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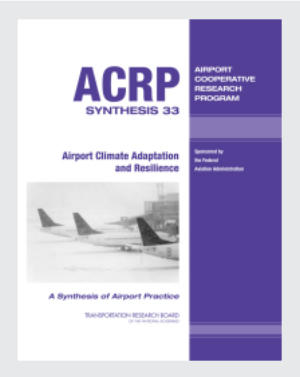

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP SYNTHESIS 33

Airport Climate Adaptation and Resilience

A Synthesis of Airport Practice

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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). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The 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) the 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 Academies formally initiating the program.

The 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 the ACRP are solicited periodically but may be submitted to the 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 the 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 end-users of the research: airport operating agencies, service providers, and suppliers. The ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties, and industry associations may arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by airport-industry practitioners.

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FOREWORD

Airport administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to the airport industry. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire airport community, the Airport Cooperative Research Program authorized the Transportation Research Board to undertake a continuing project. This project, ACRP Project 11-03, "Synthesis of Information Related to Airport Practices," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an ACRP report series, *Synthesis of Airport Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

Gail R. Staba
Senior Program Officer
Transportation Research Board

This synthesis study is intended to provide airport heads and their technical managers with a document that reviews the range of risks to airports from projected climate change and the emerging approaches for handling them. To gather relevant information on current practices, primary and grey literature was reviewed, and 16 airports were surveyed, supplying a profile of emerging practices and identifying personnel for subsequent interviews. From this information, a summary of likely climate effects and illustrative response actions was developed. The literature review, survey, and interviews also were used to identify the ways decision makers and their stakeholders use general information on climate effects and potential adaptation measures to define, plan for, and otherwise address climate risks to their own situation, including to their assets and operations. Detailed case examples were prepared to capture several distinct approaches to airport climate change resilience and adaptation.

Chris Baglin, AEA Group-Project Performance Corporation, McLean, Virginia, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

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AIRPORT CLIMATE ADAPTATION AND RESILIENCE

SUMMARY

Hotter days, heavier rainfall, increased snow and ice, and more intense storms are some of the direct impacts airports may experience from climate change. Very few airports, however, are considering ways to address these effects. Yet 70% of airport delays are the result of extreme weather, and such weather events are on the increase. In 2011, the United States witnessed a record 12 weather/climate disasters, each costing $1 billion or more. Such events grab headlines that, combined with attendant flight delays, come to the attention of policymakers. Quite often, how airports respond to these events influences future planning.

By defining and more explicitly addressing the risks that climate change now presents to air travel, airports can extend and enhance the benefits from present day investments in maintenance, data collection, and capital improvements. For example, in 2011 Tropical Storm Irene closed all major New York airports. Although not a hurricane, but recording 5 to 8 in. of rain, the storm generated news that certain categories of hurricanes would put JFK International Airport under more than 15 ft of water. That very substantial risk is known and understood by the airport. However, few U.S. airports can identify how the varied risks from climate change will affect their assets and operations.

Climate effects vary and their risks pose a diverse set of issues for airports. In some places, increases in precipitation will not only flood runways but overwhelm stormwater systems, implicating water quality compliance. Elsewhere, warmer weather may damage aircraft tires and tarmac. The projected increases in severe winter storms may create a "new normal" for airports unaccustomed to increased snow removal requirements.

Airports are diverse and complex. They vary in their size, capacity, and in the services they provide and the assets they need to protect. Airports have runways, taxiways, aprons, aviation signage, access roads, bridges, walkways, energy, telecommunications, security systems, pipelines, and other infrastructure. Tenants, vendors, and others own property and equipment that also need protection. All of these assets can be affected by different climate change effects, such as heat, intense precipitation, extreme storm events, and new wildlife patterns. Beyond airside and landside assets and operations, airports provide key links for other transportation modes and support regional economies. During an extreme weather event, an airport may provide shelter, support for aviation in disaster relief, and other essentials. When airports in one state or country deal with a climate risk, many other airports, both nationally and globally, are affected. Research on the transportation sector's resilience and adaptation to climate change has been on the increase for over a decade; however, there is very little research specifically on airports. This report presents findings of first impression, collected in 2011, including results of what appears to be the first formal and voluntary survey of airport practices for addressing climate risks.

The objective of this synthesis is to provide airport administrators and their technical managers with a document that reviews the range of risks to airports from projected climate change and the emerging approaches for handling these risks. To gather relevant information on current practices, primary and secondary literature was reviewed. In addition, 16 airports were surveyed, supplying a profile of emerging practices and identifying personnel

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for subsequent interviews. From this information, a summary of likely climate effects and response actions was developed. The literature review, survey, and interviews were also used to identify the ways decision makers and their stakeholders use general information on climate effects and potential adaptation measures to define, plan for, and otherwise address climate risks to their own situation, including to their assets and operations. Detailed case examples were prepared to capture several distinct approaches to airport climate change resilience and adaptation.

At Oakland International Airport, planners and engineers included sea level rise as a factor in the design changes being developed to address compliance with new runway safety area requirements, seismic risk, and post-Hurricane Katrina dike standards. At Toronto Pearson International Airport, the head of Environmental Systems Management used his engineering profession's model climate change vulnerability assessment protocol as a tool for considering climate risk in stormwater system reviews and water quality regulatory compliance activities. These activities were conducted without an overarching adaptation strategy. In Atlanta, Jacksonville, and San Diego, airports are putting into place the awareness-raising processes, research, and procedures that will be the foundation to the adoption of a climate adaptation strategy and its incorporation into airport planning. In Alaska, planning efforts on airport resilience and adaptation have matured in the face of real climate impacts.

The survey conducted for this Synthesis report found that most airport managers believed disruptions from weather events were increasing. A majority also believed that emergency procedures could handle climate risks, whereas fewer believed that irregular operations processes were a satisfactory means for addressing them. Although risk management systems have been identified as a key method for addressing climate change, this approach had not yet become formal practice at U.S. airports. Research does indicate that some airports are following the high-level, iterative planning cycle for climate change adaptation that many sources commonly advocate—beginning with identification of relevant climate impacts, assessment of vulnerabilities, high-level identification of risks, development and implementation of a plan, and monitoring and revisiting earlier decisions based on new information. Other airports have asset management and environmental systems management staff who are determining their own course of action, such as researching best practices in light of the climate risks they saw.

Key drivers for addressing climate risk at airports were:

- Severe weather events and related costs
- Awareness raised from sustainability and greenhouse gas mitigation activities
- Model adaptation guidance prepared by a professional society in a technical field
- Executive leaders serving as advocates
- Internal organizational champions serving as advocates
- Professional judgment of staff
- Participation in state, regional, and local adaptation planning efforts
- Federal grants and planning frameworks.

Insurance and bonding requirements may be an emerging driver as well, but were not cited as much as the others. A barrier to more complete coordination with other stakeholders is the quasi-independent status of airports in most locations except Alaska. Where a government has little direct management control over airport operations, there is likely to be less influence over airport adaptation. In some places, local stakeholder-driven adaptation planning has increased participation by airports, which has resulted in awareness raising and consideration of climate risk.

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There is a considerable amount of literature and guidance on the impacts of climate change, resilience, and adaptation, but very little specifically on how it relates to airports. However, new resources in the general topic area are continually emerging. The findings here reflect one snapshot in time in 2011. This synthesis intends to provide both a baseline of relevant information for an airport beginning to consider climate change and a springboard for further research into an airport's risks under climate change and the resilience and adaptation measures that can provide an efficient and effective response.

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CHAPTER ONE

INTRODUCTION

OBJECTIVE

The objective of this synthesis was to identify the risks to airports from climate change and, using case examples and supplementary review, describe the activities airports are taking to address these risks.

Very few U.S. airports are currently considering ways to address the effects of climate change, although 70% of airport delays are the result of severe weather, and such weather events are on the increase. In 2011, the United States saw a record 12 weather/climate disasters costing at least $1 billion each. How airports respond to these events can inform debates over future planning. By defining and more explicitly addressing the risks that climate change present to airports, they can extend and enhance the benefits from present day investments in maintenance, data collection, and capital improvements.

REPORT ORGANIZATION

This report's intended audience is airport directors and their technical managers who are interested in airport-relevant information on the risks from climate change and what their peers are doing to address such risks.

Case examples from airports therefore appear upfront, and a comprehensive chart of climate effects is presented in the report text, for easy review and reference. The chapter two case examples detail the evolving practices at airport facilities in the United States and Canada.

Chapter three summarizes in chart form the likely climate change effects at airports and some measures for addressing them. It also reviews the trends observed in a survey on climate change adaptation practices.

Chapter four provides a sample list of the physical, business, security, and financial risks implicated by the climate change effects listed in the chapter three chart. The remainder of chapter four presents the results of a review of the following subject areas:

- A short overview of climate science, a sampling of potential climate risks to airports, and ways to manage its uncertainties about these risks.
- Actual climate adaptation and resilience activities underway in the United States.
- Climate risk identification and prioritization.
- Financing mechanisms to address climate risks.
- Formal incorporation of climate risk considerations into airport planning.

Chapter five concludes with observations, findings, knowledge gaps, and suggestions for further research.

STUDY METHODS

There were three key study elements:

- A literature review of reports, guidance, interviews, studies, and other work reflecting the emerging methods for evaluating climate risks and developing adaptation and resilience options.
- A survey of airports designed to capture information about current capacity at airports to address disruptions from weather-related events, risks anticipated under climate change, and approaches for managing them. The survey was sent to 20 airports and 16 responded (an 80% response rate).
- Case examples based on survey replies and research as validated and enhanced by interviews.

This Synthesis report was supported by a panel of experts from multiple disciplines, including aviation, planning, engineering, the environment, and the law. Several topic panel members are responsible for the operation and management of certain major airports in the United States.

TERMINOLOGY AND KEY DEFINITIONS

This Synthesis report uses the following definitions from a major study on climate change adaptation sponsored by the U.S.DOT (CCSP 2008).

- Exposure: the combination of stress associated with climate-related change and the probability or likelihood that this stress will affect transportation infrastructure.

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- Vulnerability: the structural strength and integrity of key facilities or systems and the resulting potential for damage and disruption in transportation services from climate change stressors.
- Resilience: the capacity of a system to absorb disturbances and retain essential processes.
- Adaptation: a decision that stakeholders can make in response to perceptions or objective measurements of vulnerability or exposure. Included in this concept is the recognition that thresholds exist where a stimulus leads to a significant response.

These definitions are provided because their emphasis is on the transportation sector; however, they are very similar to definitions used outside the transportation sector (see, e.g., Carter et al. 2007). A short glossary is included before the References.

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CHAPTER TWO

CASE EXAMPLES

INTRODUCTION

The goal of this Synthesis report is to identify current plans and practices for managing climate risks at airports through analysis of case examples and supplementary review. The cases that follow begin with an example of a mature response to climate change, illustrating the reality of climate change at Alaskan airports. The chapter closes with a profile of one Mississippi airport's response to the tornadoes that accompanied Hurricane Katrina, as a reminder that extreme weather, with or without climate change, is a challenging and continual proposition for the nation's airports.

Other examples demonstrate emerging trends in addressing climate risk. At Oakland International Airport, planners and engineers included sea level rise as a factor in design changes they were developing for other purposes. At Toronto Pearson International Airport the head of Environmental Systems Management used his profession's model climate change vulnerability assessment protocol as a tool for considering climate risk in stormwater system reviews and water quality regulatory compliance activities. In the following case examples, drivers for reviewing climate risks included:

- Severe weather events and related costs;
- Awareness raised from sustainability and greenhouse gas mitigation activities;
- Model adaptation guidance prepared by a professional society in a technical field;
- Executive leaders serving as champions;
- Participation in state, regional, and local adaptation planning efforts; and
- Federal grants and planning frameworks.

Overall there are few examples of actual funding or planning decisions at airports that were based on climate change considerations, and incorporation of climate change into existing decision-making processes is just beginning to develop.

CASE EXAMPLES

Case 1: Alaska

The state of Alaska has responsibility for the maintenance of aviation facilities in more than 200 villages that have no access to the road system. Residents in these communities rely on aircraft and alternatives (barges, snowmachines/snowmobiles, etc.) for access to food, fuel, emergency care, law enforcement, and other services. The nearest hospital, for example, may be 200 miles away by airplane. Many of these villages are situated at latitudes with year-round permafrost and lie along coasts and rivers.

Severe flooding and erosion has been reported in such villages for many decades, caused by seasonal factors such as snow melt and ice jams during the winter break up (GAO 2003). Increases in average temperature in recent decades have led to glacier melt, which has exacerbated the flooding and erosion. This warming also has led to a decrease in sea ice along the western and northern coasts of Alaska, and without this buffer from the sea, severe storms are eroding the shoreline, often at a rate of up to 100 ft per year. In addition, the permafrost layer is melting, causing settling that disrupts infrastructure on the surface (GAO 2003). Airstrips and airport access roads are incurring structural damage from erosion and settling, and flooding can restrict access to airports. Response measures have included reinforcement or elevation of runways and access roads, and relocation (GAO 2003).

With the support of various agencies, several villages have taken action to meet these challenges. Regarding aviation facilities, support in 2002–2003 included a $300,000 FAA Airport Improvement Program (AIP) grant for a Master Plan for the village of Kaktovik, and the village of Koyukuk received an AIP grant of more than $10,000,000 to elevate the runway out of the 100-year flood plain. Despite these kinds of measures, academic research has reported that the potential risks from climate change in most of Alaska's transportation sector, including aviation, were not being addressed in a systematic way (McBeath 2003). The same year the Government Accountability Office (GAO) reported on the circumstances facing the villages and outlined the funding, coordination, and prioritization required to address their needs. GAO explained that two agencies with flood and watershed responsibilities, the U.S. Army Corps of Engineers and the U.S. Department of Agriculture's Natural Resource Conservation Service (NRCS), have cost–benefit analysis requirements that have inhibited the flow of aid. However, GAO cited examples where Federal Emergency Management Agency (FEMA) and FAA were supporting the reinforcement of aviation facilities in some villages and providing planning money for the potential relocation with respect to other villages

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(GAO 2003). The FAA has found ways to work within its authorities to address the cost–benefit issues that have been barriers to U.S. Army Corps of Engineers and NRCS support for the villages (FAA 2004). In addition, the AIP-funded project in Koyukuk, completed in 2006, protected the newly elevated runway from flooding occurring that same year (Coffey 2009).

The more complex process of relocating villages is slow and expensive. Construction of a new rural Alaska airport, for example, costs $15 to 20 million and takes 3 to 5 years, sometimes as much as 10, owing to building methods required in these locations (FAA 2004).

Many entities have been involved in making the management of this long-term issue as transparent and efficient as possible (GAO 2009) including a special oversight subcommittee in the U.S. Senate (FAA 2004). In 2007, Alaska made the villages' concerns about erosion and flooding a component of its Climate Change Task Force work (GAO 2009). The University of Alaska researched and developed a method for prioritizing adaptation measures for the state's transportation network (Larsen et al. 2008). Significant challenges still remain for coordinating and funding the larger issue of village erosion (GAO 2009).

In Alaska, there are new policy cues with respect to climate change and airports. The state now has a public infrastructure climate adaptation strategy, and the Alaska Department of Transportation and Public Facilities keeps the climate risk to village airports on its programmatic and public outreach agenda (e.g., Coffey 2009). More broadly, it has developed an adaptable statewide aviation system plan that is guided by the FAA Airport System Planning Process (ASPP). The Alaska Aviation System Plan, found at www.alaskaasp.com, provides a dedicated process that will

- Identify airport improvements needed;
- Set priorities for funding;
- Propose aviation policy; and
- Document the existing system with photos, maps, and data.

One critical component of the Airport System Planning Process is the preparation of studies that characterize the economic significance of rural Alaska airports. It would appear that these studies can contribute to cost–benefit analyses, where such information did not previously exist.

Observations: Climate change adaptation is a difficult and iterative process, and takes place in the context of other pressing issues and needs. In this case, early investments were made in an ad hoc manner, prior to systematic planning. However, having large sums of money at stake was a driver for significant, higher-profile planning efforts. Oversight measures have been used as the work progressed. Planning and prioritizing are also informed by systemized documentation of airport facilities and economic analyses that may facilitate decisions on aviation infrastructure funding.

Case 2: Jacksonville, Florida

The Jacksonville Aviation Authority (JAA), located in northeast Florida, manages Jacksonville International Airport (JIA), Cecil Airport, Jacksonville Executive at Craig Airport, and Herlong Recreational Airport, all of which are 25 to 75 ft above sea level. The largest airport under JAA purview, JIA, is located 15 miles from the Atlantic Ocean and 6 miles from an inland waterway. The terminal, apron areas, and runways were built on former pasture land and a large amount of fill was needed to raise the level of the base of the structures. Many areas around JIA are at a lower elevation. A total of 5.6 million passengers used this airport in 2010.

Cecil Airport is 34 miles from the ocean and 13 miles from an inland waterway. Cecil Airport is a former Navy base that was closed in the Base Realignment and Closure process and deeded to the JAA in 1999. This airport is a JAA planning priority, as the authority seeks to develop it into an aviation business center attracting military contractors, aviation-related businesses, and their suppliers. This plan combined with increasing the current level of freight service would make Cecil Airport a major economic engine for Jacksonville.

The current chief executive officer (CEO) of JAA arrived in September 2009 from Oakland International Airport in California, where he had been Director of Aviation for 17 years. Oakland International Airport is a revenue division of the Port of Oakland, which has had a sustainability policy since 2000. That sustainability policy's foundational principles are environmental responsibility, social equity, and economic vitality (referred to as the "3 E's": environment/equity/economics). When hired in 2009, the CEO emphasized the need to run JAA as a business, and viewed the concept of sustainability as a piece of that strategy. More specifically, he viewed addressing potential risks to operations and infrastructure from climate changes as a part of planning for and support of "economic vitality" in the Jacksonville area.

In early 2011, the JAA CEO commissioned a white paper from his staff to examine possible changes in climate conditions, identify their potential effects on JAA operations and infrastructure, and suggest possible actions. With respect to climate change effects, the CEO tasked the JAA's environmental planner with developing the climate effects white paper for final approval within 3 months. At the time the white paper was commissioned, the JAA also was in the early stages of developing a sustainability plan; although some conference calls and meetings had taken place, this project was just beginning to take shape. In commissioning the paper,

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it was that clear climate change was its own topic, although connected in many ways to sustainability.

Early drafts of the white paper required some revisions to reach a consensus among internal departments, because it was a new topic area. The final version describes the changes in climate relevant to the Southeast region of the United States (as projected within 20 years, at mid-century, and by 2100); the effects and hazards that may result from these impacts, along with a set of potential solutions for each; and some potential next steps. The next steps would be to monitor projected changes, "consider incorporating adaptation considerations into future airport planning and operating documents," and consider developing design and construction guidance to prepare current and future infrastructure for potential climate change. In addition to making the white paper's content (e.g., the list of possible climate effects and likely adaption measures) relevant to JAA's situation, its structure had another notable aspect; it did not use terms from the adaptation lexicon, such as adaptive capacity or vulnerability. The resulting document, however, was a cogent and informed overview, designed to create awareness and stimulate discussion.

Despite a lack of relevant policy, guidance, or other sources of information within JAA, the environmental planner had tapped into the state-wide discussions on both sustainability and climate change. He also had access to several data bases that permitted him to successfully complete this assignment. First, in developing the white paper, the environmental planner was able to draw on two reports on potential climate impacts, the U.S. Global Change Research Program report on regional climate impacts in the United States and an FHWA report on climate impacts to transportation ("Regional Climate Effects . . . " 2010), also organized on a regional basis for the United States. Next, the CEO served as champion for the project, and provided active and sustained support and awareness as to its importance. In addition, the city of Jacksonville had opened an Office of Sustainability under the purview of the mayor's office in 2008. This office in turn created a city government-wide sustainability policy. Through this office, public awareness about the broader topic would lend support to this exercise to review climate change effects. Other resources were JAA colleagues, who shared common concerns if not in-depth knowledge of climate change per se. A simple but important aspect of this endeavor was that JAA holds weekly interdepartmental briefing sessions where all topics of common concern are discussed. Coincidentally, soon after the white paper was released, there was a interdepartmental briefing held at Jacksonville's Emergency Operations Center as an informational field trip exercise. City officials in the Jacksonville Emergency Preparedness Division mentioned and reinforced many of the issues raised in the climate change effects white paper, particularly in relation to a severe storm event.

Observations: The CEO's commissioning of the white paper began a dialogue on climate change risk, resilience, and adaptation, providing a means for people to discuss and digest information on the topic. It also built a strong knowledge base within the environmental planning office that can support ongoing education and inform decisions on the issue.

Case 3: San Diego, California

Located in the southwest corner of Southern California, the San Diego County Regional Airport Authority plans and operates San Diego International Airport (SAN). The third busiest passenger airport in California, San Diego International Airport served approximately 17 million passengers in 2010. The single-runway airport is located on 661 acres near downtown San Diego on the north end of San Diego Bay, just above sea level.

ICLEI (Local Governments for Sustainability) is an international membership organization whose mission is to educate and empower communities to set and achieve greenhouse gas emission and sustainability goals. In 2010, ICLEI joined forces with two organizations local to San Diego: the Tijuana National Estuarine Research Reserve and the San Diego Foundation, whose civic engagement projects include a climate initiative. The organizations became partners in developing a sea level rise adaptation strategy for San Diego Bay.

The partners convened a steering committee composed of those entities with land use and jurisdictional control of the land areas adjacent to San Diego Bay. Among these was the San Diego County Regional Airport Authority, with two representatives to the steering committee: its manager of airport planning and its director of environmental affairs. The three partners also created a stakeholder working group and technical advisory committee to provide input into development of the strategy.

The project vision relied on ICLEI's adaptation model. ICLEI describes adaptation as a process involving leadership commitment and five milestones, as depicted in Figure 1.

FIGURE 1 ICLEI's Five Milestones of Adaptation.

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The project's focus was on sea level rise, the single most prominent climate threat to the collected entities. Under the ICLEI model, development of an adaptation strategy would move San Diego Bay through Milestones, 1, 2, and 3 for adapting to sea level rise and related issues. ICLEI and the steering committee developed a series of project-level milestones and deliverables to be met between August 2010 and October 2011, including an existing conditions report, a vulnerability assessment to sea level rise for 13 sectors for the time frames 2050 and 2100, policy recommendations, and an overall adaptation strategy derived from the other three documents. The 13 sectors included potable water, stormwater, and wastewater utilities; energy facilities; local transportation facilities; emergency response facilities; commercial and residential building stock; and regional airport operations.

The project first examined the outputs of sea level rise models for the area surrounding San Diego Bay; the added effect of tides; and the likely impacts to result, including the hazards from increased erosion, flooding, inundation, and salt water intrusion.

Under the vulnerability assessment methodology, project participants analyzed existing and future conditions in relation to the following three adaptation planning factors:

Exposure: a determination of whether the system as a whole or parts of the system will experience a specific changing climate condition.

Sensitivity: the degree to which a system would be impaired by the impacts of climate change were the system to hypothetically experience those impacts. Systems that are greatly impaired by small changes in climate have a high sensitivity, whereas systems that are minimally impaired by the same small change in climate have a low sensitivity.

Adaptive capacity: the ability of a specific system to make adjustments or changes to maintain its primary functions even with the impacts of climate change. This does not imply that the system must look the same as before the impact; however, it must provide the same services and functions it did before the impact occurred.

Each of the 13 sector's vulnerabilities were rated in a qualitative way, and the project described the potential impacts in 2050 and 2100 from sea level rise, as exacerbated by, for example, high tides and potential problems in the stormwater drainage system. As noted, among the 13 sectors examined closely for vulnerabilities to sea level rise were regional airport operations.

The findings indicated that there are risks to regional airport operations, especially in 2100, assuming San Diego International Airport continues its role as the primary airport for the San Diego region. For the interim year 2050, model outputs showed that San Diego International Airport would not be flooded from the shoreline. However, localized inundation from flooding as well as backups in storm drains may be possible. By 2100, models showed that the primary access road to the airport (North Harbor Drive) would be inundated regularly, and under extreme events a portion of the airfield area would flood. Where a new passenger terminal may be planned, there would be extensive flooding in 2100. With regular flooding and closure of a primary access road, there would be regular airport closures in 2100. Experts believed that all air traffic to San Diego International Airport could not be handled by other local airports, as their runways are shorter and other airport facilities are smaller and cannot accommodate the forecast demand for air passenger service.

With respect to regional airport operations, two strategies were presented as potential options for addressing the flooding and inundation vulnerabilities, as prioritized by the stakeholder working group and technical advisory committee.

1. Incorporate sea level rise flood scenarios at San Diego International Airport into the Regional Aviation Strategic Plan process and the consideration of alternative sites.
2. In the San Diego International Airport Master Plan, explore the potential for reconfiguring airport access away from key roads that may experience significant flooding and are threatened by inundation.

The steering committee, which as noted includes the two representatives from the San Diego County Regional Airport Authority, participated in the preparation of the adaptation strategy. ICLEI views the adaptation strategy's release in late 2011 as completion of Milestones 1, 2, and 3, with the next step being Milestone 4, Implementation. At that time, the San Diego County Regional Airport Authority was considering integrating the relevant components of the strategy into its sustainability policy.

Observations: This regional effort raised awareness of a very significant climate change effect, sea level rise, throughout the San Diego Bay area. Use of the ICLEI model and its resources meant the region could start the project at an advanced level and progress to more evolved strategies more rapidly. It helped communicate to the public and decision makers the extent of the risk to the airport; for example, that inundation from the shoreline is not likely but stormwater problems may require future investment. More broadly, including San Diego County Regional Airport Authority representatives on the steering committee helped to define the airports' interests in regional activities and bring the findings and potential next steps back to their own organization.

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Case 4: Atlanta, Georgia

Hartsfield–Jackson Atlanta International Airport (ATL) is located in Atlanta, Georgia. On average it handles 250,000 passengers daily; nearly 90 million passengers a year. ATL is presently the world's busiest airport, supporting 1 million take-offs and landings annually. It has a 5.6 million-square-foot terminal complex with a 4,800-acre campus containing cargo, maintenance, and support facilities. A recent $6 billion capital improvement project has included projects such as the new consolidated rental car center, a fifth runway, and a new international terminal.

The airport is owned and operated by the city of Atlanta Department of Aviation. In 2008, the city sought to host a convention, but lost out to another city perceived as "greener." In February 2009, the city and several partners began a program to create "Zero Waste" zones, which became a highly successful initiative as reported in the national news. In October 2010, the city launched a sustainability plan that set targets in key areas, such as waste minimization and energy efficiency. The city encouraged its residents and city departments to support this plan.

The Department of Aviation began considering strategies for addressing sustainability at Hartsfield–Jackson in support of the city's initiative, and formed the Asset Management and Sustainability Division. Furthermore, the Department of Aviation secured funding from an FAA pilot program designed to support the development of either a sustainable management plan or sustainable master plan. Hartsfield–Jackson was one of ten airports chosen, and it elected to develop a sustainable management plan. The airport's decision to develop such a plan was based on timing; the next cycle for the airport master plan was more than two years away. When the Sustainable Management Plan was finalized in late 2011, procurement for the 18-month master plan process was just getting underway.

In 2010, once FAA funding for a sustainable management plan was in place, ATL conducted several exercises:

- Agency scoping sessions as part of the initial brainstorming and visioning process;
- Development of baseline information on resource consumption to identify opportunities for improvement;
- Review of sustainability initiatives for similar airports and industries;
- Review of global reporting initiative indicators for sustainability monitoring categories; and
- Public and stakeholder meetings to establish goals, targets, and initiatives.

The airport organized its work into four focus areas: procurement, construction, operations and maintenance, and policy. It focused on the collection of baseline data in electricity, water, greenhouse gas emissions, and waste, as well as natural gas, jet fuel, diesel, and hazardous material usage. Through the exercise listed earlier, the plan took shape. The resulting sustainable master plan document identifies metrics for achieving goals established for each focus area and anticipates tracking accountability for those metrics year by year. An annual report card will be developed and policies will be updated each fiscal year to ensure progress toward the end goals. A significant area of relevance to projected climate change impacts include water conservation, because the southeast United States, including the Atlanta area, has experienced persistent drought over the last several years.

The Department of Aviation anticipates developing an environmental and sustainability system that documents the airport's environmental footprint on a continual basis, complementing the work of the Planning and Environmental Division that already monitors the regulatory impact of environmental operations at the airport. Future study will be given to preparing for projected climate change in the southeast United States, specifically relating to impacts on Hartsfield–Jackson.

Once the sustainable management plan was completed in late 2011, the airport's aggressive implementation strategy included the drafting of the scope of work for on-call consultants to support the plan. This scope of work included a Request for Proposals that went out for tender in the same month that the airport delivered its completed sustainable management plan to FAA. The scope of work anticipates significant public outreach and communications activity, including the release of an annual sustainability report card, to ensure understanding and buy-in. The primary requirement, however, is development of a combined asset management and sustainability plan that would be long range and include a climate action plan, water master plan, energy management plan, and updated sustainable management plan.

At a more strategic level, airport management anticipates making the sustainable management plan one chapter in the master plan currently under development. With the institutional policies and processes in place or on schedule for development, the airport management reports that it is well-positioned to identify and address emerging climate change issues that may affect airport assets and other resources.

Observations: The airport took policy cues from its owner, the city of Atlanta, and pursued a sustainability initiative that puts in place avenues for identifying and addressing climate risks, such as organizational changes reflecting the importance of sustainability, a sustainable management plan, a combined sustainability and asset management plan (including climate action plan, water master plan, and energy management plan),

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and a master plan that includes a section devoted to sustainability. There is a flexible process in place, including signals from leadership, for considering climate change impacts at the appropriate time.

Case 5: Oakland, California

Oakland International Airport is a major airport on the coast of Northern California. It has two terminals, four runways, and significant general aviation activity. Approximately 11 million passengers use the airport annually. In 2009, it had the highest on-time arrival percentage among the 40 busiest North American airports. The airport lies near sea level, and the possibility of even partial inundation already drives decision making in several areas.

California has significant seismic activity and, as with most infrastructure in that state, there are earthquake-related risks at the airport; for example, seismically induced liquefaction of sediment has been a long-standing concern among planners. Separately, FEMA has standards and accreditation relevant to the robustness of dikes that apply to the perimeter dike at the airport. Although there has not been flooding, there has been some seepage at the dike. The accumulated water creates wetlands, and impacts to these are regulated. An added directive affecting these wetlands is the required development of "Runway Safety Areas" by the end of 2015, which may require filling in the wetlands. Each of these diverse regulatory drivers call for technical reviews by planners and engineers. Also, in recent years, the broader region has been concerned about sea level rise stemming from climate change; as a result, the airport's planners and engineers have focused on the potential risks from this climate change-related effect as well.

Airport staff cites one ongoing awareness-building and adaptation planning project as being particularly influential in securing their attention to adaptation and resilience planning. This project is Adapting to Rising Tides (ART), sponsored by the San Francisco Bay Conservation and Development Commission and the National Oceanic and Atmospheric Administration, which is being conducted at the sub-regional level. Its goal is to provide future scenarios and develop strategies for reducing and managing risks from projected climate change impacts. Oakland International Airport staff credits this effort with raising awareness on that subject. As part of the inventorying of sub-regional assets of interest, ART stakeholders select asset categories, choose metrics to characterize the assets, and use these metrics to assess existing conditions and stressors of assets. Sector-specific metrics were developed in many areas, including airports.

As noted, the airport's staff had been reviewing the perimeter dike and other infrastructure for several reasons. They viewed sea level rise as a minor risk relative to others. However, it was decided to incorporate sea level rise into design requirements for the perimeter dike because it was feasible to do so. Given that sea level models do not provide definitive information on the projected sea level rise, a rough average of modeling results was determined. The result for the perimeter dike's design was a 1 ft increase in height, and the ability to receive additional load in the future. As noted, this decision was made within a broader planning context that addressed, for example, seismic and FEMA standards related to the perimeter dike. At this time, a budget earmark for this work is awaiting final approval.

Lesson Learned: Climate change impacts can be a consideration in the preparation of design requirements and, in some cases, there is less of a need to wait for absolute rigor and precision in the technical information supporting them. Participation in broader climate adaptation planning efforts can cultivate this thinking. Airport planners also benefited from having modeling of projected climate impacts already available, as this freed the planners and engineers to think and act within a set of given parameters.

Case 6: Toronto, Ontario

Toronto Pearson International Airport is in a region with harsh winters and significant precipitation year round. The airport is bounded on one side with by a significant creek and a tributary.

At the airport, there was some awareness of potential climate change issues because a senior manager had reviewed a climate change vulnerability assessment protocol issued by an engineer's professional society. Specifically, the Director of Environmental Management Systems with purview over the airport took an interest in this protocol, which was recommended (but not required) by government, and believed that it provided the flexibility needed to address certain issues. Airport staff also was aware of anecdotal reports of microbursts in the local watershed.

The unpredictability of the weather became a consideration in development of stormwater design criteria. The airport follows a long-standing master plan process to conduct cyclical reviews that ensure stormwater events, and possible environmental impacts are mitigated and flooding of the creek are understood. Typically, engineers oversize certain elements of a stormwater system. As part of the most recent review, the airport had found that its infrastructure was already sufficient and there would not be localized flooding despite several modeled severe storm events. However, if the system was compromised in some way; for example, the clogging of a pipe, there could be a problem. The addition of another runway would require the extension of an existing triple box culvert approaching 50 years in age, which would require additional hydraulic capacity to convey the tributary by means of a new large-diameter pipe. When conducting the necessary hydraulic study, there was a general understand-

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ing among the professional staff that the weather and climate may become less predictable.

Another instance involved de-icing. Currently, at the airport, all de-icing fluids are collected; however, low concentrations are allowed to be discharged to the municipal wastewater treatment plant through surcharge agreements. Airport managers have observed less snow and more precipitation mix in the region, with more wing ice a possible effect. Also, the airport takes flights from many other regions that will experience changes away from historical weather patterns, and this will require potential use of more de-icing. An increase in the use of de-icing fluids may increase concentrations in run-off, potentially triggering increases to the surcharge agreements. Since the winter of 2010–2011, the airport staff has considered this issue and at the end of 2011 was in the process of finalizing the scope of a study on this subject.

In short, from its knowledge of the model climate change vulnerability assessment protocol: (1) the airport gave consideration to climate change as it conducted a hydraulic analysis for a new culvert; and (2) the airport expects to formally study the potential impacts of a new precipitation mix on de-icing fluid use and water quality.

Observations: Climate change vulnerability or risk assessment guidance and protocols tailored to a specific profession can help the target professionals assimilate information on potential climate change impacts and adapt related considerations into their current practices.

Case 7: Dallas and Fort Worth, Texas

Dallas/Fort Worth International Airport (DFW) encompasses more than 18,000 acres, making it the second largest airport in the United States in terms of land area. It has five terminals, seven runways, and its own post office, zip code, and public services. DFW is the fourth busiest airport in the world in terms of aircraft movements.

In recent years, DFW has managed several weather-related risks to its business and operations, including regional water scarcity and an unusual snow event. These events have raised awareness of climate risks and the effects climate changes can have on other activities, such as regulatory compliance. At the same time, DFW has a $1.9 billion renovation and expansion initiative underway, with an expected completion date in 2017. Three cases described here demonstrate the growing awareness of climate risks to DFW and to its growth, as well as its increasing capacity to address those risks.

The first case arose when, on February 4, 2011, the Dallas, Texas, region received 2.6 in. of snow, just two days before the Super Bowl. As a result, more than 300 arriving flights were canceled at DFW, a hub for American Airlines. The Southwest Airlines hub, Dallas Love Field, closed temporarily. As a result, thousands of football fans were left in limbo making for a major public relations problem that was a potential threat to DFW's reputation and business goals.

At DFW, runways and taxiways could not be cleared quickly enough because the existing snow and ice removal equipment had significant limitations; the existing equipment could only clear one of DFW's seven runways in one hour after a deicer had been applied. For more than 25 years, the existing fleet had consisted of the following highway-grade snow and ice removal equipment:

- For the airfield, DFW had ten plows mounted on dump trucks, with eight of the trucks also outfitted with airfield sand spreaders. The airfield equipment also included two snow blowers, two de-icer tanker trucks with boom sprayers, and two loaders.
- For the terminals ramps (aprons) near the airline gates there was inadequate preparation and snow removal equipment.
- For roads, there were 3 plows mounted on dump trucks, 2 loaders, and 12 gravel spreaders mounted on small dump trucks or pickup trucks.

Several inherent deficiencies led to the clearance problems at the time of the 2011 Super Bowl. Almost one-third of the dump trucks and pick-up trucks used with the plows and spreaders were beyond their useful life. The plows had only a minimal top curvature; therefore, overspray continually reached truck windshields, slowing the work. In contrast, airfield plows are designed with more curvature and a rubber deflector to reduce overspray. The plows also were for highway use and therefore their effective width was only 12 ft, whereas airfield plows are designed with a 22-ft effective width.

Based on this analysis of their current capacity to deal with snowstorms, after experiencing significant snow and ice storms during three of the four previous winter seasons, including the Super Bowl snowstorm catalyst, DFW developed a strategy with a set of objectives designed to meet certain snow and ice removal requirements. In addition to aiming to increase support to ramps and increase road response, DFW defined its objectives for the airfield as the following:

- Be prepared for back-to-back, 2-in. snow or ice storm events.
- Have the capability to remove snow and ice from all select runways in one hour.
- Be able to keep two parallel runways and one diagonal runway open at all times.

Although development of these objectives did not follow from a review of climate change projections, the snow and

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ice storms experienced during the past few years and the impact of the most recent storm to DFW operations especially during a major event in the DFW metroplex caused DFW to re-examine its capability to respond appropriately to weather events. DFW therefore sought information from airports with similar climate conditions as those experienced February 4, 2011. Specifically, to develop a comparative analysis, DFW obtained information from peer airports experienced in addressing ice and snow events, including Atlanta, Denver, Minneapolis–St. Paul, Chicago O'Hare, and Boston Logan.

As a result of this research and planning effort, DFW selected a set of equipment upgrades that enables it to clear three runways in 14 minutes for a 2-in. snow event, with a cost of $10 million for the new equipment, and $3 million for a storage facility, as well as $560,000 annually for operations and maintenance. DFW plans for airport-grade equipment including 10 pieces of multi-functional snow removal equipment that can plow, broom, and blow snow; 4 dedicated high-speed snow brooms; 2 dedicated 4,000 gallon tanker/sprayer trucks for airside pavement de-icing; and a 2,000 gallon tanker for landside pavement de-icing. In contrast, Denver and Chicago have 40 and 41 multi-tasking snow removal systems, respectively; Minneapolis–St. Paul has 4 and Atlanta none. Atlanta has four deicer tanker/sprayers, and through this exercise DFW doubled its tanker fleet from 2 to 4.

This case demonstrates the significance of a single, catalyzing event, and it is clear that DFW rebounded quickly. Less than a month after the snowstorm a formal funding request for the new equipment was submitted. The funding request stated the following: "The amount of revenue loss to both DFW and the airlines due to the suspension of aircraft landing and takeoff operations during one snow and ice event would more than compensate for the proposed purchase of new snow and ice removal equipment." This request was approved four months later on August 1, 2011, with the full support of the airlines.

This equipment upgrade makes the airport more resilient to at least one climate risk, the extreme winter weather projected to occur more frequently in the future. DFW considers this upgrade as a major accomplishment; all airport stakeholders including the airlines accepted that it was time DFW had the airfield-grade snow and ice removal equipment that was comparable to peer airports, without knowledge that the winter storm events may be associated with climate change.

The second case at DFW relates to another climate change expected for the North Central Texas region; more frequent drought. DFW is in a water-scarce region that already periodically experiences drought. The airport also experiences consecutive days of temperatures above 100°F, and has implemented water use restrictions during the past few years. As a result, water conservation measures at DFW have severely limited the use of water for irrigation, pavement power washing, and gas well facing. Also, although not restricted, the Central Utilities Plant at DFW uses potable water in its cooling towers, because the airport cools approximately 700,000 gallons of water per night to keep terminals air conditioned during the hottest part of the day. A terminal expansion will increase annual departures by 7,500 as early as 2014, significantly adding to the expected increase in water use per year.

As the city of Fort Worth planned for the development of a new reclaimed water facility, it was clear DFW would be the majority user of the water. Indeed, because of the stress on regional water supplies and the expected increase in costs for potable water used for nondrinking purposes, DFW staff hope to shift about 25% of water used in the Central Utilities Plant cooling towers from potable to reclaimed water, as well as for the previously mentioned irrigation of airport open space and the gas drilling operations conducted on airport property. The cost of the city's water plant and related infrastructure was estimated at $26 million, with a $16 million pipeline ultimately paid for through American Recovery and Reinvestment Act funding. The city would deliver water right up to the airport's property line, requiring DFW to build its own infrastructure to distribute the reclaimed water across its property and facilities, at a cost of $18 million for the first phase.

Reclaimed water—which is waste water processed to a nonpotable standard acceptable for industrial and other uses not affecting human health—has a stigma that can be difficult to overcome. Additionally, although reclaimed water is not as expensive as potable water, an appropriate rate needed to be set for the city to justify the project. In March 2008, the DFW board authorized the negotiation of cost sharing and/or set rates for the time when the water would be available and delivered to DFW. DFW, as well as the cities of Dallas and Fort Worth, agreed that the use of reclaimed water for nonpotable water usage at the airport was a prudent initiative based on the continuing North Central Texas extreme drought conditions and scarcity of water resources.

Eighteen months later, in September 2009, the DFW board approved the agreement reached with the city. That same month, funding also was approved for the $18 million. The justification for these decisions was that reclaimed water would provide a long-term, less-expensive, and sustainable water supply and that its substitution for potable water would provide economic and environmental benefits to DFW and the region. DFW also justified the expense on the basis that an additional water supply would provide service reliability and reduce demands on existing water supplies and infrastructure. DFW calculated that the airport would save $4 million in costs over 20 years, and $121 million more over 60 years, through use of reclaimed water. Drought resistance was cited as an unquantified but anticipated benefit as well.

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However, DFW's major tenant airlines needed to be convinced. In 2011, the region experienced the worst drought on record, which justified proceeding with this initiative. This circumstance helped make the case for finalizing the DFW's reclaimed water distribution project. Despite the prominence of the water scarcity issue, the initiative, as with the winter storms case, was not developed or discussed as a climate change adaptation measure.

The third case at DFW relates to the projected increases in regional temperature. DFW is undertaking a $1.8 billion terminal expansion and renovation initiative (Terminal D). Projects under this initiative are subject to environmental compliance review, including those covering federal and state air quality requirements. Early in 2011, the North Central Texas region was downgraded by the EPA from "moderate non-attainment" to "serious non-attainment" under federal air quality standards. This reduced the de minimus threshold for two pollutants, nitrogen oxide (NOx) and volatile organic compounds (VOC), from 100 tons per year to 50 tons per year, for both direct emissions (such as construction) and indirect emissions (such as operational emissions). The change could affect DFW's proposal to construct and operate new gates at Terminal D. Aircraft emissions from the air services using the additional gate capacity, when added to the emissions from construction and passenger busing, may exceed the new 50 ton per year de minimus standard. In effect, this air quality compliance issue could stall the expansion. Increased temperatures under climate change are likely to increase NOx and VOC emissions. For example, EPA estimates that a 10°C increase in temperature doubles emissions of these pollutants (Grambsch n.d.). For the short term, DFW will work through its air quality issues; however, the exacerbating effect of climate change on regulatory compliance is directly influencing the thinking of DFW personnel.

Observations: Because of the projected climate variations for the region and these three unrelated experiences—involving ways to address the risk of another extreme winter storm in the future, continuing drought, and compromised air quality—the DFW will continue to consider new initiatives and/or programs for climate change adaptation.

Case 8: Jackson, Mississippi

The Jackson Municipal Airport Authority (JMAA) is located in Jackson, Mississippi, 170 miles from the Gulf of Mexico. JMAA manages the Jackson–Evers International Airport and the Hawkins Field Airport, with more than 600,000 enplanements in 2010.

In 2010, Mississippi experienced 182 confirmed tornadoes, with 24 fatalities; in 2011, there were 94 confirmed tornadoes. Because JMAA's two airports are in a region with a tornado frequency higher than the infamous Tornado Alley in the Great Plains, they are accustomed to handling irregular operations and disaster situations, an issue illustrated by the following summary of JMAA's procedures as well as its activities after a major hurricane.

JMAA standard operating procedures call for continual assessment of the weather in the surrounding area and at the most logical points where its airports' operations will be affected. In the absence of a forecast major weather event, a routine day means that JMAA checks the weather in the area, which includes all of Mississippi with a concentration on the Gulf of Mexico activity, and large parts of Louisiana, Arkansas, and Tennessee. Next, JMAA reviews the cities where it has direct service. If they are to be affected by an event, Jackson-based staff knows it will likely result in delays and/or have service interruptions. JMAA next reviews national events that are likely to affect areas over the following two days.

If in watching the weather there are predictions of thunderstorms or tornado activity, JMAA keeps phones and computers running with weather information/radar reports in the background and pages out information on National Weather Service Watches all day. When a "watch" becomes a "warning," JMAA implements its Crisis Management Center, makes calls to confirm the status and paths, and alerts the airlines, fixed-based operations (FBOs), and other tenants of the likely impacts. It is at this point that the emergency management processes technically begin.

Where a major weather event, such as a hurricane, can be expected and there is lead time, the process is as follows. At first notice of activity in the Gulf of Mexico, JMAA holds an internal staff meeting to assess the tracks and impacts. They confirm contact lists, basic supplies such as water, ready made meals, cots, etc., and staff availability.

When a track shows a direct impact to the Jackson metro area, JMAA calls a meeting of key JMAA personnel, tenant managers, TSA, and FAA management to review plans for fuel, standby power, and basic food and water supplies. They then reach out to the airlines that serve the main airport and provide notice of the predicted impacts. At this point, JMAA begins to work with the airlines to determine when they will "intentionally interrupt" operations. This outreach helps JMAA plan in several ways; for example, with respect to reaching the media to ensure that people do not make travel decisions that leave them stranded at the terminal. If a hurricane is more likely to hit Texas, Louisiana, or Alabama than Jackson, JMAA reaches out to those airports and the airlines that operate both in Jackson and in those other areas. JMAA begins to allocate space for aircraft to be intentionally ferried to Jackson to protect them during the storms. Although this proactive approach does not fix the problem of unannounced diversions, it helps JMAA to allocate space for the additional aircraft that can be planned for.

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At 10:00 a.m. on August 29, 2005, Hurricane Katrina made landfall in Mississippi with sustained winds of 120 mph. Inland, the last attempted aircraft departure as the hurricane approached the Jackson area was at 2:30 p.m. During the event, Jackson experienced sustained winds of 40 mph and nearly 4 in. of rain over a 10-hour period. Across the state, there were 13 tornadoes, rated F1 (73–112 mph) and F2 (113–157 mph).

There was serious damage to the airports and the region. Commercial flights were suspended from about 3:00 p.m. August 29 to about 11:00 a.m. the next day. Helicopters were the primary form of transportation used by federal emergency response management team leaders to reach the impacted areas of Mississippi.

The airports received evacuees and first responders. There were several hangars available for use; however, a terminal and a parking lot were under construction, and the land was wet from the storm. As a result of damage from the extreme weather, the airports lacked the following: commercial power, landlines, cell phones, gasoline, Jet A fuel, parking spaces, staff, air conditioning, and local hotel rooms. There were not enough rental cars or restaurants for the people present.

Conditions in the aftermath of the weather event hindered operations and required JMAA's management to find ways to overcome them. The following is a list of those major operational issues that needed resolution:

- Because resources were expected to be limited for some time, JMAA focused on the primary mission of the airport; that is, keeping the airfield open, securing fuel for generators, ensuring that lights and navigational aids are in working order, and requiring staff to clear debris.
- JMAA, as the owner/operator of the two airports in Jackson, also was called on to manage relationships with the tenant airlines, FBOs, and emergency response teams to ensure coordination of operations and availability of supplies and equipment. Various issues arose; for example, emergency responders often had challenges working through the TSA's protocols governing last-minute flight changes.
- JMAA had to manage the public's expectation of using the airport as a safe haven. It worked directly with the local and regional media to provide timely information on airline operations, availability of flights, and local housing options to assist people leaving the area and prevent them from arriving at the airport with no transportation options. JMAA worked with aid agencies to ensure that evacuees were advised of and/or taken to shelters so that the airport could perform its primary mission.
- To address inefficiency in shift changes, JMAA instituted several governance actions.
  - An essential personnel system. By identifying only essential personnel, JMAA reduced 108 full-time positions to 18, who worked 12-hour shifts, but as a small group they could more effectively use and communicate information. Nonessential personnel were put on paid administrative leave. Senior management personnel did not take days off in a regular pattern, but worked short and long days in turn as they could after the first week. The communications center remained staffed at all times, and generally six law enforcement personal were on duty at all times. JMAA had two operations staff on duty at all times. Maintenance and administrative staff were retained on an as-needed basis.
  - JMAA reserved leadership personnel for key negotiations and regional coordination and kept a running log of actions taken and services restored to reduce duplication of efforts.
  - JMAA's communications center was kept open 24-7 to provide for a secure central information center for status reports, resource allocations, remaining reserves, and expenditures.
  - JMAA sought to ensure a productive system for managing data, keeping documentation to ensure reimbursement from insurance companies and vendors.
  - Because cell phones and landline service was intermittent at best, JMAA scheduled daily in-person meetings with staff, then with tenants and emergency agencies, to review daily schedules. Also with respect to telecommunications, JMAA learned that continuing operations planning that included higher end technology did not work as well as predicted. A key example was the use of satellite phones. JMAA has satellite communications systems, but were not able to communicate with other agencies that relied on land lines or cell systems.
- As a result of the intensity of the storm, the hundreds of miles of damaged roadways, and the direct impact of the hurricane on fuel refineries based along the Gulf of Mexico, the fuel supply chain was interrupted nationwide.
  - JMAA worked with the FBOs directly to learn if they were going to be able to provide fuel to commercial airplanes. In turn, this knowledge allowed JMAA to advise the airlines on what their best fueling options were, there in Jackson or "fueling through," by carrying extra fuel on board to reach their next destination safely without having to fuel up in Jackson.
  - Unleaded gasoline and diesel fuel was in such low supply across the region that JMAA provided fuel to both FAA Air Traffic Control and Aircraft Rescue and Fire Fighting personnel for use in their personal vehicles at the rate of 5 gallons per day to ensure that they could report to the airport to support operations. In some cases these employees chose to temporarily reside at the airport versus travelling to and from their residences to conserve that fuel.

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- JMAA also provided fuel to essential JMAA personnel such as JMAA police officers, maintenance personnel, and operations personnel. This approach was taken to conserve fuel supplies and to reduce the strain on limited resources such as water and batteries.
- Fuel service vehicles were hesitant to enter the region owing to violence and reports of hijackings on the roadways. Faced with the need to provide both unleaded fuel for ground vehicles and Jet A fuel to support air operations, JMAA arranged for a two-car police escort to meet a fuel tanker at the Alabama/Mississippi border, approximately 150 miles east of Jackson.

Some issues had to wait until operations were back to normal. When they were, JMAA quickly moved to address ways to ensure supplies of the essential resource for an airport's operation: fuel. Since Hurricane Katrina, JMAA has acquired an additional 500-gallon above-ground storage tank for unleaded fuel, and it is in the design stages of a project that will allow for 72 hours of power based on bi-fuel generators.

Observations: Current weather variations are unpredictable and present a significant challenge in some locations. Existing procedures are in place to address interdependencies, such as with the airlines and other airports.

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CHAPTER THREE

METHODS AND SURVEY RESPONSES

INTRODUCTION

Interviews, a literature review, and a survey were the methods used to collect information. Detailed descriptions of methods, data, and the materials reviewed are contained in the appendices.

INTERVIEWS

Structured interviews were conducted with managers and technical staff at airports and relevant agencies. The case examples in chapter two were informed and reviewed by a relevant interviewee. Interviewees were identified through several means, including the Topic Panel; discussions at the May 2011, TRB workshop on climate change adaptation at airports; and through the survey described later in this chapter. Each interviewee received a standard set of questions (see Appendix A) with which to prepare for the interview.

LITERATURE REVIEW, WITH SUMMARY OF CLIMATE CHANGE EFFECTS AND ILLUSTRATIVE ADAPTIVE MEASURES

A review of existing literature was conducted with respect to climate adaptation and resilience activities for airports and other infrastructure, with a view to what has been helpful to transportation facilities. Results of this review are presented in the following two formats in this chapter:

1. Summaries of each literature category helpful to transportation facilities, with representative sources; and
2. A summary of airport-specific information on projected climate change effects and illustrative adaptation and resilience measures, presented in table form.

The literature review revealed that there has not been a comprehensive analysis of the risks to airports from climate change or a full assessment of practices for addressing these risks. Also, new reports, articles, plans, and other materials on climate change adaptation and resilience are produced continually, with the volume of transportation-focused adaptation and resilience information increasing rapidly. Therefore, it is important to note that this literature review and its results reflect a snapshot in time for 2011.

Detailed information on the methods used for the literature review can be found in Appendix B. Summaries of relevant sources used for the literature review are in Appendix C. Given that climate change resilience and adaptation constitute an emerging issue, are complex, and require knowledge from multiple disciplines, across diverse sectors and scales, the Appendix C summaries contain substantial amounts of information to provide airports with a strong understanding of adaptation and resilience. From these sources and those listed in the References, information specific to airports was summarized and arranged in Table 1.

Descriptions of literature review source categories, Table 1, and their airport-specific climate change information, follow.

Summaries of Literature Review Sources

The sources in the literature review fall into certain broad categories. Many sources are at a high level compared with the sort of decision making and planning an airport conducts on a day-to-day basis, reflecting the nascent state of adaptation and resilience at airports, in the transportation sector, and generally.

Projections of Climate Change and Its Impacts as They Relate to Transportation

This category of sources provides projections of the impacts of climate change on the transportation sector and, to a lesser extent, airports. A notable source is the FHWA report *Regional Climate Change Effects: Useful Information for Transportation Agencies* (2010). Other sources may report on a specific regional- or state-level adaptation and resilience planning process and therefore include discussion of climate scenarios relevant to that region. In cases where an airport is in one of these regions and seeks general information these sources may be useful.

Foundational and Authoritative Resources on Climate Change Impacts and Adaptation

There are a significant number of potential sources available, and adaptation and resilience is a complex and evolving field with resources continually emerging from diverse disciplines and circumstances. In this context, publications that can serve as authoritative resources are useful. Publications of this kind include those produced by research bodies, which, although technical, are also accessible and provide useful discussion on the uncertainties inherent in climate change and related adaptation and resilience activities. TRB's *Potential Impacts of Climate Change on US Transportation, Special Report 290* (2008) is frequently cited and relied upon.

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TABLE 1
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)
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)	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)

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TABLE 1
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Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
			Flashpoint of aviation fuel exceeded on hot days (*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)
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)

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Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
			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)		
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)

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Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
					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)
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)

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Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
						Abandon or move coastal transportation system (Schwartz 2011) Generally, future transportation planning account for projected change in coastlines (Peterson et al. 2008)
Sea Level Rise	Rising water levels in coastal areas and rivers (Meyer 2011)	All or part of airport	In combination with subsidence and/or tidal actions, threat of inundation (Peterson et al. 2008)	Airport closures or restrictions affecting airport operations (Love et al. 2010; TRB 2008) and airport emergency response role (Stewart et al. 2008) Salt damage to aircraft (Stewart et al. 2011)	Inundation of airport runways in coastal areas (TRB 2008)	Same as above, but in earlier timeframe At 40–100 years in the future, stringent design for flooding and for building in saturated soils (Meyer 2008)
Sea Level Rise	Rising water levels in coastal areas and rivers (Meyer 2011)	All or part of airport	In combination with possible increase in storm intensity and frequency, storm surge leading to flooding and inundation (Peterson et al. 2008)	Airport closures or restrictions affecting airport operations (Love et al. 2010; TRB 2008) and airport emergency response role (Stewart et al. 2011) Salt damage to aircraft (Stewart et al. 2011)	Inundation of airport runways in coastal areas (TRB 2008)	Same as above, but in earlier timeframe Construction of storm retention basins for short, high-intensity storms; i.e., flash flooding (Schwartz 2011) Provide good evacuation routes and operational plans (Schwartz 2011) Over next 30–40 years, design changes to bridge height in vulnerable areas, more probabilistic approaches to predicting storm surges (Meyer 2008) At 40–100 years in the future, greater protection of infrastructure, changes for bridge design, both superstructure and foundations, change in material specifications, more protective strategies for critical components (Meyer 2008)
Extreme Events	Increased hurricane intensity (IPCC 2011)	All	Damage to exposed assets (TRB 2008) More frequent evacuations (TRB 2008) Pressure on cargo storage if cargo cannot leave site (*Evaluating the Risk Assessment . . .* 2011)	Damage and evacuations cause disruption to operations (TRB 2008) Increased handling of redirected flights from other airports (*Evaluating the Risk Assessment . . .* 2011) Difficulties for employees, including safety crews, to get to work (*Evaluating the Risk Assessment . . .* 2011)	Damage to landside facilities (e.g., terminals, navigation aids, fencing around perimeters, signs) (TRB 2008)	Build or reconstruct more robust and resilient structures (Schwartz 2011) Move critical infrastructure systems inland (Schwartz 2011)

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TABLE 1
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Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Extreme Events	More intense aspects of storms: precipitation, winds, wind-induced storm surge; (Peterson et al. 2008) greater wave height (Meyer 2008)	Icing on aircraft (Peterson et al. 2008)	Increase in intense extra-tropical storms may increase warm fronts that lead to icing in some regions (Peterson et al. 2008)	Water quality compliance from increased icing (*Evaluating the Risk Assessment* . . . 2011; Stewart et al. 2011)		Incorporate the potential of climate change events into the existing systems of planning for irregular operations (Stewart et al. 2011)
Extreme Events	With increased amplitude of temperature (e.g.,extreme cold) increase in winter storms in the northern mid-latitudes (IPCC 2011; TRB 2008)	Airfield and aircraft operations (Peterson et al. 2008; (*Evaluating the Risk Assessment* . . . 2011)	Increase in winter storms, with increases in winds, waves	Dangerous flying, takeoff and landing conditions (*Evaluating the Risk Assessment* . . . 2011) Staff and passenger health and safety risk (*Evaluating the Risk Assessment* . . . 2011) Increase in de-icing needs (*Evaluating the Risk Assessment* . . . 2011) Disruption in key supplies (aviation fuel, glycol, rock salt) (*Evaluating the Risk Assessment* . . . 2011) Disruption of key access points and parking impede flow of passengers and staff (*Evaluating the Risk Assessment* . . . 2011)	Loss of use of infrastructure, causing disruption (*Evaluating the Risk Assessment* . . . 2011)	Planning for availability and readiness of equipment and supplies (salt/sand for roadways and parking areas, other materials for runways and taxiways) and that of partners (e.g., where airlines manage de-icing) (WIST 2002)
Extreme Events	More intense aspects of storms: precipitation, winds, wind-induced storm surge (Peterson et al. 2008) greater wave height (Meyer 2008)	Aircraft	Microbursts and gust fronts (Peterson et al. 2008)	Delays (Peterson et al. 2008) Increased damage from foreign objects (*Evaluating the Risk Assessment* . . . 2011)		Progressively incorporate consideration of this risk factor into existing design specifications, asset management systems, and maintenance work systems (Stewart et al. 2011)

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Climate Change Phenomenon	Change in Environmental Condition	Airport Asset or Activity	Primary Impact	Effect of Impact		Illustrative Responses
				Operations and Interruptions	Infrastructure	
Extreme Events	More intense aspects of storms: precipitation, winds, wind-induced storm surge (Peterson et al. 2008) greater wave height (Meyer 2008)	Ground operations	Lightning (Peterson et al. 2008)	Delays from suspension of refueling and other ground operations (Peterson et al. 2008; (*Evaluating the Risk Assessment . . .* 2011) Delays from aircraft affected by lightning strike being taken out of service (*Evaluating the Risk Assessment . . .* 2011)		Progressively incorporate consideration of this risk factor into existing design specifications, asset management systems, and maintenance work systems (Stewart et al. 2011)
Extreme Events	More intense aspects of storms: precipitation, winds, wind-induced storm surge (Peterson et al. 2008) greater wave height (Meyer 2008)	Aircraft; aircraft operations	Hail (Peterson et al. 2008)	Delays (Peterson et al. 2008; WIST 2002)	Damage to aircraft (Peterson et al. 2008, WIST 2002)	Progressively incorporate consideration of this risk factor into existing design specifications, asset management systems, and maintenance work systems (Stewart et al. 2011)
Wind Loads	Increases and decreases in wind speeds and loading	Aircraft; ground transportation; ground structures (Peterson et al. 2008)	More turbulence (Meyer 2008) More fuel burn when flying into the wind (Peterson 2008) Damage to structures (Love et al. 2010) Decreased wind speeds leading to increased longevity of wing tip vortices that endanger lighter aircraft, requiring aircraft separation (*Evaluating the Risk Assessment . . .* 2011)	Other than the likelihood of delays and rerouting (Love et al. 2010), the specific impacts and effects from climate change; e.g., on surface wind at airports and at flight levels, are not yet extensively assessed (Peterson et al. 2008; Pejovic et al. 2009a)		Hardening facilities for higher wind loads (e.g., building shell replacement, aerodynamic load analysis of building complexes, and extra tie-downs for aircraft and containers) (Stewart et al. 2011; Klin et al. 2011) Over the next 30–40 years, wind tunnel testing will have to consider more turbulent wind conditions, change in design factors (Meyer 2008)
Wind Loads	Change in prevailing wind	Runway; operations (*Evaluating the Risk Assessment . . .* 2011)	Effect on runway utilization (*Evaluating the Risk Assessment . . .* 2011)	Backlog, delays, diversions, cancellations, and schedule changes (*Evaluating the Risk Assessment . . .* 2011). Other than the likelihood of delays and rerouting (Love et al. 2011), the specific impacts and effects from climate change and wind are not yet extensively assessed (Peterson et al. 2008; Pejovic et al. 2009a).		Permanent change in prevailing wind could require realignment of runway direction (*Evaluating the Risk Assessment . . .* 2011)

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General Adaptation Guidance and Planning

This category of resources includes "how-to" guidance relied on by state and local planners, and these types of guidance, tool-kits, and other instructional materials on climate change adaptation are quite numerous and widely available. As described in *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* (2007), practices commonly cited include the selection of a champion and the proper governance structure for running a climate planning initiative, an analysis of metrics used in determining the vulnerability or value of an asset, and how to evaluate subject matter experts, including climate scientists, needed for certain analyses.

Transportation Sector Adaptation

Many resources address climate impacts and adaptation planning in the transportation sector in varying levels of regional or technical detail. An important finding in this review is that the transportation sector is represented predominantly by the highway sub-sector, which covers some, but not all, aspects of airport facilities. That said, there are examples in broader transportation planning that can be applied to the development of airport adaptation planning, including a 2011 article published by ASCE describing the asset inventory and high-level risk analysis conducted by the Port Authority of New York and New Jersey, "Anticipating Climate Change" (2011).

Sources Focused on the General Airport Context Under Climate Change

Virtually all sources that address airports do so in the context of a larger report or research project. Other articles are narrowly focused and academic. Work products focusing on airport adaptation and resilience provide information and conclusions based on the professional judgment of aviation experts. The summary of adaptation planning efforts received by the government of the United Kingdom in response to required reporting provides a useful list of climate risks for reference and consideration, *Evaluating the Risk Assessment of Adaptation Reports under the Adaptation Reporting Power: Aviation Sector Summary* (2011).

Sources Detailing Climate Risk Assessment and Other Decision Support Tools and Methodologies

Many transportation sector sources describe risk assessment practices. FHWA has been a leader in developing methods and piloting their use in regions and cities, and its conceptual climate risk assessment model is influential. A helpful resource is therefore *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model* (n.d.). The general approach to risk analysis, with minor variations from the FHWA model, includes defining the climate change variables and projections, setting baseline conditions (e.g., current stressors), developing asset inventories based on policy priorities, assessing vulnerabilities, analyzing risks, prioritizing the assets, and developing adaptation strategies. With respect to risk analysis, the traditional approach is followed, with risk as a function of the likelihood of occurrence and the gravity of the consequences. Metrics are developed to evaluate the magnitude of the consequences, and these may include capital and operating costs, effects on society, health, economics, and the environment. With respect to the likelihood of occurrence, one critical factor is whether there is a likelihood of occurrence of the impact in the lifetime of the asset. With limited data and guidance, the lifetime of the asset can be a subjective judgment that differs across and within asset classes; a good practice is to develop a quantitative scale for this purpose. In-depth studies of certain climate risks and methods for their analysis tend to be academic in nature. For example, there have been efforts at modeling the impact of weather events on flight delays in the atmosphere and those nearer to the ground. This is a new field and although the work product is often carefully qualified it can provide insights of use across diverse sectors and organizations. For example, a common insight is the type of observational data needed for meaningful analysis.

Summary of Projected Climate Change Effects and Illustrative Adaptive Measures for Airports

The literature contained significant information on projected climate change effects, impacts, and potential responses. Working from a table of categories of climate effects on transportation (*Potential Impacts of Climate Change . . .* 2008), this information from the literature review was organized into Table 1 for ease of review.

SURVEY RESPONSES

Results From a Small Survey of Airport Leadership

Sixteen individuals, each a senior executive, operational, or technical manager representing a single airport, responded to a 20-minute survey distributed to 20 airports (see Table D1 in Appendix D for information on the number of respondents that completed the first and the second set of questions). The survey had two parts: the first covered how airports address current weather-related disruptions, without regard to climate change, to gauge their capacity to address climate change, in the second part, airports responded to questions about projected climate change impacts.

Most respondents (12 of 16, or 75%) stated that they thought airport disruptions related to weather were becoming more frequent or more intense, without attribution to climate change or any other cause. A similar percentage was

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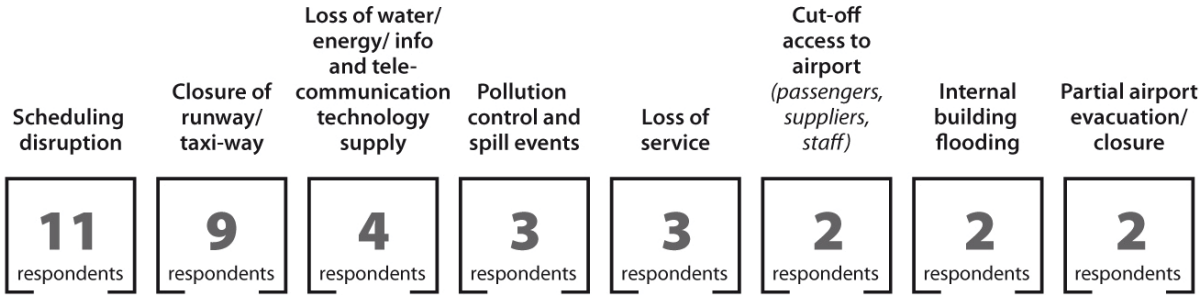

FIGURE 2 Weather-related disruptions in 2010, with number of respondents selecting each.

concerned about the effect of climate change on their airport, citing heat waves, increases in storm intensity, and visibility as issues of most concern. Several drivers for considering climate change in decisions were identified by the respondents. The most cited driver was awareness raised from greenhouse gas mitigation efforts, and another of note was staff professional judgment, weather, and emergency management activities. Insurance and bonding requirements were not cited as much. U.K. respondents identified mandatory reporting requirements as an important driver.

Appendix D describes the Survey Method. The survey text is in Appendix E, and Appendix F presents the results for each survey question.

Results Relating to Current Weather

As noted, 75% of the survey respondents (12 of 16) thought airport disruptions related to weather were becoming more frequent and/or more intense. Respondents were next asked to state whether their airport was considering ways to specifically address more frequent or intense weather disruptions. Considering such action would indicate an awareness reflecting some level of adaptive capacity. If an airport was not considering ways to specifically address more frequent or intense disruptions from weather, the respondent's obligations were completed. Three of the 16 left at that point; the remaining 13 answered questions regarding their airports' responses to current disruptions from weather.

The most frequent weather-related disruption reported for 2010 was scheduling disruptions, with 11 of the 13 respondents (82%) reporting this issue. Figure 2 depicts the types of disruptions reported for 2010 and how many airports were affected.

The airports also identified the effects or outcomes from weather-related disruptions. The one most frequently cited was lost revenue. When asked what resources they used to prevent, reduce, or otherwise address threats from weather, U.S. respondents gave a variety of answers, with the most common sources of funding being local funds and a budget line item for that purpose, as seen in Figure 3.

Figure 4 depicts effects and outcomes from weather-related disruptions in 2010, for only 12 of the 13 respondents; one respondent could not answer the question. Slightly more than half reported a re-allocation of funding or human resources as an effect or outcome.

As shown in Figure 4, five respondents reported that the effects or outcomes of a specific disruption from weather led to coordination with airport service providers. In response to another survey question, respondents listed the external stakeholders with which they worked to address weather disruptions and related impacts. Airlines were the most frequently cited external partner, while two airports reported that they did not work with any external partner.

In 2010, several forms of physical damage occurred at the respondent airports during weather-related events. Figure 5 shows their frequency within this group of 13, with damage to the infrastructure relating to taxiways/runways, roads, and drainage cited most often.

Asked if their airports keep records of increased or extraordinary maintenance caused by weather events, more than half (7 of 13) said they did not know, whereas 3 said no and 3 yes. Overall, 12 of the 13 respondents (92%) believed, "the airport could manage current weather variability adequately."

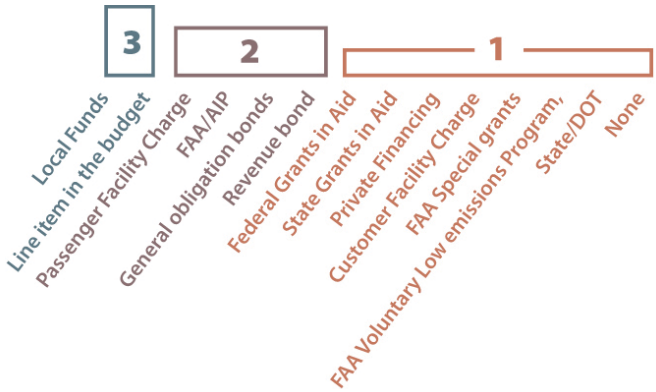

FIGURE 3 Resources used by U.S. respondents to prevent, reduce, or otherwise address threats from weather.

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FIGURE 4 Effects from weather-related disruptions in 2010, with number of respondents selecting each.

Results Relating to Climate Change and Related Risks

After completing questions about current weather, the 13 respondents were asked if they were familiar with the way climate is projected to change in their airport's region. If a respondent replied "no" the survey was terminated. Two respondents replied in the negative, and the remaining 11 responded to in-depth questions about their activities regarding projected climate change.

Respondents were presented with a list of climate change variables and told to consider four airport areas that can be affected by weather and climate change:

1. Airside
2. Landside
3. The inter-modal transportation system
4. The local and regional geographic area.

The respondents then answered two questions based on their personal knowledge or judgment:

1. For 2010, did the respondent's airport experience a major disruption from weather (or events in the natural environment caused by weather). Each respondent was to use the list of climate variables in the survey as a guide and record an answer for each airport area. The first column in Tables 2 and 3 show all responses to this question.
2. For 2030, do the respondents believe there would be increases in disruptions by that time frame for each of the given climate variables. Each respondent was to use the list of climate variables as a guide and record answers for each airport area. The second column in Tables 2 and 3 show all responses to this question.

A 20-year difference was used because that is a typical planning horizon for U.S. airports, with 20 to 30 years seen as the farthest extent (*Potential Impacts of Climate Change* . . . 2008). Table 2 presents the results ranked by total responses, with the most frequently cited climate variable first. This presentation highlights the areas of most concern currently, and those perceived as concerns for the future. The type and the scope of concern appears to shift from 2010 to the 2030 time frame, with snow and ice the primary concern in 2010, but and heat waves and high-intensity storms of more concern for 2030.

Table 3 presents the same data as in Table 2, but it directly compares the number of responses for each climate and weather variable. The two columns are compared based on the highest ranked answer for the future; that is, the 2030 time frame. The respondent's collective ranking of perceived

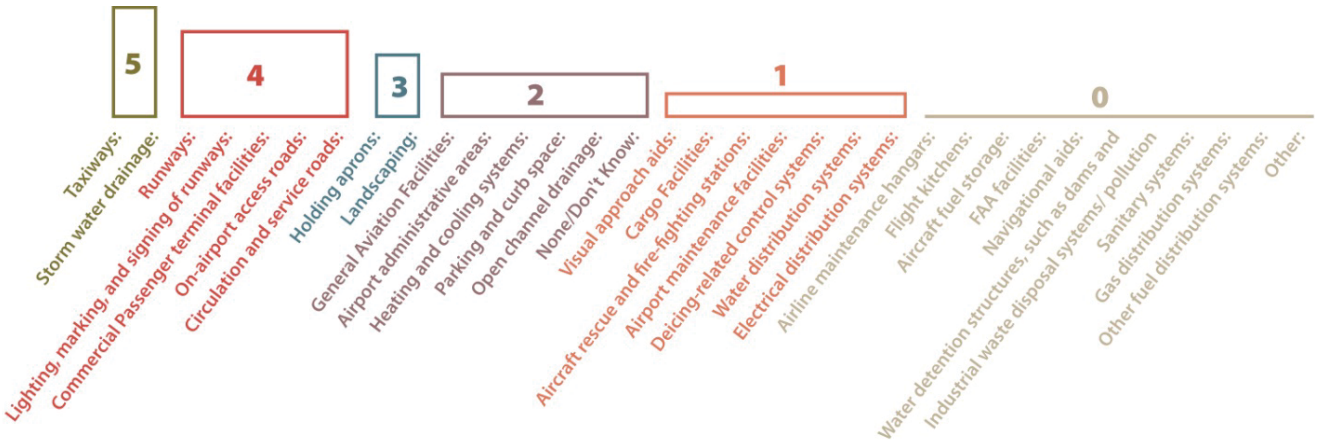

FIGURE 5 Physical damage during weather and weather-related events in 2010.

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TABLE 2
TOTAL RESPONSES FOR EACH CLIMATE VARIABLE, RANKED HIGHEST TO LOWEST, FOR THE 2010 AND THE 2030 TIME FRAMES

	2010						2030				
	Airside 2010	Landside 2010	Intermodal Transport System 2010	Local and Regional Area 2010	***Total responses***		Airside 2030	Landside 2030	Intermodal Transport System 2030	Local and Regional Area 2030	***Total response***
Snow (no drifting)	4	4		2	***10***	Heat wave	7	6	2	2	***17***
Ice (surfaces)	4	4	1	1	***10***	High-intensity storm	6	6	3	2	***17***
Fog/poor visibility	4	1			***5***	Fog/poor visibility	7	5	1	3	***16***
Snow (with drifting)	2	2		1	***5***	Changes in the precipitation mix	6	5	2	1	***14***
Ice (loading)	1	2	1	1	***5***	Snow (with drifting)	5	4	2	3	***14***
Flash flood	1	2		1	***4***	Snow (no drifting)	5	3	2	3	***13***
Heat wave	1	2			***3***	Drought	5	4	2	2	***13***
High-intensity storm	1	1		1	***3***	Ice (surfaces)	3	3	1	2	***9***
Changes in the precipitation mix	1	2			***3***	Flash flood	2	4	2	1	***9***
Variable wind direction	2	1			***3***	Variable wind direction	5	2		1	***8***
River flood	1	1			***2***	River flood	2	3	2		***7***
High winds	1	1			***2***	Inundation from sea level rise	2	2		2	***6***
Lightning	2				***2***	Storm surge	3	1		2	***6***
Drought		1			***1***	High winds	4	1			***5***
Inundation from sea level rise					***0***	Increased wave action in flooding	2	1		2	***5***
Storm surge					***0***	Ice (loading)	1	2		1	***4***
Increased wave action in flooding					***0***	Tornado	1	1	1	1	***4***
Tornado					***0***	Dust storm	1	1		1	***3***
Dust storm					***0***	Wild fire (encroachment)	1	1		1	***3***
Wild fire (encroachment)					***0***	Wild fire (visibility issues)	1	1		1	***3***
Wild fire (visibility issues)					***0***	Lightning	1	1			***2***
Hurricane					***0***	Hurricane	1	1			***2***
Subsidence damage					***0***	Subsidence damage					***0***
Increase in noxious species					***0***	Increase in noxious species					***0***

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TABLE 3
TOTAL RESPONSES FOR EACH CLIMATE VARIABLE, RANKED HIGHEST TO LOWEST, BASED ON FUTURE CONCERNS (2030)

	2010						2030				
	Airside 2010	Landside 2010	Intermodal Transport System 2010	Local and Regional Area 2010	***Total responses***		Airside 2030	Landside 2030	Intermodal Transport System 2030	Local and Regional Area 2030	***Total responses***
Heat wave	1	2			***3***	Heat wave	7	6	2	2	***17***
High-intensity storm	1	1		1	***3***	High intensity storm	6	6	3	2	***17***
Fog/poor visibility	4	1			***5***	Fog/poor visibility	7	5	1	3	***16***
Changes in the precipitation mix	1	2			***3***	Changes in the precipitation mix	6	5	2	1	***14***
Snow (with drifting)	2	2		1	***5***	Snow (with drifting)	5	4	2	3	***14***
Snow (no drifting)	4	4		2	***10***	Snow (no drifting)	5	3	2	3	***13***
Drought		1			***1***	Drought	5	4	2	2	***13***
Ice (surfaces)	4	4	1	1	***10***	Ice (surfaces)	3	3	1	2	***9***
Flash flood	1	2		1	***4***	Flash flood	2	4	2	1	***9***
Variable wind direction	2	1			***3***	Variable wind direction	5	2		1	***8***
River flood	1	1			***2***	River flood	2	3	2		***7***
Inundation from sea level rise					***0***	Inundation from sea level rise	2	2		2	***6***
Storm surge					***0***	Storm surge	3	1		2	***6***
High winds	1	1			***2***	High winds	4	1			***5***
Increased wave action in flooding					***0***	Increased wave action in flooding	2	1		2	***5***
Ice (loading)	1	2	1	1	***5***	Ice (loading)	1	2		1	***4***
Tornado					***0***	Tornado	1	1	1	1	***4***
Dust storm					***0***	Dust storm	1	1		1	***3***
Wild fire (encroachment)					***0***	Wild fire (encroachment)	1	1		1	***3***
Wild fire (visibility issues)					***0***	Wild fire (visibility issues)	1	1		1	***3***
Lightning	2				***2***	Lightning	1	1			***2***
Hurricane					***0***	Hurricane	1	1			***2***
Subsidence damage					***0***	Subsidence damage					***0***
Increase in noxious species					***0***	Increase in noxious species					***0***

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impacts in 2030 contrasts with those experienced in 2010, indicating an increased level of concern for certain variables; for example, high winds, in 2030.

The results suggest that certain climatic changes, such as heat waves and wind changes, are expected to become more severe by this group of respondents, having influence over airport operations and planning. The greater number of responses relative to the airside business area suggests that the respondents are more likely to focus on impacts related to the airport's immediate operations rather than those of relevance to the region.

Next, given a list of climate risks, the 11 respondents indicated which risks their airport has addressed in planning (whether as a climate risk or not). Every risk was addressed by at least one airport, and one added an item to the list: airfield inundation (as opposed to flooding) from sea level rise. Table 4 divides the responses into three groups, based on the number of responses for each climate risk. Air traffic disruption, physical damage from flooding, and decreases in infrastructure performance were those risks most often addressed.

Although survey respondents had stated earlier that they are aware of the climate changes projected for their region,

TABLE 4
RISKS ASSOCIATED WITH PROJECTED CLIMATE CHANGES THAT AIRPORTS MAY HAVE ADDRESSED IN PLANNING

Responses Indicating a Given Risk Is Addressed in Planning	Risks Associated with Projected Climate Changes That Airports May Have Addressed in Planning
0—3 Responses	Risk of airfield inundation from sea level rise (1)
	Risk to sustained water supplies, including risks to water supply infrastructure at the airport site (2)
	Risk to the provision of services by contractors, sub-contractors, partners, or service providers critical to airport operations (2)
	Construction schedule risk due to increased disruptions from weather or other events in the natural environment caused by climate changes (2)
	Risk to the grid and energy supply infrastructure, plus risks to back-up systems (3)
	Risk to the efficiency or success of airport security operations from increased disruptions from weather or other events in the natural environment caused by climate changes (3)
	Pollution control problems arising from increased flooding or other climate impacts (3)
	Risk to funding opportunities, given the uncertainty over future conditions that may affect the need for or the feasibility of a project (3)
	Negative impacts on the region caused by disruption at the airport (3)
4—6 Responses	Disruption to the airport's operations arising from the increased allocation of resources away from normal operations to activities required for the airport's role in emergency response or logistics planning exercises (4)
	Risk to infrastructure supporting information and telecommunications technology, including radar (5)
	Passenger access risk, including transportation disruptions to road, rail, and underground networks and stations (5)
	Risk to terminal buildings that would affect passenger comfort, health, and safety or passenger-focused commercial operations (5)
	Risk to the health and safety of airport employees and the direct employees of suppliers on site (where there may be reputational impacts for airport owner), such as heat illness (5)
	Risk to the airport's operation from the follow on effects of climate impacts at other U.S. and international airports (e.g., schedule problems, etc.) (5)
	Risk to the medium and/or long-term financial factors that are of interest to insurers or investors, including those related to the potential acquisition or sale of assets or sites (e.g., a potential lower sale price for "high-risk" assets, higher insurance premiums, etc.) (5)
7—11 Responses	Risk associated with future climate change effects in the performance of infrastructure over time, caused by incremental or short-term fluctuations in climate (7)
	Disruptions to air traffic due to increases in extreme weather or events in the natural environment caused by climate changes (7)
	Risk of physical damage, including damage from increased flooding, subsidence, and/or heat (8)

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FIGURE 6 Answers to the question: Are you satisfied with the climate science information your airport has available to use in future planning?

there were divergent views at this stage about the confidence they put into climate change information. Most respondents were only "Somewhat Satisfied" with climate change information (see Figure 6).

In addition to varying opinions on climate change information, when respondents were asked if they were concerned about the impacts climate change could have on their airport's operations, all who answered the question registered some level of concern (see Figure 7). No respondent was "not concerned" or "extremely concerned."

FIGURE 7 Answers to the question: On a scale of 1 to 5, with 1 being "Not Concerned" and 5 being "Extremely Concerned" are you concerned about the impacts that climate change could have on your airport's operation?

Although most respondents registered some level of concern over climate change, the catalysts for considering climate risk at the airports varied among the respondents. The most common catalyst, cited by more than half the

TABLE 5
INTEGRATION OF CLIMATE CONSIDERATIONS INTO ORGANIZATIONAL PROCESSES

Has the Airport Integrated Analysis of Projected Climate Change Impacts and/or Related Future Risks into Any of the Following?	U.S. $N = 5$	Canada $N = 1$	U.K. $N = 5$	Total
Design standards for physical assets	3	0	4	7
Capital Improvement Plan	2	0	2	4
Organizational decision making	2	0	1	3
Disaster management and emergency response	1	0	2	3
Master plan in development	2	0	2	4
Airport does not integrate climate change risks into organizational processes	2	1	0	3
Other: Considered in design standard for one project	1	—	—	1
Other: In the process of integrating into planning	—	—	1	1
Security planning	0	0	0	0
Early warning systems	0	0	0	0
Approved master plan	0	0	0	0
Supply contract	0	0	0	0
Budget development	0	0	0	0
Do not know	0	0	0	0

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respondents, was the awareness raised from climate change mitigation efforts (e.g., carbon emissions reduction). The following are the catalysts the airports cited, from the most to least frequently cited.

- Awareness raised by efforts on climate change mitigation (e.g., carbon emissions reduction) (7)
- Weather events and/or disruptions (6)
- Employee professional judgment (5)
- Required climate change analysis or reporting in a federal/national, state, local, or other governmental program (4)
- Insurance requirements (3)
- Issues emerging from emergency response plans (3)
- Bonding requirements (1)
- Master plan forecasts (1)
- Other (incorporation in assessment of infrastructure for safety purposes; i.e., seismic and flood control) (1)
- Master plan work, not including forecasts (0).

The tools or resources used when airports considered climate change fell into a handful of categories. Some used more than one approach, and three replied that they did not use any tool or resource. The following is the entire list of tools and resources cited by the eight respondents that use tools and resources, from most to least frequently cited:

- Climate impact and/or vulnerability assessment (6)
- Education or training (4)
- Existing risk management processes (3)
- Full inventory of infrastructure/assets, including quality assessment (3)
- Scenario planning (2)
- Participation in a community-wide climate change adaptation process (1).

FIGURE 8 Answers to the question: Do you feel emergency planning processes are a satisfactory method for addressing future climate change risks?

Table 5 lists areas where the surveyed airports have integrated analysis of projected climate change impacts and/or related future risks into their organizational processes. In 2011, the United Kingdom required reporting on climate adaptation planning, which was not required in the United States or Canada. Therefore, Table 5 lists the survey results by country.

With respect to disaster management and emergency response, Table 5 indicates that 3 of 11 airports have integrated analysis of projected climate change impacts and/or related, future risks into organizational processes in that area. Six of the 11 believe emergency planning processes are a satisfactory method for addressing future climate change risks, as indicated in Figure 8.

In contrast, a larger majority within this same group, 7 of 11 respondents rejected the use of irregular operations as a method for addressing future climate change risks. These respondents believed irregular operations were not a satisfactory method for addressing future climate risks, although four thought it was.

Almost all respondents (10 of 11) agreed that climate change adaptation required investment in capital expenditures as well as operations and maintenance. Only one respondent reported capital expenditures alone were the appropriate means for investing in adaptation.

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CHAPTER FOUR

CLIMATE RISKS AND ADAPTATION AND RESILIENCE ACTIVITIES

INTRODUCTION

This chapter details the general physical, business, security, and financial risks to airports, as well as the various types of climate change resilience and adaptation activities being undertaken, including ways for an individual airport to identify and prioritize its own risks, financing mechanisms, and ways airport climate adaptation and resilience is incorporated into planning and organizational decision making. A brief discussion of climate change science is presented first to aid understanding of the climate risks discussed in more depth later.

CLIMATE SCIENCE AND UNCERTAINTIES

What Airport Decisions Makers Need to Know About Climate Change Science

Currently, in planning, design, and other decisions about airport operations and infrastructure, airport executives and technical managers use information and analysis that is derived from an historical record of weather and climate. To consider potential changes to the climate that have no precedent in historical measurements, scientists have developed other sources of information to support decision making, including past trends based on paleoclimate data (e.g., drought spells indicated by tree rings) and projections of future trends in climate.

Projections from climate change models and paleoclimate data suggest there may be a broad range of possible climate phenomena in the future. Such phenomena would involve changes in environmental conditions (e.g., sea level rise and more severe winter storms) and their impacts (IPCC 2007). Research efforts have identified climate effects that would be the most significant to the transportation sector and their likelihood of occurrence (*Potential Impacts of Climate Change* . . . 2008) as shown in Table 6.

Including a level of uncertainty, as done in the TRB table reproduced in Table 6, is a convention adopted by the Intergovernmental Panel on Climate Change and replicated by others because uncertainty is one of the most difficult aspects about defining and managing climate risk. As seen in an earlier chapter, for example, only 2 of 11 respondents to this report's survey were satisfied or fully satisfied with the climate information available to their airport. The survey respondents' comments, some of which are listed here, illustrate the challenges in translating climate change science into actionable information. The following are sample concerns, identified by the respondents:

- A need for climate projections relevant to airports; for example, those regarding changes in visibility, precipitation mix, and wind direction.
- A need to understand with more specificity the impacts of the projections relevant to airports.
- Better consensus among sea level rise models to allow for corresponding action.
- The need for an annual report summarizing climate research in plain terms and the meaning of the findings.
- A need for coordination with airports with similar climate change projections.

There can be many reasons for the lack of certainty from the science community, in part because there are several types of uncertainty in climate science and Appendix F describes such uncertainties in greater detail. These forms of uncertainty can affect decision making in many ways. There may be uncertainty in, for example, modeling, measurements, and timescales. Scientists involved in climate change adaptation stress that it is important that uncertainty is acknowledged and understood, to the extent possible (Willows and Connell 2003). Also, climate change adaptation and resilience is a relatively new area of study, and no one discipline can capture its scope. Understanding the sources of uncertainty in other disciplines, and the ways of managing them, are an important facet of adaptation. One example of an uncertainty of likely interest to airport managers relates to wind; some sources in the literature consider changes in prevailing wind to be a significant climate risk (Koetse and Rietveld 2009; McGuirk et al. 2009). To date, however, there has been less confidence in climate model projections for wind (Pejovic et al. 2009a) and there is limited analysis available of this risk in the context of climate change and transportation (see, for example, Peterson et al. 2008). Research can help synthesize climate projections so that planners and others can have a clearer view of their utility, as in the case of the NCHRP's "Synthesis of Information on Projections of Change in Regional Climates and Recommendations of Analysis Regions" (Meyer et al. 2011).

In addition to the likelihood of the occurrence of a projected climate change, how relevant the projection might be

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TABLE 6
CLIMATE CHANGES OF RELEVANCE TO U.S. TRANSPORTATION AND THEIR LIKELIHOOD OF OCCURRENCE, AS IDENTIFIED IN *TRB SPECIAL REPORT 290,* TABLE 2-1

Potential Climate Changes of Relevance to U.S. Transportation	Level of Uncertainty
Temperature	
Increases in very hot days and heat waves	Very likely
Decreases in very cold days	Virtually certain
Increases in Arctic temperatures	Virtually certain
Later onset of seasonal freeze and earlier onset of seasonal thaw	Virtually certain
Sea level rise	Virtually certain
Precipitation	
Increases in intense precipitation events	Very likely
Increases in drought conditions for some regions	Likely
Changes in seasonal precipitation and flooding patterns	Likely
Storms	
Increases in hurricane intensity	Likely
Increased intensity of cold-season storms, with increases in winds and in waves and storm surges	Likely

to a given airport depends on the airport's location. Broad, regional projections for climate variables, and a discussion of their relevance to transportation, are available for each region of the United States ("Regional Climate Effects . . ." 2010); however, actual changes can be expected to vary within the same region (NRC 2011). Another relevant factor is the time frame in which the climate variable is expected to occur. In Table 6, for example, sea level rise is "virtually certain" to occur in some places, whereas it is only "likely" that there will be more intense hurricanes; however, sea level rise may cause permanent inundation only after several decades, possibly much later than the occurrence of the more intense hurricanes that climate models project. The farthest-reaching time frame for airport planning is typically 20 to 30 years; airport infrastructure is expected to last 40 to 50 years and pavement approximately 10 years (*Potential Impacts of Climate Change* . . . 2008). Uncertainties over climate effect time horizons can complicate planning.

How Adaptation and Resilience Decisions Can Be Reached Given Uncertainties in Climate Science

As noted, climate science can provide airports with information on possible climate effects as well as support transportation experts as they define the attendant risks. However, until a climate effect appears, as with airstrip erosion at certain Alaskan airports, uncertainties about climate science can confound decision making. Ways to approach the consideration of climate change resilience and adaptation under uncertainty include the following categories (CCS 2011), as further illustrated by this report's research results:

- No regrets adaptation. No regret options are those justifiable in the absence of climate change and even more justifiable under climate change. A downside of this approach is that it may promote incremental adaptation actions at the expense of more far reaching ones (CCS 2011). In the Jackson, Mississippi, case example, airports identified deficiencies in their preparedness when they assessed tornado damage stemming from Hurricane Katrina, and they are now shoring up and diversifying infrastructure related to fuel supply.
- Low regrets options. These options are taken to specifically address vulnerabilities from climate change. These would not have been taken in the absence of climate change but they are low in cost or impact (CCS 2011). An example of a low regret option is the Toronto Pearson International Airport decision to scope a study of de-icing fluid and water quality given a possible new precipitation mix.
- Adaptive management. This process requires explicit recognition of uncertainty and the planned revisiting of decisions when monitoring and/or research obtains information that reduces uncertainties (CCS 2011). At Oakland International Airport, the runway perimeter dike re-design will allow for raising its height again in the future, which is an adaptive management approach.
- Risk management. Risk management is used to render decisions under uncertainty, by identifying and prioritizing risks based on their consequences and likelihoods (CCS 2011). As will be described in more detail later, the Port Authority of New York and New Jersey (PANYNJ) took cues from a high-level risk analysis and methods developed by New York City and adapted it to the facility level. They developed a common method for inventorying assets, seeking to standardize how assets can be described (e.g., with respect to asset life) and thereby enabling comparisons across assets ("Anticipating Climate Change" 2011).

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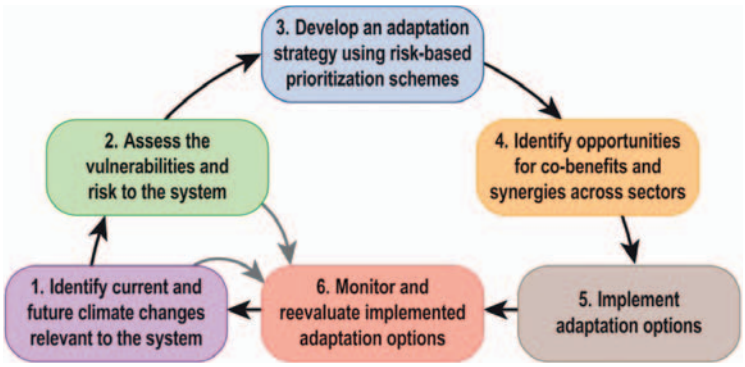

FIGURE 9 National Research Council, *America's Climate Choices,* Adaptation Planning Framework.

These are planned approaches to adaptation, which contrast with the Dallas/Fort Worth International Airport example of what can be termed "autonomous" adaptation, wherein major investments in snow removal equipment were made without reference to the current climate modeling results that suggests more severe winter storms are likely. The NRC notes that planned climate change adaptation is essentially a risk management exercise (NRC 2010). Figure 9 depicts the NRC's adaptation planning framework, which is similar to others in the adaptation literature.

SAMPLING OF LIKELY CLIMATE RISKS TO AIRPORTS

Climate change effects, such as those listed in Table 1 in chapter three, are the starting point for defining climate risks to airports. The sampling of risks here illustrates how transportation and aviation experts have been viewing the projected effects of climate change on the assets and operations at airports. Whether a climate change effect in Table 1 or a sample risk constitutes a risk requiring attention depends on the individual airport. An individual airport also would determine whether to manage this as a physical, business, financial, security, or other type of risk.

Present day risks similar to those anticipated under climate change are likely to remain a consideration for airports because weather extremes cause 70% of airport delays (Koetse and Rietveld 2009). At some airports, a closure can cost more than $1 million an hour (Pejovic et al. 2009b). As pointed out by FHWA, "Decisionmakers may not wish to respond to every potential climate risk, but identifying those risks will allow them to anticipate potential disruptions and prioritize their responses" ("Regional Climate Effects . . ." 2010).

After listing sample climate risks—that is, several types of physical, business, financial, and security risks—this chapter describes climate resilience and adaptation activities being undertaken, which includes a review of the risks actually identified at individual airports.

Physical Risks

Physical risks to an airport are those that will physically damage its infrastructure and the property located within its environs; for example, airplanes and cargo. Sample physical risks from effects noted in Table 1 include the following:

Damage from Water

Increases in precipitation can result in excess loading in culverts and other stormwater infrastructure designed for lesser flows, increasing the risk of flooding. Increases in the severity of storms can cause flooding, along with and damage to signage and increased wave action that wears infrastructure.

Damage Resulting from Temperature Changes

Increases in hot days can cause heat buckling on runways and other infrastructure damage. With changes in seasons and thawing, colder regions can experience different freeze/thaw cycles, which would be disruptive to buildings and other infrastructure designed for less dynamic changes.

Business Risks

Business risks are those that affect the ability of the airport to meet its mission and responsibilities. Business risks may stem directly from physical risks, such as an airport closure resulting from hurricane damage. Business risks also may arise from the scarcity of a critical resource caused by climate change impacts. Sample business risks from effects noted in Table 1 include the following.

Flight Delays, Airport Closures, and Related Costs

Increases in intense precipitation can decrease visibility, requiring greater distances between aircraft, which slows the system and can cause delay.

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Increases in storms can close airports diverting flights, their passengers, and airline assets to other locations and carrying a substantial hourly cost, sometimes in the millions of dollars.

Impact of Temperature Change on Airport Operations

Increases in the number of hot days at an airport can necessitate additional ground cooling, requiring investment in upgrades to gate-based cooling systems.

Risk to Contractual, Regulatory, and Other Legal Compliance

Increases in storms and heavy precipitation can put construction schedules at risk.

Increases in the number of hot days will activate health and safety requirements under labor and employment laws for airport and construction personnel, and will degrade air quality, threatening compliance with environmental laws.

Changes in Flora and Fauna Near Airports

An increase in the number of hot days is expected to increase migration and propagation of invasive species, which in turn can damage landscaping and incur other maintenance costs.

Security Risks

Security risks are those relating to human activities that threaten the life, safety, and interests of other human beings. A sample security risk from the effects noted in Table 1 would be increases in storms and, particularly, increases in lightning that escalate the potential for voltage spikes and interruptions in the power supply that can disrupt control systems, including security scanners.

Financial Risks

Financial risks are those that compromise the ability of an airport to meet revenue targets, pay expenses, or otherwise remain a going concern. Factors that can affect the financial profile of an airport include unplanned expenditures, impaired performance on a contract, and litigation. A sample financial risk from the effects noted in Table 1 is the risk to factors of interest to investors. Increases in the number of hot days and seasonal changes can affect tourism in regions that rely on a tourism-based economy, which will affect demand for airport services and infrastructure investments (Burbidge et al. 2011).

General Options for Addressing Climate Risks

There are some general approaches or options used to address these and other physical, business, security, financial, and other risks to transportation resulting from climate change. Four are summarized in a white paper produced by the Bipartisan Policy Center identified in Appendix C. One option is to "manage/maintain" infrastructure that is less significant to transportation goals, using maintenance cycles to absorb the costs of climate impacts. Another option is to "protect/harden" infrastructure through engineered solutions that enhance the resilience of infrastructure that must stay in operation. Another option is to ensure redundancy in a transportation system, such as alternative routes and services. "Relocate/abandon" options reduce exposure of infrastructure to climate risks, as with the case of Alaskan airstrip relocation (*White Paper* . . . 2009).

An additional approach supporting these four options is to monitor and collect data and information that can support decisions on a perceived climate risk (*A Transportation Research Program* . . . 2009). Respondents to the survey supporting this Synthesis report were asked whether their airport collected information on extraordinary maintenance caused by weather events; 23% said yes, 23% no, and 54% that they did not know. There may be new data needs associated with the new types of decisions airports may make under climate change.

ADAPTATION AND RESILIENCE ACTIVITIES BEING UNDERTAKEN IN LIGHT OF CLIMATE RISK

As suggested earlier in this chapter, the degree to which a physical, business, security, and financial risk may concern a given airport depends in part on the likelihood that the relevant climate change effect will occur and the magnitude of its impact. Other factors, such as stakeholder opinions and perceptions of asset values, for example, can be relevant considerations as well (*Assessing Infrastructure for Criticality in Mobile* . . . 2011). This section reports on climate change resilience and adaptation activities currently being undertaken. These activities might be viewed broadly as attempts to choose among the general options listed in the previous section.

Activity: Ad Hoc Responses to Climate Risk at Airports, in the Absence of an Explicit Adaptation Strategy

When no strategy is in place at an airport, this report's review of current activities suggests there are technically sound ways for internal champions and others to assess and potentially address perceived climate risks. The drivers of such activities can include awareness raised by outside adaptation planning efforts, the influence of professional society leadership, and experiences with greenhouse gas mitigation and sustainability initiatives. Several survey respondents noted that their own professional judgment triggered consideration of climate risks and adaptation measures.

As seen in the case examples, at both Toronto Pearson and Oakland International Airports, managers in technical fields

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such as planning, engineering, and environment management reviewed and modified design criteria based on their understanding of potential climate change effects. Although there was no definitive conclusion about future climate effects, the technical staff operated within their professional guidelines to address the risk. At Toronto Pearson International Airport, for example, a routine, cyclical review of stormwater involved flood modeling. Although there was no risk indicated in the models, the airport environmental management service (EMS) head considered the possibility of increased microbursts in the area and increased a pipe size with that in mind.

Consideration of climate change effects may be enabled by the identification and accessibility of technologies to manage climate's effects on facilities and operations. Sensors embedded in pavement, for example, are in use, and they can monitor runway degradation from the sun or from standing water and thereby assist in monitoring climate change. These and other technologies can mitigate some impacts and assemble the data to manage others (*Potential Impacts of Climate Change* . . . 2008; *A Transportation Research Program* . . . 2009).

In Alaska, drivers of ad hoc action on climate change were the actual climate change-induced impacts. Erosion of airstrips caused disruption to villages wholly reliant on aviation for year-round supplies and travel. Early on communities sought assistance from multiple federal agencies such as the U.S. Army Corps of Engineers, NRCS, FAA, and FEMA to reinforce or adapt airstrips or study their relocation in part because there was no overall strategy. A state-level task force and strategic planning effort later brought more attention and cohesion to the response.

These are instances where there was no climate change adaptation strategy for an airport in place but where climate change effects, for example, sea level rise exacerbated by storms, remained a distinct possibility. Most often, the decision making was conducted in reaction to a well-defined risk, with climate as one likely element. In other instances, climate risk may not be well-defined to airport staff, and as a result it is not monitored as such; it simply may manifest itself as a bad weather event or environmental condition. In these cases, airports have standard operating procedures to achieve their mission, keeping operations and assets safe.

Irregular operations (IROPS) are a type of procedure employed by the aviation community to manage unusual events. IROPS address operational demands that are outside the normal range for a given airport. Such demands on aviation can result from a major sporting event in a city served by an airport, unusual weather, or many other issues. Severe weather alone does not trigger IROPS, because many airports and their vendors are accustomed to and expect severe weather, such as heavy snow in Minneapolis. Efforts are underway to assist airports in their handling of IROPS, including a guidebook on developing and implementing an IROPS plan sponsored by TRB (Nash and Ward 2012). This TRB guidebook does not address climate change; its focus is on planning for the immediacy and demands of IROPS events, only a portion of which, as noted, relate to unusual weather (Nash and Ward 2012). The Jackson, Mississippi, case example in chapter two illustrates an airport's interdependencies with airlines and others during severe weather events, and that efforts are made to proactively interact when there is a risk of service disruption. It is noteworthy that a small majority of airport managers responding to this synthesis report's survey (7 of 11 respondents) reported that IROPS is not a satisfactory way for addressing future climate change risks. In contrast, there is interest among aviation experts in having climate change included in IROPS plans because climate change is expected to cause increased delays or other disruptions to aviation (Stewart et al. 2011).

What planning process is most appropriate for climate resilience and adaptation action can depend on many factors, including the type of climate risk expected at a given airport. For example, in the San Diego case example, so far only sea level rise has been identified and formally reviewed as a climate risk. A high-level strategic planning process, such as that recommended by the NRC in Figure 9 and described in more detail in the following section, can provide an initial forum for discussion, as well as trigger moves toward a more coordinated approach to tracking and managing climate effects at airports.

Activity: Coordinated Review of Climate Change Impacts and Development of a High-Level Adaptation Strategy

One possible activity is to address concerns over potential climate change through a high-level, collaborative review of the issue and development of potential next steps, often in the form of a strategy document. However, few airports in the United States have initiated such activity. Importantly, however, several airports have participated in a broader effort spurred by local, regional, or state stakeholders. These efforts often become both awareness-raising and planning exercises, involving fact finding and workshops. Nonprofit organizations such as ICLEI–Local Governments for Sustainability are often critical agents in these efforts, using their expertise in climate change science, resilience, adaptation, and other disciplines to provide relevant and location-specific guidance to communities. ICLEI was a key partner in the King County, Washington, adaptation initiative, which is widely viewed as a pioneering effort (NRC 2010) and that resulted in a useful handbook. The following are a sampling of similar initiatives that have catalyzed airport activities in climate resilience and adaptation.

Airport-Level Initiatives

The Jacksonville Aviation Authority case example is an instance of an airport-initiated effort at addressing climate

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risk. The CEO there supports local and regional economic development through direct action by the airports under his purview, and views sustainability as a key facet of economic development. He therefore commissioned a white paper to review the likely effects of climate change on the airport and its operations. Although a white paper does not direct action, in this case it raised awareness and articulated potential next steps for discussion.

State, Regional, Sub-Regional, and Local-Level Initiatives

New York Mayor Michael Bloomberg provided high-level leadership in directing an initiative to develop a risk-based response to the impacts of climate change. At the mayor's request, the New York City Panel on Climate Change (NPCC) commissioned regional climate change projections, created sector workgroups to conduct an in-depth regional study, and developed a report, released in 2009 ("Building a Risk Management Response . . ." 2010). Land use, energy, water, communications, and transportation were examined in detail. For these areas, the NPCC developed planning tools and tactical next steps, analyzed the regulatory environment relevant to options, and described best practices for an adaptation program for the New York City area, including a set of workbooks to guide on-the-ground planning. A risk to airports from climate change effects that was identified, for example, was the risk of brownouts or blackouts at a certain terminal that was likely to disrupt baggage and security operations. Also, in addition to articulating the type of high-level themes that can promote understanding across stakeholder groups, the NPCC's 2009 report was detailed enough to suggest a data collection role for airports in support of climate change indicators and metrics ("Building a Risk Management Response . . ." 2010).

In California, the governor initiated a climate change task force by executive order, and state government staff developed an action plan. The transportation component had a set of next steps for the relevant state offices. The state department of transportation was already engaged and able to take up its next steps, and did so using a detailed schematic aligned with the transportation planning process (*Climate Change Adaptation* . . . 2008). With both a high-level strategy and tactical actions identified in the schematic, government staff could determine how to proceed. For example, for a set of major planning phases, the state directed a climate change analysis and related economic study, and the schematic directed each program to the precise instrument in the planning process in which to address climate change impacts (*Climate Change Adaptation* . . . 2008). To ensure that priorities could be identified early, the strategy called for "hot spot" maps that showed where climate change effects were most likely to be a problem (*California Climate Adaptation Strategy* . . . 2009).

Instruction at this level of detail is helpful, but it is important to note that in the absence of direct management control a state sometimes can only directly drive action in agencies under its immediate jurisdiction. For example, the California initiative was not as detailed with respect to airports as it was for state highways. Airports are typically under the control of a local government or an independent authority (*Potential Impacts of Climate Change* . . . 2008). The aviation community has noted that this circumstance can influence the governance of climate adaptation and resilience (Stewart et al. 2011). The following examples, also from California, suggest airports can become involved through more local coordination. In San Diego, the airport became engaged in a community effort to assess the impact of sea level rise when ICLEI joined with local nonprofits to conduct a review of this risk within the San Diego Bay area. A stakeholder working group, technical advisory committee, and a steering committee were formed. The steering committee included two representatives from the San Diego Regional Airport Authority. Working from the ICLEI climate adaptation tool kit and framework, a Vulnerability Assessment of 13 sectors was conducted, including a review of the main airport's vulnerability to sea level rise. One recommendation to the steering committee was to review sea level rise through the Regional Aviation Strategic Plan process. As a result of the awareness raised through participation on the steering committee, airport authority staff can better communicate the short-term risk to the airport, which is low, and consider ways to incorporate sea rise considerations into long-term planning. In the San Francisco Bay area, Oakland International Airport participated in a sub-regional effort to review the impacts of sea level rise, which as noted earlier was called Adapting to Rising Tides. The airport staff credits this initiative with making known sea level rise model outputs, which they used in determining decision criteria for airport infrastructure improvements specifically modification of the runway perimeter dike.

Some general observations can be made from these strategic and often collaborative adaptation planning efforts. High-level strategies by local or state governments are typically initiated by legislation or an administrative driver such as an executive order. Often, there is a high-level champion such as a mayor or governor who articulates a vision and purpose and rallies participants to review the climate change impacts projected for the area, assess their significance, and address them. Academic and nonprofit experts, such as ICLEI, can support the effort, which is typically time-limited. It either explicitly or implicitly involves an education and awareness-raising component. It also establishes governance structures (e.g., task force or sector working groups) that may have a legacy effect even when the initial effort is completed. The outcome is a high-level climate change adaptation strategy or plan with next steps that can be adapted at the program level within the government, as in the case of California and New York City. Although local and state governments typically do not have direct management control over airports,

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climate change adaptation and resilience strategies and plans can encourage airports to define for themselves how they can participate and contribute. As suggested by the California example, strategies developed at state, regional, and local levels typically do not require binding commitments from participants.

National-level Initiatives

In the United States, the National Climate Assessment (NCA) is the primary means at the national level for linking interdependent sectors in climate change resilience and adaptation. The NCA provides a forum for coordination and is supported by the scientific and technical efforts of the U.S. Global Change Research Program. The NCA role is to facilitate and provide leadership rather than direct the responses to climate change by the private, nonprofit, and state, local, and tribal government sectors (NRC 2010). Also at the national level there are federal agencies that view their mission as preparing the public for climate change, including development of science and technical information. These agencies include the National Oceanic and Atmospheric Administration, Department of the Interior (including the U.S. Geological Survey, Fish and Wildlife Service, National Park Service, Bureau of Indian Affairs, Bureau of Land Management, and Bureau of Reclamation), and the U.S. Department of Agriculture (e.g., Forest Service). The Army Corps of Engineers is piloting a risk method that includes climate change considerations (USACE 2011).

Through Executive Order (EO) 13514 and related guidance the federal government requires each of its agencies to have a climate adaptation plan that address risks to not only federal facilities and businesses but also federal programs (EO 13514 2009). Such programs can affect state, local, and tribal government, the private sector, and the general public, through regulation, technical assistance, or financial assistance. As part of its EO 13514 implementation process, FAA is implementing its own sustainability and adaptation policies through EMS (Multi Year EMS Plan 2011). Additionally, the FAA Airport Office makes AIP funding available for EMS planning (JDPO 2010). The U.S.DOT has a climate change adaptation policy (DOT 2011b) and it supports the use of asset management as one means of enabling decision making on climate risks, as seen in the FTA adaptation plan (Hodges 2011). Although neither approach is required of airports, the experience of these important airport partners can inform future thinking. Also potentially relevant to federal projects and programs (Klin et al. 2011) is the Council on Environmental Quality's draft memorandum on addressing climate change impacts under the rubric of the National Environmental Policy Act (CEQ 2010).

As of 2011, the work of the NCA, federal agencies, and others at the national level has yet to take the form of hard drivers or directives applicable to airport activities.

Climate Risk Identification and Prioritization

Several tools are used for collecting and assessing information to support development of high-level adaptation strategies and action plans. These help stakeholders focus on issues of most concern and can lay the foundation for risk analysis. This section describes these tools, many of which have been used by respondents to the survey conducted for this report.

Scenario Planning

Change adaptation strategies and plans use climate scenarios to indicate the changes to climate that will occur, determine likely impacts, and help identify vulnerabilities and opportunities in a community or organization. Climate scenarios are also used in a directed discussion of potential futures under climate change, called scenario planning. The process relies on qualitative information from stakeholders and is typically a one-time exercise that orients management toward new thinking. Two of 11 survey respondents participated in climate change scenario planning. Scenario planning reviews the range of variables, climate and nonclimate, that will affect a community or organization. Each variable is rated for its range of variations and for its significance (good or bad). Participants in the scenario planning process are encouraged to manipulate these ratings and, thereby, the total product or aggregate rating of the two. After an assessment of the most significant or highest rated variables, "plausible futures" are developed by estimating the results of various interactions among the most important variables, usually the top two identified by stakeholders, by means of a matrix. When scenario planning is used in climate change decision support, a particular adaptation response such as investing in new infrastructure, can be reviewed across several plausible futures to examine its viability in different contexts. A useful complement to the scenario planning approach is the use of system mapping to show relationships between climate and other drivers and outcomes of concern to an organization; such as an airport (and its partners). A scenario planning exercise often is chosen when there are too many uncertainties to proceed to a risk-based prioritization stage.

Economic Analysis

An economic analysis is another tool for preparing an airport to address the effects of climate change. A European case study, for example, studied possible shifts in tourism (and therefore airline destinations) at a Greek island vacation destination under climate change (Burbidge et al. 2011). Investigators reviewed local government strategies and conducted an economic analysis that would help explain how and when climate change would impact the demand-side variables supporting tourism development. They also ran a forecast study of passenger traffic estimations (demand) for the years 2020, 2030, 2050, and 2080. Using thermal discomfort

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in northern European tourism as a measure of demand, they examined likely changes in this measure over time. The study found that in 30 to 50 years, thermal discomfort could drive tourists to cooler locations or shift their visits to cooler months. Tourism shifts such as this would have implications for airport and air traffic management planning, making this form of analysis useful in assessing the significance of a climate risk. Economic analysis can describe climate effects that will reduce or increase demand for an airport's services. There are some methodological challenges in assessing shifts in tourism (Gossling and Hall 2006), but effects on demand could be seen at airports reliant on climate-dependent tourism, including ski and beach resorts (Klin et al. 2011).

Climate Impacts Profile

Another tool is a climate impacts assessment. It reviews past extreme weather events for a period of years and analyzes areas where responses were not optimal. The method involves identifying an extreme weather day and, through interviews, desktop research (news articles, etc.) of localized weather-related disruptions, and reviews of relevant weather data, the systemic response to the extreme weather event is depicted. This approach helps identify systemic and site-specific problems. However, its results do not use or rely on projections of future climate. Local and state transportation agencies sometimes conduct "storm reports" that can serve a similar purpose after a high profile weather event; one example is New York City's Metropolitan Transit Authority (MTA 2007).

Vulnerability Assessments

Vulnerability assessments review the current profile of a community and its capacity to handle future stressors stemming from climate change; for example, by recording the performance of an asset or activity under historical weather conditions. Evidence of vulnerability may be the amount of repair costs resulting from past weather events or the role of the asset in emergency response. Then, using projections of climate impacts, the effects of a climate stressor on that asset or activity is determined, and the vulnerability to climate change is described.

With more than half of survey respondents reporting the use of vulnerability assessments, this tool was the most common one used by survey respondents. Its popularity is illustrated by Figure 1, showing the influential ICLEI adaptation milestone chart, which begins with a vulnerability study. It can be part of a risk assessment or a stand-alone tool. As part of a risk analysis approach, this assessment of vulnerability helps determine the assets for priority review under the risk assessment.

Risk Management

Risk management is used to render decisions under uncertainty. This tool can be used to determine which resource allocation questions progress to decision making. Under the traditional formula, risk equals the probability of occurrence of an event multiplied by the magnitude of the event's outcome; this typically applies where a numerical value can be ascribed to each factor. With respect to climate change, the "event" of interest would be a climate change impact such as sea level rise combined with storm surge. Numerical values based on environmental or other quantitative data, however, are often not available. An emerging best practice is to provide a numerical rating for qualitative levels of risk for easier rating and comparison across projects and sectors (CCS 2011). Matrices developed in high-level risk assessments, those conducted in both broad, stakeholder-supported regional planning efforts and within organizations, often involve rough degrees of risk; for example, "low," "medium," and "high." This approach is not exclusive to climate change; its use is also seen in engineering for extreme events (Thompson et al. 2007).

The NPCC's high-level risk assessment approach is highly regarded. The NRC showcased the NPCC risk matrix in its series, America's Climate Choices (NRC 2010). Using the traditional formula of risk, NPCC stakeholders qualitatively described the likelihood of impact; that is, if a given climate hazard were to occur, and the magnitude of the consequence of the impact, using low, medium, and high to rate each factor. If a climate change adaptation measure were already underway or planned and fully funded, the stakeholders were instructed to take into account the benefits already gained. Similarly, the approach factored in actions already underway within an organization or agency but not specifically conducted for addressing climate change. Combining the two factors (likelihood of impact, magnitude of harm), a two-dimensional risk matrix could be generated, as reproduced in Figure 10. An asset would be in the most darkly shaded box, in the upper-right-hand corner if, for example, it had a "Very High" likelihood of experiencing an impact from a climate change-driven event during its lifetime and would experience a "High" magnitude consequence from that impact.

Among the entities that participated in the NPCC process was PANYNJ, and its effort to carry forward the NPCC risk assessment process into its own facilities may provide an example of how individual facilities can tailor high-level adaptation planning exercises for their own use. PANYNJ owns and maintains some of the largest and most valuable transportation infrastructure in the United States, including the New York–New Jersey rail system, six tunnels and bridges, the Port Authority Bus Terminal, the World Trade Center, and five airports: JFK International Airport, LaGuardia Airport, Newark Liberty International Airport, Stewart International Airport, and Teterboro Airport. In response to the NPCC initiative, PANYNJ evaluated the vulnerability of its system to a range of climate effects based on NPCC-commissioned projections in three time horizons (2020, 2050s, and 2080s). A sample climate effect to PANYNJ

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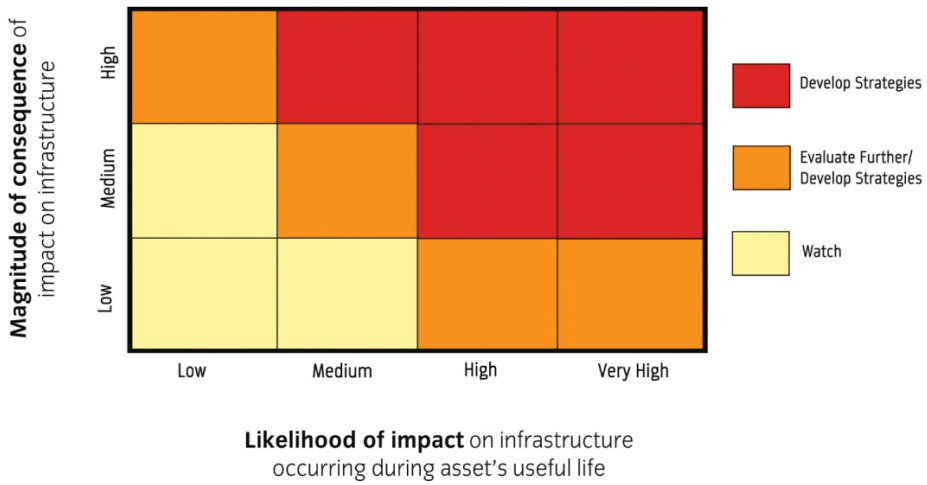

FIGURE 10 New York City Panel on Climate Change risk matrix (NRC 2010).

assets was that JFK International Airport, which lies near sea level, would be under more than 15 ft of water given certain extreme storm conditions (Jacob et al. 2001).

As part of the risk assessment process, PANYNJ created an inventory of infrastructure likely at risk and developed adaptation strategies. Specifically, six tasks were performed: defining climate change variables and projections, developing asset inventories (with a view to interagency coordination), assessing vulnerabilities, analyzing risks, prioritizing the assets, and developing adaptation strategies. Ultimately, PANYNJ divided adaptation strategies into three categories as defined by New York City: (1) maintenance and operations (e.g., using portable pumps and conducting detailed studies), (2) capital investments (e.g., permanent improvements), and (3) regulatory (e.g., design standards). With this work as a starting point, PANYNJ has since developed interim design criteria for use in new construction or major rehabilitation projects. These criteria will be reviewed every two years to remain responsive to new climate science and other relevant information. PANYNJ is also more aware of how system redundancies engineered for other purposes, for example, pavement for heavy traffic, also help increase adaptive capacity and system resilience and how other capital improvement investments, such as security barriers, can protect against high water possible from storm surge and sea level rise (*Anticipating Climate Change* 2011).

Climate risk work in the transportation sector also provides examples of current practice (*Literature Review* . . . 2009). FHWA is piloting a conceptual climate risk assessment model, depicted in Figure 11, to help organizations evaluate the risks from climate change (*Assessing Vulnerability* . . . n.d.) The five pilot areas are the Metropolitan Transportation Commission—San Francisco Bay, California; New Jersey Department of Transportation/North Jersey Transportation Planning Authority—Coastal and Central New Jersey; Virginia Department of Transportation—Hampton Roads, Virginia; Washington State Department of Transportation—State of Washington; and Oahu Metropolitan Planning Organization—Island of Oahu, Hawaii. Also, the U.S.DOT is sponsoring a risk assessment of the Mobile, Alabama, transportation infrastructure, including airports, which uses an approach similar the FHWA conceptual risk assessment model (DOT 2011a).

The FHWA conceptual climate risk assessment model involves several steps (*Assessing Vulnerability* . . . n.d.):

1. Compile a list of assets by categories that correspond to planning priorities. It recommends gathering information that can later inform evaluation of the assets' resiliency to climate change and how costly any damage to the asset would be.
2. Screen out assets based on their "criticality" or importance, which may be gauged by existing evaluation tools and criteria used by a state or other authority.
3. Collect local- or regional-level climate data, both historical and projected.
4. Review uncertainties. Effects that are small in magnitude and relatively uncertain would be screened out, but reviewed at a later time.
5. Review an asset's vulnerability. Vulnerability is determined by examining the assets' performance under historical weather conditions. If a climate stressor does not have a significant impact on an asset, that climate stressor and asset combination is to be screened from review and revisited at a later date. Importantly, the conceptual model encourages the identification of climate stressors already taken into account in the design, operation, and maintenance of the asset.
6. Assess whether future climate stressors will affect the asset and consider the cumulative impacts of more frequent climate stressors. To assess the likelihood of impacts, the conceptual model would have the user divide impacts into high and low climate stressors, based on their severity. The determination of high or low severity of impact is a qualitative judgment that

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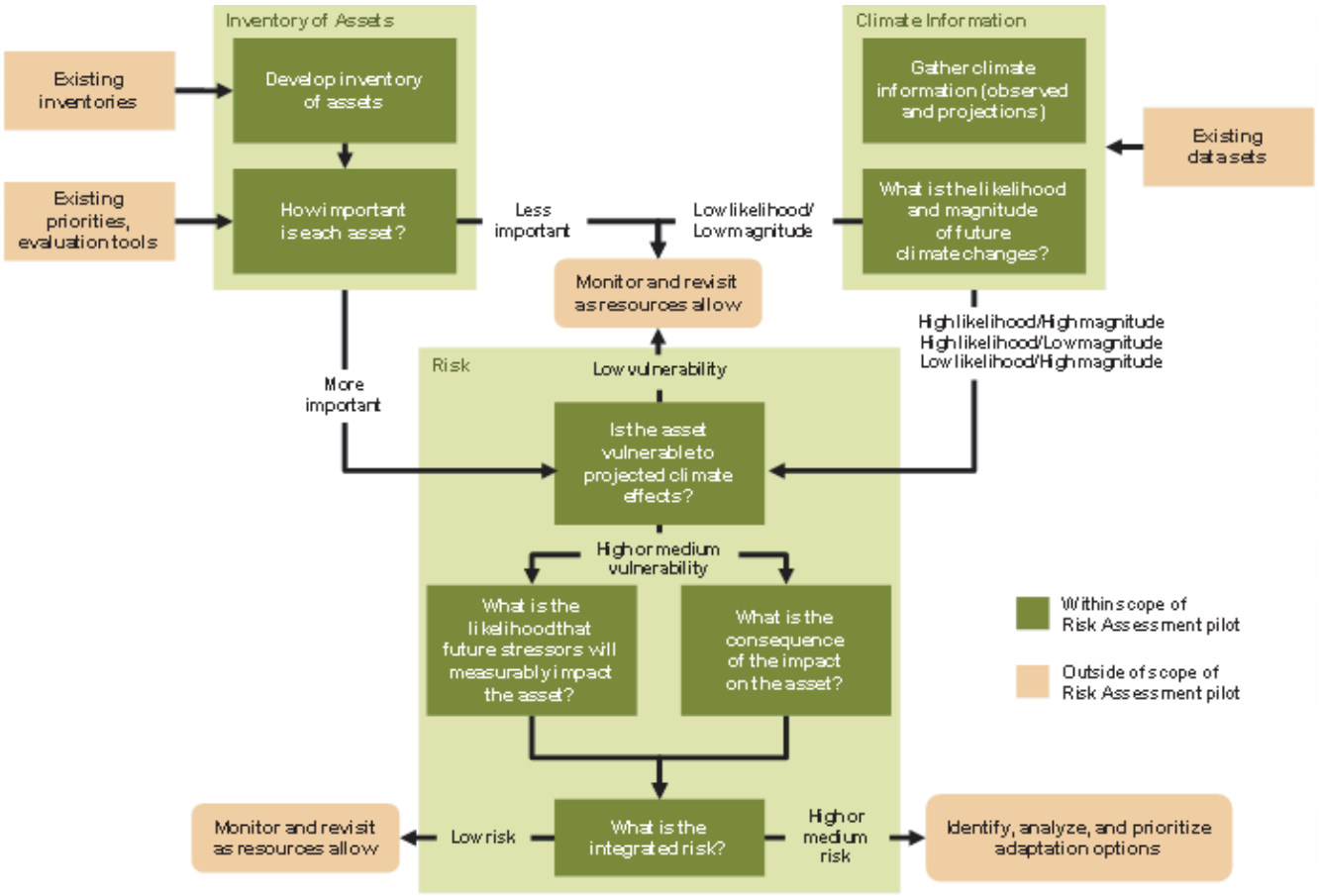

FIGURE 11 FHWA conceptual climate risk assessment model (FHWA n.d.).

relies on the expertise of the intended user of this draft model. Next, the model would have the user consider the consequences to society of the impact, in part through use of the earlier criticality assessments.

7. To integrate the two factors, with their low and high likelihood of impact and low and high consequences, arrange them in a matrix based on the combined effects of their likelihood: low, medium, and high. This approach provides a visual depiction of the assets most at risk from climate change.
8. Identify adaptation options based the criticality and at-risk status of the assets. It notes adaptation measures can take advantage of existing or scheduled planning cycles ("opportunistic" adaptation) or be pro-active in that the measure would be implemented before scheduled or necessary planning or maintenance.

As noted, the U.S.DOT uses an approach similar to the FHWA risk assessment model in a study focusing on the Mobile, Alabama, metropolitan area. The study covers multiple organizations, including airports. Information on the detailed scale of the study (and the level of effort involved) is useful when reviewing and assessing current practices. The Mobile study focused on the airport facility level through (1) an initial "scan" of airports and their many services, (2) an assessment of certain airport-specific metrics developed for the study, and (3) a "criticality" rating. The criticality review focused on assets for the most part, although the size of the airport, for example, runway length and other measures of capacity, have been proxies or metrics for the "importance" of the airport. This review was a factor in determining vulnerability. To date, Mobile's 17 airports have been reviewed for their criticality and 2 of these airports are likely to proceed to a risk assessment (DOT 2011a).

With respect to prioritization, costing of adaptation options is one key step. Investment decision tools commonly used by airports include financial analysis, economic impact analysis, and benefit–cost analysis. Prior TRB research by Landau and Weisbrod, "Effective Practices for Preparing Airport Improvement Program Benefit-Cost Analysis," provides useful background on this point. Financial analysis focuses on the estimation and comparison of revenue streams and cost streams generated or affected by a project. Economic impact analysis focuses on the estimation of changes in jobs and income in a region that are a consequence of airport operations or changes in airport activities that result from a project. Benefit–cost analysis weighs the quantified benefits and costs of a project and is used for project selection and prioritization (Landau and Weisbrod 2009). Climate change risks are just one risk in the benefit–cost analysis equation.

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There are models that can assist in estimating the cost of potential adaptation options. Researchers at the University of Alaska were able to estimate that climate change could add $3.6 to $6.1 billion (more than 10% to 20% above normal wear and tear) to future costs for public infrastructure from 2008 to 2030, and $5.6 billion to $7.6 billion from 2008 to 2080. They estimated that replacing the 250 Alaska airports would cost $5.6 billion. To develop this estimate and ones for other infrastructure, investigators acquired climate projections for Alaska, created a database of public infrastructure, and estimated the infrastructure replacement. The model assumed that climate change will reduce the useful life of infrastructure requiring that it be replaced sooner. The replacement costs estimate was calculated with and without climate change and assumed that planners will adapt structures strategically. Developing the database involved defining what was critical infrastructure and determining whether records were kept on both the infrastructure and its replacement costs; some datasets were not available. Infrastructure was assigned a location and each location given a set of values associated with the projected climate effects; for example, proximity to the coast and susceptibility to flooding (e.g., "exposed," "protected," "interior," and "prone to flooding"), as well as local permafrost conditions ("frost-susceptible" and "non-frost-susceptible"). Investigators also estimated the useful life of the infrastructure, and these calculations often required estimates because datasets were not readily available (Larsen et al. 2008).

Other cost calculation tools have been developed, such as the Coastal Adaptation to Sea Level Rise Tool (COAST). The city of Groton, Connecticut, used COAST to model the economic impact (in terms of lost real estate and building contents) from various sea level rise and storm surge scenarios at three specific locations. The state of Maine's DOT is using a variation of COAST to review cost and risk issues in support of developing design standards for large, tidally influenced transportation structures (FHWA 2011).

As of 2011, outside of pilot studies, U.S. airports were not engaged in formal climate risk prioritization processes. Evidence from the Oakland case example suggests an opportunistic approach, wherein staff considers climate change in design when reviewing a technical issue that responds to another priority; for example, seismic activity, which is not defined as a climate change problem.

Financing Mechanisms to Address Climate Risks

The possible sources of funding for addressing climate risks at airports are diverse. With respect to how airports perceive climate risk financially, all but one survey respondent (10 of 11) agreed that climate change adaptation required investment in both capital expenditures and operations and maintenance. Only one respondent said capital expenditures alone were the appropriate means for investing in adaptation. Regarding actual funding sources, it is helpful to review survey responses about the funding sources airports currently use to address threats from weather. The eight U.S. survey respondents produced a diverse list of the resources that are used to prevent, reduce, or otherwise address threats from weather: three of the eight used local funds and a line item in the budget was also used by three airports. Passenger facility charge revenue, general obligation bonds, revenue bonds, and/or FAA AIP grants were used by two of the eight. The following sources were used by one respondent: federal grants-in-aid, state grants-in-aid, customer facility charge, FAA special grants, FAA Voluntary Low Emissions Program, and state DOT. One respondent used no such resource and did not indicate any others it might use to address threats from weather. Based on these responses, the category of funds for climate change resilience and adaptation, when considered in the future, may vary by airport.

In the Dallas/Fort Worth International Airport case example, the source of funding for both the $10 million snow removal equipment and the new reclaimed water pipeline to address future water scarcity was the Capital Improvement Program. There will be more than $500,000 in yearly operations and maintenance costs as well for the snow equipment. In Alaska, airport improvements in communities at risk from erosion and flooding partially induced by climate change have been funded by FAA AIP and FEMA resources.

Incorporation of Climate Risk Considerations into Airport Planning

Although airports have participated in region-wide climate change planning efforts, and some airports have made technical decisions with a view to future climate risks, the formal incorporation of climate change resilience and adaptation into planning and organizational decision making has occurred at few airports. Incorporation of climate risk considerations into planning and organizational decision making can better define the problem from a corporate or enterprise perspective, but it does not ensure that an airport will render decisions on climate risks, as seen in the result of the first round of climate risk reporting by U.K. airports (*Evaluating the Risk Assessment* . . . 2011). Some notable work follows:

- Several U.K. airports have incorporated climate change into their organizational decision processes, as required by government oversight bodies; however, routine implementation is not underway.
- According to its survey response, the San Francisco International Airport is considering climate change in its master plan currently under development.
- Jacksonville Aviation Authority has taken a first step at climate change adaptation and resilience planning by developing a white paper on climate change adaptation.
- At the San Diego Regional Airport Authority, a sea level rise strategy confirmed that the area's major air-

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port is not under immediate threat; however, its staff is now considering integrating the relevant components of the strategy into the San Diego Regional Airport Authority's sustainability policy.
- In the case of Atlanta's major airport, an FAA grant to develop a sustainability plan has resulted in a plan that will require an annual review of goals. The head of asset management and sustainability believes this plan's dynamic and iterative approach will allow for and facilitate consideration of new issues such as climate change adaptation.

HIGHLIGHTS FROM A REVIEW OF CLIMATE CHANGE ADAPTATION AND RESILIENCE ACTIVITIES

The following are highlights from this chapter's review of relevant activities, as informed by the case examples, literature review, and the survey.

- Airports have interdependencies with tenants, other airports, and other partners that may be locally, regionally, and nationally based. As shown in the Jackson, Mississippi, case example, a weather event may trigger a dialog with airports in Texas. Also, there is a routine scan of national events that could lead to delays. A Toronto Pearson International Airport manager realized changes in temperature elsewhere could require a change to his airport's de-icing measures. Interdependencies such as these arise with respect to weather events and are addressed through certain existing procedures that draw on these relationships to help minimize disruptions.
- Adaptation planning efforts occurring in an airport's geographic region can raise awareness at the airport. Such efforts also may define airport issues even before an airport has reviewed climate impacts in a formal way.
- Risk management, especially as informed by vulnerability assessments, is a commonly suggested approach to adaptation. Related tools of interest include asset management and EMS.
- There are various types of information useful to determining baseline conditions and helpful to planning and other activities related to climate risks. The identification of needed datasets such as asset inventories and information on the useful life of assets, is an important exercise.

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CHAPTER FIVE

CONCLUSIONS

OBSERVATIONS AND FINDINGS

The objective of this Synthesis report was to identify the risks to airports from climate change and to survey activities used in addressing such risks. Research indicates that climate change will affect airports in multiple and diverse ways, involving impacts to physical infrastructure, business costs and opportunities, new financial considerations, and increased security challenges. However, there is currently little information available on climate change adaptation at U.S. airports.

Airports share many attributes with other transportation sectors. They also have diverse sets of assets with varied ownership status and life cycles, and also experience the effect of climate change nationally, even globally. They are dynamic communities that have complex business and social roles and responsibilities that can be affected by adaptation planning occurring outside their immediate purview and infrastructure.

Despite interdependencies with other interests and services, surveyed airports did not address questions about their intermodal links and local climate impacts as readily as they projected their own climate risks, although airport operations are reliant on these local links to effectively meet their mission. Regarding projected impacts, there have been some adaptation projects directly addressing climate risk at airports. These include practical efforts conducted at a technical level such as design criteria for a specific project and participation in more strategic planning processes. Generally, however, airports have just begun to consider the formal integration of climate impacts into planning processes. The U.K. government's experience with its adaptation reporting requirement is a promising area for a comparative view.

Key drivers for addressing climate risk at airports were:

- Severe weather events and related costs
- Awareness raised from sustainability and greenhouse gas mitigation activities
- Model adaptation guidance prepared by a professional society in a technical field
- Executive leaders serving as advocate
- Internal organizational champions serving as advocate
- Professional judgment of staff
- Participation in state, regional, and local adaptation planning efforts
- Federal grants and planning frameworks.

Other drivers in the United States are insurance and bonding requirements. Actual adaptation projects can be opportunistic, with climate change sometimes as an ancillary or secondary consideration; that said, the cases studied indicated there was sound technical appraisal of climate change aspects.

A barrier to coordinated planning with other transportation sector partners includes the quasi-independent status of airports. In the absence of a high-level executive or other internal champion advocating for consideration of climate change impacts, there is no hard driver within an airport's governance structure, as there can be, for example, within a state department of transportation under the direct management control of a governor.

It is important for an asset- and infrastructure-focused sector such as aviation to concentrate on the distinctions among climate impacts, their respective time horizons, and datasets needed to assess impacts on assets and infrastructure. For example, there are varying time frames in which projected climate change effects may become significant risks to an airport's asset inventory. For that reason, a review and understanding of maintenance practices and timelines can help determine and/or project the degree of adaptation or resilience building needed.

These observations and findings suggest that airports present a compelling case for closer review by the research community. Both their position as entities affected by variations on weather and the sophisticated decisions they undertake daily indicate that airports hold a potential leadership role in climate change adaptation and resilience.

KNOWLEDGE GAPS AND SUGGESTIONS FOR FURTHER RESEARCH

Prior TRB suggestions noted in *Special Report 299,* and numbered here, provide a helpful framework for identifying knowledge gaps in the context of airport climate resilience and adaptation.

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1. Transportation officials at all levels of government and in the private sector should inventory potentially vulnerable critical assets.

   With the exception of a few airports involved in key studies, airports have not inventoried their critical assets in a strategic effort to address climate change. Many partners on site at an airport could play a part in this process.

   - Future research could provide guidance for inventorying assets and activities at airports, including identification of potential metrics and datasets that can support risk assessments and investment decisions.

2. Transportation officials should incorporate climate change into their long-range plans for new facilities and maintenance.

   The greatest extent of airport planning timelines is 20 years; however, airport infrastructure generally lasts 50 years. In addition, surveyed airports did not address questions about their intermodal links and local climate impacts as readily as they projected their own, although airport operations rely on these areas for success. Also, there are many identified and as yet unidentified data needs that will be relevant to an effort to conduct long-term planning.

   - Research might include a comprehensive review of climate impacts and risks to airports and all aspects of their facilities, operations and interdependencies related to passenger, cargo, and other air service activities.
   - Comparative research on how extreme weather and climate change can affect airports and methods for related risk management across different spatial, temporal, geographic, and geopolitical spheres may assist in the understanding of the uncertainty over where and when impacts will occur.
     – Research might include a synthesis of sea level rise modeling, storm surge, and coastal subsidence methodologies as relevant to how they would be used by airports and other coastal transportation infrastructure. This might be similar in scope and approach to the recent "Synthesis of Information on Projections of Change in Regional Climates and Recommendations of Analysis Regions" prepared for NCHRP.

3. Transportation officials should rely more on probabilistic techniques to guide decisions that weigh the cost of upgrading or protecting assets against the risk and consequences of failure.

   There has been some work in developing climate risk assessment techniques for the transportation sector, and some airports surveyed are prepared to address climate risk under existing risk practices. However, standard techniques are not in place that can sufficiently address uncertainties under climate change.

   - Applied research could review airport needs from data producers and data stewards in federal, state, tribal, and municipal agencies to support the identification and collection of baseline and other data to support future decisions on climate risks.
   - Research could include a broader survey of airport adaptive capacity, focusing on the ability to address projected climate risks in the context of local and regional social, environmental, and economic needs and stressors.
   - Applied research could develop an annual report on relevant climate projections in a readable form, tailored to airport facility and operational concerns, as suggested by one respondent to the report's survey.

4. Research programs should invest in developing monitoring technologies that can measure stresses and strains on key infrastructure assets and provide warning of pending failures.

   There has been discussion of general technology needs in the literature; however, there has not been a comprehensive review and understanding of climate risks for airport facilities and operations with a view to the development of the technologies that could facilitate a response at airports.

   - A research roadmap for the technologies that could be brought to bear on the anticipated risks to airport facilities and operations.

5. Transportation professional associations should develop procedures to identify and share best practices in managing assets.

   Research for this Synthesis confirms that professional societies, especially those in engineering, have a significant role to play in developing champions with the requisite technical expertise to properly assess climate risks and options. However, in addition to engineers and planners at airports, the aviation industry has a variety of professionals that contribute to its functioning, and education and engagement by them may be useful as well. These conclusions suggest:

   - Research into the unique perspective of airport personnel with respect to weather and climate and the ways to leverage their expertise and knowledge base with local partners seeking transportation sector leadership.
   - Review of all airport and aviation-related professions and the standards and protocols to which they adhere, to develop understanding of entry points for climate change education and awareness raising.

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GLOSSARY

Adaptation: A decision that stakeholders can make in response to perceptions or objective measurements of vulnerability or exposure. Included in this concept is the recognition that thresholds exist where a stimulus leads to a significant response.

Adaptive capacity: The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantages of opportunities, or to cope with the consequences.

Exposure: The combination of stress associated with climate-related change and the probability or likelihood that this stress will affect transportation infrastructure.

Maladaption: Ineffective or inefficient actions taken in response to projected climate change effects but supported by poor information or inadequate decision criteria.

Resilience: The capacity of a system to absorb disturbances and retain essential processes.

Vulnerability: the structural strength and integrity of key facilities or systems and the resulting potential for damage and disruption in transportation services from climate change stressors.

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APPENDIX A

Interview Questions

Interview for case example: Airport adaptation and resilience activities underway

Thank you for completing the recent survey for the Airport Cooperative Research Program's Synthesis S11-02-06: Airport Climate Adaptation and Resilience. In your responses to that survey, you indicated that your airport could serve as a case study in the Synthesis Report.

We are developing case studies which provide examples of adaptation or resilience activities being undertaken, the risks identified, the priorities set, the mechanisms for funding, and how airport climate change adaptation and resilience is incorporated into other plans.

The following is a discussion guide designed to help develop the basis of the case study. If you so choose, your airport does not need to be named in the case study. Climate change adaptation and resilience is an emerging area with few examples in the airport sector, and we hope you remain interested in contributing to the knowledge base in this important area. Please review the following discussion guide. At the time of the interview, the questions may be asked in a different order than shown here, be modified, or be edited as appropriate to the project being discussed.

1. Interview information

   a. Airport: _____
   b. Airport type: _____
   c. Project description: _____
   d. Name of person interviewed: _____
   e. Title of person interviewed: _____
   f. Contact information (phone/e-mail): _____

2. Overview of relevant climate change impacts

   a. Briefly describe the projected extreme weather or climate change effects at your airport. Identify those that have received the most attention and why.
   b. For the project you have chosen to describe, was the projected effect an actual or imminent threat? If not, in what decade did airport decision makers believe it would become a threat?

3. Organizational readiness to address extreme weather/climate change effects

   a. Describe the organizational or governance conditions at your airport which facilitated consideration of a future risks related to extreme weather or climate change effects. For example, was there a champion internally?
   b. Describe the provincial, state, or local efforts that facilitated or catalyzed consideration of such future risk. For example, was there a government plan in place?
   c. Are your insurers considering such risks to your airport? If so, was this a consideration in developing the project?

4. Decision process

   a. In what year was this project first developed? Funded?
   b. Were other projects considered?
   c. Please describe in detail the decision support methods you used for identifying then rendering a final decision on this project. For example, did it stem from a scenario planning exercise, and/or did it emerge from risk analysis?
   d. What modeling or projections did the airport rely on? If you don't know specifically, please state that.
   e. What other data/information was needed to support the decision and how was it identified and collected?
   f. Who made the final decision on the project?
   g. Did this project go through a regular budget justification and analysis process? Which one?
   h. What was the funding source? Was there leveraging of other funds?
   i. Was there an adaptation planning process in place at some point during the time the project was under consideration? When?
   j. Is climate change adaptation and resilience planning integrated into other, specific decision processes at the airport? Please name them, for example, emergency response plans, operation preparedness plans, master plans, etc.
   k. Describe whether the decision process for this project is repeatable or whether it was a unique circumstance.

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5. Outcomes/looking ahead

a. What is the status of the project? For example, is it completed or still under construction or development?
b. Are routine inspections planned for this project when it is completed? Will the inspections be the same as for any other project? Are there metrics in place to evaluate its performance?
c. Are there climate change-related risks the airport is looking at this time? If so, describe the approach the airport will take in identifying and funding projects to address them.

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APPENDIX B

Literature Review Method

Use of the TRB's TRID database facilitated the literature review. TRID is a newly integrated database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the Organisation for Economic Cooperation and Development's (OECD's) Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. TRID provides access to more than 900,000 records of transportation research worldwide. Other databases, particularly those in the environmental and engineering fields were used, as were bibliographies from various sources.

Suggestions from the TRB Topic Panel were also reviewed.

Recent and ongoing transportation studies that are developing or piloting data collection and analytical methods related to climate change and likely to be applicable to the airport sector were reviewed as well. Other sources and relevant FAA circulars (e.g., regarding master plans, emergency plans) were reviewed, but they are not summarized.

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APPENDIX C

Literature Review Sources

Projections of climate change and its impacts

National Research Council, *Warming World: Impacts by Degree,* Washington, D.C., 2011.

This booklet was published in 2011 by the NRC of the National Academies and written by Robert Henson. It describes climate change impacts with some efforts at a regional geographic focus. All of its content is a summary of the findings from the larger NRC report, *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia* (2011), which examined the range of future climates projected to emerge if the human population stabilized its emissions of greenhouse gases at a corresponding set of target levels. This booklet confirms for the layperson that, very broadly, climate change impacts can be projected in a linear fashion, with certain changes and associated risks expected for each degree Celsius increase in temperature. Increases in intense precipitation, "very hot" summers, and risk of fire in the western United States are sample impacts.

***Regional Climate Change Effects: Useful Information for Transportation Agencies,* Federal Highway Administration, Washington, D.C. [Online]. Available: http://www.fhwa.dot.gov/hep/climate/climate_effects/ [accessed Oct. 7, 2011].**

FHWA issued this report in 2010. It provides a summary of projected climate changes by geographic region of the United States. The report emphasizes that these are projected trends and may not reflect the climate changes that might actually occur in a locality. It describes general climate change effects expected in terms of temperature, precipitation and storm events, and sea level. It walks through the ways each climate effect translates into impacts on infrastructure and operations. It also provides a detailed and instructive discussion of the methodology used in developing projections of climate change effects in the report. A series of sections discusses each climate change effect for the following regions of the United States: Northeast, Southeast, Midwest, Great Plains, Southwest, Pacific Northwest, Alaska, Hawaii, and Puerto Rico.

Foundational resources on climate change impacts and adaptation

Carter, T. R., et al., *New Assessment Methods and the Characterisation of Future Conditions, Climate Change 2007: Impacts, Adaptation, and Vulnerability,* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, Eds., Cambridge University Press, Cambridge, U.K., 2007, pp. 133–171.

The IPCC Fourth Assessment Report was published in 2007, five years after the last. As with other chapters, this chapter provides updates on developments in key areas, in this case it describes the methods and approaches for assessing climate change impacts, adaptation, and vulnerability. It defines what an integrated assessment is, such as one using more than one model or linking different disciplines and groups of people. It also devotes significant discussion to risk management approaches but at a highly conceptual level that introduces the topic to the climate change discipline rather than providing guidance on it. This chapter draws the distinctions among the various kinds of assessments, acknowledges that there can be confusing overlap among them, and describes developments in all areas. This chapter also describes the various types of scenarios used in planning, the types of modeling that may make up scenarios, and the need to apply them consistently across studies and regions.

As with the IPCC report in general, it is written at a high and abstract level, in order to be relevant to the broadest audience. For this reason, it provides a helpful introduction to key concepts and developments; and typically, like the entire IPCC report, it can serve as the primary resource and last word where there is a misunderstanding of terms.

Willows, R. and R. Connell, "Climate Adaptation: Risk, Uncertainty, and Decision-making," *UKCIP Technical Report,* United Kingdom Climate Impacts Program, Oxford, 2003.

This report, published in 2003, is a seminal document in the adaptation literature, with its climate change-specific risk assessment framework influencing many later efforts: (1) Identify problem and objectives; (2) establish decision-making criteria; (3) assess by an initial screening, then through qualitative and/or quantitative means detailed in the document; (4) identify options; (5) appraise options; (6) make decision; (7) implement the decision; (8) monitor, evaluate, and review. It describes types of decision making, data, uncertainty, and scenario planning in a technical, comprehensive, but accessible way.

***America's Climate Choices: Adapting to the Impacts of Climate Change,* National Research Council, Washington, D.C., 2010.**

This report is part of a four part series entitled America's Climate Choices, all of which were published in 2010 by the NRC. It was developed by a panel of experts that was charged with describing, analyzing, and assessing actions and strategies to reduce vulnerability, increase adaptive capacity, improve resiliency, and promote successful adaptation to climate change in different regions, sectors, systems, and populations. The focus is the United States, but several sections necessarily address the national security driver within the larger climate change impacts challenge. The report analyzes the current state of the information and tools that can provide decision support in this area and identifies case examples of pioneering adaptation leadership in the United States. Its report states that "Adaptation is fundamentally a risk management strategy" and walks the reader through stages in the risk analysis process, with illustrations from the New York City adaptation effort, describes various methods for ranking adaptation options, and details the impediments to implementing adaptation plans and policies. It also devotes a chapter to linking adaptation efforts institutionally and geographically. The report also summarizes potential short-term adaptations to climate change by sector. The discussion on the transportation sector relies on the Transportation Research Board *Special Report 290: Potential Impacts of Climate Change on US Transportation* (2008).

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Potential Impacts of Climate Change on US Transportation, Special Report 290, **Transportation Research Board of the National Academies, Washington, D.C., 2008.**

This report was published in 2008 and represents the work product of a 13 member committee of experts formed by the Division of Earth and Life Sciences to conduct research requested by the Executive Committee of the TRB. The purpose of the report is to describe the nature of potential impacts of climate change of greatest relevance to U.S. transportation and suggest appropriate adaptation strategies and organizational responses. The 13 member committee reviewed the literature in the field, requested briefings, held a one-day conference, and commissioned five papers. It structured its effort into three tasks involving discussion of: (1) potential climate change effects, (2) impacts on U.S. transportation, and (3) possible adaptation strategies.

The report makes findings and recommendations in several areas: Climate changes of Greatest Relevance for U.S. Transportation; Potential Impacts on Transportation; the Decision Framework for Transportation Professionals to Use in Addressing Impacts of Climate Change on U.S. Transportation Infrastructure; Data and Decision Support Tools; Adaptation Options, including Operational Responses, Monitoring and Use of Technology, Sharing of Best Practices, Design Changes, Transportation Planning and Land Use Controls, Insurance, and New Organizational Arrangements. The report reviews all major transportation modes.

The areas of the report addressing airports include a general list of climate changes and certain illustrative impacts on transportation, including air transportation. It emphasizes that the impacts of climate change on infrastructure will differ depending on the mode of transportation, its geographic location, and its condition, and that the committee selected climate changes and weather parameters that climate scientists agree are most likely to occur in this century and which are most relevant to transportation. A later table links the impacts to possible adaptation actions in three broad areas: land, marine, and air transportation. Other sections address the impact of each projected climate change on air transportation; for example, temperature increases and extremes will cause permafrost melt that damages Alaskan airport infrastructure, heat buckling of runways, affect aircraft lift and therefore load capacity; increased heavy precipitation will cause airport flooding and erosion especially on the coasts; more intense tropical storms will close airports and cause physical damage to them. The report reviews previously published climate impact assessments for regions or areas that describe threats to airports, noting that those reviewed are the "handful" of studies addressing climate change impacts on transportation. The report notes the planning horizon for airport facilities and the multiple entities with responsibility over them, including airport authorities (hangars, maintenance facilities, and other infrastructure), airlines (fleet, hangars, and maintenance facilities); as well as the design lives of such infrastructure. It observes that there are significant costs to designing for adaptation to long-term climate impacts, there is a tendency for transportation planners and engineers to extrapolate from the past and adopt incremental solutions, and there is a lack of relevant information and guidance on which to base appropriate actions. The report calls for more strategic, risk-based approaches to decision making and infrastructure design, and it cites the state of California's seismic assessment of hundreds of states bridges as a potential model. The report concludes with several high-level but highly relevant recommendations that can help frame the response of the transportation sector to climate change.

The five papers commissioned by the committee are in an appendix to *Special Report 290.* They are not considered the work product of TRB; however, they provide detailed information and analysis of great use to decision makers in the transportation sector. Reports that would provide an airport manager with background information directly applicable to airport adaptation and resilience planning include, "Case Study of the Transportation Sector's Response to and Recovery from Hurricanes Katrina and Rita" (noting the role of transportation network disaster planning and modal redundancy in moderating the impacts of the hurricanes); "Design Standards for US Transportation Infrastructure, The Implications of Climate Change" (providing a useful primer on transportation engineering design standards, review of risk-oriented, probabilistic design procedures, discussion of water-related impacts as a priority area in the short-term, and an overview of promising technologies for decision support); "Climate Variability and Change with Implications for Transportations," listing climate impacts and the consequences for various transportation modes, with a focus on their geographical relevance.

General adaptation guidance and planning

Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments, **University of Washington, King County, Washington, and ICLEI—Local Governments for Sustainability, 2007.**

This guidebook was written by several Washington State entities in association with ICLEI—Local Governments for Sustainability and published in 2007. The Washington State entities are King County and the University of Washington's Center for Science in the Earth System (The Climate Impacts Group) and Joint Institute for the Study of Atmosphere and Ocean. The guidebook and its recommendations are written for a general audience that may be located anywhere; for example, outside King County and Washington State, using examples from King County's experience in creating a climate adaptation plan.

The *Guidebook* provides milestones and key steps toward developing, implementing, and updating a climate preparedness plan. The guidance begins with a scientific overview of climate change and its impacts, including a useful primer on climate models, as well as the arguments for proceeding with climate change planning without scientific certainty. In this context it introduces the National Assessment that provides broad projections of climate changes. The *Guidebook* then outlines a process for developing an adaptation plan that will be implementable. It recommends (A) scoping the climate change impacts to sectors, noting sources of impacts information and largely using sector examples from government that are statutorily and program driven, given that the guidebook is for governments; (B) building and maintaining support among stakeholders, including identification of "champions"; (C) building a climate preparedness team within the organization, including designation of a point person; (D) identifying planning areas relevant to climate change impacts; (E) conducting a vulnerability assessment that describes sensitivity and adaptive capacity; (F) conducting a risk assessment, largely qualitative that incorporates risk tolerance and community values and thereby supports work in priority planning areas; (G) establishing a vision and guiding principles for how you expect to achieve and sustain a climate resilient community; (H) using the guiding principles to set preparedness goals; (I) developing, selecting and prioritizing preparedness actions that constitute a plan; (J) identifying plan implementation tools, including risk management and methods for "mainstreaming" climate preparedness; (K) developing measures of

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resilience to track results; (L) reviewing and updating the plan and its assumptions.

Throughout, the guidebook is very detailed and lists important questions to ask that help government officials arrive at the information they need. It provides a long list of sources of information on climate change science, impacts, and adaptation; these are general without a strong focus on transportation or airports. The guidebook also provides a glossary as well as several friendly aphorisms ("The future ain't what it used to be") that serve as guideposts among the many terms that may be new and unfamiliar to government leaders and staff.

The guidebook is instructive to people inside and outside government. It provides a lucid, plainly written, and intelligent outline of critical considerations and milestones in developing processes in an area that can be abstract and that previously has not had any programmatic drivers or directives to guide action. It provides real-life examples of the vulnerability and risk analyses or the King County list of preparedness goals by sector, for example, which makes the topic more accessible.

***A Framework for Climate Change Adaptation in Hawaii,* Office of Planning, State of Hawaii, Honolulu, 2009.**

This document was prepared by the state of Hawaii's Ocean Resources Management Plan Working Group (within the state's Coastal Zone Management Program), with assistance from the University of Hawaii's Center for Island Climate Adaptation and Policy. It was published in 2009. As noted in its Introduction, the document draws much of its structure and approach from the *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments,* and at times it refers the reader to that guidebook. It emphasizes the need to identify the scale at which adaptation plans and actions would occur, state, island, county, agency, or planning sector; as a result it identifies in a detailed way the agencies that would be responsible for actions in key sectors.

***Center for Climate Strategies Adaptation Handbook: Comprehensive Climate Action,* Center for Climate Strategies, Washington, D.C., Sep. 2011.**

This guidebook was published in 2011. It outlines a process for climate change adaptation action planning and policy development to be completed in a year: (1) initiate action through a high-level directive; (2) organize the process and its governance; (3) organize vulnerabilities and adaptation actions by major topic areas; (4) set initial priority actions; (5) execute a systematic process to measure cost-effectiveness; (6) complete deeper evaluation of adaptation options; (7) consider related consequences and impacts of adaptation options; (8) analyze aggregate economic, environmental, and social impact of all options in plan before finalization; (9) finalize recommendations, analysis, and documentation in a report with detailed appendices; and (10) launch comprehensive adaptation plan.

Many of these steps are familiar and are seen in the planning efforts cited in the report. Up-to-date experience from implementation of these steps is reflected in several areas of the guidance. The guidebook has an immediate focus on adaptation options, rather than walking through the process for identifying the vulnerabilities that they may address. It compares and contrasts its risk assessment process to that in two guides summarized elsewhere in this appendix, *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* and *Climate Adaptation in New York: Building a Risk Management Response,* stating that its numerical ratings better allow for ranking.

The guidebook makes a key observation that many adaptation plans and guidance do not include economic analyses. Another discussion addresses the use of indices and metrics, which includes a caveat to the effect that important characteristics of an adaptation option may not be included in the metric. Other considerations include the point that values of metrics may differ across geographies, with water having a relatively higher value in a water-poor area; that a metric's functionality can be strong in some situations and weak in others; for example, water use as a metric can depend on the aridness of the region; and that time and spatial scales also can qualify the continued use of a metric. It is in the discussion of metrics that the guidebooks discuss vulnerability criteria and adaptation criteria.

The guidebook summarizes several methods relating to various stages in adaptation in decision support. It discusses an alternative approach to traditional risk assessment, called Robust Decision Making, which uses many different climate scenarios rather than a few. Alternatives are tested under each for robustness, to gain understanding as to whether an option will perform reasonably well in many instances.

To assist practitioners, the guidebook's appendix includes baseline datasets for identification of risks, including existing climate projections, several "overall" assessments of risks and impacts, and assessments by sectors and categories.

***Draft NEPA Guidance on Consideration of the Effects of Climate Change and Greenhouse Gas Emissions,* Council on Environmental Quality, Washington, D.C., Feb. 2010.**

This draft guidance memorandum was issued by the Council on Environmental Quality (CEQ) in February 2010 to address the ways in which federal agencies can improve their consideration of the effects of greenhouse gas emissions and climate change in their evaluation of proposals for federal actions under the National Environmental Policy Act (NEPA). CEQ proposes that federal agencies consider, in scoping their NEPA analyses, whether analysis of the direct and indirect emissions from the proposed action may provide meaningful information to both decision makers and the public.

Given that the federal government is committed to the goals of energy conservation and greenhouse gas (GHG) emissions reduction, wherever a proposed federal agency action implicates these goals, useful and relevant information on GHG emissions may be used when deciding among alternatives. In addition, where a federal action that is analyzed in an EA or EIS would be anticipated to emit GHGs in quantities that an agency finds may be meaningful, CEQ advises that it is appropriate for the agency to quantify and disclose these estimates in the environmental documentation for the proposed action.

With respect to current or projected effects of climate change, CEQ proposes that agencies ought to address the observed and projected effects of climate change as part of the proposed actions "affected environment." For climate change effects that warrant consideration, the agency may assess the extent that the effects of the proposed action or its alternatives will add to, modify, or mitigate these effects. These effects may include, but are not limited to, effects on the environment, public health and

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safety, and on populations vulnerable to the adverse effects of climate change.

Implementing Climate Change Adaptation Planning in Accordance with Executive Order 13514: Federal Agency Climate Change Adaptation Planning, Mar. 4, 2011.

These guidance documents to Executive Order (EO) 13514 provide information to agencies on how to implement the EO, specifically as it applies to climate change adaptation related to both federal buildings and programs. The guidance specifies that by June 3, 2011, agencies were to have adopted an adaptation policy, that includes adaptation planning, consideration of potential climate change impacts on long-term planning, and an analysis of how climate change may impact the agency's overall mission and policies. By September 30, 2011, agencies were to have prepared a set of 3 to 5 priority adaptation actions, as well as a draft, high-level analysis of their vulnerability to climate change.

Transportation sector adaptation

"Building a Risk Management Response: New York City Panel on Climate Change 2010 Report," ***Annals of the New York Academy of Sciences,*** **Vol. 1196, May 2010, pp. 1–354.**

This report was published in the *Annals of the New York Academy of Sciences* in 2010 and represents the full findings of the New York City Panel on Climate Change (NPCC). The NPCC was convened by Mayor Bloomberg in 2007 to develop a risk-based response to climate change impacts and a report, issued in 2009. This report describes the regional climate change projections commissioned by the NPCC, the planning tools developed for the area, the regulatory environment relevant to adaptation and resilience options, and the major themes and best practices recommended for a comprehensive adaptation program for the area. Specific sectors were examined in detail: Land Use, Energy, Water, Communications, and Transportation. The Transportation sector review did not cover airport issues in depth, mainly citing their vulnerability to sea level rise and coastal storms, and a data collection role relevant to climate change indicators and metrics. The report also refers to recommendations in TRB *Special Report 290.* The report is useful for its framing of short- and long-term program needs and decision support tools, as well as its coupling of high-level discussion with (1) tactical recommendations for concrete next steps; (2) in-depth review of ancillary issues such as the role of the insurance sector; and (3) a set of NPCC workbooks, included as appendices, to guide on-the-ground planning.

2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008, **California Natural Resources Agency, Sacramento, 2009 [Online]. Available: www.climatechange.ca.gov/adaptation [accessed Oct. 7, 2011].**

This strategy was developed by a Climate Action Team formed within the state government and led by the California Natural Resources Agency. It was released for public comment and then published in 2009. The first part of the strategy explains climate science and modeling. It offers an interesting distinction to readers, describing hazards based climate modeling, which focuses on the variance of climate changes from the historic norm to demonstrate the degree to which adaptation may be required. Non-climatic factors are not addressed in this form of modeling. A vulnerability-based approach focuses on socio-economic and ecological factors that determine a systems vulnerability and ability to cope with and adapt to climate change. A baseline of the system's ability to handle past climate variability can be established; for example, how existing drought cycles may be exacerbated by climate change. It also describes the climate scenarios already developed for the state and summarizes projections relating to temperature, precipitation, sea level rise, and extreme events, as well as abrupt climate changes.

The strategy took a cross-sector look at climate change, identifying four overall strategies (comprehensive planning, land use, emergency preparedness and response, and research) and several sector-specific strategies: public health, biodiversity and habitat, oceans and coastal resources, water supply, agriculture, forestry, and transportation and energy infrastructure. The discussion of the transportation infrastructure briefly notes the possible inundation of coastal airports under sea level rise. The recommendations for transportation call for activity at several levels: State-wide Strategy; System Planning; Regional Transportation Planning; Project Planning; and Programming. It also calls for developing transportation design and engineering standards to minimize climate change risks, developing guidelines for buffers and setbacks to avoid impacts from sea level rise, and assessing needed changes to stormwater design requirements. It also calls for assessment of the climate impact information needed to respond to emergencies and for other decision support. Stepped down actions include vulnerability and adaptation planning, development of an economic impact assessment for climate impacts on the state transportation infrastructure, creation of a transportation "hot spot" map to show which communities will be more vulnerable given their transportation needs, and identification of hot spots based on economic analysis, integration of greenhouse gas mitigation, and adaptation strategies.

"Climate Change Adaptation and Transportation System," California Department of Transportation, Sacramento [Online]. Available: http://www.pdfio.com/k-976196.html and formally available at http://www.climatechange.ca.gov/adaptation/infrastructure/2008-12-05_meeting/CAS_INF_PDF.pdf.

This PowerPoint presentation provides a summary overview of the climate effects of concern to the California Department of Transportation as well as its climate change adaptation approach, which has two objectives: (1) proactive steps to assess vulnerabilities to climate variations, and (2) mainstreaming of climate change adaptation considerations into transportation investment decision making. High-impact slides depict the climate change effects of primary concern and their potential damage: sea level rise and storm surge (e.g., implicating heavy coastal development); increased hot days and heat waves (e.g., causing pavement degradation or warped train tracks); and changes in precipitation that cannot be forecasted (e.g., leading to roadway washouts and landslides). The presentation makes the point that integration of adaptation into complex transportation planning cycles is not a simple task, introducing the processes involved in a sophisticated, "simplified" chart.

The presentation shows that as a highly generalized depiction of a seven-stage, state-level transportation planning process proceeds, there will be two other activities occurring in tandem: a Climate Action Program and economic and financial assessments. These will intersect with transportation planning at key points in its process, bridging "cross-functional requirements" and providing technical assistance. The slides show how the state may cross-walk each of the seven planning steps through an "adaptive response" or adaptation strategy for each stage. Under the "Advance Planning and Programming" stage, which

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lists, for example, the need to develop a "Project Initiative Document (PID)," there is a set of "adaptive responses" that suggest a corresponding action with respect to adaptation. In the case of a PID, the direction is to "include preliminary analysis of the adaptation." As with the broader California adaptation strategy, these suggestions for the transportation planning system are transferable to other states or areas that may experience similar climate variations. The presentation concludes with an acknowledgement that more research is needed on the scale of climate change effects, rate of change, anticipated impacts, and potential responses. Other considerations are regional equity, environmental justice, and coordination.

Lindquist, E., *Climate Change/Variability Science and Adaptive Strategies for State and Regional Transportation Decisionmaking,* Report SWUTC/10/167165-1, Southwest Region University Transportation Center, College Station, Tex., Apr. 2010.

This report summarizes research conducted in 2007 and repeated in 2009 with respect to the adoption of climate adaptation policies in the 50 states. In 2007, four states transportation policies mentioned climate change, and this number grew to seven in 2009. Almost no attention was being paid to adaptation and the investigators found this to be significant.

Survey results of state transportation officials and MPOs suggest that more research into the research capacity and training needs for these entities is necessary with respect to climate change. Neatly 70% of respondents had never contacted a scientist for information related to global warming and climate change. Where agencies were engaged in climate change it was related to impacts, air quality, and long-range planning. A primary reason for not considering climate change in decision making was the lack of a federal mandate. Only 13% of respondent thought impacts would be significant in 10 years or less; nearly 25% believed 10 to 25 years; 22%, 25 to 50 years; and nearly 15%, 50 to 100 years. MPOs were more likely to consider climate change to be a significant issue.

The research suggested to the investigators that without reports and best practices from reliable sources; for example, federal or state departments of transportation, agencies were reluctant to move forward on climate change. Interviews revealed that people were reviewing a wide range of sources of information and there was a sense that the climate change issue suffered from a lack of detailed or downscaled state- and regional-level information. Such information was seen as critical to decision making and public participation in the adaptation issue.

"International Scan on Climate Change Adaptation," *Transportation Research Circular E-C152,* Transportation Research Board of the National Academies, Washington, D.C., June 2011

This call out box in a TRB circular devoted to adaptation provides a useful list of the pertinent questions transportation experts are asking about methods and data needs for addressing climate change impacts in the transportation sector. Its questions reflect the professional judgment of transportation organizations such as FHWA, AASHTO, and NCHRP.

- Understanding how best to include climate change information in existing or new analysis techniques for planning new infrastructure and maintaining transportation systems.
- Assessing how climate change impacts will affect asset management investment cycles and the life cycles of major investments.
- Developing pavement, bridge, and other infrastructure design and materials specifications that account for expected climate change impacts, including climate change considerations in hydraulic modeling and design.
- Considering climate change adaptation in the transportation planning process.
- Developing policies and procedures for inventorying critical infrastructure and assessing vulnerabilities and risks as a result of climate change impacts.
- Developing options for risk analysis frameworks.
- Developing data collection standards to inform risk analysis, asset management, and decision making.
- Finding opportunities to improve the resiliency of transportation infrastructure naturally, through the benefits of ecosystem services.
- Documenting effective management strategies that are able to accommodate the climate change impacts on highway safety and operations.

McGuirk, M., S. Shuford, T.C. Peterson, and P. Pisano, "Weather and Climate Change Implications for Surface Transportation in the USA," *WMO Bulletin,* Vol. 58, 2009, p. 84.

This report summarized the implications of weather changes that affect the operation of transportation systems, and climate change that affects transportation infrastructure. It notes that when weather patterns become more extreme as a result of climate change, transportation infrastructure may become less reliable and less safe. The report summarizes different weather parameters and the potential impacts of these to ground transportation, including airport ground operations. Extreme temperatures can also have a negative impact on surface transportation infrastructure, including thermal cracking of roadways and a reduced lifespan for road surfaces. Extreme precipitation events can result in flooding that damages transportation infrastructure and causes disruptions in the transportation system.

The bulletin suggests that as a result of climate change, extreme weather events are expected to occur more frequently in the future, increasing the transport's sectors vulnerability to weather-related disruptions and infrastructure damage. Airports, especially those located in low-lying coastal areas, are at risk from rising sea levels, severe weather, subsidence, changes in shoreline shape, and inland precipitation flooding. In addition, the report found that many coastal structures, including airports, are designed for a working economic life of 50 years or less. For these airport locations, the relatively frequent repair, replacement, and re-design could be modified to take into account local sea level rise.

***White Paper: Transportation Adaptation to Global Climate Change,* Bipartisan Policy Center, Washington, D.C., 2009.**

This white paper examines the impact of climate change on the transportation sector, and studies various adaptations to transportation infrastructure to mitigate the effects of climate change. The study makes recommendations on short-term federal legislative action needed to increase the transportation system's resilience to long-term costs of climate change. The white paper recognizes the need for the federal government to compile the interdisciplinary climate research, modeling, mapping, and comprehensive planning needed.

The white paper recommends that the government increase support for climate research and interagency initiatives, as well as requiring that climate adaptation be addressed in transportation planning and project development.

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Recommendations were also made for the passage of combined energy and climate legislation, as well as executive policy action to address climate adaptation in the NEPA process and to incorporate climate risk analysis into Federal infrastructure investment policies.

A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy: Special Report 299, **Transportation Research Board of the National Academies, Washington, D.C., 2009.**

This report analyzes policies and practices that could be considered for adapting the transportation system to climate change and for mitigating GHG emissions and energy consumption related to transportation. Federal, state and local policy makers need informed guidance about the effectiveness, costs, feasibility, and acceptability of transportation mitigation and adaptation strategies, and to this end, the report recommends an annual investment of $40 to $45 million to quickly develop guidance based on existing research, and to foster new research to improve this guidance over time.

The report also suggests possible preliminary topics for research, with the expectation that these will be further refined over time. This research ideally would be guided by several principles detailed in the report, including that research topics investigated be relevant to the needs of federal, state, and local policy makers. Research program managers also need to have the flexibility to shift areas of investment as knowledge is developed, and the research to be evaluated on an ongoing basis by an independent group that would report directly to Congress.

Hodges, T., "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation," prepared for the Federal Transit Administration, U.S. Department of Transportation, Washington, D.C., Aug. 2011.

This report summarizes the impacts of climate change on public transit, and ways that agencies can adapt to these changes. Impacts range from sudden, disruptive events such as intense rainfall and flooding, to longer-term effects that may impair an agency's ability to maintain a state of good repair and reliability. While it may not be possible to link specific weather events to climate change, extreme weather is already having an impact on transit systems across the country, causing delays and disruptions during blizzards, floods, and other events.

Risk assessment tools developed by governments offer guidance on how to prioritize climate risks by assessing the likelihood of occurrence and the magnitude of the consequences of climate change impacts. And, although climate change adaptation may be a new topic for the transit industry as a whole, several transit agencies, such as Portland's TriMet, have already begun work in this area. There are four broad categories of adaptation strategy for transit: maintain and manage, strengthen and protect, enhance redundancy, and abandon infrastructure in very vulnerable areas.

Implementing these adaptation strategies effectively requires linking them to transit agency organizational structures and activities, such as asset management systems. Asset management systems offer a streamlined framework for identifying climate risks, tracking climate impacts on asset condition, and incorporating adaptation strategies into capital plans and budgets. Climate change adaptation involves long-term planning for system preservation and safe operation under current and projected conditions and interdisciplinary efforts among experts and stakeholders.

Sources focused on the general airport context under climate change

Stewart, B., I. Klin, and M. Vigilante, "Climate Change Adaptation and Preparedness Planning for Airports," ***Adapting Transportation to the Impacts of Climate Change, Transportation Research Circular E-C152,*** **Transportation Research Board of the National Academies, Washington, D.C., June 2011.**

This article's authors are aviation consultants and they describe the context in which airport decision makers operate when considering climate change impacts and risks.

It notes that most airport infrastructure is built for a 50-year life. Also, it notes two important aspects about airports: protection of aircraft is as important as protecting the airport structures, and airport function depends on connectivity to other modes of transportation that may or may not be owned by the airport, such as roads and rail connectors. Also an airport's role as a command center during times of crisis is an opportunity to play a role in regional adaptation.

The authors identify three broad areas of work implicated by adaptation needs:

- Hardening and redeveloping the physical plant
- Assessing and adapting to a variety of operational risks and opportunities
- Building communications, collaboration, and strategic alignment with the full range of airport stakeholders.

They also identify research needs based on their professional judgment.

Burbidge, R., A. Melrose, and A. Watt, "Potential Adaptation to Impacts of Climate Change on Air Traffic Management," prepared for the Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany, June 14–17, 2011.

This article summarizes research and analysis conducted by the European agency in charge of the safety of air navigation, EUROCONTROL. As such it is related to airport adaptation but only as air traffic management relates to an airport. This research identified three areas where climate change impacts may create adaptation issues for air traffic management, describing case studies for each of the following: (1) shifts in passenger demand resulting from changes in local temperature; (2) loss of airport capacity through sea level rise; and (3) impacts to en-route operations resulting from increases in extreme weather events. Case Study 1 also is summarized elsewhere in this appendix (see p. 65, *Challenges of Growth . . .*).

The article also identifies two primary reasons why aviation in particular is vulnerable to climate change: it is weather-dependent and its interconnectedness allows a single node to create knock-on effects through the system. It then analyzes each case study from a larger policy perspective, something not done in each of the separate case studies. With respect to the case study on shifts in passenger demand, the article notes that aviation infrastructure is driven by forecast demand and the long lead times for infrastructure development require planning significantly in advance of operations. As a result, current demand forecasts may not be the appropriate driver for planning and new infrastructure projects forecasts need to begin to integrate the potential of climate change-induced change demands into their risk

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assessments. The article also notes that aircraft operators can adapt quickly, given the mobility of their assets, whereas air navigation infrastructure is too fixed to adapt quickly.

The summary of the second case study, on sea level rise, outlines familiar impacts seen in other literature sources. It also notes that airports are not alone in being under threat; even where the airport is protected from sea level rise, compromised access roads may render the airport inaccessible. In addition, secondary and reliever airports may be threatened as well. The third case study reviews the impact on flight operations of a single day of severe weather in an area of airspace over Europe, finding that bad weather in the skies affects the functioning of the airspace in a negative way.

The article concludes that more detailed research is needed, with a special emphasis on the possible timescales over which impacts may be felt, in order to construct the scenarios on which to base adaptation planning. Other research needed would regard the quantification of the potential financial implications of expected impacts and adaptation measures. They suggest that business planning would be aided by simulations of costs of unforeseen airport closures or market analyses of potential changes in passenger demand.

***Evaluating the Risk Assessment of Adaptation Report under the Adaptation Reporting Power: Aviation Sector Summary,* prepared for the U.K. Department for Environment, Food, and Rural Affairs by Cranfield University, Oct. 2011.**

This report summarizes and highlights key findings from the results of a review of risk assessments in several aviation sector adaptation reports submitted to the U.K. government in 2011 (and embargoed and unavailable for review for part of that year). The report focuses particularly on key risks for the sector, areas of strength for the industry, areas of good practice, areas for further research, and emerging trends and themes. Climate change risk assessment currently forms a component of corporate risk appraisal for the aviation sector.

The review found a number of key risks for the sector, including risks to air traffic control and air traffic movements from changes in weather patterns. There may also be risks to airfield operations and airport terminal and cargo operations as a result of changes in weather patterns, temperature changes, or changes in the distribution of wildlife or vegetation. Infrastructure and engineering at airports may also be at risk owing to climate change, as well as access and transport. Finally, there are global risks to the aviation sector from climate change, including the changes in sea level or global distribution of disease.

In addition to these risks, the review found a number of areas of strength, including engagement with relevant staff, departments, and stakeholders. The risk assessments reviewed were completed using existing corporate risk assessment methodologies, and the review found that climate change risk is already being embedded in risk management processes. The review also found clear timescales and responsibilities for adaptation, and plans for continued assessment and monitoring.

The review also identified many possible areas for further research, including changes in travel behavior and risks to cargo flows stemming from the effects of climate change. Further research is also needed into the potential reputational and financial risks and adaptation investment issues related to climate change. Other risks found included disruption of water supply, impact on employees, and changes in wildlife and vegetation.

Finally, the review found several emerging trends in the area of climate change adaptation in the aviation sector. Among these were consistencies in the risk assessment approach, including the use of semi-qualitative risk assessment methodologies and the assessment of short-, medium-, and long-term risks. Trends also appeared in the actions proposed to address risks.

***Environmental Management System Strategy and Framework for the Next Generation Air Transportation System,* Joint Planning and Development Office, Environment Working Group, Nov. 2010.**

This report explores the use of a strategic Environmental Management System (EMS) approach to help integrate environmental protection and energy goals into the business and operational strategies of the Next Generation Air Transportation System. The most common framework for an EMS is the Plan-Do-Check-Act process, with the goal of continuous improvement in environmental performance. EMS frameworks, of which ISO-14001 is the most common and internationally accepted standard, is intended to facilitate an effective environmental management approach, while still ensuring sustained industry growth.

In the initial Plan phase of an EMS the goal is to identify significant environmental aspects of Next Generation aviation systems. These might include air quality, global climate effects, energy, and water quality. Ongoing planning efforts establish baselines and environmental goals, as well as plans to address and achieve these goals. In the Do section of the EMS process, organizations systematically manage environmental performance in order to achieve the goals set in the Plan phase.

During the Check phase of the EMS, environmental performance is regularly monitored to ensure that the strategies and initiatives are working and will achieve the desired outcomes. In addition to monitoring and measuring environmental performance, organizations ought to also communicate with key stakeholders during this phase. Finally, in the Act phase the ongoing EMS cycle of planning, implementing, and checking leads to ongoing adaptations and re-adjustments based on feedback and measurements.

Sources detailing climate risk assessment and other decision support tools and methodologies

McLaughlin, B., S. Murrell, and S. DesRoches, "Anticipating Climate Change," *Civil Engineering,* Apr. 2011, pp. 50–55.

This article was published *in Civil Engineering,* the magazine of ASCE. It authors are Brian McLaughlin, P.E., LEED AP, M. ASCE; Scott Murrell, P.E., M. ASCE; and Susanne DesRoches, LEED AP, of the Port Authority of New York and New Jersey (PANYNJ). They describe the PANYNJ's activities in support of the New York City Panel on Climate Change's effort to develop a risk-based response to climate change impacts (summarized elsewhere in this appendix). The PANYNJ owns and maintains some of the largest and most valuable transportation infrastructure in the United States, including the Port Authority Trans-Hudson rail system (PATH), six tunnels and bridges linking New York and New Jersey, the Port Authority Bus Terminal, the World Trade Center, JFK International Airport (JFK), LaGuardia Airport, Stewart International Airport, Teterboro Airport, and Newark Liberty International Airport.

The PANYNJ evaluated the vulnerability of its infrastructure to a range of climate effects to determine those that might be

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affected by projections in three time horizons: 2020, 2050s, and 2080s. This article describes the challenges in undertaking this evaluation of vulnerability and the way climate change projections can inform design guidelines, maintenance programs, and long-term planning. The PANYNJ, along with other agencies, were asked to create an inventory of infrastructure that might be at risk and develop adaptation strategies with a view to interagency coordination. There were six tasks performed: defining the climate change variables and projections, developing asset inventories, assessing vulnerabilities, analyzing risks, prioritizing the assets, and developing adaptation strategies. This was the sequence of activities followed, with some iteration.

Initial challenges encountered included access to data, including its collection from multiple sources, and the assessment of its accuracy, which also entailed analysis of alternative sources. With respect to risk analysis, the traditional approach was followed: risk being a function of the likelihood of occurrence and the gravity of the consequence. Through professional judgment, the PANYNJ defined these factors in greater detail. For example, several factors were used to evaluate the magnitude of the consequence, including internal operations, capital and operating costs, effects on society, patron health, economics, and the environment. With respect to the likelihood of occurrence, one critical factor was whether there was a likelihood of occurrence in the lifetime of the asset, which is a subjective judgment where there are no normalized criteria across and within asset classes. The PANYNJ created a quantitative scale for its purposes. Another useful practice articulated in the article is that the PANYNJ divided adaptation strategies into three categories: maintenance and operations (e.g., use of portable pumps and conducting detailed studies), capital investments (e.g., permanent improvements), and regulatory (e.g., design standards).

The authors noted two sample inventories at risk at airports. The airfields at JFK and LaGuardia, runways and taxiways in particular, are at risk of increased flooding from nor'easters and hurricanes, owing to the likelihood of extreme weather events and storm surge with sea level rise. Operations at the terminal buildings at JFK and LaGuardia are at risk from rising temperatures and heat waves resulting from the increased risk of power failure that may shut down baggage handling systems.

The authors describe ways that the assessment process matured PANYNJ practices. First, they have developed interim design criteria for use in new construction or major rehabilitation projects, and these criteria will be reviewed every two years. It also is evaluating facility emergency plans. System redundancies engineered for other purposes also help increase adaptive capacity and system resilience. Another finding by the PANYNJ was that earlier capital improvement investments that involved engineering design redundancy also may help ameliorate infrastructure vulnerabilities. Security projects; for example, barriers, help reduce the impact of high water.

The PANYNJ experience provides a long list of lessons learned that can inform and refine best practices in transportation sector responses to climate change risks.

***Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model,* Federal Highway Administration, Washington, D.C. [Online]. Available: http://www.fhwa.dot.gov/hep/climate/conceptual_model62410.htm [accessed Oct. 7, 2011].**

FHWA developed its draft conceptual Risk Assessment Model in 2010, and based on the experience in piloting it with a handful of state DOTs and MPOs in 2010–2011, FHWA will develop a final version. The conceptual model helps a planner or other user to develop an inventory of important assets, gather climate information, and assess the risk to the assets from projected climate change.

The conceptual model's approach is to first compile a list of assets by categories that correspond to planning priorities. It recommends gathering information that can later inform evaluation of the assets resiliency to climate change and how costly damage to the asset would be. The model then suggests screening out assets based on their "criticality" or importance, which may be gauged by existing evaluation tools and criteria used by a state or MPO.

Next the conceptual model asks the user to collect local or regional level climate data, both historical and projected. Uncertainties are to be reviewed. Effects that are small in magnitude and relatively uncertain would be screened out but reviewed at a later time. FHWA notes that it will provide guidance to the pilot agencies on how to take these two factors into account.

Next, the conceptual model describes a risk assessment process to be applied for each asset, using the common formula of likelihood of impact multiplied by that consequence of the impact.

The conceptual model reviews the vulnerability of the asset. Vulnerability is determined by examining the assets' performance under historical weather conditions. Sample evidence may be repair costs caused by past weather events, budgets for snowplowing, and the role of the asset in emergency response. If a climate stressor does not have a significant impact on an asset, that climate stressor and asset combination can be screened from review and revisited. The conceptual model encourages the identification of climate stressors already taken into account in the design, operation, and maintenance of the asset.

Next the conceptual model calls for an assessment of whether future climate stressors will affect the asset and consideration of the cumulative impacts of more frequent climate stressors. To assess the likelihood of impacts, the conceptual model would have the user split impacts into high and low climate stressors, based on their severity. The determination of high or low severity of impact is a qualitative judgment reliant on the expertise of the intended user of this draft model. Next the model would have the user consider the consequences to society of the impact, in part through use of the earlier criticality assessments. To integrate the two factors, with their low and high likelihood of impact and low and high consequence, the conceptual model suggests arranging them in a matrix based on the combined effects of their likelihood; low, medium, and high. This approach provides a visual depiction of the assets most at risk from climate change. The conceptual model then suggests identification of adaptation options based the criticality and at risk status of the assets. It notes that adaptation measures can take advantage of existing or scheduled planning cycles ("opportunistic" adaptation) or be pro-active in that the measure would be implemented before scheduled or necessary planning or maintenance.

FHWA: Climate Change and Transportation, Washington, D.C. [Online]. Available: http://www.fhwa.dot.gov/hep/climate/index.htm.

The FHWA website is a useful resource because it has several sources of information on climate change adaptation, climate risk and resilience, and transportation. Given the mission of

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FHWA, it does not include reports or other documents focused on airports, although their information and guidance can be utilized by airports.

Literature Review: Climate Change Vulnerability Assessment, Risk Assessment, and Adaptation Approaches, **Federal Highway Administration, Washington, D.C., 2009, 32 pp.**

FHWA released this document online in 2009. It provides the result of a literature review of certain approaches that transportation agencies have taken in addressing climate change impacts to transportation. It focuses on vulnerability assessments, which review the existing stressors to transportation and identifies new stressors under climate change; risk assessments, which evaluate the likelihood and consequences of climate change impacts to support decisions under climate uncertainty; and adaptation assessments, which identify, prioritize, and measure options for adapting to climate changes. For each approach, key terms are introduced and summaries of published reports are provided to illustrate the application of that approach.

CCSP, ***Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I,*** **A Report by the U.S. Climate Change Science Program and Subcommittee on Global Change Research, M. J. Savonis, V.R. Burkett, and J.R. Potter, Eds., U.S. Department of Transportation, Washington, D.C., 2008, 445 pp.**

This report was commissioned and published as Synthesis and Assessment Product 4.7 under the auspices of the U.S. Climate Change Science Program, which now forms part of the U.S. Global Change Research Program within the White House Office of Science and Technology Policy. It is the first of a three-phase research effort that aims to provide knowledge and tools that would enable transportation planners to better understand the risks, adaptation strategies, and tradeoffs involved in planning, investment, design, and operational decisions given projected climate change impacts. Phase I is a preliminary assessment of risks and vulnerabilities given data collected on the region, while later work will focus on a select location as well as report on implications for long-range plans and impacts on safety, operations, and maintenance; analyze adaptation and response strategies; develop tools to assess these strategies; and identify future research needs.

The Phase I report describes the Gulf Coast region, projected climate impacts, and the likely effects of these impacts on the transportation system in the region. The report notes that while transportation planning already factors in significant uncertainty and planners take an iterative approach in many instances, in order to manage climate change, planning horizons may need to be expanded and deterministic decision support methods may need to be joined with iterative risk assessment. The report describes the results of its literature review, including a large table of climate impacts identified in the literature, with citations to sources. Conclusions from the authors' literature review were that (1) more data collection is needed to assess transportation vulnerability to climate change; (2) there are gaps in impacts research, including a dearth of quantitative assessments, operations impacts, network and performance impacts, and secondary impacts (e.g., air quality changes that affect airport investment decisions); (3) assessments of risks has been largely qualitative, and there is a need for quantitative assessments of costs or performance impacts, especially in the area of economic implications; (4) there has not been an effort to develop a generalized approach for risk analysis; (5) there is a need for work in developing strategies for adaptation and planning, as opposed to a facility engineering approach; and (6) there is a need for decision support tools, including probabilistic approaches to address uncertainty.

The authors described the physical setting and natural environment of the region in depth, noting geophysical dynamics that could influence the response of transportation infrastructure to climate changes. The report then describes the climate scenarios developed for the study, including the models and datasets utilized to develop this summary list of issues: Temperature, Precipitation, and Runoff; Hurricanes and Less Intense Tropical Storms; Sea Level Rise and Subsidence; Storm Surge; and Other aspects (Wind and Wave regime; Humidity and Cloudiness; Convective activity). The report lists the implication and impacts of these variables. The report notes several impacts to airports; for example, temperature increases will affect construction labor schedules as well as aircraft lift, requiring consideration of runway lengths or manufacturer review of aircraft specifications; more intense precipitation may decrease visibility (requiring greater distances between aircraft and slowing the system), decrease braking effectiveness, increase stormwater management demands, weaken inundated roadways, increase turbulence, increase wing icing, affect engine thrust, increase the need for pilot training in Instrument Flight Rules, increase the need to evaluate airport design on floodplains, increase hurricane intensity that will cause physical damage and operational disruption to airports; increase the risk of airport inundation owing to the combination of sea level rise and storm surge.

The report includes a valuable discussion of key terms used extensively in the climate change adaptation literature and how they can be aligned with risk assessment concepts for use in the transportation sector. It provides the following working definitions.

> Exposure: The combination of stress associated with climate-related change and the probability or likelihood that this stress will affect transportation infrastructure.
>
> Vulnerability: The structural strength and integrity of key facilities or systems and the resulting potential for damage and disruption in transportation services from climate change stressors.
>
> Resilience: The capacity of a system to absorb disturbances and retain essential processes.
>
> Adaptation: A decision that stakeholders can make in response to perceptions or objective measurements of vulnerability or exposure. Included in this concept is the recognition that thresholds exist where a stimulus leads to a significant response.

From the probability of an exposure to a climate impact and the assessment of vulnerability, some idea of the risk the facility or the system faces can be determined. Here the report again notes that quantitative methods are needed. The report notes that an assessment of the resilience of facilities; for example, their ability to maintain full performance in their life span, requires different data than the resilience of a system, most notably redundancies that maintain the movement of goods and people. The report notes three broad areas for adaptation options (protect, accommodate, and retreat) and how improvements to capital, maintenance, or operational improvements can emerge from these analyses. The report asserts that it is premature to consider formal changes to the established federal transportation planning process, but the

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framework it outlines can be part of a visioning process that now and later inform the development and evaluation of alternative improvement strategies. It does list general areas for focus and consideration, including supplementing long-term plans with consideration of climate change horizons, ensuring review of the connectivity of the intermodal system, and providing an integrated analysis of impacts and risk wherein climate change per se is not analyzed separately from other non-climate stressors and conditions.

Assessing Infrastructure for Criticality in Mobile, Alabama: Draft Final Technical Memorandum, Task 1, Gulf Coast Study, Phase II, **Preprint, U.S. Department of Transportation. Washington, D.C., Mar. 4, 2011.**

This report is currently in development. It was commissioned by the U.S.DOT and is a focused look at climate impacts on transportation, and related vulnerabilities, in Mobile, Alabama. Phase II involves several tasks, and the first task has been completed, with a draft final technical memorandum on its findings released to stakeholders in "draft final" form. The information herein is based solely on that draft final report, dated March 2011.

According to the report, Phase 2 involves the following tasks: (1) identify critical transportation assets; (2) develop climate information and assess sensitivity of assets to climate stressors; (3) determine the vulnerability for key links and assets; (4) develop and apply detailed risk management tools; (5) coordinate with local planning authorities and the public on the process and implications of the analysis; and (6) publish and disseminate the information learned.

The March 2011 draft provides a definition of "critical" infrastructure: infrastructure that serves to keep the mobility and accessibility functions of the transportation network viable as they enable economic and social activities. In short, the investigators were looking at its importance to the functioning of the community.

The authors reviewed the following transportation modes: highways, transit, railroads, ports, pipelines, and airports. The authors examined criticality by mode, conducting analysis within each mode. However, they deemed an assessment of criticality across modes too subjective given the data available and for lack of an analytical framework.

The framework for determining the criticality of certain transportation infrastructure involved these components: socio-economic, use and operational characteristics, and health and safety, which may include its role in emergencies. For each mode the data used to evaluate infrastructure under these criteria would vary. Desk top reviews, interviews, and professional judgment guided the data analysis. In some instances, however, stakeholder input provided qualitative statements on the importance of certain infrastructure and the report takes earlier collection and incorporation of local values as lessons learned in methodology. The authors include a discussion of how the study's scope evolved and expanded. Initially, their conception of critical infrastructure focused primarily on highway and rail and their importance to homeland security and emergency management. The methodology was broadened to include socioeconomic and operational considerations, as well as other modes.

The authors developed a methodology for testing system redundancy, used primarily for roadways. This methodology helped create a score for redundancy for each link in the system.

In their review of the 17 airports in the area, the authors relied largely on FAA-reported data, as well as information in the Statewide Airport System Plan. With respect to the latter, the authors used state information in an initial "scan" of transportation plans and demand models. They recorded and assessed the existence of several functions and activities at each airport. They examined whether each airport had the following functions: air carrier; commuter; air charter; air taxi; hangar rental; tie downs; aircraft rental; aircraft sales; flight instruction; jet fuel; aviation gas; aircraft repair; avionics repair; U.S. customs; public telephone; restaurant; vending; car rental; skydiving; loaner car; FTZ; industrial park; and FAA test center. The authors also examined whether each airport had the following services: recreational flying; agricultural spraying; corporate/business activity; aerial inspections; just in time shipping; gateway for resort visitors; community events; police/law enforcement; prisoner transport; community facilities; flight instructions/education; cap; environmental patrol; emergency medical evacuations; medical shipments/patients; forest fire fighting; aerial photo survey; real estate tours; banner towing; traffic news; air shows; fly-ins.

The scan of transportation plans and demand models was followed by analysis of each airport facility for its criticality. The authors developed 20 criteria, described in detail here, for assessing the criticality of the aviation facilities (airports, fields, and heliports) and these encompassed three aviation categories: general aviation, civil aviation, and military aviation. Notably, none of the facilities was mentioned in evacuation or disaster management plans.

The information selected to form the criteria for assessing criticality were as follows:

Socioeconomic

- Part of the national/international commerce system
- Important multi-modal linkage
- Functions as community connection
- No system redundancy
- Serves regional economic centers.

Use/Operational

- Status as a commercial use airport, military airport, public airport, or private airport
- Federal Acquisition Regulations Part 139 certification
- Aircraft performance and dimensions (approach speed codes—A, B, C, D, E; Aircraft design group—I, II, III, IV, V, VI)
- Instrumentation (precision, nonprecision, visual)
- Category within the National Plan of Integrated Airport Systems (primary, reliever, general aviation)
- Category within Statewide Airport System Plan (international, national, regional, community, local)
- Passenger enplanements (most recent year)
- Annual aircraft operations (most recent year)
- Based aircraft (most recent year)
- Economic impact ($million/annually) (most recent year available).

Health and Safety

- Identified in evacuation plans
- Component of a disaster relief and recovery plan
- Component of national defense system

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- Provides support to health facilities
- Provides support to offshore facilities
- The report concluded that 2 of 17 facilities were critical airport network assets, based on these criteria.

Adapting to Rising Tides: Community Based Adaptation Planning, **Preprint, NOAA, Coastal Services Center, Charleston, S.C., 2011.**

Adapting to Rising Tides Metrics Evaluation Worksheet, Asset Category: Airport, **Preprint, NOAA, Coastal Services Center, Charleston, S.C., 2011.**

This report, *Adapting to Rising Tides: Community Based Adaptation Planning,* is in draft form and will be part of the project record for Adapting to Rising Tides (ART), a community awareness, vulnerability assessment, and risk assessment project jointly sponsored by NOAA and the San Francisco Bay Area Conservation and Development Commission. ART has conducted public workshops at a sub-regional level, wherein stakeholders learn about climate change impacts, identify key assets, agree to a process for determining their vulnerability to climate change, and then actually conduct vulnerability and risk assessments. The goal is to develop strategies for reducing and managing risks to the Bay Area from climate change impacts.

As part of the process for inventorying sub-regional assets of interest, stakeholders were asked to select asset categories, choose metrics to characterize the assets, and use these metrics to assess existing conditions and stressors of assets. Representatives from various sectors have filled out worksheets that seek data on metrics that can describe conditions and characteristics of the asset as they relate to environmental, equity/society, economic, and governance factors and to broad climate change vulnerability components: exposure, sensitivity, and adaptive capacity. The worksheet cross-walks these factors and components with five sets of metrics: physical/ecological, management, public health and safety, community and economic value, and exposure to current stressors. The following metrics were used for airports:

Physical/ecological:

- Number of runways
- Number of ground access roadways into airport
- Age of asset/remaining service life
- Level of use (commercial passenger service, number of passengers/flights)
- Level of use (general aviation, number of passengers/flights)
- Level of use (number of cargo flights)
- Current/historical performance or condition
- Topographic elevation of site; for example, systems and facilities
- Depth to groundwater
- Proximity of site to wetlands, parks, and other protected natural resources.

Management

- Ownership; for example, public or private
- Repair and maintenance schedule and costs
- Replacement or retrofit costs
- Regulations governing design
- Status of existing plans; for example, master plan, improvement plan, etc.
- Current/existing prioritization assessments.

Public health and safety

- Role in emergency management
- Hazardous materials that pose a public health or environmental risk
- Proximity to emergency management centers; for example, police, fire, emergency operation, facilities, etc.

Community and economic value

- Population served, current capacity and demand
- Future capacity and demand
- Serves low-income or disadvantaged community
- Number of jobs dependent upon use
- Serves major economic investment/employment center
- Intermodal Corridor of Significance.

Exposure to current stressors

- Historic exposure, cost, and response to flooding
- Redundancy in the system
- Seismic susceptibility
- Located within current 100-year flood plain
- Historical evidence of past disruptions (damage caused, changes in system operations).

Sources describing specific risks in depth

Pejovic, T., V.A. Williams, R.B. Noland, and R. Toumi, "Factors Affecting the Frequency and Severity of Airport Weather Delays and the Implications of Climate Change for Future Delays," ***Transportation Research Record: Journal of the Transportation Research Board, No. 2139,*** **Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 97–106.**

This paper identifies the role of weather in delays experienced at Heathrow Airport between 2002 and 2006. Weather predictors were identified, and the authors were able to classify the severity of delays correctly in 84% of cases. The results showed that weather events that affect visibility (i.e., fog and snow), as well as thunderstorms, tend to have the largest effect on delays. With confidence in these weather predictors, the authors then applied them to the outputs of the U.K. climate model projections for the Heathrow airport area in 2050s (2041–2070) time horizon. Of the predictors used in modeling delays, only minimum temperature is directly available from climate models. The authors used three other predictors, wind speed, crosswind speed, and head or tailwind speed, adopting some qualitative analysis. They conclude that increases in temperature are likely to decrease delays. It was concluded, using all four predictors, that there was probability of a 7% increase in delays in wintertime at Heathrow Airport for the 2050s time horizon. Inclusion of rain (using London as a proxy for Heathrow) increased delays in winter and decreased them in summer. The authors highlighted the need for better, more precise data for the purposes of this kind of study. They state that a study of delays requires detailed information on specific flight delays rather than daily averages. Another limitation that they note is the availability of weather parameters from climate model outputs, such as fog, snow, visibility, and wind.

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Larsen, P., et al., "Estimating Future Costs for Alaska Public Infrastructure at Risk from Climate Change," ***Global Environmental Change,*** **Vol. 18, 2008, pp. 442–457.**

This article reports on research supported by University of Alaska, including the Institute of Social and Economic Research (ISER), and on the projected cost of the infrastructure at risk from climate change impacts in Alaska, largely thawing permafrost, flooding, and coastal erosion. It concludes that climate change could add from $3.6 to $6.1 billion (more than 10%–20% above normal wear and tear) to future costs for public infrastructure from 2008 to 2030, and from $5.6 billion to $7.6 billion (plus 10%–12%) from 2008 to 2080. Airports are included in the analysis of public infrastructure. Unlike many other states, Alaska owns most airports; more than 250 will need replacing at a cost of $5.6 billion. The investigators acquired climate projections for Alaska, created a database of public infrastructure, and estimated the replacement costs for existing infrastructure. This information would support the use of its model, the ISER Comprehensive Infrastructure Climate Life-cycle Estimator (ICICLE) to value costs. ICICLE assumes climate change will reduce the useful life of infrastructure so that it has to be replaced sooner. Using ICICLE, the replacement costs estimate was calculated with and without climate change, while assuming that planners will adapt structures strategically.

Developing the database involved defining what was critical infrastructure and determining whether records were kept on both the infrastructure and its replacement costs. Often these cost data were not available; therefore, estimates were used based on average insured value and other information. Infrastructure was assigned a location and each location given a set of values associated with the projected climate effects; for example, proximity to the coast and susceptibility to flooding (e.g., "exposed," "protected," "interior," and "prone to flooding"), as well as local permafrost conditions ("frost-susceptible" and "non-frost-susceptible"). Investigators also estimated the useful life of the infrastructure.

Investigators calculated net present value cost of infrastructure at risk owing to climate change as driven by changes in temperature and precipitation. They consider this a True Economic Depreciation approach, which is a representation of how the value of an asset declines over time as it moves toward its retirement from service. The investigators looked at the net present value of infrastructure replacement over time under different conditions. They calculated a base case useful life of the asset; for example, the typical 20 years for a road's life span. Then they determined an "adjusted useful life" based on climate change effects on the infrastructure. The investigators list many sources of degradation that will result in increases in ordinary maintenance (including extraordinary maintenance), complete replacement of the facility at a different site, or alternative responses.

The investigators provide an informative discussion of assumptions they make about the damage infrastructure will experience under climate drivers such as temperature and precipitation. They assume a linear relationship between increased temperature, increased precipitation, and the reduction in useful life. However, they note that social systems respond not to gradual changes but to variability and extreme events. Therefore, they assume that when the temperature and precipitation are both in the 1st and 99th percentile of historical variance, there is an extreme event. In those instances, they accelerate depreciation by 10%. The investigators note that research is needed within the engineering community; they would like to see on the ground case studies that monitor slight changes in the useful life of structures over time. This information would help them establish a more appropriate damage function.

Again, to allow for social system behavior, the investigator then selected a model of adaptation behavior. They chose an event-driven adaptation model that assumes that although adaptation research is being conducted, no action will be taken until there is damage to the structure at some critical threshold. Until that threshold is met, the investigators assume that additional repair money could maintain a reasonable useful life of the asset. They note that a rule of thumb in planning is that once a building loses 20% of its useful life, it becomes more feasible to build than repair; therefore, the threshold used in the ICICLE model was 20%.

The models' outputs provide a base case example, where there is no climate change; a no-adaptation case with climate change; and an event-based adaptation case wherein adaptation actions are taken to reduce the effects of climate change. The investigators determined that in the event-driven case, there are costs for adaptation, but overall the cost was less than the no-adaptation case. They found that adapting airports to climate change, under the warmest climate projection, would cost 85% as much as if there were no adaptation actions taken. In other words, adapting airports to climate change could save an estimated 15%. Overall projected climate change could add 10% to 20% to infrastructure costs by 2030 and 10% to 12% by 2080 under different climate projections and taking design adaptations into account.

The article has a beneficial discussion of terminology. Investigators note that there is a significant amount of literature devoted to formally defining adaptive capacity, resilience, and vulnerability, often in a hypothetical context. The investigators choose the term "infrastructure at risk" to denote the additional costs from projected climate change net of event-based structural adaptation.

The investigators cite many data needs: more complete information on the amount, assumed useful life, age, and average replacement costs of the infrastructure they are studying. They seek information on how changing building conditions affect life-cycle costs for infrastructure. They also seek what they term "plausible adaptation scenarios"; for example, the cost of adaptation options; what option not only ameliorate climate change effects but are also cost-effective.

Challenges of Growth Environmental Update Study: Climate Adaptation Case Studies, **EUROCONTROL, Brussels, Belgium, 2010.**

This case study of possible shifts in tourism (and therefore airline destinations) under climate change provides insight into the potential secondary effects and business risk from climate change impacts. It also outlines a potentially useful methodological framework for determining the impacts of climate on an economic sector, rather than the commonly seen asset-focused approaches. As described in another article in this appendix, there are implications for airport and air traffic management planning.

The location of interest was the Greek island of Crete. Investigators interviewed government officials on strategies and priorities for tourism development and aviation development, and reviewed the likely cost and capacity level of a new airport under various demand scenarios, based on the tourism development. Next, the investigators conducted a Strength, Weakness, Opportunity, and Threat (SWOT) analysis for the new airport. This was followed by a SWOT analysis of aviation development in Greece generally, to identify key parameters regarding aviation and tourism development, evaluate benefits and weaknesses,

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and support strategic planning decisions. Next, they conducted an economic analysis that would help explain how and when climate change impacts would impact the demand-side variables supporting tourism development. Finally, they ran a forecast study of passenger traffic estimations (demand) for the years 2020, 2030, 2050, and 2080. To do so they identified a measure that would explain future changes in tourism behavior, northern European tourist thermal discomfort, and examined likely changes in this measure over time. The study found that in 30 to 50 years thermal discomfort may drive tourists to cooler locations or cause them to shift their visits to cooler months.

Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," In *Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation,* C.B. Field, et al., Eds., Cambridge University Press, Cambridge, U.K. and New York, N.Y., 2011.

This report summarizes key findings from the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (*SREX*). The SREX report assesses the interaction of climatic, environmental, and human factors that can lead to impacts and disasters, options for managing the risks posed by impacts and disasters, and the important role that non-climatic factors play in determining impacts.

The impacts of climate extremes and the potential for disasters result from both the climate extremes themselves and from the exposure and vulnerability of human and natural systems. Past experience with climate extremes contributes to the understanding of effective disaster risk management and the corresponding adaptation approaches to manage these risks, and the severity of the impacts of climate extremes depends strongly on the level of exposure and vulnerability to these extremes. Trends in exposure and vulnerability are major drivers of changes in disaster risk. Attention to the temporal and spatial dynamics of exposure and vulnerability is particularly important given that the design and implementation of adaptation and disaster risk management strategies and policies can reduce risk in the short term, but may increase vulnerability in the longer term.

Future changes in exposure, vulnerability, and climate extremes resulting from natural climate variability, anthropogenic climate change, and socioeconomic development can alter the impacts of climate extremes on natural and human systems, and may change the potential for disasters. Confidence in projecting these changes will depend on many factors, including the type of extreme, the region and season, the amount of data, and the level of understanding of the underlying processes. There is a range of approaches for adaptation to climate change and disaster risk management, and effectively applying and combining these approaches may benefit from considering the broader challenge of sustainable development. Measures that provide benefits under current climate and a range of future climate change scenarios have the potential to offer benefits now and lay the foundation for addressing projected changes.

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APPENDIX D

Survey Respondents and Survey Method

SURVEY RESPONDENTS

Recipient	Completed
Ted Stevens International Airport, Anchorage, AK	x
Fairbanks International Airport	x
Logan International Airport, Boston, MA	x
Dallas Love Field Airport, Dallas, TX	x
Hartsfield–Jackson Atlanta International Airport, Atlanta, GA	x
Jacksonville International Airport, Jacksonville, FL	x
San Francisco International Airport	x
Oakland International Airport	x
Dallas/Fort Worth International Airport	x
Port Authority of New York and New Jersey (Newark Liberty International Airport)	x
Greater Toronto Airports Authority (Toronto Pearson International Airport) Toronto, Canada	x
Heathrow Airport, London, U.K.	x
Glasgow Prestwick, Prestwick, U.K.	x
Edinburgh International Airport, Edinburgh, U.K.	x
Birmingham–Shuttlesworth International Airport, Birmingham, U.K.	x
Glasgow Airport, Glasgow, U.K.	x

SURVEY RESPONSE RATE

The TRB Topic Panel received a draft list of potential recipients and a final distribution list was derived from that list. Surveys numbering 20 were distributed via e-mail that provided background on the ACRP program and emphasized the importance of the purpose and importance of this Synthesis Report. The Principal Investigator sent reminders, and follow up e-mails and phone calls were made to those who did not complete the survey within the requested time frame.

A total of 20 entities were contacted; and 16 surveys were completed, each one for a single airport. The target response rate set for the survey was 80%, the response rate specified for ACRP studies. With 16 respondents completing the first set of questions, regarding their experience with airport disruptions from weather, the response rate for this study's survey effort was 80%.

The following table (Table D1) depicts how the group of 16 respondents self-selected their participation in the survey and how many proceeded to the final set of questions, regarding climate change adaptation and resilience.

SURVEY METHOD—GENERAL

A survey instrument was designed, tested, and implemented in order to collect information for this synthesis addressing climate change adaptation and resilience. Its questions were designed to gather data that would provide a sound basis for describing what airports are doing to address the critical yet wide-ranging issue of climate change impacts and risks.

Questions were developed to gather responses that were consistent and comparable. Climate change adaptation and resilience is an emerging area, so in several questions, respondents were provided the opportunity to choose multiple answers as well as provide additional or alternative responses that could better describe their experiences. Open-ended questions were limited in number but utilized where anecdotal information might reveal practices of interest for case examples. The survey was conducted in the summer of 2011.

In the professional judgment of the Topic Panel and Principal Investigator, few U.S. airports have considered climate change adaptation and resilience per se in their planning or other activities. This understanding influenced the survey's design in several ways:

1. The group of airports queried would include non-U.S. airports in locations with more mature policies to address climate change impacts; that is, in Canada and in Europe (primarily the U.K.).
2. The number of survey recipients would be low since it was not anticipated that many airports would have conducted the types of activities on which the survey was seeking details.
3. The first part of the survey would seek answers about current weather impacts on airport infrastructure and operations at airports, to put into better relief the answers to subsequent questions focused explicitly on climate change.
4. The survey sought to ensure a basic competency; that is, respondents answered questions regarding their professional judgment about the airport's corporate response to (1) weather events generally and (2) climate change in particular. As a result, there were threshold questions to answer before the respondent answered additional questions in each of these two areas.

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TABLE D1
SURVEY RESPONDENTS BY COUNTRY AND LEVEL OF PARTICIPATION

Type of Survey Participation	U.S.	Canada	U.K.
Began the survey ($N = 16$)	10	1	5
Continued after Question 2 ($N = 13$) Questions 3–9 asked how the airport handles disruptions related to weather	7	1	5
Continued after Question 10 ($N = 11$) Questions 11–24 related to climate change adaptation and resilience	5	1	5
Completed the entire survey ($N = 11$)	5	1	5

SPECIFIC QUESTIONS IN THE SURVEY

In reviewing survey responses regarding weather disruption, it may be helpful to have the definition provided to the respondents. The terms "weather and weather-related" damage and disruption were defined by a sidebar with the following text:

> *Damage and disruption can be caused either directly by weather, or by changes in the natural environment caused by weather; for example, increased wildland fire. We are interested in examining all disruptions in this survey. The term "weather-related disruptions" captures all kinds of damage and disruption, including those caused directly and indirectly by weather.*
>
> *Examples of weather and changes in the natural environment caused by weather:*
>
> - *Pollution caused by flooding*
> - *Visibility issues caused by increased wildland fire*
> - *Storm*
> - *Hurricanes*
> - *Tornadoes*
> - *Snow*
> - *Heatwaves*
> - *Other, including drought.*

In reviewing Tables 2 and 3 in the report, it is helpful to understand some aspects of the corresponding question in the survey, Question 11.

- Respondents worked from the list of weather and climate variables provided. They were not given space in the survey to add others.
- The year 2010 was selected because it was the most recent full calendar year. The year 2030 was selected because it is a proxy for the broader time frame 2020–2040 for which climate modeling projections suggest a degree of climate change.
- The 20-year difference between 2010 and 2030 is a familiar planning horizon for an airport. In the United States, for example, 20 years is typically the longest forecast conducted by airports in the Master Planning process. It also is the required time frame for the Department of Transportation-required Long Range Transportation Plans, in which states are to consider a multi-modal analysis approach that can involve airports. In short, if airports are required to think long term it is typically 20 years out, not much longer.
- The answers for 2010 and 2030 cannot be compared directly. Information on 2010 is composed of historical facts as reported by each respondent. The responses for 2030 indicated the anticipated increase from that baseline across all respondents.

Since each respondent selected the relevant business area and/or weather or climate variable, one respondent may have selected multiple business areas for the same climate or weather variable.

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APPENDIX E

Survey

AIRPORT CLIMATE ADAPTATION AND RESILIENCE SURVEY

Introduction

The Transportation Research Board is preparing a synthesis on Airport Climate Adaptation and Resilience. This is being done for the Airport Cooperative Research Program (ACRP), an industry-driven, applied research program that develops near-term, practical solutions to problems faced by airport operators. ACRP is administered by TRB and sponsored by the Federal Aviation Administration.

The goal of this TRB study is to identify current plans and practices for managing climate risks at airports and to synthesize them into a single reference for airport directors, their staffs, and other aviation stakeholders responsible for the national aviation system. The final report will be available to responding airports at no charge.

This survey questionnaire is being distributed to people with personal knowledge and experience in managing risks at airports. If you are not the appropriate person at your airport to complete this survey, please forward it to the correct person. If the airport you are associated with has not addressed climate change risks, your response may be short but it will still be very important to this study and its ultimate audience.

Please compete and submit this survey questionnaire by June 24, 2011. If you have any questions, please do not hesitate to contact our principal investigator Chris Baglin, Christine.Baglin@ppc.com, 703-748-7547.

Confidentiality: All answers provided by survey respondents will be treated as confidential and aggregated with other responses in the reporting.

Thank you very much for participating in this survey!

Questionnaire Instructions

To view and print the entire questionnaire, Click on the following link and print using "control p." http://surveygizmolibrary.s3.amazonaws.com/library/64484/Airport_Climate_Adaptation_and_Resilience_Survey.pdf.

To save your partial answers, or to forward a partially completed questionnaire to another party, click on the "Save and Continue Later" link in the upper right hand corner of your screen. A link to the partially completed questionnaire will be e-mailed to you from *SurveyGizmo.* To return to the questionnaire later, open the e-mail from *SurveyGizmo* and click on the link. To invite a colleague to complete part of the survey, simply click on the "Save and Continue" link and enter your colleague's e-mail address. Please note that the questionnaire can be saved and passed around multiple times, but respondents must use the link emailed from *SurveyGizmo.*

To view and print your answers before submitting the survey, click forward to the page following question 28. Print using "control p."

To submit the survey, click on "Submit" on the last page.

Personal Information

Please enter the date (MM/DD/YYYY).*

_____

Please enter your contact information.

First Name*: _____

Last Name*: _____

Title*: _____

Agency/Organization*: _____

IATA code of subject airport*: _____

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Street Address*: _____

Suite: _____

City*: _____

State*: _____

Zip Code*: _____

Country*: _____

E-mail Address*: _____

Phone Number*: _____

Mobile Phone: _____

URL: _____

Section A: Key Questions

1) **Do you think airport disruptions due to weather are becoming more frequent or more intense?***

( ) Yes

( ) No

2) **Is your airport considering ways to address specifically more frequent or intense disruptions from weather?***

If you answer "No" to this question, you will be brought to the end of the survey. You will be able to come back to this question by selecting the "Back" button at the end of the page.

( ) Yes

( ) No

We are interested in knowing the reasons for airport decisions in this area. If your airport is not taking measures to manage more frequent or intense disruptions from weather, why not? Please check all that apply.*

[ ] N/A (The airport is taking measures to manage more frequent or intense disruptions from weather)

[ ] Low awareness of the issues and risks

[ ] It doesn't fit my or anyone else's job description

[ ] Not identified as a priority of the leadership

[ ] No directives at or above the national level (e.g., no FAA directive)

[ ] No directives from other authorities

[ ] No guidance

[ ] Funding not sufficient

[ ] Other reason (please state):

[ ] Don't know

Section B: Weather Disruption

Weather and Weather-Related Disruption

Damage and disruption can be caused either directly by weather, or by changes in the natural environment caused by weather; for example, increased wildland fire. We are interested in examining all disruptions in this survey. The term "weather-related disruptions" captures all kinds of damage and disruption, including those caused directly and indirectly by weather.

Examples of weather and changes in the natural environment caused by weather:

- Flood
- Pollution caused by flooding
- Visibility issues caused by increased wildland fire
- Storm

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- Hurricanes
- Tornadoes
- Snow
- Heatwaves
- Other, including drought.

3) **In 2010, did weather cause PHYSICAL DAMAGE to the following at your airport?***

Please see discussion in the left panel, and check all that apply in the list below.

[ ] Runways
[ ] Taxiways
[ ] Holding aprons
[ ] Lighting, marking, and signing of runways
[ ] Navigational aids
[ ] Visual approach aids
[ ] Commercial passenger terminal facilities
[ ] General aviation facilities
[ ] Cargo facilities
[ ] Aircraft rescue and fire-fighting stations
[ ] Airport administrative areas
[ ] Airport maintenance facilities
[ ] Airline maintenance hangars
[ ] Flight kitchens
[ ] Aircraft fuel storage
[ ] Heating and cooling systems
[ ] FAA facilities
[ ] On-airport access roads
[ ] Circulation and service roads
[ ] Parking and curb space
[ ] Storm water drainage
[ ] Open channel drainage
[ ] Water detention structures, such as dams and levees
[ ] Deicing-related control systems
[ ] Industrial waste disposal systems/pollution control systems
[ ] Water distribution systems
[ ] Sanitary systems
[ ] Gas distribution systems
[ ] Other fuel distribution systems
[ ] Electrical distribution systems
[ ] Landscaping
[ ] Other:
[ ] None

4) **In 2010, did weather lead to any of the following DISRUPTIONS in airport operations at your airport? Please check all that apply.***

[ ] Scheduling disruption
[ ] Cut-off access to airport (passengers, suppliers, staff)
[ ] Closure of runway/taxi-way
[ ] Pollution control and spill events
[ ] Internal building flooding
[ ] Loss of services

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[ ] Disease epidemic/pandemic
[ ] Loss of water/energy/information and telecommunications technology supply
[ ] Structural integrity/maintenance of runway and other assets
[ ] Rolling black-outs
[ ] Partial airport evacuation/closure
[ ] Other:
[ ] None
[ ] Cannot answer question

5) In 2010, did weather-related disruptions cause any of the following effects at your airport? Please check all that apply.*

[ ] Security issues associated with partial closure/evacuation
[ ] Increased costs or lost revenue
[ ] Re-allocation of funding and human resources
[ ] Increased coordination with local and regional stakeholders
[ ] Coordination with airport service providers
[ ] Regulatory violation
[ ] Emergency response procedure
[ ] Construction project delays
[ ] Injury or harm to health or safety of staff or passengers (indirectly caused by weather)
[ ] Other:
[ ] None
[ ] Cannot answer question

6) Do you believe the airport can manage current weather variability adequately?*

( ) Yes
( ) No

7) Does the airport use any of the following resources to prevent, reduce, or otherwise address threats from weather? Please check all that apply.*

[ ] Federal grants in aid (U.S.)
[ ] State grants in aid (U.S.)
[ ] Private financing
[ ] Third party development
[ ] Passenger facility charge
[ ] Customer facility charge
[ ] General obligation bonds
[ ] Revenue bonds
[ ] Special facility revenue bonds
[ ] Industrial development bonds
[ ] Local funds
[ ] Line item in budget
[ ] FAA/AIP (U.S.)
[ ] FAA Special Grants (U.S.)
[ ] Voluntary Airport Low Emissions program (U.S.)
[ ] Support from the Airport Sustainability and Sustainable Master Plan program (U.S.)
[ ] State/DOT (U.S.)
[ ] None
[ ] Other:

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Please state the other resources used:*

8) **Please indicate the groups of external partners or stakeholders with which you are working to strategically address weather disruptions and related impacts. Please check all that apply.***

[ ] Airport to Airport Mutual Aid Programs (such as the Airport Disaster Operations Groups)

[ ] Regional community emergency plans

[ ] Regional planning authority

[ ] Municipal/state/provincial planning groups, other than a regional planning authority

[ ] Local fire department

[ ] Air rescue and firefighting, other than local fire department

[ ] Other state or provincial agencies

[ ] Other local government

[ ] Federal or national government

[ ] Consultants

[ ] Suppliers

[ ] Reliever airports

[ ] Airlines/carriers

[ ] Businesses

[ ] Other (please state):

[ ] None

9) **Does the airport keep records of increased or extraordinary maintenance caused by weather events?***

( ) Yes

( ) No

( ) I don't know

Section C: Climate Awareness

10) **Are you familiar with the way the climate is projected to change in your airport's region?***

If you answer "No" to this question, you will be brought to the end of the survey. You will be able to come back to this question by selecting the "Back" button at the end of the page.

( ) Yes

( ) No

Section D: Climate Change

11) **Based on your personal knowledge and/or judgment, please indicate**

A. if in 2010 your airport experienced a "major disruption" from weather (or events in the natural environment caused by weather) affecting the following: an airport airside operations area (AOA), landside operating area, intermodal transport system, and/or the local area/region in which the airport is located.

and

B. if you expect that by 2030, your airport will experience more frequent/more damaging "major disruptions" in these areas.

Regarding A, if you have answers in the affirmative, please place a check in all relevant boxes associated with such event, for 2010.

Regarding B, please place a check in the column for 2030 if you expect to see an INCREASE in the disruption described.

A "major disruption" means one that is unexpected or unusually large based on the historical record.

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	Airside 2010	Airside 2030	Landside 2010	Landside 2030	Intermodal Transport System 2010	Intermodal Transport System 2030	Local and Regional Area 2010	Local and Regional Area 2010	N/A
Tornado									
Hurricane									
High-intensity storm									
Ligthning									
Fog/poor visibility									
High winds									
Variable wind direction									
Inundation from sea level rise									
Storm surge									
River flood									
Flash flood									
Increased wave action in flooding									
Changes in the precipitation mix									
Snow (no drifting)									
Snow (with drifting)									
Ice (surfaces)									
Ice (loading)									
Heat wave									
Drought									
Dust storm									
Wild fire (encroachment)									
Wild fire (visibility issues)									
Increase in noxious species									

12) Have you noticed any gradual change in weather patterns in recent years that affect airport operations?*

( ) Yes

( ) No

Please expand on your response (optional):

13) On a scale of 1 to 5, with 0 being Not Concerned and 5 being Extremely Concerned, are you concerned about the impacts that climate change could have on the airport's operation?*

( ) 0—Cannot answer question

( ) 1—Not concerned

( ) 2—Somewhat concerned

( ) 3—Concerned

( ) 4—Very concerned

( ) 5—Extremely concerned

14) On a scale of 1 to 5, with 0 being Unsatisfied and 5 being Fully Satisfied, are you satisfied with the climate science information your airport has available to use in future planning?*

( ) 0—Cannot answer question

( ) 1—Unsatisfied

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( ) 2—Somewhat satisfied

( ) 3—Usually satisfied

( ) 4—Satisfied

( ) 5—Fully satisfied

( ) Don't know

If you are not fully satisfied with current information (for example, score other than 5 in the question above), what additional information or services related to climate change would you find helpful for future planning? If you are unable to answer the question please state "cannot answer."*

15) The following are potential risks from the impacts of future climate change identified at a major airport. Based on personal knowledge, please indicate the risk(s) that your airport has addressed in planning:*

[ ] Risk of physical damage, including damage from increased flooding, subsidence, and/or heat.

[ ] Risk associated with future climate change effects in the performance of infrastructure over time, caused by incremental or short-term fluctuations in climate.

[ ] Disruptions to air traffic due to increases in extreme weather or events in the natural environment caused by climate changes.

[ ] Risk to sustained water supplies, including risks to water supply infrastructure at the airport site.

[ ] Risk to the grid and energy supply infrastructure, plus risks to back-up systems.

[ ] Risk to infrastructure supporting information and telecommunications technology, including radar infrastructure.

[ ] Construction schedule risk due to increased disruptions from weather or other events in the natural environment caused by climate changes.

[ ] Passenger access risk, including transportation disruptions to road, rail, and underground networks and stations.

[ ] Risk to the efficiency or success of airport security operations from increased disruptions from weather or other events in the natural environment caused by climate changes.

[ ] Risk to terminal buildings that would affect passenger comfort, health and safety or passenger-focused commercial operations.

[ ] Pollution control problems arising from increased flooding or other climate impacts.

[ ] Risk to the health and safety of airport employees and the direct employees of suppliers on site (where there may be reputational impacts for airport owner), such as heat illness.

[ ] Risk to the provision of services by contractors, sub-contractors, partners, or service providers critical to airport operations.

[ ] Risk to the airport's operation from the follow on effects of climate impacts at other U.S. and international airports (e.g., schedule problems, etc.).

[ ] Risk to the medium and/or long-term financial factors that are of interest to insurers or investors, including those related to the potential acquisition or sale of assets or sites (e.g., a potential lower sale price for "high-risk" assets, higher insurance premiums, etc.).

[ ] Disruption to the airport's operations arising from the increased allocation of resources away from normal operations to activities required for the airport's role in emergency response or logistics planning exercises.

[ ] Risk to funding opportunities, given the uncertainty over future conditions that may affect the need for or the feasibility of a project.

[ ] Negative impacts on the region caused by disruption at the airport.

[ ] Other:

[ ] N/A

16) To your knowledge, does your airport conduct planning for climate risk(s), such as those risks described in the question above?*

( ) Yes

( ) No

Please describe any actual projects that respond to the risk(s). State "none" or "don't know" if that is the case.

17) Has the airport integrated analysis of projected climate change impacts and/or related future risks into any of the following?*

[ ] Master plan in development

[ ] Approved master plans

[ ] Capital improvement plans

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[ ] Design standards for physical assets

[ ] Supply contracts

[ ] Budget development

[ ] Security planning

[ ] Disaster management and emergency response

[ ] Early warning systems

[ ] Organizational decision making

[ ] N/A, I have personal knowledge that the airport does not integrate current and/or future climate change considerations into guidance and protocols.

[ ] Don't know

[ ] Other (please state):

18) Please indicate the climate change projections or similar resources that your airport is using. State "none" or "don't know" if that is the case.*

19) Please indicate which of the following tools or resources your airport uses when considering climate change in planning and/or airport operations. Please check all that apply.*

[ ] Climate education or training

[ ] Climate impact and/or vulnerability assessment

[ ] Scenario planning

[ ] Airport Enterprise Risk Management process

[ ] Airport authority risk processes

[ ] Municipal risk managers and processes

[ ] Full inventory of infrastructure/assets, including quality assessment

[ ] None

[ ] Other (please state):

20) Do you feel emergency planning processes are a satisfactory method for addressing future climate change risks?*

( ) Yes

( ) No

21) Do you feel irregular operations planning processes are a satisfactory method for addressing future climate change risks?*

( ) Yes

( ) No

22) If your airport is conducting planning for future climate change risks, what triggered consideration of climate change? Please check all that apply.*

[ ] Required climate change analysis or reporting in a federal/national, state, local, or other governmental program. Please specify (optional):

[ ] Weather events and/or disruptions

[ ] Employee professional judgment

[ ] Awareness raised by efforts on climate change mitigation (e.g., carbon emissions reduction)

[ ] Insurance requirements

[ ] Bonding requirements

[ ] Master plan forecasts

[ ] Master plan work, not including forecasts

[ ] Issues emerging from emergency response plans

[ ] N/A

[ ] Other:

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23) Which of the following expenditure categories do you think future climate change risks should be addressed through?*

( ) Capital expenditures

( ) Operational expenditures

( ) Both

( ) Neither

24) If your airport has activities underway that are relevant to the subject of this survey, would you like to provide more information at this time?*

( ) Yes

( ) No

Please list the activities relevant to the subject of this survey*

In follow-up to this survey, are you willing to have yourself or a relevant person at your airport take part in a 15–20 minute phone interview?*

( ) Yes

( ) No

25) Are you willing to provide information that might be used as a case example for the report? (Information will remain anonymous unless written consent is provided.)*

( ) Yes

( ) No

26) Do you know of other airports and/or individuals at airports reviewing climate change impacts, uncertainties, or adaptation options?*

( ) Yes

( ) No

If yes, please provide names and contact details, if appropriate.

Please include name, position, e-mail address, and telephone number if possible.

27) Please indicate whether you would like a link to the report when published.*

( ) Yes

( ) No

If yes, please provide your preferred e-mail address:*

_____

Response Review

Survey Answers

Thank you for your assistance through your completion of this survey. Your responses will help provide valuable insights into current climate change adaptation at airports. If you have any questions regarding the survey, please contact Chris Baglin, Christine.Baglin@ppc.com, 703.748.7547. You also can mail any documentation that you might feel will be helpful to this study to the following address:

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APPENDIX F
Survey Results

Percentages for questions 1 & 2 are based on 16 respondents

Q1 Do you think airport disruptions due to weather are becoming more frequent or more intense?

Yes	12	75%
No	4	24%

Q2 Is your airport considering ways to address specifically more frequent or intense disruptions from weather?

Yes	13	81%
No	3	19%
N/A:	0	0%
Low awareness of the issues and risks:	1	6%
It doesn't fit my or anyone else's job description:	1	6%
Not identified as a priority of the leadership:	1	6%
No directives at or above the national level (e.g., no FAA directive):	1	6%
No directives from other authorities:	0	0%
No guidance:	0	0%
Funding not sufficient:	1	6%
Don't know:	0	0%
Other reason (please state):	2	13%

Don't believe weather is becoming more intense (sic)

Percentages for questions 3–10 are based on 13 respondents

Q3 In 2010, did weather cause PHYSICAL DAMAGE to the following at your airport?

Runways:	4	31%
Taxiways:	5	38%
Holding aprons:	3	23%
Lighting, marking, and signing of runways:	4	31%
Navigational aids:	0	0%
Visual approach aids:	1	8%
Commercial passenger terminal facilities:	4	31%
General aviation facilities:	2	15%
Cargo facilities:	1	8%
Aircraft rescue and fire-fighting stations:	1	8%
Airport administrative areas:	2	15%
Airport maintenance facilities:	1	8%
Airline maintenance hangars:	0	0%
Flight kitchens:	0	0%
Aircraft fuel storage:	0	0%
Heating and cooling systems:	2	15%
FAA facilities:	0	0%

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On-airport access roads:	4	31%
Circulation and service roads:	4	31%
Parking and curb space:	2	15%
Storm water drainage:	5	38%
Open channel drainage:	2	15%
Water detention structures, such as dams and levees:	0	0%
Deicing-related control systems:	1	8%
Industrial waste disposal systems/pollution control systems:	0	0%
Water distribution systems:	1	8%
Sanitary systems:	0	0%
Gas distribution systems:	0	0%
Other fuel distribution systems:	0	0%
Electrical distribution systems:	1	8%
Landscaping:	3	23%
Other:	0	0%
None/don't know:	2	15%

Q4 In 2010, did weather lead to any of the following DISRUPTIONS in airport operations at your airport?

Scheduling disruption:	11	85%
Cut-off access to airport (passengers, suppliers, staff):	2	15%
Closure of runway/taxi-way:	9	69%
Pollution control and spill events:	3	23%
Internal building flooding:	2	15%
Loss of services:	3	23%
Disease epidemic/pandemic:	0	0%
Loss of water/energy/information and telecommunications technology supply:	3	23%
Structural integrity/maintenance of runway and other assets:	0	0%
Rolling black-outs:	0	0%
Partial airport evacuation/closure:	2	15%
None:	0	0%
Cannot answer question:	0	0%
None:	0	0%
Other:	1	8%

IT outage

Q5 In 2010, did weather-related disruptions cause any of the following effects at your airport?

Security issues associated with partial closure/evacuation:	0	0%
Increased costs/lost revenue:	9	69%
Re-allocation of funding and human resources:	7	54%
Increased coordination with local and regional stakeholders:	3	23%
Coordination with airport service providers:	5	38%
Regulatory violation:	0	0%
Emergency response procedure:	4	31%
Construction project delays:	6	46%
Injury or harm to health or safety of staff or passengers (indirectly caused by weather):	2	15%
Other:	1	8%

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None:	0	0%
Cannot answer question:	1	8%

additional snow clearance personnel drafted in to clear runways etc.

Q6 Do you believe the airport can manage current weather variability adequately?

Yes	12	92%
No	1	8%

Q7 Does the airport use any of the following resources to prevent, reduce, or otherwise address threats from weather?

Federal grants in aid (U.S.):	2	15%
State grants in aid (U.S.):	2	15%
Private financing:	1	8%
Third party development:	0	0%
Passenger facility charge:	3	23%
Customer facility charge:	1	8%
General obligation bonds:	2	15%
Revenue bonds:	2	15%
Special facility revenue bonds:	0	0%
Industrial development bonds:	0	0%
Local funds:	5	38%
Line item in budget:	3	23%
FAA/AIP (U.S.):	3	23%
FAA Special Grants (U.S.):	1	8%
Voluntary Airport Low Emissions program (U.S.):	1	8%
Support from the Airport Sustainability and Sustainable Master Plan program (U.S.):	0	0%
State/DOT (U.S.):	1	8%
None:	5	38%
Other:	0	0%

Q8 Please indicate the groups of external partners or stakeholders with which you are working to strategically address weather disruptions and related impacts.

Airport to Airport Mutual Aid Programs:	1	8%
Regional community emergency plans:	5	38%
Regional planning authority:	5	38%
Municipal/state/provincial planning groups:	3	23%
Local fire department:	5	38%
Air rescue and firefighting, other than local fire department:	1	8%
Other state or provincial agencies:	2	15%
Other local government:	5	38%
Federal or national government:	2	15%
Consultants:	2	15%
Suppliers:	2	15%
Reliever airports:	1	8%
Airlines/carriers:	8	62%
Businesses:	3	23%
Other (please state):	1	8%

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	None:	2	15%

Local Conservation Authority TRCA

Q9 Does the airport keep records of increased or extraordinary maintenance caused by weather events?

Yes	3	23%
No	3	23%
Don't know	7	54%

Q10 Are you familiar with the way the climate is projected to change in your airport's region?

Yes	11	85%
No	2	15%

Percentages for questions 11–23 are based on 11 respondents Q11

Q12 Have you noticed any gradual change in weather patterns in recent years that affect airport operations?

Yes	6	55%
No	5	45%

Larger seasonal temperature swings

More rain and wind

A wet spring in 2011 had a significant impact in our ability to complete our construction package. May 2011 precipitation was 140.2 mm vs. 30-year average of 86.6 mm

Lack of precipitation affects landscaping and cost of potable water

Major snow and ice events in three (3) of the last four (4) years

Increase in snow disruption due to severe cold snaps

Q13 On a scale of 1 to 5, with 0 being Not Concerned and 5 being Extremely Concerned, are you concerned about the impacts that climate change could have on the airport's operation?

0—Cannot answer question	1
1	0
2—Somewhat concerned	3
3—Concerned	6
4—Very concerned	2
5	0

Q14 On a scale of 1 to 5, with 0 being Unsatisfied and 5 being Fully Satisfied, are you satisfied with the climate science information your airport has available to use in future planning?

0—Cannot answer question	1
1—Unsatisfied	2
2—Somewhat satisfied	4
3—Usually satisfied	3
4—Satisfied	1
5—Fully satisfied	1

Much of the information seems to be driven by politics as much as science.

Sea level rise projections and forecasts vary from an expert, which makes planning for adaptation difficult.

Changing nature of winter storms (from snow to mixed precipitation) impacts on Low vis events (fog), changing wind direction (runway orientation and operational impact).

Future wind direction modeling

More robust modeling on changes to prevailing wind direction

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An annual report summarizing recent research and explaining in plain terms the meaning of the findings.

(1) Forecasted climate change for the region, (2) preparation by other regions of similar climate and forecasted climate change, and (3) preparation by other large hub airports.

We would benefit from greater scientific consensus regarding rate of sea level rise.

The high uncertainty surrounding the future prediction of the effects on the business make it hard to convey at times in terms of action and potential investment/capital expenditure.

Q15 The following are potential risks from the impacts of future climate change identified at a major airport. Based on personal knowledge, please indicate the risk(s) that your airport has addressed in planning.

Risk of physical damage, including damage from increased flooding, subsidence, and/or heat:	8	73%
Risk associated with future climate change effects in the performance of infrastructure over time, caused by incremental or short-term fluctuations in climate:	7	64%
Disruptions to air traffic due to increases in extreme weather or events in the natural environment caused by climate changes:	7	64%
Risk to sustained water supplies, including risks to water supply infrastructure at the airport site:	2	18%
Risk to the grid and energy supply infrastructure, plus risks to back-up systems:	3	27%
Risk to infrastructure supporting information and telecommunications technology, including radar infrastructure:	5	45%
Construction schedule risk due to increased disruptions from weather or other events in the natural environment caused by climate changes:	2	18%
Passenger access risk, including transportation disruptions to road, rail, and underground networks and stations:	5	45%
Risk to the efficiency or success of airport security operations from increased disruptions from weather or other events in the natural environment caused by climate changes:	3	27%
Risk to terminal buildings that would affect passenger comfort, health, and safety or passenger-focused commercial operations:	5	45%
Pollution control problems arising from increased flooding or other climate impacts:	3	27%
Risk to the health and safety of airport employees and the direct employees of suppliers on site (where there may be reputational impacts for airport owner), such as heat illness:	5	45%
Risk to the provision of services by contractors, sub-contractors, partners, or service providers critical to airport operations:	2	18%
Risk to the airport's operation from the follow on effects of climate impacts at other US and international airports (e.g., schedule problems, etc.):	5	45%
Risk to the medium and/or long-term financial factors that are of interest to insurers or investors, including those related to the potential acquisition or sale of assets or sites (e.g., a potential lower sale price for "high-risk" assets, higher insurance premiums, etc.):	5	45%
Disruption to the airport's operations arising from the increased allocation of resources away from normal operations to activities required for the airport's role in emergency response or logistics planning exercises:	4	36%
Risk to funding opportunities, given the uncertainty over future conditions that may affect the need for or the feasibility of a project:	3	27%
Negative impacts on the region caused by disruption at the airport	3	27%
N/A:	0	0%
Other:	1	9%

Risk of airfield inundation from sea level rise

Q16 To your knowledge, does your airport conduct planning for climate risk(s), such as those risks described in the question above?

Yes	7	64%
No	4	36%

Stormwater drain study

Plan for flood risk, increased wind

Previous flooding study looked at localized flooding on the airport due to infrastructure.

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We have completed a climate adaptation risk analysis.

Improvements to perimeter dike to protect against flooding; improvements to stormwater management system airport-wide.

Airfield draining project runway extension project and river culverting Climate Change Adaptation report.

Q17 Has the airport integrated analysis of projected climate change impacts and/or related future risks into any of the following?

Master plan in development:	4	36%
Approved master plans:	0	0%
Capital improvement plans:	4	36%
Design standards for physical assets:	7	64%
Supply contracts:	0	0%
Budget development:	0	0%
Security planning:	0	0%
Disaster management and emergency response:	3	27%
Early warning systems:	0	0%
Organizational decision making:	3	27%
N/A, I have personal knowledge that the airport does not integrate current and/or future climate change considerations into guidance and protocols:	3	27%
Don't know:	0	0%
Other (please state):	2	18%

Design standards for perimeter dike

We are in process of integrating

Q18 Please indicate the climate change projections or similar resources that your airport is using. State "none" or "don't know" if that is the case.

Don't know

UKCIP

Don't know

More frequent and severe weather as a result of climate changes and that these changes will include higher temperatures, extreme heat, heavy rainfalls, drought and the introduction of new and invasive species

We use UK climate projections from met office—referred to as UKCIP

UKCP09

None

Don't know

None

Don't know but can find out

UKCP09 climate change model

Q19 Please indicate which of the following tools or resources your airport uses when considering climate change in planning and/or airport operations.

Climate education or training:	4	36%
Climate impact and/or vulnerability assessment:	6	55%
Scenario planning:	2	18%
Airport Enterprise Risk Management process:	1	9%
Airport authority risk processes:	2	18%
Municipal risk managers and processes:	0	0%
Full inventory of infrastructure/assets, including quality assessment:	3	27%

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None:	3	27%
Other (please state):	1	9%

Participating in a subregional pilot project, Adapting to Rising Tides

Q20 Do you feel emergency planning processes are a satisfactory method for addressing future climate change risks?

Yes	6	55%
No	5	45%

Q21 Do you feel irregular operations planning processes are a satisfactory method for addressing future climate change risks?

Yes	4	36%
No	7	64%

Q22 If your airport is conducting planning for future climate change risks, what triggered consideration of climate change?

Required climate change analysis or reporting in a federal/national, state, local or other governmental program:	4	36%

U.K. requirement to report on Climate Change Adaptation

U.K. government requirement

Part of our Local Authority Section 106 Planning Agreement

Weather events and/or disruptions:	6	55%
Employee professional judgment:	5	45%
Awareness raised by efforts on climate change mitigation (e.g., carbon emissions reduction):	7	64%
Insurance requirements:	3	27%
Bonding requirements:	1	9%
Master plan forecasts:	1	9%
Master plan work, not including forecasts:	0	0%
Issues emerging from emergency response plans:	3	27%
N/A:	1	9%
Other:	1	9%

incorporation of sea level rise in vulnerability assessment of perimeter dike (focus is on flood control and seismic improvements)

Q23 Which of the following expenditure categories do you think future climate change risks should be addressed through?

Capex	1	9%
Both	10	91%

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APPENDIX G

Uncertainty, Including Natural Variability

The following review of major categories of uncertainty is taken from "Climate Adaptation: Risk, Uncertainty and Decision Making," a U.K. Climate Impacts Programme Technical Report published in 2003. These types of uncertainty can lead to or worsen existing barriers to addressing climate change impacts. Therefore, the following information may be useful for airport managers or their technical staff to bear in mind in considering climate change adaptation and resilience.

NATURAL VARIABILITY

The first type of uncertainty regards the natural variability of the environment. Weather, for example, entails uncertainty in the timing, duration, spatial location, extent, and other characteristics of weather events such as storms. Other environmental events, such as the timing and magnitude earthquakes, have a natural variability that adds uncertainty to the system in which an adaptation or resilience choice might be made.

DATA UNCERTAINTY

Another type of uncertainty is data uncertainty, which arises from the following:

- Measurement error (random and systematic, such as bias)
- Incomplete or insufficient data (e.g., limited in temporal and spatial resolution)
- Extrapolation (due to uncertain data).

As noted in the report, sound adaptation and resilience decisions require good information, and often the datasets needed do not yet exist.

KNOWLEDGE UNCERTAINTY

This type of uncertainty includes lack of knowledge or data about processes, dependencies, or probabilities of outcomes. It also includes uncertainty about the future. This includes the amount of future greenhouse gas emissions, which models must assume in order to develop climate change projections. Incomplete knowledge, or ignorance, needs to be acknowledged.

MODEL UNCERTAINTY

A model is a representation of a system that can be used to make decisions. Technical models, for example, describe data (statistical models) and assess risks (e.g., risk assessment). Decisions on the choice and structure of the processes represented in the model are instances where uncertainty can be introduced. The values of the model inputs, parameters, and outputs may have uncertainties. Where model outputs carrying some uncertainty are used as inputs into other analyses, such as an impact assessment or downscaling of climate models to a regional level, the uncertainty can propagate. Uncertainties in this area carry an added challenge in that climate models may be less accessible in concept to a decision maker, than, perhaps data on stream flows, for example.

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Abbreviations used without definitions in TRB publications:

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
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
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
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

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