

# Improving Lead Time for Tropical Cyclone Forecasting

Review of Operational  
Practices and Implications  
for Bangladesh





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# Preface

This report was published in June 2015. In republishing the report, an in-depth follow-up study to determine in detail what may have changed since then has not been done. However, to the best of the team’s understanding, the descriptions of both the science of forecasting and the operational practices at the institutions involved remain largely accurate, with one substantive exception.

In the original conclusions section, the possibility of cyclone track and intensity forecasts being produced before cyclogenesis has occurred was discussed. The 2015 report stated that while such forecasts had been produced by numerical weather prediction centers and a university group, “there is no evidence of a national center that has actual responsibility for issuing forecasts for any country actually issuing official forecasts of this type yet, although the National Hurricane Center (NHC) has begun experimenting with such products internally.” In 2017 the NHC did, in fact, begin issuing such products to the public. These forecast products are issued for what the NHC calls “potential tropical

cyclones.” Since this development is highly germane, the above statement is no longer correct. The conclusions have been revised accordingly, as follows: “Starting this year, NHC has the option to issue advisories, track and intensity forecasts, watches, and warnings *for disturbances that are not yet a tropical cyclone, but which pose the threat of bringing tropical storm or hurricane conditions to land areas within 48 hours.*” Details are available at <https://noaanhc.wordpress.com/2017/06/29/potential-tropical-cyclones-fitting-the-bill-for-more-timely-warnings/>. While these products are issued only in the limited circumstances described—for lead times less than 48 hours, not for the 10-15 day lead times described in the report—this is clearly a substantive change, and indicates that the state of the art as practiced by national centers is evolving.

Beyond this, only minor facts that have changed, such as titles or affiliations of individuals mentioned in the report (including some of those listed in the acknowledgments).



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# Acronyms

ADT	Advanced Dvorak Technique
ATCF	Automated Tropical Cyclone Forecasting System
BoB	Bay of Bengal
BMD	Bangladesh Meteorological Department
CIFDP	Coastal Inundation Forecasting Demonstration Project
CIFDP-B	Coastal Inundation Forecasting Demonstration Project for Bangladesh
CPP	Cyclone Preparedness Program
DDM	Department of Disaster Management
DEM	digital elevation model
ECMWF	European Centre for Medium-Range Forecasting
ESCAP	Economic and Social Commission for Asia and Pacific (United Nations)
FFWC	Flood Forecasting and Warning Centre
GFS	Global Forecast System
GTS	global telecommunication system
HFIP	Hurricane Forecast Improvement Program
HWRF	Hurricane Weather Research and Forecast
IIT	Indian Institute of Technology
IMD	India Meteorological Department
JICA	Japan International Cooperation Agency
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
MOU	Memorandum of Understanding
NCEP	National Centers for Environmental Prediction
NHC	National Hurricane Center (U.S.)
NOAA	National Oceanic and Atmospheric Administration (U.S.)
RIMES	Regional Integrated Multi-Hazard Early Warning System
RSMC	Regional Specialized Meteorological Center
SLOSH	sea, lake, and overland surges from hurricanes
UTC	universal time clock
WIS	World Meteorological Organization Information System
WMO	World Meteorological Organization
WRF	Weather, Research, and Forecast





# Executive Summary



Stretching across part of southwestern Bangladesh, the Sundarbans is the largest remaining tract of mangrove forest in the world. Credit: NASA

**Bangladesh is historically one of the most vulnerable nations to tropical cyclone–induced storm surge.** Unlike previous tropical cyclones, such as in 1970 and 1991, the most recent storms have not caused the enormous numbers of fatalities due to better shelters, better warning, last-mile connectivity, and evacuation procedures. Nonetheless, the large population in the low-lying coastal areas of the country remains vulnerable to flooding in cyclone events, particularly as sea level continues to rise.

Sundarbans. Credit: Thinkstock.com



A key contributor to improved disaster preparedness in Bangladesh would be improved lead times for tropical cyclone and storm surge forecasts. At present, the Bangladesh Meteorological Department (BMD), the main government agency responsible for forecasts for tropical cyclone and storm surges, issues explicit forecasts of tropical cyclone behavior only three days ahead of time. Forecasts with longer lead times are possible and would bring significant benefits.

The Regional Specialized Meteorological Centre (RSMC), operated by the India Meteorological Department (IMD) with responsibility for the South Asia region, has recently increased the lead time for their tropical cyclone forecasts to five days, which is the operational standard in most other basins. Advances in numerical weather prediction—particularly ensemble prediction systems operated at numerical weather prediction centers in several countries (often separate institutions from those with a mandate to produce tropical cyclone forecasts)—may allow probabilistic forecasts with useful skill to be issued at still longer lead times, perhaps as long as 10 or 15 days, to the extent that users can understand and accommodate the large uncertainties at those lead times.

Critical to extending the lead times for forecasting is a better understanding of the factors that limit the lead time of current forecasts. This issue is important not just for Bangladesh but for all of the Bay of Bengal countries, including Myanmar, Sri Lanka, and India—all of which are at risk from tropical cyclones and at increasing risk of storm surge-driven flooding as sea level rises.

## OBJECTIVES

The main objectives of this report are to (i) assess the current state-of-the-art tools and operational practices in tropical cyclone and storm surge forecasting, (ii) assess existing operational practices at the BMD and regionally, and (iii) propose recommendations for improvements in the lead times of tropical cyclone forecasts for Bangladesh.



## APPROACH

The paper is based on a review of documentary research and consultations with stakeholders. Extensive discussions were held with officials at the BMD, the IMD, and other weather services. In reviewing international operational practices, considerable focus is placed on the practices of the U.S. National Hurricane Center in Miami, with input from a number of other well-equipped and well-staffed centers, primarily in industrial nations. Further analysis can be undertaken as a follow-up to this report.



## KEY FINDINGS

### Review of international and regional operational practices

**Tropical cyclone forecast lead time:** At state-of-the-art national centers, tropical cyclone forecasts are produced with lead times of up to five days. Storm surge forecasts are produced with shorter lead times of 72 hours or less. While the necessary science and technology to further increase this lead time—and thus to allow forecasts of landfall more than five days ahead of time for all storms in the Bay of Bengal—exist at the level of research and development, they have not yet been mainstreamed into operational forecast practices of most national meteorological services (including those of the most industrialized nations).

**Skill of forecast track has improved faster than skill of forecast intensity:** The skill of tropical cyclone track forecasts has improved dramatically in recent decades, in large part due to steady improvements in global numerical weather prediction models, observations and data assimilation systems used to initiate those models, and ensemble methods. Ensemble methods allow improvement over individual model performance and also allow estimation of forecast uncertainty. Forecasts of tropical cyclone intensity, on the other hand, have not improved at anywhere near the rate that track forecasts have. The goal of improved intensity forecasts is currently driving a large scientific research effort, particularly in the United States.

**Timing of operational tropical cyclone forecasts:** Forecasts of tropical cyclogenesis—the initial formation of tropical cyclones—have improved greatly in recent years. Genesis can now be forecast with some accuracy at leads of five days or longer. Operational forecasts of the subsequent tropical cyclone’s track and intensity, however, are not begun until genesis has occurred, although ensemble prediction systems already provide the raw material to enable such forecasts to start before genesis and although such forecasts have been made, both by academic researchers and by U.S. forecasters, on an experimental basis.

**Uncertainty and storm surge forecasting:** Storm surge forecasting is being carried out as a part of operational tropical cyclone forecasting. Distinct numerical models representing the ocean, separate from those used to forecast the tropical cyclone itself, are used to predict the surge. The tropical cyclone forecast provides the winds that drive the storm surge forecast. The greatest

source of uncertainty in storm surge forecasts, which limits the lead time, is uncertainty in the tropical cyclone forecast.

**Tropical cyclone forecasts at the IMD:** The RSMC for tropical cyclones at the IMD identifies and names tropical cyclones in the Bay of Bengal; provides outlooks, advisories, and warnings to the BMD and other countries in a panel on tropical cyclones for the Bay of Bengal and the Arabian Sea region; and serves as the hub for the transmission of meteorological data via the global telecommunication system (GTS)/World Meteorological Organization (WMO) Information System (WIS).<sup>1</sup> Objective tropical cyclone track and intensity forecasts have been produced at the IMD since 2003, at which time the maximum lead time was 24 hours; the maximum lead time was increased to 72 hours in 2009 and to 120 hours in 2013. Storm surge guidance is also included, based on the Indian Institute of Technology Delhi and Indian National Centre for Ocean Information Services storm surge model, at shorter lead times.

The IMD has considerably higher capabilities in terms of observing system, research and development support base, computing power, modelling and skill levels of available human resource than the BMD does. It has computer workstations dedicated to tropical cyclone forecasting. Dedicated software packages, comparable to those at the National Hurricane Center, are available to ingest necessary data and automate some tasks to streamline and facilitate the forecaster’s job. Dvorak analysis is carried out on these workstations once the necessary satellite data have been ingested. Its forecasts are quantitative and extend to longer lead time than the BMD’s. In a few respects, however, IMD forecast technologies lag what is available at some other centers. For instance, while much numerical model guidance is ingested into the forecast software, the only tropical cyclone tracks ingested are those from the deterministic model runs. Any improvement in IMD forecasts has the potential to improve BMD forecasts as well. But due to capacity constraints at the BMD, data and information already publicly available and provided regionally are often not used for forecasting at the BMD.

<sup>1</sup> Bangladesh is connected to the Global Telecommunication System (GTS) and is in the process of transitioning to the WMO Information System (WIS). The two terms are used interchangeably in this report.

## FORECASTING PRACTICES AT THE BMD

 **BMD tropical cyclone forecasts:** The BMD produces tropical cyclone and storm surge forecasts for Bangladesh. The lead times for these forecasts are 72 hours or less. It appears that the BMD does not issue—at least not on the Internet—quantitative track or intensity forecasts. A map showing the observed track (up to the present time) is issued, but it does not extend into the future. BMD forecasts of tropical cyclones tend to be limited to textual forecasts and warnings. These give only qualitative information about the storm’s future behavior and do not extend far in the future.

 **Factors constraining lead time for BMD forecasts:** The lead-time and skill of BMD forecasts are limited by a number of factors, both material and human. First, the agency lacks much of the state-of-the-art hardware and software used elsewhere for tropical cyclone forecasts and does not obtain all the globally available and potentially useful data from observations and numerical models. For instance, BMD forecasters currently lack tools to carry out key tasks such as visualization of model forecast guidance and production of graphic track forecasts based from that guidance, as well as Dvorak analysis and other steps associated with assessment of the storm’s present state. These are made easier and more effective by computer hardware and especially by software designed specifically for the purpose. Further, at present the BMD does not operationally run models dedicated to tropical cyclone forecasting. The BMD also faces frequent power outages that disrupt its operations.

Second, a critical limitation for the BMD is the bandwidth of its GTS/WIS link. For instance, coastal radar data from Bangladesh are not sent back to the IMD through the GTS and thus are not available for assimilation into the IMD’s numerical models. Currently the bandwidth of BMD’s GTS link is 64 kilobytes per second, whereas 5 megabytes per second are estimated to be required for sharing BMD’s coastal radar observations over the GTS back to the IMD. Moreover, due to the limited bandwidth of the GTS link, many data are available to the BMD only through the Internet in the form of images viewed on a Web browser and are not available in a digital form for assimilation into models. Some data from polar orbiting satellites, such as microwave sounders and imager scatterometers for surface winds are not used at all in

tropical cyclone forecasting at the BMD. These data are not available digitally and even the images are not consulted. Since these data can be valuable for estimates of tropical cyclone intensity and structure, it would be advantageous if they were available and used. Part of the issue may be training in the use of these data.

Third, the observational networks over land and the adjacent ocean, which are an essential component of the tropical cyclone forecast process, also need improvement. For instance, adequate bathymetric data for coastal Bangladesh are not available for storm surge and coastal inundation forecasting. Automated tide gauges are also needed for measurements of storm surge.

Fourth, the BMD does not have a dedicated staff for forecasting tropical cyclones. When a tropical cyclone is present in the Bay of Bengal, forecasts of its track and intensity are prepared at the BMD by the same forecasters who normally forecast other types of weather during the remainder of the year. The education and training opportunities available to staff are also limited, making it more difficult for forecasters to take advantage of the latest developments in tropical cyclone and storm surge forecasting. At present, there is no Department of Atmospheric Sciences (or Meteorology, or any equivalent or comparable designation of the field) anywhere in Bangladesh. There is an atmospheric physics research group in the Physics Department at the Bangladesh University of Engineering and Technology and scattered individual faculty members in related fields at other Bangladeshi universities, but no group that is equivalent to an entire department or that has strong ties to the BMD. This seriously compromises the government’s ability to forge links with academic institutions on weather- and climate-related research—linkages and partnerships that are often at the crux of innovation and research-based service delivery.

 **Influence of the size of the Bay of Bengal:** In addition to the above factors, the nature of the Bay of Bengal also plays a role in influencing the lead time for tropical cyclone forecasting in the region. A key limitation on the maximum lead time of forecasts for Bangladesh—whether they are produced by the BMD, the IMD, or someone else—is the natural physical constraint imposed by the smallness of the Bay of Bengal. Because Bay storms cannot move far without reaching land,

most of them have lifetimes significantly shorter than five days, measured from the time of genesis to landfall. As long as track forecasts begin at genesis, landfall forecasts for such storms cannot be made with more than five days of lead time.

 **Most national centers are operationally producing 5 day forecasts.** If forecasts of landfall are desired with lead times greater than five days for all storms, it will be essential that the forecasts begin before genesis. Such

forecasts are now being produced by some numerical weather prediction centers and university groups using ensemble methods and products with the necessary information. The National Hurricane Center in the US has started issuing watches and forecasts for potential tropical cyclones, though this is very recent and is being done out to 48 hours. If IMD and BMD were to begin issuing forecasts of genesis, they would be matching what some of the more sophisticated forecasting centers have only recently started to operationalize.

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## RECOMMENDATIONS

For the BMD to improve its forecast lead times, a number of actions can be taken.

 **Strengthen BMD hardware, software, and infrastructure:** In the short term, some relatively basic and inexpensive improvements could help improve BMD's capacity for tropical cyclone forecasting. The BMD should obtain dedicated workstations with appropriate software to carry out key tasks associated with tropical cyclone forecasting, such as model analysis, visualization, and so forth. The department should also ensure backup systems for its computers in case of power outage.

 **Enhance data and information sharing through improved network systems:** In addition to improvements in computer hardware and software, the BMD can have better access to useful data—both from observations and from numerical weather prediction models—that are already, in principle, available through improvements in network systems. The department should make efforts to increase the bandwidth available for its GTS link so that it can obtain information and products available regionally and globally. This will also allow the BMD to share data and information with the IMD and other relevant agencies.

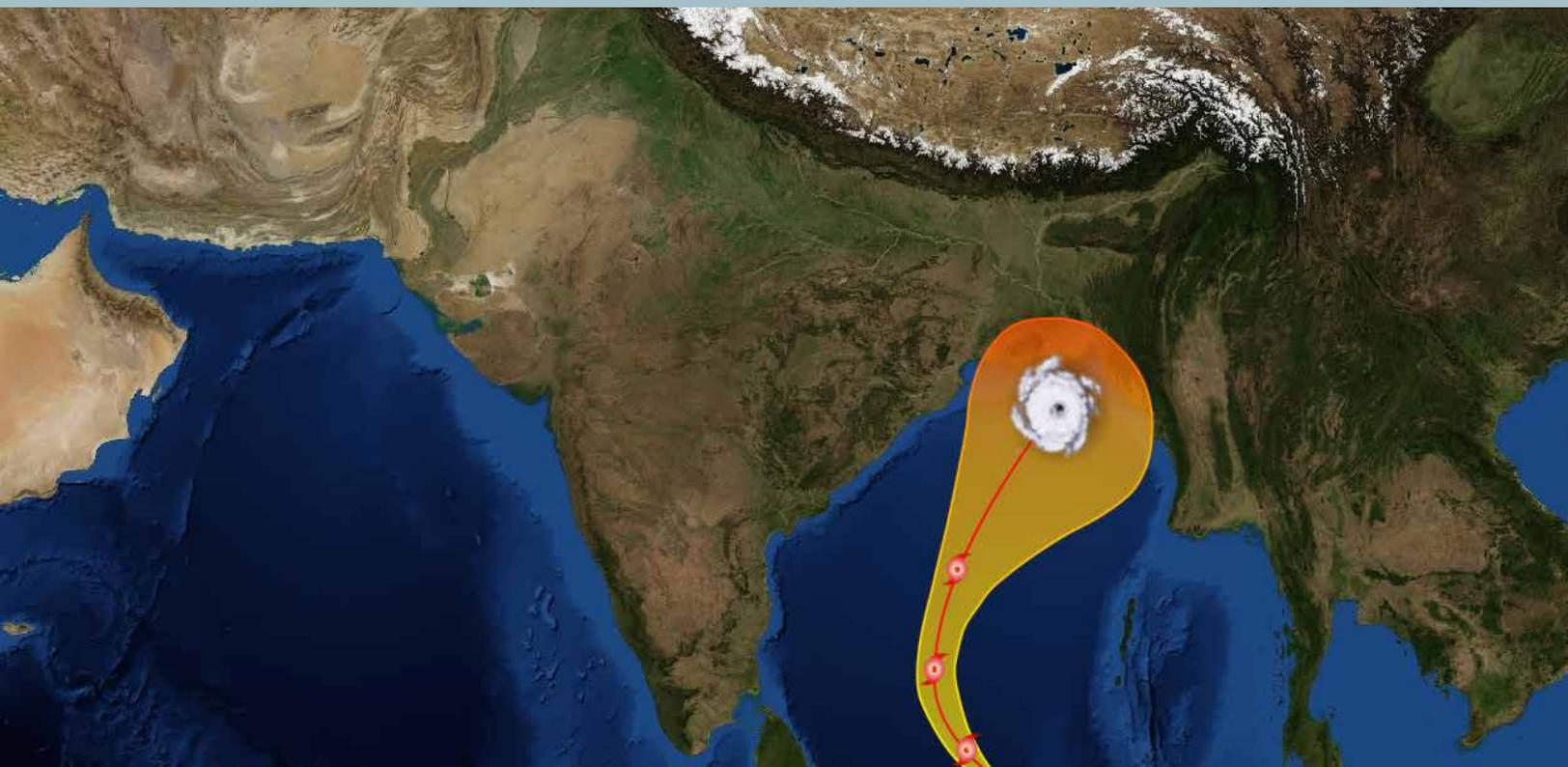
 **Strengthen the observation network for tropical cyclone forecasting:** The BMD would benefit from improvements and expansion of the current observing system, such as access to automated tide gauges at the coast for measurements of storm surge, better bathymetric and topographic data for storm surge

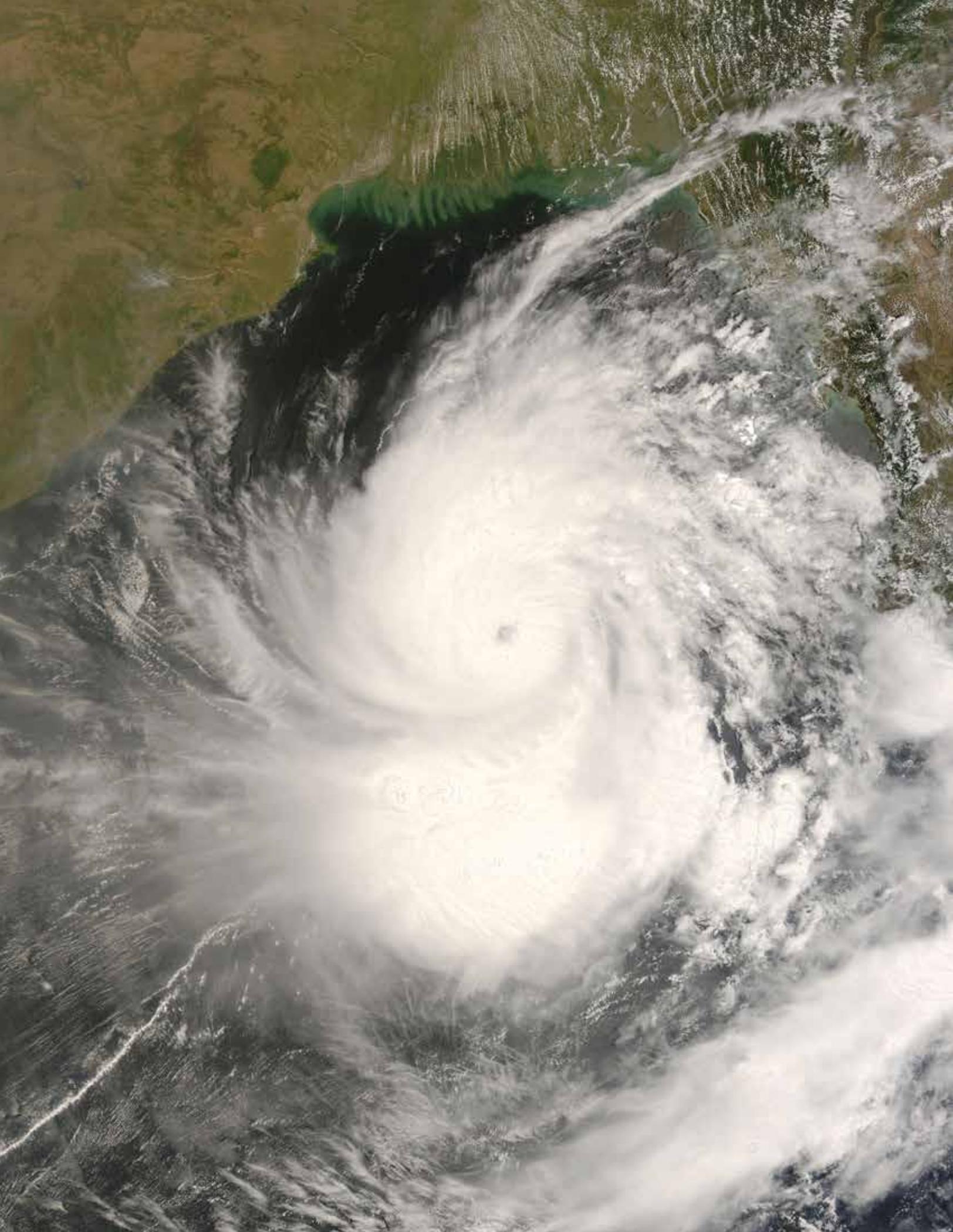
and inundation forecasting, and calibration of coastal radars, as well as intercomparison against rain gauges and installation of buoys for oceanographic and meteorological observations offshore.

 **Improve training and capacity building:** Improved education and training opportunities for BMD staff are critical in improving the agency's capacity for improved service delivery. In the short term, the goal of improving forecasts requires more training of BMD personnel in existing and developing science and technology that specifically address that goal: Dvorak technique, numerical weather prediction, ensemble prediction methodologies, radar data analysis, and the like. It would be particularly valuable for BMD forecasters to become better acquainted with the capabilities of the modern global model ensemble prediction systems. In the long term, however, the government of Bangladesh will need to invest in development of a cadre of trained meteorologists and atmospheric scientists by supporting teaching of these topics at the university level. Another recommendation is to establish a National Meteorological Training and Research Center in Bangladesh to meet the national requirements. In that case, the existing Meteorological Training Institute of the BMD can be upgraded to contemporary standards. Support should also be provided for establishing university level departments focusing on meteorology and atmospheric sciences.

- Improve coordination between the BMD and other agencies:** For improvements in forecasting to contribute meaningfully to disaster preparedness and improved early warning systems, close coordination between the BMD and other agencies such as the Bangladesh Water Development Board and the Department of Disaster Management is needed. There are already strong relations between these agencies that can be further enhanced. In storm surge forecasting, WMO's Coastal Inundation Forecast Demonstration Project for Bangladesh aims to improve the state of the art and is expected to provide important lessons on how to improve coastal inundation forecasts in Bangladesh, and it should be supported. This could include facilitation of better cooperation between the BMD and other national agencies, particularly the Bangladesh Water Development Board. The critical problems of forecast evaluation and verification need to be addressed by improvements to the observational network—in particular, by automated gauges that can measure water levels at the coast and inland.
- Strengthen regional collaboration, including the IMD's role in research, technology transfer, and training:** The RSMC at the IMD is the regional center for predicting tropical cyclones and storm surges and its role as a coordinator of research, technology transfer, and training should be strengthened for the benefit of the IMD, the BMD, and other operational agencies in the region.
- Study the use of ensemble forecasts for improving lead times for tropical cyclone forecasting:** The possibility of producing ensemble forecasts for South Asia with lead times greater than five days should be actively studied. The active interest and engagement of the local agencies—the BMD and the IMD—is essential to this effort, as they bear responsibility for forecasting for Bangladesh for the region respectively. Important questions in this regard include not just those addressed in this report but also the extent to which the greater uncertainties associated with longer lead-time forecasts may be compatible with their use in emergency management.

Tropical Cyclone Mahasen. Credit: [www.skymetweather.com](http://www.skymetweather.com)





# Tropical Cyclones in the Bay of Bengal

Bangladesh is one of the most densely populated countries in the world. Owing to its low-lying topography, dense river network, location, and climate, it is exposed to a range of water- and climate-related hazards. Tropical cyclones are among the most severe of these hazards.

Although the Bay of Bengal (BoB) accounts for only a small fraction of the world's tropical cyclones, 10 of the 14 of these storms associated with the highest fatalities globally have occurred in the Bay of Bengal, with a large fraction of those affecting Bangladesh (Webster 2012). Bangladesh is historically among the most vulnerable nations to tropical cyclone-induced storm surge. Over 300,000 people were killed by a devastating cyclone in 1970 and 140,000 in 1991. Cyclone Sidr, which made landfall in Bangladesh in 2007, caused around 3,500 deaths; this much smaller number, compared with the 1970 and 1991 events, has been attributed to better shelters and better warning and evacuation procedures. Nonetheless, the large population in the low-lying coastal areas of the country remains vulnerable to flooding in cyclone events, particularly as sea level continues to rise.

A key focus for improving disaster preparedness and early warning systems in Bangladesh is improved lead times for tropical cyclone forecasting including the quality and skill of the forecast. At present, the lead time for tropical cyclone forecast used by the Bangladesh Meteorological Department (BMD), the main government agency responsible for issuing forecasts for tropical cyclone and storm surges, is three days. However, based on publicly available data (for example, from satellites) and existing weather models, it is possible to increase the lead time at which useful tropical cyclone

forecasts can be produced so that landfall can be predicted five days or more ahead of time.

Webster (2008, 2012, 2013), in particular, argues that probabilistic forecasts with useful skill can be issued at times longer than five days in advance—perhaps even as much as 15 days before landfall. The essential ingredients of such forecasts already exist in the outputs from ensemble prediction systems such as those produced by the European Centre for Medium-Range Forecasting (ECMWF). Such extended lead times for tropical cyclone forecasts could, if the forecasts were accurate enough to be useful in decision making, enable significant cost savings and a palpable positive impact on local livelihood and assets.

If lead times of 10–15 days with relatively high accuracy are possible, as the literature suggests, why is it not being done in Bangladesh and what can be done to improve the forecast lead time?? This question motivated the writing of this paper. Critical to extending the lead times for forecasting is a better understanding of the factors that limit increasing the lead time of current forecasts. This issue is important not just for Bangladesh but for all of the Bay of Bengal countries, including Sri Lanka, Myanmar, and India—all of which are at risk from tropical cyclones and at increasing risk of storm surge-driven flooding as sea level rises.

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## OBJECTIVES

The main objectives of this report are to:

-  Assess state-of-the-art tools and operational practices in tropical cyclone and storm surge forecasting, including regional operational practices in South Asia at the Regional Specialized Meteorological Center (RSMC) located at the India Meteorological Department (IMD) in Delhi
-  Assess current operational practices and identify key factors constraining improvement of lead time for tropical cyclone forecasting at BMD
-  Propose recommendations for improving current operational practices at BMD.

To the extent that the IMD is designated as the RSMC by the World Meteorological Organization (WMO) and issues tropical

cyclone forecasts for the South Asia region, its operational practices with respect to tropical cyclone forecasting are also considered. The issue of whether the small size of the Bay of Bengal is a limiting factor in increasing lead times for tropical cyclone forecasts is also explored.

This report extends previous literature on the topic in several ways. First, it presents a broad overview of current international operational practices as undertaken by national meteorological centers with responsibility for tropical cyclone forecasting, which has so far not been undertaken. This analysis provides an important context for understanding operational practices in developing countries such as Bangladesh. Second, based on consultations with relevant agencies and stakeholders, the paper also assesses the current practices and capabilities of the BMD in some detail, comparing them with current practices at other centers.

The report has a limited focus as indicated above, and several important questions are not addressed here. One is the relative value of improvements in forecasts versus improvements in other aspects of disaster preparedness, including communications, local preparedness activities, and the building of shelters. Much of the large reduction in fatalities in Sidr in 2007 compared with the 1970 and 1991 storms in Bangladesh is attributed to these other measures. Another is the extent to which the greater uncertainties associated with longer lead-time forecasts diminish their

usefulness in disaster preparedness. How certain must a forecast be in order for useful action to be taken based on it? While these questions are centrally important to the broader task of reducing harmful tropical cyclone impacts, they are outside the scope of this report. Finally, the review of international and regional operational practices mainly relies on the operational practices of agencies in a few countries due to limitations of budget. A more detailed analysis based on the experiences of additional countries should be undertaken as a follow-up to this report.

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## APPROACH AND METHODOLOGY

The information and points of view in this paper are derived from a literature review and discussions with a range of officials and experts (see Annex 1). This included consultations with staff at the U.S. National Hurricane Center (NHC) and the Hurricane Research Division of the U.S. National Oceanic and Atmospheric Administration (NOAA), both in Miami, Florida, and with officials in several national meteorological agencies, such as the Australian Bureau of Meteorology and regional weather forecasting agencies. Officials at the IMD and experts at the Indian Institute of Technology (IIT) in Delhi

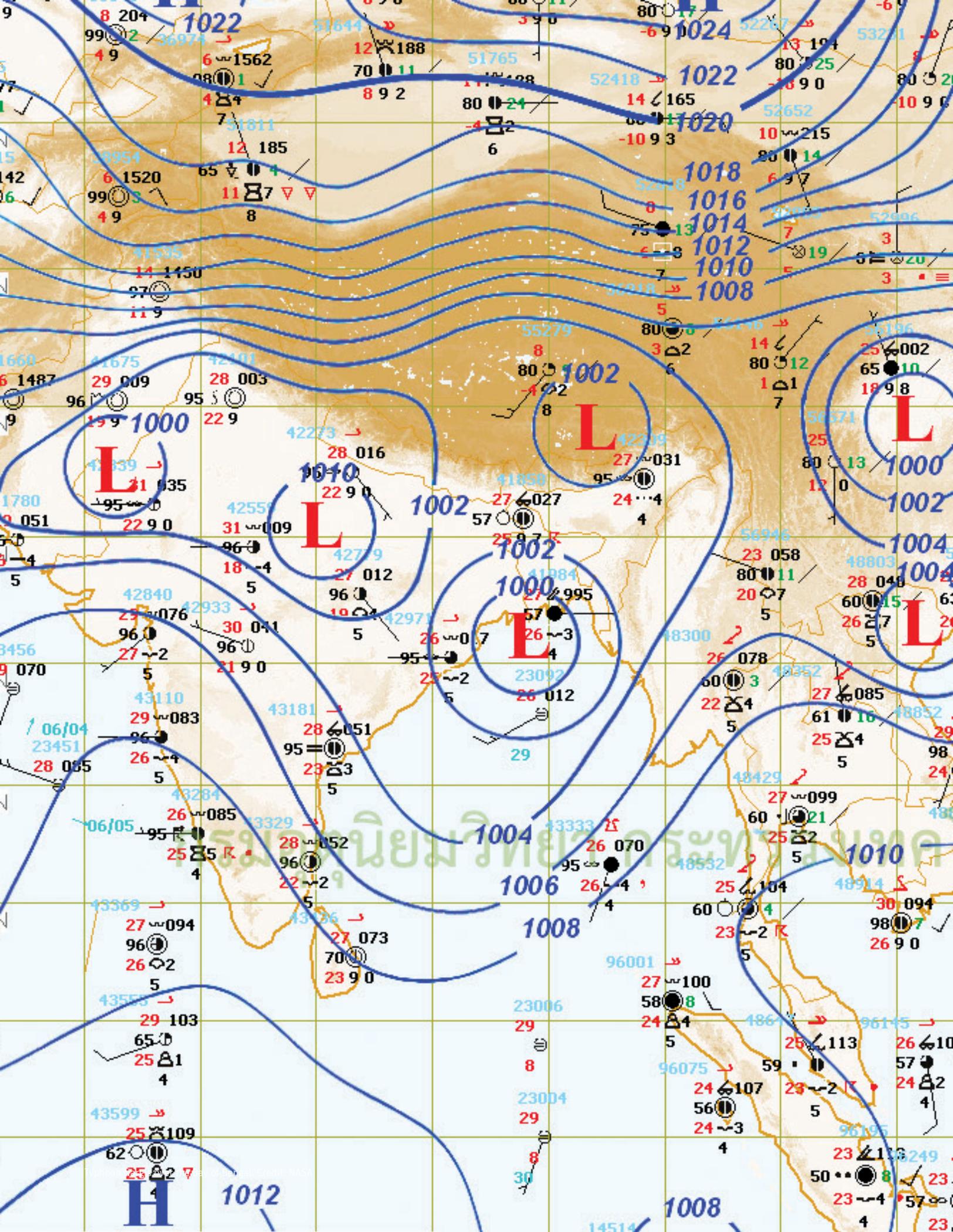
were also consulted. A visit to the WMO provided additional perspectives on its role in facilitating and organizing tropical cyclone and storm surge prediction activities in South Asia and worldwide. In Bangladesh, extensive consultations were undertaken with officials at the BMD, the Bangladesh Water Development Board, and other agencies. These discussions were important particularly to clarify current operational forecast practices, which are often not documented fully in the peer-reviewed scientific literature.

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## ORGANIZATION OF THE REPORT

Following this description of the background and rationale for the report, Chapter 2 describes current global operational practices for forecasting tropical cyclones and storm surges, including practices at other national agencies. Chapter 3 assesses current operational practices in Bangladesh. In

particular, we examine the extent to which Bangladesh uses international and regional operational practices and the technical and governance issues that limit their use. Chapter 4 provides a summary and recommendations.



# Forecasting:

## Analysis of Operational Practices

### TROPICAL CYCLONE FORECAST

#### *WHAT IS A TROPICAL CYCLONE?*

The formal definition of a tropical cyclone is not simple. The American Meteorological Society's Glossary of Meteorology, for example, gives a long and complex definition (see [http://glossary.ametsoc.org/wiki/Tropical\\_cyclone](http://glossary.ametsoc.org/wiki/Tropical_cyclone)). A shorter definition is that used by the U.S. National Hurricane Center: "A warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center."

A tropical cyclone whose wind speeds are below 34 knots (17 meters per second) is a *tropical depression*. When a tropical cyclone's wind speeds reach 34 knots, it is labeled a *tropical storm* in several basins and a *cyclonic storm* in the North Indian Ocean. Definitions of storms with higher intensities also vary from basin to basin, as discussed further in Chapter 3 (see Tables 3.1 and 3.2 and accompanying discussion).

In practice, there is broad agreement in most important cases about whether a given weather disturbance is a tropical cyclone or not, but there can be disagreement, particularly for weak systems or systems with some properties of extratropical cyclones (cold core, less deep convection, etc.). The fact that different definitions are used for weak systems has ramifications for forecasting. In the operational systems used at present by all national forecast centers we are aware of, tropical cyclone forecasts are begun once a given system meets specific criteria that are used to define a tropical

cyclone. These criteria are basin-dependent and include thresholds for maximum sustained surface wind speed in some basins but not others. The U.S. National Hurricane Center, for example, requires no wind speed threshold but begins forecasts when disturbances reach the depression stage, as defined by the presence of organized deep convection and a closed circulation. The IMD, on the other hand, begins forecasting when winds reach 28 knots, while the Australian Bureau of Meteorology begins 24–48 hours before the storm is expected to reach 34 knots.

The process of a tropical cyclone's coming into existence by meeting these criteria for the first time—whatever the criteria are in the basin in question—is known as *genesis*. Forecasting genesis is traditionally distinct from forecasting the behavior of existing storms (although they are done by the same forecasters). These are described separately below.

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## WHAT IS A TROPICAL CYCLONE FORECAST?

A tropical cyclone forecast predicts the future behavior of a tropical cyclone. National centers currently produce forecasts of tropical cyclone track, intensity, and other parameters for a given tropical cyclone once it already exists—that is, once it has met a basin-dependent set of criteria, as just described. Before discussing specific types of forecasts, it is important to clarify how some terms are defined in this report.

The *lead time* of a forecast is understood as the difference between the time at which the forecast is issued and the time for which the forecast applies, known as the verification time. If a forecast is issued today at 12 noon that predicts what the weather will be tomorrow at 12 noon, the verification time is tomorrow at 12 noon and the lead time is one day. Forecasts are typically issued with lead times between zero—a statement of the storm's present properties at the forecast time, known as the “analysis”—and either three or five days, at either 6- or 12-hour intervals.

Forecasts can be categorized as either *deterministic* or *probabilistic*.

A *deterministic forecast* gives categorical predictions of the values of the forecast storm parameters at a given lead time, with no explicit statement of uncertainty. At each lead time, a deterministic forecast gives a single value for each variable

of interest, such as the position or intensity of the storm. The error in the forecast is the difference between that value and that observed at the verification time. Deterministic forecasts are virtually never precisely correct, particularly at longer lead times, but the goal is for the error to be small, averaged over many forecasts. For example, if the forecast maximum wind speed of a tropical cyclone at a given lead time is 50 knots, and the intensity observed at the verification time is 55 knots, the intensity error is 5 knots. The skill of deterministic forecasts is typically evaluated by averaging these errors over all storms for which forecasts were issued over some period of time. The averaging must be done separately for each lead time, because errors typically increase with lead time; 24-hour forecasts should be compared with other 24-hour forecasts but not with 48-hour forecasts, for example.

A *probabilistic forecast* predicts outcomes as probabilities rather than categorically. For example, a probabilistic forecast could state that there is a 20 percent probability that a particular location will experience winds of 65 knots or greater during a particular 12-hour time period. Unlike a deterministic forecast, a single probabilistic forecast can never be incorrect (unless the probabilities stated are 0 percent or 100 percent, in which case it is effectively a deterministic forecast), nor can the error in a single forecast be measured.

The skill of probabilistic forecasts can only be measured over a large set of such forecasts. The skill can be broken down into two components: reliability and resolution. Reliability measures whether the forecast outcomes actually occur with frequencies given in the forecast. Taking the example above, consider a large set of forecasts predicting a 50 percent probability of 65 knot winds or greater. If winds of 65 knots or greater are observed at the time of verification in 50 percent of the cases, these forecasts will be found to be reliable. Resolution, on the other hand, measures how different the probabilities are from their climatological value— that is, from the average frequency of the given outcome over time. A forecast of 50 percent probability of being above the median, issued repeatedly, will have low resolution (even if it is reliable). The ideal is to have good resolution—probabilities that capture significant departures from the climatology—without losing reliability. (Significant

departures from climatology indicate that the forecast contains information. Since the climatology is known even if there is no forecast, a forecast of climatological probabilities, such as 50 percent chance of being above the median, does not add anything.) Evaluating probabilistic forecasts is more complex than evaluating deterministic forecasts.<sup>2</sup>

Probabilistic forecasts offer the potential for a faithful expression of the actual knowledge available to the forecaster at the time of forecast, since there is always some uncertainty in that knowledge. However, understanding the nature of that uncertainty requires some sophistication on the part of the user. Deterministic forecasts are easier for the user to understand, but they implicitly (or explicitly) overstate the forecaster’s certainty about the future.

<sup>2</sup> Special thanks to Michael Tippett (Associate Professor, Columbia University) for clarifying this issue.

## FORECASTING EXISTING STORMS

Tropical cyclone forecast centers might issue a variety of products to communicate the impending arrival of a cyclone. The intended audience for these products may include emergency managers, the media, and the general public. The forecast is usually presented with some combination of words, images, and numerical information (for example, in tabular form). These describe the present state of the storm as well as predictions for its future. In addition to the forecast itself, special alert messages may be issued when the threat to populations or other interests is deemed to have reached specific pre-determined levels; in the United States and some other places, these are *watches and warnings*, defined below.

The behavior of a tropical cyclone is represented in a forecast by a small set of parameters that describe the state of the storm at each time for which forecasts are issued. The parameters predicted usually include the following:

-  **Track:** The latitude and longitude of the storm center with time.
-  **Intensity:** The maximum surface wind speed associated with the storm that is sustained for a specific averaging time (where the averaging time varies from basin to basin). It is common to measure wind speed in knots and to predict intensity to within 5 knots. For reference, 1 knot = 1.15 miles per hour = 1.85 kilometers per

hour = 0.51 meters per second. (Intensity can also be quantified by the minimum surface pressure of the storm, in units of hectopascals, although this measure is less directly relevant to users than wind and so usually is not featured prominently in forecasts for the public.)

-  **Size:** Several measures of storm size may be forecast. Common measures are the radii at which winds decrease below given thresholds (e.g., 34 or 64 knots, although the IMD also issues forecasts of 28 knot and 50 knot wind radii). Because real storm wind fields are not circularly symmetric, these radii are often forecast separately for four different quadrants, or 90-degree wedges, surrounding the storm center.

The track, intensity, and size of the storm may be forecast deterministically or probabilistically. Probabilistic forecasts yield products such as cones of uncertainty. Many forecast centers use such cones, although their precise meaning varies slightly from center to center. For example, the National Hurricane Center in Miami, Florida, uses the following definition: The cone represents the probable track of the center of a tropical cyclone and is formed by enclosing the area swept out by a set of circles along the forecast track (at 12, 24, 36 hours, and so forth). The size of each circle is set so that two-thirds of historical official forecast errors over the previous five-year sample fall within the circle. In other words,

the forecast states that there is a 67 percent probability that the center of the storm will lie within the given circle at each lead time.

Because the probabilities used by NHC to define the sizes of the circles forming the cone are estimated by the set of historical errors in these deterministic forecasts over the last five years, they are static; throughout a season, at each given lead time (for example, 48 hours), the radius of the 67 percent probability circle is the same for each storm. However, the actual degree of scientific uncertainty about the forecast position of the storm at a particular lead time may be different from one storm to the next. Such situational, dynamic uncertainties can be estimated from model ensembles. Some centers are beginning to use such ensemble information in defining their cones of uncertainty (Dupont et al. 2011); this is discussed further below.

Forecasts of storm track, intensity, and size alone are not optimal for many users, as they do not explicitly tell people what hazards will be experienced at their location. Other forecast products are designed to give the user this information. *Watches*, *Warnings*, and *Alerts*, in particular, express the likelihood of wind hazard at a specific location over an interval of time. We discuss these products as defined in the United States by the NHC and in India by the IMD; other centers may use different definitions, but typically have broadly analogous categories expressing different levels of imminence or severity of the threat.

The different products differ in the degree of certainty and the closeness in time of the impending hazard. The NHC defines a Hurricane Watch as “an announcement that hurricane conditions are possible within the specified area,” while a Hurricane Warning is “an announcement that hurricane conditions are expected within the specified area.” Analogous definitions are used for Tropical Storm (greater than 34 knots) Watches and Warnings. These are issued for specific localities, which may be listed in text form (as a list of counties or other administrative geographic units, such as towns) or as areas demarcated on a map. Watches are issued by NHC 48 hours in advance of the expected hazard, while warnings are issued 36 hours ahead.<sup>3</sup> In India, the IMD issues Precyclone Watches at least 72 hours, Cyclone Alerts at least

48 hours, and Cyclone Warnings at least 24 hours ahead of the expected hazard on the coast.

As “possible” and “expected” are qualitative terms, some centers also issue quantitative forecasts of the specific probabilities that tropical storm-force and hurricane-force winds will be experienced. These can be expressed as areas indicated on a map where the range of probabilities for winds of a given strength or greater fall within a particular range (say, 30–50 percent) are filled in a single color, while those in other ranges are filled in other colors.

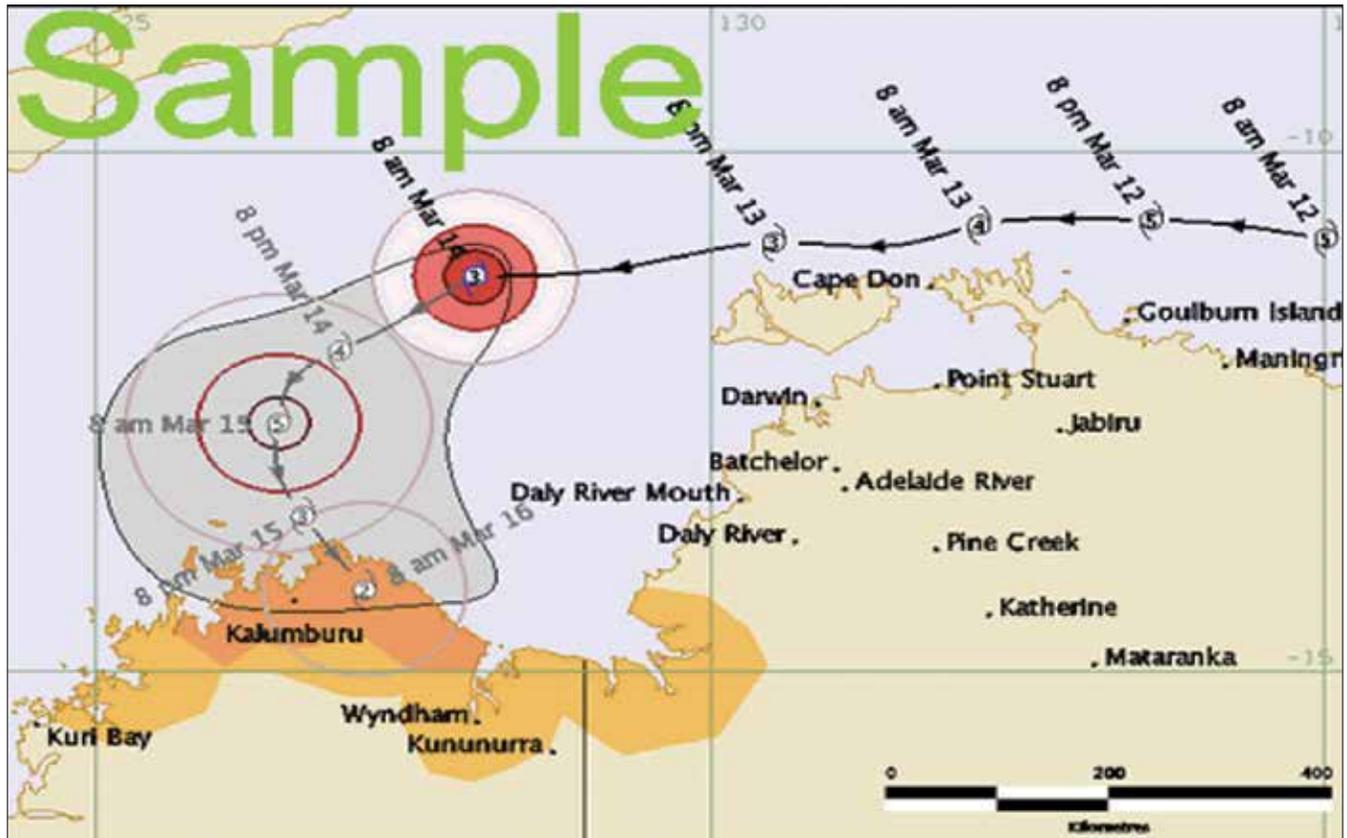
Figure 2.1 shows a sample forecast map from the Australian Bureau of Meteorology. This was issued for Severe Cyclone Alfred in March 2006. The map indicates the current location and intensity of the cyclone (category 3 in the Australian system); current and forecast radii of very destructive, destructive, and gale-force winds (here depicted by circular areas, as different radii are not forecast for different quadrants); the most likely track and range of likely tracks; and warning zones for gale-force winds within 24 and 48 hours. The range of likely tracks is broadly analogous to the cone of uncertainty used by the U.S. NHC and other centers. Here it is not quite a cone, in that the range is not a set of perfect circles centered on the most likely track with radii fixed to predetermined values at each lead time; the Australian forecasters adjust their range of likely tracks manually for each storm. At present, that adjustment may be made based on the spread in the ensemble of tracks from one or more forecast models (Andrew Burton, personal communication).

In addition to the range of quantitative products with fixed formats—track, intensity, and size forecasts, watches and warnings, and so forth—forecast centers typically issue verbal statements. These allow a greater degree of flexibility and nuance. They may explain the nature of the uncertainty, the logic of the forecasters’ thinking, or the severity of the potential hazards in ways that the formatted products do not allow. As an example, the map shown in [Figure 2.1](#) was accompanied by the following remarks: “Severe tropical cyclone Alfred is expected to continue intensifying and start moving towards the North Kimberley coast today. Tomorrow, it should recurve toward the southeast and impact the coast later in the day. It will be weakening, however destructive winds are still expected on the far north coast. Significant rainfall is expected over much of the northern Kimberley causing significant flooding.”

<sup>3</sup> NHC issues Hurricane Warnings 36 hours ahead of the expected arrival of tropical storm conditions, because many preparedness actions need to start once winds reach tropical storm strength.

While the remarks restate information available in the forecast map, they also contain additional information. In particular, they describe the hazard due to rainfall and consequent flooding, which are not indicated in the map.

**Figure 2.1** Sample Forecast Map from the Australian Bureau of Meteorology, March 2006



Community Threat		Past Cyclone Details	
Warning Zone – Gales within 24 hours		Forecast Location and Intensity Number	③ or L
Warning Zone – Gale from 24 to 48 hours		Past Track and Movement	
Current Cyclone Details		Forecast Cyclone Details (at 24 and 48 hours from issue)	
Current Location and Intensity Number	③ or L	Forecast Location and Intensity Number	③ or L
Very Destructive Winds		Very Destructive Wind Boundary	
Destructive Winds		Destructive Wind Boundary	
Gale Force Winds		Gale Force Wind Boundary	
		Most Likely Future Track	
		Range of Likely Tracks	
<p><b>The forecast path shown above is the Bureau’s best estimate of the cyclone’s future movement and intensity. There is always some uncertainty associated with tropical cyclone forecasting and the grey zone indicates the range of likely tracks.</b></p>			

Source: From <http://www.bom.gov.au/cyclone/about>.

Note: This map issued for Severe Tropical Cyclone Alfred, March 2006.

## FORECASTING GENESIS

Forecasting the genesis of a tropical cyclone is qualitatively different from forecasting the behavior of a tropical cyclone after it exists. In forecasting the genesis, the forecaster is predicting the behavior of a weaker tropical weather disturbance and trying to predict whether it will undergo the process of tropical cyclogenesis—becoming a tropical cyclone.

The process of tropical cyclogenesis is less well understood than the processes that control the track of a mature tropical cyclone. Until relatively recently, numerical models of any kind were not capable of predicting genesis with any skill. The practice of genesis forecasting has thus traditionally been heavily reliant on the forecaster’s judgment and skill. This has been rapidly changing in recent years as the ability of numerical models to simulate genesis has improved dramatically.

In many basins—the North Atlantic or Western North Pacific, for example—genesis often (though by no means always) occurs far from land, so that the time between genesis and the possibility of landfall is relatively large—say, five days or longer. Additionally, systems are, by definition, weak immediately after genesis and less threatening than they will become if they intensify. These factors may have historically led to less effort being spent on the forecasting of genesis than on the forecasting of the tracks and intensities of existing storms. Genesis forecasting was not seen as essential to the protection of life and property in most cases. In some basins, however—such as the North Indian Ocean or the Australian region—it is more common for genesis to occur relatively close to land, and such systems may pose dangers despite the short time available for intensification before landfall (either because they intensify rapidly or because some hazards, particularly rainfall-driven flooding, can be acute even for nominally weak systems). Existing forecast systems may not handle such cases well.

Across different centers, forecasts of tropical cyclogenesis are less uniform in content and format than track and intensity forecasts for mature storms. Some centers do not forecast genesis at all, and those that do typically do so at shorter lead times and with less quantitative precision (at least until very recently) than they use when forecasting track and intensity for existing storms. The NHC produces genesis forecasts that are among the more detailed and quantitative of those issued

across centers globally. In these forecasts, the probabilities of genesis are forecast in 10 percent increments. These forecasts have been produced since 2008, initially at lead times up to 48 hours, then increased to 120 hours in 2013.

In recent years, the ability of global dynamical models to predict genesis accurately has increased significantly, particularly when multiple models are considered as a group (Halperin et al. 2013). Additionally, scientific understanding of large-scale influences on genesis, particularly the Madden-Julian oscillation and convectively coupled equatorial waves (for example, Zhang 2005; Bessafi and Wheeler 2006; Kiladis et al. 2009; Camargo, Wheeler, and Sobel 2009), has improved. As a consequence of both of these factors, the NHC has now extended their genesis forecasts to 120 hours. The Australian Bureau of Meteorology produces genesis forecasts for the public up to three days in advance and may provide some general text on the likelihood of genesis as much as seven days in advance in some circumstances. The Bureau, on a commercial basis, also produces specialized forecasts for industrial clients with lead times as long as 28 days (Andrew Burton, personal communication). Using a dynamical-statistical model, the IMD produces a forecast of a Genesis Potential Parameter for the Northern Indian Ocean, which expresses the probability of tropical cyclogenesis for the next seven days.

Even when genesis is forecast with high confidence, however, it is still kept separate from forecasts of the resulting mature storm. The traditional forecast process does not “cross” the genesis event. In other words, if forecasts of track and intensity are issued out to 120 hours for existing tropical cyclones, and genesis is believed very likely to occur within the next 48 hours, in theory it would be possible to issue a forecast product that would include both the genesis event itself (however defined, recognizing that this is different from one basin and forecast center to another) and the first 72 hours of the post-genesis tropical cyclone. Ensemble prediction systems do, in fact, allow such forecasts to be produced in principle (e.g., Belanger et al. 2013). However, at the time of writing this report most national centers with formal responsibility for tropical cyclone forecasting do not issue such forecasts to the public as part of routine operations, although the NHC (and perhaps other agencies) have begun doing so recently at short lead times in a limited set of circumstances.

## WHAT TYPES OF OBSERVATIONS ARE USED?

The start of any forecast system is data and observations. The following types of observations are relevant to tropical cyclone analysis and prediction:

-  *Surface observations* include surface meteorological stations on land, instrumented buoys at sea, and ships at sea. These may measure wind, pressure, temperature, humidity, and sometimes other variables such as precipitation or radiation.
-  *Radiosondes* include weather balloons launched from specific weather-observing stations. These measure wind, pressure, temperature, and humidity over a large vertical range, typically the entire depth of the troposphere, or into the lower stratosphere (above 15 kilometers). The number of radiosonde stations owned and operated by national meteorological agencies is much smaller than the number of surface meteorological observing stations. Radiosonde observations are generally not available over the ocean, apart from a few select islands.
-  *Geostationary satellites* stay in a fixed position relative to Earth and image a large area of Earth's surface. They produce images from the infrared wavelengths during all hours as well as visible wavelengths during daylight hours. Several countries, including the United States, Japan, China, India, and the European Union, operate a group of geostationary satellites that continuously image the entire Earth. They are essential to modern tropical cyclone analysis and prediction because they make it virtually impossible for a tropical cyclone to go undetected. Images are typically available every 30 minutes.
-  *Polar orbiting satellites* move relative to Earth's surface and image only a small area every day. Some sensors on polar orbiting satellites make observations in the microwave portion of the electromagnetic spectrum; these instruments can see through clouds and allow more clear imaging of the inner structure of a tropical cyclone. When available, such images are very useful for characterizing the structure and intensity of tropical cyclones. Because polar orbiters only image a small fraction of Earth's surface at any time, however, a given storm typically passes through their view only intermittently—perhaps several times a day, with some views covering only part of the storm. Polar orbiters also include scatterometers, which can estimate the speed and direction of surface winds; when available,

they are also very valuable, but they have limitations in either strong precipitation or very high wind conditions.

-  *Weather radar* can image the precipitation field, and, if it is a Doppler radar, the wind field in areas of precipitation, at high resolution in both space and time. Radars are typically based on land and have a horizontal range of 100–200 kilometers. Radars can scan vertically to obtain three-dimensional volumetric observations of radar reflectivity (related to the quantity and type of precipitation-sized particles) and velocity of the precipitation particles (which is normally assumed to be close to the velocity of the air) in the case of Doppler radar, at all altitudes at which there are hydrometeors large enough to reflect the radar beam. They are valuable for tropical cyclone observations once a storm gets close enough to land to be within range, but they are generally not available over the open ocean. Exceptions are the space-borne radars aboard the tropical rainfall measuring mission and CloudSat satellites, operated by the U.S. National Aeronautics and Space Administration, both of which capture intermittent snapshots of tropical cyclones over the ocean.
-  *Aircraft* specifically instrumented for tropical cyclone observation may be deployed when available. At present, such aircraft are deployed routinely only by the United States in the North Atlantic and East Pacific and by Taiwan and Hong Kong in the Western North Pacific. These aircraft take a range of observations, including flight-level measurements of all normal meteorological variables (wind, temperature, humidity). Some aircraft carry radar, including in some cases Doppler radar. They may have the capability to launch dropsondes, which are equivalent to radiosondes except that they fall downward rather than rising upward and thus are available only below the flight level. Some aircraft may have additional remote sensors, such as radiometers (similar to those deployed on polar orbiting satellites), which can measure surface winds over the ocean.

A large subset of the available observations over the entire globe is incorporated by several numerical weather prediction centers into global dynamical models to derive global meteorological *analyses*. The process by which the observations are incorporated into the models is known as *data assimilation*. This is a process by which all available observations are blended with the model itself to produce an

estimate of the state of the atmosphere (winds, temperatures, pressures, etc.) that is an optimal combination of the two.<sup>4</sup> Ideally, the resulting analysis should be close to the observations wherever high-quality observations of these meteorological variables exist, while using the model as a substitute where they do not. The meteorological analyses produced by the data assimilation process have the advantage of uniformity, being available on regular three-dimensional grids (although their quality may not be uniform). Such analyses are the best estimates of the atmospheric state on a large scale and are also initial conditions for global numerical model forecasts.

The data assimilation process is not typically carried out at tropical cyclone forecast centers but rather at national or international numerical weather prediction centers whose products are made available to all national forecast offices

<sup>4</sup> China and India do their own data assimilation.

(as well as those in other nations, in many cases). Examples of such centers include the National Center for Environmental Prediction (NCEP) in the United States, the European Centre for Medium-Range Weather Forecasts based in the UK, and the National Center for Medium Range Weather Forecasting (NCMRWF) in India. The analyses are available to tropical cyclone forecasters.

Data assimilation with numerical models has largely replaced the process of hand analysis, by which a human forecaster produced a large-scale weather map from raw observations. However, hand analysis is still performed as well at a few forecast centers, including the Bangladesh Meteorological Department and the Darwin office of the Australian Bureau of Meteorology.

## WHAT TYPES OF MODELS ARE USED?

### *GLOBAL DYNAMICAL MODELS*

Global dynamical models are the workhorses of modern numerical weather prediction. Global refers to the model domain, which covers the entire Earth. Dynamical refers to the fact that the models simulate the behavior of the atmosphere explicitly by solving mathematical equations that express the laws of physics.

The state of the atmosphere in a dynamical model can be thought of as represented by the numerical values of meteorological fields—such as temperature, wind, pressure, and humidity—on a discrete grid—that is, at a finite set of points, usually regularly spaced apart.<sup>5</sup> The spacing between grid points is often referred to as the resolution of the model;<sup>6</sup> typical horizontal resolutions in state-of-the-art global forecast models at present are in the range 10–50 kilometers.

<sup>5</sup> In practice, many operational global models are spectral, meaning that fields are represented by waves of different wavelengths rather than grid point values, and the resolution is the smallest wavelength retained. The inherent limitations of finite resolution are the same, and this discussion is phrased in terms of the more intuitive grids in physical space.

<sup>6</sup> The use of the word “resolution” to refer to what is actually the “grid spacing” is technically incorrect, as a model only truly resolves features large enough to span multiple grid points. This is nonetheless standard usage and is adopted here.

Vertical resolutions are much finer—typically hundreds of meters, perhaps less near the surface—due to the inherently much smaller vertical scale of the atmosphere compared with its horizontal scale. A model’s resolution determines the minimum size of the features it can represent accurately, in much the same way as the pixel size determines the minimum size of an object that can be distinguished in an image from a digital camera.

Global dynamical models are run operationally, typically either two or four times per day every day, by national weather prediction centers. Some centers have developed their own models and run them operationally, such as NCEP (whose model is known as the Global Forecast System (GFS) model), ECMWF, the United Kingdom Meteorological Office, the Japan Meteorological Agency (JMA), Environment Canada, the U.S. Navy, the India Meteorological Department and India’s NCMRWF, and the China Meteorological Administration.

The models are initialized with an analysis. This represents the best estimate of the atmospheric state at the initial time (zero lead time) and is produced by assimilating all of the available observations into the model, as described earlier. An important feature of data assimilation for this purpose

is that it reduces inconsistencies between the model and observations, which may result from errors in either the model or the observations. The results are better suited for initializing a model forecast than using an estimate based on the observations alone; initialization directly with observations would typically result in an artificial period of rapid change, or “shock,” at early times as the model adjusts to the initial conditions.

Because global models are run on global domains, they can be used to inform forecasts of weather occurring anywhere. For the most part, forecast data from the models are routinely available to operational centers worldwide, so that a given center has access in real time to the output of global weather forecast models from most or all of the national centers that produce such output. Thus it is not necessary for each country to develop its own global modeling system in order to have access to the results from such systems.

The basic outputs consist of physical fields, pressure, temperature, precipitation, and winds on two- or three-dimensional numerical grids. For the purpose of tropical cyclone forecasting, many centers, including NCEP, ECMWF, and JMA, also run automated tracking programs that identify tropical cyclones in the model output. These produce model tracks—position, intensity, and possibly size information—that can be used directly in forecasting tropical cyclones. This spares the forecaster the task of extracting a model-predicted track from the full three-dimensional meteorological fields predicted by the model.

The smallest flow features that can be resolved in a dynamical model are several times the grid spacing. Grid spacings of tens of kilometers, typical of current global models, are still inadequate for a truly realistic representation of the structure of a tropical cyclone, particularly in the inner core where the eyewall, for example (the ring-shaped region of intense precipitation, deep convective cloud, and high winds surrounding the clear eye in a strong tropical cyclone), can have a width of only a few kilometers. As the strongest winds typically occur over a small region in or close to this inner core, a lack of adequate spatial resolution to resolve that core typically leads to the simulation of maximum sustained wind speeds weaker than those observed. As a result, the current generation of global weather models is still largely incapable of producing model tropical cyclones with intensities at the higher end of those observed. Intensity estimates produced

directly from global model output will invariably be biased low for strong storms, although it may be possible for a forecaster (or automated algorithm) to correct for this bias to some extent.

All told, the ability of modern global models to simulate tropical cyclones overall—not only the tracks, but also the initial formation, or genesis of the storms—is remarkably improved over that of previous generations and allows for skillful forecasts with rather little human assistance in many cases. This is discussed further below.

### *REGIONAL DYNAMICAL MODELS*

A regional dynamical model differs from a global one in that it represents only a specific geographic region rather than the whole global atmosphere. This means that the model domain has lateral boundaries within the atmosphere, at which boundary conditions must be specified. These are taken from a global forecast model. The primary reason for running a regional model is that the smaller domain allows higher spatial resolution, which is highly beneficial for simulating tropical cyclones. A regional model can have a resolution of a few kilometers or less. This allows simulation of the strongest intensities, allowing at least the potential for more accurate forecasts of intensity than are possible with global models.

Whereas global models are run operationally every day—for forecasting of all weather, not just tropical cyclones—regional prediction models configured specifically for tropical cyclone forecasting are typically brought into operation only when a center has identified a storm as being of significant concern. This may happen when a storm has reached sufficient intensity to be named, by whatever criteria are used in the basin in question, or earlier, when a disturbance has become a depression and thus presents the possibility of intensification to a named storm. The model is often run on a domain centered on the storm and moving with the storm, to allow optimal use of computational resources.

Some older regional models use simplified forms of the governing equations and sets of model choices designed specifically for predicting tropical cyclones. Examples include representing the atmosphere as a single layer with no vertical structure, the so-called barotropic model; as only a few vertical layers, as in the quasi-Lagrangian model (Mathur 1991); or as the beta and advection model, in which the storm moves with the large-scale flow plus a deviation due

to the effect of Earth's rotation and sphericity (Marks 1992). The large-scale flow at the boundaries and in the initial conditions can be taken from a global weather prediction model. An idealized vortex whose properties are based on those deduced in real time by forecasters to represent a given tropical cyclone is superimposed on the large-scale initial conditions. These models were developed in a period when the more comprehensive dynamical models either could not represent tropical cyclones well at all or could not be run quickly enough, given available computational resources, to be available to the forecast process. Although some are still in operational use, these models have been supplanted to a large extent by more comprehensive models that use much more complete and sophisticated representations of atmospheric physics, as model improvements and greatly increased computer power have made these comprehensive or "full-physics" models more competitive.

A widely used full-physics regional model has been NOAA's Geophysical Fluid Dynamics Laboratory hurricane model. This is run not only for the U.S. NHC to forecast Atlantic and Eastern Pacific storms; the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center also runs a version of this model for most named tropical cyclones in other basins worldwide. Thus forecasters in every basin can, at least in principle, have access to results from at least one regional high-resolution model. The Hurricane Weather Research and Forecast System (HWRF), a newer model, is used operationally at the U.S. National Center for Environmental Prediction and the India Meteorology Department. HWRF output is also provided globally, including for the Bay of Bengal, to the Joint Typhoon Warning Center (JTWC) by the NCEP as an experimental product under the Hurricane Forecast Improvement Program (HFIP).<sup>7</sup>

Initialization of regional weather models is a more difficult problem than initialization of global models because regional models involve fine spatial scales. While the purpose of a regional weather or tropical cyclone model is to capture the structure of the storm in fine spatial detail, the available observations are often inadequate to represent that level of detail at the initial time. This strongly degrades the forecast of those structural details at future times. Standard analyses from global models are usually too coarse to resolve the inner core of the storm. It is common to produce a bogus, or artificial, vortex into the initial conditions, based on the forecasters'

interpretation of all available information. If aircraft or other specialized observations are available, these may be used to construct more accurately constrained initial conditions. Recent research has demonstrated positive impacts on both track and intensity forecasts from assimilation of aircraft-based Doppler radar data, for example in Hurricane Katrina in 2005 (Weng and Zhang 2012) and Typhoon Jangmi in 2008 (Zhang et al. 2012), although this remains an area of active research.

### ENSEMBLE METHODS

Numerical forecast models are run in two different modes: deterministic and ensemble. A deterministic forecast run is a single run of the best version of a given model, typically meaning at the highest spatial resolution currently available, starting from the best estimate of the initial state. An ensemble is a set of runs, usually with lower spatial resolution than used for the deterministic forecast run. Each run in the ensemble starts from slightly different initial conditions. Adding a different small perturbation to the best estimate of the initial state produces each set of initial conditions. These small perturbations are still consistent with that estimate, within the uncertainties inherent in the observation, analysis, and data assimilation process. As the model runs progress, the differences between ensemble members will grow, because the atmosphere is *chaotic*. This means that small differences in initial conditions amplify rapidly, leading to large differences after a finite time (Lorenz 1963).

The ensemble spread, or range of solutions among the ensemble members, can be used as a practical measure of the uncertainty in the prediction. The spread almost invariably grows with lead time, indicating increasing uncertainty at longer lead times. However, the spread also varies from forecast to forecast at the same lead time. This indicates that the uncertainty at a given lead time is not a unique function of lead time. Rather, it is to some extent situational—some forecasts will have a greater degree of uncertainty than others, independent of the quality of the model or the skill of the forecaster who is interpreting it.

Tropical cyclone forecast centers typically have access to output from numerical model ensembles produced by several national weather forecast centers globally. Each may contain several to perhaps tens of individual ensemble members. These ensemble outputs in many cases include tropical cyclone tracks produced by automated tracking algorithms applied to the model output fields. In addition

<sup>7</sup> See <http://www.emc.ncep.noaa.gov/HWRF/WestPacific/index.html>.

to these products from individual forecast centers, the forecaster has access to consensus forecast aids, which are produced by taking weighted averages of results from a set of different models. Examples are the Florida State University Superensemble described by Krishnamurti et al. (1999) and consensus products used at NHC and the Joint Typhoon Warning Center listed by Heming and Goerss (2009). These consensus products are typically found, on average, to be superior to any individual model in the ensemble (for example, Goerss, Sampson, and Gross 2004), an indication that the differences between models can be considered random errors to some extent.

### STATISTICAL MODELS

A statistical model is one that predicts an event based on the statistics of past events. A set of predictors is chosen that is believed *a priori* to be relevant; in the case of statistical models for tropical cyclone prediction, predictors could be environmental variables such as sea surface temperature, vertical wind shear (the difference in speed and direction of the horizontal wind at different altitudes), or parameters describing the present state of the storm. The predictors representing the environment are typically averaged over a region larger than the storm itself. Empirical relationships are derived between the predictor variables at the initial time and the behavior of storms at later times, using statistical methods such as linear regression. These models do not use the equations of motion or any other aspect of atmospheric physics, except inasmuch as understanding the physics informs the choices of predictors. As a consequence, statistical models are many orders of magnitude cheaper computationally than dynamical models.

The simplest statistical model, for example, is persistence: the storm will maintain its present intensity and continue its

motion at its present speed and direction. Statistical models that are more complex than persistence have been developed to predict both the tracks and intensities of tropical cyclones. Because dynamical models have become so skillful at predicting tracks, statistical track models are for the most part no longer useful, except as benchmarks against which to measure skill—that is, a forecast that is no better than the statistical models may be considered not to have useful skill. For the purpose of predicting intensity, statistical models are still considered to be at least the equal of dynamical models, because there has been relatively little improvement in the ability of dynamical models to predict intensity in recent decades. However, statistical models have some well-known limitations, such as their inability to predict rapid intensification periods, when the intensity of a tropical cyclone increases by 30 kt or more over a period shorter than 24 hours.

### STATISTICAL-DYNAMICAL MODELS

Statistical-dynamical models are, as the name suggests, hybrids of the two approaches. These are statistical models in that tropical cyclone characteristics are predicted as specified functions of larger-scale environmental variables, but dynamical in that the large-scale environmental variables are obtained at future times from dynamical model output. The statistical component attempts to overcome the deficiencies of the dynamical model in representing the tropical cyclone, while the dynamical component makes use of the skill that the dynamical model does have in predicting the large-scale environment in which the storm is evolving. Important examples are the Statistical Hurricane Intensity Prediction Scheme (DeMaria and Kaplan 1994, 1999; DeMaria et al. 2005), Logistic Growth Equation Model, and the Rapid Intensity Index. These models remain competitive with dynamical models in prediction of tropical cyclone intensity and provide important guidance to forecasters.

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## THE FORECAST PROCESS

### THE TRADITIONAL PROCESS, WITH A HUMAN FORECASTER

As carried out in most national tropical cyclone forecast centers, the forecast process involves one or more human forecasters. The first component is a tropical cyclone analysis, meaning an estimate of the state of an existing tropical cyclone at the present time. (This is not to be confused with a global or synoptic analysis, which represents the state of

the atmosphere everywhere on a global or at least regional scale.) The analyst will use all available observations for this purpose. Many types of observations are available only at a limited set of times or locations—for example, if the cyclone happens to pass over a ship or buoy or when a polar orbiting satellite swath happens to capture it. Even when available, surface in situ observations or radiosondes are available at a

small number of locations and thus would poorly define the structure of the storm on their own. Aircraft observations are valuable but are available only in a subset of basins and then for a subset of storms in those basins. Geostationary satellite imagery is virtually guaranteed to be available and as a consequence is essential to modern tropical cyclone analysis.

The Dvorak technique (Dvorak 1984) is the standard method for using geostationary imagery to estimate the intensity of the storm and the location of its center. This involves several steps that require pattern recognition on the part of a human analyst. It is thus partly subjective, and different analysts can obtain somewhat different results. Besides differences from one individual to the next, there are systematic differences in the application of the Dvorak technique from one forecasting center to another, which can lead to inconsistencies in analyzed storm position and intensity for a given storm in real time.

Automated implementations of the Dvorak technique have been developed that are objective. One such implementation, the Advanced Dvorak Technique (ADT), has skill comparable to that achieved by human analysts (Olander and Velden 2007). ADT is produced for storms in all basins (including the North Indian Ocean) and made publicly available by the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin, Madison. Nonetheless, human analysts are still prevalent in operational practice worldwide.

At the start of the forecast, the forecaster uses his or her judgment to assess all available observations, including a Dvorak analysis, to produce an estimate of the current position and intensity of the storm, as well as wind radii. This is the analysis, or forecast, at zero lead time. Such an analysis is produced for any storm that has already been determined to be a tropical cyclone (by the criteria in use in the particular basin) but it may also be produced for a weather system that is just approaching that threshold, in order to determine if it has become a tropical cyclone.

For each tropical cyclone, the forecaster must next produce a forecast for each lead time. The lead times are typically spaced 6 or 12 hours apart and extend to a maximum, typically

120 hours. The forecaster consults all available guidance—a generic term used here to refer to any external information, but typically referring to the results from dynamical or statistical prediction models.

Ideally, all guidance is available to the forecaster in real time and in a form that makes the process of interpreting that guidance and synthesizing it into a forecast as straightforward as possible. In the more advanced centers, the process is done on digital computers. The software environment in which both observations and model guidance are presented to the forecaster is a significant component of the forecast system. At the NHC and JTWC, the Automated Tropical Cyclone Forecasting System (ATCF) is used to display model guidance, while observations are displayed primarily using the NCEP Advanced Weather Interactive Processing System (ATCF also has a limited capability to display satellite data). All model track predictions, for example, are displayed as lines on a map on the screen in ATCF. The system is also able to correct biases due to initial position error in model guidance by relocating the start of each track to the center fix determined by the forecaster. After also consulting three-dimensional model output fields in order to interpret the model tracks, the forecaster produces a forecast by drawing a track on the same screen on which the guidance tracks appear.

Faced with all available guidance, the forecaster makes a judgment about which guidance to trust more than others or how to average or interpolate between different guidance products. The forecaster may be guided by intuition, physical insight, experience with previous storms, or other factors. It is not impossible that expectations about users' potential reactions to the forecast may be taken into account in some circumstances—for example, the risk of forecasting an event more severe than actually occurs may be perceived differently than the risk of forecasting one less severe than actually occurs—although the goal is forecasts with zero bias.

There may also be a desire for consistency from one forecast to the next. This is relevant either because the guidance changes rapidly between forecast cycles or simply because each forecast may be made by a different forecaster or

For each tropical cyclone, the forecaster must next produce a forecast for each lead time up to the maximum. **The lead times are typically spaced 6 or 12 hours apart and extend to a maximum, typically 120 hours.**

group of forecasters, and one set may judge the available guidance differently than the next one. Even in the presence of such impetus for a change in the forecast, the forecaster may decide not to alter the forecast as rapidly as he or she otherwise might, in order to maintain consistency. This is viewed as important to avoid confusing the users with forecasts that oscillate or otherwise vary from one cycle to the next and to average out short-term variations in guidance that may occur over time. A policy of maintaining continuity over consecutive forecast cycles—apart from any clear reason for a dramatic change—is a strong constraint on forecasters at the NHC in Miami, for example (James Franklin, personal communication).

In this process, as it is implemented in many if not most of the forecast centers, information from numerical guidance is invariably used to inform the forecast, but it may not be explicitly presented as part of the forecast. The forecaster will almost certainly look at the track predictions in the model ensembles—ensembles constructed from multiple runs of a single model with different initial conditions as well as multimodel ensembles consisting of runs of independent models—and the degree of spread will inform the perception of the uncertainty. However, many centers do not explicitly use the ensemble spread to compute their quantitative metrics of uncertainty (for example, the cone of uncertainty) or to show the tracks from the ensembles in their forecast products. In the case of the NHC, at least, this is the result of a conscious decision; it is believed that many users are not capable of understanding the ensemble information and that incorporating it would make the forecast less effective (James Franklin, personal communication).

Some formal products do use ensemble information; in the case of NHC, ensemble spread is used to construct the wind speed probability product. More broadly, information about ensemble spread may also enter the forecasts in less formal ways. At the RSMC New Delhi, the cone of uncertainty is constructed based on the past climatology of errors, as at NHC. In the text bulletin, however, the area of possible landfall is indicated taking into consideration the spread in deterministic models and ensembles.

### ENSEMBLE PREDICTION SYSTEMS

As the ability of global dynamical models to simulate tropical cyclones accurately has improved, and as ensemble methods for using those models in forecasting have advanced, new

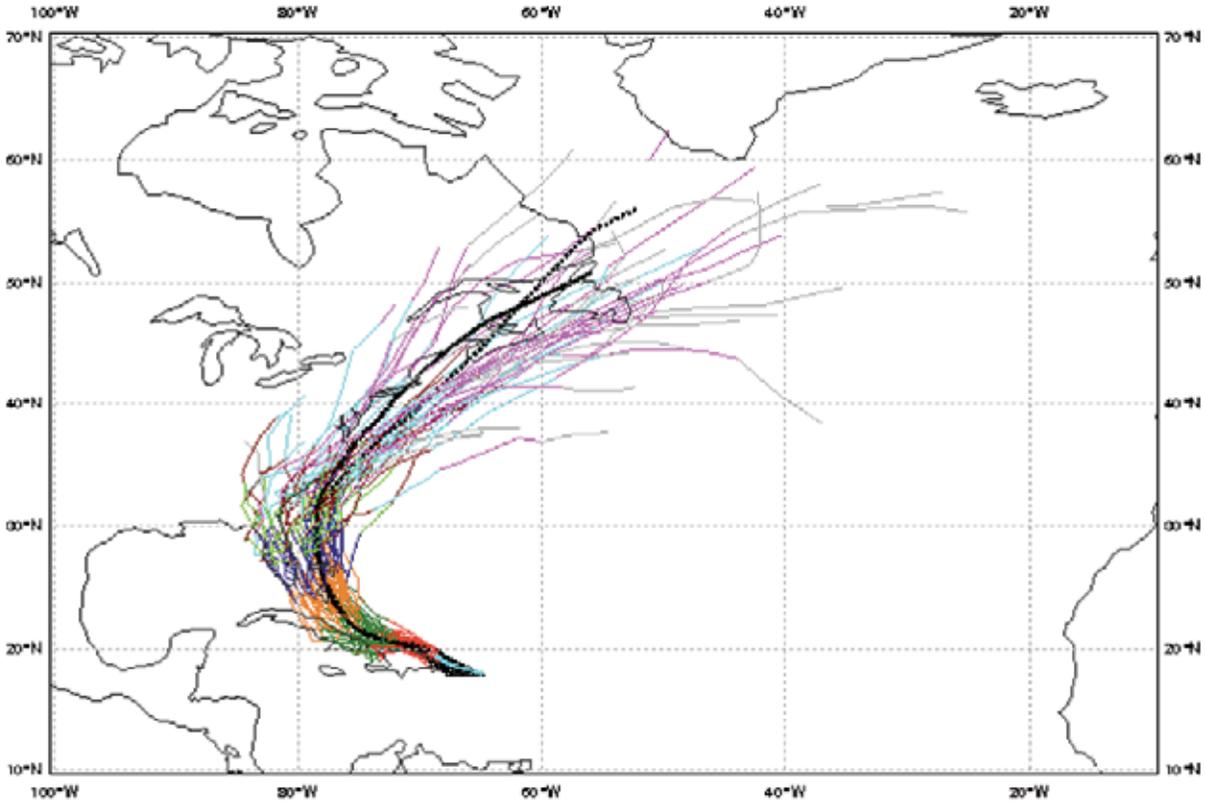
ensemble prediction systems for tropical cyclone prediction have emerged in the last several years. Once an ensemble prediction system of this kind is set up, it can, in principle, be entirely automated.<sup>8</sup> No human forecaster is needed, strictly speaking, to produce the forecast, although a human forecaster may be involved, in practice, for quality control. The JMA, a national forecast center and one of the WMO regional centers for predicting tropical cyclones, operates such a system (in parallel with a more traditional forecast process involving human forecasters); the ECMWF does as well (although ECMWF forecasts are not publicly available but are provided only to certain national centers and other clients).

These systems use numerical models exclusively. A typical system uses a single numerical model that is run at a single center and in ensemble mode and uses objective algorithms to produce a forecast directly from the model output. An objective tracking algorithm is used to detect and track tropical cyclones in each model run. Once one or more tropical cyclones are detected, special ensemble members may be initialized, using a procedure designed to optimize the perturbations in the initial conditions specifically for the purpose of estimating the uncertainty in the prediction of those tropical cyclones. The tracking algorithm is applied to the resulting model integrations to produce an ensemble of tracks, and then objective algorithms are used to produce forecast quantities from those tracks.

The forecasts produced by ensemble systems lend themselves to probabilistic interpretation. The probabilities are derived directly from the ensemble model tracks. For example, the probability of wind speed greater than 65 knots at a given location can be estimated by dividing the number of ensemble members in which the wind speed exceeds that value by the total number of ensemble members. These probabilities are inherently situational and dynamic; the range of possible forecast outcomes will depend on the ensemble spread (for example, Dupont et al. 2011). Visual inspection of the “spaghetti plot”—the set of tracks from individual ensemble members—gives a qualitative impression of the uncertainty in the track forecast, as shown in an example from ECMWF in Figure 2.2 (Vitart et al. 2011).

<sup>8</sup> It is also possible to develop an automated forecast system based on single model runs with no ensemble information, although we are not aware of such a system currently operational.

**Figure 2.2** Individual Tracks for Tropical Cyclone Irene



Date 20110822 00 UTC @ECMWF

Individual trajectories for **IRENE** during the next **240** hours

tracks: **thick solid**=OPER; **thick dot**=CTRL; **thin solid**=EPS members [coloured]

**0-24h 24-48h 48-72h 72-96h 96-120h 120-144h 144-168h 168-192h 192-216h 216-240h**

Source: Vitart et al. 2011, courtesy F. Vitart, ECMWF. From the ECMWF Ensemble Prediction System forecast starting at 00 UTC on August 22, 2011, using various colors to indicate tracks over 24-hour intervals out to 240 hours.

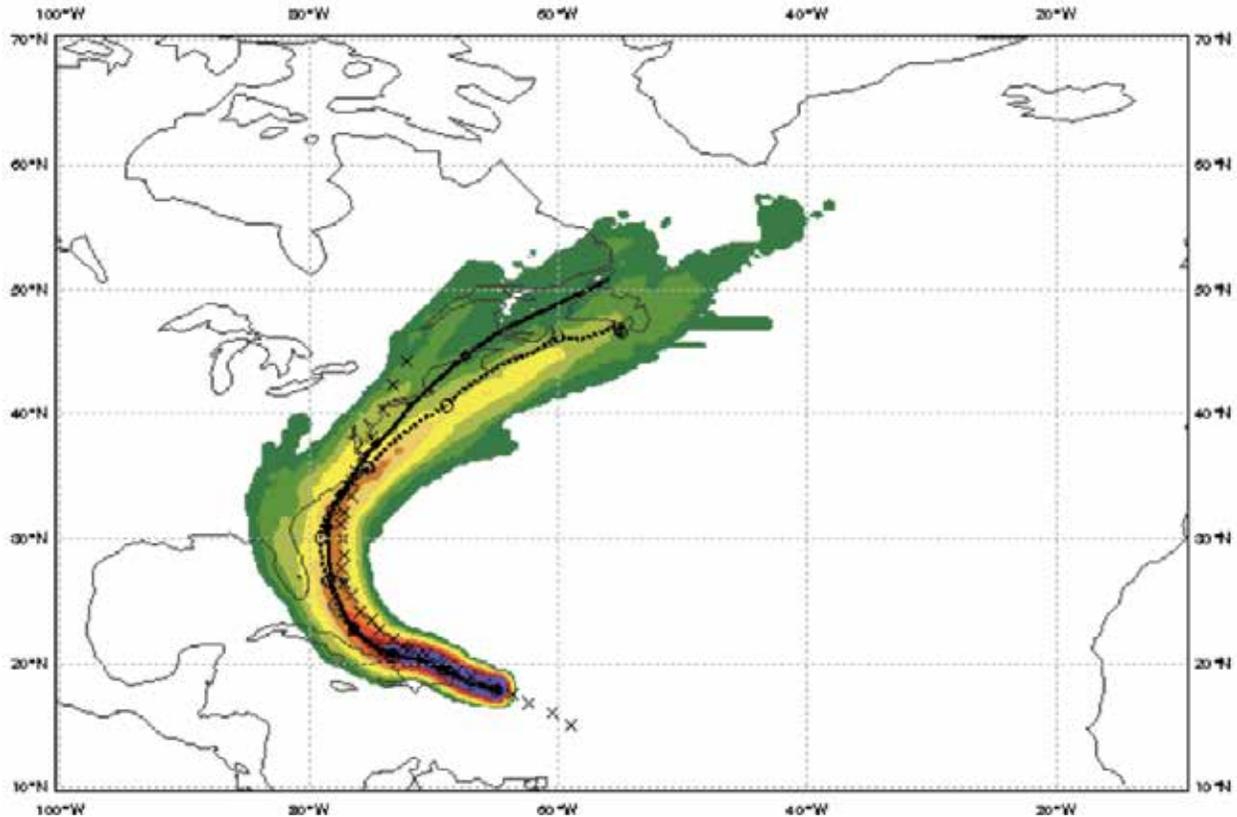
Note: Black lines represent the tracks produced by the model at two different horizontal resolutions, T1279 (solid) and T699 control (dot).

Ensemble forecast systems might predict quantities different from those in traditional forecasts. As an example, in addition to producing an ensemble mean track prediction (the average of all tracks for a given storm over the ensemble) for storms that have already been named, the JMA and ECMWF’s ensemble prediction systems predict a strike probability—the probability that a tropical cyclone center will pass within a specified distance of a given location—not only for named

storms but also for storms that have not yet been named but that some ensemble members predict will form.

Figure 2.3 shows an example of an ECMWF strike probability forecast for a storm (Irene in 2011) that had already been named. Figure 2.4 shows a strike probability forecast issued two and four days before the formations of Harvey and Irene, respectively (both from Vitart et al. 2011). The latter figure

**Figure 2.3** Strike Probability (%) for Tropical Cyclone Activity within 300 Kilometers (Systems with Maximum Wind Speed Greater Than 8 Meters per Second) for the Two-Day Period of August 20–22 Based on the ECMWF Ensemble Prediction System Forecast from 00 UTC on August 17, 2011



Date 20110822 00 UTC @ECMWF

Probability that **IRENE** will pass within 120km radius during the next **240** hours  
tracks: **solid**=OPER; **dot**=Ens Mean [reported minimum central pressure (hPa) **994** ]

■ 5-10 ■ 10-20 ■ 20-30 ■ 30-40 ■ 40-50 ■ 50-60 ■ 60-70 ■ 70-80 ■ 80-90 ■ > 90

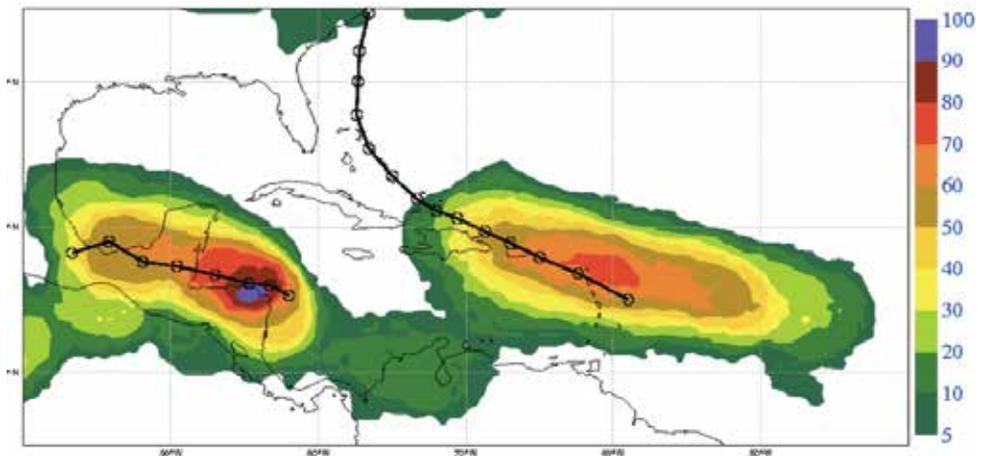
Source: Vitart et al. 2011, courtesy F. Vitart, ECMWF.

Note: Solid lines and open circles represent the observed tracks of tropical storm Harvey (to west) and hurricane Irene (to east) between August 20 and August 24. Harvey formed on August 19, Irene on August 21—two and four days after this forecast was produced.

thus is a forecast simultaneously of genesis and the track of the storm (in this case, two storms) after genesis. This product is qualitatively different from any produced by the traditional forecast process, in which forecasts of genesis and of storm evolution after genesis are kept completely distinct, and the latter are not produced at all until genesis has occurred. While the point at which track and intensity forecasts are begun for existing disturbances differs at different centers—

in particular, IMD uses a 28-knot threshold, while some other centers use a 34-knot threshold, and NHC does not use any wind speed threshold but instead criteria based on the organization of the system's convection and circulation—ensemble-based products such as that shown in Figure 2.3 do not require any specific criteria to have been reached at the time the product is issued or for any disturbance to exist at all yet.

**Figure 2.4** Strike Probability (%) for Tropical Cyclone Activity within 300 Kilometers (Systems with Maximum Wind Speed Greater Than 8 Meters per Second) for the Two-Day Period of August 20–22 Based on the ECMWF Ensemble Prediction System Forecast from 00 UTC on August 17, 2011



Source: Vitart et al. 2011, courtesy F. Vitart, ECMWF.

Note: Solid lines and open circles represent the observed tracks of tropical storm Harvey (to west) and hurricane Irene (to east) between August 20 and August 24. Harvey formed on August 19, Irene on August 21—two and four days after this forecast was produced.

## CURRENTLY AVAILABLE SKILLS AND RECENT DEVELOPMENTS

This section briefly summarizes the level of skill that is currently available operationally and the trends in skill in recent decades. The U.S. NHC is taken as broadly representative of the state of the art. Figure 2.5 shows average annual track errors in the NHC official forecasts (in nautical miles; 1 nautical mile = 1.85 kilometers) as a function of time over the last two decades, while Figure 2.6 shows average annual intensity errors over nearly the same period. Different curves are shown separately for each lead

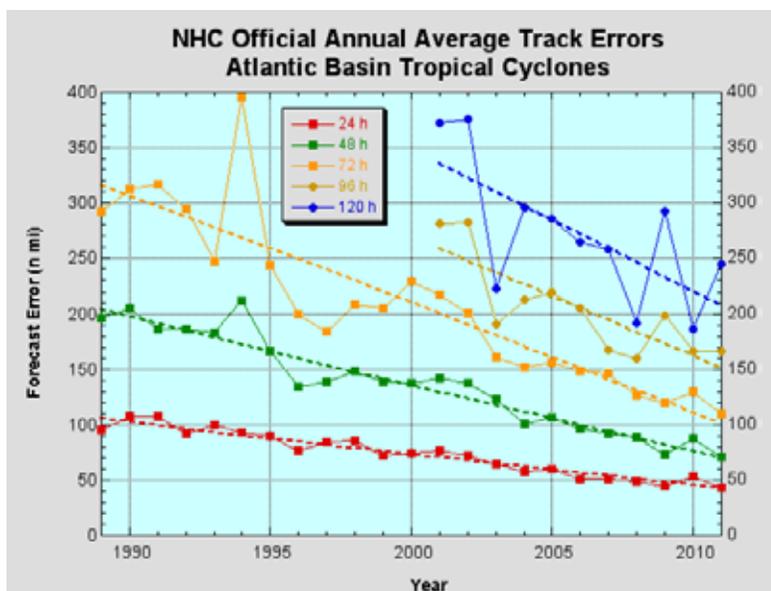
time; note that forecasts for 96 and 120 hours were not made before 2001.

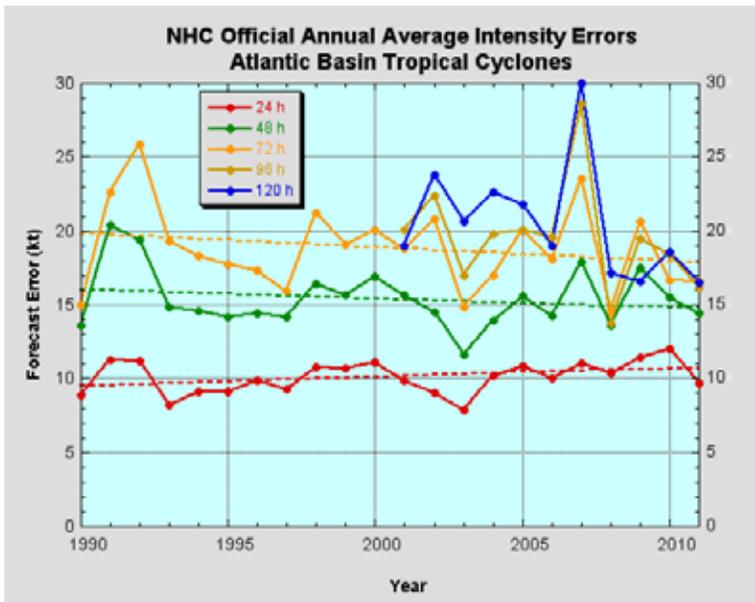
It is evident from Figure 2.5 that the accuracy of track forecasts has improved steadily with time. The accuracy of today’s 72-hour track forecast, for example, is comparable to that of a 24-hour forecast of 20 years ago. At the same time, Figure 2.6 shows that there has been little improvement in intensity forecasts. The accuracy of intensity forecasts is

**Figure 2.5** Average Track Errors, in Nautical Miles, in the U.S. National Hurricane Center’s Forecasts as a Function of the Year in Which the Forecasts Were Made

Source: From <http://www.nhc.noaa.gov/verification>.

Note: Different curves show different lead times, as indicated in the legend.





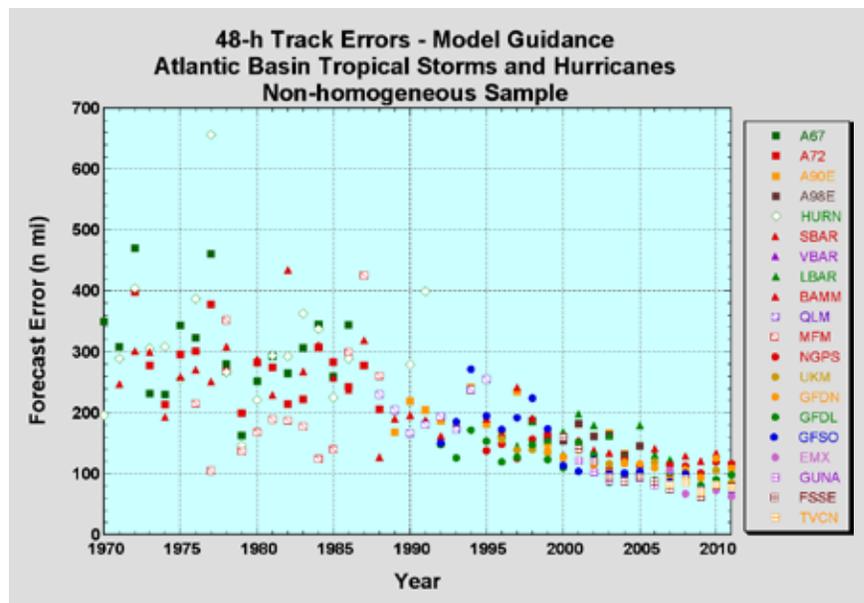
**Figure 2.6** Average Track Errors, in Knots, in the U.S. National Hurricane Center’s Forecasts as a Function of the Year in Which the Forecasts Were Made

Source: From <http://www.nhc.noaa.gov/verification>.

**Figure 2.7** Track Errors at 48 Hours Lead Time (Nautical Miles), as a Function of Year

Source: From <http://www.nhc.noaa.gov/verification>.

Note: From model guidance. Each symbol represents a different model, as indicated in the legend.



indistinguishable now from what it was 15 or 20 years ago, particularly at lead times of 72 hours or less.

Much of the improvement in track forecasts is clearly attributable to the improvement in numerical model guidance. Figure 2.7 shows the trends in track forecast errors at 48 hours lead time since 1970 from various individual numerical models. The downward trend in the forecast errors since 1990 shown in Figure 2.6, with a decrease from about 200 nautical miles in 1990 to about 100 nautical miles in 2005, closely matches the downward trend in the models shown in Figure 2.7. Forecasters at modern centers are quite frank about the tremendous improvement in the models and the

fact that their own ability to improve accuracy is decreasing to the point that they soon may not be able to add any value to the model tracks (for example, James Franklin, NHC, and Andrew Burton, Australian Bureau of Meteorology, personal communications).

Intensity is a different issue. The lack of improvement in intensity forecasts is widely recognized as a major scientific challenge. The contrast between track and intensity forecasts is clearly traceable to the contrast between the accuracy of the model guidance of track and that of intensity. Numerical model forecasts of intensity have not improved at the rate that track forecasts have. In contrast, statistical and

statistical-dynamical models of intensity remain comparable in accuracy to the best dynamical models.

The reasons for this are not entirely clear. The quality of the models is one issue; resolution (and thus computing power), model physics, and numerical implementation are likely all important to some degree. Initialization is also important. Even a very good model will not give an accurate forecast if the initial conditions are not correct, and this depends on accurate observations of the storm. Whereas track depends mostly on the large-scale wind field, intensity appears to depend to a significant extent on the internal structure of smaller-scale features in the storm's inner core. Defining that structure requires high-quality observations near the storm center, such as can be obtained by aircraft.

At a more fundamental level, however, it is not entirely clear how predictable tropical cyclone intensity is, even in principle. To the extent that it depends on the detailed internal structure of the storm, it can be expected that the structure may evolve chaotically, in the sense of sensitive dependence on initial conditions and on time scales shorter than those on which the large-scale flow does. The large-scale flow is understood to be potentially predictable out to time scales of a week or two (Lorenz 1963). It is possible that at least in some situations, a change in tropical cyclone intensity cannot be predicted—even in principle and even with a perfect model—for more than, say, one day. That may be an overly pessimistic speculation, but the question of potential predictability of tropical cyclone intensity has not been addressed well enough yet to allow confident statements about how well intensity might ever be predicted.

In 2010 NOAA started the Hurricane Forecast Improvement Program. This is a major research effort with a budget of \$25

million a year and the following goals, with the 5-year mark set at 2014 and the 10-year mark at 2019 (Gall et al. 2013):

-  Reduce numerical forecast errors in track and intensity by 20 percent in 5 years and by 50 percent in 10 years for forecast days 1–5
-  Extend forecast skill to 7 days, with skill equivalent to that of the 5-day forecasts when they were introduced in 2003
-  Increase probability of detecting rapid intensification to 90 percent at day 1 and 60 percent at day 5, and decrease the false alarm ratio for rapid intensification to 10 percent at day 1 and 30 percent at day 5.

Although intensity prediction is not the only target of HFIP, it is clearly the central difficulty—and the one that has largely motivated the program. This program is sponsoring much work in numerical modeling, observations, and data assimilation. As one example, Doppler radar observations taken from aircraft are now being assimilated operationally into a high-resolution, limited-area, dynamical model, namely the Hurricane Weather Research and Forecast model; these computations show the promise of substantive improvement in intensity and structure forecasts (for example, Zhang et al. 2011; Aksoy et al. 2012).

In a recent publication, Gall et al. (2013) state that the HFIP is on target to meet its goals by the stated timelines. Landsea and Franklin (2013), in contrast, argue that the improvements in intensity targeted by HFIP may be difficult to reach simply because of limitations in the accuracy (now and in the near future) of observational estimates of storm intensity.

## STORM SURGE FORECASTING

Although intensity prediction is not the only target of HFIP, it is clearly the central difficulty—and the one that has largely motivated the program. **This program is sponsoring much work in numerical modeling, observations, and data assimilation.**

## WHAT IS A STORM SURGE FORECAST?

*Storm surge* is the temporary elevation of sea level due to meteorological disturbance. A tropical cyclone can induce storm surge via wind stress on the sea surface, reduction in atmospheric surface pressure, and transfer of momentum from breaking waves into the mean current. Storm surge is defined as the difference between the mean water level over some period of time (at least long enough to average out waves) and what it would otherwise be due only to the astronomical tide. The total mean water level due to tide and surge combined is the *storm tide*.

Storm surge is normally defined by the vertical rise in water level at the coast—or more properly, at the location where the coast normally is, since the boundary between water and dry

land moves inland during a surge event. The extent of flooding on normally dry land, both vertically and horizontally—that is, where flooding occurs and how high the water is above ground at those locations—is known as *inundation*.

A storm surge forecast is a prediction of the storm surge. In practice, a storm surge forecast may be a prediction of the surge only along the coast or may include a prediction of inundation. Like a tropical cyclone forecast, a storm surge forecast may be deterministic or probabilistic.

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## WHAT TYPES OF OBSERVATIONS ARE USED?

A storm surge forecast is driven primarily by a meteorological forecast of wind and pressure fields as functions of time, by observational data defining the solid surface over which water flows, and by data defining the elevation and flow of water at the lateral (side) boundaries of the numerical model used to produce the forecast. The meteorological forecast comes either from dynamical or statistical models or from human forecasters' synthesis of those models, as described earlier.

The height of the solid surface over which water flows is called *bathymetry* when the surface is below the water in normal conditions and *topography* when the surface is normally on dry land. Bathymetric and topographic data are essential inputs to storm surge forecasts. Bathymetry has a strong role in controlling the height of the storm surge for given meteorological conditions. Grossly, a shallower bottom over a larger shelf leads to a higher surge (see, for example, Dube et al. 2009). Topography has an equally strong role in determining which regions will be inundated for a given surge along the coast. Not only is the natural topography relevant, but built structures—including flood control structures such as levees, dikes, and polders—are as well.

Bathymetric and topographic data are needed at high spatial resolutions—much higher than those at which meteorological fields are ever required (or available). Accurate high-resolution topographic data in gridded form are often referred to as a *digital elevation model* (the word model here does not imply a

mathematical representation of a physical process occurring dynamically in time, as in the case of a meteorological model or storm surge model, but simply a static data set in a digital format). High-quality topographic data may be obtained, for example, from aircraft surveys using lidar (laser imaging detection and ranging).

Unlike other observations that enter a tropical cyclone forecast or storm surge forecast, bathymetric and topographic data can be considered static over a relatively long period of time because the solid surface does not change rapidly, as the atmosphere and ocean do. These data can be gathered once and then reused in all forecasts, although they may need to be updated periodically as the landscape evolves over time; the topographic data for New Orleans, for example, are updated once a year (J. Rhome, personal communication).

A specification of the water elevation and currents of the ocean, including those due to the tides, is needed at the lateral boundaries of a storm surge model. This can be taken from a larger-scale ocean model in which a storm surge model is embedded. Such a larger-scale model may assimilate ocean observations in addition to being driven by meteorological forcings. Some more-advanced models, which treat the potentially inundated land surface explicitly as well as the sea, may also consider river inflows and precipitation in the domain, so observations of these quantities may be incorporated.

## WHAT TYPES OF MODELS ARE USED?

A storm surge model is a model of the flow of the ocean, given atmospheric and oceanic inputs as described above. Like the dynamical atmospheric models used for weather prediction, storm surge models are dynamical models that represent the evolution of the fluid by solving the mathematical equations of motion in an approximate form on a grid. Being specifically designed to predict storm surge, these models make specific assumptions and approximations that are appropriate for that purpose and different from those used in other sorts of ocean models.

Many storm surge models use so-called shallow water equations, which approximate the ocean as a fluid with a constant density that moves with the same horizontal velocity at all depths. The state of the fluid is represented by velocity of the water and height of the water surface, both of which are two-dimensional fields because of the assumption of uniformity of the velocity with depth. Some models use the full three-dimensional equations of motion rather than the shallow water equations and thus represent the variations of current with depth. This increases computational cost substantially and is believed to yield only minor improvements in accuracy. A range of grids and numerical methods are used for solving the dynamical equations. Higher resolution is often used closer to the coast, to focus computational power where it is most needed to resolve the surge.

One important feature of a model for these purposes is the nature of the boundary condition at the coast. Some models treat the coast as though it were a wall, impermeable to the surge. Such models are incapable of simulating inundation explicitly. Other models allow for the wetting of dry surfaces and the inland migration of the water line and thus explicitly simulate inundation.

Another set of distinctions of model types is between those that explicitly account for waves and those that do not, as well as those that explicitly account for tides and those that do not. Waves can transfer momentum to the mean flow of water and thus influence the surge level. This can be a quantitatively significant effect in some cases (and is distinct

from any direct effect of waves on structures on land). A similar distinction holds with tides. If a model does not explicitly include the tides, the total storm tide can be estimated by simply adding the known astronomical tide to the simulated storm surge. This may be accurate in many cases, but there is also the possibility of nonlinear interactions between the tide and the surge that can change the surge itself. Models that include the tide explicitly can account for such interactions on a physical basis. It is also possible to use such models to develop parameterizations of the nonlinear surge-tide interaction so that it can be taken approximately into account in simulations that do not explicitly include the tide (see, for example, Lin et al. 2012).

Another model choice that may have some quantitative impact is the bulk drag coefficient used in the computation of momentum transfer from the air to the sea. For a given wind speed, this coefficient determines the force exerted on the ocean. The drag coefficient is a consequence of a range of physical processes, including interaction of the wind with waves and sea spray, and varies as a function the wind speed itself. There is considerable uncertainty in the value of the drag coefficient, especially at high wind speeds. This uncertainty translates into uncertainty in the surge.

Surface winds are specified in two different ways in storm surge models for operational forecasting. First, winds can be taken directly from a meteorological forecast model. In this case the winds are specified as functions of horizontal position and time, at the grid spacing of the meteorological model. This has the advantage of not imposing a priori assumptions about the structure of the storm, and it allows for an arbitrarily complex wind field. On the other hand, the surge model must commit to that particular numerical model rather than to the tropical cyclone forecast, which is produced (typically by a human forecaster) after considering multiple models and other information.

Alternatively, winds can be derived from the much more limited set of tropical cyclone forecast parameters—including track, intensity, size, and speed of forward

**Many storm surge models use so-called shallow water equations, which approximate the ocean as a fluid with a constant density that moves with the same horizontal velocity at all depths**

motion—and then have internal parametric models determine the distributions of wind from those using predetermined functional relationships. This has the disadvantage, in principle, of having the parametric models impose *a priori* assumptions about the structure of the wind field. An advantage of this method, however, is that the parameters it requires are those that are produced in a typical tropical cyclone forecast, so that the storm surge model can take the forecast itself directly as input. Another advantage of the parametric approach is that the number of data that must be specified is much smaller than if a meteorological forecast model is used. Thus it is simpler to perform a wide range of storm surge simulations (either in real time, for forecast purposes, or in research mode) to allow for variations in track, intensity, and so forth, as it is simpler to specify variations in those few parameters than it is to specify variations in the entire wind field.

Use in operational forecasting requires that computations be completed quickly. The computations are likely to be

carried out at a tropical cyclone forecast center, and the computational resources available for predicting storm surge may be substantially less than those used for running global dynamical models at the major numerical weather prediction centers.

As a result, some of the more sophisticated models used for storm surge research may not be practical for use in forecasting because of their higher computational cost. The SLOSH (sea, lake, and overland surges from hurricanes) model, for example (Jelesnianski, Chen, and Shafer 1992), used by the U.S. National Hurricane Center (Glahn et al. 2009), is among the simplest available: it does not include waves or tides, and it has a no-normal-flow lateral boundary condition at the coast so that it cannot explicitly simulate inundation. However, it is computationally light. This allows simulations to be completed quickly, so that, for example, an ensemble of simulations can be done during a six-hour forecast cycle to generate a probabilistic forecast, as described in the next section.

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## THE FORECAST PROCESS

The process of forecasting a tropical cyclone-induced storm surge is closely coupled to the process of forecasting the tropical cyclone itself. The surge forecast requires as input a forecast of tropical cyclone winds, either directly from a meteorological model or from a forecast of track, intensity, and size parameters. These data are then input to a storm surge model, which generates a prediction of surge. If tides are not included in the model, the total peak storm tide forecast depends on the time of peak surge relative to the high tide, so the timing of the peak surge must either be predicted accurately or give a range of possibilities.

A forecast of storm surge or storm tide may be, strictly, just a forecast of water rise at the coast (and perhaps also at locations seaward of the coast). There is potential for confusion on the part of users about the reference level above which water rise is being forecast. Choices include a forecast of just the surge (water level above the astronomical tide at any given time) or of total storm tide. If storm tide, the latter may be expressed as an increase above a fixed specific level (datum), the mean level of low water (essentially the average

low tide), or the level above the mean tide (approximately the midpoint between high and low tide). The National Hurricane Center forecasts water heights as a range of values above ground, presumably referring to ground at the coast.

An inundation forecast is a specific prediction of water height above ground at specific locations—for example, expressed as a map. If the forecast is produced by a model that explicitly predicts inundation (wetting of dry surfaces), then an inundation forecast can, in principle, be produced directly from model output. Otherwise, an inundation forecast can be produced separately. The NHC has recently developed an inundation forecast, made public on an experimental basis in 2014. It is based on an ensemble of SLOSH model forecasts of water rise along the coast, combined with a high-resolution topographic data set or “digital elevation model” (DEM), to generate a map of water elevations above ground, based on assumptions broadly similar to but somewhat more sophisticated than assuming constant water surface height above a fixed datum (J. Rhome, personal communication).

## TREATMENT OF UNCERTAINTY

Because the storm surge forecast depends strongly on the wind forecast, it inherits errors associated with the latter. Additional errors result from the uncertainties inherent in the storm surge model and possibly from the other input data, such as bathymetry, topography, or oceanic lateral boundary conditions. The storm surge forecast can thus generally be expected to be more uncertain than the tropical cyclone forecast itself. The treatment of this uncertainty and its communication to users are critically important. One response to the additional uncertainty in storm surge forecasts may be a reduction in the maximum lead time at which forecasts are produced. The NHC, for example, produces storm surge forecasts out to 72 hours, although tropical cyclone forecasts are produced to 120 hours.

As with forecasts of tropical cyclones (or any other phenomenon, for that matter), uncertainty in storm surge forecasts may be addressed by producing forecast products that are explicitly probabilistic. This is most straightforwardly done through ensemble methods. An ensemble of surge forecasts can be generated from an ensemble of wind

forecasts applied to a storm surge model. The ensemble of wind forecasts can be obtained directly from an ensemble of meteorological model forecasts, if the surge model takes forecast winds directly as input. If (as appears to be more typical) the surge model takes forecast track, intensity, and wind radii as inputs, then an ensemble of these parameters is needed. This can be generated by perturbing a deterministic forecast in some way, for example (as done at the NHC) using a set of perturbations based on the range of historical forecast errors. An ensemble of tracks could also be obtained from a numerical model ensemble after application of a tracking routine. Once an ensemble of surge forecasts has been generated, it can be expressed, for instance, as a set of probabilities that a given value of surge will be exceeded, as in NHCs Probabilistic Hurricane Storm Surge (p-surge) product.<sup>9</sup> Verbal advisories may state a range of possible values.

<sup>9</sup> See <http://www.nws.noaa.gov/mdl/psurge2.0/about.php?S=Karen2013&Adv=10&Ty=e10&Z=m1&D=agl&Ti=incr&Msg=1&Help=about>

An aerial view of damage to villages and infrastructure following Cyclone Sidr. Credit: U.S. Marine Corps photo by Sgt. Ezekiel R. Kitandwe (RELEASED)



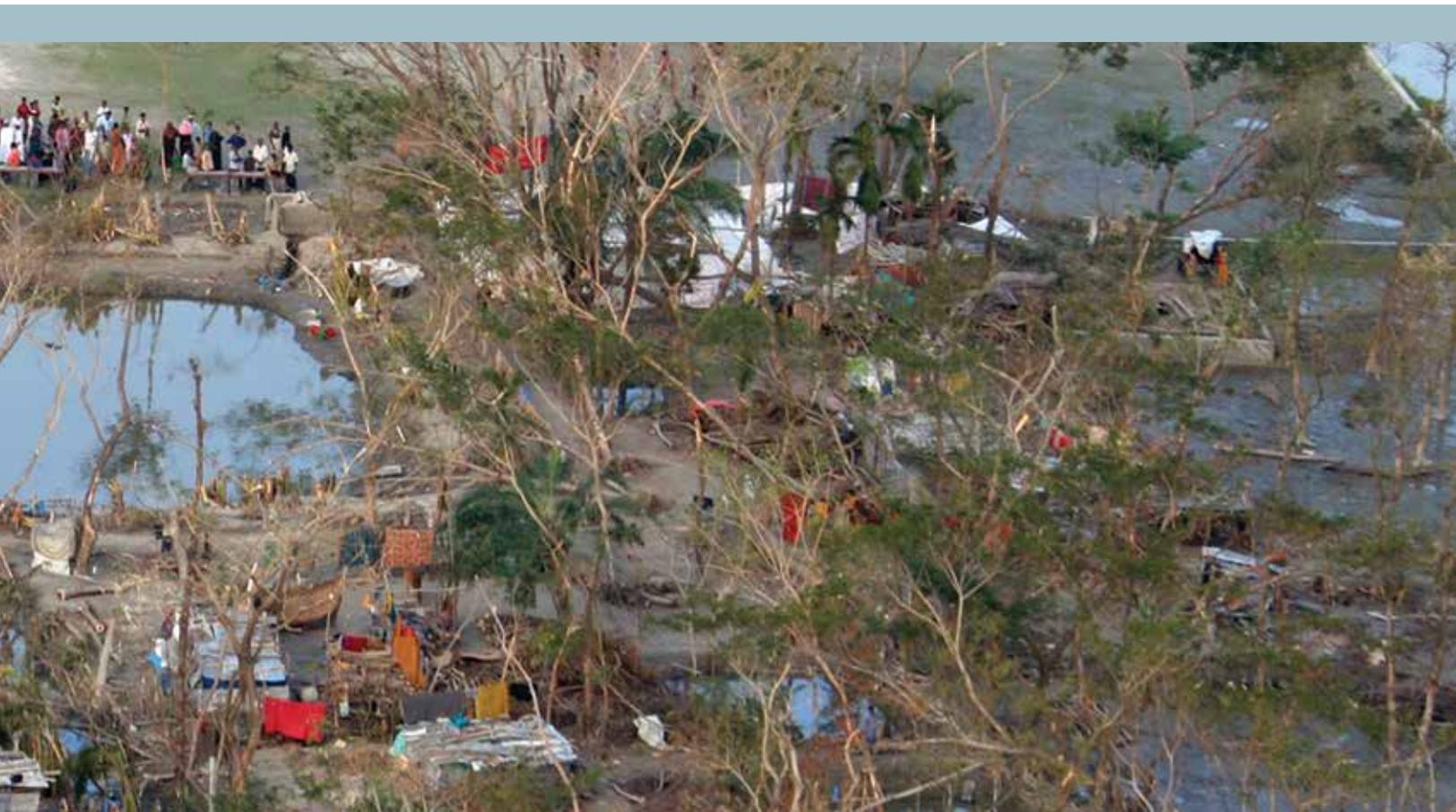
## THE CIFDP APPROACH

The Joint WMO-Intergovernmental Oceanic Commission's Technical Commission for Oceanography and Marine Meteorology and the WMO Commission for Hydrology have together initiated the Coastal Inundation Forecasting Demonstration Project (CIFDP), "in order to meet the challenges of coastal communities' safety and socioeconomic sustainability through the development of coastal inundation forecasting and warning systems at the regional scale" (JCOMM 2013). The project recommends a specific set of practices for developing storm surge and inundation forecast systems and offers technical assistance to countries in implementing those systems. This section describes briefly some aspects of the approach recommended by CIFDP (D. Resio, personal communication).

CIFDP does not recommend running a dynamical storm surge model in real time. Rather, it recommends performing a large number of simulations with such a model just once, in advance of any forecast operations, to produce a library of simulation results that spans the range of conditions believed to be possible at the location of interest. A set of 350 simulations, with a wide range of tropical cyclone track, intensity, and size parameters, was judged to be adequate for a demonstration

system set up for the Hawaiian island of Oahu (Taflanidis et al. 2012). In real time, the cyclone forecast parameters could be used to sample or interpolate from this library of results to obtain a storm surge prediction that corresponds to those parameters. This is then repeated with a range of variations in the cyclone forecast parameters to generate a probabilistic forecast. Because the library was pre-computed, the storm surge model itself does not have to be run in real time.

The advantage of this approach is that by decoupling the intensive computation from the forecast process, it removes the requirement that the model be computationally inexpensive enough to run in real time. A more sophisticated and realistic model can be used for the surge simulations than would be feasible in real time. Further, the intensive computation to produce the library does not have to be done in the same place or by the same group of people as those operating the forecast system in real time. Although there is some error associated with the use of a surrogate model to interrogate the precomputed database for a given scenario, relative to direct computation with the dynamical surge model for that same scenario, that error is modest and is included in the computed uncertainty in the forecast (Taflanidis et al. 2012).



## BIG PICTURE

This section considers the relative merits of different automated ensemble forecast systems based directly on global model ensembles versus traditional forecast systems that use a wider range of guidance and a greater role for the human forecaster.

The practice of tropical cyclone forecasting, in something like its modern form, dates back to the 1950s, as practiced in the United States. During that period, aircraft reconnaissance began to be routinely done, and the first numerical weather prediction models came into operation. At least until the 1980s, however, dynamical models were not particularly skillful at tropical cyclone prediction. Global dynamical models—in particular, the ones used for general weather forecasting—did not have great skill at forecasting tropical cyclone track and had even less skill at forecasting intensity or genesis.

As a result, tropical cyclone forecasting relied heavily on a range of specialized models and tools. These were both dynamical and statistical in nature. None was especially accurate by today's standards, and a high degree of forecaster expertise was needed to interpret all this guidance and turn it into a skillful forecast of the track of a tropical cyclone. Intensity forecasting was even more primitive than track forecasting; dynamical models were nearly useless, and intensity forecasts were based largely on statistical model guidance and the forecaster's judgment. Genesis forecasting was not seriously attempted; the forecast operation did not truly begin until a tropical cyclone was clearly in existence.

After a roughly five-year period in the late 1980s during which dynamical models did not improve (DeMaria and Gross 2003), a period of steady improvement began around 1990 and has continued up to the present. The role of numerical models in the field at that time is indicated by the WMO Global Guide to Tropical Cyclones (WMO 1992), which stated that numerical model output was becoming an increasingly reliable source of guidance for operational forecasters. This document reported that 50 percent of the countries surveyed

at the International Workshop on Tropical Cyclones held in Manila in 1982 indicated that they had access to guidance from global models.

Today it is safe to assume that every country desiring it has some access to guidance from global models. A great deal of such guidance is available freely on the Internet,<sup>10</sup> and more is available through agreements between national centers. The quality of this guidance has improved dramatically, particularly for track and genesis. The global dynamical models from which this high-quality guidance for tropical cyclone track and genesis comes are the same ones used to forecast other types of weather; they are not specialized tools developed just for tropical cyclones.

Automated storm tracking from model output and ensemble forecast systems allow sophisticated tropical cyclone forecasts to be generated without any intervention from a human forecaster other than for quality control and interpretation. Given access to currently available global ensemble forecast systems, it takes relatively few resources to produce a forecast today whose accuracy—for track, at least, if perhaps not yet intensity—is comparable to that attained by the best national centers a relatively short time ago—perhaps a decade, perhaps even less. This is still a new development, however. Virtually all currently operating national centers came into existence and developed their structures at a time when numerical model guidance was much poorer than it is today and when the human forecaster's judgment played a much greater role.

These national centers strive to do better than the baseline offered by global dynamical model ensembles. The best-supported and most sophisticated centers, such as the WMO RSMCs, have access to resources well beyond the global models and other publicly available data (for example,

<sup>10</sup> See, for example, <http://www.ral.ucar.edu/guidance/realtime/current/>, <http://mag.ncep.noaa.gov/>, and <https://www.fnmoc.navy.mil/wxmap.cgi/>.

**Many storm surge models use so-called shallow water equations, which approximate the ocean as a fluid with a constant density that moves with the same horizontal velocity at all depths**

satellite data). These resources may include high-resolution regional models, highly trained expert forecasters, and possibly aircraft reconnaissance. With all these assets, forecasters at such centers are able, on average, to improve on the skill of the global multimodel ensemble.

Figure 2.8 shows track errors at 48-hour lead time from individual models, similar to Figure 2.7; however, it shows only “early” models (available to the forecaster at the start of the forecast cycle), starts in 1990, and also shows the official NHC forecasts. The NHC forecasts have similar errors to the “consensus” forecasts, constructed by averaging multiple models (the lowest points on the plots, with plus symbols), indicating that NHC forecasters (in the Atlantic, at 48 hours lead time) have less skill at track prediction than the average of the models. Yet the trend toward model improvement suggests that this may not be true for much longer, if for no other reason than at some point the models will approach the theoretical limits of predictability, beyond which chaos theory tells us that further improvement is impossible.

Global models are still poor at predicting tropical cyclone intensity, so there may be much greater room for national centers to beat the global models there; yet improvement in intensity forecasts has been slow in practice. Genesis forecasting is now becoming a reality, at lead times of five days and longer, yet this again is largely due to the global models.

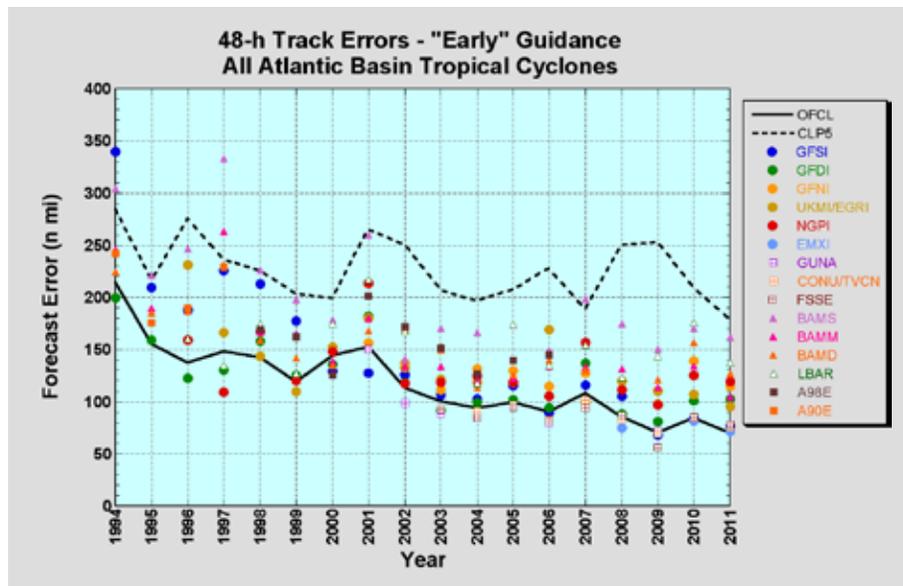
Imagine for a moment that someone has to start a new tropical cyclone forecast center in a place where none exists. If the quality of the forecast is defined solely by technical metrics—that is, by the accuracy of the track and intensity forecasts alone, leaving aside the effectiveness with which that information is communicated to users—it is now possible to produce a good tropical cyclone forecast (by quite recent historical standards) very cheaply, simply by using automated algorithms applied to global ensemble products already produced elsewhere. Some expertise and effort are needed to produce actual forecasts from those products, but the necessary investment is much smaller than those required to produce the ensemble products (or any other state-of-the-art numerical weather prediction products) in the first place. An additional advantage of this approach is that the ensemble prediction systems allow, in principle, a long-range forecast that seamlessly crosses the genesis event, facilitating longer-range forecasts without new or special methods (though the development and evaluation of specific forecast products still requires skill and effort).

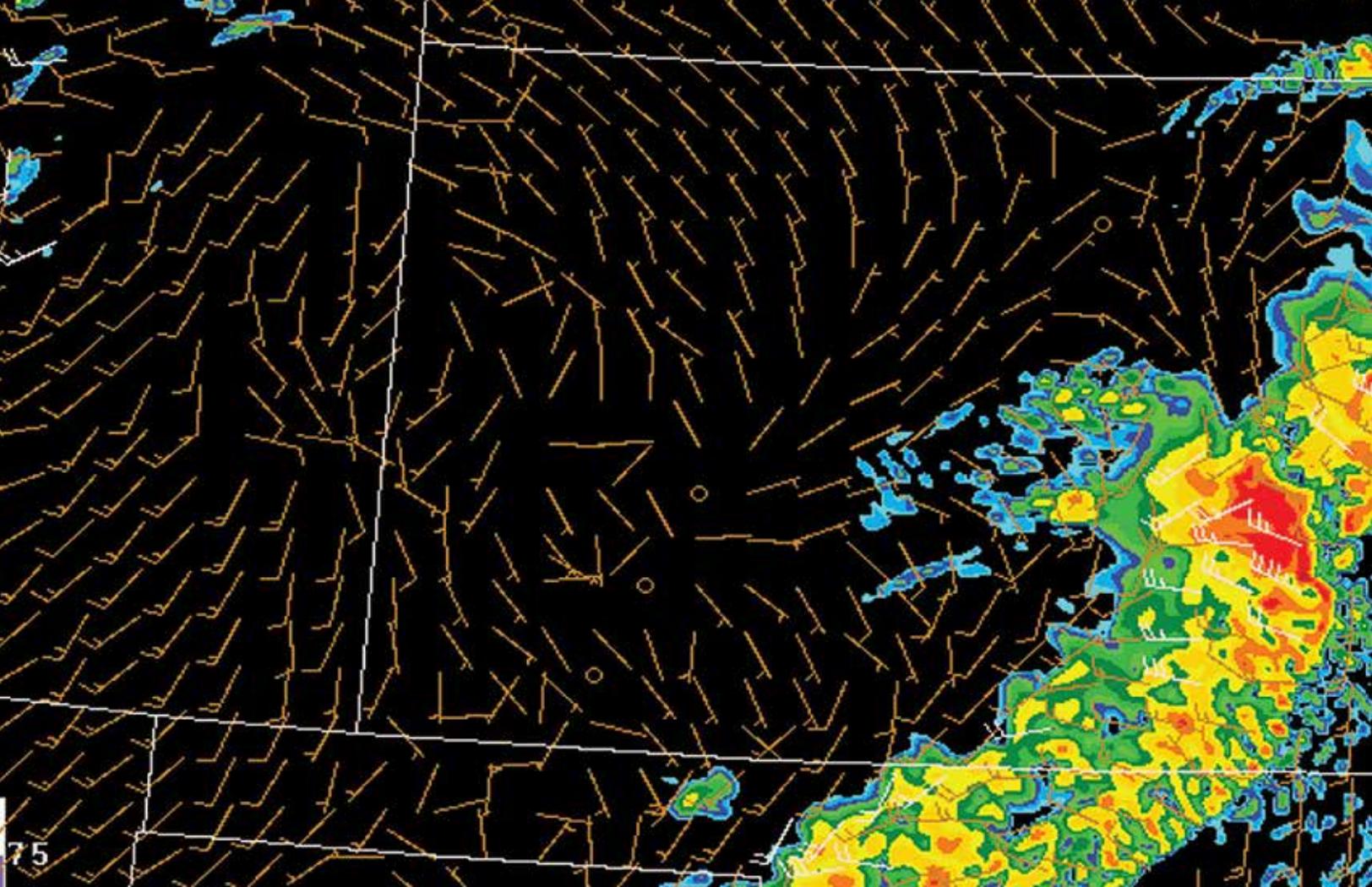
Alternatively, someone can make a large investment of human, financial, computer, and other resources to replicate the capabilities of the best numerical weather prediction centers: perform data assimilation, run the models, and produce ensemble and other numerical weather prediction products. By doing this sufficiently well, as well as training forecasters to use the numerical guidance to produce forecasts—

**Figure 2.8** Track Errors at 48 Hours Lead Time (Nautical Miles), as a Function of Year

Source: From <http://www.nhc.noaa.gov/verification>.

Note: From model guidance. Each symbol represents a different model, as indicated in the legend. Only “early” models, available to the forecaster at the start of the forecast cycle, are included. The NHC official forecasts are shown by the solid curve, while the CLIPER (climatology and persistence) statistical forecast is shown by the dashed curve.



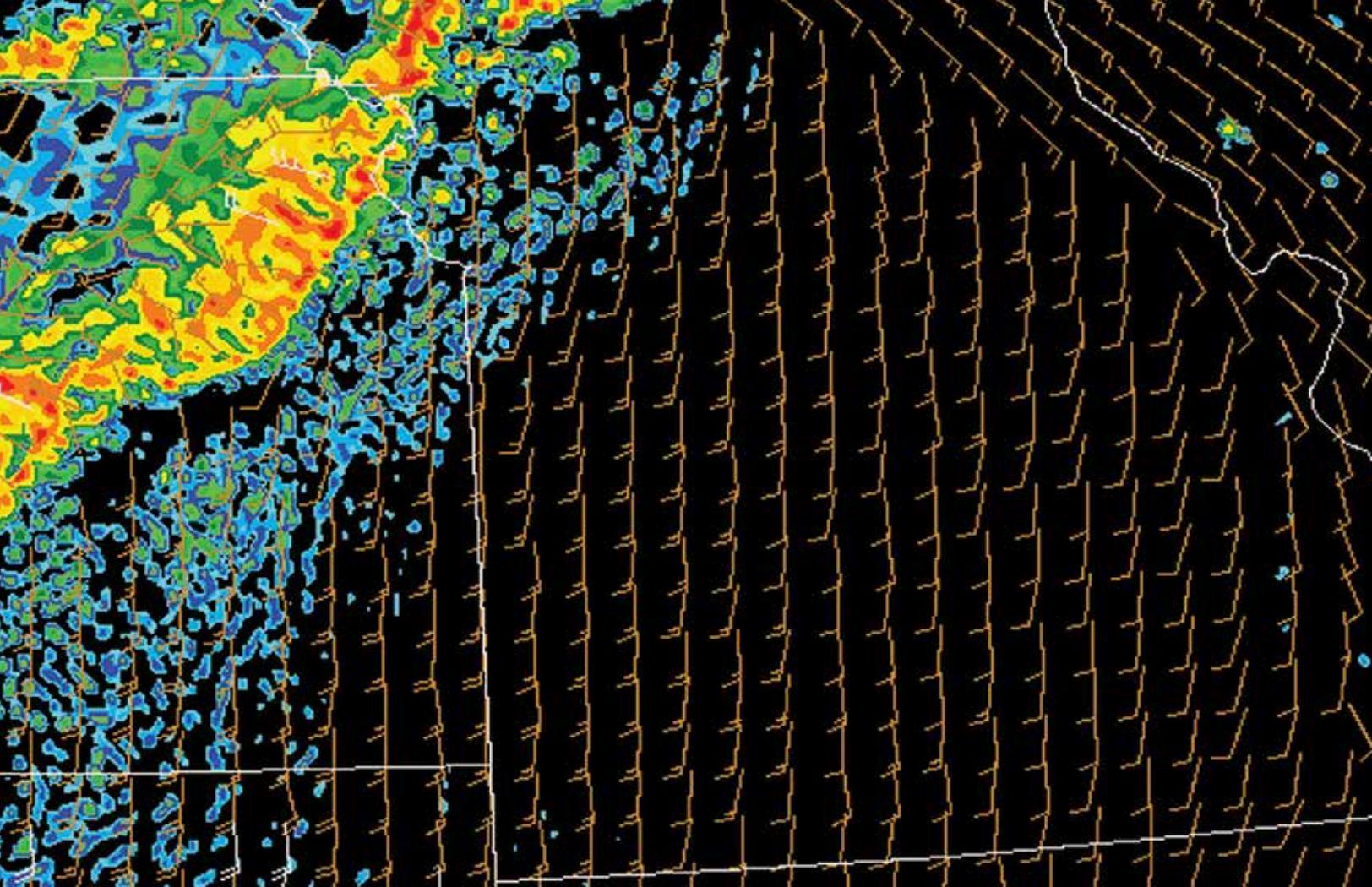


essentially by replicating all the combined capabilities of both advanced forecast centers such as NHC and numerical weather prediction centers such as NCEP or ECMWF—a forecast could be produced that may be better than what could be achieved using only automated algorithms based on existing global model ensembles. But if it is better, that is not likely to be by a large margin. If resources are limited, this all-out approach does not make sense. It would make more sense just to train a group of forecasters to use existing global ensemble products.

This is not to devalue the increase in accuracy that does come from a substantial investment in improved forecasts. Any improvement in track or intensity prediction has the real

potential to save lives and may be well worth the resources invested in it. It is also possible that the latest research on intensity prediction will lead to new improvements on that front, widening (at least for a time) the margin between what the best available methods can do at a regional scale (for example, high-resolution regional models assimilating aircraft-based radar observations, all interpreted by expert forecasters) and what the global models can achieve. But it is important to recognize that the tremendous improvement in accuracy over the last couple of decades makes it much easier to produce a tropical cyclone forecast with reasonable accuracy and also makes it much more difficult (though still possible) to produce a forecast with better accuracy than the global models.

**The increasing availability of sophisticated meteorological information from many sources, on the Internet and otherwise, leads to greater attention and expectations on the part of users, but this interest may not be accompanied by adequate knowledge and sophistication to allow them to understand the information.**



In practice, however, a forecast is not defined only by the quantitative predictions of track and intensity. A modern forecast incorporates many other elements, including a wide range of graphic products, watches and warnings, and verbal advisories. These are critically important to the users' ability to understand both the nature of the hazard (since the position of the center and maximum sustained wind speed are very limited metrics) and the uncertainties in the forecast. Communication of uncertainty is particularly important when the uncertainty is largest, as it normally is for track at long lead times and for intensity at all but the shortest lead times.

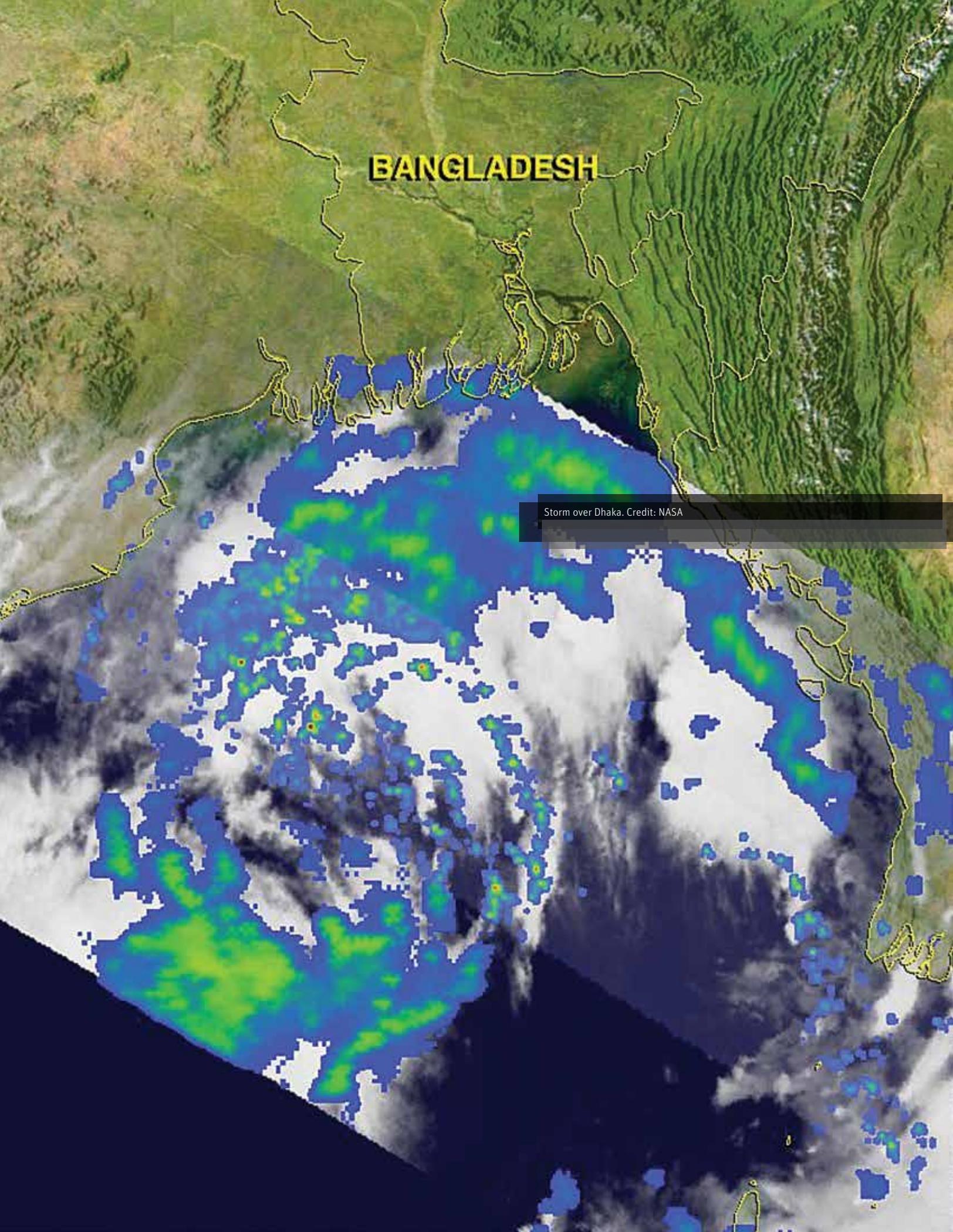
The increasing availability of sophisticated meteorological information from many sources, on the Internet and otherwise, leads to greater attention and expectations on the part of users, but this interest may not be accompanied by adequate knowledge and sophistication to allow them to understand the information. A forecast at five days may have useful accuracy, but large uncertainty. For example, a forecast that landfall will occur in some region five days from now may come with a large uncertainty in the exact location of landfall (or perhaps even whether landfall will occur) and even greater uncertainty in the intensity of the storm at landfall, storm surge, precipitation, and other variables

that determine impacts. It would be premature for decision makers to take major action, such as ordering evacuation, based on such an uncertain forecast. Such a forecast might, however, justify taking some preliminary preparatory actions, such as moving supplies or key personnel closer to where they might be needed.

Given this, the tropical cyclone forecast center has a critical role as an educator as well as a communicator. The necessary education may target both relevant professionals, such as emergency managers and government officials, and the public, and it may occur over the long term as well as within a single forecast. Though outside the scope of this report, these education and communication aspects are at least as critical to disaster preparedness as is the science of forecasting. A prerequisite for the effective education of forecast users is that the forecasters themselves must have a good understanding of the underlying science, much of which—such as that behind ensemble forecast systems—is still relatively new and rapidly evolving.

# BANGLADESH

Storm over Dhaka. Credit: NASA



# Tropical Cyclone and Storm Surge Forecasting in Bangladesh

This chapter assesses tropical cyclone and storm surge prediction as they are practiced in Bangladesh. The focus is on the operational practice of the Bangladesh Meteorological Department. Given that India's Meteorological Department is the Regional Specialized Meteorological Center, its practices and links with the BMD are also discussed. The overall aim is to see how lead time for tropical cyclone forecasting in Bangladesh can be increased, in light of the operational practices discussed in Chapter 2, and the constraints that need to be addressed.

## CHARACTERISTICS OF TROPICAL CYCLONES IN THE BAY OF BENGAL

Storms in the Bay of Bengal are of shorter duration than storms in other basins, and this has important implications for forecasting. This conclusion is based on “best track” data from the U.S. Joint Typhoon Warning Center for the BoB and Western North Pacific basins, as well as data from the U.S. National Hurricane Center for the North Atlantic—specifically, statistics for the period 1981–2010, a period with reliable, consistent data. To allow direct comparison with data for other basins, the Saffir-Simpson scale, shown in Table 3.1, is used to categorize storms according to their intensity. Although the BoB countries use the intensity scale of the India Meteorological Department, shown in Table

3.2, the Saffir-Simpson scale allows comparison of BoB data more directly with statistics for other basins. (The IMD’s scale has fewer categories at high intensities but adds an additional category, “deep depression,” at the low end. In both systems, a “depression” is not strictly defined, except that its maximum sustained winds must be below the lowest threshold on the scale—28 knots in the IMD scale, 34 knots in the Saffir-Simpson scale. An additional difference is that the IMD defines maximum sustained winds by 3-minute averages, while other countries use either 1 minute (U.S.) or 10 minutes, which is the WMO standard.)

**Table 3.1** The Saffir-Simpson Hurricane Intensity Scale

Category	Kt	Mph	m/s
Depression			
Tropical storm	34–63	39–74	17–32
1	64–82	75–95	33–42
2	83–95	96–110	43–49
3 (major)	96–112	111–129	50–58
4 (major)	113–136	130–156	59–69
5 (major)	137 or higher	157 or higher	70 or higher

**Table 3.2** The Tropical Cyclone Intensity Scale Used by the India Meteorological Department

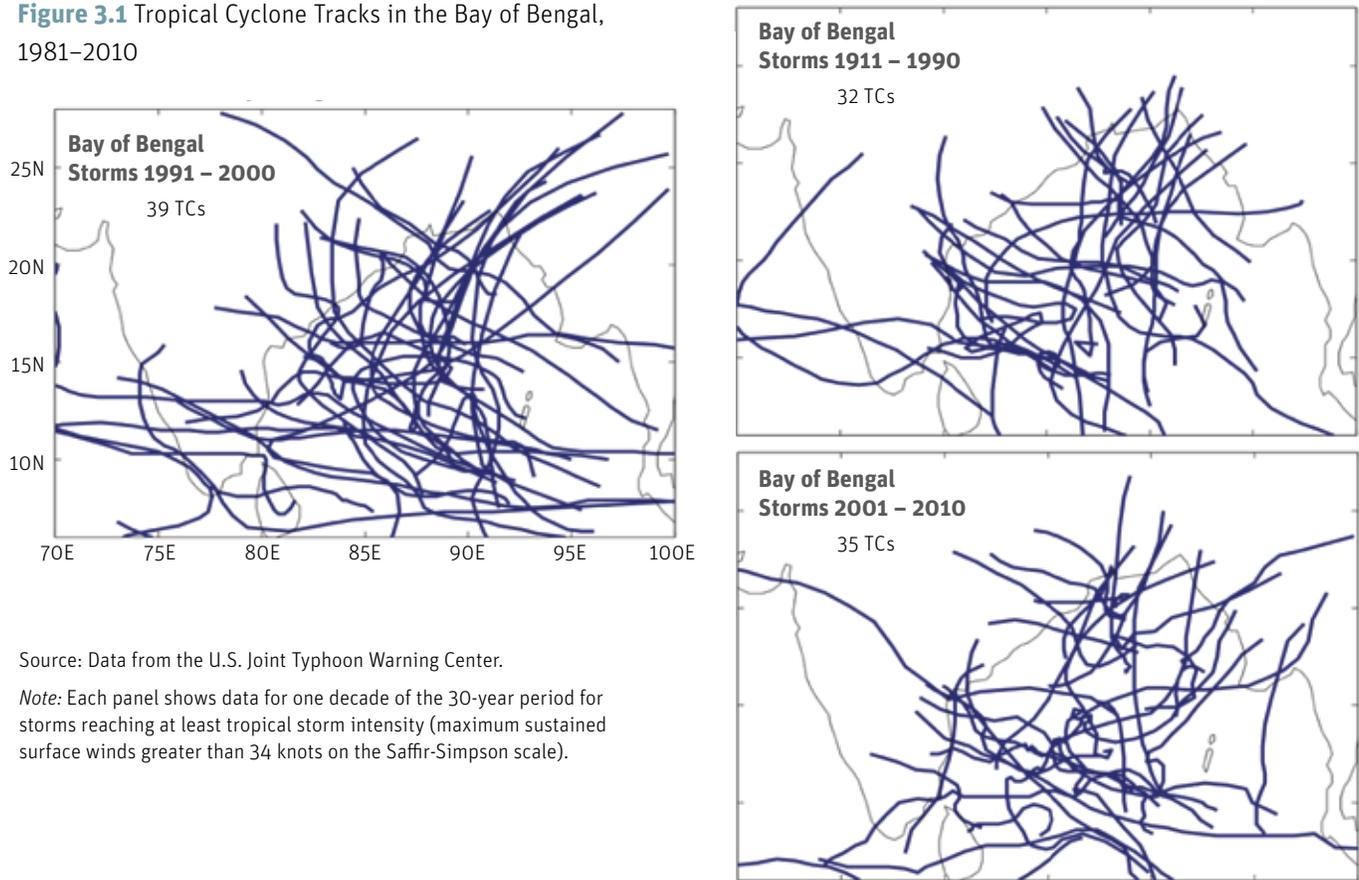
Category	Kt	Mph	m/s
Depression			
Deep depression	28–33	32–38	14–16
Cyclonic storm	34–47	39–54	17–24
Severe cyclonic storm	48–63	55–73	25–32
Very severe cyclonic storm	64–119	74–137	33–61
Super cyclonic storm	120 or higher	138 or higher	62 or higher

Figure 3.1 depicts tracks of tropical cyclones (those reaching at least tropical storm intensity, maximum wind speed of 34 knots or greater) in the Bay of Bengal for the decades 1981–90, 1991–2000, and 2001–10. This 30-year period corresponds roughly with the period of satellite observations and constitutes the highest-quality historical data on tropical cyclones. The analysis shows that storms tend to move from east to west or south to north, although many recurve toward the east as they reach higher latitudes near Bangladesh.

On average, the Bay of Bengal experiences 3.5 storms a year, but there is considerable variability between years: in the

period 1980–2010, one year had no storms, several had one, and several had six or seven, as shown in Figure 3.2 (panel a). The North Indian Ocean is unique among tropical cyclone basins in having two distinct active seasons, one in spring (peaking in May) and another in autumn, as shown in Figure 3.2 (panel b): during July–September, the formation of tropical cyclones is suppressed by strong vertical wind shear associated with the monsoon. Of the two seasons, the later one, occurring primarily in October–December, is the more active.

**Figure 3.1** Tropical Cyclone Tracks in the Bay of Bengal, 1981–2010

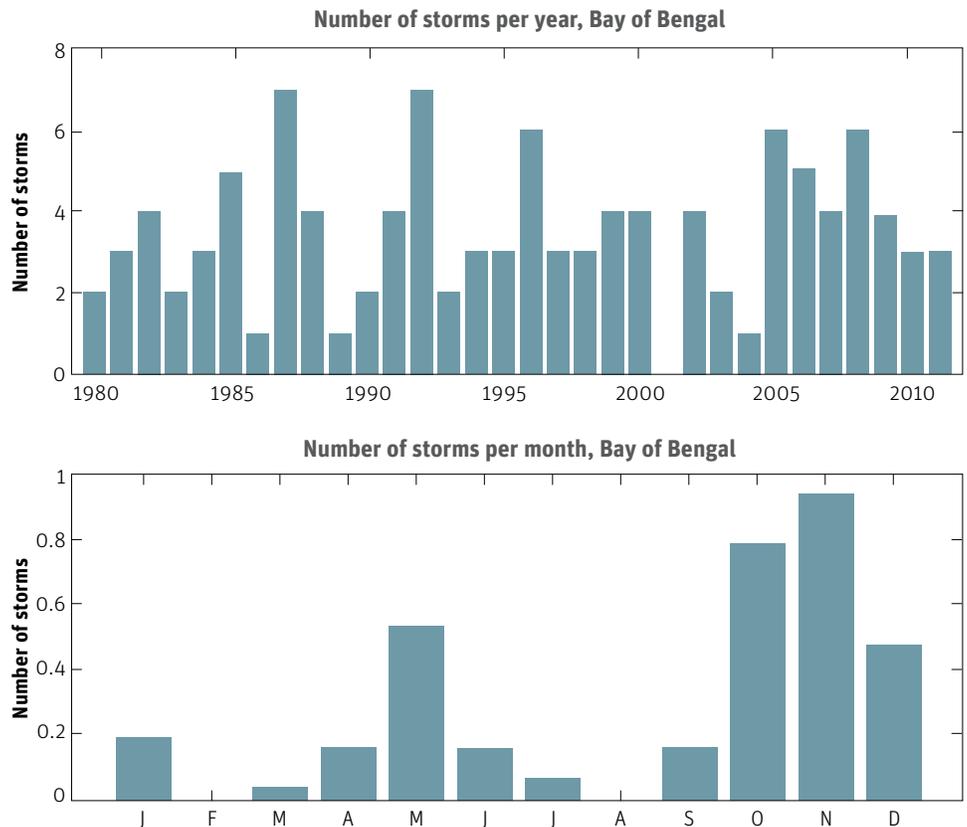


Source: Data from the U.S. Joint Typhoon Warning Center.

Note: Each panel shows data for one decade of the 30-year period for storms reaching at least tropical storm intensity (maximum sustained surface winds greater than 34 knots on the Saffir-Simpson scale).

**Figure 3.2** Total number of tropical cyclones each year (top) and mean number of tropical cyclones per month (bottom) reaching at least tropical storm intensity in the Bay of Bengal, 1981-2010.

Note: The results in the bottom graph are computed by adding the total number of storms occurring in each month during the period 1981–2010 and dividing by the number of years, hence the fractional values.

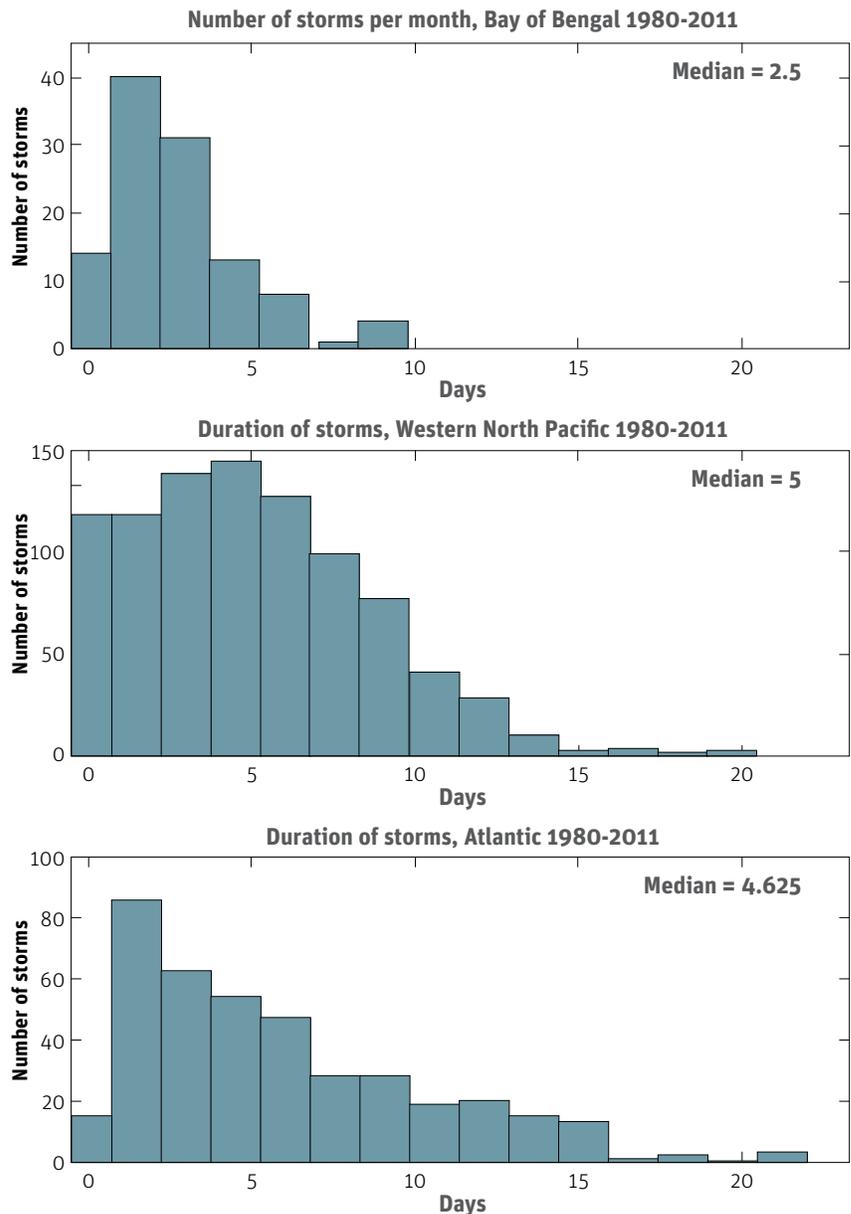


Tropical cyclones have shorter lifetimes in the Bay of Bengal, on average, than in most other basins. Figure 3.3 shows histograms of the time between genesis (defined as first achievement of maximum sustained wind greater than 34 knots) and first landfall for storms in the Bay of Bengal, Western North Pacific, and North Atlantic, during 1980–2011. The Western North Pacific and North Atlantic are chosen for comparison, as they have both relatively large numbers of tropical cyclones (the Western North Pacific is the most active basin on Earth) and good observational records. They have also been served historically by some of the largest and most advanced forecast centers, and so the behavior of storms in these basins has guided the development of tropical cyclone science and forecast practice.

The abscissa in Figure 3.3 shows the duration of this period between genesis and landfall, in days, while the ordinate shows the number of storms with the corresponding duration. The sum of all of the values in each histogram is the total number of storms observed in the basin. The median value is around 5 days in both the Pacific and Atlantic, but only half that, around 2.5 days, in the Bay of Bengal. Very few storms in the BoB last longer than 5 days. This is presumably due to the physical geography of the Bay, as it is simply a much smaller body of water than the Atlantic or Pacific. It is not possible for a Bay of Bengal storm to form nearly as far offshore as in the other basins, so that—given typical speeds of tropical cyclone motion—these storms tend to reach land sooner after formation.

**Figure 3.3** Histograms of the Time, in Days, between Genesis and the First Landfall of Tropical Cyclones in the Bay of Bengal, Western North Pacific, and North Atlantic Basins, 1980–2011

*Note:* Genesis is when the maximum sustained surface winds first exceed 34 knots. The median values are shown in the upper right corner of each plot.



Current practice—in all national forecast centers and in all basins—is to produce forecasts of a tropical cyclone’s track and intensity only after an existing disturbance has reached a specified intensity threshold. Because tropical cyclones in the BoB have shorter lifetimes, the maximum lead time of a

landfall forecast is shorter there than in the other two basins. The IMD extends its lead time by using a 28-knot threshold to begin track and intensity forecasts, rather than the 34-knot threshold used elsewhere.

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## REGIONAL CONTEXT FOR TROPICAL CYCLONE FORECASTING IN BANGLADESH

Bangladesh is a member of the WMO/United Nations Economic and Social Commission for Asia and Pacific (ESCAP) Panel on Tropical Cyclones for the Bay of Bengal and the Arabian Sea (the other panel members are India, Maldives, Myanmar, Oman, Pakistan, Sri Lanka, and Thailand). The WMO/ESCAP panel is one of five regional bodies under the WMO Tropical Cyclone Program, which fosters regional collaboration and capacity building for forecasting of tropical cyclones and storm surge.

An RSMC serves each of the regional bodies; for the WMO/ESCAP panel, the RSMC is located at the IMD in New Delhi. The RSMC issues guidance to the meteorological services of other member nations in the form of outlooks and advisories. The national services of the individual member nations retain responsibility for issuing forecasts for their own nations. Thus the BMD forecasts may differ from the guidance issued by the RSMC, based on the judgment of local forecasters or the use of local observations not available to the RSMC, but the RSMC’s advisories and outlooks are available as guidance to the BMD.

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## THE BANGLADESH METEOROLOGICAL DEPARTMENT

### MANDATE

The BMD is responsible for all meteorological activities in Bangladesh. Central to its mandate is forecasting weather, including tropical cyclones, for the nation. The BMD operates an observational meteorological network throughout the country and the adjacent oceans, including 35 synoptic observatories making surface weather observations; three

upper air radiosonde stations, of which one (in Dhaka) is made available internationally via the GTS; and five radars, three of which are Doppler radars. At its headquarters in Dhaka, the BMD operates the Storm Warning Center, which is specifically responsible for issuing tropical cyclone warnings and also storm surge warnings.

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## DATA AVAILABLE AT THE BMD

In addition to the local observations taken by its own network, the BMD obtains a range of meteorological data from outside the country via a GTS link to the RSMC in New Delhi. The GTS carries a set of standard meteorological data that are shared between meteorological services worldwide. In addition to being used to transmit data from the RSMC to the BMD, it also carries observations made by the BMD in Bangladesh back to the RSMC and to the global GTS/WIS. As with many forecast centers, the BMD does not have a dedicated staff for forecasting tropical cyclones. When a tropical cyclone is present in the Bay of Bengal, forecasts of its track and intensity are prepared at the BMD by the same forecasters who normally forecast other types of weather during the remainder of the year. The BMD does have a set of special practices for tropical cyclone analysis and forecasting. These

are described in a checklist that the forecaster uses to make assessments of a large pre-defined set of quantities in the satellite images, weather maps, and other data.

As elsewhere, satellite observations are critical to tropical cyclone analysis at the BMD. Dvorak analysis is used to estimate tropical cyclone position and intensity from geostationary infrared and visible satellite imagery. Estimates of position and intensity from other centers, including the JTWC in Hawaii, are consulted in addition to estimates produced in-house and from the RSMC. A range of global and regional numerical models are consulted for forecast guidance, including the Weather, Research, and Forecast (WRF) and the Hurricane Weather, Research, and Forecast model run in India at the IMD, the Indian Institute of Technology in

Delhi, and the National Centre for Medium Range Weather Forecasting, as well as the standard set of global models from the United Kingdom, United States, ECMWF, and elsewhere. Two regional numerical models are run in-house at the BMD: the WRF model is run operationally on a modest workstation, and another regional model (the nonhydrostatic mesoscale model, another version of the weather research

and forecasting model) is run on an experimental basis on a larger computer cluster supplied recently by the Japan International Cooperation Agency (JICA). Neither of these models is dedicated specifically to or designed for tropical cyclone forecasting; both are run routinely for all weather situations.

## BMD FORECASTS

To assess whether the lead time for tropical cyclone and storm surge forecasts issued by the BMD could be increased to five or more days, it is first necessary to understand what forecasts and warnings are issued by the BMD presently and how they are produced. The BMD's forecast products are illustrated using examples obtained from its webpage during the lifetime of Cyclone Mahasen in May 2013. IMD's forecasts of Mahasen are also described. In both cases, forecasts issued on the website are taken as indicative of the forecast center's practices. Forecast information is issued to a variety of users by other means, including by radio and television to the broader population and by direct communication with emergency management officials. It is assumed that the character of the information issued through these other channels is not radically different from what can be found on the Internet. As described, however, there is some evidence in the case of Mahasen that disaster management officials had access to information beyond that available on the BMD web page.

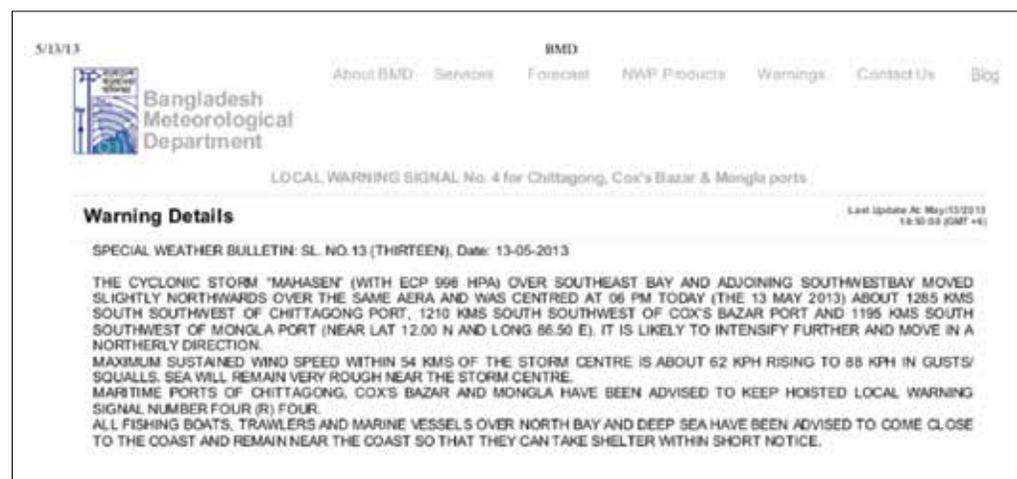
As Mahasen was quite recent, the forecasts made in this example are also taken here as representative of the current

practices of both BMD and IMD in most respects. This storm was, however, unusual in one important respect. It formed more than five days before landfall, allowing five-day forecasts to be produced without requiring that the forecasts begin before genesis.

It appears that the BMD does not issue—at least not on the Internet—quantitative track or intensity forecasts. A map showing the observed track (up to the present time) is issued, but it does not extend into the future. The BMD's forecasts of tropical cyclones appear to be limited to textual forecasts and warnings. These give only qualitative information about the storm's future behavior and do not extend far in the future. Additionally, the BMD employs a system of numerically ranked “warning signals,” which are issued to maritime ports, indicating varying degrees of imminence or severity of a weather threat. Figure 3.4 presents a warning issued on May 13, 2013, three days before the Cyclone Mahasen made landfall on May 16, 2013. It gives quantitative estimates of the storm's current position and intensity, but its explicit predictions of the future indicate only that “it is likely to intensify further and move in a northerly direction.”

**Figure 3.4** Warning Issued by Bangladesh Meteorological Department on May 13, 2013

Source: Downloaded from bmd.gov.bd on that date.



5/13/13

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Bangladesh Meteorological Department

LOCAL WARNING SIGNAL No. 4 for Chittagong, Cox's Bazar & Mongla ports

**Warning Details** Last Update At: May13/2013 12:30:00 (GMT +6)

SPECIAL WEATHER BULLETIN: SL. NO. 13 (THIRTEEN), Date: 13-05-2013

THE CYCLONIC STORM 'MAHASEN' (WITH ECP 998 HPA) OVER SOUTHEAST BAY AND ADJOINING SOUTHWEST BAY MOVED SLIGHTLY NORTHWARDS OVER THE SAME AREA AND WAS CENTRED AT 06 PM TODAY (THE 13 MAY 2013) ABOUT 1285 KMS SOUTH SOUTHWEST OF CHITTAGONG PORT, 1210 KMS SOUTH SOUTHWEST OF COX'S BAZAR PORT AND 1195 KMS SOUTH SOUTHWEST OF MONGLA PORT (NEAR LAT 12.00 N AND LONG 86.50 E). IT IS LIKELY TO INTENSIFY FURTHER AND MOVE IN A NORTHERLY DIRECTION.

MAXIMUM SUSTAINED WIND SPEED WITHIN 54 KMS OF THE STORM CENTRE IS ABOUT 62 KPH RISING TO 88 KPH IN GUSTS/ SQUALLS. SEA WILL REMAIN VERY ROUGH NEAR THE STORM CENTRE.

MARITIME PORTS OF CHITTAGONG, COX'S BAZAR AND MONGLA HAVE BEEN ADVISED TO KEEP HOISTED LOCAL WARNING SIGNAL NUMBER FOUR (R) FOUR.

ALL FISHING BOATS, TRAWLERS AND MARINE VESSELS OVER NORTH BAY AND DEEP SEA HAVE BEEN ADVISED TO COME CLOSE TO THE COAST AND REMAIN NEAR THE COAST SO THAT THEY CAN TAKE SHELTER WITHIN SHORT NOTICE.

At the same time, the warning is noteworthy for the fact that it does, in a sense, contain a longer-range probabilistic forecast, in that it orders the raising of “Local Warning Signal No. 4 for Chittagong, Cox’s Bazar, and Mongla ports.” This puts these locations on alert that they are under possible danger from the cyclone, without stating that it is imminent. Landfall occurred on May 16th, approximately three days after this warning was issued; the first warnings were issued by the BMD two days before, on May 11th, when Mahasen was named, and the first local warning signals were raised on May 12th. Thus while the BMD did not issue explicit long-range forecasts of the storm’s behavior, it did begin to alert the country to the potential threat four and five days before landfall. While this is perhaps atypical—Mahasen was a long-lived storm, forming far offshore—it was not the first time that the BMD had issued such early warnings; the first local warning signals for Cyclone Sidr in 2007 were also raised five days before landfall (S. Ahmed and T. Imam, personal communication).

Figure 3.5 shows a warning issued two days later, on May 15th, a little less than 24 hours before landfall. At this point the ports of Chittagong and Cox’s Bazar were under Danger Signal No. 7 and Mongla was under No. 5. The warning has

much more detailed information about regions likely to be affected by the storm. Quantitative storm surge information is also given, with a set of locations forecast to be inundated by storm surge of 5–7 feet above the astronomical tide.

The Internet is, according to BMD personnel, not the primary mode of disseminating forecasts in Bangladesh. Television and radio are believed to reach more of the population. The Cyclone Preparedness Programme (CPP) (Habib, Shahidullah, and Ahmed 2012) under the Government of Bangladesh and the Bangladesh Red Crescent Society are among the important organizations that respond to cyclone forecasts and warnings. Press reports at the time indicated that the District Disaster Management Committee, a local entity under the country’s Comprehensive Disaster Management Plan (Government of the People’s Republic of Bangladesh 2010), was meeting about the storm as early as May 12th, four days before landfall (“Cyclone Eyeing Chennai,” *Daily Star*, May 13, 2013). Since no explicit forecast of landfall had been made by the BMD that early, this suggests either that the BMD transmits information to disaster management officials beyond what is available on the Internet or that disaster management officials consult other sources in addition to the BMD.

**Figure 3.5** Warning Issued by Bangladesh Meteorological Department on May 15, 2013

Source: Downloaded from [bmd.gov.bd](http://bmd.gov.bd) on that date.

5/15/13

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Bangladesh Meteorological Department

DANGER SIGNAL No. 7 for CHITTAGONG & COX'S BAZAR AND 5 for MONGLA

**Warning Bay of Bengal**

Last Update At: May/15/2013 14:12:04 (GMT +6)

SPECIAL WEATHER BULLETIN SL.NO.26(TWENTY SIX),Date: 15-05-2013  
 THE CYCLONIC STORM "MAHASEN" (WITH ECP 996 HPA) OVER WEST CENTRAL BAY AND ADJOINING EAST CENTRAL BAY MOVED SLIGHTLY NORTH-NORTHEASTWARDS AND WAS CENTRED AT 03 PM TODAY (THE 15 MAY 2013) ABOUT 755 KMS SOUTHWEST OF CHITTAGONG PORT, 685 KMS SOUTHWEST OF COX'S BAZAR PORT AND 635 KMS SOUTH SOUTHWEST OF MONGLA PORT (NEAR LAT 17.00 N AND LONG 87.50 E). IT IS LIKELY TO INTENSIFY FURTHER AND MOVE IN A NORTH-NORTHEASTERLY DIRECTION AND MAY CROSS BETWEEN PATUAKHALI(KHEPUPARA)-TEKNAF COAST NEAR CHITTAGONG BY EARLY MORNING TOMORROW (16TH MAY 2013). ITS PERIPHERAL GUSTY/SQUALLY WIND MAY AFFECT COASTAL REGIONS OF BANGLADESH FROM 10 PM TODAY (15TH MAY 2013).  
 MAXIMUM SUSTAINED WIND SPEED WITHIN 54 KMS OF THE STORM CENTRE IS ABOUT 62 KPH RISING TO 88 KPH IN GUSTS/SQUALLS. SEA WILL REMAIN VERY ROUGH NEAR THE STORM CENTRE.  
 MARITIME PORTS OF CHITTAGONG AND COX'S BAZAR HAVE BEEN ADVISED TO KEEP HOISTED DANGER SIGNAL NUMBER SEVEN (R) SEVEN.  
 THE COASTAL DISTRICTS OF COX'S BAZAR, CHITTAGONG, NOAKHALI, LAXMIPUR, FENI, CHANDPUR, BHOLA, BORGUNA, PATUAKHALI, BARISAL AND THEIR OFFSHORE ISLANDS AND CHARS WILL COME UNDER DANGER SIGNAL NUMBER SEVEN (R) SEVEN.  
 MARITIME PORT OF MONGLA HAS BEEN ADVISED TO KEEP HOISTED DANGER SIGNAL NUMBER FIVE (R) FIVE.  
 THE COASTAL DISTRICTS OF PIROZPUR, JHALOKATHI, BAGHERHAT, KHULNA, SATKHIRA AND THEIR OFFSHORE ISLANDS AND CHARS WILL COME UNDER DANGER SIGNAL NUMBER FIVE (R) FIVE.  
 UNDER THE INFLUENCE OF THE STORM THE LOW-LYING AREAS OF THE COASTAL DISTRICTS OF COX'S BAZAR, CHITTAGONG, NOAKHALI, LAXMIPUR, FENI, CHANDPUR, BORGUNA, BHOLA, PATUAKHALI, BARISAL, PIROZPUR, JHALOKATHI, BAGHERHAT, KHULNA, SATKHIRA AND THEIR OFFSHORE ISLANDS AND CHARS ARE LIKELY TO BE INUNDATED BY STORM SURGE OF 5-7 FEET HEIGHT ABOVE NORMAL ASTRONOMICAL TIDE.  
 THE COASTAL DISTRICTS OF COX'S BAZAR, CHITTAGONG, NOAKHALI, LAXMIPUR, FENI, CHANDPUR, BORGUNA, PATUAKHALI, BARISAL, BHOLA, PIROZPUR, AND THEIR OFFSHORE ISLANDS AND CHARS ARE LIKELY TO EXPERIENCE WIND SPEED UP TO 90-100 KPH IN GUSTS/SQUALLS WITH HEAVY TO VERY FALLS DURING THE PASSAGE OF THE STORM.  
 THE COASTAL DISTRICTS OF JHALOKATHI, BAGHERHAT, KHULNA, SATKHIRA AND THEIR OFFSHORE ISLANDS AND CHARS ARE LIKELY TO EXPERIENCE WIND SPEED UP TO 80-90 KPH IN GUSTS/SQUALLS WITH HEAVY TO VERY FALLS DURING THE PASSAGE OF THE STORM.  
 DUE TO VERY HEAVY RAINFALL, LANDSLIDE MAY OCCUR AT PLACES OVER THE HILLY REGIONS OF CHITTAGONG DIVISION.  
 ALL FISHING BOATS, TRAWLERS AND MARINE VESSELS OVER NORTH BAY HAVE BEEN ADVISED TO REMAIN IN SHELTER TILL FURTHER NOTICE.

## FACTORS CONSTRAINING BMD'S FORECAST PRACTICES

A number of factors constrain BMD's capacity to improve its tropical cyclone forecast practices. The first limitation pertains to data from external sources. Data are available from sources outside Bangladesh, including both observational data and numerical model-produced data, to which the BMD either does not have access or does not have access in forms that would make them most useful.

Some local data are not on the WIS. Not all observations taken in the South Asian region that may be relevant to tropical cyclone prediction are shared via the WIS. This is normal; the WIS protocol does not include all observations taken by any country. Other data may be on the WIS but not obtained by BMD for reasons that are not clear. An important example is data from Indian Ocean buoys; these data are on the WIS but the BMD does not appear to obtain them currently. Similarly, some BMD observations are not shared with the RSMC; for example, coastal radar data from Bangladesh are not sent back to IMD through the WIS and thus are not available for assimilation into IMD's numerical models. Greater sharing of local, non-WIS data would benefit the entire region and could be accomplished by bilateral agreements.

A critical limitation for the BMD is the bandwidth of its WIS link. Currently this is 64 kilobytes per second, a rather low value. Sharing BMD's coastal radar observations over the WIS back to IMD, for example, is estimated to require 5 megabytes per second. While this is 20 times more than the current bandwidth, it is not a particularly large number by global (or even, probably, Bangladeshi) standards. It would be highly desirable to increase the bandwidth available to the BMD for its WIS link.

Presumably as a consequence of the limited bandwidth of the WIS link, many data are available to the BMD only through the Internet in the form of images viewed on a Web browser. This means that, while BMD forecasters are in principle able to consult a range of observations and numerical model products similar to those used at other centers (because a wide range of data are available over the Internet), many of those data are not available at the BMD directly as digital data; they are only available as images. This is a serious limitation. Dvorak analysis, for example, requires identifying areas with temperatures below certain thresholds by infrared brightness; this requires digital data. Similarly, much model output is available at the BMD only as images of model fields.

Many model data themselves are not available for analysis on BMD computers.

Some key data are not used at all. In particular, polar-orbiting satellites, such as microwave sounders and imagers and scatterometers for surface winds, are not used at all in tropical cyclone forecasting at the BMD. Although the data are not available digitally at the BMD, the images are not even consulted. As these data can be quite valuable for estimates of tropical cyclone intensity and structure, it would be advantageous if they were available and used. Part of the issue may be training in the use of these data.

The software environment could be improved. In better-equipped centers, key tasks carried out by tropical cyclone forecasters—particularly visualization of model forecast guidance and production of graphic track forecasts based from that guidance, as well as Dvorak analysis and other steps associated with assessment of the storm's present state—are made easier and more effective by computer hardware and, especially, software designed specifically for the purpose. The BMD lacks these tools. This places greater burdens on the forecasters and makes it more difficult for them to use the available data in the most optimal way. Dvorak analysis, for example, is best done on a computer workstation that has the necessary satellite data loaded into software designed for the purpose. The digital data are not available at the BMD but neither are dedicated workstations with appropriate software, so that even if the data were available, the information would not be as useful as it should be. Altogether, this renders the Dvorak analysis procedure there more primitive than at better-equipped centers.

The BMD does not have access to a software environment comparable to the Automated Tropical Cyclone Forecast System (the system used at the NHC and JTWC in the United States, described in Chapter 2) for ingesting model track guidance directly into a unified graphical environment, allowing the forecaster to directly compare different track guidance and use it to produce a forecast track directly in digital form. Rather, many different forms of guidance are consulted separately on Web browsers, and the information must be combined in the forecaster's mind. Moreover, the tropical cyclone tracks produced from global models by the various centers using their own automated tracking programs are not available at the BMD at all; only images of the model

fields are. Altogether, these limitations make the forecaster's task more difficult, as chores that could be done both accurately and automatically by the computer instead must be done by the forecaster.

Finally, some data are not used for reasons that are unclear. For example, BMD forecasters stated that they do not have access to data from the buoys in the Bay of Bengal that are owned and operated by India. These buoy data could be quite important for analysis of tropical cyclone intensity and structure in some situations. IMD personnel explained that these buoy data are available on the WIS. It is not clear why the BMD believes it does not have access to these data; it is not a bandwidth issue, as buoy data are sparse and require little bandwidth.

Another limitation pertains to the observational network of the BMD itself. The BMD's own observations, over Bangladesh itself and the adjacent ocean, are an essential component of the tropical cyclone forecast process. The BMD would benefit by improving and expanding its current observing system with the following:

-  Automated tide gauges at the coast, which would be invaluable for measurements of storm surge
-  Better bathymetric and topographic data (DEM) for storm surge and inundation forecasting
-  Calibration of coastal radars as well as intercomparison against rain gauges
-  Buoys for oceanographic and meteorological observations offshore.

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## OTHER PHYSICAL SYSTEMS NEEDS

Better hardware and software systems for tropical cyclone analysis and forecasting, such as the Automated Tropical Cyclone Forecasting System for displaying model guidance, NCEP's Advanced Weather Interactive Processing System for displaying observational data, or their equivalents would be particularly valuable. As indicated, the BMD does not have systems equivalent to these. Such systems are currently available at regional centers such as NHC (and IMD), which synthesize many data sources and automate and streamline many of the tasks involved in tropical cyclone analysis and forecasting, including Dvorak analysis of satellite observations. Installing such systems, acquiring the necessary data streams to realize their full capabilities, and training BMD personnel in their use would be a very low-cost improvement that could lead to a significant improvement in BMD operational practices in the short term.

BMD would like to have a stronger in-house facility in operational numerical weather prediction. This could include tools specifically targeted at tropical cyclones, such as the Hurricane Weather Research and Forecast model.

In-house data assimilation of WIS and local observations, including radar, upper air observations, and surface synoptic observations, would also be desirable. Compared with installation of hardware and software systems, the costs here are more substantial and the required training is more significant. Additionally, the impact on forecasts would not necessarily be immediate; some aspects of these technologies are experimental, and their ability to improve forecasts has not been fully demonstrated, even at the best-equipped centers. Nonetheless, in-house numerical weather predictions with high-performance computing should at least be a long-term goal.

The BMD offices are subject to regular electric power outages. While some computers have backup power systems, the outages are nonetheless at best an inconvenience and at worst potentially disruptive to BMD's operations. Besides the need to keep computers and other critical equipment running, Bangladesh has a warm climate, and the loss of air conditioning during parts of the year may inhibit the performance of BMD personnel.

## HUMAN RESOURCES NEEDS

Compared with some other agencies—that is, meteorological services in other countries of comparable or smaller size—the opportunities available to BMD personnel for contact with other institutions, people, and thus scientific trends and developments in the broader field of meteorology and atmospheric sciences are limited. The goal of improving forecasts requires, in the short term, more training of BMD personnel in existing and developing science and technology that specifically address that goal: Dvorak technique, numerical weather prediction, ensemble prediction methodologies, radar data analysis, and the like. While a narrow focus on these methods might be adequate to achieve some improvement in forecast practices, these methods do not exist in isolation from the broader scientific field out of which they have emerged. The long-term implementation of these technologies at the BMD will be more effective—and the adoption of future technologies not yet envisioned will also be greatly facilitated and accelerated—if they are part of a broader effort to improve the foundational education and training opportunities available to BMD personnel in meteorology and atmospheric sciences.

According to BMD personnel, as well as to scientists at the South Asia Association for Regional Cooperation Meteorological Research Center, there is no Department of Atmospheric Sciences (or Meteorology, or any equivalent or comparable designation of the field) anywhere in Bangladesh. (There is an atmospheric physics research group in the Physics Department at the Bangladesh University of Engineering and Technology, and perhaps scattered individual faculty members in related fields at other Bangladeshi universities, but no group that is equivalent to an entire department or that has strong ties to the BMD.)

The lack of any university department to which the BMD might develop ties puts the department at a great disadvantage compared with comparable institutions elsewhere. Most important, it limits the scope of the education available to BMD personnel. The BMD obtains staff mainly by hiring graduates in physics and applied mathematics, typically from Dhaka University, and then training them in-house for one year before they start work as forecasters. A smaller subset of forecasters spends periods of time—typically one year or

Women in rural village, southern Bangladesh. Video Still: Stephan Bachenheimer / World Bank



less—obtaining training at institutions outside the country (often in India, but sometimes elsewhere). While these in-house and foreign training experiences are critically important and valuable, it is not likely that they are able to cover the foundations and more recent developments in the field to the extent that would be possible in a full undergraduate degree program, let alone a graduate program.

Additionally, the value of relationships between universities and government agencies can, in the best cases, extend well beyond the obvious educational role. A good university department will perform research, some of which may be of interest and possibly even operational use, to forecasters. Intellectual exchange between different types of institutions—that is, a government mission agency versus an academic university or research institute—that share common

intellectual ground and geographic proximity can take many forms and bring many benefits. The BMD has no intellectual partner of this type.

The BMD does benefit from interactions with institutions overseas, including the IMD in India, JICA and the Japan Meteorological Agency, the Norwegian Meteorological Service, and perhaps others. Nonetheless, a stronger partnership with an institution in the region, if not the country, would be of great value. Of course, such a partnership would likely require BMD personnel to spend significant time at the partner institution and thus away from their duties. This may not be possible, as the BMD does not have a sufficiently large staff to allow many long absences, but in the long term such development opportunities for staff would bring considerable benefit.

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## COLLABORATION WITH THE IMD

The IMD is the government agency responsible for weather forecasting for India. As part of its responsibilities to the nation, the IMD produces tropical cyclone forecasts. Additionally, it hosts the Regional Specialized Meteorological Center for the WMO/ESCAP panel at its central office in New Delhi, thus providing an important service to the other nations on the panel.

The RSMC issues a tropical weather outlook once daily, at six hours universal time (06 UTC), under all circumstances. When a tropical depression—the embryonic form of a tropical cyclone—has formed, the RSMC issues special tropical weather outlooks twice daily. When the storm becomes a deep depression (winds greater than 28 knots but less than 35 knots) these outlooks are issued five times daily, and track and intensity forecasts for the next 120 hours are produced. When the maximum sustained winds exceed 34 knots, the system is named and the RSMC issues tropical cyclone advisories eight times daily (WMO 2012). Tropical cyclone advisories include (among other information) track and intensity forecasts.

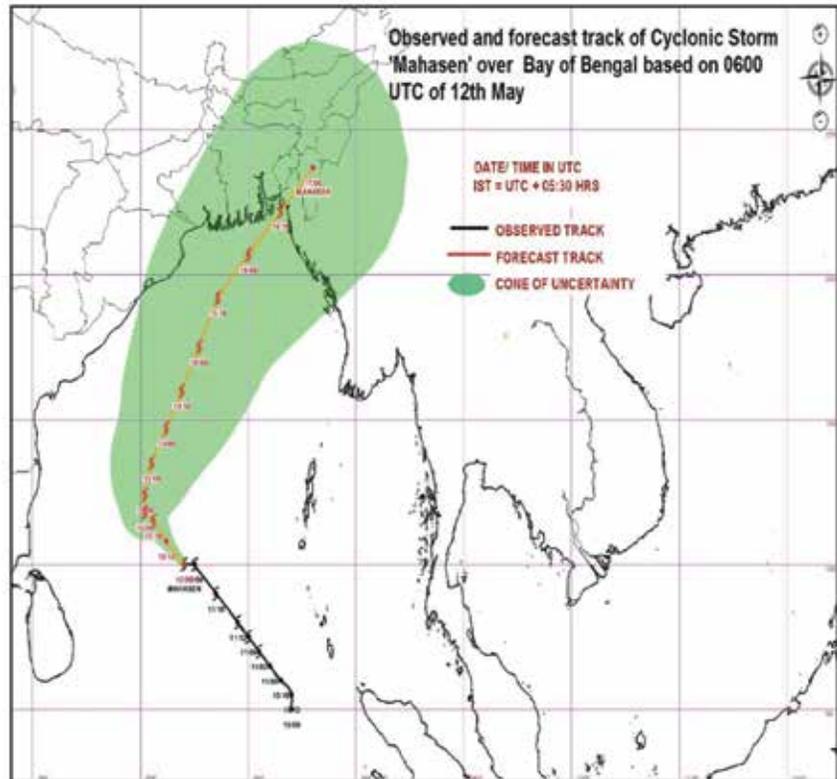
Objective tropical cyclone track and intensity forecasts have been produced at IMD since 2003, at which time the maximum lead time was 24 hours; the maximum lead time was increased to 72 hours in 2009 and to 120 hours in 2013. Storm surge guidance is also included, based on the Indian Institute of Technology Delhi and the Indian National Centre for Ocean Information Services storm surge model, at shorter lead times. The IMD's forecasts for the northern

Indian Ocean (BoB and Arabian Sea) have been thoroughly evaluated in two recent studies (Mohapatra et al. 2013a,b). The skill in the track forecasts is somewhat less than that of the Western North Pacific forecasts by the RSMC in Tokyo or the NHC in Miami, but it is increasing more rapidly with time (Mohapatra et al. 2013a). Skill in the IMD's intensity forecasts is not as straightforwardly evaluated as in these other basins (because of the different baseline references against which skill is evaluated; persistence is used by IMD in the Northern Indian Ocean whereas the “climatology and persistence (CLIPER)” model is used as a reference in the Pacific and Atlantic; Mohapatra et al. 2013b). Similar to the other basins, however, it is clear that the IMD's intensity forecasts are both significantly less skillful than their track forecasts and show much more gradual improvement with time.

This section describes some technical aspects of the IMD's operations in New Delhi as they pertain to Bangladesh via IMD's role as the RSMC. As might be expected, given its role as the RSMC as well as the larger size of India's population and economy, the IMD has capabilities considerably greater than those at the BMD. At New Delhi, the IMD has a high-performance computing facility with a 14.4 teraflop capacity, which was expected to be increased to 110 teraflop by July 2013, that is used for numerical weather prediction. Smaller but still substantial computer facilities and numerical weather prediction operations are carried out at IMD regional offices in other states. In New Delhi, the WRF regional model is run routinely under all weather conditions for forecasts

**Figure 3.6** Track Forecast Issued by the IMD RSMC on May 12, 2013, for Cyclone Mahasen

*Note:* The observed track is shown in black, the forecast track in red, and the cone of uncertainty in green. The forecast extends to 120 hours from the time at which it was made.



out to 72 hours, using an outer domain with 27-kilometer horizontal resolution and a nested inner domain, covering India and its immediate surroundings (including the Bay of Bengal and some of the Arabian Sea as well as Bangladesh and other neighboring countries) with 9-kilometer horizontal resolution. The Global Forecast System model and data assimilation system are also run in-house; advantages of this local version over the U.S. GFS are that the IMD version is able to incorporate a broader set of local observations (including many that are not on the WIS) and that the model run times are better synchronized to the operational needs of IMD and the region. A similar GFS system is also run at the National Center for Medium-Range Weather Forecasting, also in Delhi, and those results are made available to the IMD.

The RSMC's facilities specifically for tropical cyclone forecasting are comparable to those at other RSMCs. The IMD has computer workstations dedicated to tropical cyclone forecasting. Dedicated software packages, comparable to those at the National Hurricane Center described in Chapter 2, are available to ingest necessary data and automate some tasks to streamline and facilitate the forecaster's job. Dvorak analysis is carried out on these workstations once the necessary satellite data have been ingested. This is in contrast to the current situation at the BMD, where only satellite imagery is available and dedicated hardware and software

for the purpose are not present. Numerical guidance from a broad range of numerical models is ingested and tracks are shown on the screen, allowing the forecaster to visualize the guidance in its most useful form and produce a track forecast graphically on the screen.

The RSMC produces products—graphical and text-based—that are broadly similar to those produced at other regional centers. While the BMD's Internet forecasts, shown earlier, were limited to qualitative verbal statements at short lead times, the IMD's are quantitative and extend to longer lead times. Figure 3.6 shows, for example, a track forecast issued for Cyclone Mahasen (May 2013). Besides illustrating the format used, including the cone of uncertainty, it is noteworthy that this was a 120-hour forecast; it was issued on 06 UTC on May 12th, and the last forecast time was 06 UTC on May 17th. This demonstrates unequivocally that the IMD now can and will issue five-day forecasts in situations where it is deemed appropriate.

The IMD's forecasts are available to the BMD (and to the public). As a regional partner of the RSMC, the BMD could, for example, use the IMD's forecasts as the basis for its own, adjusting them according to its own forecasters' judgment and adding detail about the expected local impacts of an event.

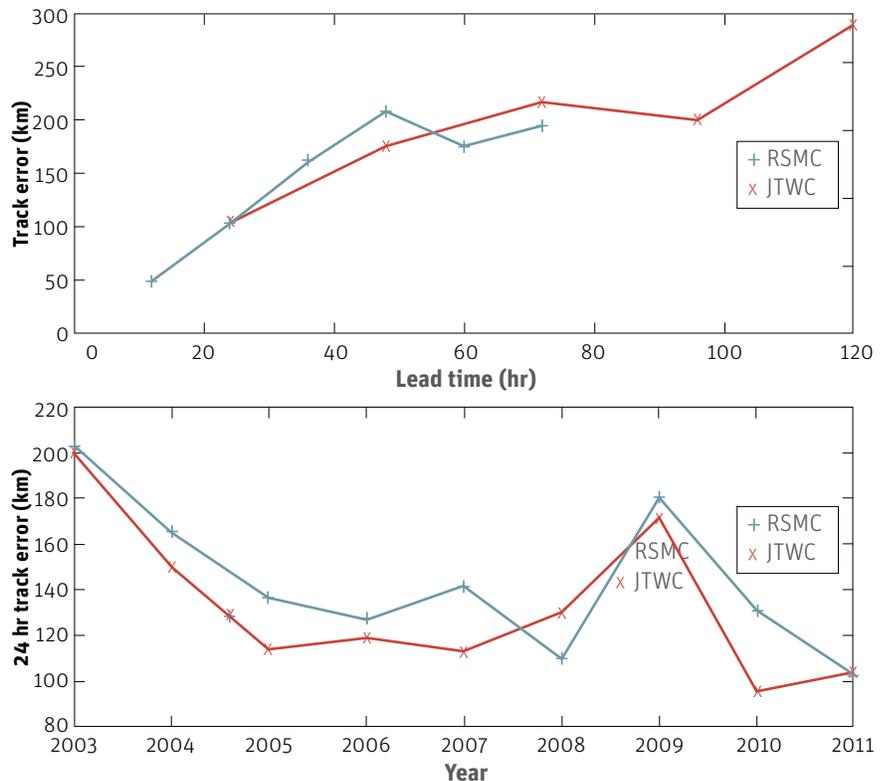
The skill of the IMD/RSMC track and intensity forecasts are similar to those of other centers. Figure 3.7 compares errors in forecast storm position produced by the RSMC to those produced by the U.S. Joint Typhoon Warning Center, which also forecasts for the North Indian Ocean. In both cases, the errors shown are for the whole basin (including the BoB and the Arabian Sea) and are taken from the reports published by the two centers after the 2011 season (RSMC 2012; JTWC 2011). The top panel shows the errors, in kilometers, for the 2011 season, as a function of lead time. The two centers clearly have similar accuracy; the differences are likely too small to be considered significant, given that these results are from a single season and thus consist of a small number of forecasts (particularly at the longer lead times). The only difference that is clearly significant is that the JTWC produced forecasts at lead times out to 120 hours during this period, whereas the RSMC produced forecasts at a maximum lead time of 72 hours. Panel b of Figure 3.7 gives a somewhat longer perspective, comparing the position error at 24 hours lead time during the period 2003–11. The JTWC's errors appear to be systematically slightly lower, though not in every year, and the differences are not great.<sup>11</sup>

<sup>11</sup> A more comprehensive evaluation of the RSMC's forecasts can be found at <http://www.wmo.int/pages/prog/www/tcp/TCM-7-2012.html>, as well as in Mohapatra et al. (2013a,b).

**Figure 3.7** Historical Track Errors for the RSMC (in Blue) and the Joint Typhoon Warning Center (in Red) for Tropical Cyclones in the North Indian Ocean (including both Bay of Bengal and Arabian Sea)

Source: From data published by the RSMC and the JTWC.

Note: Panel a shows the position errors as a function of lead time for the 2011 season. Panel b shows the errors at 24 hours lead time as a function of the year in which the forecasts were issued, from 2003 to 2011.



horizon of 24 hours. The IMD is currently developing some new capabilities for tropical cyclone forecasting. It is developing an in-house capability to run the HWRF, through a Memorandum of Understanding (MOU) with NOAA in the United States and close collaboration with scientists at NOAA's Hurricane Research Division. This capability includes data assimilation and other techniques developed under the Hurricane Forecast Improvement Program. Another major development, part of the same MOU, will be the acquisition of aircraft for tropical cyclone reconnaissance.

The goal is for India to acquire instrumented C-130 aircraft similar to those used by the U.S. Air Force for tropical cyclone reconnaissance in the Atlantic. These would have the potential to make a substantial positive difference in the analysis and forecasting of tropical cyclones by providing accurate observations of storm structure and intensity over the Bay of Bengal. HFIP results from the Atlantic suggest that these data would be particularly effective when assimilated into the HWRF (see, for example, Gall et al. 2013).

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## COLLABORATION WITH OTHER ORGANIZATIONS

Several other organizations in Bangladesh and in the region interact with the BMD on issues related to tropical cyclone and storm surge forecasting.

The *Regional Integrated Multi-Hazard Early Warning System* (RIMES) is an international and intergovernmental organization that generates and applies early warning information for natural disasters. RIMES is based in Thailand but has 13 member states and 18 collaborating countries throughout South, Southeast, and East Asia as well as East Africa. RIMES provides technical support to the BMD both in cyclone and storm surge forecasting and facilitates for the WMO Coastal Inundation Forecasting Demonstration Project for Bangladesh (CIFDP-B).

The *Bangladesh Department of Disaster Management* (DDM), which includes the Cyclone Preparedness Program, interacts with the BMD on cyclone warning and response. The DDM and the CPP have signed as participants in the CIFDP-B. The *Bangladesh Water Development Board* includes the Flood Forecasting and Warning Centre (FFWC), which is responsible for predicting floods on land. Although the FFWC's activities historically have focused largely on riverine and precipitation-driven floods, their mandate includes all flooding on land.

The *Japan International Cooperation Agency* has a long history of support of and collaboration with the BMD. Recent examples include JICA's supply and installation of a high-performance computer and configuration of that computer to run the mesoscale model; support for installation of observational facilities, including automatic weather systems and coastal radars; and development of new forecast products.

The BMD collaborates with the *Norwegian Meteorological Institute*. The BMD obtains weather data from ECMWF via this collaboration, which may include other activities but is not specific to tropical cyclones. The Centre for Atmospheric Sciences at the *India Institute of Technology, Delhi*, has a close relationship with the IMD and (somewhat less directly) with the BMD. The storm surge model used at both the IMD and the BMD was developed at IIT by Professor Emeritus Shishir Dube and is currently maintained by Professor A. D. Rao, who heads an active research group with a significant focus on storm surge and coastal inundation. Professor U. C. Mohanty maintains an active research program on tropical cyclone modeling and prediction, including high-resolution tropical cyclone simulation and prediction using the WRF model, data assimilation, and other topics, and maintains a close connection to the IMD.

## Chapter 4

# Findings and Recommendations

This concluding Chapter summarizes key finds of the report and proposes recommendations.

## KEY FINDINGS

### *TROPICAL CYCLONE FORECAST LEAD TIME IN STATE-OF-THE-ART NATIONAL CENTERS*

The review of operational practices suggests that at state-of-the-art national centers, tropical cyclone forecasts are produced with lead times of up to five days. Both the U.S. NHC and the IMD (as of 2013), for example, issue five-day forecasts of track and intensity. We are not aware of any national center yet issuing forecasts of track or intensity for a specific tropical cyclone with lead times greater than five days on an operational basis. Storm surge forecasts are produced with maximum lead times shorter than those used for the storm itself, and it seems that no centers produce a storm surge forecast with lead time longer than 72 hours.

### *SKILL OF FORECAST TRACK HAS IMPROVED FASTER THAN SKILL OF FORECAST INTENSITY*

Track forecasts have improved dramatically in recent decades, in large part due to steady improvements in global numerical weather prediction models, data assimilation systems used to initiate those models, and ensemble methods. Ensemble methods allow improvement over individual model performance and also allow estimation of forecast uncertainty. Forecasters make active use of these capabilities, and modern cyclone forecasts rely heavily on ensemble and consensus products from a range of global models. Formal estimates of uncertainty provided in forecasts, such as cones of uncertainty, do not explicitly rely on ensemble information in most cases, although a minority of centers do base those estimates on ensemble spread in whole or in part.

Intensity forecasts have not improved at anywhere nearly as fast as track forecasts have. Intensity prediction is currently regarded as a critical problem and is the subject of a major research program in the United States. High-resolution numerical models and assimilation of observations that capture mesoscale processes near the storm center, such as Doppler radar observations from aircraft, are the most promising tools for improvement. These tools show promise in research mode, but they have not yet been clearly realized in operations.

### *TIMING OF OPERATIONAL TROPICAL CYCLONE FORECASTS*

The ability of global models to predict tropical cyclogenesis

has improved greatly in recent years. The accuracy of these models, combined with improved understanding of the influence of coherent large-scale modes of variability on genesis, now allow genesis to be forecast with some accuracy at leads of five days or longer in some basins.

### *UNCERTAINTY IN STORM SURGE FORECASTING*

Storm surge forecasting is carried out as a part of tropical cyclone forecasting. A range of numerical models are used; in some cases, the models used for forecasting may not be the equivalent of the best research-grade models due to the need for fast computation in real time, typically on computers that are much less powerful than those used by global numerical weather prediction centers. Storm surge forecasting may be probabilistic, with a range of simulations done to allow for uncertainties in forecast storm track and intensity.

### *FORECASTING INUNDATION STILL IN A STATE OF RELATIVE INFANCY*

Forecasting inundation—the horizontal and vertical extent of flooding on normally dry land (as opposed to storm surge, which is the height of water above astronomical tide along the coast)—is still in a state of relative infancy. The technology exists, but it is only beginning to be introduced operationally. Verification of inundation forecasts, once they exist, will be an important challenge. In many places, including Bangladesh, upgrades to the existing observational network will be required for quantitative measurements of sufficient quality to evaluate the accuracy of an inundation forecast after the fact.

### *TROPICAL CYCLONE FORECASTS AT IMD*

The RSMC for tropical cyclones at the IMD identifies and names tropical cyclones in the Bay of Bengal; provides outlooks, advisories, and warnings to the BMD and other countries in a panel on tropical cyclones for the Bay of Bengal and the Arabian Sea region; and serves as the hub for the transmission of meteorological data via the GTS/WMO Information System. Objective tropical cyclone track and intensity forecasts have been produced at the IMD since 2003, at which time the maximum lead time was 24 hours; the maximum lead time was increased to 72 hours in 2009, and beginning with Cyclone Mahasen in May 2013, the IMD issues forecasts out to 120 hours. Storm surge guidance is

also included, based on the Indian Institute of Technology Delhi and Indian National Centre for Ocean Information Services (INCOIS) storm surge model, at shorter lead times.

The IMD has access to considerably more material and human resources than the BMD does. It has computer workstations dedicated to tropical cyclone forecasting. Dedicated software packages, comparable to those at the National Hurricane Center, are available to ingest necessary data and automate some tasks to streamline and facilitate the forecaster's job. Dvorak analysis is carried out on these workstations once the necessary satellite data have been ingested. Its forecasts are quantitative and extend to longer lead times than the BMD's. In a few respects, however, IMD forecast technologies lag what is available at some other centers. For instance, while much numerical model guidance is ingested into the forecast software, the only tropical cyclone tracks ingested are those from the deterministic model runs.

The RSMC is a sophisticated facility, using a wide range of observations and numerical model products (both produced in-house and from other national centers) to generate a range of forecast products broadly comparable to those at other RSMCs. Some specific products found at other centers, such as probabilistic storm surge forecasts, are not yet available, but some new capabilities are being developed through collaboration with NOAA in the United States. The Hurricane Weather Research and Forecast model has already been implemented under this collaboration, and development of an aircraft reconnaissance capability is planned. The latter could be particularly effective in remedying a relative lack of in situ observations over the Bay of Bengal. IMD's role as the RSMC means that IMD provides a range of analysis and forecast products to the other members of the WMO Tropical Cyclone Panel, so improvements in IMD's capabilities have the immediate potential to help Bangladesh and other countries in the region. Any improvement in IMD's forecasts has the potential to improve BMD's forecasts as well, to the extent that BMD uses IMD as one of its sources of guidance. But due to capacity constraints at the BMD, data and information already publicly available and provided regionally are often not used for forecasting at the BMD.

### **ANALYSIS OF FORECASTING PRACTICES AT BMD**

Tropical cyclone and storm surge forecasts for Bangladesh are produced by the BMD in Dhaka. The lead times for these

forecasts are 72 hours or less. The BMD issues a smaller range of products than the IMD, and its forecasts are informed by a smaller range of data and resources. The BMD obtains a range of numerical model outputs through the GTS link, but it does not appear to make use of them to the extent that it might. Ensemble methods are not heavily used. The BMD's forecasts are essentially deterministic rather than probabilistic.

### **FACTORS CONSTRAINING LEAD TIME FOR BMD FORECASTS**

The lead time and skill of BMD forecasts are limited by a number of factors, both material and human.

**First, the agency lacks much of the state-of-the-art hardware and software used elsewhere for tropical cyclone forecasts and does not obtain all the globally available and potentially useful data from observations and numerical models.** For instance, BMD forecasters currently lack tools to carry out key tasks such as visualization of model forecast guidance and production of graphic track forecasts based from that guidance, as well as Dvorak analysis and other steps associated with assessment of the storm's present state. These are made easier and more effective by computer hardware and especially by software designed specifically for the purpose. Further, at present the BMD does not operationally run models dedicated to tropical cyclone forecasting. The BMD also faces frequent power outages that disrupt its operations.

**Second, a critical limitation for the BMD is the bandwidth of its GTS/WIS link.** For instance, coastal radar data from Bangladesh are not sent back to the IMD through the GTS and thus are not available for assimilation into the IMD's numerical models. Currently the bandwidth of BMD's GTS link is 256 kilobytes per second, whereas 5 megabytes per second are estimated to be required for sharing BMD's coastal radar observations over the GTS back to the IMD. Moreover, due to the limited bandwidth of the GTS link, many data are available to the BMD only through the Internet in the form of images viewed on a Web browser and are not available in a digital form for assimilation into models. Satellite data, for example, are obtained only in the form of images, which do not allow Dvorak analysis—the global standard method for determining the position and intensity of a tropical cyclone—to be carried out in its most optimal form. Some data from polar orbiting satellites, such as microwave sounders and imager scatterometers for surface winds are not used at all

in tropical cyclone forecasting at the BMD. These data are not available digitally and even the images are not consulted. Since these data can be valuable for estimates of tropical cyclone intensity and structure, it would be advantageous if they were available and used. Part of the issue may be training in the use of these data.

***Third, the observational networks over land and the adjacent ocean, which are an essential component of the tropical cyclone forecast process, also need improvement.***

For instance, adequate bathymetric data for coastal Bangladesh are not available for storm surge and coastal inundation forecasting. Automated tide gauges are also needed for measurements of storm surge.

***Fourth, the BMD does not have a dedicated staff with requisite skills for forecasting tropical cyclones.***

When a tropical cyclone is present in the Bay of Bengal, forecasts of its track and intensity are prepared at the BMD by the same forecasters who normally forecast other types of weather during the remainder of the year. The education and training opportunities available to staff are also limited, making it more difficult for forecasters to take advantage of the latest developments in tropical cyclone and storm surge forecasting. At present, there is no Department of Atmospheric Sciences (or Meteorology, or any equivalent or comparable designation of the field) anywhere in Bangladesh. There is an atmospheric physics research group in the Physics Department at the Bangladesh University of Engineering and Technology and scattered individual faculty members in related fields at other Bangladeshi universities, but no group that is equivalent to an entire department or that has strong ties to the BMD. This seriously compromises the government's ability to forge links with academic institutions on weather- and climate-related research—linkages and partnerships that are often at the crux of innovation and research-based service delivery.

## ***INFLUENCE OF THE SIZE OF THE BAY OF BENGAL***

One significant reason that typical maximum lead time by either BMD or IMD until recently was 72 hours—as emphasized by both BMD and IMD personnel in discussions—is the natural physical constraint imposed by the smallness of the Bay of Bengal. A consequence of this constraint, as shown above, is that most Bay of Bengal storms have lifetimes significantly shorter than five days, measured from the time of genesis as defined by tropical storm intensity. This factor will continue to limit the lead time at which landfall can be forecast as long as track forecasts begin at genesis (even defined using a 28-knot threshold). If genesis occurs less than five days before landfall, then even if a five-day forecast is issued at the moment of genesis, landfall will still occur before the last day of that forecast. If forecasts of landfall are desired with lead times greater than five days, it will still be essential that such forecasts begin before genesis.

## ***FORECASTS WITH LONGER THAN FIVE DAY LEAD TIMES USING ENSEMBLE METHODS ISSUED EXPERIMENTALLY***

Extensions in lead time could result from the use of numerical models producing forecasts without the requirement of an existing disturbance (as defined by any threshold), to the extent that the models can forecast the formation of the disturbance. Such forecasts are now possible using ensemble methods, and products with the necessary information are being produced by some numerical weather prediction centers (for example, ECMWF) (see Vitart et al. 2011) and at least one university group (under Prof. Peter Webster at Georgia Institute of Technology (see Belanger et al. 2012)). The National Hurricane Center in the US has started issuing watches and forecasts for “potential tropical cyclones”, though this is very recent and is being done only out to 48 hours when a storm is expected to threaten land shortly after genesis. If IMD and BMD were to begin issuing forecasts of this type, they would be matching what some of the more sophisticated forecasting centers have only recently started to operationalize.

## RECOMMENDATIONS

For BMD to improve its forecast lead times, a number of actions can be taken. These include the following:

 **Strengthen BMD hardware, software, and infrastructure:** In the short term, some relatively basic and inexpensive improvements could help to bring the BMD closer to the current operational state of the art in tropical cyclone forecasting. BMD should access dedicated workstations with appropriate software to carry out key tasks associated with tropical cyclone forecasting such as data assimilation, model analysis, visualization, and so forth. Improved hardware and software should include installation of a modern system for ingesting and analyzing all data relevant to tropical cyclone forecasts, as is available at larger centers such as the NHC and the IMD. BMD should also ensure backup systems for its computers in case of power outage.

 **Enhance data and information sharing through improved network systems:** In addition to improvements in computer hardware and software, BMD can have better access to useful data—both from observations and from numerical weather prediction models—that are already, in principle, available through improvements in network systems. BMD should make efforts to increase the bandwidth available for its GTS/WIS link so that it can obtain information and products available regionally and globally. This will also enable data and information sharing from BMD with IMD and other relevant agencies.

 **Strengthen observation network for tropical cyclone forecasting:** The BMD would benefit from improvements and expansion of the current observing system, such as access to automated tide gauges at the coast for measurements of storm surge, better bathymetric and topographic data (DEM) for storm surge and inundation forecasting, and calibration of coastal radars, as well as intercomparison against rain gauges and installation of buoys for oceanographic and meteorological observations offshore.

 **Training and capacity building:** Improved education and training opportunities for BMD staff are critical in improving the agency's capacity for improved service delivery. In the short term, the goal of improving forecasts requires more training of BMD personnel in existing and developing science and technology that specifically address that goal: Dvorak technique, numerical weather prediction, ensemble prediction

methodologies, radar data analysis, and the like and also in the underlying fundamentals of atmospheric science. It would be particularly valuable for BMD forecasters to become better acquainted with the capabilities of the modern global model ensemble prediction systems. In the long term, however, the government of Bangladesh will need to invest in development of a cadre of trained meteorologists and atmospheric scientists by supporting teaching of these topics at the university level. Another recommendation is to establish a National Meteorological Training and Research Center in Bangladesh to meet the national requirements. In that case, the existing Meteorological Training Institute of BMD can be upgraded to contemporary standards.

 **Coordination between the BMD and other agencies:** For improvements in forecasting to contribute meaningfully to disaster preparedness and improved early warning systems, close coordination between BMD and other agencies such as the BWDB and Department of Disaster Management is needed. There are already strong relations between these agencies that can be enhanced. In storm surge forecasting, the World Meteorological Organization's Coastal Inundation Forecast Demonstration Project for Bangladesh aims to improve the state of the art and is expected to provide important lessons on how to improve coastal inundation forecasts in Bangladesh, and it should be supported. It would be most desirable if a way could be found to integrate the surge and inundation forecast computations performed in Bangladesh into a single model, ideally through a collaborative effort involving the BMD, the Bangladesh Water Development Board, the Bangladesh Inland Water Transport Authority, the Hydrographic Department of the Bangladesh Navy, the Survey of Bangladesh, and any other relevant entities for bathymetry, water level, river discharge, and other data sharing. It would be particularly desirable to develop a probabilistic (as opposed to a deterministic) forecast capability for both surge and inundation, accounting for the uncertainties in storm track and intensity. The IMD's forecasts using the IIT Delhi and INCOIS models can also be generalized to produce a probabilistic forecast of storm surge based on a range of simulations to allow for uncertainties in forecasts of track and intensity. Perhaps most important, the critical problems of forecast evaluation and verification need to be addressed by improvements to the observational network—in particular, automated gauges that can measure water levels both at the coast and inland.

 **Strengthen regional and global collaboration including IMD's role in research, technology transfer and training:**

The RSMC at IMD is the regional center for predicting tropical cyclones and storm surges and its role as a coordinator of research, technology transfer, and training should be strengthened for the benefit of the IMD, the BMD, and other operational agencies in the region. The RSMC could play a role broadly comparable to that of the NOAA Hurricane Research Division in the United States (in addition to the role it already plays, which is more analogous to that of the NHC, the U.S. operational forecast center). The research activities on tropical cyclones and storm surge could be strengthened at Indian universities such as Indian Institute of Technology Delhi, another IIT, the Indian Institute of Science Bangalore, or IITM Pune, and these could be more coordinated with the operational activities at IMD. A broader range of basic and applied research could be carried out, focused on implementing the latest developments in prediction of tropical cyclones and storm surges and transferring them into operations. Regular training could be carried out, and personnel from the forecast centers could also spend longer periods in residence for more in-depth training and collaborative research. In addition, the BMD should reach bilateral agreements with the IMD and perhaps other entities to obtain useful data that are not publicly available on the WIS. Obtaining satellite data in proper digital form on workstations with software designed for Dvorak analysis is important. Obtaining tropical cyclone tracks produced by global model ensembles in a software environment designed to use them as inputs to the forecast process is perhaps even more important. Regional collaboration in training, as mentioned earlier, could support BMD forecasters to become better acquainted with the capabilities of the modern global model ensembles that produce these tracks.

 **The use of ensemble forecasts for improving lead time for tropical cyclone forecasting should be actively studied:**

The possibility of producing ensemble forecasts for South Asia with lead times greater than five days, as recommended by Webster (2008, 2012, 2013) and Belanger et al. (2013), should be actively studied. Such long-range forecasts, including both genesis and subsequent storm behavior, would be of tremendous value for Bangladesh and South Asia more broadly. Greater involvement of the international research community in this task is important in this, as advocated by Webster (2013). The active interest and engagement of the local agencies—the BMD and the IMD—is essential to this effort, as they bear responsibility for forecasting for the nation of Bangladesh. They are the entities responsible for predicting tropical cyclones and storm surges and, ultimately, for protecting life and property in the region. Any effort toward the goal of longer-range forecasts must recognize that forecasts of track and intensity that are issued before genesis are being issued to the public by even the more sophisticated national forecasting centers only recently. If such forecasts are to become operational in South Asia in any useful way, it will only be with the engagement of the local agencies, requiring a substantial period of development and testing. Efforts should be made for capacity development toward this end through training of forecasters, knowledge transfer from industrial countries, and development of software tools for visualization of ensemble products in a graphical user interface and geographic information system-based platform. Important questions in this regard include not just those addressed in this report but also the extent to which the greater uncertainties associated with longer lead-time forecasts may be compatible with their use in emergency management.

## ANNEX 1: LIST OF STAKEHOLDERS CONSULTED

Name	Title	Organization
Md. Shah Alam	Former Director	Bangladesh Meteorology Department
Arjuman Habib	Former Director	Bangladesh Meteorology Department
Shamsuddin Ahmed	Director	Bangladesh Meteorology Department
Taslima Imam	Meteorologist	Bangladesh Meteorology Department
Md. Amirul Hussain	Executive Engineer	Bangladesh Meteorology Department
Dr. L. S. Rathore	Former Director General	India Meteorological Department
Md. Mobassarul Hasan	Senior Specialist	Institute of Water Modeling, Bangladesh
Zahir-ul Haque Khan	Director	Institute of Water Modeling, Bangladesh
M. Mohapatra,	Scientist	India Meteorological Department
B. K. Bandyopadhyay	Scientist	India Meteorological Department
S. K. Roy Bhowmik	Scientist	India Meteorological Department
U. C. Mohanty	Professor	India Institute of Technology
A. D. Rao	Professor	India Institute of Technology
S. K. Dube	Emeritus	India Institute of Technology
Koji Kuroiwa	Former Chief, Tropical Cyclone Programme	World Meteorological Organization
Maryam Golnaraghi	Chief, Disaster Risk Reduction Programme	World Meteorological Organization
Michael Brennan	Senior Hurricane Specialist	National Hurricane Center
Eric Blake	Hurricane Specialist	National Hurricane Center
Todd Kimberlain,	Hurricane Specialist	National Hurricane Center
Chris Landsea	Science and Operations Officer	National Hurricane Center
Stacy Stewart	Senior Hurricane Specialist	National Hurricane Center
Jamie Rhome	Storm Surge Team Lead	National Hurricane Center
Frank Marks	Research Meteorologist and Director	NOAA Hurricane Research Division
S. G. Gopalakrishnan	Research Meteorologist	NOAA Hurricane Research Division
Sim Aberson	Research Meteorologist	NOAA Hurricane Research Division
Tim Neely	Chief, Environment, Science & Technology Affairs	U.S. Embassy, New Delhi
Dec Ly	Science and Technology Officer	U.S. Embassy, New Delhi
Robert Falvey	Director	Joint Typhoon Warning Center
James Doyle	Head, Mesoscale Modeling Section	Naval Research Laboratory
Russell Elsberry	Distinguished Research Professor	Naval Postgraduate School
Frederic Vitart	Senior Scientist	European Centre for Medium-Range Weather Forecasting
Don Resio	Professor	U. North Florida, Coastal Inundation Forecast Project
Andrew Burton	Regional Forecasting Centre Operations Manager	Australian Bureau of Meteorology
Treng-Shi Huang		Taiwan Central Weather Bureau
Chun-Chieh Wu	Professor	National Taiwan University
Michela Biasutti	Lamont Associate Research Professor	Columbia University
Suzana Camargo	Lamont Research Professor	Columbia University
Michael Tippett	Associate Professor, Applied Mathematics	Columbia University
Peter Webster	Professor	Georgia Tech University



Storm over Dhaka. Credit: crazydiva/Thinkstock.com

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