FINAL REPORT

Social and Economic Effects of Severe Winter Storms: New York Case Study

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Abt Associates Inc. Boulder, Colorado



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The National Weather Service (NWS) is a component of the National Oceanic and Atmospheric Administration (NOAA). NOAA is an Operating Unit of the U.S. Department of Commerce.

NWS Mission. Provide weather, water, and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy.

NWS Vision. A Weather-Ready Nation: Society is prepared for and responds to weather-dependent events. **NWS Organization.** The headquarters of the NWS is located in Silver Spring, Maryland, with regional headquarters located in Kansas City, Missouri; Bohemia, New York; Fort Worth, Texas; Salt Lake City, Utah; Anchorage, Alaska; and Honolulu, Hawaii. With some 4,000 plus employees in 122 weather forecast offices, 13 river forecast centers, 9 national centers, and other support offices around the country, NWS provides a national infrastructure to gather and process data worldwide. Each year, NWS collects some 76 billion observations and issues approximately 1.5 million forecasts and 50,000 warnings.

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List of Acronyms and Abbreviations

AWWD Aviation Winter Weather Dashboard

CDC Centers for Disease Control and Prevention

Consolidated Edison Consolidated Edison, Inc.

DEP Department of Environmental Protection

DOT Department of Transportation

DPR Parks Department

DSNY New York Department of Sanitation

EIA U.S. Energy Information
EMS Emergency Medical Services
ERH Eastern Region Headquarters
EST Eastern Standard Time

FAA Federal Aviation Administration FDNY Fire Department of New York

FEMA Federal Emergency Management Agency

GDS global distribution fees

HVRI Hazards Vulnerability Research Institute

IDSS impact-based decision support services

Kennedy John F. Kennedy International

LCC low-cost carriers

LEPC Local Emergency Planning Committee

LIRR Long Island Rail Road

MTA Metropolitan Transportation Authority

NDFD National Digital Forecast Database

NESIS Northeast Snowfall Impact Scale

Newark Newark Liberty International

NOAA National Oceanic and Atmospheric Administration

NOM National Operations Manager NWS National Weather Service

NWSI National Weather Service Instruction

NYC New York City

NYC DOT NYC Department of Transportation NYCEM New York City Emergency Management

NYPD New York Policy Department

NYSDOT New York State Department of Transportation

PANYNJ Port Authority of New York & New Jersey
PATH Port Authority Trans-Hudson Corporation

PCS Property Claim Services

PSEG Public Service Electric and Gas Company

SVI Social Vulnerability Index
TMI Traffic Management Initiative

ULCC ultra-low-cost carriers

VTTS Value of Travel Time Savings

WFO Weather Forecast Office

1. Introduction

Recently, the National Weather Service (NWS) increased its focus on providing decision support services to the emergency management community and core partners¹ to help them understand its forecasts and take appropriate actions in the face of upcoming extreme events. In 2011, the Weather-Ready Nation Strategic Plan began to formalize the NWS approach to impact-based decision support services (IDSS; NWS, 2011). NWS defines IDSS as the "provision of relevant information and interpretive services to enable core partners' decisions when weather, water, or climate has a direct impact on the protection of lives and livelihoods" (NWS, 2013b, p. 5). NWS recognizes IDSS as a primary service and is working to fully and more effectively provide this service to federal, state, local, and tribal decision-makers. To do so, it is important that NWS understands how users are benefitting from existing IDSS and how they could benefit from improved IDSS.

This study analyzes four severe winter storms affecting the New York City (NYC) area² in 2010, 2013, 2015, and 2016 to evaluate the resulting economic and health effects, and to assess the degree to which forecasts, warnings, and IDSS can reduce economic losses and other impacts. This report describes the systematic data collection effort and expert elicitation used for the study (Section 2). We briefly evaluate how severe winter storms affect vulnerable populations (Section 3). We then provide an overview of four severe winter storms in the NYC area, including forecasted and observed snowfall, a brief overview of storm impacts, and the NWS decision support services provided for each storm event (Section 4). We compare the December 2010 and January 2016 winter storms to understand the role of IDSS in reducing socioeconomic impacts to three sectors: aviation, ground transportation, and energy (Section 5). Lastly, we provide findings from our study, including the extent to which IDSS may reduce economic losses and the critical attributes of IDSS, and offer recommendations about the dissemination of NWS information and data and ways to further evaluate the impact of winter storms and the value of IDSS (Section 6).

^{1.} NWS "core partner" is defined as government and nongovernment entities directly involved in the preparation, dissemination, and discussions involving hazardous weather or other emergency information put out by the NWS, and may include members of the emergency management community, government partners, and member of the electronic media. For more information, see Appendix A of the National Weather Service Instruction 1-1003.

^{2.} For the purposes of this report, the NYC area refers to the five NYC counties that are part of NYC's five boroughs [New York County (Manhattan), Bronx County (The Bronx), Kings County (Brooklyn), Queens County (Queens), and Richmond County (Staten Island)]; two Long Island counties (Nassau County and Suffolk County); and one northeastern New Jersey county (Essex County).

2. Approach

This study analyzes four severe winter storms affecting the NYC area to evaluate the resulting economic and health effects, and to assess the degree to which these impacts were mitigated by forecasts, warnings, and IDSS. In addition to the economic impacts, we wanted to evaluate how storms affect vulnerable populations; however, these data are limited and the best we could do is provide a high-level analysis overlaying snowfall data with vulnerable population data to provide a high-level indication of potential impacts on vulnerable populations.

2.1 Social and economic impacts of severe winter storms

No standard loss estimation models or methodologies exist to quantify the economic impact of severe winter storms. In most cases, potential losses from winter storms are indirect and difficult to quantify. To understand the extent of the social and economic impacts of these four severe winter storms, we first conducted a systematic literature review and data collection effort. We focused on capturing and synthesizing information on the social and economic impacts of severe winter weather in three sectors: aviation, ground transportation, and energy. We gathered data and information on the storm events from the NWS, damage assessments produced by other federal or state agencies, and media reports. We collected economic data from federal, state, and local sources; and from peer-reviewed as well as unpublished literature. We conducted informal interviews with two groups of experts. First, we interviewed NWS and National Oceanic and Atmospheric Administration (NOAA) staff to gather information about these four winter storm events, and the types of NWS products and services that were provided to the public and partners to prepare the region for these storms. Second, we interviewed federal, local, and other sector experts to understand protocols for responding to severe winter weather, the types of economic and social impacts associated with severe winter storms, and available data (Table 1).

Table 1. Agencies and organizations interviewed about the impacts of severe winter storms.

Agency/organization categories	Agencies and organizations interviewed (and dates)		
	• Eastern Region (October 25, 2016; November 3, 2016; June 26, 2017)		
	Performance and Evaluation Branch (October 12, 2016)		
NWS	 Science and Technology Services Division (December 2, 2016) 		
	• Integrated Dissemination Program, Geographic Information Systems (December 2, 2016)		
	Objective Lead for Evolve (June 22, 2017)		
NOAA	National Climatic Data Center (January 31, 2017; February 7, 2017)		
E	New York Governor's Office of Storm Recovery (December 2, 2016)		
Emergency	 New York City Economic Development Corporation (December 15, 2016) 		
management	 New York City Emergency Management (December 15 and December 28, 2016) 		
Human health	Federal Emergency Management Agency (February 6, 2016)		
Aviation	• Federal Aviation Administration (March 13, 2017)		
Aviation	• The MITRE Corporation (March 13, 2017)		
Ground transportation	Federal Highway Administration (December 8, 2016)		
Energy	 Office of Infrastructure Security and Energy Restoration, Department of Energy (via email April 18, 2017) 		

We organized our findings into five broad but interrelated impact categories: defensive investments, mitigating actions, asset damages, service interruptions, and human health (Figure 1). Defensive investments are expenditures made in advance of any particular winter weather event that help protect against the potential impacts of an event.⁴ Mitigating actions cover real-time decisions made by system operators to reduce the consequences of an event that is anticipated or underway. Mitigating actions introduce costs but may reduce the impacts of storms. Asset damages refer to any physical

2

^{3.} We focused the analysis on aviation, ground transportation, and energy because we conjectured that IDSS could affect operational decisions made under different weather events for each sector. We were not sure that other sectoral experts – for example, businesses or the Chamber of Commerce – could provide detailed information about their operations decisions – such as closing businesses – under different weather events, and how NWS products and services improved or could improve their decision-making.

^{4.} Given the limited number of events and the short time between storm events, we do not consider the social and economic effect of defensive investments on the outcomes of our storm events, but, where applicable, we do describe defensive investments made between storm events in our sectors.

damage that may result from winter weather events; damage can occur suddenly ("acute") or it can occur slowly over time ("chronic"). Service interruptions address impacts seen by end users, such as changes in provision, quality, or pricing of a service. Finally, the human health category covers any direct potential hazard to human well-being or life from severe winter storms.⁵

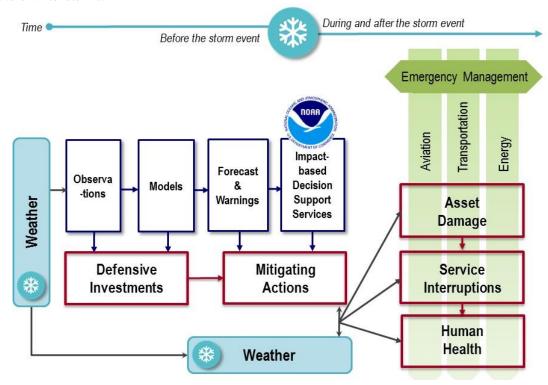


Figure 1. The range of potential economic and societal impacts of severe winter weather to different sectors can be organized into five different but interrelated categories (red boxes). A range of products and services offered by NWS are valuable at different points in time and have the potential to reduce specific types of impacts.

In Figure 1, weather is shown as "pre-event" conditions (far left of figure) that are observed and modeled, leading to forecasts and warnings of impending winter storm events. At the bottom of the figure, weather is shown again as the actualization of the event. The actual weather outcome occurs within the context of the defensive investments and mitigating actions leading to the social and economic outcomes. As shown in Figure 1, the "traditional" weather forecasting system entails only the first three boxes of observations, models, and forecasts and warnings. Prior to the implementation of IDSS, this would have fed into mitigating actions directly. With the implementation of IDSS, the improvement in the dissemination and communication of forecasts and warnings is designed to improve mitigating actions and stakeholder decision-making. The interaction of defensive investments and mitigating actions with the actualization of the weather event leads to social and economic impacts with potential asset damages, service interruptions, and human health impacts in all sectors. Which impacts occur in each sector is highly dependent on the structure of the sector and the decision processes. For instance, we expect a larger portion of the impacts in aviation to be in service interruptions than in human health impacts, whereas in road transportation there may be a significant component of human health impacts if severe weather leads to more traffic accidents. Emergency management cuts across all sectors as an intermediary in communicating and implementing public responses to severe weather events. These actions will impact the specific economic sectors and potentially have direct impacts on social and economic outcomes such as potential injuries or loss of life.

^{5.} The human health category does not include effects that would result from other impact areas, such as effects to human health from extended power outages, for the purposes of our analysis and discussion.

Our assessment and quantification of storm impacts varied by sector; Appendix B describes our methodology for each sector. In our economic analysis, we do not distinguish between reactive costs and proactive costs, although we note where we believe impacts are reactive versus proactive.

2.2 Extent to which IDSS reduces social and economic impacts

IDSS are the weather forecast advice and interpretive services provided by NWS to help core partners – such as emergency managers – make decisions that protect lives and livelihoods (NWS, 2013b). NWS staff ensure partners have accurate and consistent weather information through the use of science and technology, as well as building deep relationships with key decision-makers (NWS, Undated). NWS field offices identify core partners for IDSS as well as deep relationship core partners (NWS, Undated). Deep relationship partners are core partners who, relative to others, more strongly exhibit characteristics of the following four comparative assessment criteria:

- 1. There is a legal mandate to support the core partner (e.g., Executive Order, statute) or support is a matter of national security;
- 2. Exercises a large degree of authority or influence on public safety or management of the nation's water resources for the public good;
- 3. Serves a population or entity particularly vulnerable to impacts of weather, water, or climate hazards;
- 4. Acts as a force multiplier to help amplify NWS messages to other partners.

IDSS services include general and specialized briefings, trainings and exercises, and onsite support; decision support services are more specialized and more frequent for core partners and deep relationship core partners (Table 2).

Table 2. NWS partner service levels and examples of services.

General partner/public services	Core partner services	Deep relationship core partner services
Routine production [e.g., National Digital Forecast Database (NDFD), model output, forecasts, watches, warnings, advisories, streamflow forecasts, probability forecasts, inundation maps] Website Social media NWS dissemination services Outreach, preparedness education.	General partner services and added focus on episodic IDSS, such as: NWS initiated calls Webinars, briefings, and email alerts NWSChat and InteractiveNWS Spot forecasts, plume modeling, specialized inflow/streamflow forecasts, contingency forecasts, ice analysis Annual talks, trainings, and exercises Specialized briefings, emails, and graphics for episodic support Occasional onsite deployment.	Core services, plus added focus on recurring IDSS, such as: Onsite deployments; embedding specialized recurring forecasts/briefings/graphics Multiple pre-event/scenario planning; water resources planning yearly exercises (e.g., table top) Recovery activities After-action event reviews Local Emergency Planning Committee exercises/briefings Collaboration on gauge and observation network placement Access to hydrologic model results.

Note: not a complete list of services.

The value of IDSS is a function of the quality of NWS data, services, and products – including improved relationships with core partners – to allow for improved decision-making. In theory, observed social and economic impacts increase as storms produce heavier snowfall over larger areas that include major metropolitan centers. We used the Northeast Snowfall Impact Scale (NESIS) rating to characterize the size and severity of the storm events (Box 1). NESIS focuses on the amount of snow that falls and maps snow accumulations onto the population density that experiences the snow (Kocin and Uccellini, 2004). Without formal IDSS, we hypothesized that observed social and economic impacts would increase significantly for storms with greater snow accumulation over high-density areas. With the provision of IDSS, core partners and deep relationship core partners have better information and support to take actions that reduce impacts. Therefore, with IDSS we hypothesized that observed social and economic impacts would increase less for storms with greater snow accumulation over high-density areas. The value of IDSS is the difference between the observed impacts for winter storms with IDSS versus the impacts that would have occurred without IDSS (Figure 2). However, we cannot directly measure how IDSS would change observed impacts for any given storm; instead, we must estimate the value of IDSS by comparing impacts across multiple storms.

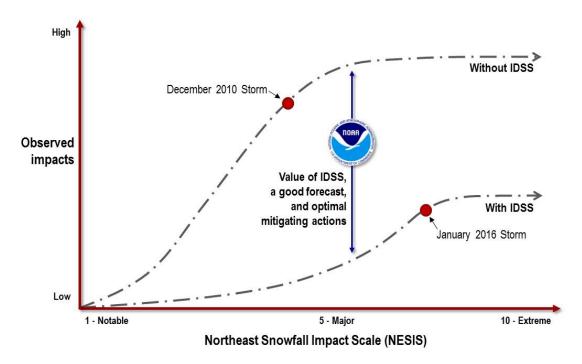


Figure 2. Conceptual model of the relationship between observed impacts and snow accumulation as it relates to the value of IDSS.

Box 1. NESIS categories, their corresponding NESIS values, and a descriptive adjective

NESIS characterizes and ranks snowstorms in the Northeast urban corridor. NESIS scores are a function of the area affected by the snowstorm, the amount of snow, and the number of people living in the path of the storm.

Category	NESIS value	Description
1	1.0-2.49	Notable
2	2.5-3.99	Significant
3	4.0-5.99	Major
4	6.0-9.99	Crippling
5	10.0+	Extreme

To estimate the effect of IDSS, ideally we would compare two storms with similar characteristics (i.e., primarily the NESIS rating, but also the timing of the storm, the spatial pattern of snowfall, the maximum rate of snowfall, and other characteristics), but differing in their implementation of IDSS (one storm without IDSS and one storm with IDSS). Out of our four case study storms, the December 2010 and January 2016 winter storms had similar observed snowfall accumulation and differed in the implementation of IDSS. We compared these two winter storms to describe the potential value of IDSS (Section 5). However, these storms also differed in their NESIS scores, as well as the time of year the event occurred, the forecast quality, and sectoral operational procedures. These differences between the storms made it challenging to precisely estimate the value of IDSS using these two storm events. Using expert interviews and our literature review, we qualitatively described the extent to which IDSS reduced storm impacts

versus the extent to which other factors reduced storm impacts.

We used expert elicitation to assess the degree to which IDSS may reduce economic losses and other impacts from severe winter storms. We elicited expert opinions through telephone interviews with state and local officials with first-hand knowledge about the operational decisions made under different weather events. We conducted interviews with local and state experts to (1) understand the extent to which winter storms' social and economic impacts were mitigated by IDSS; (2) comprehend how these economic impacts could have been further mitigated by improved IDSS; and (3) identify the attributes of IDSS that would lead to better outcomes, including faster recovery time and avoided costs (Table 3).

Table 3. Organizations interviewed to understand the extent to which IDSS affects social and economic impacts of severe winter storms.

Sector	Agencies and organizations interviewed (and dates)		
Federal Aviation Administration (September 25, 2017)			
Aviation	• Port Authority of New York & New Jersey (PANYNJ; September 11, 2017 and October 12, 2017)		
	NOAA NWS Aviation Weather Center (September 22, 2017)		
	New York City Emergency Management (via email, October 27, 2017)		
Ground transportation	New York Department of Transportation (via email, October 23, 2017)		
	Metropolitan Transportation Authority (October 20, 2017)		
Еномог	Consolidated Edison Inc. (via email, October 03, 2017)		
Energy	PSEG (via email, October 19, 2017)		

The interviews were semi-structured and followed a questionnaire that was tailored for each sector (Appendix A provides a sample questionnaire for the aviation sector). To ensure interviewees understood IDSS, we defined and provided examples of IDSS. Interviews focused on two storms: the December 2010 winter storm, a severe winter storm that occurred before the implementation of IDSS; and the January 2016 winter storm, a severe winter storm that occurred after the implementation of IDSS. For each storm, the interviews included a description of the storm events and questions about interviewees' familiarity with the storm and the decisions made during the storm. The interviewees were then offered a description of the impacts to each sector based on our background research and asked if these findings were consistent with their understanding of the storm impacts. Next, we described the type of IDSS provided for the storm event based on our interviews with NWS staff and asked how IDSS affected or would have affected storm impacts. We also asked about the critical aspects of IDSS for sectoral decisions and how trust and confidence in the NWS has changed over time.

3. Winter storms and social vulnerability

Winter storms are frequent in the NYC area (NYCEM, 2014). Although the Northeast is accustomed to winter storms, the NYC study area may not necessarily have the capacity to prepare for and respond to winter storms and other environmental hazards (HVRI, 2014). Compared to other counties within the State of New York and within the United States, the NYC area is highly vulnerable to environmental hazards, which include winter storms (HVRI, 2014). Social factors can weaken a community's ability to reduce social and economic losses from environmental hazards; these factors are referred to as social vulnerability. The Hazard Vulnerability Research Institute (HVRI, 2014) uses eight U.S. Census American Community Survey (2010–2014) variables to determine social vulnerability: wealth, race (Black) and social status, age (Elderly), ethnicity (Hispanic) and lack of health insurance, special needs populations, service industry employment, race (Native American), and gender (Female). Based on these variables, the HVRI indicates that the Bronx, Queens, and Kings counties have a high vulnerability to environmental hazards; and New York and Essex (New Jersey), have a medium to high vulnerability to environmental hazards (HVRI, 2014). Other counties in the NYC study area have a medium to low vulnerability to environmental hazards (HVRI, 2014).

For severe winter storms, the most at-risk populations are those that spend much of their time outdoors, including the homeless and laborers, low-wage workers, and the elderly (NYCEM, 2014). Since we did not have spatial data on populations who spend their time outdoors or the homeless, we focused on low-wage workers and the elderly. Low-wage workers are typically hardest hit during mass-transit disruptions because they rely on public transportation to travel to work, and this population is less likely to recover from lost wages during transportation disruptions (NYCEM, 2014). In addition, low-income populations living in New York City Housing Authority developments are vulnerable to power outages and power voltage reductions because they are more likely to live in high-rise buildings and buildings that are prone to lose power, heat, and hot water. Power outages in the winter can lead to the inappropriate use of backup generators, gas stoves, ovens, etc., for heat, putting individuals at greater risk of carbon monoxide poisoning. This is particularly true for immigrants with low English proficiency who may not be aware of existing carbon monoxide safety regulations (NYCEM, 2014). In the NYC study area, the distribution of low-income households is greatest in the Bronx and Kings counties, and parts of Essex County (Figure 3).

The elderly, persons with preexisting chronic medical conditions, and those without home heating are also vulnerable to severe winter weather (CDC, 2006; NYCEM, 2014). As people age, their thermoregulatory ability decreases and they have difficulty compensating for sudden temperature change, which makes elders more vulnerable to winter storms (NYCEM, 2014). In addition, individuals who are reliant on power-dependent medical equipment or medicines that must be refrigerated can suddenly find themselves in life-and-death situations during power outages. If elevators stop functioning during outages, seniors and individuals with disabilities can become trapped in their homes. Evacuating these individuals from tall buildings can be very challenging. In the NYC study area, elders (75 years of age and older) are largely concentrated outside NYC, either on Long Island or in Essex County (Figure 4).

We sought to evaluate the spatial extent of the area of impacts for each storm and, for each area of impacts, characterize the demographic characteristics, critical infrastructure, and other assets at risk of storm-related impacts. However, we were unable characterize the exposure of the winter storm because we lacked sufficient data. The spatial information to identify forecasted and observed spatial area for the impact of each event was difficult to obtain and interpret. Critical infrastructure data, such as the Homeland Infrastructure Foundation-Level Data, was largely proprietary or inaccessible because of safety concerns. In addition, at the time of the analysis, the social vulnerability data were either proprietary or based on outdated data. If future studies intend to evaluate exposure to winter storms, we suggest using the NDFD for forecasted data; and the NOAA National Snowfall Analysis, version 2, for observed data (see maps in Sections 4.2–4.4 for an example of these data). In addition, researchers should consider using the Centers for Disease Control and Prevention Agency for Toxic Substances and Disease Registry's Social Vulnerability Index or other social vulnerability indices. A better spatial analysis of vulnerable populations could allow us to draw conclusions about the effects of winter storms on vulnerable populations.

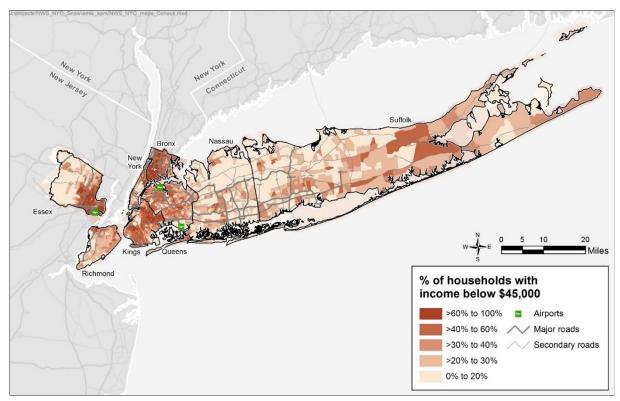


Figure 3. Percent of households with income below \$45,000 in NYC, Long Island, and Essex County.

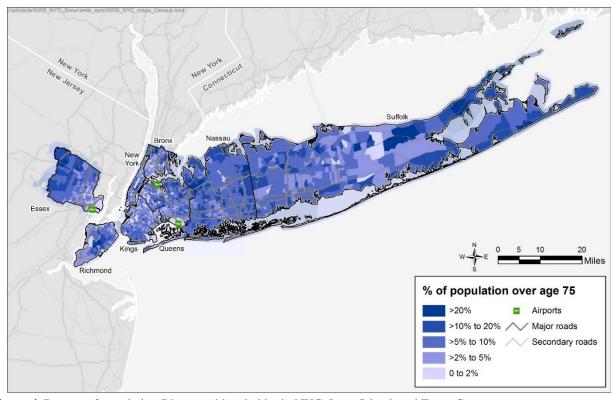


Figure 4. Percent of population 75 years old and older in NYC, Long Island, and Essex County.

4. Severe winter storm case studies

In this study, we focus on four winter storm events that occurred in December 2010, February 2013, January 2015, and January 2016. These severe winter storms differ in forecast timing and quality, observed snowfall accumulation, time of the year of impact, and the location of highest impact. In addition, the implementation of IDSS was at different stages for each storm event, with no formal IDSS for the December 2010 winter storm and gradual implementation of IDSS for the other three winter storms (Table 4). In this section, we describe the four winter storm events, including forecasted and observed snowfall, NWS decision support services provided for each event, and an overview of storm impacts.

Table 4. Overview of	of the four winter sto	orm events.
	MEGIC	

Storm event	NESIS score and category	Formal IDSS	Brief overview
December 2010	4.92; Category 3	No	Forecast underestimated measured snowfall, event occurred over holiday season, significant social and economic impacts
February 2013	4.35; Category 3	Yes	Forecast similar to measured snowfall, hit Long Island during rush hour, significant social and economic impacts
January 2015	2.62; Category 2	Yes	Forecast overestimated measured snowfall, took precautionary approach, some social and economic impacts
January 2016	7.66; Category 4	Yes	Forecast similar to measured snowfall, took precautionary approach, significant social and economic impacts

4.1 December 2010 winter storm

From December 25 to December 27, 2010, a large blizzard impacted the Northeast and severely affected the NYC metropolitan area (Soltow, 2010). The storm first appeared in the NWS Hazardous Weather Outlook on December 21, 2010. However, the forecasts were volatile. Early forecasts predicted light-to-moderate snowfall, as many expected that the storm would stay offshore (Kocin et al., 2011; Weinstein and Funk, 2011). European, Canadian, and U.S. forecast models did not converge on a consistent forecast scenario until 36 to 48 hours before the onset of the heaviest snow (Kocin et al., 2011). On Saturday, December 25, the storm severity was upgraded, and a blizzard warning was issued at 3:55 p.m. on December 25, with predicted snowfall between 11 and 16 inches; this forecast underestimated the snowfall (Weinstein and Funk, 2011).

Forecasts did not provide a solid basis for storm preparations until 24 to 36 hours before the onset of the storm (Kocin et al., 2011). Although IDSS was not formalized in 2010, NWS provided some decision support services (Box 2). NYC agencies deployed more than 3,030 pieces of snow removal equipment throughout the city, but the city did not ensure sufficient private contractors were on call to assist with plowing, towing, and shoveling during the storm (Weinstein and Funk, 2011). In addition, the city decided against declaring a snow emergency and did not issue other advisories (Weinstein and Funk, 2011; Table 5, Mitigating Actions).

Box 2. Overview of IDSS for the December 2010 winter storm

NWS did not provide formal IDSS during this winter storm. However, the New York Weather Forecast Office (WFO) provided remote IDSS using emails, phone conversations, and WebEx (Ross Dickman, National Weather Service, personal communication, July 26, 2017). As storm forecasts indicated a strengthening storm, the WFO hosted a live webinar for additional visibility (Ross Dickman, National Weather Service, personal communication, July 26, 2017).

Snowfall began across the greater NYC area in the early afternoon of Sunday, December 26, and the storm rapidly intensified. Manhattan and other parts of NYC reported heavy, moisture-laden snow on Sunday, December 26, and the early hours of Monday, December 27, accompanied by high winds (Kocin et al., 2011). Snow accumulations totaled 20 to 30 inches across NYC and the Lower Hudson Valley, with 10 to 20 inches across Long Island (Kocin et al., 2011). At the peak of the storm, snow fell at an hourly rate of 1 to 2 inches and winds were 30 to 45 mph with gusts commonly exceeding 50 to 60 mph (Kocin et al., 2011). The snow was a result of a strong low pressure system that tracked up the East Coast (Soltow, 2010). The winter storm was a Category 3 event on the NESIS, with an NESIS score of 4.92 (see Box 1).

Table 5. Overview of impacts for the December 2010 winter storm.

Mitigating actions	Service interruptions	Asset damages	Human health
0	\$\$\$\$	\\\	◊◊◊
 No Hazardous Weather Advisory issued. No prohibition of standing or parking a vehicle on Snow Emergency Streets and no chain or snow tire requirements when driving on Snow Emergency Streets. Delayed snow removal in NYC. NYC deployed 3,030 snow removal vehicles. NYC towed 119 vehicles. 	 Widespread flight cancellations and delays due to weather. Approximately 3,760 weather-related flight cancellations cost airlines \$20.5 million and passengers \$93.1 million. Public transportation severely hampered [e.g., Long Island Rail Road (LIRR) service suspensions, Metro North Railroad services reduced, Metropolitan Transportation Authority (MTA) bus delays, MTA subway delays and interruptions to aboveground service). Severe roadway blockages with disabled vehicles on arterial roadways and local roadways due to snow conditions. Approximately 76,930 customer power interruptions at an average duration of 12.2 hours, with an estimated interruption cost of \$106.8 million. Immediate decline in employment of 3,850 jobs with 2,850 jobs recovering in the following 2 months (overall decline of approximately 1,000 jobs). 	 No private property losses reported. \$18.3 million in public property losses recorded (\$7.4 million for NYC). 	 At least one storm-related death (fallen tree) and possibly other deaths from emergency vehicles stuck in snow. New York Police Department (NYPD) response times delayed because NYPD vehicles stuck in the snow. Fire Department of New York (FDNY) Emergency Medical Services (EMS) experienced severe citywide backlog due to many ambulances stuck in the snow, and reported multiple fire apparatus stuck in the snow in Brooklyn.

Notes:

- The mitigating actions symbol (\circ) provides a relative estimate, where \circ = limited advisories and actions; $\circ \circ =$ some advisories and actions; $\circ \circ =$ significant advisories and actions; and $\circ \circ \circ =$ maximum advisories and actions, e.g., the city was shut down.
- The impacts symbol (◊) also provides an order of magnitude estimate, where ◊ = limited social and economic impacts; ◊◊ = some social and economic impacts; ◊◊◊ = significant social and economic impacts; and ◊◊◊◊ = maximum social and economic impacts, e.g., following the storm, the city took unprecedented actions to change operations and procedures.
- We describe the data sources and methods for monetary estimates in Appendix B.
- We compare all storm impacts in Appendix C.

Disruptions began in the evening of Sunday, December 26 (Table 5, Service Interruptions). All three major airports in the NYC area had widespread flight cancellations and delays (BTS, 2017). Bus service was severely hampered; the NYCEM (2014) estimates that holiday and weekend pay for workers called in to operate buses, subways, railroads, and crossings totaled \$14 million. In addition, services on the LIRR were suspended, and services on the Metro North Railroad were reduced (NYCEM, 2017). MTA subways experienced delays and interruptions on above-ground services, and the NYCEM (2014) estimates that the MTA lost \$30 million due to overtime expenses and lost ridership revenue. The Port Authority Trans-Hudson Corporation transit system services were suspended Sunday night into Monday morning due to high snow drifts (NYCEM, 2017). There were severe roadway blockages with disabled vehicles on arterial and local roadways due to snow conditions (NYCEM, 2017). Throughout Oueens, Nassau, and Suffolk counties, customers experienced widespread power interruptions. Approximately 76,900 customers in Queens, Nassau, and Suffolk counties experienced power interruptions during the December 2010 winter storm, with an average power outage duration of 12.2 hours for customers in Queens County (Charles Viemeister, Consolidated Edison, personal communication, October 3, 2017). Using snowfall data, we estimate the December 2010 storm had an immediate negative impact on employment across all industry sectors; however, employment largely rebounded during the following two months (see Appendix B for a description of our methodology). While we expect some sales were permanently lost, it is difficult to quantify that loss using employment data. For example, if a catering company cancels several jobs during a snowstorm, those losses may be passed on to the employees through cancelled shift and lost wages rather than decreases in employment.

New York State received \$60.1 million and New Jersey State \$70.6 million for disaster recovery; of these disaster recovery funds, \$14.1 million (New York) and \$4.1 million (New Jersey) was for permanent work required to restore eligible facilities (FEMA, 2010a, 2010b; Table 5, Asset Damages). NYC received \$37.7 million of New York State's federal disaster funding, of which \$7.4 million was for permanent work (NYCEM, 2014). In terms of private property insured losses, the Property Claim Services (PCS) state-aggregated loss estimates do not report losses in the States of New York or New Jersey for this winter storm; however, PCS estimates losses only when insured losses exceed a

\$25 million threshold per storm event; losses for individual states are often less than \$25 million (Adam Smith, NOAA, personal communication, January 31, 2017). NYC reported one fatality from a fallen tree (NYCEM, 2014; Table 5, Human Health). In addition, Kocin et al. (2011) indicated that snow plow operators were unable to clear roads and emergency workers were unable to reach people facing human health risks, which resulted in several deaths during the storm. The recovery process was slow and the city was paralyzed for several days (Kocin et al., 2011).

After the December 2010 winter storm, the New York City Council held hearings to examine the city's efforts to handle snow-related emergencies and analyze issues that arose with the city's response to the storm event (New York City Council, 2011). The Mayor's Offices of Operations and Citywide Emergency Communications issued a Preliminary Review of the city's response to the December 2010 storm. According to the Preliminary Review, the "City's response to the snowfall failed in many ways" (Weinstein and Funk, 2011, p. 2). The Mayor's Offices Preliminary Review identified several problem areas that contributed to the city's poor response to the storm, and proposed a 15-point action plan to improve future snow and emergency response efforts (Weinstein and Funk, 2011). In addition to the city's failures, the Preliminary Review indicated that *natural factors* exacerbated the city's ability to respond to the storm, including "weather forecasts predicted low accumulations up until 18 hours prior to the storm," snowfall rates of over two inches per hour or more, and the fact that the storm fell over a holiday weekend when more cars were on the roads.

Simultaneously, the City Council prepared numerous pieces of legislation to improve the city's response to weather-related emergencies. Legislation included three new local laws (Local Laws 24, 25, and 26) to guide the city's response to weather emergencies, including plans for winter weather, and required agencies responsible for preparing for and responding to snow emergencies to develop an annual snow preparedness and response report for each snow event of six inches or more (New York City Council, 2011). In addition, MTA developed 25 recommendations for improving MTA-wide system storm performance, including appointing a full-time Emergency Coordinator to provide oversight of storm readiness, and coordinate mitigation actions and recovery across the MTA (MTA, 2011).

4.2 February 2013 winter storm

The February 2013 storm originated with a low pressure system in the Gulf of Alaska that advanced through the Great Lakes region and then converged with a very moist, low pressure system moving northeast from the Mexican plateau. This led to the rapid intensification of a major winter storm that affected the Great Lakes and the Northeast from February 7 to February 9, 2013 (Dickman, 2013; Kreckeler, 2013). The 48-hour forecasts predicted up to 8 inches of snow across NYC and Nassau County, with more snow accumulation predicted in Suffolk County (Figure 5). NYC agencies deployed 2,620 pieces of snow removal equipment throughout the city, issued advisories and weather emergency declarations, and took actions to protect public safety (NYCEM, 2016; Table 6, Mitigating Actions). NWS provided IDSS activities, including stakeholder briefings (Box 3).

Box 3. Overview of IDSS for the February 2013 winter storm

The NWS began providing briefings to the media and other stakeholders on February 6, 2013 through webinars, telephone calls, and PowerPoint presentations. Between 12:30 p.m. Eastern Standard Time (EST) on February 6 and 4:00 p.m. EST on February 8, the NWS gave 10 weather briefings on the event. The goal of these briefings was to provide up-to-date information on forecasted snow accumulation, wind gust strength, and coastal flooding. This information guided the emergency planning in NYC.

The storm produced heavy, wet snow and strong winds that reduced visibility from mid-afternoon on Friday, February 8 through Saturday, February 9 (Dickman, 2013). Northern and central Suffolk County experienced the worst of the storm. Snowfall accumulations were greater than 36 inches on some parts of Long Island (Figure 6), with strong winds ranging from 35 to 50 mph, and the highest gusts up to 75 mph on Friday night (Dickman, 2013). In NYC, snow accumulation varied from 6 to 18 inches (Figure 6); and winds gusts ranged from 36 to 40 mph at Central Park,

11

^{6.} According to Weinstein and Funk (2011), the six problem areas included (1) the decision not to declare a snow emergency, (2) insufficient accountability tools that led to a lack of real-time information on street conditions, (3) insufficient and delayed deployment of city assets that could have assisted with snow removal operations, (4) failure to procure and position private resources, (5) insufficient communication within the city government and to the public, and (6) problems with emergency communications and response.

John F. Kennedy International (Kennedy) Airport, and LaGuardia Airport (NWS, 2013a). The winter storm was a Category 3 event on the NESIS, with an NESIS score of 4.35 (Box 1).

The blizzard had far-reaching impacts across Suffolk County (Table 6, Service Interruptions). NYC area airports canceled flights preemptively; however, the storm's largest impact was east of these airports (BTS, 2017). Thousands of people traveling Friday afternoon and evening were stuck, and snow plows and passenger vehicles were stranded overnight on the Long Island Expressway. Metro North railroad and LIRR services were suspended on multiple branches (NYCEM, 2017). Multiple MTA subway lines experienced delays due to weather conditions and some MTA buses were suspended (NYCEM, 2017). Heavy, wet snow and strong winds downed thousands of trees and tree limbs, resulting in significant power outages and property damage throughout Queens, Nassau, and Suffolk counties. We estimate that the February 2013 storm had a large immediate decline in employment across industry sectors; however, because employment was strong over the following two months, the decline in employment for this storm event was relatively small.

The PCS state-aggregated loss estimates do not report property losses in the States of New York or New Jersey for this winter storm; however, PCS estimates losses only when insured losses exceed a \$25 million threshold per storm event; losses for individual states are often less than \$25 million (Adam Smith, NOAA, personal communication, January 31, 2017). The State of New York received \$32.06 million from the federal government for disaster recovery from the February 2013 storm, of which approximately \$14.2 million was for permanent work required to restore eligible facilities (FEMA, 2013; Table 6, Asset Damages).

NOAA Storm Data reported seven deaths in Suffolk County during the February 2013 winter storm (Table 6, Human Health). Overexertion from snow shoveling may have caused four of these deaths (Associated Press, 2013; Bush, 2013). No information is available about the other three deaths. However, hundreds of cars were stuck on the Long Island Expressway (Trapasso et al., 2013), which could have caused deaths or injuries.

Table 6. Overview of impacts for the February 2013 winter storm.

Mitigating actions	Service interruptions	Asset damages	Human health
00	♦♦♦	♦	◊◊
 Hazardous Weather Advisory issued. No prohibition of standing or parking a vehicle on Snow Emergency Streets and no chain or snow tire requirements when driving on Snow Emergency Streets. NYC deployed 2,620 snow removal vehicles. One vehicle towed in NYC. 	 Airports experienced cancellations and delays due to weather. Approximately 1,780 weather-related flight cancellations cost airlines \$9.7 million and passengers \$46.8 million. Thousands of people were stranded overnight on the Long Island Expressway. LIRR and Metro North services suspended, and MTA buses implemented widespread detours or service modifications system-wide due to icy road conditions. Approximately 67,610 customer power interruptions. Immediate decline in employment of 780 jobs, with 580 jobs recovering in the following 2 months (overall decline of approximately 200 jobs). 	 No private property losses recorded. \$14.2 million in public property losses recorded. 	 At least seven storm-related deaths (shoveling snow). NYPD visited homes without heat or electricity affected by Hurricane Sandy. No FDNY EMS backlog. No hospitals on diversion status.

Notes:

- The mitigating actions symbol (\circ) provides a relative estimate, where \circ = limited advisories and actions; $\circ \circ$ = some advisories and actions; $\circ \circ \circ$ = significant advisories and actions; and $\circ \circ \circ \circ \circ$ = maximum advisories and actions, e.g., the city was shut down.
- The impacts symbol (◊) also provides an order of magnitude estimate, where ◊ = limited social and economic impacts; ◊◊ = some social and economic impacts; obox = significant social and economic impacts; and ◊◊◊◊ = maximum social and economic impacts, e.g., following the storm, the city took unprecedented actions to change operations and procedures.
- We describe the data sources and methods for monetary estimates in Appendix B.
- We compare all storm impacts in Appendix C.

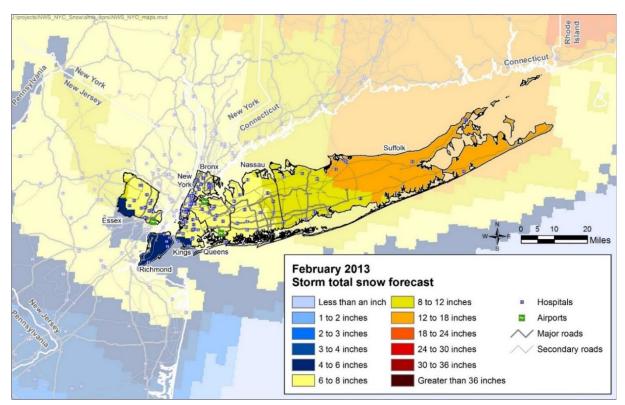


Figure 5. Forecasted snowfall for the February 2013 winter storm. Forecast data are for 48 hours of the event, starting on the evening of February 8, 2013. Source: NDFD.

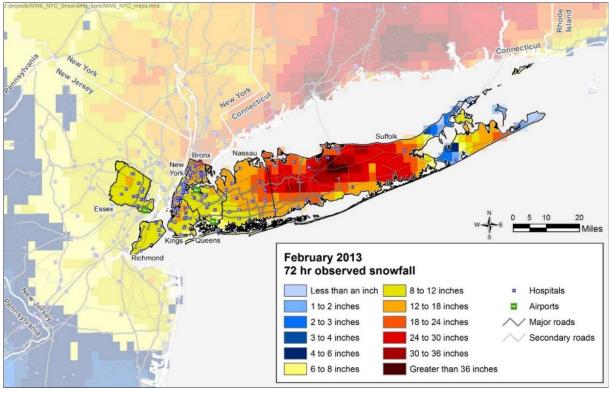


Figure 6. Observed snowfall for the February 2013 winter storm. Observed data are for 72 hours of the event, which includes February 8–10, 2013. Source: NOAA National Snowfall Analysis, version 2.

4.3 January 2015 winter storm

Mid- to upper-level low pressure from the Ohio Valley moved east and intensified as it reached the East Coast, allowing a shift in energy to low pressure that organized into a storm just off the Mid-Atlantic Coast from January 26 to January 27, 2015 (Otto, 2015). The initial forecasts of snow accumulations were 30 to 36 inches in NYC and 24 to 36 inches in Long Island (Figure 7); these forecasts held steady as late as January 26. However, there was uncertainty on where the heaviest bands of snow would be located. By early morning January 27, these snowfall estimates were lowered to 14 to 18 inches as the system stalled in Fairfield, New Haven, and Suffolk counties; and it became clear that the heaviest bands would not reach NYC (WFO OKX, 2015).

NYC and the State of New York issued several advisories and actions to reduce storm impacts (NYCEM, 2016; Table 7, Mitigating Actions). Governor Cuomo declared a state of emergency. In NYC, buses were cancelled and subway service was limited. The New York Department of Sanitation (DSNY) and other NYC agencies deployed 3,320 pieces of snow removal equipment throughout the city (NYCEM, 2016). In addition, NYC schools closed on January 27, Broadway shows were canceled, and a National Basketball Association Knicks game was rescheduled. NWS provided IDSS activities, including stakeholder briefings, onsite IDSS to the New York City Emergency Management (NYCEM), and messaging to the aviation community about the potential for a high-impact event; and used social media to inform the public about forecast uncertainty (Box 4).

The storm strengthened and tracked northeastward (Otto, 2015). As a result, during January 26–28, 2015, moderate to heavy snow fell across Long Island and eastern New England (Figure 8). At the peak of the storm, snow fell at a record rate of three to four inches per hour. In NYC, snow accumulation ranged from 8 to 12 inches (Figure 8). Winds gusted up to 38 and 39 mph at LaGuardia and Kennedy airports, respectively (NWS, 2015). The winter storm was a Category 2 event on the NESIS, with an NESIS score of 2.62 (Box 1).

This winter storm had fewer impacts than expected (Table 7, Service Interruptions). Most impacts were proactive cancellations of schools, businesses, entertainment events, and flights. At NYC airports, approximately 2,410 flight were canceled during and after the event (BTS, 2017). NYC Metro services experienced limited disruptions (NYCEM, 2017). Throughout Queens, Nassau, and Suffolk counties, approximately 8,620 customers experienced power interruptions. Using snowfall data, we estimate the storm had a large immediate decline in employment across industry sectors; however, because employment was strong over the following two months, the decline in employment for this storm event is relatively small.

PCS estimates losses in the State of New York at \$12.3 million, but no losses in the State of New Jersey (Verisk Analytics, 2017). The Federal Emergency Management Agency did not declare a federal disaster in New York or New Jersey, but did declare federal disasters in Rhode Island, Connecticut, and Massachusetts. NWS recorded 1 fatality when a 17-year-old male struck a light pole while sledding in Suffolk County at night (WFO OKX, 2015; Table 7).

 $^{7.\} Private\ property\ damages\ elsewhere\ drove\ the\ PCS\ total\ estimated\ losses\ over\ the\ threshold\ of\ \$25\ million.$

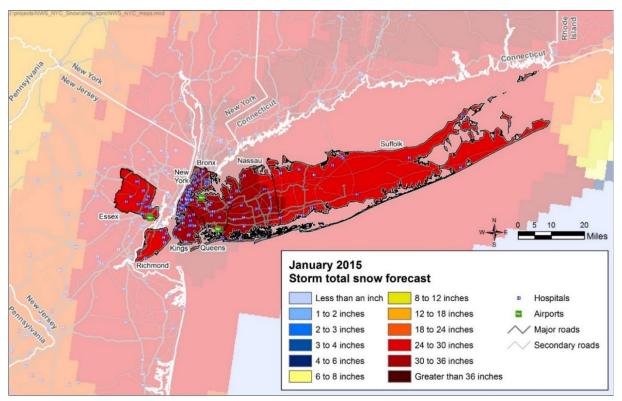


Figure 7. Forecasted snowfall for the January 2015 winter storm. Forecast data are for 48 hours of the event, starting in the evening of January 25, 2015. Source: NDFD.

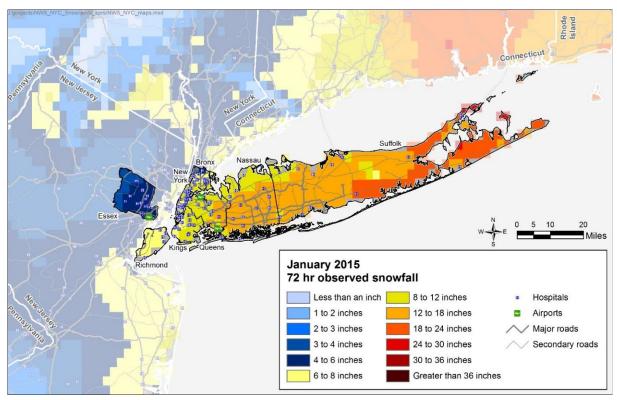


Figure 8. Observed snowfall for the January 2015 winter storm. Observed data are for 72 hours of the event, which includes January 25–27, 2015. Source: NOAA National Snowfall Analysis, version 2.

Box 4. Overview of IDSS for January 2015 winter storm

Beginning on January 21, 2015 at 3:30 p.m., the NWS provided seven webinar briefings to key stakeholders throughout the storm event, the last occurring at 2:30 p.m. on January 26. These briefings provided up-to-date forecasts on snow fall totals, wind gusts, and storm surge potential. In addition, NWS members were in constant communication with officials at all levels of government as a part of its IDSS. IDSS included informational emails, electronic presentations, telephone conference calls, and webinars for all local emergency managers – including the New York State Department of Transportation, the NYCEM, the PANYNJ, the U.S. Army Corps of Engineers, and Governor Cuomo's office – and the media (WFO OKX, 2015). Onsite IDSS were provided by a general forecaster from Eastern Region Headquarters (ERH) to the NYCEM (WFO OKX, 2015). NWS provided the aviation community with a steady stream of consistent, high-impact messaging to prepare for and allow a quick recovery to normal operations, as well as routine forecast products (WFO OKX, 2015).

In 2014, the Federal Aviation Administration (FAA) introduced the Aviation Winter Weather Dashboard (AWWD), a winter weather decision-making tool for aircraft operators. Updated every six hours, AWWD allows operators to determine potential winter weather impacts across the National Air Space for the next 84 hours. Color-coding makes it easy to identify where weather is nominal (green), slight (yellow), moderate (orange), or a high (red) impact event (Figure 9).

In addition to these efforts, NWS used social media to inform the public on forecast uncertainty through posts that described the minimum, maximum, and likely snowfall forecasts of this storm. Overall, their social media efforts through Facebook and Twitter reached over 2 million people (WFO OKX, 2015).

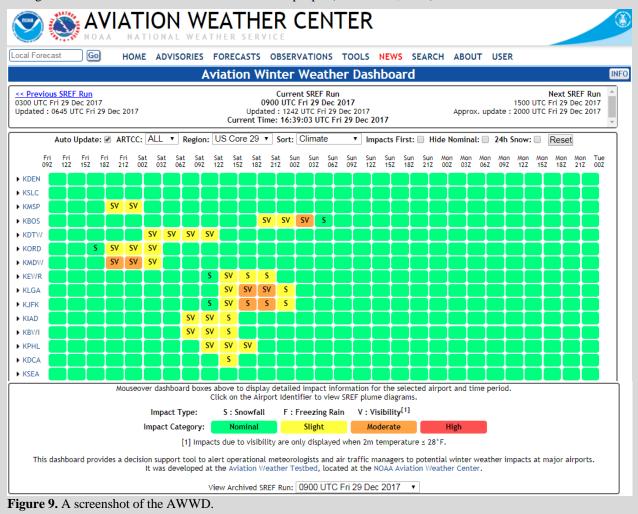


Table 7. Overview of impacts for the January 2015 winter storm.

Mitigating actions	Service interruptions	Asset damages	Human health
00	♦♦	♦♦	♦
 Hazardous Weather Advisory issued. No prohibition of standing or parking a vehicle on Snow Emergency Streets and no chain or snow tire requirements when driving on Snow Emergency Streets. NYC deployed 3,320 snow removal vehicles. No vehicles towed in NYC. 	 Airports experienced cancellations and delays due to weather. Approximately 2,410 weather-related flight cancellations cost airlines \$13.1 million and passengers \$66.6 million. Roads were closed to traffic and subways were halted. Limited disruption to MTA service. Approximately 8,620 customer power interruptions. Immediate decline in employment of 450 jobs with 330 jobs recovering in the following two months (overall decline of approximately 120 jobs). 	 \$12.3 million in private property losses recorded. No public property losses recorded. 	 At least one winter-related death (sledding accident). 911 call volume below average. No EMS backlog.

Notes:

- The mitigating actions symbol (○) provides a relative estimate, where = limited advisories and actions; ○○ = some advisories and actions; ○○○ = significant advisories and actions; and ○○○○ = maximum advisories and actions, e.g., the city was shut down.
- − The impacts symbol (\Diamond) also provides an order of magnitude estimate, where \Diamond = limited social and economic impacts; \Diamond \Diamond = some social and economic impacts; \Diamond \Diamond 0 = significant social and economic impacts; and \Diamond \Diamond \Diamond 0 = maximum social and economic impacts, e.g., following the storm, the city took unprecedented actions to change operations and procedures.
- We describe the data sources and methods for monetary estimates provided in Appendix B.
- We compare all storm impacts in Appendix C.

4.4 January 2016 winter storm

From January 22 to January 25, 2016, a record-breaking storm dropped heavy snow from Louisiana to Maine. Heavy snow and strong winds created blizzard conditions along the New Jersey, New York, and Connecticut coastlines; and near-blizzard conditions elsewhere (WFO OKX, 2016). The storm first appeared in the NWS Hazardous Weather Outlook on Monday, January 18, more than four days before the event developed (WFO OKX, 2016). On the morning of January 21, NWS issued the first watches for a Blizzard and Winter Storm; and on the morning of January 22, it issued the first warnings (WFO OKX, 2016), forecasting 8 to 12 inches of snow (Figure 10). The day before the event, the severity of the forecast was upgraded with predicted snowfall between 24 and 28 inches.

NYC and the State of New York issued several advisories and actions to reduce storm impacts (Table 8, Mitigating Actions). Governor Cuomo and Mayor De Blasio declared a state of emergency and a winter weather emergency during the morning of January 23, 2016. At 12:40 p.m., the Governor ordered a shutdown of NYC in response to the worsening winter storm. NYC implemented a driving ban, which allowed the DSNY to clear roads. NYC agencies deployed 3,990 pieces of snow removal equipment throughout the city (NYCEM, 2016), with DSNY deploying all spreaders on Friday evening to spread the snow to make it easier to remove snow once the storm arrived (DSNY, 2016). NWS provided extensive IDSS activities, including stakeholder briefings, onsite IDSS to NYCEM, and high-impact messaging to the aviation community; and used social media to inform the public about the forecast uncertainty (Box 5).

Snowfall peaked in the Mid-Atlantic region where accumulations upward of 22 inches were reported from the Washington, DC metropolitan region into Long Island, NY (Fanning, 2016). The NYC area experienced snowfall accumulation of 20 to 30 inches (Figure 11), with unofficial totals of 34 inches reported in Queens and wind gusts up to 50 mph across NYC (Uccellini, 2016). Snow fell at a rate of three inches per hour during periods of the storm, causing whiteout conditions (DSNY, 2016). Snow accumulations totaled approximately 18 inches across Long Island. The storm recovery was gradual on Sunday and Monday (January 25 and January 26), with near-normal conditions returning to the area by Tuesday (WFO OKX, 2016). Total accumulations at Central Park reached 27.5 inches, making it the largest snow storm recorded by the NWS at Central Park since 1869. The storm caused widespread erosion and local coastal

^{8.} Over time, NYC agencies invested in snow equipment upgrades to effectively remove snow and treat streets (New York City Council, 2011; DSNY, 2016).

flooding occurred during high tides (WFO OKX, 2016). The winter storm is a Category 4 event on the NESIS, with an NESIS score of 7.66.

The storm resulted in significant disruptions in the NYC area (Table 8, Service Interruptions). All three major airports in the NYC area had widespread flight cancellations and delays (BTS, 2017). In recent years, airlines are more likely to proactively cancel flights to save money, improve customer relations, and improve the speed of recovery (Weed, 2017; Wichter, 2017). Without flights on the ground, airports can quickly remove snow and reposition staff to allow airports and airlines to resume operations (Wichter, 2017). NYC suspended many services, including the East River Ferry, the aboveground subway, bus services, and LIRR and Metro-North railroads (NYCEM, 2017). Throughout Queens, Nassau, and Suffolk counties, customers experienced widespread power interruptions. Approximately 30,690 customers in Queens, Nassau, and Suffolk counties experienced power interruptions during the January 2016 winter storm, with an average power outage duration of 4.8 hours for customers in Queens (Charles Viemeister, Consolidated Edison, personal communication, October 3, 2017). We estimate the January 2016 storm had a large immediate decline in employment across industry sectors. However, employment largely rebounded during the following two months (see Appendix B for a description of our methodology).

Asset damages and human health also had large impacts in the NYC study area (Table 8). PCS estimates losses of \$10.5 million in the State of New York and \$33.3 million in the State of New Jersey (Verisk Analytics, 2017). The State of New Jersey received \$90.5 million from the federal government for disaster recovery, of which approximately \$9.5 million was for permanent work (FEMA, 2016b). Five storm-related deaths were reported in NYC, all of which were heart attacks from shoveling snow (NYCEM, 2016). Other indirect injuries from the storm came from multiple traffic accidents that occurred during the storm (WFO OKX, 2016).

Table 8. Overview of impacts for the January 2016 winter storm.

Mitigating actions	Service interruptions	Asset damages	Human health
0000	♦♦♦	♦♦♦	♦♦
 Hazardous Weather Advisory issued. Citywide travel ban issued. Prohibition of standing or parking a vehicle on Snow Emergency Streets and chain or snow tire use requirements when driving on Snow Emergency Streets. NYC deployed 3,990 snow removal vehicles. Towed 192 vehicles in NYC. Shut down NYC. 	 Airports experienced cancellations and delays due to weather. Approximately 2,420 weather-related flight cancellations cost airlines \$13.2 million and passengers \$69.5 million. Delays in plowing tertiary streets in Queens. PANYNJ bridges and tunnels, and MTA bridges and tunnels closed to non-essential vehicles. Suspended bus, MTA subway, and LIRR and Metro-North railroad services. Approximately 30,690 customer power interruptions at an average duration of 4.8 hours, with an estimated interruption cost of \$14.7 million. Immediate decline in employment with 2,310 jobs recovering in the following 2 months (overall decline of approximately 810 jobs). 	 \$43.8 million in private property losses recorded. \$9.5 million in public property losses recorded. 	At least five winter-related deaths (heart attacks from shoveling snow). Normal 911 and EMS call volumes.

Notes:

- The mitigating actions symbol (\circ) provides a relative estimate, where \circ = limited advisories and actions; $\circ \circ$ = some advisories and actions; $\circ \circ \circ$ = significant advisories and actions; and $\circ \circ \circ \circ$ = maximum advisories and actions, e.g., the city was shut down.
- The impacts symbol (\Diamond) also provides an order of magnitude estimate, where \Diamond = limited social and economic impacts; $\Diamond \Diamond$ = some social and economic impacts; $\Diamond \Diamond \Diamond$ = significant social and economic impacts; and $\Diamond \Diamond \Diamond \Diamond$ = maximum social and economic impacts, e.g., following the storm, the city took unprecedented actions to change operations and procedures.
- We describe the data sources and methods for monetary estimates provided in Appendix B.
- We compare all storm impacts in Appendix C.

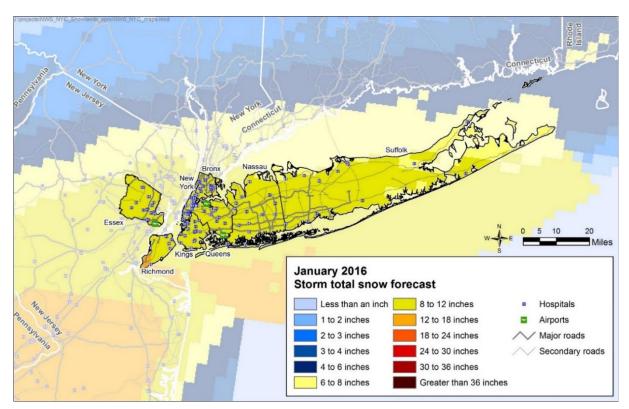


Figure 10. Forecasted snowfall for the January 2016 winter storm. Forecast data are for 48 hours of the event, starting on the afternoon of January 23, 2016. This forecast was significantly upgraded the night of January 23. Source: NDFD.

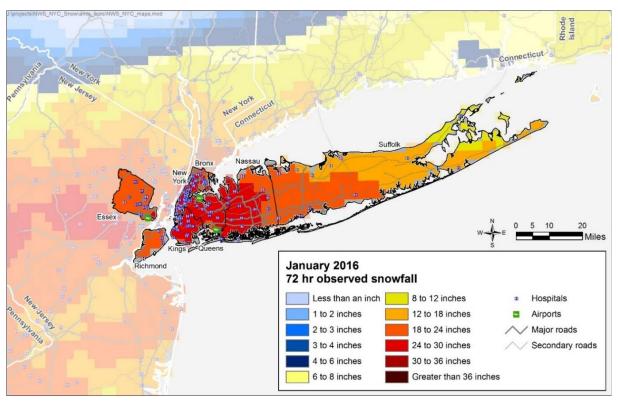


Figure 11. Observed snowfall for the January 2016 winter storm. Observed data are for 72 hours of the event, which includes January 23–25, 2013. Source: NOAA National Snowfall Analysis, version 2.

Box 5. Overview of IDSS for January 2016 winter storm

WFO New York was proactive in its provision of IDSS before and during the January 2016 winter storm. IDSS began on Saturday, January 16, with telephone briefings to NYC Emergency Management that lasted throughout the following week during recovery efforts. NWS staff spent about 80 hours on the telephone from Saturday, January 16 through Tuesday, January 26, providing weather briefings, servicing media requests, and answering spotter calls or calls from storm spotter volunteers who improve NWS warning services by providing real-time reports on hail size, wind damage, flash flooding, and heavy rain to effectively warn the public of inclement weather (WFO OKX, 2016).

NWS staff also participated in executive-level conference calls with Governor Chris Christie, Governor Cuomo, and Mayor DeBlasio (Uccellini, 2016; WFO OKX, 2016). Separate email briefings were provided to coastal partners on coastal flooding hazards and impacts for Nassau and Suffolk counties (Uccellini, 2016). The email included a link to the NOAA Coastal Flooding Viewer for partners who wanted a rough estimate of areas that might get inundated at the NWS forecasted water levels. NWS staff also reached a number of people on social media. Their Facebook reach was over 1.2 million; an increase of 242% from the previous week. On Twitter their tweets about the storm earned 3.3 million impressions (WFO OKX, 2016). Onsite IDSS were provided by general forecasters from WFO New York and ERH to the NYCEM from Friday, January 22 through Sunday, January 24 (WFO OKX, 2016; Figure 12). Long Island's Nassau County requested onsite support 24 hours before the storm, but WFO New York was unable to provide this support because of limited staffing (Uccellini, 2016; WFO OKX, 2016).

WFO New York alerted aviation partners that blizzard conditions were expected on Saturday, January 23 via the Aviation Forecast Discussion Outlook five days before the storm (WFO OKX, 2016). WFO New York provided aviation partners with information for operations and staffing decision-making. In addition, WFO New York sent a "High Impact" summary email to all aviation partners on the morning of Friday, January 22, which highlighted the potential for over 20 inches of snowfall in the NYC metropolitan area and Long Island, and indicated that surface travel for airport employees would be difficult or impossible on Saturday, January 23.



Figure 12. NWS meteorologist Bill Goodman providing NYC agencies with storm forecast updates.

5. Storm comparison by sector

In this section, we compare the December 2010 and January 2016 winter storms for three sectors: aviation, ground transportation, and energy. For each sector, we first describe the types of defensive investments made in the sector and the mitigating actions taken to reduce impacts, and provide an overview of the types of service interruptions, asset damages, and human health effects caused by winter storms. We then compare the two storm events: the December 2010 winter storm without formalized IDSS and the January 2016 winter storm event with formalized IDSS. Out of the four case study storms, the December 2010 and January 2016 winter storms had the most similar observed snowfall accumulation and differed in the implementation of IDSS. However, these storms also differed in the time of year the event occurred, forecast quality, and sectoral operational procedures; these differences provide challenges to precisely estimate the value of IDSS using these two storm events, but do offer insights into how the process of IDSS before an event provides the various decision-makers with up-to-date information that can serve as a basis for a more informative response to changing forecasts. We provide key takeaways that emerged from our review of the extant literature; discussions with NWS and other key personnel (as indicated in Table 1); and the expert interviews (as indicated in Table 3), including our assessment on the role of IDSS in reducing impacts to each sector.

5.1 Aviation

During severe winter weather events, snow, ice, drifting snow, and reduced visibility can severely affect airport and airline operations and safety. The presence of snow or ice can cause hazardous conditions at airports and contribute to aircraft accidents and reduced traffic volumes, including flight delays, diversions, and cancellations (Table 9). Forecasts and decision support services can minimize these effects and improve airport operations. The aviation stakeholders making operational decisions about mitigating actions and recovery for winter weather events include airports, airlines, and the FAA.

Table 9. Impact matrix summarizing the effects of winter weather on aviation by stakeholder group.

Stake- holders	Defensive investments	Mitigating actions	Service interruptions	Asset damages	Human health	
Airports	 Investments in de-icing and snow removal equipment. 	 Staff for maintenance and service treatments. Pretreat runways. Snow removal and surface treatment. 	 Flight cancellations, delays, and diversions. 	Aircraft accidents.Equipment failure.	 Airport stranding. 	
Airlines	 Investments in de-icing and snow removal equipment. Three-Hour Tarmac Rule. 	 Staff plans for aircraft maintenance and service, and for changes to flight schedules. Relocate or reposition aircrafts. Define and execute flight schedule cancellations. Prepare de-icing and snow removal equipment. Deice and snow removal. 	Flight cancellations, delays, and diversions.	 Snowed-in (inoperable) aircraft. Aircraft accidents. Equipment failure. 	 Injuries and fatalities. 	
FAA		Monitor Traffic Management Initiative (TMI) issuance.	 Flight cancellations, delays, and diversions. 		 Stress impacts on air traffic control. 	

In the aviation industry, *defensive investments* in advance of any particular winter storm can help build resilience against severe winter storms and make the system more robust to all hazards. Prior to 2010, long tarmac delays were common. In 2009, Congress passed the Three-Hour Tarmac Rule after an airline kept passengers on-board an aircraft for six hours following a weather diversion (Kocin et al., 2011). This rule penalizes airlines with a fine of up to \$27,500 per passenger for tarmac delays exceeding three hours. As a result of this rule, the airline industry is changing its approach to managing weather delays and has become more proactive in canceling flights to avoid costly tarmac delays (Kocin et al., 2011). Specific to severe winter weather, airports and airlines invest in de-icing and snow removal equipment to ensure they are prepared for winter storms.

All aviation stakeholders undertake *mitigating actions* in preparation for an anticipated severe winter storm or in response to one that is underway to limit potential impacts. About 24 to 48 hours before an event, airports and airlines make critical decisions about recalling personnel to ensure they have adequate maintenance staff to undertake service treatments for the events (Bewley et al., 2015). To make these decisions, airports and airlines look at precipitation timing so they know when to recall personnel, precipitation type to prepare the equipment needed, and total accumulation so they have an idea of the intensity of the operation (Bewley et al., 2015). In addition, airlines also make plans to relocate or reposition aircrafts, especially if heavy winds are forecasted; they develop de-icing plans; and they begin to define and execute schedule cancellations based on anticipated airport capacity (Bewley et al., 2015). About two to four hours before an event, airports focus on pretreating the runways, and airlines prepare their de-icing and snow removal equipment and begin repositioning, relocating, and preparing their aircraft (Bewley et al., 2015). During and after the event, the emphasis shifts from snow removal, surface treatment, and de-icing to planning and executing their recovery operations (Bewley et al., 2015). Airport authorities, such as PANYNJ for the NYC area airports, support coordination with the airline industry, airline operators, maintenance crews, ground crews, and local authorities to ensure safe and expedient aircraft recovery. Airlines focus on refining and executing their recovery operations, including aircraft swapping, flight delays, flight cancellations, and passenger reassignments (Bewley et al., 2015). Airline recovery teams determine the costs associated with these options. During this time, the FAA is focused on coordination efforts and monitoring the event to determine if it needs to issue a TMI (Bewley et al., 2015), a technique used to balance demand with capacity during events to ensure airports do not have too many aircraft at one time. FAA continues to monitor TMI issuance during and after the event (Bewley et al., 2015). Decisions made early can affect the recovery options available later in the process, and reduce costs associated with those options (Barnhart and Vaze, 2016).

Severe winter weather can make assets permanently or temporarily inoperable. *Asset damage* includes wear and tear on aircraft, as well as snow removal and de-icing equipment that accelerate their aging and reduce lifespan. Asset damage might also result from aircraft accidents because of reduced visibility or hazardous conditions. Asset damage is mitigated through aircraft repositioning and relocating, and flight cancellations; however, it takes a few days to restage the aircraft, leading to service interruptions.

Winter weather disrupts airport and airline operations, resulting in *service interruptions* through flight delays, diversions, and cancellations (Wieland et al., 2013). Adverse weather accounts for the majority of aviation delays at the major NYC airports, including Kennedy, LaGuardia, and Newark Liberty International (Newark) airports (FAA, 2015). Four of the nation's largest airlines operate hubs at one of these airports: American, United, Delta, and JetBlue. Severe winter storms in the NYC area can significantly disrupt travel on a regional and global scale.

Human health effects are minimal. Flight accidents can cause injury or death; however, mitigating actions help prevent flight accidents during severe winter weather and such accidents are rare. Flight cancellations can cause passenger strandings; airports have cots, food, water, and other provisions available for these passengers.

December 2010 winter storm

This winter storm resulted in significant interruptions to air travel in the NYC area. The forecast model reduced the lead time for aviation decision-makers (Kocin et al., 2011). The convergence of the models on December 25, just one day before the storm, provided suboptimal time to cancel flights and provide warning to avoid airport shutdown (Kocin et al., 2011). In addition, the event occurred during heavy travel period around the Christmas holiday.

According to Kocin et al. (2011), the aviation industry was proactive in flight cancellations in advance of the December 2010 winter storm. However, the NYC metropolitan airports were closed for approximately 24 hours, with services slowly restored during the late afternoon and evening of December 27 (Kocin et al., 2011). Approximately 1,070 flights were cancelled due to weather on Sunday (60% of total flights scheduled were cancelled that day due to weather), 1,790 flights on Monday (94%), 710 flights on Tuesday (37%), and 190 flights on Wednesday (10%); BTS, 2017; Table 10). We estimate 3,760 flights were canceled during the event and recovery in the NYC metropolitan area. Using an average cost of approximately \$5,450 per canceled flight (Marks, 2014), we estimate this storm cost the airlines approximately \$20.5 million during and after the snowstorm event (all dollar values are presented in USD 2016). Applying the average value of this lost passenger time at approximately \$47 per person per lost hour (DOT, 2016), we estimate this storm cost passengers approximately \$93.1 million.

^{9.} Flight cancellations account for flights arriving or departing from Kennedy, Newark, and LaGuardia airports.

Table 10. Flight cancellations, delays, and diversions for the day before the December 2010 storm event, during the

event, and following the event.

	December 25 (Saturday)	December 26 (Sunday; snowstorm)	December 27 (Monday)	December 28 (Tuesday)	December 29 (Wednesday)	Total
Number of flights scheduled	1,480	1,790	1,900	1,900	1,900	7,480
Total number of flights cancelled	50	1,140	1,870	970	240	4,230
Number of flights cancelled because of weather	40	1,070	1,790	710	190	3,760
Percent of flights cancelled because of weather	3%	60%	94%	37%	10%	50%
Total number of flights delayed	20	60	10	230	190	480
Percent of flights delayed	1%	3%	0%	12%	10%	6%
Total number of flights diverted	0	20	0	0	10	40
Percent of flights diverted	0%	1%	0%	0%	0%	0%

Source: Data for flight disruptions are from BTS Airline On-Time Statistics (BTS, 2017). Table includes flight departures and arrivals from the NYC metropolitan airports: Kennedy, LaGuardia, and Newark. Flight cancellations, delays, and diversions rounded to nearest tens; totals may not sum due to rounding. The total column includes flights during and after the event; it does not include flights before the event (e.g., December 25, 2010).

January 2016 winter storm

NWS briefed aviation partners with continuous information for aviation operations, staffing, and decision-making (WFO OKX, 2016). On the morning of Friday, January 22, NWS sent aviation partners a "high impact" summary email highlighting the potential for significant snowfall accumulations and indicating that "surface travel for employees on Saturday is expected to be very difficult if not impossible" (Box 4; WFO OKX, 2016).

For the aviation sector, the NYC metropolitan airports were closed with approximately 1,090 flights cancelled due to weather on Saturday (95% of total flights scheduled were cancelled that day due to weather) and 1,040 flights cancelled on Sunday (69%; BTS, 2017; Table 11). Cancellations and delays continued in the start of the week as airlines began to recover, with approximately 250 flights cancelled due to weather on Monday (14%; BTS, 2017; Table 11). By Tuesday, Kennedy and LaGuardia airports had returned to near-normal operations; however, the Newark airport was still clearing snow with difficulty finding places to put the snow (WFO OKX, 2016). On Tuesday, approximately 50 flights were cancelled due to weather (3%), with the vast majority of cancellations at Newark (BTS, 2017). We estimate approximately 2,420 flights were cancelled during the event and recovery in the NYC metropolitan area. Using an average cost of \$5,450 per cancelled flight (Marks, 2014), we estimate this storm cost the airlines \$13.2 million.

Applying the average value of this lost passenger time at approximately \$47 per person per lost hour (DOT, 2016), we estimate this storm cost passengers approximately \$69.5 million.

Table 11. Flight cancellations, delays, and diversions for the day before the January 2016 storm event, during the

event, and following the event.

	January 22 (Friday)	January 23 (Saturday; snowstorm)	January 24 (Sunday)	January 25 (Monday)	January 26 (Tuesday)	Total
Number of flights scheduled	1,730	1,140	1,520	1,730	1,650	6,040
Total number of flights canceled	370	1,140	1,170	490	270	3,060
Number of flights canceled because of weather	310	1,090	1,040	250	50	2,420
Percent of flights canceled because of weather	18%	95%	69%	14%	3%	40%
Total number of flights delayed	30	0	60	60	0	120
Percent of flights delayed	2%	0%	4%	3%	0%	2%
Total number of flights diverted	0	0	10	0	0	10
Percent of flights diverted	0%	0%	0%	0%	0%	0%

Source: Data for flight disruptions are from BTS Airline On-Time Statistics (BTS, 2017). Table includes flight departures and arrivals from the NYC metropolitan airports: Kennedy, LaGuardia, and Newark. Flight cancellations, delays, and diversions rounded to nearest tens; totals may not sum due to rounding. The total column includes flights during and after the event; it does not include flights before the event (e.g., January 22, 2016).

Key takeaways from the aviation sector

The aviation expert interviews provided several messages from experience with severe winter storms:

1. NWS IDSS enables proactive decisions, which reduce flight cancellations and associated costs.

Accurate forecasts and IDSS allows air traffic control staff, airlines, and airports to proactively implement mitigating actions, including appropriately scheduling essential staff, relocating or repositioning aircraft, and executing flight schedule cancellations; these actions can improve recovery time. Between 2010 and 2016, NWS and others have introduced several IDSS activities and products, including the Aviation Forecast Discussion "High Impact" summary email and the Aviation Winter Weather Dashboard. In addition, in 2010, NWS was not located with the FAA command center. Instead, contracted meteorologists used NWS products and forecasts in conjunction with private weather services to support the FAA during severe winter storms. In 2012, NWS began to provide limited IDSS to the FAA command center. Between 2012 and 2016, NWS increased its IDSS and other services to FAA.

Although it is difficult to quantify the value of IDSS for the aviation sector, it is reasonable to conclude that the significant reduction in service interruptions from the December 2010 storm to the January 2016 storm is at least partially the result of IDSS. The December 2010 storm occurred over the holidays with more scheduled flights than the January 2016 storm; therefore, comparing the number of flight cancellations during the two storm events is challenging. Comparing the percent of flights cancelled for each storm is a better metric. During the December 2010 storm (without formal IDSS), approximately 3,760 of 7,480 flights during and 2 days after the storm event were cancelled due to weather (or 50.2% of flights). During the January 2016 storm (with formal IDSS), approximately 2,420 of 6,040 flights were canceled due to weather (or 40.1% of flights). To estimate the potential benefit of IDSS, we apply the 2016 storm cancellation rate to the 2010 storm and to flight cancellations due to weather during the 2010-2011 winter season (Table 12), and the 2010 storm cancellation rate to the 2016 storm and to flight cancellations due to weather during the 2015–2016 winter season (Table 13). We find that IDSS provides a potential value of approximately \$20.9 million to \$22.9 million during a severe winter storm, and approximately \$33.1 million to \$65.8 million during a winter season (Tables 12 and 13).

Figure 13 displays the flight cancellations during the 2010–2011 and 2015–2016 winter seasons.

Table 12. Potential benefit of IDSS to the aviation sector during the December 2010 winter storm and the 2010–
2011 winter season.

	December 2010 storm flights	December 2010 storm airline	2010–2011 winter season	2010–2011 winter season
	canceled due to	and passenger	flights canceled	airline and
	weather	costs	due to weather	passenger costs
Without formal IDSS	3,760 (actual)	\$113,605,700	10,800 (actual)	\$326,404,900
With formal IDSS	3,000 (estimated)	\$90,688,900	8,620 (estimated)	\$260,561,800
Difference (partial value of IDSS)	760	\$22,916,800	2,180	\$65,843,100

Notes: We use weather-related flight cancellations during the December 2010 storm and the 2010–2011 winter season to estimate the potential cost to airlines and passengers without IDSS, and apply the 2016 storm cancellation rate to estimate the potential cost to airlines and passengers with IDSS. We use an average cost of \$5,450 per cancelled flight (Marks, 2014) to estimate airline costs and we apply the average value of this lost passenger time at approximately \$47 per person per lost hour (DOT, 2016) to estimate passenger costs (see Appendix B for more details on the methodology). Flight cancelations are rounded to nearest tens and airline and passengers costs are rounded to the nearest hundred.

Table 13. Potential benefit of IDSS to the aviation sector during the January 2016 storm and the 2015–2016 winter season.

	January 2016 storm flights canceled due to weather	January 2016 storm airline and passenger costs	2015–2016 winter season flights cancelled due to weather	2015–2016 winter season airline and passenger costs
Without formal IDSS	3,040 (estimated)	\$103,620,300	4,810 (estimated)	\$164,193,800
With formal IDSS	2,420 (actual)	\$82,717,800	3,840 (actual)	\$131,072,300
Difference (partial value of IDSS)	610	\$20,902,500	970	\$33,121,500

Notes: We apply the 2010 storm cancellation rate to estimate the potential cost to airlines and passengers without IDSS, and use weather-related flight cancellations during the December 2016 storm and the 2015–2016 winter season to estimate the potential cost to airlines and passengers without IDSS. We use an average cost of \$5,450 per canceled flight (Marks, 2014) to estimate airline costs and we apply the average value of this lost passenger time at approximately \$47 per person per lost hour (DOT, 2016) to estimate passenger costs (see Appendix B for more details on the methodology). Flight cancelations are rounded to nearest tens and airline and passengers costs are rounded to the nearest hundred.

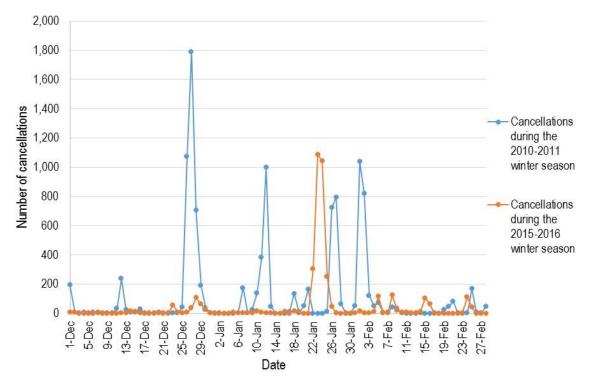


Figure 13. Number of flight cancellations due to weather during the 2010-2011 (blue) and 2015-2016 (orange)

winter seasons. The figure includes flight departures and arrivals from the major NYC metro airports. Source: Data for flight cancellations are from BTS Airline On-Time Statistics (BTS, 2017).

In addition, we see a shift from reactive service interruptions (i.e., more flight cancellations after the event) to proactive decisions (i.e., more flight cancellations before or early in the event; Figure 14).

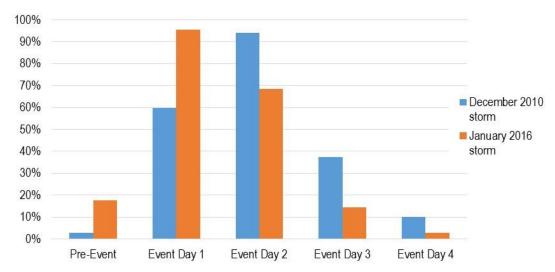


Figure 14. Comparison of the percent of flight cancellations due to weather during the December 2010 and January 2016 winter storms. Source: Data for flight cancellations are from BTS (2017).

According to Ralph Tamburro, the Delay Reduction Program Manager at the Port Authority and previously with FAA, the January 2016 storm resulted in much more snow, but recovery in the aviation sector was faster, suggesting that there was better planning and preparation by the airlines and a more effective response by the Port Authority to keep the runways open (personal communication, September 11, 2017). In addition, Kevin Johnston at FAA indicated that in 2012, the FAA National Operations Manager (NOM) was not interested in bringing NWS into the FAA, but the NOM now says bringing NWS meteorologists back into the Command Center was the best

decision made by FAA leadership at the Command Center (personal communication, September 25, 2017). According to Kevin Johnston, meteorologists with knowledge about aviation operations can provide impact-based forecasts that allow the FAA to make critical decisions proactively.

... bringing NWS meteorologists back into the Command Center was the best decision made by FAA leadership at the Command Center.

-FAA National Operations Manager via Kevin Johnston, FAA

2. Marginal winter storm events – where the signal is not as strong or there is high uncertainty – have the biggest impacts on the aviation sector; these are the storms where IDSS likely makes the largest impact.

The severe winter storm case studies are high-impact events. For these events, airlines, airports, and the FAA take precautionary actions to reduce impacts by cancelling flights, and repositioning and relocating aircraft. However, the marginal winter storm events – un-forecasted events or events with high uncertainty – have the biggest impacts on the aviation sector. These marginal storm events are typically not forecasted as well as high-impact events, and may have last-minute changes in the forecasts such as wind shifts or changes in the type of precipitation, which can catch the airlines, airports, and the FAA unprepared, causing significant impacts to the sector.

According to Kevin Johnston at FAA, marginal events are when IDSS is most valuable (personal communication, September 25, 2017). Therefore, NOAA may want to compare marginal storms to better understand the value of IDSS. For example, on October 29, 2011 – before the implementation of IDSS – weather models showed some snow; however, the snow arrived 8 to 11 hours sooner than forecasted, causing substantial negative impacts to the aviation sector (Kevin Johnston, FAA, personal communication, September 25, 2017). This storm can provide an example of impacts without IDSS and could be compared with a more recent, but similar-sized storm, to better understand the value of IDSS for these marginal events.

3. The aviation sector makes critical decisions on short timeframes, and generally two to three days is needed to recover from severe winter storms.

Even with perfect weather information and IDSS, the aviation sector may experience significant impacts from severe winter weather. The aviation sector makes critical decisions on short timeframes. Up to 2 days (48 hours) before an event, the aviation sector begins considering changes in operations; however, major decisions (e.g., flight cancellations and repositioning of aircraft) are typically made 24 hours or less before an event, with most decisions made at 24 hours, 12 hours, 8 hours, and 4 hours before the onset of a winter storm event (Mike Robinson, The MITRE Corporation, personal communication, March 13, 2017). According to the many experts we interviewed, the aviation sector had adequate time to make decisions for the December 2010 and January 2016 storm events. Although the aviation sector had adequate time to make critical decisions, the December 2010 and January 2016 storms resulted in significant flight disruptions (Tables 10 and 11). In addition, it generally takes three to five days for the aviation sector to recover from severe winter weather (Michael Eckert, NOAA NWS Aviation Weather Center, personal communication, September 22, 2017). During high-impact events, airlines relocate and reposition their aircraft; it takes a few days to get aircrafts and staff in position (Michael Eckert, NOAA NWS Aviation Weather Center, personal communication, September 22, 2017). Even with improved IDSS, it will likely still take three to four days for the aviation sector to recover from severe winter weather.

5.2 Ground transportation

Severe winter weather threatens ground transportation systems and impacts roadway safety, mobility, and productivity. Reduced visibility, precipitation, and winds can affect vehicle and infrastructure performance, driver capabilities, pavement friction, and traffic flows (FHWA, 2012). Weather can increase the risk of vehicle crashes, increase travel delays, and cause closures of transportation systems with impacts to businesses and schools (Table 14). In the NYC area, ground transportation stakeholders making operational decisions about mitigating actions and recovery for winter weather events are state and local transportation departments – such as the New York State Department of Transportation (NYSDOT), the NYC Department of Transportation (NYC DOT), DSNY, and MTA. In addition, the Federal Highway Administration conducts research and provides technical assistance to state and local agencies to improve public safety and mobility.

In the ground transportation sector, *defensive investments* in advance of any particular winter storm can help build resilience against severe winter storms and make the transportation system robust to all hazards. Ongoing research is developing and implementing technologies to reduce impacts of winter storms on the transportation sector. For example, NYC is buying road sensors to monitor temperatures on major city streets (Blau, 2017). This technology will help the NWS forecast hazardous driving conditions. The city expects to pay a minimum of \$500,000 for the technology (Blau, 2017).

^{10.} The MITRE Corporation is a nonprofit organization that works with industry and academia to advance and apply science, technology, systems engineering, and strategy to enable better government and private decisions.

^{11.} Although many expert interviewees indicated that the aviation sector had adequate time to make decisions, some material we reviewed indicated that aviation stakeholders made critical decisions with suboptimal lead time for the December 2010 storm (Kocin et al., 2011).

Table 14. Impact matrix summarizing the effects of winter weather on ground transportation by stakeholder group.

Stakeholders	Defensive investments	Mitigating actions		Asset damages	Human health	
Federal transportation departments	Research and testing of new technology.	-	-	-	-	
State and local emergency management and transportation departments	Invest in snow removal equipment.	 Issue hazardous weather advisories and travel bans. Position snow removal equipment. Remove snow and treat surfaces. Clear entrances to bridges and tunnels. Tow vehicles and buses, and suspend alternative side parking on snow emergency streets. Suspend bus, commuter rail, and aboveground subway services; and monitor and remove snow from subway and commuter rail stairs and platforms. 	 Closure of roads, bridges, and tunnels. Reduced mass transportation services. Travel time delays on roads and public transportation. 	 Snowed-in (inoperable) roadways. Equipment failure. Accidents. 	 Injuries and fatalities. Stranded motorists and passengers. 	

Road management uses three types of *mitigating actions*: (1) advisory actions that provide information about forecasted and existing weather conditions to transportation managers and motorists, (2) control actions that permit or restrict traffic flow and regulate capacity on the transportation infrastructure, and (3) treatment actions that supply equipment and resources to roads to minimize weather impacts (FHWA, 2012). Different entities are in charge of mitigating actions for their jurisdictions. In NYC, the NYCEM coordinates mitigating actions by undertaking weather emergency protocols, and issues hazardous travel advisories to increase hazard awareness for the public and reduce the number of vehicles on roadways. NYSDOT considers travel bans and restrictions for Long Island Expressway and other state highways; whereas NYC DOT considers travel restrictions for NYC and MTA makes decisions about suspending bus, subway, and railroad services during winter weather events. Treatment actions also vary by jurisdiction, with NYSDOT in charge of state highway treatments and NYC DSNY is largely responsible for NYC snow removal efforts (NYC Comptroller, 2015). In NYC, DSNY receives assistance from the Department of Transportation (DOT), the Parks Department, NYPD, and the Department of Environmental Protection (NYC Department of Investigation, 2011). Snow forecasts are used by key decision-makers to treat roads and mobilize ice and snow-removal crews and equipment before and during a storm event. Road treatment can improve safety by reducing crash risks; increase mobility through uniform traffic flow, restoring capacity, and reducing delays; and increase productivity due to reduced labor. Several benefit-costs studies in the United States found that the benefits of more efficient application of anti-icing chemicals and abrasives, and anti-icing systems deployed on bridges outweigh the costs, with benefit-cost ratios ranging from 1.8:1 to 5:1 (Maccubbin et al., 2008).

Severe winter weather can make transportation assets permanently or temporarily inoperable. *Asset damage* includes wear and tear on roads and bridges, as well as snow removal equipment that accelerates their aging and reduces lifespan. Asset damage also includes damages to vehicles in crashes because of reduced visibility or hazardous conditions. Asset damage to roads and bridges is mitigated through snow removal and surface treatment, and travel restrictions and bans.

Winter weather disrupts transportation, resulting in *service interruptions* through closures of roads, bridges, and tunnels; and suspended public transportation services, which result in travel time delays, and closures or delays for businesses and schools. MTA, for example, is the largest public transit authority in the United States, carrying over 11 million passengers on an average weekday. Suspended public transportation services have the potential to substantially disrupt the local economy. In addition, road closures can affect the flow of goods and services, which can also reduce the level of economic activity. Secondary economic impacts from transportation interruptions are likely most severe for construction, hospitality, and retail. In the food service and catering industries, transportation interruptions may disrupt regular deliveries of supplies and reduce the number of employees who can serve food or undertake other services (CNBC, 2016). We expect some sales to be permanently lost. For example, if a catering company cancels several jobs

during a snowstorm, those losses may be passed on to employees through cancelled shift and lost wages rather than decreases in employment. However, some of these impacts are made up at a later date (Bloesch and Gourio, 2015).

Severe winter can result in effects to *human health*. Approximately 22% of all vehicle accidents are weather-related. Of the weather-related crashes, the vast majority occur on wet pavement or during rainfall, with a smaller percentage of crashes occurring during winter conditions (FHWA, 2017). Analyzing NYC vehicle accident data, ¹² we found that the number of motorists injured increases with slippery pavement, whereas the number of pedestrians and cyclists injured decreases with slippery pavement. We assume the number of pedestrians and cyclists injured decreases during bad weather because there are fewer pedestrians and cyclists on the road, and motorists drive slower so accidents are less severe. We did not see a correlation among the number of motorists, pedestrians, and cyclists killed during slippery pavement conditions. Severe winter weather also results in passenger strandings on roads and mass transportation system delays.

December 2010 winter storm

During the December 2010 storm, the NYC area experienced significant disruptions to transportation and other essential services. The lack of advisories and declarations of a snow emergency, and the timing of the storm over a holiday weekend contributed to transportation disruptions. In addition, the city failed to procure and position sufficient private resources – including private contractors for towing, plowing, and shoveling services – before the storm event (Weinstein and Funk, 2011). On Saturday, December 25, NYC decided against declaring a "snow emergency," which would require private vehicles to stay off of designated snow routes and ban parking on snow routes (Weinstein and Funk, 2011). During the evening of Sunday, December 26, and the morning of Monday, December 27, NYC officials were unclear on who could issue a "snow emergency" or "state of emergency" declaration, and the actions required by those declarations (Weinstein and Funk, 2011). Sunday, December 26, was a holiday season shopping day with a large number of vehicles on the roads and high MTA-wide ridership (MTA, 2011). In Box 5, we describe the specific actions taken by DSNY for roadways and MTA for mass transportation services.

As described in Section 4.1, NYC took significant steps to improve the city's response to future snow-related emergencies (New York City Council, 2011). Many actions taken focused on transportation, including defining the roles of all agencies in a winter weather emergency (Local Law 24) and reporting requirements for NYCEM that describes the city's preparation, and response to, all snow events the previous year (Local Law 26; New York City Council, 2011). In addition, the city created the Tow Truck Task Force to improve the city's ability to remove stuck vehicles that impede DSNY plowing operations, FDNY EMS traffic, and general traffic.

^{12.} NYPD Motor Vehicle Collisions provides a breakdown of every collision in NYC by location and injury (data available: https://data.cityofnewyork.us/Public-Safety/NYPD-Motor-Vehicle-Collisions/h9gi-nx95).

Box 6. Description of actions taken by DSNY and MTA for the December 2010 storm

In advance of the storm – on December 24 – DSNY issued a Snow Alert for this storm and scheduled 2,500 employees for snowfall cleanup efforts (NYC Department of Investigation, 2011). However, DSNY was unable to effectively respond to the storm and by the evening of December 27, approximately 250 DSNY vehicles were immobile and unable to assist in clean-up efforts (NYC Department of Investigation, 2011). In addition to the timing of the storm and the lack of a snow emergency declaration, DSNY vehicles were deployed without the proper number of chains on their tires and a cease salt order was issued on December 26 because city officials determined that the snow accumulations rendered salting useless (NYC Department of Investigation, 2011). Many DSNY and DOT employees indicated that they thought the failure to pre-salt made the streets more difficult to clear during recovery efforts, and increased or continued salting during the storm could reduce the storm's impacts (NYC Department of Investigation, 2011). In addition, the storm was so severe that DSNY could not keep up with snowfall rates and, as a result, DSNY did not plow secondary and tertiary streets (NYC Department of Investigation, 2011).

On December 23, MTA declared a low-level alert for the subway. Storm tracking efforts decreased over the holidays, with the highest-level subway alert formally declared as the storm arrived on December 26 (MTA, 2011). The MTA agencies began to mobilize staff and equipment for storm response over the weekend of December 25 and 26 (MTA, 2011). Snow began across the NYC area during the afternoon of Sunday, December 26, with snowfall rapidly intensifying in the evening. Transportation delays began in the early evening, and continued throughout the night and early morning. Around 6 p.m., Amtrak suspended Northeast Corridor services between New York and Boston, the Port Authority suspended AirTrain service to Kennedy Airport, and the New Jersey Transit suspended all bus services (MTA, 2011). That night, the LIRR implemented its winter storm service suspension policy, with service suspended to Penn Station around 8:30 p.m. and system-wide suspended service an hour later (MTA, 2011). By 10:30 p.m., MTA suspended the Metro North New Haven Line service. By midnight, MTA suspended several above-ground subway services (MTA, 2011). Buses and paratransit services were suspended as roads became impassible (MTA, 2011). NYC Transit estimates that approximately 650 buses were stuck in the snow on Sunday, December 26 (Kluger, 2011). In the early morning of December 27, a subway train with over 400 passengers became stuck, and recovery of the train took over 7 hours; many of the passengers were returning home from Kennedy Airport after flight cancellations (MTA, 2011). By Monday, December 27, many MTA fleets and outdoor infrastructure were snowed in (MTA, 2011). Metro-North began morning rush hour service; however, the train became stuck and MTA suspended all services at 8:45 a.m. (MTA, 2011). Recovery was slow. By Thursday, December 30, DSNY plowed nearly all roads and MTA subway and bus services were largely restored (MTA, 2011). MTA fully restored bus services by Sunday, January 2, one week after the storm.

January 2016 winter storm

In contrast, snow removal and other actions were carried out more quickly for the January 23, 2016 storm event (DSNY, 2016). Large spreaders began spreading salt on roadways when the snow began; these spreaders are the first line of defense against snow and ice conditions (DSNY, 2016). Snow plowing operations began when snowfall exceeded two inches; plows follow designated routes to ensure they remove snow from all street segments (DSNY, 2016). After streets are cleared, plows clear municipal parking lots, bike lanes, and pedestrian infrastructure. In addition, DSNY deploys specialized equipment to address local challenges. For examples, DSNY deploys V-plows to areas where drifting or significant snow accumulations make plowing too difficult for truck plows and utility haulsters – or small spreaders with plows attached – to treat areas with limited accessibility (DSNY, 2016).

During the January 2016 winter storm, impacts to travel and mass transit were widespread (WFO OKX, 2016). NYC suspended aboveground subway operations on Sunday, January 24; by Monday, January 25, aboveground subway service resumed. Underground subway operation continued throughout the winter storm. The MTA suspended bus services on Saturday, January 23; by Sunday morning, January 24, buses were in operation on a modified schedule (a 19-hour service interruption). NYC implemented a driving ban, which allowed DSNY to clear roads. DSNY predeployed all spreaders on Friday evening, which allowed for efficient snow removal once the storm arrived; and effective messaging to the workforce ensured that routes were adequately plowed, which allowed the majority of the city to be open on Sunday morning (DSNY, 2016).

By the morning of Sunday, January 24, about 80% of the highways and arterial roadways were cleared (DSNY, 2016). Areas with a high percentage of plowed streets allowed staff to assist in clearing secondary and tertiary streets; this diversion of resources was possible because of the travel ban jointly issued by the Mayor and the Governor. Queens was particularly hard hit by the winter storm and required the use of front-end loaders to clear snow; standard plows could

not push through the accumulated snow and drifts (DSNY, 2016). DSNY diverted all available front-end loaders to Queens to assist in snow removal operations (DSNY, 2016). By Monday morning, January 25, DSNY cleared 97% of all streets citywide (DSNY, 2016). During the storm event, nearly 200 vehicles were towed in NYC; the majority of these requests were in Queens (DSNY, 2016; Bryan Mentlik, NYCEM, personal communication, March 24, 2017). Ambulances and private vehicles were the most common stuck vehicles (DSNY, 2016). In addition, over 650 DSNY vehicles were stuck on Saturday or Sunday (January 23 or January 24) (DSNY, 2016).

After the January 2016 snowstorm, the city decided to invest \$21 million in capital funds to purchase additional snow equipment to remove snow from narrow streets, especially during storms with over 12 inches of snow accumulation (DSNY, 2016). New snow equipment – including 80 additional haulsters, 21 new front-end loaders, and 40 new skid steer plows – will allow DSNY to limit the use of outside contractors who currently supplement snow clearing operations on smaller, narrow street segments; decrease turnaround time for salt loading; and quickly clear pedestrian infrastructure, including the clearing of crosswalks and bus stops (DSNY, 2016).

Key takeaways from the ground transportation sector

The transportation expert interviews and a review of the literature provided some messages for severe winter storms:

1. NWS IDSS, coupled with changes to operational procedures, benefit the transportation sector, largely shifting the transportation sector from reactive to proactive decision-making.

Between 2010 and 2016, NWS worked closely with NYCEM and other local transportation partners to improve IDSS. In 2016, NWS provided briefings to local emergency managers, including onsite briefings to NYCEM and remote or informal onsite briefings to NYSDOT, MTA, and other core partners. During this time, NYC also significantly changed operational procedures to improve the city's response to future snow emergencies. In 2016, NYC implemented a travel ban that improved the speed of snow removal efforts, allowing the transportation sector to quickly recover from the storm event. We believe the combined changes – the implementation of IDSS and the implementation of NYC weather emergency protocols – resulted in a significant reduction in ground transportation service interruptions from the December 2010 storm to the January 2016 storm. In particular, we see a shift from reactive service interruptions (i.e., where untreated roads disable vehicles and buses, and subway and railroad services are delayed in suspending services), to proactive decisions (i.e., suspend services and close roads). This shift to proactive decisions reduces the recovery time: despite greater snowfall amounts during the January 2016 storm, it took the NYC transportation sector seven days to recover from the December 2010 storm (from December 26 to January 2, 2010) and only two days to recover from the January 2016 storm (from January 23 to January 25, 2016). A quicker recovery time probably reduces secondary impacts on the services sector, such as catering, and other business activity.

2. Forecast information and IDSS are important for transportation-related decision-making.

Forecast information and IDSS provide the transportation sector with critical information, presented in an easy-to-understand manner. According to NYCEM, weather forecast information is critical to mitigation actions for the transportation sector, such as crafting public and partner messaging; deciding whether to order bridge, tunnel, or roadway closures; modifying mass transit system operations; and determining whether to order citywide travel bans. To make these decisions, NYCEM uses advisories, watches, and warnings for wind chill, freezing rain, ice storms, winter storms, and blizzards; as well as information from daily weather consults with NWS. Using this information, NYCEM (with its partners) makes decisions on how to mitigate winter storm impacts.

According to NYCEM, IDSS allows for a quicker and more complete update on the forecast, which allows NYCEM to relay the information to the appropriate agencies to take appropriate mitigating actions. For example, if forecasted snowfall totals are reduced, NYCEM can adjust staffing levels to reflect reduced risks. According to MTA, IDSS provides weather forecasts and information easily understood by an

The MTA actively uses IDSS to make decisions that affect 15.3 million people.

-Andrew McMahan, Director of Emergency Management and Operations Support, MTA

emergency manager and relevant for decision-makers. MTA's Director of Emergency Management and Operations Support does not need to translate NWS weather forecasts and information for briefings to leadership (Andrew McMahan, MTA, personal communication, October 27, 2017).

3. The timing of storms plays a significant role in storm response.

To some extent, the travel ban implemented during the January 2016 storm was possible because the severest storm impacts occurred starting the morning of Saturday, January 23 (NYCEM, 2017). Because it was a weekend, there was less of a strain on the traditional work week, so the city and its residents were more amenable to the ban (NYCEM, 2017). In contrast, the December 2010 storm occurred during the heavy travel period around the Christmas holiday when there may have been more resistance to a travel ban. That said, the lessons learned from the reactive response during the December 2010 storm shifted NYC agencies to prefer proactive suspension of non-emergency transportation services to reduce impacts and improve recovery; Hurricane Sandy reinforced this shift in thinking (Andrew McMahan, MTA, personal communication, October 27, 2017).

5.3 Energy

Severe winter storms are often categorized by extreme cold, snow, ice, and high winds. Each of these characteristics can have consequences for the energy sector, including power outages, damage to transmission lines and other utility assets, and the associated effects on human health (Table 15). Utilities make operational decisions about mitigating actions and restoration actions after winter weather events.

Table 15. Impact matrix summarizing the effects of winter weather on energy by stakeholder group.

Stake- holders	Defensive investments	Mitigating actions	Service interruptions	Asset damages	Human health
Utilities	 Storm hardening. Vegetation management. Power pole upgrades and maintenance. 	 Alert critical customers to power outages. Alert county, municipal, and state emergency officials on outages and restoration efforts. Fuel and supply vehicles with repair materials. Prepare personnel, contractors, and nearby utilities for around-the-clock response. Prepare staging areas. 	 Power outages for residential and commercial customers. Business interruptions. 	Damage to transmission lines.	Injuries and fatalities.

Defensive investments include storm hardening, such as undergrounding overhead power lines, replacing existing power poles and crossbars with stronger components, and upgrading conductors with heavier wire (Preston et al., 2016). After Hurricane Sandy, Consolidated Edison spent \$1 billion on storm hardening (Consolidated Edison, 2016a). In many areas, Consolidated Edison installed smart switches on overhead lines. These switches automatically disconnect segments of the electric grid that are experiencing problems, which allow for power to flow to other areas that are not interrupted, while making repairs to problem areas (Consolidated Edison, 2013). Smart switches reduce the number of homes and businesses that lose power when a tree brings down an electric wire (Consolidated Edison, 2013).

There are many *mitigating actions* that local and state governments, and electric power providers can take in the days and hours leading up to a severe winter storm. City officials have a number of options for mitigating the impacts of snow storms on the city, including the energy sector. The city could issue a Hazardous Weather Advisory or a Hazardous Travel Advisory that reduces the number of vehicles on the roadways, clearing the roads for emergency vehicles including utility vehicles, decreasing the response time to possible power outages (NYCEM, 2016). By issuing a Cold Weather Alert, the city will trigger increased outreach to vulnerable populations, including the elderly and the poor who depend on electricity for medical equipment or the refrigeration of medications (NYCEM, 2016). City and state officials can also declare a weather emergency, which also will trigger many of these actions (NYCEM, 2016). Aside from issuing warnings and declarations, state and local officials can coordinate with utility providers in the days and hours leading up to a storm, and keep track of current outages and restoration efforts during the storm.

Two electric power providers service the NYC area: Consolidated Edison Inc. (Consolidated Edison), which services five of the boroughs; and Public Service Electric and Gas Company (PSEG), which services Staten Island and Long Island. Consolidated Edison and PSEG have specific protocols that they follow in advance of a major storm. Some similarities in their plans include alerting critical customers, such as hospitals and airports, that need to make alternate arrangements in case of power outages; ensuring that all available personnel including employees, contractors, and nearby utilities are prepared to respond around the clock; ensuring all vehicles are fueled up and have extra repair materials such as poles, transformers, and other pole-top equipment on hand; and coordinating with county, municipal, and state emergency officials to alert them of any special concerns and keep them updated on outages and restoration

efforts (Consolidated Edison, 2016b; PSEG, 2017). In addition to these actions, PSEG also prepares staging areas for extra crews and supplies, tests generators at utility locations, and holds training sessions for additional utility crews to ensure that personnel know their storm roles in the days leading up to a major storm (PSEG, 2017).

Winter storms can seriously impact the energy sector, namely through *service interruptions*. Winter storms can often lead to significant power outages because of the extreme cold, high winds, and snow and ice. Snow and ice can accumulate on power lines and trees, increasing the likelihood of a breakage or a fallen power line. High winds can also damage overhead power lines, resulting in outages. Finally, extreme cold can make it difficult for natural gas to be delivered to electric power generators, lowering generating capacity and putting pressure on the electric grid, which can lead to outages. In NYC, most boroughs and surrounding areas, including Staten Island and parts of Queens, the Bronx, and Brooklyn, rely on overhead utility lines to distribute power to residents (NYCEM, 2014). These lines can be less reliable as they are more vulnerable to weather such as high winds and ice storms, as described above. However, these lines are also easier to repair because the damage can be easily located, accessed, and isolated (NYCEM, 2014). Manhattan is the only borough that uses only underground lines (NYCEM, 2014). These lines are not vulnerable to winter storms because they are shielded from the elements; therefore, there are fewer weather-related service interruptions in Manhattan. Power interruptions also lead to secondary impacts in many other economic sectors and activities. For instance, Anderson and Geckil (2003) estimated the loss of perishable food during the 2003 blackout in the Northeast in the hundreds of millions of dollars.

Severe winter storms can *damage assets*. Ice can accumulate on power lines, which weighs down the lines and increases the cross-sectional area for wind drag on the line. Ice accumulation can lead to an increase in the breakage of power lines and support structures (Preston et al., 2016). Ice can also accumulate on tree branches. This, with the high winds characteristic of a blizzard, can also lead to an increase in the number of fallen trees and branches. These trees can damage or down distribution power lines, which may result in power outages for many customers (Preston et al., 2016) or damage other assets, such as parked cars. High winds can also damage components at the transmission level, denying service to distribution substations, which can also lead to widespread power outages (Preston et al., 2016).

Power outages can have *human health* effects, particularly for vulnerable residents. The Department of Health and Mental Hygiene found that mortality rates rise during energy failure events (NYCEM, 2014). Individuals who are reliant on power-dependent medical equipment or medicines that must be refrigerated can suddenly find themselves in life-and-death situations during power outages. If elevators stop functioning during outages, seniors, the homebound, and individuals with disabilities can become trapped in their homes. Evacuating these individuals from tall buildings can be a substantial challenge. Low-income populations living in NYC Housing Authority developments are vulnerable to power outages and power voltage reductions because they live in older high-rise buildings, which often lack backup generators (NYCEM, 2014). Power outages in the winter can lead to the inappropriate use of backup generators and appliances for heat (e.g., use of gas stoves, ovens), putting individuals at greater risk of carbon monoxide poisoning. This is particularly true for immigrants with low English proficiency who may not be as aware of existing carbon monoxide safety regulations (NYCEM, 2014).

December 2010 winter storm

Consolidated Edison, which serves 3 million customers in NYC and its northern suburbs, reported that approximately 4,100 customers lost power during the December 2010 storm (Table 16). These customers experienced power interruptions at an average duration of 12.2 hours (Charles Viemeister, Consolidated Edison, personal communication, October 3, 2017). On Long Island, PSEG reported nearly 72,800 of its 1.1 million customers experienced a power outage (Table 16; Tim Lupski, PSEG, personal communication, October 20, 2017). Assuming these customers experienced similar interruption durations, we estimate that the interruption costs from the December 2010 storm were approximately \$106.8 million (see Appendix B for the data sources and methods for monetary estimates).

76,930

\$106,840,600

willer storm.			
Utility	Operating area	Total customers interrupted	Interruption cost
Consolidated Edison	Queens	4,130	\$5,729,100
PSEG	Queens/Nassau	20,860	\$28,967,800
PSEG	Central Nassau	11,260	\$15,644,300
PSEG	Western Suffolk	27,000	\$37,495,500
PSEG	Eastern Suffolk	13.680	\$19,004,000

Table 16. Total customers interrupted from power outages and interruption cost (USD 2016) for the December 2010 winter storm

Total Notes:

- Assumes all customers experienced power interruptions during the December 2010 winter storm at an average duration of 12 hours. The estimated average electric customer interruption cost for a twelve-hour interruption duration is approximately \$18 for a residential customer (approximately 86% of customers), \$8,749 for a small commercial or industrial customer (approximately 14% of customers), and \$116,670 for a large commercial or industrial customer (less than 1% of customers; USD 2016; Sullivan et al., 2013).
- The number of customers interrupted are rounded to the nearest tens and interruption costs are rounded to the nearest hundreds.
 Totals may not sum due to rounding.

If we assume that formal IDSS during the December 2010 storm resulted in the same number of power outages but a shorter power outage time, then customer interruption costs would decrease. For example, if formal IDSS during the December 2010 storm resulted in customers experiencing an average power interruption duration of 4.8 hours – similar to the January 2016 storm – then the interruption costs from the December 2010 storm would decreased from approximately \$106.8 million to \$36.9 million.

January 2016 winter storm

Consolidated Edison, which serves 3 million customers in NYC and its northern suburbs, reported that approximately 900 customers lost power during the January 2016 storm (Table 17). These customers experienced power interruptions at an average duration of 4.8 hours (Charles Viemeister, Consolidated Edison, personal communication, October 3, 2017). In addition, snow melt and salt caused an additional 3,600 power outages after the storm (Charles Viemeister, Consolidated Edison, personal communication, October 27, 2017). On Long Island, PSEG reported that fewer than 30,000 of its 1.1 million customers experienced a power outage (Table 17; Tim Lupski, PSEG, personal communication, October 20, 2017). Assuming these customers experienced similar durations of over four hours, we estimate that the interruption costs from the January 2016 storm were \$14.7 million (see Appendix B for the data sources and methods for monetary estimates).

Table 17. Total customers interrupted from power outages and interruption cost (USD 2016) for the January 2016 winter storm.

Utility	Operating area	Total customers interrupted	Interruption cost
Consolidated Edison	Queens	890	\$426,200
PSEG	Queens/Nassau	9,480	\$4,542,600
PSEG	Central Nassau	7,310	\$3,506,100
PSEG	Western Suffolk	2,220	\$1,063,900
PSEG	Eastern Suffolk	10,800	\$5,176,400
Total		30,690	\$14,715,200

Notes:

- Another 3,600 Consolidated Edison customers lost power after the storm due to snow melt and salt related to the storm.
- Assumes all customers experienced power interruptions during the January 2016 winter storm at an average duration of four hours. The estimated average electric customer interruption cost for a four-hour interruption duration is approximately \$9 for a residential customer (approximately 86% of customers), \$2,945 for a small commercial or industrial customer (approximately 14% of customers), and \$47,719 for a large commercial or industrial customer (less than 1% of customers; USD 2016; Sullivan et al., 2013).
- The number of customers interrupted are rounded to the nearest tens and interruption costs are rounded to the nearest hundreds.
 Totals may not sum due to rounding.

According to utilities, more customers would have experienced power interruptions without the storm hardening investments made after Hurricane Sandy (Associated Press, 2016). Consolidated Edison estimates that their \$1 billion investment in infrastructure upgrades reduced power outages by 1,000 customers (Consolidated Edison, 2016a). If we

use the same assumptions for customer interruption costs for a four-hour interruption duration, these upgrades saved 1,000 customers about \$500,000 dollars. In addition, the snow was not wet, which reduced the amount of snow on wires (Associated Press, 2016).

Key takeaways from the energy sector

The utilities provided one key message from experience with severe winter storms:

NWS decision support services may benefit the energy sectors, but storm hardening may provide more benefits.

In the NYC area, energy providers – specifically Consolidated Edison and PSEG – have strong partnerships with emergency managers (Ross Dickman, NWS, personal communication, July 26, 2017). NWS participates in drills, called table top exercises, with energy providers and emergency managers to simulate severe winter weather events and other hazardous weather events to strengthen operational plans and ensure rapid response (Ross Dickman, NWS, personal communication, July 26, 2017). NWS participation allows for improved IDSS for energy providers. We conclude that IDSS can provide energy providers with improved weather information that allows the utilities to proactively deploy staff, which can reduce the number and duration of power outages. In addition, we believe that better forecasts and warnings also allow utilities to make better decisions on energy production and trading in energy markets to hedge against possible impacts. Although we see a significant decrease in the number of power outages and outage durations between the December 2010 and January 2016 storms (from 12.2 hours to 4.8 hours). we do not have enough information to attribute this decrease in power outage durations to IDSS. We also acknowledge that utilities in the NYC area made significant investments in storm hardening after Hurricane Sandy, and more customers would have experienced power interruptions without these investments. Defensive investments likely resulted in significant reductions in power outages from the December 2010 storm to the January 2016 storm; however, we believe that IDSS also likely contributed to the decrease in power outage durations between the two storm events.

6. Findings and Recommendations

This study advances our overall understanding of the potential impacts of severe winter storms and the degree to which IDSS can reduce economic losses. The study also provides a solid and tractable foundation for future work. The systematic approach used to synthesize and understand impacts and IDSS can be applied to other sectors affected by winter weather, such as public health or other storm events, such as hurricanes. Below we summarize several key findings from this study and provide recommendations to further assess the value of IDSS for winter storms as well as other storm events.

IDSS provides core government partners with better information and support to take actions that reduce social and economic impacts.

In this study, we hypothesized that formal IDSS provides core government partners with better information and support to take actions that reduce social and economic impacts. We find that IDSS provides a shift toward more active involvement by weather forecasters to better understand societal impacts from weather events. This shift ensures NWS information and services are more relevant to decision-makers, which allows decision-makers to use NWS information and services to take proactive mitigating actions to protect life and property. Our four case study storm events show an increase in mitigating actions, with a general trend in decreased service interruptions, asset damages, and human health effects for the aviation, ground transportation, and energy sectors (Table 18).

Table 16. Com	parison of four case	study storin ev	CIIIS.			
Storm	NESIS score	Formal	Mitigating	Service	Asset	Human
month/year	and category	IDSS	actions	interruptions	damages	health
December 2010	4.92; Category 3	No	0	0000	$\Diamond \Diamond \Diamond$	◊◊◊
February 2013	4.35; Category 3	Yes	00	000	◊	◊◊
January 2015	2.62; Category 2	Yes	00	◊◊	◊◊	◊
January 2016	7.66: Category 4	Yes	0000	٥٥٥	٥٥٥	٥٥

Table 18. Comparison of four case study storm events.

Notes:

- The mitigating actions symbol (○) provides an order of magnitude estimate, where = limited advisories and actions;
 ○○ = some advisories and actions;
 ○○○ = significant advisories and actions; and ○○○○ = maximum advisories and actions,
 e.g., the city was shut down.
- − The impacts symbol (\Diamond) also provides an order of magnitude estimate, where \Diamond = limited social and economic impacts; \Diamond \Diamond = some social and economic impacts; \Diamond \Diamond 0 = significant social and economic impacts; and \Diamond \Diamond 0 = maximum social and economic impacts, e.g., following the storm, the city took unprecedented actions to change operations and procedures.
- We describe the data sources and methods for monetary estimates provided in the table in Appendix B.

In comparing the December and January 2016 storm events, we conclude that IDSS and mitigating actions reduce service interruptions in some sectors and shift from reactive to proactive actions that prevent service interruptions in other sectors. These changes provide economic benefits and reduce the recovery times after storms (Table 19). Some of these economic benefits are largely attributed to IDSS (e.g., aviation), whereas other benefits may also be the result of mitigating actions (e.g., ground transportation) or defensive investments (e.g., energy).

The findings of this study are consistent with our hypothesis that with better information and support, core government partners can take actions to reduce social and economic impacts. We feel confident that IDSS plays a role in reducing social and economic impacts; however, defensive investments and changes in operational procedures also help reduce social and economic impacts.

Recommendations: Continue to develop methods of identifying, measuring, and quantifying the social and economic impacts of IDSS. Extend the analysis of the benefits of IDSS to other sectors – such as construction, retail, tourism, and services – and to other weather events – such as floods, tornadoes, and hurricanes. In addition, explore additional approaches to valuing IDSS, such as econometric modeling, simulation modeling, input-output and computable general equilibrium modeling. Develop or implement approaches to verification of IDSS that are similar to verification of weather forecasts and warnings; a verification system would help measure the value of IDSS.

Cantana	Casial and assume in immediate sates are	Dagamban 2010	Jammann 2016	Improve-
Sectors	Social and economic impact category	December 2010	January 2016	ment
Aviation	Number of flight cancellations due to weather ¹	3,760 (50.2%)	2,420 (40.1%)	ı
	Recovery time (in days)	3	3	0
	Roadways	Severe road blocks with disabled vehicles	Proactively closed to non-essential vehicles	
Transportation	Buses	Delays	Proactive service suspension	Reactive to
	Subways	Delays	Proactive service suspension	proactive
	Rail	Reactive service suspension	Proactive service suspension	
	Recovery time (in days)	7	2	5
	Number of customers with power outages	76,930	30,690	46,230
Energy	Average duration of power outages (in hours)	12.2	4.8	7.4
Energy	Estimated average electric customer interruption cost (in millions of USD 2016)	\$106.8	\$14.7	\$92.1

Table 19. Change in service interruptions between the December 2010 and January 2016 case study storm events.

Trust and confidence in the NWS has increased over time.

The majority of NWS core partners who we interviewed indicated that their level of trust in the NWS improved over time and that they are more confident in the NWS today than they were in the past. Improved trust and confidence in the NWS is the result of closer working relationships between NWS and core partners, including a mutual understanding of sector-specific operational procedures and limitations in weather forecasts.

Recommendations: Continue to provide core partners with decision support services, effective communication, and deliverable understandable and actionable information.

Critical attributes of IDSS.

The experts we interviewed identified several critical attributes of IDSS:

- Trusted relationships: Through IDSS, NWS builds relationships and establishes trust with its core partners. NWS's existing and trusted relationships with core partners is a critical attribute of IDSS that allow emergency managers and other core partners to provide consistent messaging to the public and make critical operational decisions. NYCEM suggests that NWS continue to work with emergency management and core partners regularly to allow a free flow of information, and an understanding of the needs and challenges for each party. This allows NWS to provide a forecast related to specific concerns of the local jurisdiction and for the local jurisdiction to understand the limitations of NWS.
- Skillset of NWS support staff: NWS meteorologists who provide remote and onsite support to emergency management and core partners must understand these partners' operational procedures and be able to effectively communicate weather forecasts and uncertainty to partners. This skillset is not typical for meteorologists; however, it is critical for any NWS staff who are providing IDSS to core partners.
- Constant contact and consistent messaging: With IDSS, NWS provides regular weather briefings, information
 emails, and conference calls for local emergency managers. For severe winter storms and other high-impact weather
 events, NWS provides onsite support. These services provide core partners with regular access to NWS support
 staff, and allows partners to ask NWS support staff directly about forecast uncertainty and potential impacts. In
 some cases, core partners would not call NWS support staff to ask these questions. This regular and consistent
 weather information allows core partners to make better and more informed decisions about how to prepare for a
 storm event and how to quickly recover from a storm event.

^{1.} The December 2010 storm occurred over the holidays with more scheduled flights than the January 2016 storm; therefore, comparing the number of flight cancellations during the two storm events is challenging. Instead, to estimate the potential benefit of IDSS, we apply the 2016 storm cancellation rate to the 2010 storm and to flight cancellations due to weather during the 2010–2011 winter season, and the 2010 storm cancellation rate to the 2016 storm and to flight cancellations due to weather during the 2015–2016 winter season. We find that IDSS provides a potential value of approximately \$20.9 million to \$22.9 million during a severe winter storm, and approximately \$33.1 million to \$65.8 million during a winter season. See Section 5.1 for more details.

Recommendations: Implement or formalize a process to elicit feedback from core partners and other stakeholders on the benefits and costs of IDSS, as well as identifying gaps and opportunities for improvements.¹³ This could also relate to measuring trust and confidence in NWS information using more rigorous social science methods and perhaps linking to or building on the NWS customer satisfaction surveys.¹⁴ In addition, ensure NWS has adequate staff with appropriate training to supply onsite IDSS support to core partners whenever requested, or explore ways to further leverage limited staff to supply IDSS perhaps through other communication channels (e.g., webinars).

NWS strives to transform the way it collects, uses, and disseminates information to improve accessibility; however, NWS geospatial, verification, and social and economic data are not yet easily accessible.

The NWS Weather-Ready Nation Roadmap outlines concepts to enable IDSS and achieve its vision of a Weather-Ready Nation. One concept focuses on finding cost-effective methods to transform the way NWS collects, uses, and disseminates information to increase accessibility and usability (NWS, 2013b). NWS is taking steps to improve usability of NWS data and information. For example, NOAA is currently updating its Observed Snowfall Analysis dataset to include historical observed snowfall maps for 24-, 48-, and 72-hour accumulations. These historical data can play a large role in supporting research post-hoc evaluations. We found that NWS's historical weather forecast data are difficult to locate and use. NWS does not have a single point of access for its data and information. Instead, NWS has several centers and departments that disseminate and store weather forecast data and information, including the National Climatic Data Center, the Weather Prediction Center, and the National Digital Forecast Database. Once we located the data, it often required specialized software to convert the data into a format that was usable by our team. In many instances, we had to contact NWS staff to understand the metadata.

The NOAA Storm Data is an extremely valuable socioeconomic dataset that supports research and post-storm evaluations. NOAA Storm Data documents storm extent, time period, and damages – including loss of life, injury, and property damage – from winter storms and other severe, unusual, or high-impact weather events (NOAA, 2016). The NOAA Storm Data dataset is widely used in social and economic analyses. For example, HVRI's SHELDUS™ database largely relies on NOAA Storm Data to provide hazard loss and mortality information, spanning from 1960 to present. The NOAA Storm Data dataset relies on input from WFO preparers and emergency managers (NOAA, 2016); however, these data are not consistently updated by the WFO preparers and emergency managers with the same level of detail across storms. Instead, NOAA Storm Data entry varies across WFOs and storm types. Winter storm data in the database, for example, are not as robust as other storm events (Brent MacAloney, NOAA, personal communication, October 12, 2016).

Recommendations: Support efforts for improvements in data accessibility. ¹⁶ Create an NWS open-data portal to improve accessibility to NWS data and information, and ensure detailed metadata are available with all downloadable historical NWS data and information. In addition, support and formalize a process to collect socioeconomic storm data. Explore ways to train WFOs to collect and record socioeconomic data so that the data are useful in impact analyses. Providing the public with open NWS data and metadata will support research and post-storm evaluations, which can assist NWS in refining its approach to the communication and dissemination of weather data and information.

^{13.} IDSS implementation costs might include costs to partners to ensure adequate space for NWS staff and sufficient time to use the additional information from NWS. These costs may be small compared to the benefits, but NWS should discuss these costs with core partners to ensure this is not a barrier to using IDSS.

^{14.} For example, see the Peak Performance Newsletter at https://verification.nws.noaa.gov/peaknewsletter/peak/2017/2017 Spring Newsletter.pdf.

^{15.} NWS Observed Snowfall Analysis, Version 2, is available at the NWS National Operational Hydrologic Remote Sensing Center at http://www.nohrsc.noaa.gov/snowfall/.

^{16.} This recommendation parallels 2011 recommendations from the Environmental Information Services Working Group of the NOAA Science Advisory Board on open data access. Our focus here though is more on the availability of information for socioeconomic impact assessments (see

 $[\]frac{https://www.google.com/url?sa=t\&rct=j\&q=\&esrc=s\&source=web\&cd=1\&ved=0\\ahUKEwiFvs_laHXAhUK1WMKHYTkDiUQFggrMAA\&url=https%3A%2F%2Fnosc.noaa.gov%2FEDMC%2FDAARWG%2Fdocs%2FEISWG-$

Towards Open Weather and Climate Services DRAFT v5.docx&usg=AOvVaw3oU4a0cgwd0tW7rL52LMJs).

7. References

Anderson, P.L. and I.K. Geckil. 2003. Northeast Blackout Likely to Reduce US Earnings by \$6.4 Billion. AEG Working Paper 2003-2. Anderson Economic Group, Lansing, MI. August 19. Available:

http://www.andersoneconomicgroup.com/Portals/0/upload/Doc544.pdf. Accessed November 6, 2017.

Associated Press. 2013. Man dies clearing snow at Long Island apt. complex. The Wall Street Journal. February 9. Available: http://archive.li/cBT9w. Accessed March 26, 2017.

Associated Press. 2016. Sandy electric utility hardening effort pays off in blizzard. February 1. Associated Press; reported in Daily News New York. Available: http://www.nydailynews.com/new-york/sandy-electric-utility-hardening-effort-pays-blizzard-article-1.2515894. Accessed October 26, 2017.

Barnhart, C. and V. Vaze. 2016. Irregular operations: Schedule recovery and robustness. In The Global Airline Industry, P. Belobaba, A. Odoni, and C. Barnhart (eds.). 2nd Edition. John Wiley & Sons, Ltd., West Sussex, UK. pp. 263–286.

Bewley, J.L., J. Lichty, E. Hahn, D. O'Donnell, M. Robinson, and R.S. Lee. 2015. Winter-Weather Stakeholder Decision Mapping for Weather Decision Support Shortfall Identification. American Meteorological Society. 95th Annual meeting, January 4–8. Phoenix, AZ. Available:

https://ams.confex.com/ams/95Annual/webprogram/Paper263932.html. Accessed March 16, 2017.

Blau, R. 2017. Ice see you! Storm sensors on order to detect ice on NYC streets. Daily News New York. May 15. Available: http://www.nydailynews.com/new-york/ice-storm-sensors-order-detect-ice-nyc-streets-article-1.3168853. Accessed October 30, 2017.

Bloesch, J. and F. Gourio. 2015. The Effect of Winter Weather on U.S. Economic Activity. March 1. Federal Reserve Bank of Chicago. Economic Perspectives 1Q/2015. Available:

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.696.8783&rep=rep1&type=pdf. Accessed November 1, 2017.

BLS. 2017. Quarterly Census of Employment and Wages. NAICS-Based Data Files. County-Level. Bureau of Labor Statistics. Available: https://www.bls.gov/cew/datatoc.htm. Accessed March 9, 2017.

BTS. 2017. Airline On-Time Statistics. Bureau of Transportation Statistics, Department of Transportation. Available: https://www.transtats.bts.gov/DL_SelectFields.asp?Table_ID=236&DB_Short_Name=On-Time. Accessed March 7, 2017.

Bush, L. 2013. Three Northport Men Die While Removing Snow. Northport Patch. February 11. Available: https://patch.com/new-york/northport/three-northport-men-die-while-removing-snow. Accessed March 26, 2017.

CDC. 2006. Hypothermia-Related Deaths – United States, 1999–2002 and 2005. Centers for Disease Control and Prevention. Available: https://www.cdc.gov/mmwr/preview/mmwrhtml/mm5510a5.htm. Accessed March 27, 2017.

CNBC. 2016. Blizzard's Hit on Economy in Hundreds of Millions? Available: http://www.cbsnews.com/news/winter-storm-2016-blizzards-hit-on-economy-in-hundreds-of-millions/. Accessed March 28, 2017.

Consolidated Edison. 2013. Post Sandy Enhancement Plan. Consolidated Edison Co. of New York, Orange and Rockland Utilities. June 20. Available: https://www.coned.com/-/media/files/coned/documents/services-outages/post-sandy-enhancement-plan.pdf. Accessed October 26, 2017.

Consolidated Edison. 2016a. Con Edison Storm Upgrades Avert 1,000 Power Outages during Jonas. January 26. Available: https://www.coned.com/en/about-con-edison/media/news/20160126/storms-jonas-outages. Accessed October 26, 2017.

Consolidated Edison. 2016b. Our Outage Recovery Plan. Available: https://www.coned.com/en/community-affairs/our-storm-recovery-plan. Accessed March 28, 2017.

Dickman, R. 2013. WFO New York February 8–9 Blizzard. Memorandum to Kenneth Johnson, Chief Scientific Services Division, from I. Ross Dickman, Meteorologist-In-Charge. February 19.

DOT. 2016. The Value of Travel Time Savings: Departmental Guidance for Conducting Economic Evaluations. U.S. Department of Transportation. Available:

https://www.transportation.gov/sites/dot.dev/files/docs/vot_guidance_092811c.pdf. Accessed November 20, 2017.

DSNY. 2016. 2016–2017 Snow Plan for the Borough of the Bronx. Pursuant to Local Law 28 of 2011. The City of New York Department of Sanitation. Kathryn Garcia, Commissioner. November.

Dutton, J.A. 2002. Opportunities and Priorities in a New Era for Weather and Climate Services. American Meteorological Society. September. EBSCO Publishing.

FAA. 2015. FAQ: Weather Delay. Federal Aviation Administration. Available: https://www.faa.gov/nextgen/programs/weather/faq/. Accessed April 24, 2017.

Fanning, A. 2016. Historic Eastern U.S. Winter Storm, 22–25 January, 2016. Weather Prediction Center (WPC), National Centers for Environmental Predication (NCEP), National Oceanic and Atmospheric Administration (NOAA). Available:

http://www.wpc.ncep.noaa.gov/winter_storm_summaries/event_reviews/2016/Historic_EasternUS_WinterStorm_Jan20 16.pdf. Accessed November 6, 2017.

FEMA. 2010a. New Jersey Severe Winter Storm and Snowstorm (DR-1954). Incident Period: December 26, 2010–December 27, 2010. Major Disaster Declaration Declared on February 04, 2011. Federal Emergency Management Agency. Available: https://www.fema.gov/disaster/1954. Accessed February 28, 2016.

FEMA. 2010b. New York Severe Winter Storm and Snowstorm (DR-1957). Incident Period: December 26, 2010–December 27, 2010. Major Disaster Declaration Declared on February 18, 2011. Federal Emergency Management Agency. Available: https://www.fema.gov/disaster/1957. Accessed February 28, 2016.

FEMA. 2013. New York Severe Winter Storm and Snowstorm (DR-4111). Incident Period: February 08, 2013—February 09, 2013. Major Disaster Declaration Declared on April 23, 2013. Federal Emergency Management Agency. Available: https://www.fema.gov/disaster/4111. Accessed February 28, 2016.

FEMA. 2016a. A Guide to the Disaster Declaration Process and Federal Disaster Assistance. Available: https://www.fema.gov/disaster-declaration-process. Accessed March 26, 2017.

FEMA. 2016b. New Jersey Severe Winter Storm and Snowstorm (DR-4264). Incident Period: January 22, 2016–January 24, 2016. Major Disaster Declaration Declared on March 14, 2016. Federal Emergency Management Agency. Available: https://www.fema.gov/disaster/4264. Accessed February 28, 2016.

FHWA. 2012. Best Practices for Road Weather Management. Version 3.0. June. Federal Highway Administration, U.S. Department of Transportation. June. Available:

https://ops.fhwa.dot.gov/publications/fhwahop12046/fhwahop12046.pdf. Accessed March 16, 2017.

FHWA. 2017. How Do Weather Events Impact Roads? Road Weather Management Program. Federal Highway Administration, U.S. Department of Transportation. Available: https://ops.fhwa.dot.gov/weather/q1 roadimpact.htm. Accessed October 30, 2017.

HVRI. 2014. Social Vulnerability Index for the United States – 2010–2014. Hazards & Vulnerability Research Institute, University of South Carolina. Available: http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-0. Accessed October 24, 2017.

Kluger, B.L. 2011. NYC Transit's Response to December 2010 Blizzard. MTA/OIG Report #2011-07. Barry L. Kluger, Metropolitan Transportation Authority Inspector General, State of New York. December. Available: http://mtaig.state.ny.us/assets/pdf/11-07.pdf. Accessed February 24, 2017.

Kocin, P.J. and L.W. Uccellini. 2004. A snowfall impact scale derived from Northeast storm snowfall distributions. Bulletin of the American Meteorological Society 85:177–194. Available: https://www.ncdc.noaa.gov/snow-and-ice/rsi/docs/kocin-and-uccellini-2004.pdf. Accessed November 1, 2017.

Kocin, P.J., L.W. Uccellini, J. Alpert, B. Ballish, D. Bright, R. Grumm, and G. Manikin. 2011. The Blizzard of 25–27 December 2010: Forecast Assessment. Available:

http://www.wpc.ncep.noaa.gov/winter_storm_summaries/event_reviews/2010/December25_27_2010_Blizzard.pdf. Accessed October 31, 2017.

Kreckeler, J. 2013. Great Lakes to Northeast Major Winter Storm, February 7–9, 2013. Weather Prediction Center (WPC), National Centers for Environmental Predication (NCEP), National Oceanic and Atmospheric Administration (NOAA). Available:

http://www.wpc.ncep.noaa.gov/winter_storm_summaries/event_reviews/2013/Great_Lakes_Northeast_Winter_Storm_F eb2013.pdf. Accessed November 2, 2017.

Lazo, J.K., M. Lawson, P.H. Larsen, and D.M. Waldman. 2011. U.S. Economic Sensitivity to Weather Variability. Bulletin of the American Meteorological Society. June:709–720.

Maccubbin, R.P., B.L. Staples, F. Kabir, C.F. Lowrance, M.R. Mercer, B.H. Philips, and S.R. Gordon. 2008. Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned: 2008 Update. U.S. Department of Transportation Research and Innovative Technology Administration. September. Available: https://ntl.bts.gov/lib/30000/30400/30466/14412.pdf. Accessed April 21, 2017.

Marks, J. 2014. Updating Airline Cancellation Costs and Customer Disruption. Airline Group of the International Federation of Operational Research Societies (AGIFORS) Annual Symposium 2014. Available: https://airinsight.com/wp-content/uploads/2014/10/Updating-airline-cancellation-costs-and-customer-disruption.pdf. Accessed November 1, 2017.

MTA. 2011. MTA Storm Performance Review. June 2011. Metropolitan Transportation Authority. Available: http://web.mta.info/mta/news/books/docs/StormReviewReport.pdf. Accessed February 24, 2017.

New York City Council. 2011. Oversight: Winter Weather in NYC – Are We Prepared? Analyzing DSNY's Annual Borough-Based Winter Storm Plans and OEM's Citywide Snow Preparedness and Response Report. The Council of the City of New York. Report of the Infrastructure & Governmental Affairs Divisions, Committee on Public Safety, and Committee on Sanitation and Solid Waste Management. November 30. Available: http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=1011797&GUID=32A66E90-26CC-4002-A664-153B2F56DA4F. Accessed October 31, 2017.

NOAA. 2016. Storm Data Preparation. National Weather Service Instruction 10-1605. March 23. National Oceanic and Atmospheric Administration. Available: http://www.weather.gov/directives/sym/pd01016005curr.pdf. Accessed December 29, 2016.

NWS. 2011. Strategic Plan 2011. Weather-Ready Nation. NOAA's National Weather Service. June. National Oceanic and Atmospheric Administration. Available: http://www.weather.gov/media/wrn/strategic_plan.pdf. Accessed September 20, 2017.

NWS. 2013a. February 8–9, 2013 Blizzard. NOAA's National Weather Service. Available: https://www.weather.gov/okx/storm02092013. Accessed December 28, 2017.

NWS. 2013b. Weather-Ready Nation Roadmap. Version 2.0. National Weather Service. April. National Weather Service, National Oceanic and Atmospheric Administration. Available:

http://www.weather.gov/media/wrn/nws wrn roadmap final april17.pdf. Accessed September 20, 2017.

NWS. 2015. The Blizzard of January 26-27, 2015. NOAA's National Weather Service. Available: https://www.weather.gov/okx/Blizzard 01262715. Accessed December 28, 2017.

NWS. Undated. NWS Impact-based Decision Support Services Philosophy. National Weather Services. National Weather Service, National Oceanic and Atmospheric Administration. Available: http://www.nws.noaa.gov/sp/OWA IDSS Philosophy Material.pdf. Accessed December 6, 2017.

NYC Comptroller. 2015. The Slippery Cost Slope of Ice and Snow Removal in New York City. Bureau of Fiscal and Budget Studies. New York City Comptroller, Scott M. Stringer. January 2015. Available: https://comptroller.nyc.gov/wp-

<u>content/uploads/documents/The_Slippery_Cost_Slope_of_Ice_and_Snow_Removal_in_New_York_City.pdf</u>. Accessed February 24, 2017.

NYC Department of Investigation. 2011. Investigation into Allegations of Possible Slowdown by Department of Sanitation during Blizzard of December 2010. New York City Department of Investigation. Commissioner Rose Gill Hearn. June. Available: http://www1.nyc.gov/assets/doi/downloads/pdf/june11/snowreport_60311.pdf. Accessed March 26, 2017.

NYCEM. 2014. 2014 New York City Hazard Mitigation Plan, J. Margolies (ed.). New York City Office of Emergency Management. April 17. Available:

http://www1.nyc.gov/assets/em/downloads/pdf/hazard mitigation/plan update 2014/final nyc hmp.pdf. Accessed March 24, 2017.

NYCEM. 2016. 2016 NYC Hazard Mitigation Plan Annex. New York City Office of Emergency Management. Available: http://www1.nyc.gov/assets/em/downloads/pdf/hazard_mitigation/2016_hazard_mitigation_annex.pdf. Accessed October 10, 2017.

NYCEM. 2017. New York City Office of Emergency Management staff response to Winter Weather Questions sent to Abt Associates, Boulder, CO, on October 27, 2017.

Otto, R. 2015. Mid-Atlantic to Northeast Major Winter Storm, 26–28 January, 2015. National Centers for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA). Available: http://www.wpc.ncep.noaa.gov/winter_storm_summaries/event_reviews/2015/MidAtlantic_Northeast_Major_WinterStorm_Jan2015.pdf. Accessed November 1, 2017.

Preston, B.L., S.N. Backhaus, M. Ewers, J.A. Phillips, C.A. Silva-Monroy, J.E. Dagle, A.G. Tarditi, J.(P.) Looney, and T.J. King Jr. 2016. Resilience of the U.S. Electricity System: A Multi-Hazard Perspective. August 18. U.S. Department of Energy. Available:

https://ener0gy.gov/sites/prod/files/2017/01/f34/Resilience%20of%20the%20U.S.%20Electricity%20System%20A%20 Multi-Hazard%20Perspective.pdf. Accessed October 31, 2017.

PSEG. 2017. How PSE&G Prepares for Storms. Public Service Enterprise Group Incorporated. Available: https://www.pseg.com/home/customer_service/outage_info/prepares.jsp. Accessed October 31, 2017.

Soltow, M. 2010. Event Review: December 25–27, 2010 Winter Storm, Eastern United States. National Centers for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA). Available: http://www.wpc.ncep.noaa.gov/winter_storm_summaries/event_reviews/2010/Eastern_US_WinterStorm_December_2010.pdf. Accessed November 1, 2017.

Sridar, B. 2007. Relationship between Weather, Traffic and Delay Based on Empirical Methods. NEXTOR.

Sullivan, M.J., M.G. Mercurio, J.A. Schellenberg, and J.H. Eto. 2013. How to Estimate the Value of Service Reliability Improvements. Available: http://www.ourenergypolicy.org/wp-content/uploads/2013/08/REPORT-lbnl-3529e.pdf. Accessed November 2, 2017.

Trapasso, C., C. Lestch, V. Chinese, and L. McShane. 2013. Long Island blitzed by winter blast that left 30 inches of snow and stranded drivers on roadways. Daily News New York. February 9. Available: http://www.nydailynews.com/new-york/long-island-blitzed-30-inches-snow-article-1.1259673. Accessed March 26, 2017.

Uccellini, L.W. 2016. The Historic Nor'easter of January 2016. Service Assessment. National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA). November 2016. Available: https://www.weather.gov/media/publications/assessments/16Northeast-Blizzard.pdf. Accessed November 1, 2017.

Verisk Analytics. 2017. PCS Estimates of Insured Property Loss. Available: http://www.verisk.com/property-claim-services/estimates-of-insured-property-loss.html. Accessed February 28, 2017.

Xiong, J. and M. Hansen. 2009. Value of Flight Cancellation and Cancellation Decision Modeling: Ground Delay Program Postoperation Study. Transportation Research Record 2106:83–89. doi: 10.3141/2106-10.

Weed, J. 2017. Airlines, Now More Proactive on Weather, Allow Fliers to Shift Own Travel Plans. The New York Times. January 2, 2017. Available: https://www.nytimes.com/2017/01/02/business/flight-weather-delay-change-itinerary.html? r=0. Accessed November 21, 2017.

Weinstein, E. and S. Funk. 2011. Preliminary Review of the City's Response to the December 2010 Blizzard. Report and Recommendations to Mayor Michael R. Bloomberg. Mayor's Office of Operations and Mayor's Office of Citywide Emergency Communications. January 10. Available:

http://www.nyc.gov/html/om/pdf/2011/review of 2010 blizzard response 01-10-11.pdf. Accessed February 24, 2017.

WFO OKX. 2015. January 26–28, 2015 Winter Storm After-Action Review. WFO OKX Event Review Outline. National Weather Service Forecast Office, Upton, NY.

WFO OKX. 2016. January 22–23, 2016 Blizzard After-Action Review. WFO OKX Event Review Outline. National Weather Service Forecast Office, Upton, NY.

Wichter, Z. 2017. Airlines Take a Proactive Approach to Potential Weather Woes. The New York Times. March 14. Available: https://www.nytimes.com/2017/03/14/business/airline-cancellations-delays-snowstorm.html. Accessed November 21, 2017.

Wieland, F., R. Sharma, and M. Zettlemoyer. 2013. Assessment of Imperfect Weather Forecasts on Airline and Passenger Planning. October. <u>Intelligent Automation, Inc., Rockville, MD.</u> Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6719594. Accessed October 31, 2017.

Appendix A. Survey instrument

This appendix provides an example of the survey instrument used for the aviation sector.

IDSS background

NWS defines IDSS as the "provision of relevant information and interpretative services to enable core partners' decisions when weather, water, or climate has a direct impact on the protection of lives and livelihoods." Although NWS has always provided some level of decision support services to the emergency management community and government core partners – such as online and onsite briefings – NWS now recognizes decision support services as a primary service and is working to fully and more effectively provide this service.

Decision support services include direct, interactive support for members of the emergency management community and government core partners, including partners in the aviation sector, to inform preparedness, mitigation, response, and recovery efforts.

- Remote support may include informational emails and electronic presentations, such as the aviation weather high-impact email sent during the January 2016 snowstorm, and briefings via webinars.
- Onsite support is not typically provided for snowstorms, but can include placing trained NWS staff personnel at air traffic control centers.
- 1. Are you familiar with these NWS IDSS? What services have you used?
 - Have you participated in webinar briefings?
 - Have you received emails with high-impact weather summaries?
 - Have you used NWSChat?
- 2. Do you use these NWS IDSS for making decisions? How and what types of decisions?
- 3. In your opinion, do these NWS IDSS reduce impacts from severe winter storm events? How?

Case study snowstorm events

Now, I would like to focus on two severe winter storm events and discuss NWS IDSS in the context of these winter storms.

Before I start, severe winter weather in the NYC area includes events where snowfall exceeds six inches; sustained winds exceed 40 mph; or forecasts include ice storms or freezing rain, and cold temperatures.

December 2010 snowstorm

The first winter snowstorm we will discuss occurred in December 2010.

In December 2010, a large snowstorm occurred in the NYC area.

NWS had divergent forecasts until 36 to 48 hours before the onset of the snowstorm. Early forecasts predicted light to moderate snowfall. On December 25, the severity of the forecast was upgraded with predicted snowfall between 11 and 16 inches.

This forecast was an underestimate. Snow accumulations totaled 20–30 inches across NYC and the Lower Hudson Valley, and 10–20 inches across Long Island. At the peak of the storm, snow fell at an hourly rate of 1 to 2 inches and winds blew upward of 30 to 45 mph, with gusts commonly exceeding 50 to 60 mph.

- 4. How well do you remember this snowstorm? Can you describe one thing that surprised you about this snowstorm?
- 5. During this snowstorm, can you describe your role at your organization?
- 6. Before or during this snowstorm, can you describe the types of decisions you and your organization made to reduce impacts to the aviation sector?

- [*If airline or FAA:*] Did your organization re-route, delay, or cancel flights in anticipation of the storm (proactive)? During or after the storm (reactive)? How do you decide whether to re-route a flight or cancel it (e.g., prioritize flights based on plane size)?
 - Can you describe the types of costs associated with flight disruptions (e.g., grounding, re-routing, delaying, or cancelling a flight)? Costs to the airlines? Costs to FAA? Costs to the passengers?
 - What types of information did you use to make these decisions? [If NWS information:] Did you trust the NWS information when making your decisions?
 - What types of products and services did you use to make these decisions? [If NWS products and services:] Did you trust the NWS products and services when making your decisions?
 - Did you rely on other (non-NWS) types of weather information or services? Did you trust the other (non-NWS) products and services when making your decisions?
 - For the December 2010 storm, when did you need the forecast information to make critical decisions (e.g., 72 hours, 48 hours, 24 hours, 12 hours)? What was the critical temporal threshold for making these decisions? At what point was it too late to make decisions? Too early?
- [*If airport or Port Authority:*] Did your organization engage airport snow removal crews to clear the airside (runways, taxiways, de/anti-icing pads, and ramp areas) and landside (access roads) areas? De-ice planes? Other decisions to safely operate all facilities during a snowstorm event?
 - Can you describe the types of costs associated with snow removal? Costs associated with de-icing planes? Who bears these costs? The airline, airport, port authority, other?
 - What types of information did you use to make these decisions? [If NWS information:] Did you trust the NWS information when making your decisions?
 - What types of products and services did you use to make these decisions? [If NWS products and services:] Did you trust the NWS products and services when making your decisions?
 - Did you rely on other (non-NWS) types of weather information or services? Did you trust the other (non-NWS) products and services when making your decisions?
 - For the December 2010 storm, when did you need the forecast information to make critical decisions (e.g., 72 hours, 48 hours, 24 hours, 12 hours)? What was the critical temporal threshold for making these decisions? At what point was it too late to make decisions? Too early?

Based on our understanding of the December 2010 snowstorm, the storm resulted in significant impacts to the airlines sector.

December 2010 snowstorm impacts: NYC area airports were closed for approximately 24 hours, with services slowly restored during the late afternoon and evening of December 27. The table on the screen shows the number and percent of flights canceled, delayed, and diverted the day before the snowstorm event (December 25), during the snowstorm event (December 26), and after the snowstorm event (December 27, 28, and 29).

	Day before	Event	Days after		
	December 25 (Saturday)	December 26 (Sunday)	December 27 (Monday)		December 29 (Wednesday)
No. of flights scheduled	1,481	1,792	1,902	1,895	1,895
No. (total) of flights cancelled	50	1,141	1,869	974	244
No. of flights cancelled because of weather	42	1,073	1,791	706	190
% of flights cancelled because of weather	2.8%	59.9%	94.2%	37.3%	10.0%
No. (total) of flights delayed	17	57	9	231	187
% of flights delayed	1.2%	3.2%	0.5%	12.2%	9.9%
No. (total) of flights diverted	1	23	1	3	8
% of flights diverted	0.1%	1.3%	0.1%	0.2%	0.4%

- 7. Are the impacts I described and shown on the screen (above) from this December 2010 snowstorm consistent with what you remember?
 - Probe: Were flights re-routed, delayed, or canceled in anticipation of the storm (proactive)? During or after the storm (reactive)?
 - Probe: How did the storm affect the broader national air system? How did the timing of flight cancelations (in anticipation of the storm versus during or after the storm) affect the broader national air system?
- 8. Can you describe the recovery effort at the airport after this December 2010 snowstorm?
 - Probe: What recovery efforts were undertaken at the airport and for how long?
 - Probe: How many hours or days passed until the airports in the NYC area returned to normal (e.g., until flight schedules were normal)? How many hours or days passed until the broader national air system returned to normal?

This snowstorm occurred before IDSS were formalized. For this snowstorm, NWS coordinated with the Aviation Weather Center and the FAA National Air Traffic Control System Command Center, and held briefings via webinars.

- 9. In your opinion, what types of IDSS would have improved decision-making to reduce flight delays and cancelations?
- 10. If you received IDSS, such as the high-impact email summary shown on this screen, can you estimate how many fewer flight delays and cancelations there would have been during the 2010 snowstorm?

Screenshot of actual number of flights disrupted before, during, and after the December 2010 storm (in the first table) and the number of flights disrupted if 25%, 50%, and 75% fewer flights were disrupted with formal IDSS (last three tables).

	Day before	Event		Days after	
Actual 2010 flights cancelled	December 25	December 26	December 27	December 28	December 29
No. of flights scheduled	1,481	1,792	1,902	1,895	1,895
No. of flights cancelled because of weather	42	1,073	1,791	706	190
% of flights cancelled because of weather	2.8%	59.9%	94.2%	37.3%	10.0%
25% fewer flights cancelled	December 25	December 26	December 27	December 28	December 29
No. of flights scheduled	1,481	1,792	1,902	1,895	1,895
No. of flights cancelled because of weather	32	805	1343	530	143
% of flights cancelled because of weather	2.1%	44.9%	70.6%	27.9%	7.5%
50% fewer flights cancelled	December 25	December 26	December 27	December 28	December 29
No. of flights scheduled	1,481	1,792	1,902	1,895	1,895
No. of flights cancelled because of weather	21	537	896	353	95
% of flights cancelled because of weather	1.4%	29.9%	47.1%	18.6%	5.0%
75% fewer flights cancelled	December 25	December 26	December 27	December 28	December 29
No. of flights scheduled	1,481	1,792	1,902	1,895	1,895
No. of flights cancelled because of weather	11	268	448	177	48
% of flights cancelled because of weather	0.7%	15.0%	23.5%	9.3%	2.5%

For example, on the screen (above), I am showing the actual number of flights disrupted from this snowstorm during and after the snowstorm (in the first table). I am also showing the number of flights disrupted if 25%, 50%, and 75% fewer flights were disrupted with IDSS (in the following three tables). Can you provide an estimate for how many fewer flight disruptions there would have been during the 2010 snowstorm with IDSS?

- If 25%: Could it have been lower? How much lower?
- If 75%: Could it have been higher? How much higher?
- 11. With IDSS, such as the high-impact email summary shown on the last screen, would the recovery time have improved?
- 12. Are there other factors that affected the decisions you made for this December 2010 snowstorm (e.g., the fact that this storm occurred around the Christmas holiday)?
- 13. After this 2010 snowstorm, did your organization change operational procedures or emergency plans? If yes, why and what changed?

January 2016 snowstorm

Now, I would like to discuss the January 2016 snowstorm.

Another large snowstorm occurred in January 2016 in the NYC area.

NWS issued a Winter Storm / Blizzard Watch almost four days before the onset of the storm. Early forecasts predicted moderate or heavy snowfall. The day before the event, the severity of the forecast was upgraded with predicted snowfall between 24 and 28 inches.

This forecast was an underestimate. Snow accumulations totaled approximately 30 inches across NYC and 18 inches across Long Island. Heavy snow and strong winds created blizzard conditions across the region. During the storm event, wind speeds were 25 to 50 mph.

- 14. How well do you remember this snowstorm? Can you describe one thing that surprised you about this storm?
- 15. During this snowstorm, can you describe your role at your organization?
- 16. Before or during this snowstorm, can you describe the types of decisions you and your organization made to reduce impacts to the aviation sector?

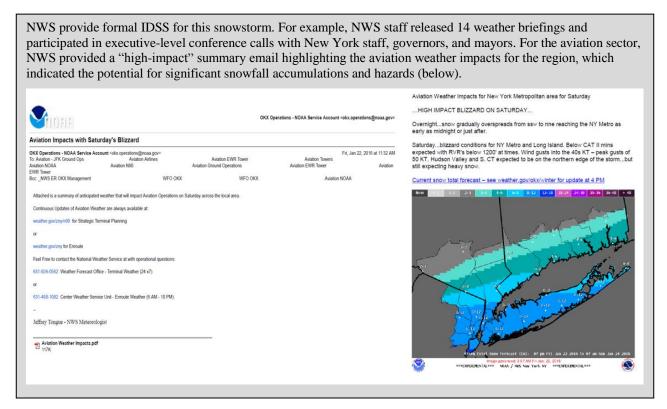
- [*If airline or FAA:*] Did your organization re-route, delay, or cancel flights in anticipation of the storm (proactive)? During or after the storm (reactive)? How do you decide whether to re-route a flight or cancel it (e.g., prioritize flights based on plane size)?
 - Can you describe the types of costs associated with flight disruptions (e.g., grounding, re-routing, delaying, cancelling a flight)? Costs to the airlines? Costs to the FAA? Costs to the passengers?
 - What types of information did you use to make these decisions? [If NWS information:] Did you trust the NWS information when making your decisions?
 - What types of products and services did you use to make these decisions? [If NWS products and services:] Did you trust the NWS products and services when making your decisions?
 - Did you rely on other (non-NWS) types of weather information or services? Did you trust the other (non-NWS) products and services when making your decisions?
 - For the January 2016 storm, when did you need the forecast information to make critical decisions (e.g., 72 hours, 48 hours, 24 hours, 12 hours)? What was the critical temporal threshold for making these decisions? At what point was it too late to make decisions? Too early?
- [If airport or Port Authority:] Did your organization engage airport snow removal crews to clear the airside (e.g., runways, taxiways, de/anti-icing pads, ramp areas) and landside (access roads) areas? De-ice planes? Other decisions to safely operate all facilities during a snowstorm event?
 - Can you describe the types of costs associated with snow removal? Costs associated with de-icing planes? Who bears these costs? The airline, airport, port authority, other?
 - What types of information did you use to make these decisions? [If NWS information:] Did you trust the NWS information when making your decisions?
 - What types of products and services did you use to make these decisions? [If NWS products and services:] Did you trust the NWS products and services when making your decisions?
 - Did you rely on other (non-NWS) types of weather information or services? Did you trust the other (non-NWS) products and services when making your decisions?
 - For the January 2016 storm, when did you need the forecast information to make critical decisions (e.g., 72 hours, 48 hours, 24 hours, 12 hours)? What was the critical temporal threshold for making these decisions? At what point was it too late to make decisions? Too early?

Based on our understanding of the January 2016 snowstorm, the storm resulted in significant impacts to the airlines sector.

January 2016 snowstorm impacts: NYC area airports were closed during the storm event, with services slowly restored during the late afternoon and evening of January 24. The table on the screen (below) shows the number and percent of flights canceled, delayed, and diverted the day before the snowstorm event (January 22); during the snowstorm event (January 23); and after the snowstorm event (January 24, 25, and 26).

uary 22 Friday)	January 23 (Saturday)	January 24	January 25	January 26
		(Sunday)	(Monday)	(Tuesday)
1,732	1,140	1,521	1,731	1,652
373	1,137	1,166	489	271
306	1,087	1,042	250	45
17.7%	95.4%	68.5%	14.4%	2.7%
27	1	57	60	3
1.6%	0.1%	3.8%	3.5%	0.2%
1	0	5	4	1
0.1%	0.0%	0.3%	0.2%	0.1%
	373 306 17.7% 27 1.6%	373 1,137 306 1,087 17.7% 95.4% 27 1 1.6% 0.1% 1 0	373 1,137 1,166 306 1,087 1,042 17.7% 95.4% 68.5% 27 1 57 1.6% 0.1% 3.8% 1 0 5	373 1,137 1,166 489 306 1,087 1,042 250 17.7% 95.4% 68.5% 14.4% 27 1 57 60 1.6% 0.1% 3.8% 3.5% 1 0 5 4

- 17. Are the impacts I described and shown on the screen (above) from this January 2016 snowstorm consistent with what you remember?
 - Probe: Were flights re-routed, delayed, or canceled in anticipation of the storm (proactive)? During or after the storm (reactive)?
 - Probe: How did the storm affect the broader national air system? How did the timing of flight cancelations (in anticipation of the storm versus during or after the storm) affect the broader national air system?
- 18. Can you describe the recovery effort at the airport after this January 2016 snowstorm?
 - Probe: What recovery efforts were undertaken at the airport and for how long?
 - Probe: How many hours or days until the airports in the NYC area returned to normal (e.g., until flight schedules were normal)? How many hours or days until the broader national air system returned to normal?
- 19. During this January 2016 snowstorm, were there formal IDSS available that were not available for the December 2010 snowstorm? Please describe.



- 20. Did you receive formal IDSS for this snowstorm (e.g., the "high-impact" summary email for this snowstorm; above)? Please describe.
 - Did you use formal IDSS (or the "high-impact" summary email) to make operational decisions? If yes, what types of support services? And, what decisions did you make using those services?
- 21. If NWS did not provide IDSS (e.g., the "high-impact" summary email for this snowstorm) for this storm, would more flights have been delayed and canceled?
 - Probe: Without these services, can you estimate how many more flight delays and cancelations there would have been during the 2016 snowstorm?

Screenshot of actual number of flights disrupted before, during, and after the January 2016 storm (in the first table) and the number of flights disrupted if 25%, 50%, and 75% more flights were disrupted without IDSS (last three tables).

	Day before	Event		Days after	
Actual 2016 flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	401	1,138	1,228	553	275
% of total flights disrupted	23%	100%	81%	32%	17%
250/ 61:	January 22	January 33	January 24	January 25	January 20
25% more flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	501	1,140	1,521	691	344
% of total flights disrupted	29%	100%	100%	40%	21%
50% more flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	602	1,140	1,521	830	413
% of total flights disrupted	35%	100%	100%	48%	25%
75% more flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	702	1,140	1,521	968	481
% of total flights disrupted	41%	100%	100%	56%	29%

For example, on the screen (above) I am showing the actual number of flights disrupted from this snowstorm (in the first table) and the number of flights disrupted if 25%, 50%, and 75% more flights were disrupted without the IDSS (in the following three tables). Can you provide an estimate of how many more flight disruptions there would have been during the 2016 snowstorm without IDSS?

- If 25%: Could it have been lower? How much lower?
- If 75%: Could it have been higher? How much higher?
- 22. Without IDSS, such as the high-impact email summary shown on the last screen, would the recovery time have improved?
- 23. Could NWS's IDSS been improved for this snowstorm? How could these services be improved for snowstorms? If yes...
 - With the improved IDSS we just discussed, how would your decisions been different during the snowstorm event? Do you think there would have been fewer flight delays and cancelations?
 - With improved IDSS, can you estimate how many fewer flight delays and cancelations there would have been during the 2016 snowstorm?

Screenshot of actual number of flights disrupted before, during, and after the January 2016 snowstorm (in the first table) and the number of flights disrupted if 25%, 50%, and 75% fewer flights were disrupted with improved IDSS (last three tables).

	Day before	Event		Days after	
Actual 2016 flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	401	1,138	1,228	553	275
% of total flights disrupted	23%	100%	81%	32%	17%
25% fewer flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	301	854	921	415	200
% of total flights disrupted	17%	75%	61%	24%	12%
50% fewer flights disrupted	January 22	January 23	January 24	January 25	January 26
No. of flights scheduled	1,732	1,140	1,521	1,731	1,652
Total flights disrupted	201	569	614	277	138
% of total flights disrupted	12%	50%	40%	16%	89
75% fewer flights disrupted	January 22	January 23	January 24	January 25	January 20
No. of flights scheduled	1,732	1,140	1,521	1,731	1,65
Total flights disrupted	100	285	307	138	69
% of total flights disrupted	6%	25%	20%	8%	49

Screen 14: For example, on the screen I am showing the actual number of flights disrupted from this snowstorm (in the first table); and the number of flights disrupted if 25%, 50%, and 75% fewer flights were disrupted with improved IDSS (in the following three tables). Can you provide an estimate of how many fewer flight disruptions there would have been during the 2016 snowstorm with improved IDSS?

- If 25%: Could it have been lower? How much lower?
- If 75%: Could it have been higher? How much higher?
- With improved IDSS, such as the high-impact email summary shown on the last screen, would the recovery time have improved?
- 24. What aspects of IDSS are critical for your operations (e.g., timing, accuracy, resolution)?
- 25. Are there other factors that affected the decisions you made for this January 2016 snowstorm (e.g., the fact that the winter storm occurred over the weekend)?
- 26. After this January 2016 snowstorm, did your organization change operational procedures or emergency plans? If yes, why and what changed?

Trust and confidence

27.	In general, has your level of trust in the NWS changed over time?	
	☐ Yes: How has your level of trust changed over time?	
	\square No: Why has your level of trust not changed over time?	
28.	Has your level of trust in NWS' IDSS changed over time?	
	☐ Yes: How has your level of trust changed over time?	
	☐ No: Why has your level of trust not changed over time?	

29.	Today are you more confident or less confident in the NWS than you were in the past?
	☐ More confident: Why are you more confident in the NWS?
	☐ Less confident: Why are you less confident in the NWS?
30.	Today are you more confident or less confident in NWS' IDSS than you were in the past?
	\square More confident: What aspects of the weather products or services make you more confident?
	\square Less confident: What could be done to improve your confidence in the weather products or services?
Re	commendations for other interviewees
31.	Do you know of others we should contact with experience regarding these two storms that would benefit this project?
32.	Is there anything that you would like to add? Anything that I should have asked you but did not ask?
33.	The findings from our conversation with you and other experts will be included in a report. In our report, can we acknowledge your participation in this study by providing your name as one of the experts we interviewed?

I appreciate your time today - thank you!

Appendix B. Data analysis methodology

In this appendix we describe the methods used to monetize service interruptions for the aviation and energy sectors. We also describe the data gathered and analyzed for economy-wide service interruptions (or changes in employment), asset damages, and human health effects (or mortalities and injuries).

Service interruptions

Aviation

Severe winter weather causes significant service disruptions to the airline industry. These disruptions impose financial costs on the airline industry, as well as to airline end users. Using BTS (2017) data, we estimated the number of flight cancellations due to weather for each storm event. For each storm, we included four days of flight cancellations: the one or two days of the actual event and two to three days of recovery. We then estimate the cost of flight cancellations to airline and airline passengers.

Cost to airlines

We used data from Marks (2014) to estimate the cost of flight cancelations to airlines. Marks (2014) data include incremental costs, allocable costs, cost offsets, and opportunity costs:

- Crew: Salaries and benefits, per diems awaiting rescheduling, transportation costs, and hotel costs
- Maintenance: Cost to prepare the aircraft, labor and material costs, and allocation of indirect maintenance to that flight
- Catering and passenger services: Costs for perishable food, and preparation and loading of catered food
- · Airport and handling: Cost for above- and below-wing handling, terminal fees, and reservation center costs
- Aircraft parking: Costs associated with waiting for new flights
- Ticket refunds and interline fees: Costs associated with passengers that cancel or rebook on another airline, merchant fees, and global distribution system (GDS) fees
- Passenger re-accommodation: Costs associated with hotels, meals, and transportation (these costs are uncommon for flight cancelations due to weather events)
- Displaced revenue: Costs associated with accommodating impacted passengers and consuming open inventory
- Offsets: Costs associated with fuel burned, and landing and airport fees.

These costs vary by aircraft type and controllable versus uncontrollable events. Uncontrollable events include weather events; therefore, we only include estimates for uncontrollable events. Marks (2014) estimates the cost per flight segment ranges from \$730 to \$13,450, with an average of cost per flight segment of \$5,450 (Table B.1). To monetize cancellation, we multiply the average cost of \$5,450 by the number of flight cancellations per storm event.

Table B.1. Estimated flight cancellation costs (USD 2016) for uncontrollable events.

Aircraft type	Cost per cancelled flight segment
Regional jets	
(CRJ, ERJ aircraft)	\$1,070
Legacy narrow bodies	
(Boeing 737 and Airbus 320 families by legacy airlines)	\$5,050
Low-cost carriers (LCC) narrow bodies	
[Boeing 737 and Airbus 320 families by LCC and ultra-low-cost carriers (ULCC) airlines]	\$730
Small wide bodies	
(Boeing 767/787 and Airbus 330 on 8-hour international routes)	\$6,930
Large wide bodies	
(Boeing 777/747 and Airbus 340 on 12-hour international routes)	\$13,450
Average across aircraft type	\$5,450

Source: Marks (2014). Note: The costs per cancelled flight segment are rounded to the nearest ten. Totals may not sum due to rounding.

Cost to passengers

We estimate the value of passenger disruptions as follows:

- 1. Estimate the number of passengers disrupted using the number of canceled flights multiplied by the average number of passengers per flight during the month of the storm¹⁷ (BTS, 2017).
- 2. Apply lost time per passenger, where we average the cancellation lengths reported in Xiong and Hansen (2009; one cancellation = 165.9 minutes) and Sridar (2009; one cancellation = 600 minutes), for an average cancellation time of 383 minutes, or 6.38 hours.
- 3. Apply the average value of this lost passenger time at ~ \$47.10 per person per lost hour (DOT, 2016). The estimate is also known as the Value of Travel Time Savings (VTTS), which values lost travel time for intercity flights at \$36.10 per person per hour for personal travel and \$63.20 per person per hour for business trips. Noting a distribution between personal and business travel that is 59.6% to 40.4%, the weighted average value equates to ~\$47.10 per person per lost hour (or \$0.785 per minute).

Power interruptions

Severe winter weather can also cause power outages, which can impose financial costs to utility customers. For each storm, we received power outage data from Consolidated Edison and PSEG, as well as power outage duration estimates for the December 2010 and January 2016 storm from Consolidated Edison (Charles Viemeister, Consolidated Edison personal communication, October 3, 2017; Tim Lupski, PSEG, personal communication, October 20, 2017).

We then used data from Sullivan et al. (2013) to monetize the cost of power outages to customers. Sullivan et al. (2013) provide estimated average electric customer interruption costs by customer type – including residential, small commercial, and medium and large commercial – and duration of power outages (Table B.2). The utilities could not provide the distribution of power outages across customer types. Instead, we used U.S. Energy Information Administration's (EIA's) number of retail customers by state for the State of New York to obtain a distribution of customer types, and assume that the power outages affect customer types in a manner consistent with the distribution of customer types across the state (Table B.2). ¹⁸

Table B.2. Estimated average	e electric cust	omer interruptio	n costs (USD 2	2016) by ci	ustomer typ	e and durati	on.

Customer type	Percent of NY State customers	Momentary	30 minutes	1 hour	4 hours	8 hours	12 hours
Medium and large commercial	0.1%	\$7,360	\$10,350	\$14,020	\$47,720	\$77,780	\$116,670
Small commercial	14.1%	\$330	\$490	\$690	\$2,940	\$5,830	\$8,750
Residential	85.8%	\$2	\$3	\$4	\$8	\$12	\$18

Source: Sullivan et al., 2013; we generated the 12-hour estimated average electric customer interruption costs by multiplying the estimated average electric customer interruption costs for 8 hours by 1.5 (12 hours divided by 8 hours). Numbers in the table are rounded; commercial interruptions costs are rounded to nearest tens and residential interruption costs are rounded to nearest ones.

We assume that the power outage duration was consistent across utilities, such that the average power outage duration was 12.21 hours for all customers affected by the December 2010 storm and 4.81 hours for all customers affected by the January 2016 storm. For the December 2010 storm, Sullivan et al. (2013) do not provide estimated average electrical interruption costs for a 12-hour power outage duration; therefore, we generated costs for a 12-hour power outage by multiplying the estimated average electric customer interruption cost for an 8-hour outage by 1.5 (12 hours divided by 8 hours). For the January 2016 storm, we use the estimated average electrical interruption costs for a 4-hour power outage. To monetize power outage interruption costs to customers, we distributed power outages across customer types, and multiplied the number of power outages by customer type by the estimate average electricity customer interruption cost. We only provide monetized power interruption costs for the December 2010 and January 2016 storm events.

^{17.} We calculated the average number of passengers per flight using data on the number of passengers and the number of flights departing Kennedy, LaGuardia, and Newark airports during the month of the storm.

^{18.} U.S. EIA's data on the number of retail customers by state are available at https://www.eia.gov/electricity/data/state/.

Economy-wide

Large snowstorms often cause slowdowns in economic activity. For example, construction crews may need to suspend projects until the snow melts; some industries, such as food service and catering, may experience permanent sales losses due to closures and cancellations. In order to estimate the impact of the four snowstorms in NYC, we applied an approach developed by Bloesch and Gourio (2015) in which we quantified the relationship between employment and snowfall, using employment as a proxy for overall economic activity. In order to estimate the impacts of the snowstorms on employment, we considered the initial decrease in employment associated with the storm, as well as the bounce-back effect (increases in employment as industries make up for the work put on hold during the storm).

Bloesch and Gourio (2015) provide coefficients that represent the percentage change in non-farm employment associated with a one-standard deviation increase in snowfall against average snowfall. They also evaluate how long the impacts last, and provide estimates of the effects of the snowfall in the three months following the storm. Bloesch and Gourio (2015) find that employment has a strong bounce-back, such that the level of economic activity returns roughly to where it was before the weather after about two months. We apply the coefficients in the Bloesch and Gourio (2015) study to estimate impacts to employment using the following steps. For each storm, we:

- 1. Calculated the number of standard deviations above average snowfall for that calendar month using snowfall data for Kennedy Airport from NOAA's Climate Data Online, averaged monthly from 1999 to 2016.¹⁹
- 2. Calculated the non-farm employment in the study area for the month of the storm (BLS, 2017).
- 3. Estimated the impact in the month after the storm as follows: Y = B * x * z; where the variables are defined as:
 - Y = the number of jobs lost in the month after the storm;
 - B = the coefficient from Bloesch and Gourio (2015);
 - x = the number of standard deviations above average snowfall for that calendar month (as calculated in Step 1), and
 - z = the non-farm employment in the study area for the month of the storm (as calculated in Step 2).
- 4. Estimated the impact in the two months following the storm²⁰ by applying the coefficients from the lagged model.

An important consideration of this research is the variation in the effect of snow across industry sector. Different industry sectors are impacted by weather differently (Dutton, 2002; Lazo et al., 2011). Bloesch and Gourio (2015) analyze economic impacts by industry sector; however, they do not report results of the lagged model at the sector level. The results of the aggregated model suggest variation. For example, the initial (month 1) impact of a one-standard deviation increase in snowfall in the construction industry is -0.181%, while the impact on the information sector is 0.021%, suggesting a reverse relationship (i.e., employment is positively correlated with snowfall in the information sector).

We expect the bounce-back effect to have similar variation across sectors. For example, in the construction industry, jobs are likely to get delayed, but employment likely fully rebounds once the weather clears; employment may even exceed pre-storm levels in some cases as project managers seek to make up for lost time. In the food service and catering industries, companies are less likely to be able to make up missed sales. While we expect some sales to be permanently lost, it is difficult to quantify that loss using employment data. For example, if a catering company cancels several jobs during a snowstorm, those losses may be passed on to employees through cancelled shift and lost wages rather than decreases in employment.

Our approach has two potential biases. First, the coefficients estimated at the national level might not apply exactly to the study area. In additional work conducted by Bloesch and Gourio (2015), they found that the states that had higher average snowfall had a lower sensitivity to snowfall (Fancois Gourio, Federal Reserve Bank of Chicago, personal communication, March 14, 2017). If this is true, the State of New York is likely less sensitive than the average. However, how these results impact NYC is less clear. While the city gets more snow than many other cities (e.g., Charlotte, NC), the impacts on such a large and densely populated city may be larger than cities with less snowfall. Another potential bias may be introduced by the snowfall data used for the employment calculation. We used snowfall data for the Kennedy Airport weather station, but we know that snowfall can vary substantially across Central Park,

20. Bloesch and Gourio (2015, p. 13) present the coefficients for three months following the snow event, but note that "the bounceback usually happens within a month or two." Thus, for our analysis, we estimate effects using the two months after the storm.

^{19.} NOAA's Climate Data Online is available at https://www.ncdc.noaa.gov/cdo-web/search.

LaGuardia Airport, Kennedy Airport, and Long Island weather stations (Kocin et al., 2011). In fact, Kennedy Airport received far less snow than the other weather stations during the 2013 event (6.4 inches compared to the average of 15.05 inches) and far more during the 2016 storm (30.5 inches compared to the average of 26 inches).

Asset damages

Asset damages are the degree of physical damage that may result from winter weather events. These damages can occur suddenly ("acute") or slowly over time ("chronic"). Acute damage includes partial or complete destruction of an asset – such as fixed property, building contents, or a vehicle – which may cause it to become temporarily or permanently inoperable. Acute damage can interrupt downstream services if it is widespread or if it occurs to assets that are unique or else critically located. Chronic damage represents additional wear and tear on assets that accelerate their aging and reduce their lifespan. Chronic damage introduces additional operational or maintenance costs to a sector as parts that then have to be fixed or replaced more frequently. We focus on acute damages from winter storms, including insured property loss estimates to estimate private damages and federal recovery estimates to estimate public damages.

For private damages, we use PCS state-aggregated loss estimates that cover fixed property, building contents, time-element losses, vehicles, and inland marine goods and properties for winter storm events and other catastrophes (Verisk Analytics, 2017). PCS estimates are developed using (1) a confidential survey of insurers, agents, adjusters, and public officials to gather data on claim volumes and amounts; and (2) an analysis of the data combined with trend factors to determine a loss estimate (Verisk Analytics, 2017). PCS only estimates losses for events that exceed a \$25 million threshold per storm event (losses for individual states are often less than \$25 million). Commercial and residential losses typically constitute a majority of the losses, as auto losses are much smaller by comparison (Adam Smith, NOAA, personal communication, January 31, 2017). Insured property loss estimates likely underestimate total damages because the data do not include non-insured, private losses. Insurance rates vary by geographic region and type of insurance. In general, New York and New Jersey have relatively high insurance coverage (over 85%) for residential, vehicles, and mid- to large-sized businesses (Adam Smith, NOAA, personal communication, March 16, 2017). Small businesses generally lack the comprehensive insurance coverage for business interruption that winter storms may create (Adam Smith, NOAA, personal communication, March 16, 2017) or asset-related insurance. Insurance also varies by socioeconomic conditions, with lower-income households less likely to participate in national homeowners insurance for wind, snow/ice, hail, and fire. ²¹

For public damages, we used FEMA disaster declarations for the States of New York and New Jersey. FEMA public assistance can fund the repair, reconstruction, or replacement of a public facility or infrastructure that is destroyed or damaged in a winter storm or other disaster (FEMA, 2016a). Eligible applicants for public assistance include state and local governments and private nonprofits that provide critical services such as power, water, communications, and emergency medical care (FEMA, 2016a). FEMA provides funds to the state, and the state distributes the money to local government agencies; FEMA requires a cost-share of 25% from the state or local government. In the main document of this report, we provide estimates of funding for permanent work required to restore eligible facilities. These estimates are for the total project amount, including the federal share obligated (approximately 75%) and the state or local share obligated (approximately 25%). FEMA assistance amounts are likely lower than the total cost to restore all public facilities and, therefore, these should be considered lower-bound estimates. For example, federal entities can act under their own authority in recovering certain facilities, and those costs would not be captured here (Christopher Moore, FEMA, personal communication, March 22, 2017).

Human health

NOAA's Storm Data publication documents the direct loss of life and injury from winter storms and other significant weather phenomena (NOAA, 2016). During winter storm events, NWS is in constant contact with local emergency managers. These emergency managers provide death and injury data, which NWS records in the NOAA Storm Data (NOAA, 2016). To augment the NOAA Storm Data, we also include loss-of-life data from the NYC Hazard Mitigation

^{21.} The American Community Survey 2011 data show that national participation rates for homeowners insurance are 41% for households below the poverty level, compared to national participation rates of 72%.

^{22.} Recovery estimates for permanent work include FEMA category C, road systems and bridges; category D, water control facilities; category E, public buildings and content; category F, public utilities; and category G, parks, recreation and other.

Plans, NOAA After Action Reports, and media reports. Some of the reported fatalities and injuries from these sources are directly attributed to the storm events, whereas other fatalities and injuries are indirectly related to the storm events. A direct fatality or injury is defined as "a fatality or injury directly attributable to the hydrometeorological event itself," such as blizzard winds that topple a tree onto a person; whereas indirect fatalities and injuries are defined as "fatalities or injuries occurring in the vicinity of a hydrometeorological event, or after it has ended, but not directly caused by impact or debris from the event," such as motor vehicle accidents on icy roads (NOAA, 2016).

Appendix C. Summary of Winter Storm Impacts

Winter storm	Mitigating actions	Service interruptions	Asset damages	Human health
December 2010	0	0000	♦♦♦	\$\$\$
	 No Hazardous Weather Advisory issued. No prohibition of standing or parking a vehicle on Snow Emergency Streets and no chain or snow tire requirements when driving on Snow Emergency Streets. Delayed snow removal in NYC. NYC deployed 3,030 snow removal vehicles. NYC towed 119 vehicles. 	 Widespread flight cancellations and delays due to weather. Approximately 3,760 weather-related flight cancellations cost airlines \$20.5 million and passengers \$93.1 million. Public transportation severely hampered [e.g., Long Island Rail Road (LIRR) service suspensions, Metro North Railroad services reduced, Metropolitan Transportation Authority (MTA) bus delays, MTA subway delays and interruptions to aboveground service). Severe roadway blockages with disabled vehicles on arterial roadways and local roadways due to snow conditions. Approximately 76,930 customer power interruptions at an average duration of 12.2 hours, with an estimated interruption cost of \$106.8 million. Immediate decline in employment of 3,850 jobs with 2,850 jobs recovering in the following 2 months (overall decline of approximately 1,000 jobs). 	No private property losses reported. \$18.3 million in public property losses recorded (\$7.4 million for NYC).	 At least one storm-related death (fallen tree) and possibly other deaths from emergency vehicles stuck in snow. New York Police Department (NYPD) response times delayed because NYPD vehicles stuck in the snow. Fire Department of New York (FDNY) Emergency Medical Services (EMS) experienced severe citywide backlog due to many ambulances stuck in the snow, and reported multiple fire apparatus stuck in the snow in Brooklyn.
February 2013	00	♦♦♦	♦	\\
	 Hazardous Weather Advisory issued. No prohibition of standing or parking a vehicle on Snow Emergency Streets and no chain or snow tire requirements when driving on Snow Emergency Streets. NYC deployed 2,620 snow removal vehicles. One vehicle towed in NYC. 	 Airports experienced cancellations and delays due to weather. Approximately 1,780 weather-related flight cancellations cost airlines \$9.7 million and passengers \$46.8 million. Thousands of people were stranded overnight on the Long Island Expressway. LIRR and Metro North services suspended, and MTA buses implemented widespread detours or service modifications system-wide due to icy road conditions. Approximately 67,610 customer power interruptions. Immediate decline in employment of 780 jobs, with 580 jobs recovering in the following 2 months (overall decline of approximately 200 jobs). 	 No private property losses recorded. \$14.2 million in public property losses recorded. 	 At least seven storm-related deaths (shoveling snow). NYPD visited homes without heat or electricity affected by Hurricane Sandy. No FDNY EMS backlog. No hospitals on diversion status.

Winter storm	Mitigating actions	Service interruptions	Asset damages	Human health
January 2015	OO Hazardous Weather Advisory issued. No prohibition of standing or parking a vehicle on Snow Emergency Streets and no chain or snow tire requirements when driving on Snow Emergency	 Airports experienced cancellations and delays due to weather. Approximately 2,410 weather-related flight cancellations cost airlines \$13.1 million and passengers \$66.6 million. Roads were closed to traffic and subways were halted. Limited disruption to MTA service. Approximately 8,620 customer power interruptions. 	\$12.3 million in private property losses recorded. No public property losses recorded.	At least one winter-related death (sledding accident). 911 call volume below average. No EMS backlog.
January 2016	Streets. NYC deployed 3,320 snow removal vehicles. No vehicles towed in NYC.	 Immediate decline in employment of 450 jobs with 330 jobs recovering in the following two months (overall decline of approximately 120 jobs). 	***	◊◊
	 Hazardous Weather Advisory issued. Citywide travel ban issued. Prohibition of standing or parking a vehicle on Snow Emergency Streets and chain or snow tire use requirements when driving on Snow Emergency Streets. NYC deployed 3,990 snow removal vehicles. Towed 192 vehicles in NYC. Shut down NYC. 	 Airports experienced cancellations and delays due to weather. Approximately 2,420 weather-related flight cancellations cost airlines \$13.2 million and passengers \$69.5 million. Delays in plowing tertiary streets in Queens. PANYNJ bridges and tunnels, and MTA bridges and tunnels closed to non-essential vehicles. Suspended bus, MTA subway, and LIRR and Metro-North railroad services. Approximately 30,690 customer power interruptions at an average duration of 4.8 hours, with an estimated interruption cost of \$14.7 million. Immediate decline in employment with 2,310 jobs recovering in the following 2 months (overall decline of approximately 810 jobs). 	 \$43.8 million in private property losses recorded. \$9.5 million in public property losses recorded. 	At least five winter-related deaths (heart attacks from shoveling snow). Normal 911 and EMS call volumes.

Notes:

- The impacts symbol (\Diamond) also provides an order-of-magnitude estimate, where \Diamond = limited social and economic impacts; $\Diamond \Diamond$ = some social and economic impacts; $\Diamond \Diamond \Diamond$ = significant social and economic impacts; and $\Diamond \Diamond \Diamond \Diamond$ = maximum social and economic impacts, e.g., following the storm, the city took unprecedented actions to change its operations and procedures.
- We describe the data sources and methods for monetary estimates provided in Appendix B.