikes and levees (Schwartz 2011) Elevate critical infrastructure (Schwartz 2011) Repairs, replacement, and re-design (Peterson et al. 2008; Stewart et al. 2011)

Source: *ACRP Synthesis 33: Airport Climate Adaptation and Resilience* (Baglin 2012), Table 1.

Bibliography Keyed to Major Topics

Climate Analysis Tools

Dewberry, Gresham, Smith and Partners, GCR Inc., and R. Marchi. *ACRP Report 147: Climate Change Adaptation Planning: Risk Assessment for Airports.* Transportation Research Board, Washington, D.C., 2015.
Gilleland, E. and R. W. Katz. extRemes 2.0: An Extreme Value Analysis Package in R, *Journal of Statistical Software*, 2016: 72:8, p. 4.
ICF International. *ACRP Report 160: Addressing Significant Weather Impacts on Airports: Quick Start Guide and Toolkit*. Transportation Research Board, Washington, D.C., 2016.
Sanderson, B. M., M. Wehner and R. Knutti. Skill and Independence Weighting for Multi-Model Assessments, manuscript under review for Geoscientific Model Development, 2016. Available at https://www.geosci-model-dev.net/10/2379/2017/gmd-10-2379-2017.pdf.
Zervas, C. *Extreme Water Levels of the United States, 1893–2010*, NOAA Technical Report NOS CO-OPS 067, 2013. Available at https://tidesandcurrents.noaa.gov/?publications/?NOAA_Technical_Report_NOS_COOPS_?067a.pdf.

Risks of Climate Change

Abadie, L. et al. Climate Risk Assessment Under Uncertainty: An Application to Main European Coastal Cities Frontiers in Marine Science, 2016.
Atreya, A., and H. Kunreuther. Measuring Community Resilience: The Role of the Community Rating System (CRS). Working Paper, Philadelphia: The Wharton Risk Management and Decision Processes Center, 2016.
Bouwer, L. M. Projections of Future Extreme Weather Losses Under Changes in Climate and Exposure. *Risk Analysis*, 2013: 915–930.
Chang, S. E., T. McDaniels, J. Fox, R. Dhariwal, and H. Longstaff. Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. *Risk Analysis*, 2014: 416-434.
Collier, B. Small Firms, Big Risk: The Challenge of Natural Disasters and What Can Be Done. Available at http://www.brinknews.com/small-firms-big-risk-the-challenge-of-natural-disasters-and-what-can-be-done/.
Czajkowski, J. Moving from Risk Assessment to Risk Reduction: An Economic Perspective on Decision Making in Natural Disasters. *Frontiers of Engineering*, 2016.
Dietz, S. et al. Climate Value at Risk of Global Financial Assets. *Nature Climate Change*, 2016: 6, 676–679.
Economist Intelligence Unit. The Cost of Inaction: Recognizing the Value at Risk from Climate Change, 2015.
Estrada, F. et al. A Methodology for the Risk Assessment of Climate Variability and Change Under Uncertainty: A Case Study: Coffee Production in Veracruz, Mexico. *Climate Change*, 2012: 113, 455–479.
Golnaraghi, M. S. Surminski, and K.-U. Schanz. An Integrated Approach to Managing Extreme Events and Climate Risks: Towards a Concerted Public–Private Approach. Zurich: The Geneva Association, 2016.
Interagency Working Group on Social Cost of Carbon. Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, 2010.
Litterman, R. Pricing Climate Change Risk Appropriately. *Financial Analysts' Journal*, 2011: 4–10.
Michel-Kerjan, E. Effective Risk Response Needs a Prepared Mindset. *Nature*, January 22, 2015: 413.
Santos, J. R., L. C. Herrera, K. Danielle, S. Yu, S. A. T. Pagsuyoin, and R. R. Tan. State of the Art in Risk Analysis of Workforce Criticality Influencing Disaster Preparedness for Interdependent Systems. *Risk Analysis*, 2014: 1056–1068.
Schwartz, H. G. et al. Chapter 5: Transportation. In *Climate Change Impacts in the United States: The Third National Climate Assessment.* 2014. Available at http://nca2014.globalchange.gov/?report/sectors/transportation.

Shang, K. and M. Vincelli. Report on Extreme Events for Insurers: Correlation, Models, and Mitigations. Society of Actuaries, 2015.

Torriani, D. Hedging with Weather Derivative to Cope with Climate Variability and Change in Grain Maize Production, 2008. Available at http://www.unige.ch/climate/?Publications/Beniston/afr2008.pdf).

United Nations. International Strategy for Disaster Reduction. *Global Assessment Report on Disaster Risk Reduction.* United Nations, 2015.

Wharton Risk Management and Decision Processes Center. *Beyond Katrina: Lessons in Creating Resilient Communities.* The Zurich Services Corporation, 2015.

World Economic Forum. *The Global Risks Report 2017*. Insight Report, Geneva, 2017.

Airport Climate Risk

Baglin, C. *ACRP Synthesis of Airport Practice 33: Airport Climate Adaptation and Resilience.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Climate Ready Boston. Climate Change and Sea Level Rise Projections for Boston, June 2016.

Coffel, E. D., T. R. Thompson, and R. M. Horton. The Impacts of Rising Temperatures on Aircraft Takeoff Performance. *Climatic Change*, July 2017.

GHD, Inc. *ACRP Report 69: Asset and Infrastructure Management for Airports—Primer and Guidebook.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Heathrow Airport. Report of the Heathrow Winter Resilience Enquiry. March 2011.

ICAO. Environmental Report, Chapter 7, Climate Change Adaptation and Resilience. 2016.

Kincaid, I., M. Tretheway, S. Gros, and D. Lewis. *ACRP Report 76: Addressing Uncertainty about Future Airport Activity Levels in Airport Decision Making.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Larsen, P. H. et al. Estimating Future Costs for Alaska Public Infrastructure at Risk From Climate Change. Global Environmental Change, 2008.

Marsh Risk Consulting. *ACRP Report 74: Application of Enterprise Risk Management at Airports.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Martin-Nagle, R. and A. Klauber. *ACRP Synthesis of Airport Practice 66: Lessons Learned from Airport Sustainability Plans.* Transportation Research Board of the National Academies, Washington, D.C., 2015.

Massachusetts Port Authority. Boston-Logan International Airport Sustainability Management Plan. 2015. Available at https://www.massport.com/media/320786/?LoganSMP_Report.pdf.

Port Authority of New York and New Jersey. Design Guidelines Climate Resilience. 2015. Available at https://www.panynj.gov/business-opportunities/pdf/ . . . guidelines/?climate-resilience.pdf.

Price, M. *ACRP Report 116: Guidebook for Successfully Assessing and Managing Risks for Airport Capital and Maintenance Projects*. Transportation Research Board of the National Academies, Washington, D.C., 2014.

Rakich, R., C. Wells, and D. Wood. *ACRP Synthesis of Airport Practice 30: Airport Insurance Coverage and Risk Management Practices.* Transportation Research Board of the National Academies, Washington, D.C., 2011.

Wall, T. and M. Meyer. Transportation Research Circular E-C181: Risk-based Adaptation Frameworks for Climate Change Planning in the Transportation Sector. Transportation Research Board of the National Academies, Washington, D.C., 2013.

General Economic and Financial Principles

Arrow, K. J. et al. How Should Benefits and Costs Be Discounted in an Intergenerational Context? The Views of an Expert Panel. Discussion paper 12-53, Resources for the Future, Washington, DC, 2012.

FAA, Office of Aviation Policy and Plans. Airport Benefit–Cost Analysis Guidance, 1999.

Holton, G. History of Value-at Risk, 1922–1998 (Working Paper 2002). Available at http://stat.wharton.upenn.edu/?~steele/Courses/434/434Context/?RiskManagement/?VaRHistlory.pdf.

Knight, F. H., Risk, Uncertainty, and Profit, Harper Torchbooks, New York, 1921.

Kocherlakota, R. The Equity Premium: It's Still a Puzzle. *Journal of Economic Literature*, 1996: 42–71.

Kunreuther, H. and E. Michel-Kerjan. Enhancing Post-Disaster Economic Resilience: Public–Private Partnership for Insuring Terrorism. In *Improving Homeland Security Decisions*, by Ali E. Abbas and Detlof von Winterfeldt. Cambridge University Press, 2016.

UNISDR, Making Development Sustainable: The Future of Disaster Risk Management. United Nations Office for Disaster Risk Reduction (UNISDR), 2015.

U.S. Office of Management and Budget. Circular No. A-94, Revised: Guidelines and Discount Rates for Benefit–Cost Analysis of Federal Programs (various years).

Other Airport Source Materials

DOT/FAA/PP-92-6, Estimating the Regional Economic Significance of Airports, 1992.

FAA. Economic Values for FAA Investment and Regulatory Decisions: A Guide, 2016.

FAA. Measuring Benefits and Costs of FAA AIP Projects at Nonprimary Airports. Final Report prepared for FAA-ARP, 2013.

FAA. Advisory Circular 150/5300-13A, Airport Design, 2014. Available at https://www.faa.gov/documentLibrary/media/?Advisory_Circular/?150-5300-13A-chg1-interactive-201612.pdf.

FAA. Advisory Circular 150/5320-6F, Airport Pavement Design and Evaluation. 2016. Available at https://www.faa.gov/documentLibrary/?media/Advisory_Circular/150-5320-6F.pdf.

FAA. Advisory Circular 150/5370-10G, Standards for Specifying Construction of Airports. 2014. Available at http://www.faa.gov/?documentLibrary/?media/Advisory_Circular/AC-150-5370-10G-updated-201605.pdf.

FAA. Change 2 to Airport Master Plans, 2015. Available at https://www.faa.gov/?documentLibrary/media/Advisory_Circular/150-5070-6B-Change-2-Consolidated.pdf.

FAA. National Policy 5100.38D. Airport Improvement Program Handbook, 2014. Available at https://www.faa.gov/airports/aip/?aip_handbook/media/AIP-Handbook-Order-5100-38D.pdf.

FAA. Order 5100.39A. Airports Capital Improvements Plan 2000. Available at https://www.faa.gov/documentLibrary/media/Order/order-5100-39A-acip.pdf.

FAA. 1050.1F Desk Reference. Environmental Desk Reference for Airport Actions, 2015.

FAA. Order 1050.1F. Environmental Impacts: Policies and Procedures, 2015. Available at https://www.faa.gov/documentLibrary/media/?Order/FAA_Order_1050_1F.pdf.

FAA. Planning Information Needed for FAA Headquarters Review of BCA, 2006. Available at https://www.faa.gov/airports/aip/bc_analysis/?media/planning-information-bca.pdf.

Karlsson, J., S. Allard, R. Viswanathan, R. Furey, and J. McCredie. *ACRP Report 120: Airport Capital Improvements: A Business Planning and Decision-Making Approach.* Transportation Research Board of the National Academies, Washington, D.C., 2014.

Karlsson, J., J. R. Ludders, D. Wilde, D. Mochrie, and C. Seymour. *ACRP Synthesis of Airport Practice 7: Airport Economic Impact Methods and Models.* Transportation Research Board of the National Academies, Washington, D.C., 2008.

Neubauer, K., D. Fleet, and M. Ayres, Jr. *ACRP Report 131: A Guidebook for Safety Risk Management at Airports.* Transportation Research Board of the National Academies, Washington, D.C., 2015.

Nichol, C. *ACRP Synthesis of Airport Practice 1: Innovative Finance and Alternative Sources of Revenue for Airports*. Transportation Research Board of the National Academies, Washington, D.C., 2007.

Glossary

Adaptive Capacity: The capacity of a system to adapt if the environment changes.

Aeronautical Revenue: Airport revenues derived primarily from landing fees or other rents related to the airside of an airport.

Airport Climate Risk Operational Screening (ACROS): A software program, published as part of *ACRP Report 147* (Dewberry et al. 2015), useful in screening for airport climate risk.

Airport Emergency Plans (AEPs): Essential emergency-related and deliberate actions planned to ensure the safety of and emergency services for the airport and the community in which the airport is located. See https://www.faa.gov/regulations_policies/?advisory_circulars/index.cfm/go/document.information/documentID/74488.

Airport Enterprise Risk Management: Enterprise risk management (ERM) is a proactive approach by which threats to and opportunities for an organization are identified, evaluated, and integrated across all disciplines. See *ACRP Report 74: Application of Enterprise Risk Management at Airports* (Marsh Risk Consulting 2012).

Airport Master Plan: A plan used for the long-term development of an airport. See https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/?go/document.information/documentID/22329.

Airport Weather Advanced Readiness (AWARE): A toolkit to help airports and their stakeholders plan for, respond to, and recover from significant weather events. See *ACRP Report 160: Addressing Significant Weather Impacts on Airports: Quick Start Guide and Toolkit* (ICF International 2016).

Airports Capital Improvement Plan (ACIP): An FAA plan to prioritize projects critical to airport development and capital needs for the National Airspace System. See https://www.faa.gov/airports/aip/acip/.

Base Case (or Baseline): A reference point in a benefit–cost analysis or financial feasibility analysis representing what is expected to occur if the proposed project is not undertaken; it should represent what the airport would do instead of the subject project.

Benefit–Cost Analysis (BCA): A formal economic analysis to determine if a proposed project has merit by assessing both its benefits and costs from society's point of view (as opposed to the more narrow focus of a financial feasibility analysis).

Center for Operational Oceanographic Products and Services (CO-OPS): NOAA organization that gathers oceanographic data along U.S. coasts to protect life, property, and the environment. CO-OPS is the authoritative source for accurate, reliable, and timely water-level and current measurements that support safe and efficient maritime commerce, sound coastal management, and recreation. See https://tidesandcurrents.noaa.gov/?about.html.

Consequences: The outputs that drive economic impacts (e.g., income, jobs, taxes, national or regional output) in an economic impact study.

Coupled Model Intercomparison Project (CMIP): A standard experimental protocol for studying the output of climate models (called "general circulation models"). CMIP provides infrastructure in support of climate model diagnosis, validation, intercomparison, documentation, and data access. See https://cmip.llnl.gov/.

Criticality: An evaluation done in a risk analysis to determine how important or costly a service interruption would be.

Economic Impacts: An evaluation of the income, taxes, jobs, and gross output produced due a change in final demand in an economy.

Economic Life: An FAA definition referring to the period of time during which an asset can be expected to perform adequately relative to alternatives or otherwise be useful to an owner.

Exceedance Curve: Function based on history or projections of the probability of water rise to specific levels.

Financial Feasibility Analysis (FFA): An analysis to determine the private returns to an investment in a particular asset (as opposed to the more general focus of a BCA).

General Circulation Models (GCMs): Numerical models representing physical processes in the atmosphere, ocean, cryosphere, and land surface; the most advanced tools currently available for simulating the response of the global climate system. See http://www.ipcc-data.org/guidelines/pages/gcm_guide.html.

Greenhouse Gases: Gases (e.g., carbon dioxide and chlorofluorocarbon) that contribute to the greenhouse effect by absorbing infrared radiation.

Heat Map: A graphic in a risk analysis showing both the vulnerability of an asset to a threat (like climate change) and criticality (importance) of the asset to its owner.

Intergovernmental Panel on Climate Change (IPCC): The international body for assessing the science related to climate change. See http://www.ipcc.ch/.

IPCC's Fifth Assessment Report (AR5): The most recently published assessment of climate change.

IPCC's Fourth Assessment Report (AR4): A prior assessment published in 2007.

Life-Cycle Cost: The investment, operating, maintenance, renewal, and shut-down costs related to an asset over its life.

Localized Constructed Analog (LOCA): Statistical method used to downscale CMIP5 climate projections for North America. See http://loca.ucsd.edu/.

Mean Higher High Water (MHHW): The average height of the daily diurnal high tide recorded at a specific tide station.

Monte Carlo Simulation: A technique used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty in prediction and forecasting model.

National Environmental Policy Act (NEPA): U.S. environmental law that promotes the enhancement of the environment and established the President's Council on Environmental Quality. The law was enacted on January 1, 1970. See https://www.energy.gov/nepa/downloads/national-environmental-policy-act-1969.

National Plan of Integrated Airport Systems (NPIAS): An FAA program that identifies nearly 3,400 existing and proposed airports that are significant to national air transportation and thus eligible to receive federal grants under the Airport Improvement Program. It also includes estimates of the amount of AIP money needed to fund infrastructure development projects that will bring these airports up to current design standards and add capacity to congested airports. See https://www.faa.gov/?airports/?planning_capacity/npias/.

National Priority Rating: A method for evaluating the relative merit of projects in the FAA's ACIP process.

Net Present Value (NPV): Measurement of net benefit or profit calculated by subtracting the present values of cash outflows (including initial cost) from the present values of cash (or benefit) inflows over a period of time, taking into account the opportunity cost of capital.

Non-Aeronautical Revenue: Sources of revenue, including rents and fees, attributable to activities outside of the aeronautical area of an airport.

North American Vertical Datum of 1988 (NAVD88): A vertical measure of height established for vertical control surveying in the United States of America based on the general adjustment of the North American Datum of 1988.

Physical Life: The time period during which an asset can physically operate for its intended purpose.

Relative Sea Level (RSL): The position and height of the sea relative to the land.

Representative Concentration Pathway (RCP): Refers to scenarios from the most recent IPCC AR5 2.6, 4.5, 6.0, and 8.5 climate scenarios, with RCP8.5 assuming the least mitigation of greenhouse gases and therefore the greatest climate risk.

Requirement Life: An FAA definition referring to the period over which the benefits of the project will be greater than the costs.

Resilience: The capacity for a system to absorb stresses and maintain function in the face of external stresses imposed on it by climate change.

Resilience Team: A group of individuals with different technical backgrounds tasked with evaluating the risks of climate change and maintaining the resilience of an airport through adaptation.

Risk: Probable exposure to uncertain outcomes that could result in identifiable losses.

Safety Management System (SMS): A process to help airports detect and correct safety problems before they result in aircraft accidents or incidents. See https://www.faa.gov/?airports/airport_safety/safety_management_systems/.

Scenario Case: Represents a range of one or more alternatives that could be undertaken to achieve the objective (such as adapting to climate risk) identified by an analyst.

Sustainability Plans: Initiatives incorporated into airport master plans for reducing environmental impacts, achieving economic benefits, and increasing integration with local communities. See https://www.faa.gov/airports/environmental/sustainability/.

Uncertainty: Refers to risks that are easily quantifiable. ("Risk" and "uncertainty" are used interchangeably in this handbook.)

Value-at-Risk (VaR): A technique used to measure and quantify the level of financial or economic risk over a specific time frame, usually using Monte Carlo simulation techniques.

Vulnerability: The probability or likelihood that an asset will be exposed to a risk.

Vulnerability Assessment Scoring Tool (VAST): An indicator-based vulnerability assessment of transportation assets. It was developed by the U.S. DOT and takes into account exposure, sensitivity, and adaptive capacity. See https://toolkit.climate.gov/?tool/vulnerability-assessment-scoring-tool-vast.

References

Abadie, L., et al. Climate Risk Assessment Under Uncertainty: An Application to Main European Coastal Cities. *Frontiers in Marine Science*, December 2016.

Arrow, K. J. et al. How Should Benefits and Costs Be Discounted in an Intergenerational Context? The Views of an Expert Panel. Discussion paper 12-53, Resources for the Future, Washington, D.C., 2012.

Atreya, A. and H. Kunreuther. *Measuring Community Resilience: The Role of the Community Rating System (CRS).* Working Paper, Philadelphia: The Wharton Risk Management and Decision Processes Center, 2016.

Baglin, C. *ACRP Synthesis of Airport Practice 33: Airport Climate Adaptation and Resilience.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Berry, F., S. Gillhespy, and J. Rogers. *ACRP Synthesis of Airport Practice 10: Airport Sustainability Practices.* Transportation Research Board of the National Academies, Washington, D.C., 2008.

Bouwer, L. M. Projections of Future Extreme Weather Losses Under Changes in Climate and Exposure. *Risk Analysis*, 2013: 915–930.

Butler, S. E. and L. J. Kiernan. Estimating the Regional Economic Significance of Airports, DOT/FAA/PP-92-6. U.S. DOT, FAA, 1992.

Chang, S. E., T. McDaniels, J. Fox, R. Dhariwal, and H. Longstaff. Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments. *Risk Analysis*, 2014: 416–434.

Climate Ready Boston. Climate Change and Sea Level Rise Projections for Boston, 2016.

Coffel, E. and R. Horton. Climate Change and the Impact of Extreme Temperatures on Aviation. *Weather, Climate, and Society*, 7, 2015, 94–102.

Coffel, E. D., T. R. Thompson, and R. M. Horton. The Impacts of Rising Temperatures on Aircraft Takeoff Performance. *Climatic Change,* 2017.

Collier, B. Small Firms, Big Risk: The Challenge of Natural Disasters and What Can Be Done. BRINK, 2015. Available at http://www.brinknews.com/small-firms-big-risk-the-challenge-of-natural-disasters-and-what-can-be-done/.

Czajkowski, J. Moving from Risk Assessment to Risk Reduction: An Economic Perspective on Decision Making in Natural Disasters, in *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2015 Symposium*, National Academy of Engineering, 2016.

Dewberry, Gresham, Smith and Partners, GCR Inc., and R. Marchi. *ACRP Report 147: Climate Change Adaptation Planning: Risk Assessment for Airports.* Transportation Research Board, Washington, D.C., 2015.

Dietz, S. et al. Climate Value at Risk of Global Financial Assets. *Nature Climate Change*, 2016: 6, 676–679.

Economist Intelligence Unit. The Cost of Inaction: Recognizing the Value at Risk from Climate Change, 2015.

Estrada, F., et al. A Methodology for the Risk Assessment of Climate Variability and Change Under Uncertainty: A Case Study: Coffee Production in Veracruz, Mexico. *Climate Change*, 2012: 455–479.

FAA. Federal Aviation Administration Policy and Final Guidance Regarding Benefit Cost Analysis (BCA) on Airport Capacity Projects for FAA Decisions on Airport Improvement Program (AIP) Discretionary Grants and Letters of Intent (LOI), 1999a. Available at https://www.faa.gov/airports/resources/publications/?federal_register_notices/??media/aip_64fr70107.pdf.

FAA. Airport Benefit–Cost Analysis Guidance, 1999b.

FAA. Order 5100.39A. Airports Capital Improvement Plan, 2000. Available at https://www.faa.gov/documentLibrary/media/Order/order-5100-39A-acip.pdf.

FAA. Advisory Circular 150/2500-31C. Airport Emergency Plan, 2009. Available at https://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5200_31c_consolidated.pdf.

FAA. Measuring Benefits and Costs of FAA AIP Projects at Nonprimary Airports, Final Report prepared for FAA-ARP, 2013.

FAA. *Airport Improvement Program Handbook.* National Policy 5100.38D, 2014a. Available at https://www.faa.gov/airports/aip/aip_handbook/media/AIP-Handbook-Order-5100-38D.pdf.

FAA. Advisory Circular 150/5300-13A, Airport Design, 2014b. Available at https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5300-13A-chg1-interactive-201612.pdf.

FAA. Advisory Circular 150/5370-10G. Standards for Specifying Construction of Airports, 2014c. Available at http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC-150-5370-10G-updated-201605.pdf.

FAA. Order 5200.11. FAA Airports (ARP) Safety Management System, 2014d. Available at https://www.faa.gov/documentLibrary/media/Order/order5200_11Consolidated.pdf.

FAA. Change 2 to Airport Master Plans, 2015a. Available at https://www.faa.gov/?documentLibrary/media/Advisory_Circular/150-5070-6B-Change-2-Consolidated.pdf.

FAA. Report to Congress, National Plan of Integrated Airport Systems (NPIAS), 2015b. Available at https://www.faa.gov/airports/planning_capacity/npias/reports/media/NPIAS-Report-2017-2021-Narrative.pdf.

FAA. Order 1050.1F. Environmental Impacts: Policies and Procedures, 2015c. Available at https://www.faa.gov/documentLibrary/media/Order/FAA_Order_1050_1F.pdf.

FAA. 1050.1F. Environmental Desk Reference for Airport Actions, 2015d. Available at https://www.faa.gov/about/office_org/headquarters_offices/apl/environ_policy_guidance/policy/?faa_nepa_order/desk_ref/media/desk-ref.pdf.

FAA. Advisory Circular 150/5320-6F. Airport Pavement Design and Evaluation, 2016a. Available at https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5320-6F.pdf.

FAA. Economic Values for FAA Investment and Regulatory Decisions: A Guide, 2016b.

FAA, Office of Aviation Policy and Plans. Airport Benefit–Cost Analysis Guidance, 1999.

GHD, Inc. *ACRP Report 69: Asset and Infrastructure Management for Airports—Primer and Guidebook.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Gilleland, E. and R. W. Katz. extRemes 2.0: An Extreme Value Analysis Package in R. *Journal of Statistical Software*, 2016, 72:8, p. 4.

Golnaraghi, M., S. Surminski, and K.-U. Schanz. An Integrated Approach to Managing Extreme Events and Climate Risks: Towards a Concerted Public-Private Approach. Zurich: The Geneva Association, 2016.

Heathrow Airport. *Report of the Heathrow Winter Resilience Enquiry,* 2011a. Available at https://im.ft-static.com/content/images/89937494-55ed-11e0-8de9-00144feab49a.pdf.

Heathrow Airport. Climate Change Adaptation Reporting Power Report, 2011b.

Holton, G. *History of Value-at Risk, 1922–1998.* Working Paper, 2002. Available at http://stat.wharton.upenn.edu/?~steele/Courses/434/434Context/RiskManagement/VaRHistlory.pdf.

ICAO. Chapter 7: Climate Change Adaptation and Resilience. *Environmental Report*, 2016.

ICF International. *ACRP Report 160: Addressing Significant Weather Impacts on Airports: Quick Start Guide and Toolkit*. Transportation Research Board, Washington, D.C., 2016.

Interagency Working Group on Social Cost of Carbon. Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, 2010.

IPCC. *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R. K. and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp., 2007.

IPCC. Summary for Policymakers. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F. et al. (eds.)]. Table SPM-2. 2013. Available at http://www.climatechange2013.org/?images/?report/WG1AR5_SPM_FINAL.pdf.

IPCC. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp., 2014.

Karlsson, J., S. Allard, R. Viswanathan, R. Furey, and J. McCredie. *ACRP Report 120: Airport Capital Improvements: A Business Planning and Decision-Making Approach.* Transportation Research Board of the National Academies, Washington, D.C., 2014.

Karlsson, J., J. R. Ludders, D. Wilde, D. Mochrie, and C. Seymour. *ACRP Synthesis of Airport Practice 7: Airport Economic Impact Methods and Models.* Transportation Research Board of the National Academies, Washington, D.C., 2008.

Kincaid, I., M. Tretheway, S. Gros, and D. Lewis. *ACRP Report 76: Addressing Uncertainty about Future Airport Activity Levels in Airport Decision Making.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Kunreuther, H. and E. Michel-Kerjan. Enhancing Post-Disaster Economic Resilience: Public–Private Partnership for Insuring Terrorism. In *Improving Homeland Security Decisions*, by A. E. Abbas and D. von Winterfeldt. Cambridge University Press, 2016.

Landau, S. and G. Weisbrod. *ACRP Synthesis of Airport Practice 13: Effective Practices for Preparing Airport Improvement Program Benefit–Cost Analysis*. Transportation Research Board of the National Academies, Washington, D.C., 2009.

Larsen, P. H. et al. Estimating Future Costs for Alaska Public Infrastructure at Risk from Climate Change. *Global Environmental Change*, 2008.

Litterman, R. Pricing Climate Change Risk Appropriately. *Financial Analysts' Journal*, 2011: 4–10.

Marsh Risk Consulting. *ACRP Report 74: Application of Enterprise Risk Management at Airports.* Transportation Research Board of the National Academies, Washington, D.C., 2012.

Martin-Nagle, R. and A. Klauber. *ACRP Synthesis of Airport Practice 66: Lessons Learned from Airport Sustainability Plans.* Transportation Research Board of the National Academies, Washington, D.C., 2015.

Massport. Boston-Logan International Airport Sustainability Management Plan, 2015. Available at https://www.massport.com/media/320786/LoganSMP_Report.pdf.

Michel-Kerjan, E. Effective Risk Response Needs a Prepared Mindset. *Nature*, January 22, 2015: 413.

Morrow, B. H. Risk Behavior and Risk Communication: Synthesis and Expert Interviews. Miami: NOAA, 2009.

Munich Airport: Integrated Report 2015. Flughafen Munchen GmbH, 2015. Available at https://www.munich-airport.com/company-business-260134.

Neubauer, K., D. Fleet, and M. Ayres, Jr. *ACRP Report 131: A Guidebook for Safety Risk Management at Airports.* Transportation Research Board of the National Academies, Washington, D.C., 2015.

Nichol, C. *ACRP Synthesis of Airport Practice 1: Innovative Finance and Alternative Sources of Revenue for Airports*. Transportation Research Board of the National Academies, Washington, D.C., 2007.

Port Authority of New York and New Jersey. Design Guidelines Climate Resilience, 2015. Available at https://www.panynj.gov/business-opportunities/pdf/...guidelines/climate-resilience.pdf.

Price, M. *ACRP Report 116: Guidebook for Successfully Assessing and Managing Risks for Airport Capital and Maintenance Projects*. Transportation Research Board of the National Academies, Washington, D.C., 2014.

Rakich, R., C. Wells, and D. Wood. *ACRP Synthesis of Airport Practice 30: Airport Insurance Coverage and Risk Management Practices.* Transportation Research Board of the National Academies, Washington, D.C., 2011.

Samuelson, K. It's So Hot in Arizona That Dozens of Flights Have Been Canceled. *Fortune,* June 20, 2017. http://fortune.com/2017/06/20/arizona-phoenix-flight-delays-cancelled-heat/.

Sanderson, B. M., M. Wehner, and R. Knutti. Skill and Independence Weighting for Multi-Model Assessments. Manuscript under review for Geoscientific Model Development, 2016. Available at https://www.geosci-model-dev.net/10/2379/2017/gmd-10-2379-2017.pdf.

Santos, J. R., L. C. Herrera, K. D. S. Yu, S. A. T. Pagsuyoin, and R. R. Tan. State of the Art in Risk Analysis of Workforce Criticality Influencing Disaster Preparedness for Interdependent Systems. *Risk Analysis*, 2014: 1056–1068.

Shang, K. and M. Vincelli. Report on Extreme Events for Insurers: Correlation, Models, and Mitigations. Society of Actuaries, 2015.

Schwartz, H. G. et al. Chapter 5: Transportation. In *Climate Change Impacts in the United States: The Third National Climate Assessment,* 2014. Available at http://nca2014.globalchange.gov/report/sectors/?transportation.

Sweet, W. V., R. E. Kopp, C. P. Weaver, J. Obeysekera, R. M. Horton, E. R. Thieler, and C. Zervas. *Global and Regional Sea Level Rise Scenarios for the United States*. NOAA Technical Report NOS CO-OPS 083. 2017. Available at https://tidesandcurrents.noaa.gov/publications/?techrpt83_Global_and_Regional_SLR_Scenarios?_for? the_US_final.pdf.

Torriani, D. Hedging with Weather Derivative to Cope with Climate Variability and Change in Grain Maize Production, 2008. Available at http://www.unige.ch/climate/Publications/Beniston/afr2008.pdf.

United Nations. United Nations International Strategy for Disaster Reduction. *Global Assessment Report on Disaster Risk Reduction,* 2015a.

United Nations. United Nations International Strategy for Disaster Reduction. Making Development Sustainable: The Future of Disaster Risk Management, United Nations Office for Disaster Risk Reduction, 2015b.

U.S. DOT. VAST User's Guide, 2015. https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/scoring_tools_guide/index.cfm.

U.S. Office of Management and Budget. Circular No. A-94 Revised, Guidelines and Discount Rates for Benefit–Cost Analysis of Federal Programs, 1992.

U.S. Office of Management and Budget. Circular No. A-4, Regulatory Analysis, 2003.

Wall, T. and M. Meyer. Transportation Research Circular E-C181: Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector. Transportation Research Board of the National Academies, Washington, D.C., 2013.

Wang, A. B. It's So Hot in Phoenix that Airplanes Can't Fly. *Washington Post*, June 21, 2017, https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/06/20/its-so-hot-in-phoenix-that-airplanes-cant-fly/.

Wharton Risk Management and Decision Processes Center. Beyond Katrina: Lessons in Creating Resilient Communities. The Zurich Services Corporation, 2015.

World Economic Forum, The Global Risks Report 2017, Insight Report, Geneva, 2017.

Zervas, C. Extreme Water Levels of the United States, 1893–2010. NOAA Technical Report NOS CO-OPS 067, 2013. Available at https://tidesandcurrents.noaa.gov/publications/?NOAA_Technical_Report_?NOS_COOPS_067a.pdf.

Endnotes

1. The Port Authority of New York and New Jersey is aware of the potential for disruptions at LGA due to flood risk and has already undertaken multiple initiatives to address them.
2. The water heights shown are measured relative to a baseline level known as the mean higher high water vertical datum; this is discussed further in Appendix D.
3. It is important to note that all ACROS projections are based on a future climate scenario known as RCP8.5; see the discussion in Appendix D for more information about climate scenarios. Also, each of the climate vector elements is tied to specific quantitative definitions (e.g., "hot days" refers to days when the maximum temperature reaches at least 90°F). The definitions are presented in more detail in Exhibit 3-3.
4. An obvious limitation here is that ACROS only provides projections for two future years, so if doing a standard analysis based on annual data, the analyst would have to interpolate between the three available years to develop annual projections for the incidence of very hot days. Another limitation is that the climate stressors are predefined assuming specific thresholds that may not be relevant for a particular airport.
5. This is potentially complicated because the analyst might realistically want to consider future growth at the airport as well as changes in the future fleet and whether that fleet would be more or less affected by very hot days than the current fleet.
6. Ideally the analyst would check with more recent climate forecasts described in Chapter 3 to ensure that the ACROS maximum forecasts are still representative of a worst-case scenario.
7. This assumes that airlines pay the full crew cost associated with each cancelled flight, plus incur an aircraft depreciation cost; the latter is a rough estimate of the opportunity cost of the aircraft being out of service due to the cancellation.
8. This result may not be surprising given that most of the benefits occur well into the future as the number of very hot days grows. As is discussed further in Appendix E, the results for long-lived projects are often dependent on the choice of discount rate.
9. A more detailed discussion of Monte Carlo simulation is provided in Appendix C.
10. The results in Exhibit 2-9 are purely for demonstration; they are not based on any actual climate projections for PNS.
11. The software is available for download at https://toolkit.climate.gov/tool/vulnerability-assessment-scoring-tool-vast.
12. In this discussion, the term "consequences" is used deliberately to distinguish them from the benefits in benefit-cost studies or the returns earned in a financial feasibility study.
13. The actual value of R could be estimated by accessing the high-temperature climate data described in Appendix D.
14. However, in some circumstances it will not be possible to do so, for example, when an existing facility is being compared with a replacement. The existing asset will likely have some remaining useful economic life, but that will not line up with the full economic life of a new replacement. This may also occur if various alternatives being compared have different economic lives. In this situation, FAA guidance suggests that the BCA time frame should be set equal to the useful life of the longest-lived alternative; then the shorter-lived alternative(s) would be assumed to be replaced as necessary, and a residual value would be assigned to the last one.
15. RCPs form a set of greenhouse gas concentration and emissions pathways designed to support research on impacts and potential policy responses to climate change. RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in the absence of climate change policies. Impacts of climate change are higher in this scenario than in others.

16. This abstracts from the possibility that more than one extreme water event could actually occur in a single year.
17. There are nine FAA Regional Airports Offices located across the country: Alaskan, Central, Eastern, Great Lakes, New England, Northwest Mountain, Southern, Southwest, and Western-Pacific.
18. In principle, the number of simulations needed for any given analysis will depend on a number of different factors, including the standard error of the mean of the actual input distribution, the desired statistical confidence level, and the sampling method used. In the present context, it will usually suffice for the analyst to run a few thousand simulations and then compare the results to those obtained when running, say, twice that number. If the mean and standard deviation of the discounted benefits and costs are very similar, then the analyst can be confident that a large enough number of simulations have been run.
19. The LOCA website at http://loca.ucsd.edu has links to download sites containing the latest LOCA data. The downscaled LOCA technique will be used in the future to provide high-resolution projections for other variables, including snow cover, soil moisture, runoff, and humidity.
20. While it is recognized that weight restrictions may begin to impinge even at temperatures below 100° at some locations, for screening purposes, it is believed that 100° is a reasonable cutoff to assess the future likelihood and impact of such restrictions.
21. In the climate science world, a vertical datum is simply a reference level. Any water level measurement must be referenced to a datum in order to be meaningful. There are many different datums used for different purposes. Some are based on tidal levels—MHHW and mean sea level (MSL) are two examples. Some are based on the overall shape of the earth (so-called "geodetic" datums) such as the North American Vertical Datum for 1988, known as NAVD88, which is applicable to large continental areas. See https://noaanhc.wordpress.com/2016/01/29/the-alphabet-soup-of-vertical-datums-why-mhhw-is-mmm-mmm-good/ for more information. Most analyses studying sea level rise and coastal storms use MHHW because measurements relative to MHHW are a good approximation of the threshold where water inundation can occur. It is straightforward to convert from one datum to another simply by adding or subtracting their relative difference. A comprehensive list of vertical datums for different locations can be found at https://tidesandcurrents.noaa.gov/stations.html?type=Datums.
22. The formula is water level above MHHW = $\mu + \sigma/\xi * [y_p^{\xi} - 1]$, where μ is the location parameter, ξ is the scale parameter, ξ is the shape parameter of the extreme value distribution, p is the annualized probability of occurrence, and $y_p = -1/\ln(1-p)$]
23. Projections are provided for sites covered by the Permanent Service for Mean Sea Level (PSMSL) based in Liverpool, UK. Available at https://tidesandcurrents.noaa.gov/publications/techrpt083.csv.
24. There are also low and high sub-scenarios presented for each case; focus is on the baseline medium sub-scenarios for purposes of the Excel template. In addition, the raw RSL tables reflect expected changes relative to the year 2000. But given that the EWL curves described here are based on historical observations through 2010, the RSL tables have been adjusted so that they reflect a 2010 baseline instead of 2000. Finally, it is important to note that the RSL projections also attempt to account for changes in vertical land movement, as applicable.
25. It is important to note that the climate science supporting the probabilities shown in Exhibit D-4 is changing rapidly. As noted in the CO-OPS 083 report, recent evidence regarding the Antarctic ice sheet, for example, may lead to significantly increased probabilities associated with the intermediate-high, high, and extreme scenarios, particularly for RCP8.5.
26. Though the raw inputs for historical extreme water levels and future sea level rise are in meters, it is important to note that all of the results in the Excel templates are presented in feet.
27. Both Excel templates are hard-wired to compute 5,000 simulations. After testing with other higher counts, the project team is confident that, regardless of specific input choices made by the user, the variation in results will be sufficiently represented by running 5,000 simulations.
28. Note that both curves exhibit several discontinuities looking like negative spikes. This is just an artifact of the sorting of results based on the *difference* between the two curves; it occurs when extreme water events with very high costs (as indicated in Exhibit E-6) randomly occur in the early years of some of the 5,000 simulations. This leads to high negative NPV costs under both the baseline and the scenario cases.
29. Again, it is important to emphasize that the results shown in the template are all relative to the MHHW datum. If the airport is using NAVD88 or some other datum, it is essential to first translate the critical elevations to be relative to MHHW.
30. Even though our case study analysis of Phoenix involved the assumption of cancelling flights entirely due to extreme temperatures, the high-temperature template focuses instead on weight restrictions, which are likely to begin to occur at much lower temperatures.
31. See Appendix D for more information on where these data can be obtained. Further instructions for accessing and downloading these data are provided in the template itself on the Weather Data sheet.
32. https://www.faa.gov/documentLibrary/media/Advisory_Circular/draft_150_5325_4c_industry_commentenabled.pdf.

33. Coffel et al. graciously agreed to provide lookup tables from their analysis that provide statistical estimates of weight restrictions for the Airbus A320 and Boeing 737-800, 777-300, and 787-8 aircraft.
34. See the discussion in Appendix D.
35. If desired, the user may elect to ignore the weights and treat all models equally.
36. The weight restrictions are computed by comparing the maximum takeoff weight allowed for each aircraft type (given the airport elevation, runway length, and temperature) with the required takeoff weight implied by the passenger count per flight and required fuel for the route. If the maximum takeoff weight restriction is binding, then following Coffel et al. 2017, it is assumed that each pound of required weight reduction translates into 0.83 pounds of payload (passengers) and 0.17 pounds of fuel.
37. Each model also was tested against historical PHX temperatures for the period 1981 through 2000 to look for any systematic bias. The testing strategy described in Appendix D was used, and it was found that the upper end of the projected temperature ranges were quite accurate, involving differences in the top 5-percentile bracket of about 2°F or less across all models.
38. Additional guidance on this subject is provided in an FAA memo entitled "Planning Information Needed for FAA Headquarters Review of Benefit Cost Analysis (BCA)," which is available at https://www.faa.gov/airports/aip/bc_analysis/media/planning-information-bca.pdf.
39. See for example, R. Kocherlakota, "The Equity Premium: It's Still a Puzzle," *Journal of Economic Literature*, 1996: 42-71.
40. It is important to note, in this case, that the nearest localized points in the NOAA data sets—both for historical extreme water levels and projected sea level rise—are actually quite distant from the airport itself (they are 40–50 miles south along the actual Gulf of Mexico coast), so their accuracy for MSY is questionable. The airport would likely have to adjust the data by evaluating the relationship between the historical NOAA data sets and the actual experience at the airport. For coastal airports subject to sea level rise, the location (and elevation) of the nearest EWL and RSL stations must be an important consideration when undertaking analyses based on these climate estimates.
41. In this case, the NOAA coastal water level stations are within 2 miles of BOS.
42. There are other impacts that could be addressed as well. Rather than cancel or reschedule flights, airlines may accept payload restrictions on their current flights during periods of high temperatures; such restrictions may begin to occur at much lower levels than the unusually high temperatures faced by Phoenix in 2017. The Excel template directly addresses the issue of aircraft weight restrictions due to high temperatures. A more general concern for an airport might be that airlines faced with increasing costs due to high temperatures might choose to concentrate hubs or focus activity elsewhere, which would have important local economic impacts. From a more general perspective, some or all of these impacts could be addressed through improved engine or other aircraft technologies.
43. A more detailed and systematic analysis of payload restrictions is discussed in Appendix E as part of the Excel model high-temperature template developed for this project.
44. The 6-hour delay was assumed based on the relatively low frequency of daily flights at Little Rock.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001

ADDRESS SERVICE REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
COLUMBIA, MD
PERMIT NO. 88

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The nation turns to the National Academies of Sciences, Engineering, and Medicine for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

ISBN 978-0-309-48045-1
90000
9 780309 480451