Chapter 5
Actionable Science for Hurricane

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Contents

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1   Introduction

Hurricanes are another type of billion-dollar natural hazard and hit our society almost every year. The frequency varies regionally, and climate change is one of the biggest driving factors. For example, Hurricane Dorian, a powerful Category 5 hurricane, struck the Bahamas and the Southeastern United States in August 2019. It was one of the strongest hurricanes ever recorded in the Atlantic, with sustained winds reaching 185 mph (298 km/h) (Mercy Corps 2020). The storm unleashed extreme winds, storm surges, and torrential rainfall, resulting in extensive infrastructure damage, widespread flooding, and loss of life. The islands of Abaco and Grand Bahama were particularly hard hit, with entire communities reduced to rubble. The powerful winds tore off the roof, shattered windows, and toppled walls (Fig. 5.1). The storm surge inundated the entire area, leaving a landscape of debris and devastation. Many families lost not only their homes but also cherished belongings and a sense of security. Power outages were widespread, leaving millions of residents without electricity for days, and disrupting critical services such as communication, transportation, and healthcare. The agricultural sector suffered substantial losses as well. High winds destroyed crops, including citrus groves, and damaged agricultural infrastructure. Regarding real estate, many coastal properties and beachfront homes were severely damaged or destroyed by the storm surge and powerful winds. Structures along the coastline faced flooding, erosion, and structural damage, rendering them uninhabitable or requiring extensive repairs (Shultz et al. 2020). This profoundly impacted property values and the housing market in affected areas.

Fig. 5.1 Widespread destruction in the Bahamas after Hurricane Dorian. (Source: BBC https:// www.bbc.com/news/world-latin-america-49553770)

In the state of Florida, the tourism industry, a vital part of local economy, also experienced significant disruptions. The threat of the hurricane and subsequent damage caused cancellations of vacations and trips, leading to a decline in tourist arrivals. The storm's aftermath impacted popular tourist destinations, such as beach resorts, hotels, and amusement parks, including flooding, property damage, and temporary closures. The loss of revenue from reduced tourism activity had economic implications for businesses and individuals employed in the hospitality and tourism sectors. The devastation caused by Hurricane Dorian in Florida resulted in billions of dollars in damages (Marchante 2019). It took months, even years, for affected communities to recover and rebuild, with many residents and businesses facing significant challenges and hardships.

As Hurricane Dorian approached the Bahamas, meteorologists utilized state-of-the-art satellite imagery, hurricane hunter aircraft, and advanced computer models to monitor and predict its path and intensity (Fig. 5.2). The forecasts provided by the National Weather Service (NWS) and National Oceanic and Atmospheric Administration (NOAA) allowed emergency management agencies and residents to take necessary precautions in advance. Advanced weather models accurately predicted Dorian's trajectory, giving authorities time to issue evacuation orders and implement emergency plans. Real-time data from weather satellites and radar systems provided critical information on the storm's movement and intensity, aiding decision-making at every stage.

Scientists collaborated with emergency management agencies to assess the damage and prioritize relief efforts. Aerial imagery and remote sensing technologies were employed to survey the affected areas, enabling scientists to create detailed damage assessment maps. This information guided the distribution of resources and facilitated targeted assistance to the most severely impacted regions. Scientists also analyzed the factors that contributed to Hurricane Dorian's intensity and slow movement. Their research helped improve the understanding of hurricane behavior and the potential influence of climate change on storm characteristics, which can inform future mitigation strategies. Scientists with expertise in disaster response and search and rescue techniques joined forces with emergency response teams to locate and rescue individuals affected by the hurricane. They utilized advanced technologies, such as drones and satellite imagery, to identify the areas with stranded or trapped individuals. They also guided safety protocols and efficient search strategies to maximize the effectiveness of rescue operations.

Researchers specializing in medical and public health fields played a critical role in providing medical support and expertise during the response phase (Powell et al. 2012). They coordinated with healthcare professionals and emergency medical teams to establish temporary medical facilities, triage centers, and field hospitals to treat injured individuals and provide necessary healthcare services. They helped address the health risks and challenges associated with post-hurricane conditions, such as waterborne diseases or exposure-related illnesses. The knowledge in engineering, geospatial analysis, and telecommunications supported the response efforts by providing technical assistance and deploying specialized equipment. They helped set up temporary communication networks, restore critical infrastructure,
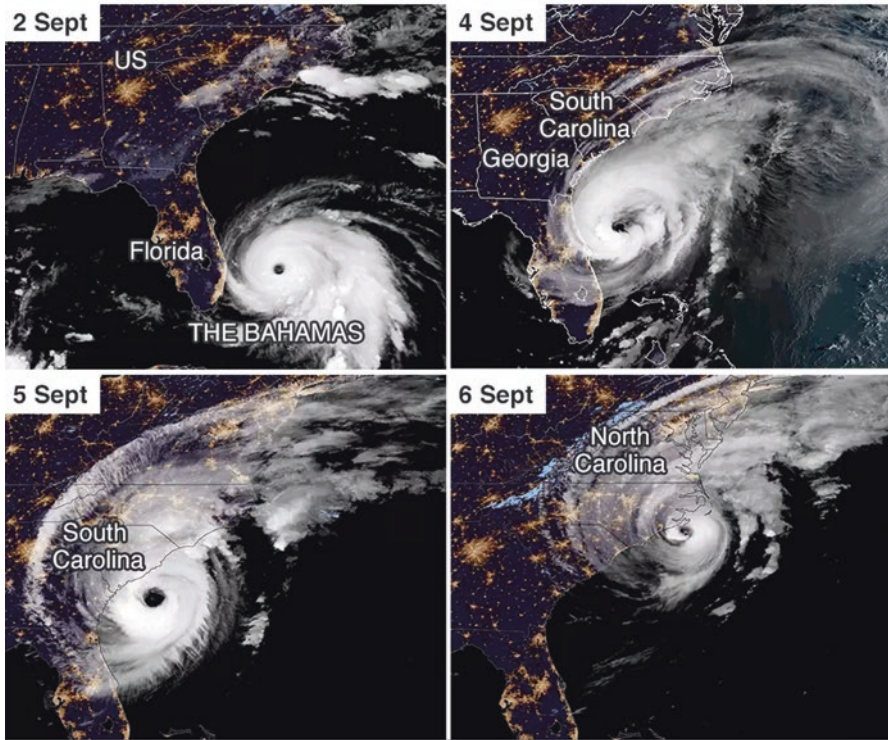
Fig. 5.2 Dorian's progression from the Bahamas toward the United States. (Source: NOAA 2019)

and ensure the functionality of emergency response systems. For example, people with knowledge of geographic information systems (GIS) provided mapping and spatial analysis support, helping responders identify accessible routes, establish evacuation centers, and plan efficient resource distribution (Sharma et al. 2016). Moreover, experts in the field of psychology and mental health worked alongside mental health professionals to address the psychological impacts of the disaster, such as trauma, stress, and anxiety (Vernberg et al. 2008). They usually offered counseling services, developed coping strategies, and conducted research to better understand the psychological effects of hurricanes on affected communities, helping to ensure adequate mental health support during the response phase. Regarding aftermath, scientists conducted extensive studies to evaluate the storm's impacts and identify lessons for future resilience. They analyzed data collected from weather stations, ocean buoys, and storm surge gauges to refine forecast models and improve predictions of storm surge heights. The findings from these analyses contribute to ongoing efforts to enhance hurricane forecasting and emergency preparedness.

We introduced during Hurricane Dorian how science played a crucial role in all stages of a major hurricane event. The utilization of advanced technologies, data analysis, and scientific expertise contributed to more accurate forecasts, timely

warnings, and informed decision-making. By integrating scientific knowledge into emergency response and recovery efforts, communities can better prepare, mitigate, and recover from devastating storms like Dorian. However, not all scientific research contributes to actions during hurricanes. On the contrary, the majority of research is not utilized or engaged by policymakers, emergency responders, or the public before, during, or after hurricanes. Here are some reasons. Many scientists dedicate their careers to understand the formation, behavior, and track of hurricanes and use sophisticated models and data analysis techniques to predict the path and intensity. While these predictions are vital for preparedness and evacuation efforts, they do not provide direct interventions or solutions to mitigate the impact of hurricanes. Hurricane impacts often manifest after their formation is already known, rendering the information about their formation less critical. Moreover, despite advancements in scientific understanding, scientists have limited control over the occurrence and intensity of hurricanes. The ability of scientists to take direct action to prevent or modify hurricanes is highly restricted. Even though scientists propose several strategies to intervene or modify hurricanes, such as cloud seeding or dispersing chemicals, these activities raise serious ethical concerns and have substantial practical limitations. Altering a hurricane's trajectory or intensity can have unintended consequences and potentially lead to even more significant damage or disrupt natural ecosystems. Then come the uncertainties of scientific models. The inherent complexity of hurricanes, including temperature, humidity, wind patterns, and ocean conditions limits the ability to provide actionable guidance with high certainty. Predicting their behavior with absolute certainty is very hard, and uncertainties in modeling and data inputs can seriously affect the accuracy of predictions and may contribute to wrong conclusions.

Although most scientific research is not in action, their results are important for mitigation and preparedness, like helping decision-makers create building codes, land planning, early warning systems, and evacuation plans. However, these codes need a lot of community decisions and involve not only the science of hurricanes, but also social sciences and the local economy, culture, demography, and religious factors that have even more weight in the decision-making than science, especially in the coastal areas of developing countries. That is another important reason why science is nonactionable in many developing countries. They may have limited financial resources to invest in advanced scientific research, sophisticated monitoring systems, or early warning technologies. This lack of resources can limit the ability to gather accurate and timely data on hurricanes and hinder the development of actionable scientific guidance. They also lack resilient infrastructure, such as hurricane-resistant buildings, robust evacuation plans, or efficient communication networks. Without the necessary infrastructure in place, even if scientific knowledge is available, its application may be hindered, leading to less effective response and recovery efforts. In some communities, traditional knowledge or religious beliefs hold greater weight than scientific information, leading to challenges in disseminating and acting upon scientific recommendations. Demographic factors like high population density, informal settlements, or poverty can pose significant challenges in evacuating and assisting vulnerable populations during hurricanes. They

make it difficult to implement scientific recommendations effectively and efficiently. Meanwhile, people with limited access to quality education and information about hurricanes also shadow their understanding and acceptance of scientific knowledge. Without a well-informed population, it can be challenging to communicate and promote actionable measures based on scientific research.

Overall, science has always been important in hurricane preparedness and response. However, not all sciences are equally emphasized and actionable. This chapter will dive into the reasons and come up with some suggestions that could improve the situation and make our efforts in scientific research more acceptable and can easily reach and help the communities being impacted. On the other hand, this chapter will list suggestions for the local community, decision-makers, and first responders on adopting science better and minimizing costs while maximizing the outputs. Besides, we will touch on the potential opportunities lying ahead in the future science research pathways to make hurricanes beneficial for us and convert them from threads to resources for humankind.

2 Emergency Management Phases and Hurricane Operation Network

This section will introduce emergency management phases and the current hurricane action networks in the world and explain current hurricane research purposes, final application goals, realistic limitations, potentials, and relevant successful (or failure) experiences.

2.1 Emergency Management Phases for Hurricanes

There are four phases of emergency management in the context of hurricanes: mitigation, preparedness, response, and recovery. These steps are interconnected and often overlap, creating a cycle that is continuously in motion (Fig. 5.3).

Mitigations involve efforts to minimize the impact of hurricanes. Mitigation strategies include developing and enforcing stringent building codes to withstand hurricane force winds, implementing land-use planning measures to avoid building in high-risk areas such as flood zones, and creating natural barriers like mangrove plantations along the coast to protect against storm surges (Godschalk et al. 1989).

Preparedness starts before the hurricane strikes and involves activities designed to build capacity and capability to respond to a hurricane (Wolshon et al. 2005). These activities can include developing, testing, and refining emergency plans, creating and maintaining emergency communication systems, and stockpiling necessary supplies and resources. Preparedness also involves training emergency personnel, establishing evacuation routes and shelters, and educating the public on how to prepare for a hurricane. This phase needs efforts from multiple departments
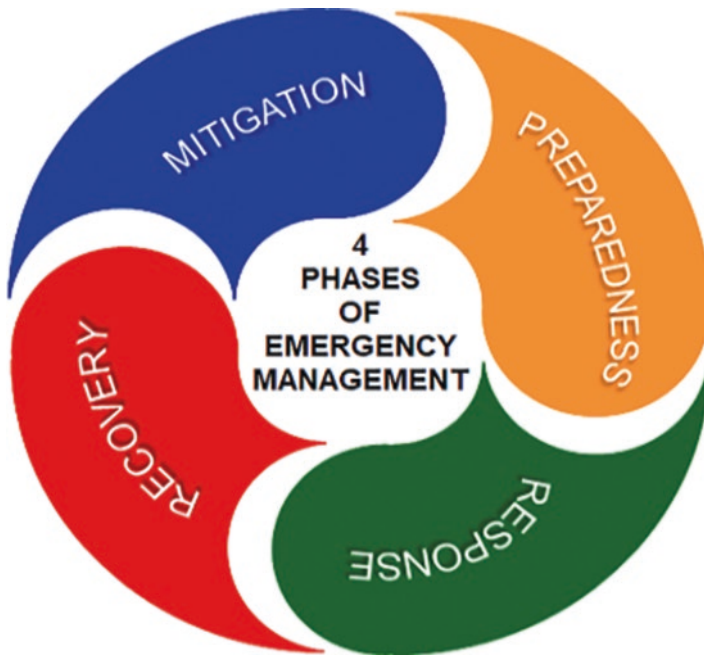
Fig. 5.3   FEMA's four phases of emergency management. (Adams et al. 2022)

at various levels of government such as the Federal Emergency Management Agency (FEMA) and local departments of emergency management, nongovernmental organizations such as the American Red Cross, community, and individuals.

When a hurricane is imminent or has already struck, the response phase starts. This includes actions taken to save lives, protect public health, and prevent further property damage. Activities in this phase include search and rescue, providing emergency medical services, disseminating public information and warnings, and meeting immediate basic needs such as food, water, and shelter (Veenema 2018).

Recovery aims to restore the affected areas to their normal or improved status (Smith and Wenger 2007). This involves repairing or reconstructing damaged infrastructure, providing medical care and counseling services, and rebuilding homes and businesses. This phase can last months to years depending on the extent of the damage and the resources available (Melemis 2015).

2.2   The Hurricane Management in the United States

The hurricane network in the United States includes multiple institutions and agencies working collaboratively to ensure effective management and response to hurricanes. They are the crucial operational venue for science to become actionable. Here we list some main organizations.

National Hurricane Center (NHC)

The NHC, a subdivision of the National Weather Service (NWS) and also a part of the National Oceanic and Atmospheric Administration (NOAA), is responsible for monitoring and forecasting hurricanes in the Atlantic and Eastern Pacific Ocean basins (National Hurricane Center 2023). The NHC is located in Miami, Florida. Staffed by meteorologists and scientists working year-round, the NHC provides accurate forecasts, warnings, and analyses that inform emergency planning. Using data from satellites, radar, aircraft, and weather stations, they employ computer models to track cyclones' movement (cyclone is the synonym for hurricane in the Pacific and Indian Ocean), intensity, and potential impacts. The NHC offers various forecast products, including advisories and graphical forecasts detailing storm specifics and potential hazards like storm surge, rainfall, and wind impacts.

State, local, and federal emergency management agencies utilize NHC's forecasts and warnings to develop emergency response plans, coordinate evacuations, and allocate resources for hurricane-impacted areas (Sabbaghtorkan et al. 2020). The NWS forecast offices across the United States receive the NHC's tropical cyclone forecasts and use them to issue local forecasts and warnings specific to their regions. This helps them provide accurate and localized information to the public and emergency responders. Television and radio stations, newspapers, and online news platforms rely on the NHC's updates and forecasts to inform the public about the potential impacts of hurricanes. Airlines, airports, and aviation authorities depend on the NHC's forecasts and advisories to assess the impact of hurricanes on air travel. It helps them make decisions regarding flight cancellations, diversions, and other operational adjustments to ensure passenger safety. Shipping companies, ports, and maritime authorities utilize the NHC's forecasts and advisories to plan vessel movements, reroute ships away from dangerous areas, and ensure the safety of maritime operations during hurricanes. Insurance providers and reinsurers rely on the NHC's forecasts and historical data to assess risks and determine insurance rates and coverage in hurricane-prone regions. Last but not least, the NHC's forecasts, advisories, and educational resources are accessible to the general public. Individuals living in or visiting hurricane-prone areas use the NHC's information to make decisions regarding preparedness, evacuation, and personal safety measures.

Federal Emergency Management Agency (FEMA)

The Federal Emergency Management Agency (FEMA) is a federal agency of the United States Department of Homeland Security (DHS). FEMA is led by an administrator who is appointed by the president of the United States and confirmed by the senate. The administrator is responsible for overseeing the agency's operations and coordinating disaster response and recovery efforts. FEMA's headquarters is located in Washington, D.C., but the agency has regional offices across the United States that are responsible for coordinating disaster response efforts within their respective regions. FEMA employs a workforce including emergency managers, logistics

specialists, public affairs officers, analysts, and other professionals with expertise in disaster response and recovery. The exact number of employees varies based on the agency's needs and budget. It receives funding from various sources, including appropriations from the Congress, disaster relief funding, grants, and partnerships with other federal agencies and organizations. The agency's budget is subject to congressional approval and is allocated based on the level of disaster activity and projected needs. FEMA's primary mission is to coordinate and support the nation's response to and recovery from disasters, including hurricanes. The agency's duties include preparing and implementing emergency management plans and policies, coordinating federal assistance to state, local, tribal, and territorial governments, providing financial assistance and resources to affected communities for disaster response, recovery, and mitigation (FEMA 2023). It also conducts disaster response and recovery operations, including logistics, resource coordination, and technical support. They collaborate with other federal agencies, state and local governments, nonprofit organizations, and the private sector to ensure a coordinated and effective response to disasters. They are also actively promoting community preparedness and resilience through public education and outreach programs. FEMA's responsibilities extend beyond hurricanes to include other natural disasters, such as floods, earthquakes, wildfires, and severe storms.

Unlike the NHC, the role of FEMA is more on coordination and resource allocation to provide actual assistance to the impacted areas. When a hurricane is forecasted or imminent, FEMA activates its National Response Coordination Center (NRCC) and Regional Response Coordination Centers (RRCCs) to facilitate coordination among agencies at various levels (FEMA 2020). These centers serve as command and control hubs for managing resources and coordinating response efforts. Once the impact of a hurricane is expected to exceed the capabilities of state and local resources, the president can issue an emergency declaration, which unlocks federal resources and funding to support response and recovery efforts. Ahead of an approaching hurricane, FEMA prepositions resources and assets to expedite the response. This includes deploying personnel, equipment, supplies, and specialized teams to staging areas near the expected impact zone. FEMA also deploys Incident Management Assistance Teams (IMAT) to affected areas to support coordination, resource management, and incident command. IMATs work directly with state and local officials to assess needs, prioritize response efforts, and coordinate the deployment of federal resources. They also provide technical expertise and guidance on various aspects of disaster response. When Hurricane Katrina approached, 11 members of FEMA's Hurricane Liason Team were at the NHC to monitor the storm and storm advisories by August 27, 2005 (Skinner and Hodges 2006). FEMA Emergency Response Teams coordinated with the states to preposition commodities and personnel in the area, activated federal operational staging areas and mobilization centers to accept delivery of commodities and distribute them to affected areas.

FEMA provides individual assistance to homeowners, renters, and businesses affected by hurricanes. This assistance may include grants for temporary housing, home repairs, and other disaster-related expenses not covered by insurance

(Gecowets and Marquis 2008). FEMA's Individuals and Households Program (IHP) helps individuals and families recover and rebuild their lives after a hurricane. FEMA's Public Assistance program provides funding to local governments, as well as certain private nonprofit organizations, to repair, rebuild, or replace damaged public infrastructure and facilities. This includes critical infrastructure such as roads, bridges, schools, hospitals, and utilities. FEMA also participates in long-term recovery and mitigation efforts. The agency provides funding and technical assistance to help communities rebuild in a more resilient manner, incorporating measures to reduce future risks and vulnerabilities. This includes initiatives like hazard mitigation grants, floodplain management, and building code enforcement. For Hurricane Katrina, FEMA had received 1,557,937 registrations for IHP assistance from residents of Alabama, Mississippi, and Louisiana, and it made 1,380,564 applicant referrals for assistance under the housing assistance component and awarded $2,401,735,486 (Skinner and Hodges 2006, p. 13).

United States Geological Survey (USGS)

The USGS is another federal scientific agency with a broad range of capabilities and is responsible for studying and providing reliable information about the nation's natural resources, including hazards like hurricanes (Holmes et al. 2013). The USGS conducts research, monitoring, and assessments related to geology, ecosystems, natural hazards, and climate change. It operates numerous field offices, laboratories, and research centers across the United States. The agency operates a network of streamgages, tide gauges, and other monitoring stations called the National Water Information System (NWIS) that collect data on water levels, streamflow, and coastal changes (USGS 2021). The USGS operates a network of seismometers that detect and monitor earthquake activity. While not directly related to hurricanes, this network helps track seismic events that could be triggered by or have an impact on hurricanes. The USGS collects and maintains satellite imagery (Landsat) that can be used to monitor changes in land cover, coastal erosion, and other impacts of hurricanes (Kriner et al. 2021). The USGS employs scientists, geologists, hydrologists, biologists, and other professionals with expertise in various disciplines relevant to hurricane management. During hurricanes, USGS personnel are involved in data collection, field surveys, and research activities. They assess storm impacts on coastal areas, water resources, ecosystems, and geological features. USGS scientists and researchers conduct ongoing studies and monitoring activities to understand the dynamics of coastal environments, floodplains, and water systems. This helps in assessing vulnerabilities and developing mitigation strategies. They analyze data from various sources to generate flood forecasts, model storm surge scenarios, and assess potential hazards.

USGS data is crucial for understanding the impacts of hurricanes on coastal areas and for issuing flood warnings. The USGS conducts coastal vulnerability assessments to evaluate the susceptibility of coastal areas to erosion, inundation, and other hazards during hurricanes. By analyzing topography, sediment dynamics,

and other factors, the agency helps identify areas at risk and provides valuable information for land-use planning and hazard mitigation (USGS 2023). After a hurricane, the USGS conducts rapid assessments to document the extent of coastal changes, including beach erosion, dune erosion, and barrier island movement. The agency uses aerial and satellite imagery, as well as ground-based surveys, to gather data on the impacts of the storm. This information is crucial for understanding the vulnerability of coastal environments and guiding recovery efforts. The USGS conducts research on the hydrological and geological aspects of hurricanes, including rainfall patterns, storm surge dynamics, and the impacts on inland waterways. This research helps improve flood forecasting models, storm surge predictions, and hazard mapping.

National Aeronautics and Space Administration (NASA)

NASA (the National Aeronautics and Space Administration) is a US government agency responsible for the nation's civilian space program and for aeronautics and aerospace research (Dembling 1959; Adams 2018). NASA studies Earth's systems, including the atmosphere, land, oceans, and ice, to better understand our planet's dynamics, climate change, and natural hazards. They collect data using satellites and aircraft, monitor environmental changes, and develop models to improve our understanding of the Earth's processes. It also pioneers new technologies and innovations that have applications both in space exploration and on Earth. They invest in research and development projects to create advanced materials, propulsion systems, robotics, and communication technologies that benefit various industries and scientific disciplines. NASA's duty is to push the boundaries of human knowledge, foster technological advancements, and explore the universe to benefit humanity (Wiles 2013).

NASA's satellites, such as the Aqua, Terra, and Suomi NPP, provide essential data for monitoring hurricanes. These satellites collect information on temperature, humidity, wind patterns, and sea surface conditions, enabling scientists and meteorologists to track the formation, intensification, and movement of hurricanes (Earth Science Data Systems 2021). Scientists at NASA use advanced remote sensing techniques to study hurricanes from space. Instruments like the Advanced Microwave Scanning Radiometer (AMSR) and the CloudSat mission help gather detailed data on precipitation, cloud properties, and the overall structure of hurricanes (Jenner 2009). This information assists in improving hurricane forecasting models and understanding the underlying processes. There are specialized research missions, such as the Hurricane and Severe Storm Sentinel (HS3) and the Cyclone Global Navigation Satellite System (CYGNSS), to study hurricanes up close (Allen 2015). These missions involve flying aircraft equipped with advanced instruments into the vicinity of hurricanes to collect valuable data on their structure, intensity, and environmental conditions. The data gathered helps improve hurricane modeling and forecasting accuracy. NASA collaborates with other agencies and research institutions to develop sophisticated computer models that simulate hurricane

behavior. These models incorporate data from NASA's satellite observations and research missions, as well as other sources, to enhance hurricane forecasting and prediction capabilities. Improved models aid in early warning systems, evacuation planning, and emergency response preparedness. In addition to scientific research, NASA also provides support to disaster response efforts by supplying high-resolution satellite imagery and mapping data after a hurricane strikes and helps identify affected areas, assess damages, and support emergency management operations on the ground (Gray 2020). It assists in coordinating relief efforts, identifying critical infrastructure, and aiding in the deployment of resources to affected communities.

Department of Defense (DOD)

As one of the largest government agencies, employing hundreds of thousands of military personnel and civilians, and primarily focused on defense and military operations, the DoD also participates in supporting civilian usage and responding to emergencies (U.S. Department of Defense 2023). It operates across various domains, including land, sea, air, space, and cyberspace. The DoD carries out operations to defend the country, deter potential threats, and support allied nations. In certain situations, the DoD can support civilian agencies and organizations during emergencies, disasters, and other crises. This support is typically coordinated through established frameworks, such as the National Response Framework, where the DoD can contribute resources, expertise, and capabilities to assist in logistics, transportation, communications, and infrastructure support. It operates globally with a vast array of military bases, installations, and facilities. The DoD's funding primarily comes from the US federal budget, allocated by the Congress to cover military operations, personnel, equipment, research, and development (Austin III 2023). The DoD invests in research and development (R&D) to advance military capabilities and technologies. The R&D effort often contributes to scientific and technological advancements with potential civilian applications. It collaborates with academia, industry, and other government agencies to drive innovation in aerospace, materials science, cybersecurity, and more.

In most cases, the DoD supports civilian authorities in responding to hurricanes. They coordinate and share information with other government agencies, including the National Hurricane Center (NHC) and Federal Emergency Management Agency (FEMA). This collaboration helps enhance situational awareness, enables timely decision-making, and facilitates allocating resources where they are most needed (U.S. Department of Transportation 2006). The DoD's U.S. Northern Command (USNORTHCOM) works closely with the NHC and FEMA during hurricane events to coordinate military support, share intelligence, and provide situational updates to support the overall response effort. The DoD's assistance is coordinated through established frameworks to ensure effective collaboration and seamless integration with civilian efforts.

State and Local Emergency Management Agencies

Each state with hurricane history has its own Emergency Management Agency responsible for coordinating emergency preparedness, response, and recovery efforts (Habets et al. 2023). These agencies work closely with local governments, nonprofit organizations, and other stakeholders to ensure a coordinated and effective response to hurricanes. Florida Division of Emergency Management (FDEM) is responsible for coordinating and overseeing emergency management activities in the state of Florida (Florida Division of Emergency Management 2023). They work closely with county emergency management agencies, local governments, and nonprofit organizations to develop hurricane response plans, coordinate resources, and provide guidance during emergencies.

At the county level, emergency management offices are responsible for developing and implementing emergency response plans tailored to their specific region. They work closely with local government departments, nonprofit organizations, and community stakeholders to coordinate preparedness, response, and recovery efforts. For example, the Miami-Dade County Office of Emergency Management is established for coordinating emergency management activities within the county. They work to develop evacuation plans, establish emergency shelters, and coordinate resources during hurricane events (Hristidis et al. 2010).

Several nonprofit organizations play a significant role in hurricane management by providing support and resources during and after hurricanes. These organizations often focus on specific aspects such as disaster response, sheltering, humanitarian aid, and long-term recovery efforts. One typical example is the American Red Cross, a primary nonprofit organization involved in hurricane management. They provide emergency sheltering, distribute essential supplies, offer medical assistance, and support long-term recovery efforts (Red Cross 2022). They work in collaboration with local governments, emergency management agencies, and community partners to deliver their services effectively.

More importantly, dedicated to each community there are local community-based organizations, such as faith-based groups, community centers, and volunteer organizations, which also act as an important part of hurricane management. They provide assistance in sheltering, food distribution, debris cleanup, and volunteer coordination to support the affected communities. One example is the All Hands and Hearts, a nonprofit organization that mobilizes volunteers to assist in disaster response and recovery efforts (All Hands and Hearts 2023). They collaborate with local communities, emergency management agencies, and other organizations to provide immediate relief and help rebuild homes and infrastructure after hurricanes.

When a hurricane hits, local organizations are crucial during hurricanes (Fothergill and Peek 2004). They understand their community's unique needs due to familiarity with the geographical, social, and cultural aspects of the region (Dynes 2006). Their local knowledge aids effective communication, identification of vulnerable populations, and community safety strategies (Tierney 2007). In crises, they are often the first to respond, providing essential services like search and rescue, emergency sheltering, and relief supplies (Perry and Lindell 2003). Their closeness

to the community allows quick resource mobilization. Trust and established relationships within the community enable them to raise preparedness awareness and encourage community participation (Dynes 2006). These organizations adapt swiftly to changing situations, tailoring services as needed, such as setting up shelters or assisting vulnerable populations (Quarantelli 1999). Post hurricane, they are vital for long-term recovery, assisting in damage assessment, infrastructure rebuilding, and offering support services (Perry and Lindell 2003). They complement federal agencies by offering extra resources and expertise (Fothergill and Peek 2004). Their deep understanding of their communities improves the effectiveness of recovery efforts (Tierney 2007). They are also key in sharing science-based information and guiding the response, evacuation, and restoration (Quarantelli 1999).

2.3   The Hurricane Management Operation in Other Countries

Hurricanes are a regional phenomenon, and hurricane-prone areas are commonly located in the Atlantic basin, eastern and western Pacific basin, and northern and southern Indian Ocean basins (Landsea et al. 2010). The Atlantic basin includes the Gulf of Mexico, the Caribbean Sea, and the western Atlantic Ocean. Countries such as the United States, Mexico, Central American countries, and Caribbean islands are located in this area. The eastern Pacific basin includes the coastal areas of Mexico, Central America, and the western coast of South America. Western Pacific Ocean, including the Philippines, Japan, China, Taiwan, and other countries in Southeast Asia. Also countries like India, Bangladesh, Sri Lanka, and Myanmar are also prone to tropical cyclones. Southern hemisphere countries such as Australia, Madagascar, Fiji, and New Zealand are also impacted by hurricanes (Knutson et al. 2010).

Similar to FEMA in the United States, the other countries with coastlines and hit seriously have many agencies and organizations specialized to respond to hurricanes. For instance, the National Center for Disaster Prevention (CENAPRED) is responsible for coordinating hurricane emergency response efforts in Mexico. The Mexican Red Cross provides humanitarian aid, medical assistance, and relief services during emergencies (Godwyn-Paulson et al. 2022). The Caribbean Disaster Emergency Management Agency (CDEMA) is responsible for navigating similar efforts among the Caribbean islands (CDEMA 2023). The Japan Meteorological Agency (JMA) monitors and issues warnings for tropical cyclones in Japan. IMD is the equivalent agency in India focusing on the Bay of Bengal and Arabian Sea area. The China Meteorological Administration (CMA) is specialized in monitoring and forecasting tropical cyclones in the Western North Pacific and the South China Sea (Lu et al. 2021). The ASEAN Coordinating Centre for Humanitarian Assistance on Disaster Management (AHA Centre) facilitates cooperation and coordination among western Pacific member states in disaster management. Meanwhile, each Southeast Asian country has its own National Disaster Management Offices (NDMO), responsible for coordinating cyclone response efforts at the national

level. In Australia, the Bureau of Meteorology (BOM) conducts weather forecasts, warnings, and cyclone tracking mainly for the Australian region of the Southern Hemisphere (Bureau of Meteorology 2023). New Zealand MetService is responsible for weather forecasting and severe weather warnings for the island country (King et al. 2008).

Generally, the invested resources in these agencies vary depending on the intensity of the storm, the population density in affected areas, infrastructure resilience, preparedness measures, and the ability to respond effectively. The United States is definitely having the most serious damages, for example, the single Hurricane Katrina in 2005 caused damages of $192.5 billion (NCEI 2023). In other countries, the damages are also very severe, mostly in fatality. For example, the Super Typhoon Haiyan in 2013 (Lum and Margesson 2014) stormed over the Philippines and China, caused damages of $12 billion, and 6190 people lost their lives (Reid 2018). Typhoon Fitow in 2013 caused an estimated $10.4 billion in damages in the southern provinces of China (Guilford 2013). Bangladesh is another major country prone to cyclones and suffered substantial economic losses. Cyclone Bhola in 1970 resulted in one of the deadliest tropical cyclones on record, with a death toll estimated between 300,000 and 500,000 (Cerveny et al. 2017).

2.4 The Opinion of the Impacted Society on Hurricane Research

Public attitudes toward hurricane research and investment vary globally, influenced by factors such as frequency of hurricanes, economic capacity, and government priorities (Lazo et al. 2009). Countries with a higher frequency of hurricanes and more significant impacts, such as those in hurricane-prone regions, often allocate resources toward hurricane research and infrastructure improvements. For example, the United States has generally widespread support for hurricane research and investment in scientific advancements. Its public recognizes the importance of understanding hurricanes, improving forecasting capabilities, and enhancing response and preparedness measures (Lazo et al. 2015). The US government allocates significant funding toward hurricane research through agencies like the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), and NASA (Pielke et al. 2008). Public–private partnerships in the United States also play a role in advancing hurricane research. Despite the outputs of hurricane research, such as improved forecasting models and early warning systems, being generally well received by the public, challenges remain in effectively communicating and translating scientific findings into actionable information for the general population (Morrow et al. 2015).

The level of investment can vary depending on economic capacity and governmental priorities. In developing countries, limited access to quality education and awareness programs on the importance of science-based strategies can contribute to

skepticism (Gaillard and Mercer 2013). Lack of scientific literacy and understanding can hinder the acceptance of scientific evidence and recommendations. When a science research wants to roll out to reality, there will always be a mix of reactions. Some individuals may trust and value hurricane science research, recognizing its importance in understanding and predicting the behavior of hurricanes. They may appreciate the efforts of scientists and experts in providing early warnings and guidance to mitigate risks. Others may be skeptical or doubtful of hurricane science research, influenced by misinformation or conspiracy theories. This skepticism can stem from a lack of scientific literacy, conflicting sources of information, or historical incidents where predictions were inaccurate (Lindell and Perry 2012). Some individuals may find it challenging to translate scientific research into actionable measures due to practical considerations. Factors such as limited resources, inadequate infrastructure, and competing priorities may hinder the implementation of recommended strategies. In certain communities, traditional knowledge and practices may hold a significant impact on hurricane responses. People may rely on local wisdom passed down through generations, which can sometimes conflict with or overshadow scientific recommendations (Mercer et al. 2012).

2.5   Are Scientists and the Impacted Communities on the Same Page?

The simple answer is no. Scientists and impacted communities are not on the same page or have the same goal most of the time, and their focus and priorities are completely different. One reason is that public outreach and communication with the public are very hard. Effectively communicating complex scientific concepts to the public, policymakers, and other stakeholders can be a challenge. Bridging the gap between scientific research and public understanding requires clear and accessible communication channels, including effective science communication and outreach programs. Implementing science-based strategies requires cooperation and collaboration among multiple stakeholders, including government agencies, policymakers, local communities, and scientific institutions. Challenges such as political agendas, conflicting interests, and bureaucratic processes can hinder the adoption and implementation of scientific recommendations. Adequate resources, including funding, infrastructure, and trained personnel, are essential to translate scientific research into actionable strategies. Being restricted on resources in some hurricane-impacted areas can pose barriers to implementing comprehensive resilience measures.

Another important factor contributing to the disconnection and making science nonactionable is the knowledge gap. Hurricane scientists possess specialized knowledge and expertise in studying and understanding hurricanes. They are trained to analyze data, develop models, and make predictions based on scientific principles. Hurricane scientists often use technical jargon, complex models, and statistical data, which may not be easily understood by nonexperts. This can lead to a lack of clarity

and misinterpretation of scientific findings, making it difficult for the public to fully grasp the implications and importance of the research. This knowledge gap between scientists and the public can create a barrier in effectively communicating the complexities of hurricane science.

In addition, individuals living in hurricane-prone areas may have different perceptions of risk and prioritize immediate concerns over long-term preparedness. While scientists focus on understanding and predicting hurricanes to mitigate risks and reduce damages from their labs (most of them never visited those regions and only have perception from the collected data), the public may have more immediate concerns such as evacuation, shelter, and recovery efforts after a hurricane hits. This difference in time perspective and priorities can lead to a disconnect between scientists and the public. Other factors like cultural beliefs, traditions, and historical experiences shape public attitudes and responses to hurricanes. Traditional knowledge and practices are deeply ingrained in the community, leading to skepticism or resistance toward scientific approaches. Additionally, previous experiences with hurricanes, including instances where predictions were inaccurate or insufficient, can contribute to public mistrust or skepticism toward scientific research. Socioeconomic factors such as income disparities, access to resources, and social vulnerability can influence the perceptions and responses of individuals as well. Communities with limited resources and high levels of vulnerability may face challenges in implementing or adhering to scientific recommendations, leading to a divergence in priorities between scientists and the public.

Actually, the difference is quite obvious and sometimes even in the opposite direction on their goals between science and the public. The public, local government, and organizations often focus on immediate needs during and after a hurricane, such as ensuring public safety, providing emergency response, and facilitating recovery efforts. Their primary concern is the well-being and immediate needs of the affected communities. On the other hand, the goal of hurricane scientists is to understand the complex dynamics of hurricanes, improve prediction accuracy, and develop long-term mitigation strategies. This long-term planning perspective may not align with the immediate needs and priorities of the public and local stakeholders. For the sake of better records of hurricanes and better understand the formation and underlying mechanism, the huge storms could be a very valuable opportunity for scientists. Scientists are mainly to develop future strategies to mitigate risks, improve forecasting accuracy, and enhance preparedness, while the primary concern for the affected community during a hurricane is their immediate safety and well-being. Their focus is on evacuation, shelter, and basic needs.

As mentioned previously, a lot of hurricane research is neither actionable nor "action oriented." The community expects immediate practical solutions to protect lives, property, and infrastructure during a hurricane. They value tangible actions and strategies that directly address their immediate needs. Scientists are primarily engaged in scientific research and analysis to enhance understanding of hurricanes. Their focus is on studying the underlying processes, improving models and predictions, and contributing to the body of scientific knowledge. The community's concerns are localized and centered on their immediate environment, including their

homes, neighborhoods, and local infrastructure. Their priorities revolve around protecting their community and recovering from the impact of the hurricane, while scientists take a broader perspective, considering the global impact of hurricanes and how they fit within the larger climate system. Scientists emphasize long-term planning and preparedness to minimize the impact of future hurricanes, while the community's focus is often on the immediate aftermath of a hurricane, including cleanup, rebuilding, and recovery. These differences have made the community not understand the priority and importance of science, while the scientists cannot fit their result outputs into a more make-sense position to get used and help in the real world.

2.6   Consequences of Nonactionable Science

Nonactionable science might not be a serious matter from the perspective of the science community as that is not the usual goal that they are desperately pursuing compared to publishing findings, discovering and accumulating knowledge. Making science into operation is not the designated job for scientists. However, from the perspective of the public, it is at least one part of the obligation of scientists, and nonactionable science could hurt the image of science as a whole. Meantime, nonactionable science could have extra consequences, which will further the damages to both science and the impacted communities.

Nonactionable hurricane science can result in insufficient preparedness measures, such as evacuation plans, emergency shelters, and early warning systems. This can leave communities ill-equipped to respond effectively to hurricane threats, leading to delays in evacuation, lack of essential supplies, and increased risks to life and property. If a region lacks accurate and timely hurricane forecasting information, residents may not receive adequate warnings and instructions, which can hamper their ability to take appropriate actions to protect themselves. Also, it can contribute to a higher loss of life and injuries due to inadequate understanding of hurricane dynamics, storm surge risks, or the potential for rapid intensification that can leave people exposed to dangerous conditions. They may underestimate the severity of the storm and fail to take necessary precautions. Without reliable and operable science-based guidelines, communities may lack the necessary information to implement effective mitigation strategies and building codes to withstand hurricane impacts. This can result in extensive property damage and economic losses. It also hampers the ability to implement effective risk reduction measures, like land-use planning, infrastructure improvements, and community resilience programs.

3 State-of-the-Art Hurricane Research

This section will introduce several ongoing research topics and their current progress. It will provide a general overview of the future research outputs regarding hurricanes, and we will discuss how they will be used in action and the benefits and associated risks. The research topics are categorized based on their application stage of hurricanes.

3.1 Hurricane Track Forecasting

The modern technique used for Hurricane Track Forecasting is based on numerical weather prediction (NWP) models that solve the governing equations of fluid dynamics, thermodynamics, and other physical processes to simulate the behavior of the atmosphere. These models utilize complex mathematical equations to simulate the atmosphere and predict the future behavior of hurricanes. The collected data is assimilated into the NWP models to create an initial state of the atmosphere. This initial state serves as the starting point for the model's calculations. To account for uncertainties in the initial conditions and model representation of the atmosphere, ensemble forecasting is often employed. Multiple simulations with slight variations in the initial conditions or model parameters are performed to create an ensemble of forecasts. Based on the simulated atmospheric conditions, the NWP models generate forecasts of the hurricane's track that predict the future positions of the hurricane center at regular time intervals, typically up to several days in advance. These predictions are displayed as tracks on forecast maps (Fig. 5.4).

Willoughby et al. (2007) investigated advancements and recent research progress in improving the accuracy of hurricane track predictions. They find that forecasting in the late twentieth century prevented 66–90% of the hurricane-related deaths in the United States that would have resulted from techniques used in the 1950s. The researchers highlight the use of various modeling techniques and ensemble forecasting approaches to enhance the reliability of track forecasts. They also discuss three main types of models employed in hurricane track forecasting: global numerical weather prediction models, regional atmospheric models, and ensemble forecasting systems. The current accuracy of hurricane track forecasts has significantly improved, with the National Hurricane Center (NHC) producing consistently accurate forecasts. The integration of machine learning also holds promise for improving data analysis and forecast model initialization. There are numerous studies on improving the hurricane track forecasting, especially about the landing spots and the path after hurricanes touchdown. Zhang et al. (2019) used the GOES-R series satellites for improving hurricane forecasting of Hurricane Harvey and demonstrated the value of assimilating all-sky radiances from these satellites into numerical models, leading to enhanced storm analysis and track prediction accuracy. Boussioux et al. (2022) introduce a novel multimodal machine learning framework
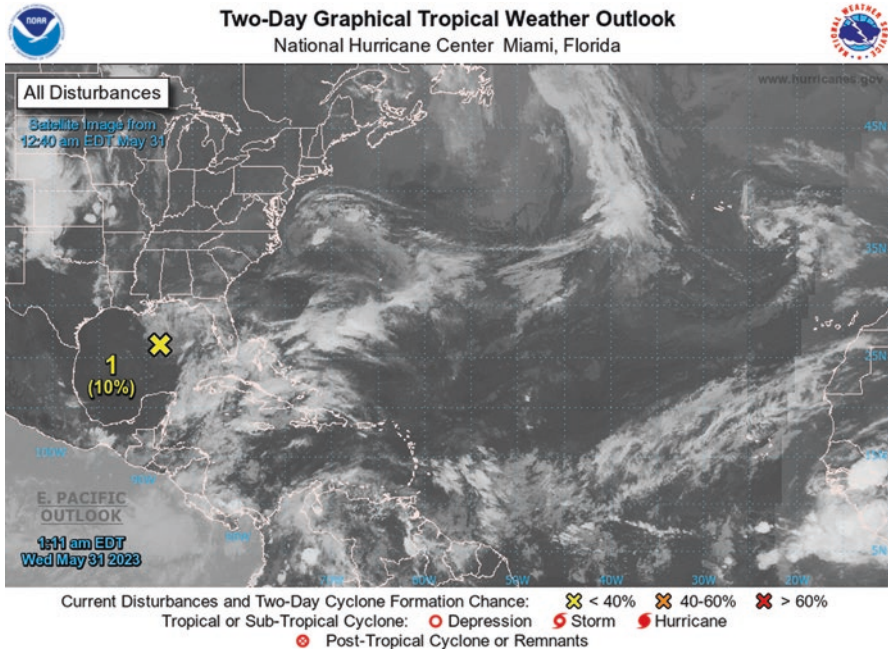
Fig. 5.4 The NHC real-time hurricane forecasting map. (Screenshot taken on May 31 from the NHC website: https://www.nhc.noaa.gov)

that combines various data sources, including meteorological and satellite data, to improve prediction accuracy. Giffard-Roisin et al. (2020) present a deep learning approach for tropical cyclone track forecasting using fused data from aligned reanalysis sources. By leveraging deep neural networks and ensemble methods, the proposed method effectively captures the complex dynamics of cyclone tracks and improves prediction accuracy. Cangialosi et al. (2020) pointed out that over the years the track forecast errors by NHC have significantly decreased, with current average errors reduced by about half since the 1990s and two-thirds since the 1970s. The improvements in track prediction are mainly attributed to advancements in numerical weather prediction (NWP) models, which provide guidance to NHC forecasters. Chen et al. (2019) evaluated the potential of the upcoming United States Next-Generation Global Prediction System (NGGPS) for hurricane prediction using the fvGFS model developed at the Geophysical Fluid Dynamics Laboratory. Retrospective forecasts initialized with the European Centre for Medium-Range Weather Forecasts (ECMWF) data show improved track forecasts compared to the ECMWF operational model for the 2017 Atlantic hurricane season. The fvGFS demonstrates better track forecast accuracy for Hurricane Maria and even lower 5-day track forecast errors for Hurricane Irma, as well as improved intensity prediction compared to both the United States and ECMWF operational models. Kim et al. (2019) proposed a Convolutional LSTM (ConvLSTM)-based spatio-temporal

model to track and predict hurricane trajectories using large-scale climate data. They utilize pixel-level spatio-temporal information of tropical cyclones to model time-sequential density maps of hurricane trajectories, capturing both temporal dynamics and spatial distribution. Experimental results using a 20-year record demonstrate that their ConvLSTM-based tracking model outperforms existing methods.

As for the perception of the public about the trajectory forecasting results, Senkbeil et al. (2020) conducted surveys during the evacuations of Hurricanes Isaac (2012), Harvey (2017), and Irma (2017) to examine the perception of track forecasts by evacuees. The findings revealed that evacuees tended to perceive the hurricane tracks as being closer to their homes than what was forecasted and what actually occurred. This perception was consistent across the different hurricanes, and participants with more hurricane experience and those residing in nonmandatory evacuation zones were more likely to perceive the tracks as closer to their homes. The study suggests that evacuees in the United States generally overestimate the proximity of storms to their homes and the associated danger.

3.2 Potential Human and Climate Change Impacts on the Formation and Genesis of Hurricanes

This is an active investigation that attracts a lot of attention. The study by Knutson et al. (2010) examined the influence of climate change on hurricane activity. The researchers used climate models to simulate hurricane behavior under different warming scenarios. The results suggested that as global temperatures rise there is likely to be an increase in the frequency and intensity of hurricanes. Kossin et al. (2014) focused on the relationship between rising sea surface temperatures (SSTs) and hurricane intensification. By analyzing historical hurricane data along with SST records, the researchers found a positive correlation between warmer SSTs and increased hurricane intensity. This study highlighted the role of climate change-induced SSTs in driving stronger hurricanes. In terms of land-use changes, Emanuel (2005) investigated the potential impact of urbanization on hurricane formation. The research demonstrated that the presence of urban areas can disrupt the natural flow of air, altering local wind patterns and potentially affecting the initiation and development of hurricanes. Patricola and Wehner (2018) used climate models to project that future hurricanes are likely to become more intense and have increased rainfall rates due to warming ocean temperatures and changes in atmospheric conditions. This research emphasized the role of anthropogenic climate change in shaping the characteristics of hurricanes. Murakami et al. (2012) explored the impact of global warming on tropical cyclone tracks. The researchers found a poleward shift in the average latitude of cyclone formation and an increase in the frequency of intense cyclones in certain regions. These changes were attributed to the expansion of the tropical belt and changes in large-scale atmospheric circulation patterns. Aerosol pollution and its influence on hurricanes have been studied by Rosenfeld

et al. (2008). Their research showed that aerosols can act as cloud condensation nuclei, affecting cloud properties and precipitation processes within hurricanes. This study suggested that human-generated aerosols, such as those from industrial emissions, may contribute to changes in hurricane behavior. Yang et al. (2018) found that high concentrations of aerosols can enhance cloud development and precipitation within hurricanes, potentially influencing their intensity and rainfall patterns. Pant and Cha (2019) examined the climate-dependent hurricane risks in different regions of the United States, considering the potential impact of future climate scenarios across eight locations along the US south and east coast. Three different metrics, including wind speed, annual individual building loss ratio, and regional loss, are used to assess the hurricane risk, and their findings indicate that future hurricane risk is generally higher than present for all locations. Reed et al. (2022) attempted to attribute the hurricane to human-induced climate change, characterized by increasing greenhouse gas emissions, as they contributed to a rise in global average surface temperature and higher sea surface temperatures in the North Atlantic basin during the 2020 hurricane season, particularly for storms of tropical storm and hurricane strength, showcasing the link between climate change and hurricane hazards such as intensity and rainfall. Strauss et al. (2021) tried to quantify the effect of anthropogenic sea level rise on the damages caused by Hurricane Sandy by simulating water levels and damage under different estimates of lower sea levels. The results show that approximately $8.1 billion of Sandy's damages are attributable to climate-mediated anthropogenic sea level rise, along with an extension of the flood area affecting additional people. This approach can be applied to assess the impacts of sea level rise on other past and future coastal storms.

These studies collectively contribute to our understanding of the potential human impacts on the formation and genesis of hurricanes. They highlight the influence of climate change, land-use changes, and aerosol pollution on hurricane dynamics. By integrating findings from these studies, scientists aim to improve hurricane forecasting, risk assessment, and disaster management strategies.

3.3 *Preparing Energy System for Hurricane Damages*

Eskandarpour and Khodaei (2016) present a machine learning-based prediction method for assessing the potential outage of power grid components during an approaching hurricane. The method utilizes logistic regression with a second-order function and parameter fitting to determine a decision boundary that categorizes the components into damaged or operational states. Bennett et al. (2021) developed an energy system optimization model that incorporates hurricane risks, combining storm probabilities with infrastructure fragility curves. They applied the model to Puerto Rico and found that accounting for hurricane trends increased projected electricity costs for 2040 by 32% based on historical frequencies and 82% for increased frequencies. However, transitioning to renewables and natural gas reduced costs and emissions, offering benefits regardless of climate mitigation policies.

Alemazkoor et al. (2020) proposed a transparent and efficient framework to link physics-based projections of hurricane activity under climate change with electric power distribution infrastructure risk models. By integrating these projections into an outage forecast model, they found that long-term power outage risk is primarily driven by the uncertainty in future hurricane frequency. The study highlights the need for robust approaches in managing power systems and setting reliability standards to effectively address climate change impacts. Muhs and Parvania (2019) developed a spatio-temporal hurricane impact analysis (STHIA) tool to quantify hurricane damage to the power grid. The model generates stochastic hurricane scenarios based on historical data and maps outage scenarios to distribution components using fragility curves. The STHIA model helps identify potential risks and can be used for contingency planning and grid-hardening measures.

Each research contribution has varying levels of actionableness, but they all provide valuable insights and tools that can be utilized by stakeholders in the power industry. These findings offer opportunities to improve emergency response, optimize energy systems, plan infrastructure investments, and enhance resilience against hurricane events. For example, Eskandarpour and Khodaei's (2016) machine learning-based prediction method provides actionable insights by categorizing power grid components into damaged or operational states, helping utilities make informed decisions during approaching hurricanes. This approach can guide emergency response and resource allocation. Bennett et al.'s energy system optimization model incorporates hurricane risks and provides valuable information for policymakers. By considering storm probabilities and infrastructure fragility curves, the model offers actionable recommendations such as transitioning to renewables and natural gas, which can reduce costs and emissions, which directly informs energy planning and policy decisions. Alemazkoor's framework linking physics-based projections of hurricane activity with power distribution infrastructure risk models has practical implications for long-term power outage risk management. By quantifying the uncertainty in future hurricane frequency, the study can guide infrastructure investments and resilience strategies. The STHIA tool enables power industry stakeholders to quantify hurricane damage to the power grid and identify potential risks. This tool supports proactive decision-making in preparing for and mitigating hurricane impacts.

However, while the research has significant value, it is important to consider the factors that may hinder their immediate implementation or use in practical applications. For Eskandarpour and Khodaei (2016), there are several challenges in applying this approach in real-time operations, like the availability and quality of data required during an approaching hurricane. Real-time data collection and integration from multiple sources may be complex and resource-intensive, making it difficult to implement this method in operational settings. The prediction model needs to be validated and tested extensively in diverse scenarios to ensure its reliability and generalizability. As for Bennett et al.'s optimization model, its implementation may face practical challenges like the coordination and collaboration among various stakeholders involved in the energy transition process. Transitioning to renewables and natural gas requires significant infrastructure investments and policy support.

Implementation barriers such as regulatory constraints, funding limitations, and public acceptance can impede the adoption of the model's recommendations. The complexity of the energy system and the need for long-term planning also make it challenging to incorporate all relevant factors accurately. Regarding the Alemazkoor framework, one key challenge lies in the availability of high-quality climate projections at the regional or local scale, which may have limitations and uncertainties. Translating climate projections into actionable insights for infrastructure planning requires interdisciplinary collaboration and expertise in both climate science and power system engineering. Implementing such a framework would demand significant data collection, model development, and validation efforts.

3.4 Advancements in Surge and Flood Modeling and Prediction

Surge and flood modeling can estimate and forecast the extent and severity of coastal storm surges and inland flooding associated with weather events such as hurricanes, tropical cyclones, or heavy rainfall. These models combine meteorological data, hydraulic principles, and topographic information to simulate the behavior of water during extreme weather events. These models use numerical simulations to calculate the water elevation and flow patterns along the coast during a storm event and take into account the rainfall patterns, watershed characteristics (such as slope, soil type, and land cover), and the hydrological processes governing the movement of water within the drainage basin. These models can estimate the extent and depth of flooding in different areas, helping to identify flood-prone regions and evaluate potential flood impacts. The model outputs need to be compared with observed data or historical events to assess the accuracy and reliability of the model predictions. Using the validated model allows us to make real-time or future predictions of storm surge or flood hazards based on the current or projected meteorological conditions.

Mulia et al. (2023) proposed a deep learning approach based on generative adversarial networks (GAN) to enhance the accuracy of storm surge modeling during typhoon events. The method translates the outputs of parametric models into more realistic atmospheric forcing fields resembling those produced by numerical weather prediction (NWP) models. The GAN model is trained using historical typhoon events, and its performance is evaluated by simulating storm surges for recent events. The results show that the storm surge model accuracy with GAN-generated forcing is comparable to that of the NWP models and outperforms parametric models. The proposed approach offers a rapid and efficient method for storm forecasting and has the potential to incorporate diverse data sources for further improvements in forecasting accuracy. Thomas et al. (2019) examined the effects of Hurricane Matthew's timing and forward speed on flooding using a simulation model. The interaction between storm surge and tides is found to contribute to

spatial variability in water levels, and changes in the storm's forward speed affect the extent and volume of inundation. Yang et al. (2020) presented the rapid forecasting and mapping system (RFMS) to quickly generate accurate coastal inundation maps within a minute based on storm advisories. The system utilizes a storm surge database consisting of high-resolution simulations of 490 optimal storms and employs an efficient interpolation scheme to predict surge responses based on various landfall parameters. The RFMS was applied to southwest Florida and the Florida Panhandle, demonstrating good agreement with observed data and high-resolution simulations. It has the potential for real-time forecasting during hurricanes, mitigation planning, and future flood mapping for coastal resilience. Ayyad et al. (2022) evaluated the Stevens Flood Advisory System (SFAS), an ensemble prediction system, for its performance in forecasting storm tide and resurgence during Tropical Cyclone Isaias in 2020. The system accurately captured the uncertainties associated with the storm surge event, and the super-ensemble spread provided a better estimate of uncertainties than sub-ensembles based on individual meteorological forcing systems. While the central forecast underpredicted peak water levels and the resurgence peak, some ensemble members predicted these events, highlighting the advantages of ensemble averaging. The SFAS demonstrated better accuracy and spread compared to the National Hurricane Center's forecast for this particular storm. Bilskie et al. (2020) optimized the northern Gulf of Mexico (NGOM3) research-grade mesh to create a computationally efficient real-time mesh for a hurricane storm surge early warning system. The real-time mesh, called NGOM-RT, is generated using a mesh decimation scheme that reduces mesh nodes and elements while preserving the representation of the bare-earth topography. Comparisons between NGOM-RT and NGOM3 show virtually no difference in simulated times series and peak water levels for several hurricanes, while the NGOM-RT mesh allows for faster model simulations, being 1.5–2.0 times faster than using NGOM3 on the same number of compute cores. Wing et al. (2019) coupled a continental-scale hydraulic model with forecasts of streamflow, rainfall, and coastal surge height to provide medium-term flood inundation forecasts for Hurricane Harvey. The results show that the hydraulic model successfully captures the benchmark flood extent, with a high level of skill in replicating observations, demonstrating the practical use of fully hydrodynamic approaches in large-scale forecast frameworks for accurate projections of inundation extent. Yang et al. (2020) introduced the Integrated Scenario-based Evacuation (ISE) framework, which integrates coastal flooding, inland flooding, and wind in a comprehensive manner to support evacuation decision-making. Considering inland areas for evacuation can substantially reduce risk without significantly increasing travel times for evacuees, highlighting the importance of treating different hazards together as a system. Also, there are many studies on the aftermath assessment, for example, Lagomasino et al. (2021) investigated the impact of Hurricane Irma on mangrove forests in southwest Florida. Their results find the importance of tidal restoration and hydrological management in vulnerable coastal areas to reduce mangrove mortality and enhance resilience against future cyclones.

However, although the mentioned research are published findings, they are still relatively nonactionable. Mulia's approach may be limited due to the requirement for historical typhoon events for training the GAN model. This reliance on historical data may restrict its effectiveness in predicting storm surges for future events or regions with limited historical data. Thomas's finding could be immediately actionable to inform flood risk assessment and mitigation strategies. Wing study's continental-scale nature may limit its practical applicability at smaller spatial scales or for localized flood events. The resources and data requirements for implementing such a large-scale hydraulic model may also be challenging for operational use. As for the Ayyad study, while the SFAS accurately captures uncertainties associated with storm surges, its immediate applicability may be limited to the specific event studied. The study highlights the advantages of ensemble prediction systems, but further development and validation are necessary before broader implementation.

4   Successful Use Cases

To highlight the actionable science, we investigated several recent hurricanes and attempted to find the example of successful application of science achievements. With this section, we aim to summarize the common places and the key points that are required to make science more applicable in reality.

4.1   Hurricane Sandy (2012)

Prior to Hurricane Sandy's landfall, scientists from the National Hurricane Center, the US Geological Survey, and academic institutions collaborated to develop improved storm surge models. The collaboration focused on enhancing storm surge models, which are sophisticated numerical tools that simulate the effects of hurricanes on coastal areas. By incorporating more accurate data, refining the models' algorithms, and utilizing advanced computational techniques, the scientists were able to improve the accuracy and reliability of the storm surge predictions. These improved models provided valuable insights into the potential magnitude and extent of the storm surge, which was crucial for emergency management agencies and coastal communities to understand the risks and take appropriate actions. The results provided by the improved storm surge models enabled emergency management agencies to issue timely evacuation orders. These models accurately predicted the unprecedented storm surge that would impact the northeast coast of the United States. As a result, emergency management agencies were able to issue timely evacuation orders and coastal communities were better prepared for the storm's impacts.

With a clear understanding of the potential impacts of the storm surge, authorities could make informed decisions about which areas were at the highest risk and needed to evacuate. This helped ensure the safety of residents in vulnerable coastal

communities by allowing them to evacuate before the storm made landfall. The work also contributed to better coastal preparedness. The accurate storm surge predictions provided by the improved models allowed coastal communities to prepare for the storm's impacts. They could implement necessary measures such as reinforcing infrastructure, securing property, and establishing emergency response plans. By having a clear understanding of the potential severity of the storm surge, communities were better equipped to mitigate risks and protect lives and property.

4.2   Hurricane Harvey (2017)

During Hurricane Harvey, scientists and engineers from the National Weather Service, the US Army Corps of Engineers, and local authorities successfully utilized advanced rainfall prediction models and real-time monitoring systems to issue accurate flood warnings and manage reservoirs. These efforts helped guide evacuation orders, prioritize rescue operations, and prevent catastrophic flooding in certain areas.

The Texas Water Development Board's Flood Operations Analysis team utilized high-resolution satellite imagery to map and monitor flood extents, which provided critical information for various operations during the response. The accurate mapping of flood extents helped identify areas where people were stranded or in need of assistance. This information aided search and rescue teams in prioritizing their efforts and reaching affected individuals more efficiently. By having a clear understanding of the flood extent, emergency responders and resource management teams were able to allocate personnel, equipment, and supplies more effectively. This allowed for a more targeted and efficient response to the disaster.

4.3   Hurricane Maria (2017)

Following the devastation caused by Hurricane Maria in Puerto Rico, scientists and engineers collaborated to develop advanced techniques for improving the resilience of the power grid. They studied the impacts of Hurricane Maria and analyzed power system failures. Based on the research findings, scientists and engineers worked on designing and implementing the identified measures, designing the integration of renewable energy sources, developing smart grid technologies, and engineering microgrid systems. The design phase involved considering factors such as system compatibility, scalability, cost-effectiveness, and local conditions. Before deployment, the developed techniques underwent rigorous testing and evaluation to ensure their effectiveness and reliability. This involved simulating hurricane scenarios, assessing performance under different conditions, and making necessary refinements. Finally, they help carry out the plan to complete the integration of renewable

energy sources, the implementation of smart grid technologies, and the development of microgrid systems.

These efforts aimed to enhance the reliability and rapid restoration of electricity in the event of future hurricanes. This involved installing solar panels and wind turbines in strategic locations to generate clean energy. By diversifying the energy sources, the power grid becomes less reliant on traditional fossil fuel-based generation, which is susceptible to disruptions during hurricanes. Renewable energy sources provide a more sustainable and resilient energy supply. Smart grid technologies were deployed to enhance the monitoring, control, and automation of the power grid. These technologies include advanced sensors, communication systems, and data analytics. By leveraging real-time data and intelligent algorithms, the smart grid enables better situational awareness of the power system, early detection of faults, and efficient management of electricity distribution. This helps in identifying and resolving issues promptly, minimizing power outages, and enabling faster restoration after a hurricane.

Microgrids are localized power systems that can operate independently from the main grid. In the context of improving power grid resilience, microgrid systems were developed to provide electricity to critical facilities and communities during emergencies. These systems integrate renewable energy sources, energy storage technologies (such as batteries), and advanced control systems. By establishing microgrids in key locations, essential services such as hospitals, emergency response centers, and critical infrastructure can continue to operate even if the main grid experiences disruptions. Throughout the process, collaboration between scientists, engineers, utility companies, government agencies, and community stakeholders was crucial. It ensured that the solutions aligned with the specific needs and requirements of Puerto Rico and addressed the challenges faced by the power grid. Engaging stakeholders facilitated knowledge sharing, decision-making, and implementation support. The implementation of advanced techniques to improve the resilience of the power grid in Puerto Rico brought several benefits, making it more resilient in the face of subsequent hurricanes. The new grid system with renewable energy integration and smart grid technologies offers increased flexibility and adaptability. During hurricanes, when conventional power plants might be offline or damaged, renewable energy sources can continue to generate electricity. Smart grid technologies enable better management and optimization of energy resources, allowing for dynamic adjustments in response to changing conditions. This adaptability helps to mitigate the impact of power disruptions and supports the rapid recovery of the grid system.

5 How to Make Hurricane Research More Actionable?

5.1 Suggestions for Researchers

After observing the usage of science results in hurricane operations, we conclude several key steps that will increase the actionableness of your research. First, scientists and engineers should conduct a detailed analysis of the specific impacts of the hurricane, such as power system failures, to identify the areas for improvement. Understand stakeholder needs and priorities by conducting interviews, surveys, and workshops to gather input on the challenges they face during hurricanes and the type of information and tools they require. Identify key decision-makers and stakeholders who can influence policy, planning, and implementation. Then foster collaborations with interdisciplinary teams, including meteorologists, hydrologists, engineers, social scientists, and policymakers, to bring diverse expertise and perspectives to the research.

To improve hurricane preparedness, response, and recovery, it is important to establish partnerships with government agencies, research institutions, and nonprofit organizations. These collaborations enable the exchange of expertise and knowledge on a global scale. Open data policies and sharing of relevant datasets, such as historical hurricane data, meteorological observations, remote sensing data, and infrastructure inventories, are crucial for informed decision-making. Standardized data formats and metadata protocols can enhance data sharing and interoperability among stakeholders. The adoption of emerging technologies, including crowd-sourced data, citizen science initiatives, and low-cost sensor networks, can augment existing data collection efforts. By integrating real-time observations, remote sensing data, and high-resolution topographic information into models, the accuracy and resolution of hurricane forecasting, flood modeling, and infrastructure resilience assessments can be improved. Validating and calibrating models using historical hurricane events and field data collected during and after hurricanes, while conducting sensitivity analyses, help understand the uncertainties associated with different model parameters and input data. These steps contribute to more reliable findings and better-informed decision-making processes. By establishing partnerships, promoting open data policies, embracing emerging technologies, and enhancing model accuracy through validation and calibration, the field of hurricane research can be advanced, leading to improved preparedness and response strategies.

At this stage, scientists should continue to translate research findings into practical decision support tools that can be easily understood and utilized by stakeholders, and develop user-friendly interfaces, interactive maps, and visualization tools to communicate complex scientific information to decision-makers and the general public. It is also important to integrate predictive models with real-time monitoring systems to provide timely information on hurricane track, intensity, storm surge, and rainfall, and further customize decision support tools to address specific needs of different user groups, such as emergency managers, infrastructure operators, and

community leaders. Once tools and systems are developed and ready for testing, conduct scenario-based analysis to assess the potential impacts of different hurricane scenarios on infrastructure, communities, and ecosystems. Collaborate with stakeholders to identify critical assets, vulnerable populations, and areas prone to flooding, and conduct detailed risk assessments. Quantify the potential economic, social, and environmental impacts of hurricanes to support informed decision-making. Develop probabilistic risk assessment frameworks to capture uncertainties and inform risk mitigation strategies. Meanwhile, engage with policymakers and participate in policy and planning processes related to hurricane preparedness, response, and recovery. Provide expert input and scientific evidence to inform the development of regulations, building codes, and land-use policies that enhance hurricane resilience. Advocate for the integration of scientific knowledge into disaster management frameworks and the allocation of resources for research and implementation. Participate in advisory committees and expert panels to provide technical guidance and support evidence-based decision-making. Eventually, go ahead to communicate research findings through peer-reviewed publications, technical reports, policy briefs, and public presentations. Engage with the media to disseminate accurate and understandable information about hurricanes, their impacts, and preparedness measures. Develop educational materials and conduct workshops to raise awareness among the general public, schools, community organizations, and policymakers. Collaborate with local communities to co-produce knowledge, respecting local knowledge systems and incorporating community perspectives into research and action plans.

5.2   Suggestions for Local Government and Communities

To make it smooth to communicate with scientists, the stakeholders also need to do some work. The first thing is to identify local vulnerabilities and needs. They need to conduct a comprehensive assessment of local vulnerabilities to hurricanes, including geographical, social, and infrastructure vulnerabilities, talk to community leaders, local government officials, and relevant stakeholders to understand their specific needs and priorities in relation to hurricane preparedness, response, and recovery. Identify critical infrastructure, high-risk areas, and vulnerable populations to inform targeted actions.

To enhance hurricane preparedness and response at the local level, collaboration between various stakeholders is vital. This includes local government agencies, community organizations, nonprofit groups, academic institutions, and relevant stakeholders. Establishing dedicated local working groups or committees with representatives from different sectors and areas of expertise can effectively address hurricane-related issues. Partnerships with universities, research institutions, and meteorological agencies provide access to scientific expertise and resources. Advocating for local data collection efforts, such as meteorological observations, rainfall measurements, flood gauges, and infrastructure inventories, is essential.

Encouraging transparency and accessibility, stakeholders should share local data among themselves.

The utilization of emerging technologies like community-based monitoring systems and citizen science initiatives can play a significant role in gathering local data. Collaboration with research institutions and meteorological agencies enables access to resources such as hurricane modeling tools, flood maps, and risk assessment frameworks. Working closely with scientists and researchers, it is important to translate scientific knowledge into practical guidance for local decision-making. Leveraging existing resources developed by national or regional agencies, such as storm surge models, flood forecasting systems, and early warning tools, is crucial. Developing and regularly updating localized emergency response plans tailored to hurricanes is necessary. These plans should consider local vulnerabilities, available resources, and community needs. Integrating scientific data, predictive models, and risk assessments into emergency response plans can inform decision-making during hurricane events. Conducting drills and exercises helps test the effectiveness of response plans and identifies areas for improvement. Incorporating scientific knowledge into infrastructure planning and design is essential to enhance resilience against hurricanes. This includes integrating risk assessments and modeling results into land-use planning processes to identify suitable development areas and restrict construction in high-risk zones. Promoting the use of resilient building codes, flood-resistant construction techniques, and nature-based solutions further reduces vulnerability to hurricanes.

Meanwhile, conduct public awareness campaigns to educate the community about hurricane risks, preparedness measures, evacuation routes, and emergency contacts, and organize community workshops, training sessions, and informational meetings to disseminate scientific knowledge about hurricanes and their impacts. Foster partnerships with schools, community organizations, and local media to amplify outreach efforts and engage a wide range of audiences. Establish monitoring systems to track the effectiveness of actions taken based on scientific knowledge. Regularly evaluate the impact of implemented strategies and initiatives, gathering feedback from the community and stakeholders. Adjust approaches as needed based on lessons learned and changing local conditions.

6   Summary

The effective utilization of scientific knowledge is crucial in enhancing preparedness, response, and recovery efforts for hurricanes. By making science actionable, local governments, communities, and stakeholders can improve their ability to mitigate risks, protect lives, and reduce damages caused by these powerful storms. Throughout this chapter, we have explored strategies and key points on how to make science more actionable for hurricanes. The key points to make science more actionable for hurricanes include fostering collaborative partnerships between local government agencies, community organizations, research institutions, and stakeholders

to leverage scientific expertise and resources. Enhance local data collection efforts and promote the sharing of data among stakeholders to facilitate informed decision-making. Work with research institutions and meteorological agencies to access scientific tools, models, and resources tailored to local contexts. Develop localized emergency response plans that incorporate scientific data, predictive models, and risk assessments to inform decision-making during hurricane events, and integrate scientific knowledge into infrastructure planning and design, incorporating resilient building codes and nature-based solutions to reduce vulnerability. Also, the science community should conduct public awareness campaigns and community engagement activities to raise awareness about hurricane risks and disseminate knowledge.

In the future, the community should focus on enhancing hurricane track forecasting accuracy and the lead time for warnings to provide more precise and timely information to communities at risk, and invest in further research to improve flood modeling and prediction capabilities, incorporating real-time data and high-resolution modeling techniques. Explore community-driven science initiatives, citizen science, and participatory approaches to engage communities in data collection, monitoring, and decision-making processes. Deepen our understanding of the impacts of climate change on hurricanes and develop strategies to adapt to changing hurricane characteristics and associated risks. By continuing to advance actionable science for hurricanes and addressing these future areas of focus, we can further strengthen our resilience to hurricanes and improve our ability to protect lives, infrastructure, and ecosystems in the face of these powerful natural disasters.

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