# Chapter Nine

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# 9. Warning Strategies

## 9.1 Introduction

Some of this Warning Strategy chapter is extracted from the original Warning Strategy chapter by the late Mr. Robert Southern, as much of his basic input is still valid. The remainder of the material is taken from newer studies and presentations provided by various international subject matter experts.

### 9.1.1 Purpose of strategies

The purpose of strategies, according to management theory (Koontz et al. 1984), is to determine and communicate, through a system of major objectives and policies, a concept of how the main mission of an organization may be accomplished. Emphasis is placed on the acquisition and deployment of resources (physical, human and information). Warning, response, and preparedness strategies thus may be described as:

- Guidelines that promote objective assessments of the current and changing nature of a hazardous weather threat; and,
- Sequences of actions and announcements that provide the most appropriate and timely response by threatened or affected communities.

Thus, the strategies here provide a framework of guidelines to assist decision-making required to counter the threat of an approaching tropical cyclone (TC). For example, as a TC threatens a vulnerable section of coast, initially there is a large degree of uncertainty associated with forecast errors at longer time periods. As the TC approaches, the uncertainty decreases, but so does the available preparation time. Thus, an effective warning and response strategy is to react prudently and alertly at the initial threat, then to marshal the necessary resources to progressively prepare for the developing threat. The type of strategy requires a balance between the costs and the hardship associated with unnecessary response and the consequences of being caught ill-prepared. For extreme risk areas with slow response times, for example, it is prudent to evacuate early to avoid catastrophic loss of life. In other regions, with rapid response facilities, a different strategy could be employed.

### 9.1.2 Objective of an integrated national warning service

The broader objective or mission of an integrated national warning service therefore is:

*to promote effective community response, in order to avoid potential disaster, and thereby reduce the loss of life, property and environmental damage, while holding the community disruption to a realistic and appropriate minimum.*

While avoiding potential disaster is a major component of this mission, attention also must be given to reduction of consumption of national resources already scheduled for deployment in national development programs, and consequential triggering of a host of other adverse socio-economic impacts on a nation's prosperity.

In a TC context, the strategies may be sub-divided into three, highly interrelated subcomponents: forecast strategy, warning strategy and response strategy. The first is presented in Chapter 8. The last two are discussed in this chapter. It should be noted that Forecast Strategy and Warning Strategy are highly interrelated, especially in the areas of forecast uncertainty and message formulation and content, and thus, there may be some overlap between the chapters. While the Response Strategy is primarily the responsibility of Emergency Managers, it is imperative that forecasters have a good understanding of Response Strategy in order to effectively support the Emergency Managers and the community. There should be a close working relationship between the TCWC and the Emergency Management community and even closer working relationships between local weather offices and local emergency managers.

### 9.1.3 Forecast strategy

Includes the strategy for collection of observations, with enhanced collection in the TC vicinity; specialized analysis methods; and the preparation of forecasts using the most appropriate techniques for the situation.

### 9.1.4 Warning strategy

Includes an explicit understanding of the forecast uncertainties; an appreciation of the most vulnerable and susceptible communities and populations in the potential warning area, the "least regret" approach to ensuring no catastrophes occur; and a sharp sense of timeliness to fit with communication capacities and community cycles.

### 9.1.5 Response strategy

Includes preparedness activities such as public education and awareness programs aimed at ensuring good community responses; developing an infrastructure capable of handling the threat; ensuring a balanced preparation appropriate to the community under threat, to ensure full response without unnecessary over-reaction; taking contingency action, such as establishing and activating emergency operations centers and implementation of ordered evacuations; deploying available resources to meet the threat and to be available for post-event response; and planning ahead to mitigate the detrimental effects of future events. To ensure the most cost-effective strategy, an all-hazards approach is highly encouraged, where preparedness, response, recovery and mitigation measures can be applied to any one of a large suite of hazards.

### 9.1.6 Help make critical decisions more effective

A major objective of the TC strategy should be to provide a strong element of innovative oversight to plan and facilitate the effectiveness of the critical decisions made during the event. This planning will vary considerably according to the meteorological conditions, the facilities and communications available to the community, and to its degree of sophistication in responding to the threat. It also will be readily understood that the effectiveness of warning strategies needs examination from the perspective not only of national meteorological/hydrological services, but from the viewpoint of many diverse agencies located in the sequential cycle of disaster response and mitigation functions. This includes, primarily, the host of potential victims at community levels most threatened, and having most to gain from the implementation of effective warning strategies. Thus, experience in one country may or may not be readily translated to another. It may be noted, however, that this chapter incorporates the warning experiences and lessons learned from a number of recent major TCs of global significance.

Warning strategy should not be so focused on principles and definitions as on common sense and practical application. People in responsible agencies and organizations need to observe the response to their warnings, assess the effectiveness of the warnings, and take steps to correct shortfalls. They need to be proactive and flexible.

This chapter draws on published and unpublished sources of information, in addition to the author's own practical experience. Readers not familiar with modern concepts, principles and practices of data management are invited to refer to two excellent publications by the Asian Development Bank (ADB 1991, Carter 1992). Despite their age, these are still valid and excellent common sense references for emergency managers and for those who support emergency managers.

## 9.2 The nature of warning and response

Warning and response are interrelated; one is of little effect without the other. They are quantifiable actions consisting of:

**Warning:** a positive action-oriented stimulus intended to alert people about an impending hazardous event or circumstance in their location, which may threaten their safety and security, and which requires an "adaptive human response";

**Adaptive Human Response:** the degree of organized reaction to a warning stimulus, which enables rational communication between individuals and communities, and which facilitates avoidance or mitigation of the perceived threat.

To be of maximum effect, a warning must therefore alert the community at risk, clearly communicate the physical nature, potential danger and urgency of the threat, and recommend avoidance/preparedness measures. Such warning and alerting stimuli may take many audio-visual forms and actions, which will vary according to the type and capabilities of a community.

There are basically two primary methods of real-time dissemination of warnings, each with its specific audience. These methods are radio and live or recently recorded television. Warning information is highly perishable, and must be updated frequently. Television is the method of choice, provided it is live or recently recorded. This is usually available in well-developed countries. However, a second and very effective medium is the radio, provided the warnings are frequently updated and well-prepared for the radio medium. The purpose of the warning is to illicit a desired human response to the hazard. The purpose of the media is to clearly spread the warning message to the majority of the threatened population.

### 9.2.1 Principles for good major hazard warnings

General issue of warnings is made through the mass media, where opportunities for queries and feedback are limited. In such cases the following general principles apply:

- Design messages to attract attention and evoke timely rational response;
- Specify the nature, severity and imminence of the threat, in accordance with relevant officially announced warning stages or phases;
- Specify the location of threatened areas with reference to well-known geographical locations or landmarks;

- Advise optimum avoidance or preparedness measures related to the degree and imminence of the threat;
- Achieve a balance in content between detail and simplicity in terms meaningful to the majority of recipients;
- Allocate the highest priority to the more critical elements in messages, especially those requiring urgent responsive action;
- Increase frequency of issue or updates as the threat increases (warnings are perishable products);
- Take into account pre-event behavioral response studies, the level of community experience, and the vulnerability of threatened areas;
- Advise how, when and where to obtain further information.

It is most important that warnings utilize the selected medium to the best advantage. For example, radio alerts can be preceded by a distinctive siren or melody, television can utilize background footage of typical conditions, and perhaps maps of where to proceed.
According to WMO (2006), below are the characteristics of an effective warning issued by NHMSs:

(i) Accurate — on the onset and intensity of the weather hazard, and the geographic area likely to be affected. It is also important to include discussion of the uncertainties so that the warning recipients will understand how to deal with the warnings effectively.

(ii) Clear and understandable — about the expected phenomenon and the risks to person, community and property. This allows the community to respond in commensurate with the risk involved as the weather situation develops.

(iii) Available to all — the warning must be disseminated to all affected, including those unable to receive television, radio or the Internet.

(iv) Reliable and timely — so as to develop trust in the warnings from the users, who would then be prepared to act when a warning is issued.

(v) Authoritative — the media and partners participating in addressing the hazard must not create or broadcast conflicting information.

(vi) Collaborative — through development of strong partnerships with all levels of decision-makers involved in disaster prevention and mitigation.

### 9.2.2 Response to warnings: behavioral factors

Response occurs at a spectrum of levels:

(a) individual,
(b) family,

(c) neighbourhood or village,
(d) local autonomous community,
(e) district (e.g., taluk, upazilla, etc.),
(f) province,
(g) region or state,
(h) national,
(i) regional or international (global).

The immediacy of response decreases from (a) to (i) but the availability of resources needed for effective response increases from (a) to (i). Warnings need to be conveyed in languages and modes of communication relevant to the response level required.

Many studies, surveys, and general observations during TC events have identified numerous factors that influence human response to TC warnings. One specific summary freely available is WMO (1983). Each catastrophic TC event reveals a spectrum of causes for major deficiencies in effective community response, some of which may not be closely related to the effectiveness of formal warning messages.

Commonly experienced response factors may be grouped into three overlapping categories:

**Human (personal) factors:** Age, sex, health, mobility, education and literacy, occupation, comprehension of danger, family and neighbourhood influence, cultural or religious attitudes, previous experience, poverty and economic circumstance, security of house and livestock, urban or rural residence, etc;

**Hazard factors:** Nature, severity and imminence of hazard(s), hazard frequency, immediate past experience of hazard including warning performance, credibility of warning service, visible evidence of threat, clarity of warnings, vulnerability of the community, etc;

**Community aspects:** Supporting infrastructure, availability of safe shelter and supporting welfare, extent of published evacuation planning, flood-free road access, confidence in counter-disaster officials, evidence of contingency planning, media collaboration to upgrade information, integrity of community lifeline services, level of community awareness, etc.

### 9.2.3 Warning strategies in an interdisciplinary perspective

Many TC specialists and forecasters have had limited opportunity to consider their particular roles of providing hazard and warning information in the perspective of a comprehensive sequential cycle of disaster management functions. The same comment applies to most personnel closely involved in natural hazard and disaster reduction and disaster management functions.

Most disaster managers consider the warning function to be a limited, though highly important part, of non-structural preparedness measures that often must proceed in relation to hazards for which little or no warning is feasible (e.g., an earthquake). In this respect, the availability of warnings for TCs may be considered a special bonus input to the comprehensive function of preparedness, since they usually provide considerable "pre-warning" of the event.

In respect of warning strategies the following quote indicates the varying perceptions, and thus criticisms, with which specialists may view the effectiveness of TC warning systems:

"The perspective from which the basic organisational effectiveness of a TC warning service is examined will depend very much upon the focus of interest of the reviewer or his organisation place in the chain of events in the warning (origination, delivery, utilization) response process. The meteorologist is anxious to see that his geophysical information, obtained by huge investment in science and technology, is usefully deployed. The social scientist will study the behavioural response of communities and individuals to a variety of warning stimuli in varied social, geographic and cultural circumstances. A systems analyst may wish to test organisation theories of human interaction in the crisis situation, which the landfall of a TC presents, while a disaster specialist may compare all aspects of the total warning-response system in the context of other natural hazard occurrences. A politician may take advantage of perceived deficiencies in the system to plead for additional resources for his electorate, and perhaps a government economist may be anxious to compare the cost-effectiveness of various inputs into a warning system with subsequent outputs to rationalise competing demands on his budget. These and many other inter-disciplinary interests are recognised as contributing to the totality of an assessment of the usefulness of a TC warning system." (WMO, 1990).

Among the most compelling factors that influence response to TC warnings are the degree of sustained community awareness of the great dangers of TC hazards, the perception of the credibility of the warning authority, and the degree of confidence in the capacity of community officials to martial resources to implement preparedness measures. Thus, an aim of warning strategies must be to take into account the roles played by the great range of interdisciplinary interests that jointly foster human response to TC warning and mitigation measures.

## 9.3 Operational strategies for tropical cyclone (TC) warning and response systems

No successful TC warning and response system can be finely tuned and objectively defined to the finest detail. The facts of life are that each TC embedded in its broader environment exhibits a physical eccentricity and predictability generally unlike any of its predecessors, whilst the human and physical geography of the most threatened areas are constantly changing. Warning strategies thus have to be sufficiently flexible to enable forecasters, emergency services and affected communities to respond effectively under conditions in which there is not a precise model and the hazard potential is constantly changing. Unlike many other natural hazards, however, TCs do have a development life cycle and seasonal occurrence, which assists in logical planning and in allocation of required resources. A solid effort devoted to assessment of demographic and economic vulnerability, and to the community response capacity, will prove to be a very good investment when a TC occurs.

**Four Phases of National Action Plans: Preparedness, response, recovery, mitigation.**

**Levels of warnings of approaching hazards: Advisories, watches, warnings**

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(ii) Clear and understandable - about the expected phenomenon and the risks to person, community and property. This allows the community to respond in commensurate with the risk involved as the weather situation develops.

(iii) Available to all - the warning must be disseminated to all affected, including those unable to receive television, radio or the Internet.

(iv) Reliable and timely - so as to develop trust in the warnings from the users, who would then be prepared to act when a warning is issued.

(v) Authoritative - the media and partners participating in addressing the hazard must not create or broadcast conflicting information.

(vi) Collaborative - through development of strong partnerships with all levels of decision-makers involved in disaster prevention and mitigation.

### 9.3.1 Warning and response system

The warning and response system objectives are threefold: to *alert* communities of a potential danger, to *identify* areas likely to be affected, and to *call* the community to action through w*arning* messages and recommendations of specific actions. The strategy follows an evolutionary, persuasive process starting with pre-season education and awareness programs. As a threat develops, the strategy evolves to early alerts of potential, but uncertain threats. The strategy further evolves as the TC approaches or develops by increasing the detail and urgency of the information. Finally, the strategy should end with a review of the effectiveness of the warning-response system.

The major components of the warning and response system required to support these objectives are:

**Tropical Cyclone Forecast:** A scientific prediction of the future location, motion and intensity, and main parameters of a TC. These predictions must be in a form useful for the derivation of warnings for the public and be capable of objective verification.

**Tropical Cyclone Warning:** An imperative TC forecast that consists of several stages: *Early Alert* of potential threat more than 48 hours away, especially for industrial and emergency service operations; *Watch* for a TC that is likely to affect the community, but not within 24-36 hours; and *Warning* of imminent onset of TC conditions within 24-36 hours. The time designated for a warning is dictated by the time necessary to evacuate vulnerable populations. [Note: For most locations the warning time is 24 hours, but for many United States locations, the warning time is 36 hours.] This graded system consists of messages compiled in meaningful laymen's language, which conveys the personal danger imposed by the destructive elements of an approaching TC, first raising the community awareness of the threat, then inviting and finally demanding active response commensurate with the urgency and severity of the threat.

**Utilisation:** Adaptation of warnings by recipients into required preparedness measures and announcements in accord with contingency plans for the threatened areas.

**Emergency Response:** Implementation of community emergency procedures under the coordination of the relevant counter-disaster organisations.

**System Evaluation:** Review and evaluation of the total system to identify deficiencies and effect improvements in both warning and response functions.

The warning and response system thus consists of several interrelated components, all of which must function effectively and in a complementary manner for effective operation of the whole system. Perfect warnings are of little use if no response organisation exists.

An objective approach is to take the effectiveness of implementation of the warning inputs and of the community response organisation on a scale of 1-10, then multiply these to arrive at the percentage effectiveness of the overall warning-response system. Thus, an excellent warning effectiveness of 9 with a poor community response of 1 would result in a poor 9% effectiveness of the overall system. A very satisfactory result and overall practical objective would be to achieve a 9 for each component giving an 81% measure of effectiveness. This requires a co-ordinated approach, which includes the following essential ingredients:

- Development of official, community and special user awareness of the nature of the threat of TCs and preparedness measures to counter this threat.
- Assessment of hazard risk and vulnerability of the local areas prone to the TC threat, particularly in respect of preservation of community lifeline facilities and services.
- Preparation of contingency plans of action to facilitate decision making during TC crises, covering resources allocation and nomination of agency and individual duties.
- Training and rehearsal of simulated TC exercises to test the effectiveness of plans for deployment of human and physical resources.

- Appropriation of funds and resources to support departmental and community response.
- Development or institution of longer-term mitigation programs to minimise losses, which are difficult to avoid by short-term preparedness measures.

### 9.3.2 Warning and response phases

Effective warning-response strategies cover all aspects from pre-season review and preparation to post-event evaluation. From the perspective of a forecaster, ten major phases may be identified. (See also Chapter 8.)

**(i) The Pre-Season Check Phase:** All aspects of the system are checked and reviewed, including: observational and communication equipment, operational procedures, emergency service organisation contacts and revised procedures. Available techniques are updated and forecasters review their own methodologies. Community awareness campaigns are conducted in conjunction with counter-disaster authorities.

**(ii) Routine Monitoring Phase:** Continuous surveillance by a national meteorological centre, a TC warning centre or preferably both using twice-daily (or more frequent as necessary) scientifically-based procedural checks for signs of potential TC activity.

**(iii) Cyclone Information Phase:** Media and preparedness authorities are advised that a TC has formed near or within the area of warning responsibility but is not forecast to cause dangerous conditions within a specified time, often 48 hours. The information is contained in low-key statements issued once or twice daily with the aim of arousing initial interest and creating a climate of expectancy should the system move to the next phase. Very specific information may be passed to highly vulnerable areas such as offshore oil operations and fishing fleets.

**(iv) Cyclone Watch or Alert Phase:** The alert phase commences when an existing or potential cyclone poses a threat within 48 hours, but not within 24-36 hours. The objective is to build public awareness of the increasing threat without making definitive predictions that are beyond the forecast system capacity at this early stage. The frequency of warning advices is increased, generally to 6 hours, but provided only in general terms, for example, potential landfall along extended coastal sectors several times the lateral dimensions of gale or storm force winds and which incorporate the degree of uncertainty in the forecast. This phase may activate costly public counter-disaster plans, such as the setting up of emergency operations centres and initial deployment of resources. Preparedness recommendations include return of fishing craft to home ports and preliminary precautions by residents. In general, this phase means "get ready to get ready"; do the inexpensive preparations and save the most expensive for the warning phase.

**(v) Cyclone Warning Phase:** This is initiated when TC conditions, in the form of gale-force winds, are expected within at least 24 hours at a vulnerable location (some regions may require longer lead times). It is usual at the beginning of this phase to have to place at least 600-800 km length of coastline under expectancy of damaging winds, with perhaps another 200 km remaining under a watch stage at the peripheries. For a TC approaching at an acute angle, the warning/watch region may be substantially larger. As a general strategy, discrete coastal sectors between named well-known locations should be identified in warning statements. This is the highest level of operation of the warning system and is accompanied by significant cost impact for all concerned parties. Disaster operations centres are staffed on a 24-hour basis to implement contingency action plans, which will often include opening of shelters and evacuations starting from the more exposed areas. The community is expected to make immediate arrangements for its safety and security, and businesses and industry commence shutdown procedures.

The frequency of warnings is progressively increased to 3 hours. When practical, such as with radar tracking, abbreviated hourly warnings may be issued to media. The warning system is fully extended to enable rapid response to changes in the cyclone motion and structure. Additional persuasive information is martialled and broadcast to heighten the sense of urgency in the community and to hasten public response in the decreasing safe lead time available. As the landfall lead time shortens, more specific information on the destructive power of the TC and general warning of abnormal tides (storm surge) and flash floods are issued, and attention is drawn to unusual features about the storm, such as unusual intensity, speed of approach, or large size of the wind field.

**(vi) Imminent-Landfall Phase:** At this advanced stage of the warning phase gale or stronger force winds are imminent or have commenced along with heavy rain, rough seas and increasing tides, and the community should be already sheltering in expectation of landfall of the TC within 6-8 hours. Well-equipped emergency services personnel checking on the safety of people in the most vulnerable areas and the continuing operation of community lifeline facilities should be among the few persons not sheltering inside safe refuges.

Broadcast warnings contain highly pertinent information concerning the impact of the cyclone in the most vulnerable areas. The expected landfall region for the destructive cyclone core should be detailed to within an accuracy of 50-100 km, but it is essential to stress the asymmetric extent of destructive winds and rainfall to ensure communities do not concentrate unnecessarily on the TC centre. Preliminary flood warnings may be issued for coastal catchments and river basins. During this phase when increasing gales are being experienced, monitoring and prediction focus on nowcasting. Predictions are usually given on the basis of persistence and current surface synoptic conditions.

Because the track and structure of a TC may change in the hours approaching landfall, Simpson (1971) advocated last-minute warnings on a "course of least regret". This assumes that the most serious impact will occur close to the region or towns of highest vulnerability. If these locations suffer lesser damage then so much the better. If the situation is marginal then the higher rated TC category or public warning signal number should be quoted in warnings. For the same reasons, immediate pre-landfall announcements that the TC is weakening should generally be avoided, especially as serious misinterpretations may be made with disastrous consequences. At this point, there is nothing to gain by indicating a weakening trend.

It is recommended that the highest priority, *Flash Cyclone Warning* prefix (or the local warning equivalent) be used for the first urgent advice of destructive cyclonic effects within 24-36 hours in areas not previously alerted. Flash warnings (or the local equivalent) also should be used to indicate sudden changes in the TC track or intensity, which could seriously affect vulnerable communities.

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**(vii) Post-Landfall Phase:** The warning advices continue at 3-hour intervals for about 12 hours after landfall, advising communities of the location of landfall, the subsequent track of the cyclone and rate of weakening, and potential developments, such as movement back offshore. The emphasis now centres on the issue of warnings for rapid riverine and flash floods, and for tornados, where necessary. At this phase, all power (except emergency power) and

<<Previous Next>>

communications may be out. In addition, most meteorological instrumentation may be damaged or destroyed.

A Final Cyclone Warning should be issued, in consultation with counter-disaster authorities, to indicate the passage of the TC threat and recommend a gradual resumption of normal community activities, and deployment of medical and engineering crews to badly hit regions. The final warning should not only consider the reduction of the wind danger but also the reduction of the danger of the inundation from the sea.

**(viii) Impact Assessment Phase.** This phase is entered as soon as a TC has dissipated, or passed into another area of warning responsibility. Meteorological officers, accompanied by disaster personnel, visit the affected areas to gather relevant observational and hazard-related data and discuss warning-response performance with people and officials.

**(ix) Documentation Phase:** This covers the period from genesis of a TC through the sequential warning phases until dissipation or passage of the TC from an area of warning responsibility. All relevant information about the TC including copies of warnings, press items and damage photographs, criticisms, and a chronology of events, is collected in a substantial case history file for reporting and archival. Selected data are extracted for storage in computer compatible form to facilitate enquiries and research. Supervising meteorologists should keep diaries for strategic planning, remedial training, and procedural improvement purposes.

A summary of each season's TC activity is prepared annually. Special reports on major disaster-impact TCs are given wide distribution to interested parties.

**(x) System Review Phase:** At the end of the TC season, a review is conducted of the total performance of the warning and response system. This usually culminates in annual review conferences covering internal procedures as well as external liaison with counter-disaster authorities. As noted earlier, each new TC brings unique experience with respect to warning and response aspects, which may need to be incorporated into warning procedures and or preparedness contingency plans.

Major innovations involving the community at large may need to be tested for their feasibility before final adoption into national procedures. In some cases, such as when a TC has not impacted a country or coastal sector for many years and/or there has been a substantial breakdown in the warning and response process, the opportunity should be taken for a thorough appraisal of the system. Annual preparedness and response exercises can reduce the chances that the system will fail when it is needed for an actual hazard event.

## 9.4 Constraints that challenge warning strategies

Several meteorological, climatological, regional and human perception uncertainties apply to constrain the application of warning strategies. These include the uncertainty in TC forecasts, regional and seasonal variations in TC characteristics and forecast difficulty, and language and communication ambiguities that lead to misinterpretation of warning content.

Because the atmosphere is non-linear, some level of uncertainty or error is present in all forecasts and must be accounted for in warning strategies. This uncertainty can be quantified by mean forecast errors (Chapter 3) that generally increase in 75 km increments for every 12 hours of the forecast. Pike and Neumann (1987, see Chapter 2) have shown that the degree of uncertainty, as defined by a forecast difficulty index using the CLIPER technique, varies considerably between ocean basins. Marked seasonal and latitudinal variation also is experienced.

In many situations, the forecast errors will prove to be less than indicated by the forecasting difficulty level because the forecaster will use a number of techniques, allied with professional judgment and experience. In addition, there may be much better than normal observations available. In other cases, the warning strategy must account for the worst case scenario, for example, the high degree of uncertainty that can be present when a TC is in a potential recurvature or rapid intensification situation.

The warning strategy, therefore, is to account for regional characteristics and the current situation for the forecast period, and then to provide a prudent margin for error. At the alert or watch stage, a large section of coast will be notified, and this will be reduced and focused as the TC landfall approaches and the forecast confidence level increases.

### 9.4.1 Forecast uncertainty

Care needs to be taken to maintain realistic and conservative levels of forecast uncertainty in the warnings. Counter-disaster managers tend to regard the occasional instances of excellent forecasts as the basis for routine expectancy of exceptional performance, which if not achieved on subsequent occasions, quickly inspires criticism of apparent monitoring negligence. Forecasters have a natural tendency to overestimate their real predictive skills by making overconfident forecasts of the probable location of landfall in warning announcements several days in advance. This can subsequently lead to substantial amendments, confusion and potential tragedy.

Tropical cyclone (TC) track forecasts have greatly improved in the past several years. Benefiting from the advances of numerical weather prediction and the multi-model consensus technique, reduction in the track forecast errors has been impressive. RSMC La Reunion saw a big step forward in their operational performances in 2006, when a spectacular gain exceeding 30% for forecasts beyond 48 hours was attained. Since then, the track errors have stabilized with a slight downward trend (Fig. 9.1). The improvement in the track forecasting has led to the extension of La Reunion's official forecasts out to 5 days starting from February 2010. Day 3 track forecasts are now better than were the day 2 forecasts before 2006 and the forecasts for day 5 are also better than were the forecasts for day 3 compared with four years ago.

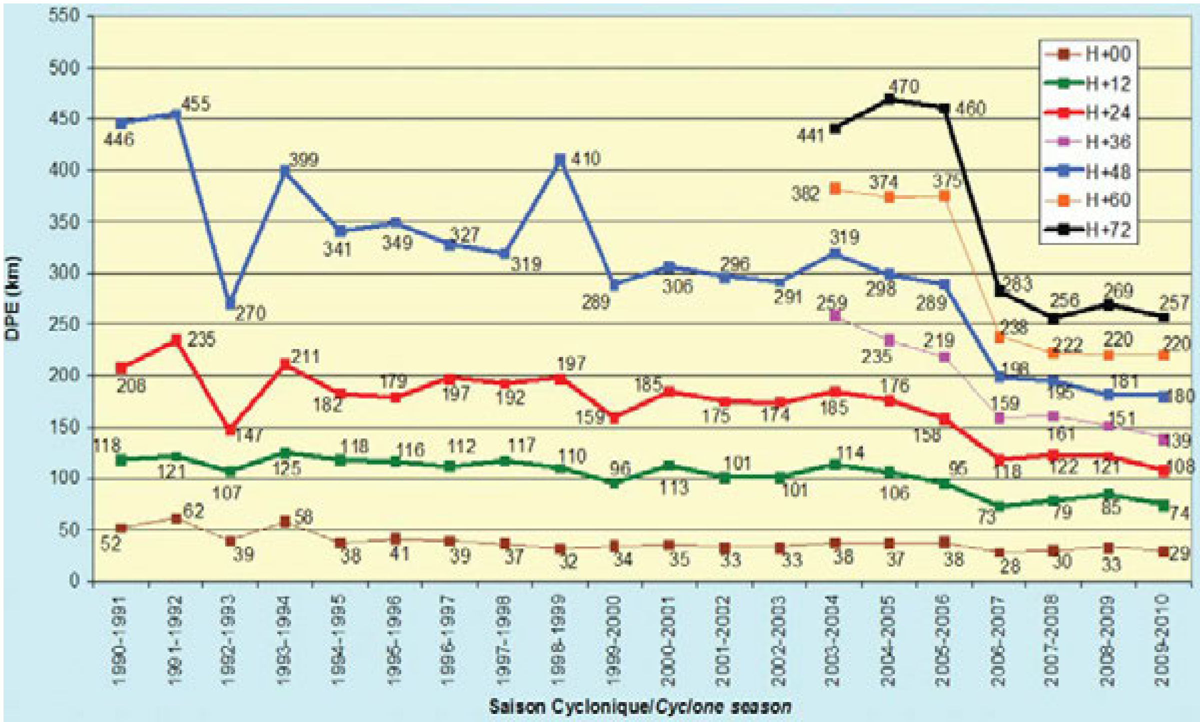


**Figure 9.1.** Annual mean position errors of TC track forecasts issued by RSMC La Reunion from 1990 onward.

Similar enhancement was also implemented in other centres - RSMC Tokyo extended its TC track forecasts from 3 days to 5 days in April 2009. As a primary basis for TC trackforecasting, JMA refers to the Global Spectral Model (GSM), the horizontal resolution of which was upgraded to approximately 20 km in November 2007, and also to the Typhoon Ensemble Prediction System (TEPS) which became operational in February 2008. The annual mean errors of 24-, 48-, 72-, 96-, and 120-hour forecasts of the TC centre position in 2009 were 122 km, 216 km, 312 km, 415 km and 528 km respectively. China Meteorological Administration (CMA) also followed suit to extend its track forecast from 3 days to 5 days in 2010, based on one-year test in 2009. The annual mean errors of 24-, 48-, 72-, 96-, 120-h track forecast in 2009 were 119 km, 205 km, 299 km, 392 km and 514 km respectively.

While track forecast improvements over the past decade have been substantial, intensity forecast improvements have been virtually flat. Improved track forecast models and new ensemble track forecasting techniques have made it much more difficult for the forecaster to add improvement to the numerically-derived track forecasts. When considered in terms of the increases in coastal populations, intensive coastal land-usage and vulnerable investments, the risk in human and economic terms continues to increase even with the significant track forecast improvements, just at a slower rate. Thus, while the track forecasts may continue to improve, because the number of people or resources at risk continues to grow, the size of the warning zone may not shrink accordingly.

Despite the significant reduction in track forecast errors in recent years, we have not yet reached the point where this could result in a major change in the approach of decision making for emergency management and warning strategy. With the 24-hour track forecast errors still above 100 km on average, the contingency of being hit or not hit by the core of a TC remains too uncertain to avoid taking preventive measures that may eventually turn out to be excessive or unnecessary. This is especially the case for small islands like La Reunion or the metropolitans like Hong Kong where the issue may amount to an "all or nothing" question when a midget TC passes nearby.

An indication of the best possible forecast skill is provided by that obtained by the United States National Hurricane Center at Miami, staffed by specialist hurricane forecasters who have the best available initial location accuracy and forecast track guidance. The mean errors for the decade 2001-2010 were around:

**Table9.1:** Track forecast errors for NHC (Miami)

| **Forecast Period (h)** | **12** | **24** | **48** | **72** |
|---|---|---|---|---|
| Mean Error (nm) | 45 | 90 | 180 | 270 |
| Mean Error (km) | 83 | 167 | 333 | 500 |

Whilst current research and model development (Chapter 3) indicates that a substantial improvement in forecast accuracy is occurring, the best forecast performance that can be reasonably expected will result in errors greater than half those listed above. This should be accounted for in planning for future warning strategies.

### 9.4.2 Strike probability forecasts

One method of quantifying the uncertainties inherent in a particular situation is by the issue of strike probability forecasts (Chapter 3). However, many forecasters are unaware of the practical significance of these statistics, since forecasts are judged correct, partially correct or incorrect according to other criteria. They thus may not appropriately relate hit or miss probabilities to suitable preparedness measures by people living in the threatened areas.

For the purpose of determining hurricane strike probabilities in the U.S.A. a hit is adjudged a successful forecast for appropriate preparedness decision-making if actual landfall occurs within 100 kilometres to left or right of predicted landfall. This is the approximate length of coastline that may be considered liable to the severe destructive power of hurricane-force winds and storm surge encompassed by the central core of an intense tropical cyclone (Carter 1983).

A stricter interpretation would incorporate the left-right asymmetry due to storm motion. The probabilities of successful hit predictions, given the above mean errors for specific forecast validity periods can be shown to be:

**Table9.2:** Probabilities of successful hit predictions

| **Forecast Period (h)** | **72** | **48** | **36** | **24** | **12** |
| --- | --- | --- | --- | --- | --- |
| Maximum Probability (%) | 10 | 15-20 | 25-30 | 45-55 | 70-80 |
| Miss to Hit Ratio | 8:1 | 6:1 | 4:1 | 2:1 | 2:3 |

Thus the odds of a specific location forecast issued more than 36 hours in advance of estimated landfall being assessed as a successful hit prediction are rather slim. An even probability of success is not reached until nearing 18 hours before landfall.

As a caveat to this discussion it should be noted that the narrow assessment used in the U.S.A. for hit and miss criteria, based on the premise that the destructive power of a mature cyclone will be limited to a spread of destruction of about 200 km from the coastal crossing of its centre, may be expanded for the Asian and other regions. Asian cyclones tend to be larger than those in the North Atlantic (Merrill 1984). In developing countries the impact of winds within 300 km or so of the centre of a mature storm may well cause significant damage to modest houses built of traditional materials. Similarly, gale to storm force winds may develop very rough seas sufficient to endanger the huge number of small craft engaged in fishing off most tropical coasts.

### 9.4.3 Expect the unusual, it is normal

As has been emphasised in Chapter 3, the view of a "normal" TC track extending along a straight or neatly parabolic arc into the subtropics while the TC develops along the standard Dvorak climatological curve is actually the exception. The majority of TCs are associated with some sort of abnormal behaviour. Examples include:

- rapidly changing trends in motion and intensity;
- monitoring difficulties, especially related to the central core of the TC and obscuring effects of wind shear, and unusual asymmetry in the strong wind circulation;
- large potential errors in predicting the track of TCs for longer periods prior to a clear indication of initial movement becoming apparent;
- several TCs interacting (Fujiwhara effect) and simultaneously threatening within the same area of warning responsibility (e.g., Philippines and mainland China);
- quasi-stationary TCs close to landfall (e.g., China, Australia, United States);
- TCs, which develop or intensify close to a populated coastline or island group, sometimes from an origin over land (e.g., Australia, Pacific Islands, Caribbean, Philippines);
- TCs approaching a vulnerable coastline at an acute angle so that minor forecast errors introduce large landfall uncertainty (e.g., India, US Atlantic coast, Western Australia, China NE coast);
- TCs, which occur outside or at the margin of the normal TC season, or in locations not seriously threatened for a decade or more (Gulf of Thailand, Sri Lanka, Hawaii);

- TCs, which threaten communities during a high pitch of seasonal activity such as harvesting, festivals, holidays, often with workers or tourists from non-TC areas;
- TCs, which simultaneously offer a greatly varying threat to adjacent coastal areas in the same country due to irregular coastal configuration of varying physical vulnerability (e.g., Gulf of Thailand, Gulf of Carpentaria);
- extratropical re-intensification accompanying loss of typical TC core structure affecting monitoring (e.g., SW Australia, New Zealand, Japan, NE United States);
- TCs with physical characteristics that vary substantially from their immediate predecessors;

These "unusual" characteristics must be properly accounted for in warning strategies. In particular, communities need to understand that TCs are capable of erratic behaviour and that the uncertainty in warnings is designed to account for such behaviour.

While track forecasts have improved, the main roadblock of TC forecasting remains with the lack of significant improvement in TC intensity and structure change forecast. Limiting factors for TC intensity forecasting include the lack of understanding of rapid changes in storm structure and intensity, routinely available in situ observations, and high-resolution coupled air-sea-land models (Chen et al., 2007). Although forecasters have now integrated some harbinger signals on the microwave imageries (structure of the convection and low level circulation as seen on 36 or 37 GHz — see example in Fig. 3 of the early stage of development of TC Ernest as seen on microwave imageries) that may help anticipate a rapid intensification (RI) to come, this may often be at a rather short notice. A situation of RI can become critical when it occurs close to a populated area with the landfall happening soon after, since the lead time may then become too short for the issue of a proper warning to the public.

An example of a potentially catastrophic rapid intensification event is shown in Figure 9.2. On 20 January 2005 Tropical Cyclone ERNEST developed very rapidly on the northern Mozambique Channel passing from 25 to 65 kt max 10-min average winds in 24 hours' time. This unexpected evolution (all numerical models had failed to predict this RI and even the genesis of this storm — some even hardly seeing a significant low) resulted in gale force winds affecting Mayotte Island (easternmost island of the Comoros Archipelago). As a result no warning had been issued for the island. But would have the island been situated 150 km to the southwest it would have been hit by a stronger storm and would have undergone gusts over 150 km/h by the end of the afternoon. In that situation the 1st warning would have been issued only 8 hours prior to the occurrence of such cyclonic conditions — too short for activating the warning process.

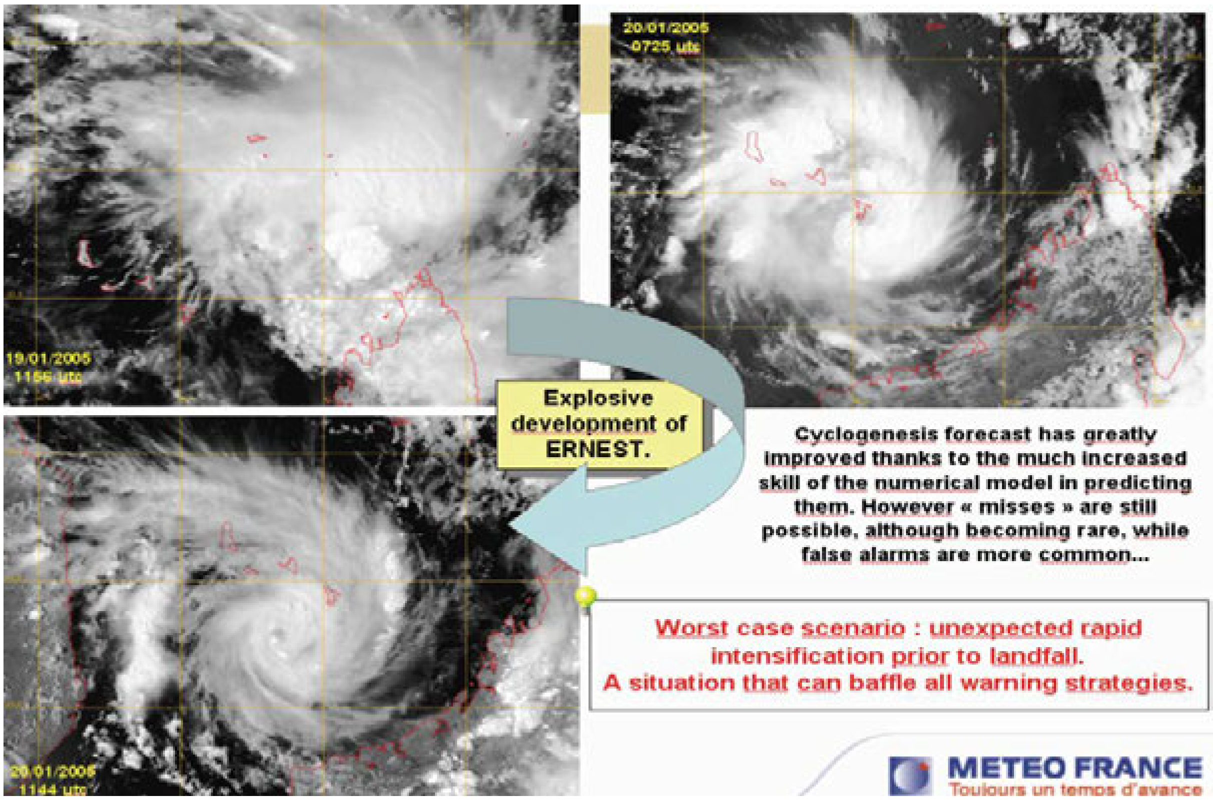


**Figure 9.2.** 20 January 2005 satellite imagery of Tropical Cyclone ERNEST illustrating very rapid intensification in the northern Mozambique Channel from 18 January 2005 to 20 January 2005. The intensity increased from 25 to 65 kt max 10-min average winds in 24 hours.

## 9.4.4 Warning content and terminology

The content of a TC warning message is of prime importance in an effective warning system. This information has to be converted into convincing and credible images of the approaching threat, which will create a climate of expectancy and responsive action over a very wide spectrum of people with differing preparedness interests and responsibilities. In countries, which possess a communications and media infrastructure capable of presenting a current visual view aided by expert commentary, the reliance on the technical formulation of a warning message is not so high. In most countries affected by TCs, however, one prime warning message for the general public often carries the responsibility of catering for a vast diversity of user needs. At best a limited number of messages semi-tailored to the needs of major socio-economic groups must suffice. In some cases, the dissemination relies on a series of relays, often by telephone and single-side-band radio, during which the message may be abbreviated or distorted and loses some of its original intent. These dissemination modes tend to degrade and often become inoperable as a TC approaches the area of interest.

The format, content and terminology of warning messages should be determined by the status of the warning phase, category of user, level of public understanding, vulnerability of the threatened areas, particular medium used for dissemination, and regional agreements on standardised procedures. A major difficulty is that the messages are prepared by technical

<<Previous Next>>

experts, and even the most obvious technical terms can often cause considerable confusion amongst many members of the community. For this reason, careful use of key words, backed up by public education programs, is essential.

Inspection of recent warnings issued by many different warning services indicates a wide variety in either pragmatic or narrative style, and a seemingly reluctance to introduce new styles of persuasiveness and format to focus on the most critical information. Examples of various styles of messages are shown at the end of this chapter.

The optimum design for TC warning advices, including audio-visual signals, is discussed in detail in WMO (1990). This discussion takes into account the diverse requirements of users and the available communication modes. Special consideration should be given to the limited attention span of most people and their ability to retain the important elements of a message. The essential information may be determined through surveys of disaster specialists, the media and communities. The use of information and communications specialists and social scientists is highly advisable.

### 9.4.4.1 Forms of presentation

In transforming weather forecasts into warnings, it is essential that the warning messages be clear and understandable, so that the warning recipients know how to incorporate the information into their decision-making process, and most importantly, be prepared to take appropriate actions. The warning messages should be developed so that they take full advantage of the dissemination platforms and target the greatest number of warning recipients to enable effective communication of the warnings. The broadband capacity of the Internet allows detailed information such as real-time observational data, radar and satellite imageries, predicted TC tracks, etc. to be made available to the public. This enables the more sophisticated users to assess, for themselves, the risk associated with their particular circumstances and to devise response actions accordingly.

A lot of work was done by RSMC La Reunion to design a new specialized website in order to provide the best access to the Centre's products (both real-time and archived) and to relevant information such as satellite imageries and NWP outputs. The site is a bilingual (French and English) site, which includes GIS-related facilities for "dynamical" visualization of maps of tracks and related data such as wind radii. It was opened in April 2010.

The NHC in Miami, Florida, USA issues TC watches and warnings in both textual and graphical advisory products. TC watches and warnings for the United States are issued in a coded text product called the Tropical Cyclone Watch-Warning Product (TCV). This product summarizes all new, continued, and cancelled TC watches and warnings for the United States in a coded format that is used by computer plotting programs. Areas under a TC watch or warning in the United States are defined using a list of well-known, recognizable geographical locations along the coast. The NHC also provides a summary of all coastal TC watches and warnings in effect in the TC Public Advisory and Forecast/Advisory. These are text products that include TC forecast information. The NHC also graphically depicts the watch and warning areas for the United

States and foreign countries on the TC Track Forecast Cone and Watch/Warning Graphic (Fig. 9.3) and the Initial Wind Field Graphic. In addition, NHC provides watch/warning information in GIS format with each forecast advisory.

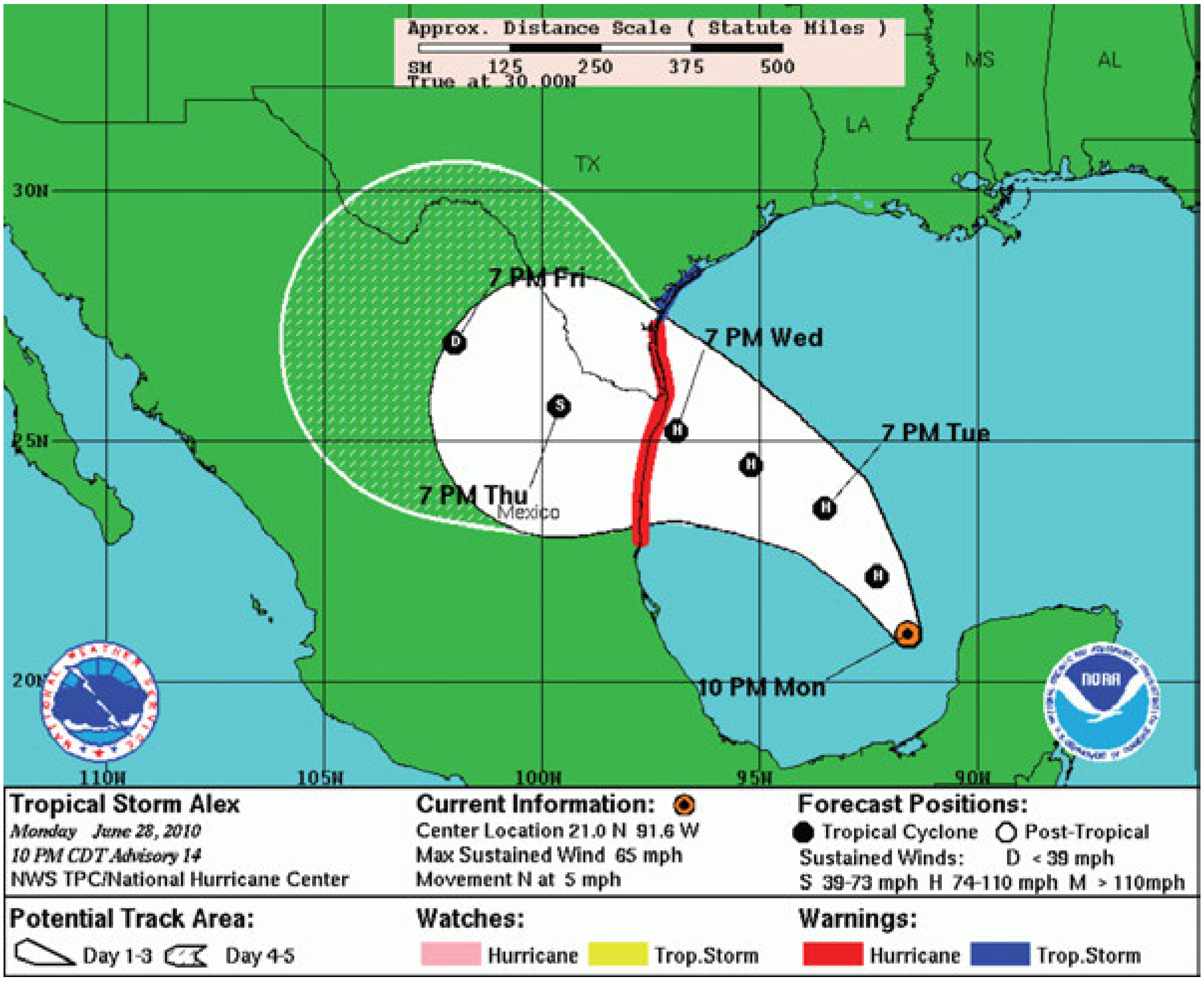


**Figure 9.3.** Example of the NHC Track Forecast Cone and Watch/Warning Graphic. The graphic depicts the most recent NHC forecast track of the center of a TC with representation of coastal areas under a hurricane warning (red), hurricane watch (pink), tropical storm warning (blue), and tropical storm watch (yellow).

CMA labels 24-hour and 48-hour warning zones within its responsible area. Normally, CMA issues TC track forecasts 4 times a day at 00, 06, 12, 18 UTC. When a TC enters the 48-hour warning zone, CMA provides an additional 4 forecasts at 03, 09, 15, 21 UTC. With a TC further approaching the mainland and entering the 24-hour warning zone, CMA issues TC position and intensity every hour to the meteorological communities and public in a variety of ways. Similar product density is provided by warning centers in the USA (NHC, CPHC, and the Weather Forecast Office in Guam for the US-affiliated islands of Micronesia).

Bulletins of TC advisories are issued by RSMC Tokyo in text and CREX, the table driven codes introduced by WMO to replace the various alphanumeric codes. Those in Extensible Markup Language (XML) format, an Internet-based language format which facilitates the exchange of data between incompatible systems and applications, were disseminated to domestic users starting in 2011.

### 9.4.4.2 Communicating forecast uncertainties

As weather forecasting involves an element of probability, it is important that the forecast information provided to emergency services and government decision makers includes a discussion of any uncertainties, so that they can factor that information into their decisions. With increased skill and confidence in the forecast tracks of TCs, there are now situations where we can save resources by not issuing a warning when and where we would have issued one a few years ago. Having a much better idea of the degree of uncertainty of the forecast also helps to convey the degree of confidence of the forecast to the users and decision makers. In 2007, based on the past 5-year mean track forecast errors, CMA introduced the 70% probability circle into their official TC track forecasts. In Hong Kong, uncertainty circles are also presented, the radii of which represent the historical errors of the respective forecast range.

Instead of referring to simple climatological uncertainties, RSMC La Reunion is working on a dynamical approach to convey track forecast uncertainty based on the outputs of the ensemble prediction systems (EPS) - www.wmo.int/pages/prog/arep/wwrp/new/documents/Reunion_TCens.ppt (9MB). The tests using ECMWF EPS data have revealed that the uncertainty of the spread of the ensemble (with 50 members) contains skillful information on the uncertainty in the track forecast at least up to the 72-hour range. A plan was underway at La Reunion to produce the EPS-based dynamical cones of uncertainty with radii of the 75% probability circles and include them in the operational products on the centre's website by the end of 2010.

RSMC Tokyo also issues radii of the 70% probability circles of four and five-day track forecasts determined using the degree of forecast uncertainty derived from the ensemble spread of the JMA's TEPS.

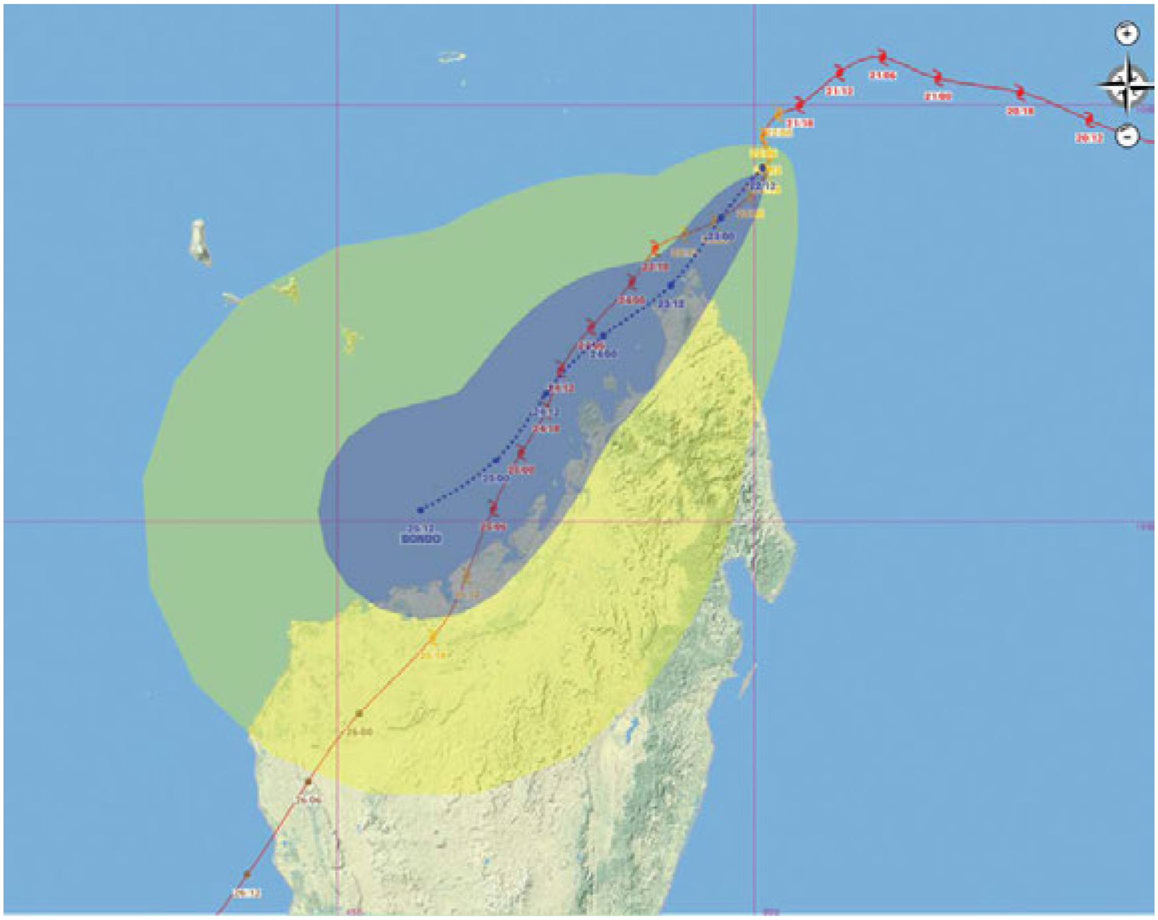

**Figure 9.4.** An example illustrating the difference between the "cone" of uncertainty based on the spread of the ensemble forecast from ECMWF model (radii of the 75% probability circle in blue) and a climatological "cone" of uncertainty (in yellow) in the case of limited uncertainty in the track forecast for Tropical Cyclone Bondo issued at 12 UTC, 22 December 2006.

In US, when issuing TC watches and warnings, the NHC forecasters take into account the uncertainties in the track, size, and intensity forecasts. Typically, the NHC forecasters determine the watch or warning area by adding the 5-year mean track forecast error to the deterministic forecast track, after accounting for the forecast size of the wind field. Uncertainties in the timing of the arrival of tropical-storm-force winds, and in the size and intensity of the TC are also considered when determining the type of watch or warning (tropical storm vs. hurricane) and the area to be placed under a TC watch or warning. Figure 9.5 illustrates how track uncertainty is incorporated when determining coastal watch and warning areas.

<<Previous Next>>

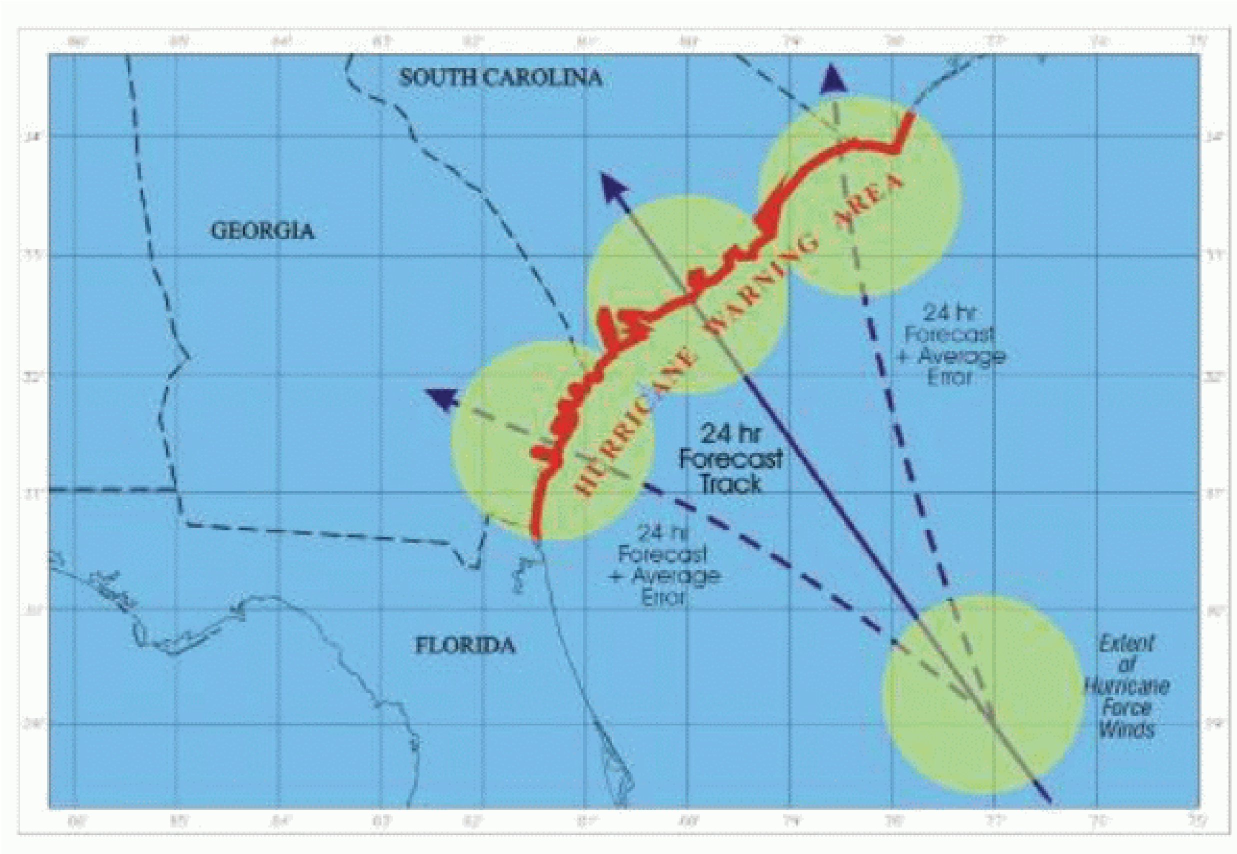


**Figure 9.5.** Example of how the NHC incorporates forecast uncertainty in the placement of coastal TC watches and warnings. NHC would issue a hurricane warning about 36 hours prior to the expected on-set of hurricane force winds. NHC would also likely issue tropical storm warnings for areas on either side of the hurricane warning where tropical-storm-force winds are expected to occur.

NHC also communicates forecast uncertainty by issuing text and graphic wind speed probability products. These products show the chance of 34-, 50-, and 64-kt or greater winds occurring at individual locations during the 5-day forecast period (Fig. 9.6). The probabilities are calculated using a set of 1000 realizations, or alternate tracks and intensities, that vary around the official forecast based on a Monte Carlo sampling of the previous 5-year errors in NHC track and intensity forecasts (DeMaria et al., 2009). Figure 9.6 shows an example of the hurricane-force-wind probabilities when a hurricane warning was issued for south Texas and northeastern Mexico for Tropical Storm Alex in June 2010. As indicated by the product, the highest probability of hurricane-force-winds at any individual location within the warning area was about 18% (at Brownsville, Texas, located near the Mexico-U.S. border). This example illustrates how emergency planners often deal with small probabilities of hurricane force winds when making evacuation decisions.

<<Previous Next>>

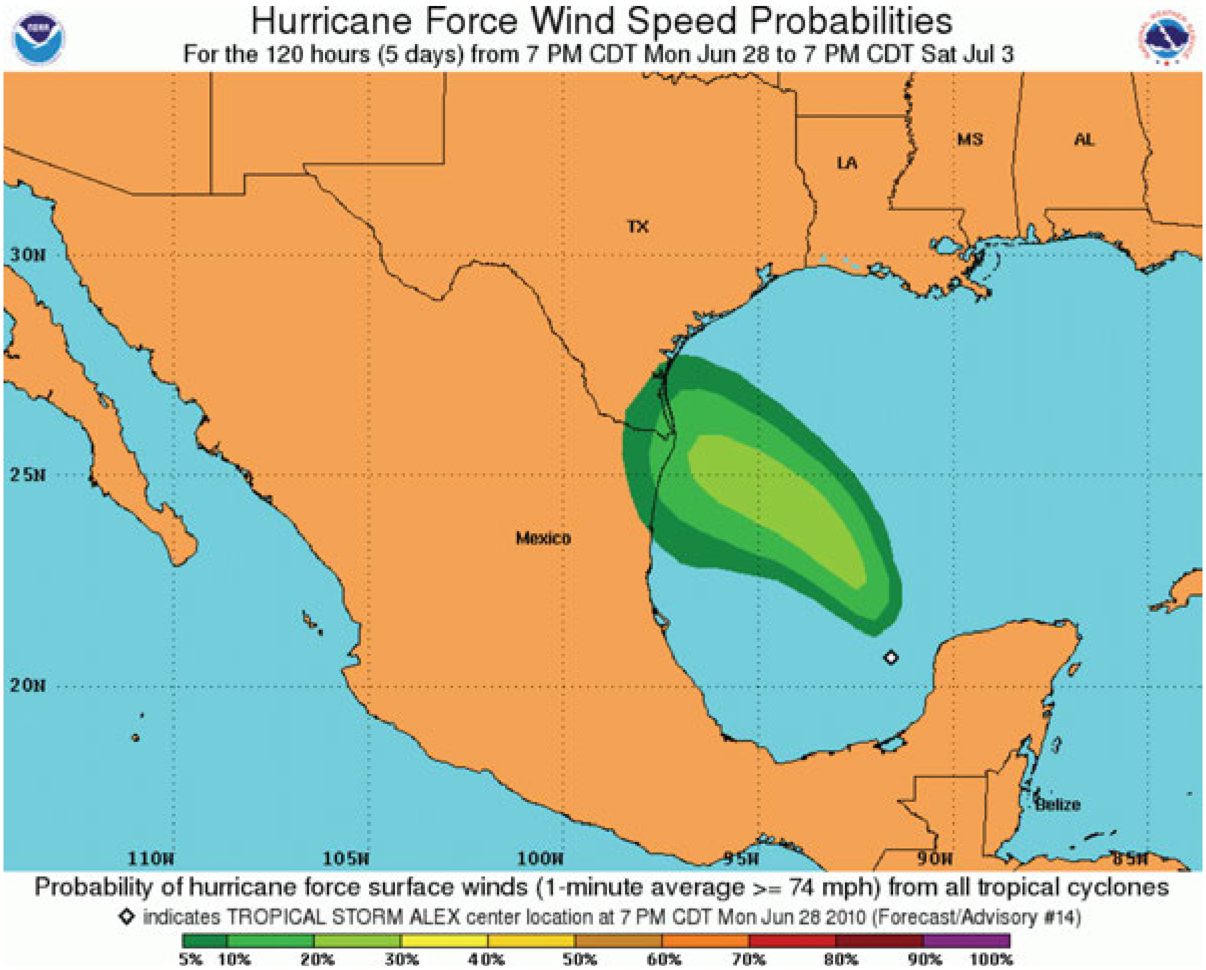


**Figure 9.6.** The probability of hurricane-force-winds during the next 5 days at individual locations issued by NHC.

### 9.4.4.3 From weather prediction to weather impacts prediction (National Research Council, 2010)

The atmospheric community has been spending a lot of efforts to improve the accuracy and resolution of the atmospheric quantities predicted by NWP models, such as temperature, wind and precipitation. Users have largely taken these weather predictions and used them in their own decision support and risk management process. However, this approach has not always produced the desired outcome, especially when complex weather forecasts are difficult to understand and yet require public action in response to the forecast. For instance, probabilistic forecasts of a land-falling hurricane's track and intensity, without specific impact information such as timing and location of storm surge, extent of flooding, extreme winds, and power outages, are insufficient for effective responses from emergency managers. A new paradigm is for both the scientists and the end-users to work together to provide explicit weather impact forecasts and warnings. This transition from simple weather prediction to weather impacts prediction demands a full integration of the physical sciences with the socioeconomic sciences. One key component of the prediction of impacts is to more fully exploit the capabilities of ensemble modeling to produce probabilistic forecasts of atmospheric quantities, and for these to then be used to generate probabilistic forecasts of the weather impacts, thereby enabled improved decision making.

Fig. 9.7 shows an example comparing traditional portrayals of weather forecasting, and the potential for impacts forecasting. The weather services should place priority on providing not only improved weather forecasts but also explicit impact forecasts.

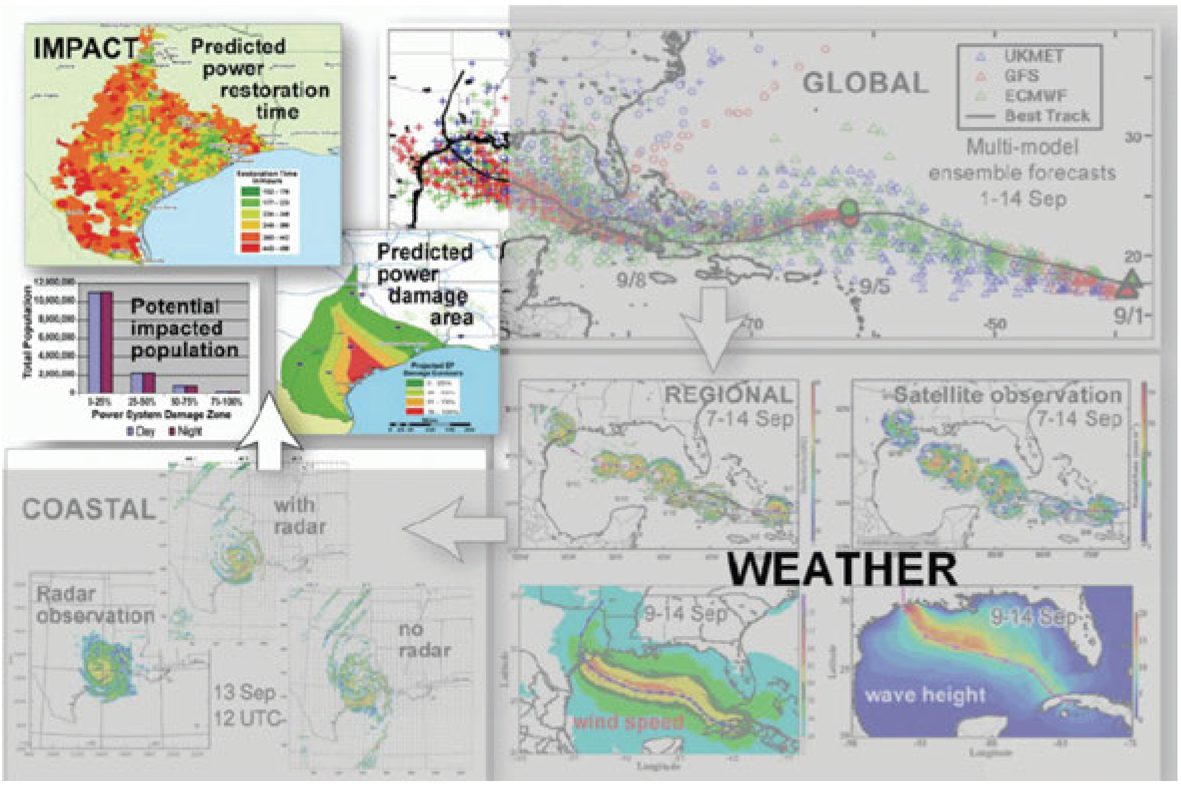


**Figure 9.7.** Schematic representation of weather impact forecasting. At upper right and lower right are traditional depictions of predicted TC paths, wind and wave height swaths, rain, and satellite observations. At lower left are radar observations and NWP radar renditions of the TC. The figure in the upper left predicts areas of power outages and restoration times. (National Research Council, 2010).

### 9.4.5 Warning dissemination

#### 9.4.5.1 Various modes of warning dissemination

Timely delivery of warnings to the public is essential for disaster preparedness and mitigation. In India and Vietnam, like most other countries, the TC warnings are disseminated to users through telephone, fax, email and GTS. These warnings/advisories are also put on the website of the Hydro-Meteorological Service of Vietnam (VHMS, www.nchmf.gov.vn) and the Indian Meteorological Department (IMD, www.imd.gov.in). Another means to transmit the warning is through the Voice of Vietnam (VOV) television channel. During TCs, VHMS staff will attend live interviews on VOV to explain to the public the latest weather situation. This kind of warning dissemination is one of the fastest and most direct ways to reach the public. At IMD, one other

<<Previous Next>>

effective mode of warning transmission is via IVRS (Interactive Voice Response system). The requests for weather information and forecasts from the general public are automatically answered by this system. Besides, high speed data terminals (HSDT), installed across the whole country, are capable of sending short warning messages as SMS and the whole warning message as email.

Coastal TC watches and warnings issued by the NHC are officially disseminated via the NOAA Weather Wire. Watch/warning information is also available on the NHC Internet website and email. While email is not the official NHC mechanism for warning dissemination, this delivery option has become quite effective for NHC users. External partners such as the media and emergency managers play a critical role in the dissemination process by relaying watch/warning information to the general public.

During hurricane threats, NHC typically makes spokesperson, usually the NHC Director, Deputy Director, Hurricane Specialist Unit Branch Chief, or one of the Hurricane Specialists, available to the media. When hurricane watches or warnings are in effect for the United States, NHC activates a media pool, which allows local and national media to schedule short windows of time to interview the spokesperson. NHC also activates a Hurricane Liaison Team (HLT) to assist in the communication of information with federal and state emergency responders. The HLT is led by the U.S. Federal Emergency Management Agency and is staffed by emergency managers and meteorologists from outside the affected region. Informational briefings, typically led by the NHC Director or Deputy Director, are provided to federal and state emergency managers through the HLT when it is activated. The channels through which the warnings are relayed to the public have indeed, undergone evolvement, in response to user needs and taking advantage of the advancement of communication technology. Television and radio remain the most popular means of dissemination by HKO. This is followed by the HKO web site.

The warning recipients span a wide spectrum, ranging from the little-educated and the underprivileged to sophisticated users capable of assimilating large amount of information themselves. As shown in Fig. 9.8, the rapid rise in internet usage has not diminished the use of telephone calls to get weather information. It illustrates very well the persistent needs of a sector of the community which still relies on simple, cheap technology to access weather information or warnings. While adding advanced technology into their operation, NMHSs should not forget the former category of recipients, otherwise, the most vulnerable sector of the community would be left out in the disaster mitigation effort. In addition to a "pull", the Internet also allows an information "push" to the user. It also makes individual alerting and customization possible. A case in point is the provision of lightning location information by HKO on the Internet. Here a user may pick his/her location of interest and choose the alert range circles for receiving distinct audio and/or visual alarms when lightning occurs within a particular alert range. Coupled with geographic information, user-specific alerts thus set up provide fast and very relevant information, which is conducive to prompt and effective response actions.

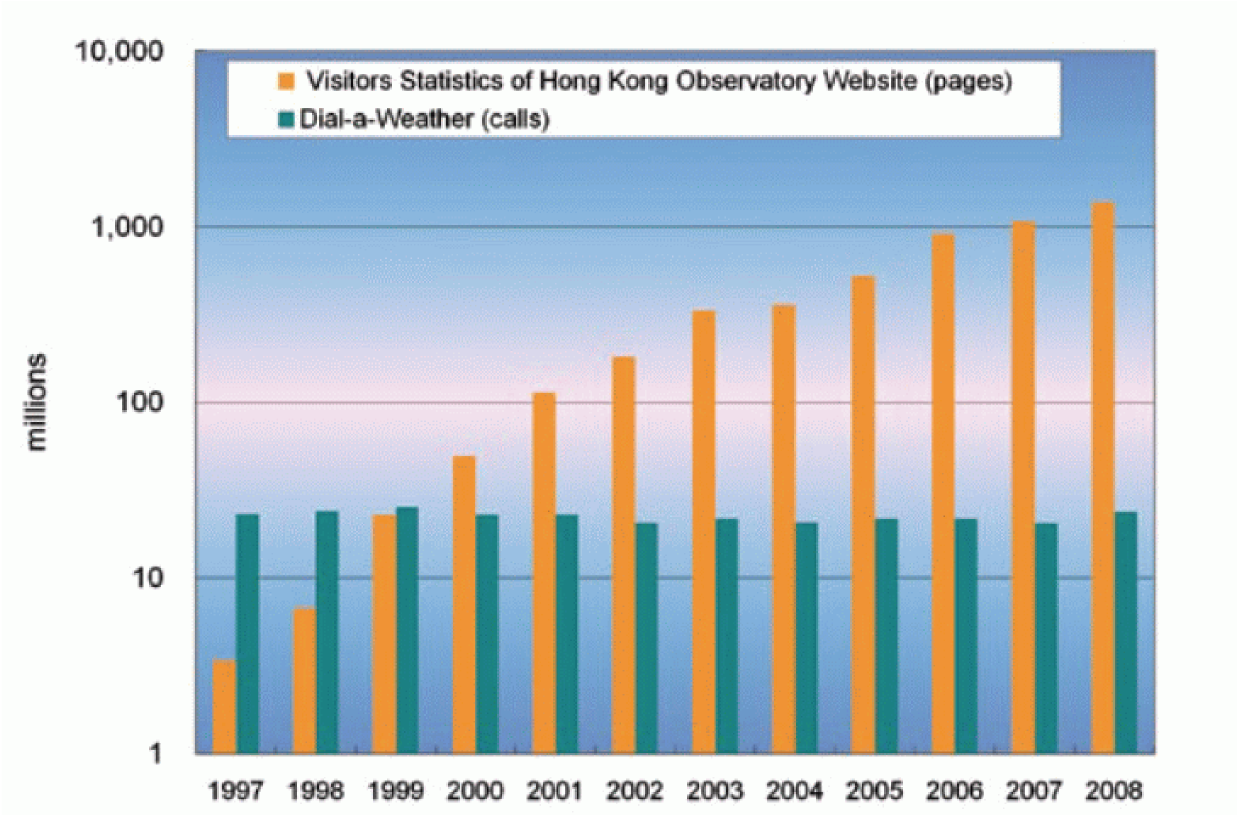


**Figure 9.8.** The usage of telephone for weather information remained steady in spite of growth in internet usage.

The HKO recently has also started exploring social networking services for warning dissemination. The Twitter service in both PC and mobile setup (Fig. 9.9) is being tried out. Weather warning, in the form of a "Tweet", will be published on the Observatory's Twitter profile and spread to all users. Tweets are text-based messages of up to 140 characters, which are suitable for conveying simple warning messages, in a one-way broadcast mode. The advantage of using Twitter is that it is relatively inexpensive to implement and maintain. The drawback is that the dissemination relies on the proper functioning of the Twitter service. At present, many international and national weather organizations are using Twitter for information dissemination. Examples are: WMO (http://twitter.com/WMOnews), UK Met Office (http://twitter.com/metoffice) and NOAA (http://twitter.com/usnoaagov).


**Figure 9.9.** Warning message issued via Twitter.

### 9.4.5.2 Warnings to the last mile

The warning messages must be disseminated to all affected persons and groups, including those unable to receive television, radio or the Internet. This entails the operation of a robust warning dissemination system which could withstand the furious onslaught of TCs and deliver the warning messages through to the "last mile/kilometer".

For quick dissemination of warning against impending disaster from approaching cyclones, IMD has installed specially designed receivers within the vulnerable coastal areas for transmission of warnings to the concerned officials and people using broadcast capacity of INSAT satellite. This is a direct broadcast service of TC warnings in the regional languages meant for the areas affected or likely to be affected by the TC. There are 352 Cyclone Warning Dissemination System (CWDS) stations along the Indian coast; out of these 101 digital CWDS are located along Andhra coast. The warning bulletins are generated and transmitted every hour via the INSAT in C-band. The warning distribution is selective and will be received only by the affected or likely to be affected stations. It is a very useful system which has saved millions of lives and enormous amount of property from the fury of TCs. The advantages of C-band transmission are its bigger footprint, high bandwidth, and less likely to be affected by severe weather.

EMWIN (Emergency Managers Weather Information Network) and RANET (RAdio InterNET) are two communications programs that have had a great impact on advancing the warning capabilities and strategies of many developing countries, especially in the Pacific basin. EMWIN has been discussed at many WMO conferences and workshops, and RANET was discussed in some detail at the International Workshop on Tropical Cyclones (IWTC)-VI in San Jose, Costa Rica by Anderson-Berry (WMO, 2007). Since IWTC-VI, several new capabilities have come on-line or are being tested.

EMWIN has been in use for nearly two decades in the US and for over a decade in the Pacific basin as a low-cost method for passing weather and warning information to emergency managers, weather service offices, and other critical locations such as hospitals and college campuses (http://www.nws.noaa.gov/emwin/). In some cases, EMWIN has been used as a backup system, but for many developing island nations, it has been the primary or only source of reliable weather information. GOES satellites that no longer provide meteorological data but that still have communications capability are sometimes repositioned near the International Date Line to support EMWIN and another US communications program called the Pan-Pacific Education and Communication Experiments by Satellite (PEACESAT) (http://www.peacesat.hawaii.edu/). This program transmits, via satellite from the University of Hawaii and via satellite and HF Radio from the University of Guam, important distance education programs and critical storm and warning information to many isolated islands in the Pacific basin. The program also coordinates search and rescue in the Micronesian islands and passes daily weather information to the remote islands. Occasionally, the operator at the PEACESAT terminal at the University of Guam will call forecasters at the Weather Forecast Office on Guam (WFO Guam) and request them to provide a live, real-time assessment of upcoming weather. In the US, EMWIN has been using the digital Low Rate Information Transmission (LRIT) standard in areas covered by GOES-East and GOES-West. LRIT and EMWIN are now being made available in other parts of the Pacific not in the footprint of the operational GOES-West satellite (http://noaasis.noaa.gov/LRIT/). A High Rate Information Transmission (HRIT) capability is being developed for US users in the future (http://www.goes-r.gov/users/hrit.html). This capability will combine the current LRIT broadcast services with the EMWIN broadcast services and transmit both at a significantly higher data transfer rate.

The purpose of RANET (https://www.wmo.int/pages/prog/www/Planning-Impl/RA-5/2005-APIA/Ranet-Emwin-Doc5-2%284%29.pdf) (Clarke et al, 2010) is to get important information about TCs and other hazards down to the community level. Over the years, RANET has taken on many forms, especially in terms of the types of hardware and communications methods used. In the western Pacific, two new uses of RANET are highlighted. The first is the installation of FM radio stations (Fig. 9.10a) in some island weather facilities, allowing them to pass critical weather and warning information from the weather service office directly to the community level. The second is the development of the "Chatty Beetle" (http://beetle.ranet.mobi/) (Fig. 9.10b), a durable, low-power, easy-to-maintain, two-way communications device designed to get emergency warning information down to the most isolated locations, such as remote atolls and islets. Both of these systems have proved to be very useful, and could be used in many other locations.

In July and August 2008, Mr. Bruce Best of the University of Guam and his team installed an 80-foot FM radio transmitting tower and an FM transmission and recording console at the Weather Service Office (WSO) in Chuuk State, Federated States of Micronesia (FSM) (Best and Marquez 2008). There was no reliable radio station in Chuuk State, and the island State is very vulnerable to numerous natural hazards such as typhoons, flash floods, mudslides, droughts and high surf events. An FM Radio solution was ascertained as the most economical way to pass critical weather information and warnings to the 40,000+ residents living on islands in the Chuuk Lagoon. Special radios, such as the VHF radios that are required with the US NOAA Weather Radio program, are not needed. In fact, simple transistor radios, car radios and "boom boxes" can be used by residents to get the weather and warning information. A repeater was later installed to extend the range and coverage of the signal to more locations in the lagoon. In 2009, a similar FM radio station was installed in Majuro, Republic of the Marshall Islands (RMI). Since there is reliable radio service there, the FM station is used in times of emergency rather than routinely. A repeater is planned to push the signal to the neighbouring atoll of Arno in the RMI. This FM radio concept is an inexpensive, highly reliable, and relatively simple method to pass critical and routine weather information to the public. It could be considered as a potential solution for developing countries with communications challenges, especially those oceanic nations with small islands in close proximity or inside lagoons.

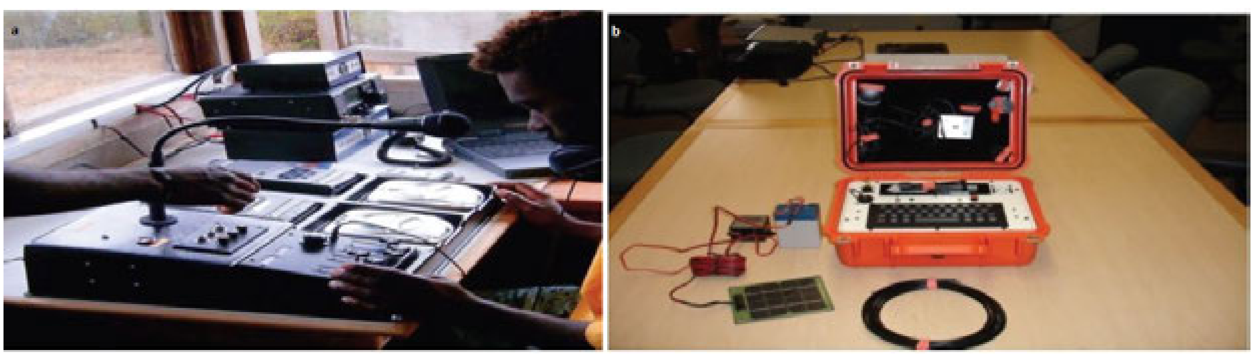

**Figure 9.10.** (a) Wantok FM radio Station similar to the one installed at the Weather Service Office in Chuuk Lagoon, Federated States of Micronesia; (b) The "Chatty Beetle".

## 9.5 Hazard, vulnerability and risk assessment

Because of the inherent forecast uncertainty, TCs initially offer a macroscale threat to large areas and significant populations. This condenses to a mesoscale highly destructive impact in which the greatest loss of life and property generally occurs in small areas comprising a small subgroup of the autonomous local government authorities initially under threat. Since the warning task is to persuasively *alert* and to *promote response* to counter this developing threat, it follows that any developments in the warning system should commence with hazard risk and vulnerability assessments of the elemental local government authority areas. When integrated, these indicate the total vulnerability of all components of the system, districts, provinces, and nations. However, each house has its own vulnerability and only sustained community programs can hope to bridge the gap between the formality of government protection at the higher level and the street -by-street level of the local community.

In several advanced countries, notably the USA, detailed hazard risk and vulnerability assessments, often initiated by meteorologists themselves, have been performed over much of their cyclone-prone coastal zones for many years. This preparedness homework has enabled detailed evacuation planning to be implemented on the basis of operational processing of the SPLASH and SLOSH storm surge models in accord with bathymetric and topographic risk mapping, assisted by community behavioural response studies in the most vulnerable sectors. This capability is incorporated in recommended response activity announced in hurricane local statements issued by national weather service offices around the US coast that follow authoritative national hurricane advisories issued by the NHC. Detailed topographic mapping makes it possible to recommend evacuation on a street-by-street basis in respect of forecast storm surge inundations augmented by heavy rainfall runoff.

Regrettably it is recognised that although most other countries have published information on the frequency of cyclone occurrences, and some have computed return periods for cyclones of stated intensity or cyclone parameter statistics, only a few countries have undertaken comprehensive vulnerability assessments, especially at community or district level. The absence of adequate hazard mapping and skills may have contributed to this situation. A result is the almost complete absence of localised contingency action plans in these countries, which negates many of the benefits of improved warnings and inhibits the deployment of warning strategies.

### 9.5.1 Quantification of risk

Vulnerability and risk analysis provides a structured analytical procedure to identify and quantify hazards and to estimate the probability and consequences of their occurrence. It must be emphasised that the absolute risk is a complex, multiplicative function of the hazard threat level, the vulnerability of a community and the consequences of the event on the community. In an illustrative sense, this means that:

**Disaster Risk = Hazard or Threat x Vulnerability x Consequences.**

Say we were to rate the hazard and vulnerability on scales of 1-5, then a community with high vulnerability and hazard levels of 5 would be many times more at risk (25) than would a community with low levels of 1. However, if the consequences are low or negligible, then the risk will be low even with high threat and vulnerability levels. If the consequences of an event to a population are low, that population is said to have high resiliency.

### 9.5.2 Hazard or threat assessment

Although many countries use designated cyclone warning phases or stages, few have adopted scales which combine a rating of the intensity of cyclone parameters with corresponding estimates of the typical damage that may be expected. Examples of this categorisation include the US Saffir-Simpson Hurricane Scale (Simpson 1974), the US Saffir-Simpson Tropical Cyclone Scale (Guard and Lander 1999), and the Australian Cyclone Severity scale, all of which classify cyclones of hurricane intensity from 1-5, weakest to strongest. The Saffir-Simpson Tropical Cyclone Scale also utilizes two tropical storm categories to include sub-hurricane-force winds. It is recommended that such categorisations be undertaken by all countries with a tropical cyclone threat.

The hazard/threat component can be assessed in terms of the frequency return period or recurrence interval of a particular intensity category for the specified location. This method is particularly useful in countries where detailed observations are not available, and assessment is best made using derived parameters from the known tropical cyclone statistics. These scales are also extremely useful for planning and exercise purposes. Alternatively, return period estimates of particular cyclone parameters, such as maximum wind gusts, storm surge heights, river flood levels or rainfall intensities may be developed or estimated. These latter criteria are favoured for engineered structural mitigation measures. In any case, an estimate is required of the return period frequency of cyclones of each intensity category as guidance to provide an objective indication of the cyclone hazard in each coastal sector.

For the purpose of general community preparedness a worst-case scenario for a period of 30 years may be reasonable. If this is translated into appropriate contingency planning, any cyclone of lesser intensity should not cause major unexpected adverse effects (provided community vulnerability does not increase). Preservation of essential community lifeline facilities (hospitals, power and water supplies, communication systems, meteorological radar tracking stations, cyclone shelters and operations centres etc.) require design criteria for a longer time period.

National standards associations generally determine regional engineering design wind loadings. An indicative example, normalised by Australian Cyclone Severity Scale (or category), for a stretch of coast from Port Douglas to Fraser Island on the Australian East Coast and applicable to 50 km inland is (SAA, 1989):

**Table9.3:** TC Occurrence rates on Australian east coast

| **Category** | **Cat 2**<br>**<170 km $h^{-1}$** | **Cat 3**<br>**170-225 km $h^{-1}$** | **Cat 4**<br>**226-280 km $h^{-1}$** | **Cat 5**<br>**>280 km $h^{-1}$** |
|---|---|---|---|---|
| Occurrence/year | 1/3 | 1/6 | 1/30 | 1/100 |

These statistics refer to cyclones directly impacting coastal areas. Approximately twice as many cyclones in each category threaten the coastal section, without direct impact.

An indication of return periods for tropical cyclone parameters for Andhra Pradesh and West Bengal (which provides a guide for Bangladesh) has been published by Jayanthi and Sen Sarma (1988) based on a 95-year data base. This includes the following statistics for maximum wind speed and storm surge height:

**Table9.4:** TC Occurrence rates: North Inian Ocean

| | **Return Period (years)** | | | | |
|---|---|---|---|---|---|
| | **10** | **25** | **50** | **100** | **200** |
| Andhra Pradesh | 104 kt 3.8 m | 113 kt 4.2 m | 119 kt 4.8 m | 125 kt 5.2 m | 129 kt 5.6 m |
| West Bengal | 90 kt 4.5 m | 105 kt 6.3 m | 116 kt 7.8 m | 125 kt 9.2 m | 135 kt 10.9 m |

The two cyclones that occurred in nearly the same locations in Andhra Pradesh in 1977 and 1990 and the two that occurred in Bangladesh in 1970 and 1991 were of a similar intensity that lay within the 25-50 year return period in this table. This illustrates the problem with literal use of return period statistics. Although catastrophic, with 300,000 and 140,000 deaths, respectively, in Bangladesh, and 10,000 and 1000 deaths in Andhra Pradesh, these statistics illustrate the advances in warning-response systems in these regions. In 2002, the eye of a Category 2 typhoon and a Category 4 typhoon passed across the 50-km long island of Guam in July and December 2002, respectively. Each typhoon produced 24-hour rainfall amounts (610 mm) that were classified as 100-year events. Again, this points out the problem with using return periods: Were these really 100-year events?

### 9.5.3 Vulnerability assessment

Vulnerability comprises the people in their environment and their exposure to the cyclone hazard. The geographical and physical components of provincial, district and local level vulnerability are assessed through a combination of hazard risk maps, detailed demographic maps, and information on supporting community infrastructure and facilities. Such assessment can be made by satellite remote sensing, aircraft photography, and on the ground by surveyors, engineers and urban and rural planners. A good survey will provide details of:

- Siting and constructional integrity of community lifeline facilities, including access roads;
- Proportions of flimsy, partly cyclone-resistant, and cyclone resistant residential housing, commercial buildings and markets;
- Existence and state of maintenance of cyclone protective works, river and coastal dykes and embankments, drainage systems and public shelters;
- Degree of protective forestation and mangroves, which can reduce wind, wave and surge energy.

The non-physical social and economic aspects of vulnerability of a community also need to be assessed. These include a measure of the community's capacity for coping with the occurrence of cyclones by martialing resources and organising effective response actions. Readily assessable elements include:

- The existence of a local counter-disaster council, an equipped emergency operations centre, a cyclone contingency plan of action which has been resourced, implemented and rehearsed;
- Evidence of an ongoing community cyclone awareness program.

An obvious indication of the vulnerability of a community may be found from its performance in coping with a previous cyclone, after noting subsequent improvements.

An extensive program of interdisciplinary training courses entitled "Improving Cyclone Warning Response and Mitigation" is now conducted by the Asian Disaster Preparedness Center (ADPC), based at the Asian Institute of Technology in Bangkok. The ADPC has introduced practical experience for participants through the conduct of field vulnerability assessment studies in towns and villages. Such studies take advantage of any available hazard maps and primarily comprise visual inspections of potentially hazardous terrain, community life and facilities, aided by interviews with officials and residents on cyclone and flood hazard experiences and on the current state of preparedness measures, local communications and warning arrangements. The course participants, comprising meteorologists and hydrologists, disaster managers, engineers, planners and technical personnel interacting in workshop sessions. Reports to a workshop plenary session, supported by maps and sketches, are discussed and published and the total exercise takes little more than a day's work.

While these exercises obviously comprise a fair degree of subjectivity they summarise a good deal of human hazard experience of residents in a short time and probably acquire about 80% of the environmental, physical, and socio-economic information needed for a useful vulnerability assessment. An immediate feel for the community's hazard awareness is gained, as well as knowledge of the cyclone-resistant integrity and maintenance standards of the principal lifeline facilities.

In general, a nation's effectiveness in disaster prevention, mitigation and preparedness is related to its level of economic activity (PAHO, 1992). This indicates that current socio-economic indices, such as per-capita income, may provide one objective basis for quantifying vulnerability in the above equation.

A complementary input to the vulnerability index should come from recent disaster experience. For example, damage evidence in relation to 20 categories of socio-economic activity is clearly noted for the April 1991 Bangladesh cyclone in BCAS (1992). This cyclone effected 10,800,000 people with a total damage of US$2.1 billion, or roughly the per-capita GDP of US$210 (FEER, 1993) This simple analysis could be extended to local districts and normalised on a scale of 1-5. Separate quantification could be developed for deaths and casualties.

Where recent damage statistics are not available, the current per-capita income probably provides an objective basis for relating statistics from other regions and quantifying both the economic and social effects of a tropical cyclone.

Vulnerability depends on several factors. These include: the level of preparedness, the efficiency of response, ability to recover, and the implementation of mitigation measures.

### 9.5.4 Potential disaster risk scales

No objective method has yet been devised to integrate the cyclone hazard and vulnerability into a disaster risk scale similar to the Saffir-Simpson Hurricane (Intensity) Scale. Such a scale would first require the development of a suitable vulnerability scale, as recommended in the previous section, then a method needs to be developed for incorporating this with the hazard scale. It is almost certain that the total risk will be a multiplicative combination of the hazard and vulnerability scales, but research is needed to determine the optimum combination.

Such a scale could markedly simplify the development of warning and response strategies and the allocation of mitigation measures. It could provide a globally consistent indication of disaster risk. The scale could be printed on maps and displayed on computer workstations as indicators of the relative vulnerability of hundreds of autonomous local government areas threatened by an approaching cyclone. National potential disaster risk maps can be prepared and disseminated to indicate an objective measure of the real danger of the threat, compared to previous occurrences, and thus to promote preparedness measures. By agreement an tropical cyclone warning centre could include such information in its advisory warning messages, together with potential disaster risk predictions for each community, in a manner reminiscent of the issue of hurricane strike probabilities in the USA.

### 9.5.5 Conveying forecast uncertainty

Tropical cyclone prediction involves a great deal of uncertainty. There is uncertainty in the limited input storm data and in the even more limited environmental data, uncertainty in the prediction model physics and due to truncated terms, uncertainty introduced by the time-steps, and other, less obvious, sources of uncertainty. Most of the storm data and the environmental input data are indirectly determined. The numerous algorithms that have been developed to derive that indirect data are also sources of uncertainty.

This uncertainty must be conveyed to the general public so that the users understand that there is error associated with the forecast tracks and intensities. While the errors can be estimated, there is uncertainty in those estimates. So, how do we convey this uncertainty to the customers? This has been a perplexing question that has been addressed by many different methods. These methods include uncertainty swaths based on historical error information such as is shown in the US National Hurricane Center depiction in figure 9.3 and by the Japan

Meteorological Agency (JMA) in Tokyo (not shown). Over the last decade, more sophisticated techniques have been developed employing ensemble methods as shown in figure 9.6.

## 9.6 Societal impacts of tropical cyclones

### 9.6.1 Introduction

Despite significant advances in the meteorological science and understanding of tropical cyclones and the associated capacity of sophisticated warning systems, negative impacts upon societies throughout the tropical and subtropical world remain severe. Table 9.5 illustrates the enormous impact of tropical cyclones over the last 110 years. At the beginning of this period, many people died at sea and local communities bore the impact of storms without warning. Yet despite the advances that have been made, losses and impacts of tropical cyclones remain high. In recent years, cyclones such as Katrina's impact upon New Orleans, Jeanne, Ida, Mitch, and Stan in Central America and the Caribbean, and Nargis in Myanmar continued to wreak havoc, destroy structures and cause loss of life.

**Table 9.5** Tropical cyclones by continent from 1900 to 2010.

| | | No. events | Killed | Total affected | Damage (000 US$) |
|---|---|---|---|---|---|
| Africa | Tropical cyclone | 100 | 3,400 | 14,995,592 | 3,079,430 |
| | average per event | | 34 | 149,956 | 30,794 |
| Americas | Tropical cyclone | 537 | 86,332 | 46,918,376 | 402,062,632 |
| | average per event | | 161 | 87,371 | 748,720 |
| Asia | Tropical cyclone | 940 | 1,237,484 | 560,845,477 | 151,642,503 |
| | average per event | | 1,316 | 596,644 | 161,321 |
| Europe | Tropical cyclone | 22 | 201 | 94,682 | 1,817,360 |
| | average per event | | 9 | 4,304 | 82,607 |
| Oceania | Tropical cyclone | 194 | 1,721 | 2,294,553 | 7,461,364 |
| | average per event | | 9 | 11,828 | 38,461 |
| World | Tropical cyclone | 1,793 | 1,329,139 | 625,148,680 | 566,063,289 |
| | average per event | | 741 | 348,661 | 315,707 |

Source: "EM-DAT: The OFDA/CRED International Disaster Database http://www.emdat.be/ - Université Catholique de Louvain - Brussels - Belgium" Created on: Sep-17-2010. - Data version: v12.07

During the last decade alone, from 2000 to 2009, there were 540 tropical cyclone occurrences worldwide (several individual cyclones struck a number of countries, especially in the Caribbean and Central America — for example Hurricane Michelle in 2001 affected people in 8 countries and Dean in 2007 affected 9 countries). These events of the last decade killed 167,692 people, affected a further 286,222,031 and cost an estimated US$ 385.12 billion (CRED 2009). The impact of these storms was extremely uneven with the Philippines bearing the brunt of 70 cyclones. The Peoples Republic of China was impacted 46 times and Taiwan a further. The next most impacted countries were Mexico 25, Japan 23, USA 22 and Bangladesh 19. In terms of death rates, cyclone Nargis which devastated Myanmar in 2008, killed 138,366 people, followed by Sidr killing 4,234 in Bangladesh, Jeanne's death toll of 2,754 in Haiti, 1,833 killed by Katrina in the USA, 1,619 killed by Winnie in the Philippines, a death toll of 1,513 from Stan in Guatemala and 1,399 killed by Durian in the Philippines (CRED 2009).

Societal risk is formally defined as "the risk of a number of fatalities occurring." (Emergency Management Australia 1998). This can be related directly to the risk equation

**risk = hazard X vulnerability**

or

**risk = hazard X vulnerability X elements at risk**

Society's risk is identified with vulnerability, although the elements at risk may seriously impact upon social losses and recovery.

Impact is "a sudden occurrence without prior warning," and the impact area is defined as "any area which is likely to bear, is bearing, or has borne the full impact of any disaster and in which major lifesaving operations are necessary" (Emergency Management Australia 1998). Mitigation consists of "measures taken in advance of a disaster aimed at decreasing or eliminating its impact on society and environment" and prevention which is "regulatory and physical measures to ensure that emergencies are prevented, or their effects mitigated - measures to eliminate or reduce the incidence or severity of emergencies" (Emergency Management Australia 1998). Vulnerability is defined as a function of susceptibility to loss and constraints to the capacity to recover, while the capacity to recover from a disastrous impact is termed resilience. These definitions are necessarily starting points.

Following from these basic definitions, the review is structured into three main areas; physical impacts of tropical cyclones on human beings and their communities, vulnerability and resilience, and mitigation.

## 9.6.2 Physical impacts of tropical cyclones on people and communities

The physical characteristics of tropical cyclones bring destruction through wind, surge and associated flooding (Chittibabu et al 2004). The loss of life principally results from surge and flooding such as recent examples of the consequences of cyclone Nargis in Myanmar, Sidr in

Bangladesh and Katrina at New Orleans USA (Congleton 2006), but all three characteristics cause damage to structures, dwellings, infrastructure and resources.

Wind damage is affected by both terrain and vegetation, but there is no easy solution to the identification of either protective land features or appropriate vegetation. Valleys may funnel intensive high cyclonic winds and steep hills may act as a buffer or minor protection, but these effects will entirely be dependent on the direction of the wind, which will change direction after the passage of the eye anyway. The sheer size of tropical cyclones easily overcomes most features of the landscape. However, there are classifications for landscape types that acknowledge some impact upon wind damage. Knowledge of vegetation performance capacity during strong winds is well developed and translates into advice from organizations such as local councils on the best trees and shrubs to plant in cyclone prone areas. This may extend to the clearance of vegetation, and pruning of branches, etc., close to buildings and infrastructure such as power lines. Vegetation acts as both a buffer and debris. The speed of passage of the cyclone influences the potential for debris damage as well as the extended battering of structures. Once damage has occurred, debris from both structures and vegetation become missiles that extend the impacts of high winds. Wind damage is additionally exacerbated by precyclonic heavy rain and flooding, that saturates the soil, loosens the root structures of trees, and initiates soil erosion.

Before electronic communications were available to ocean going vessels, cyclones caused significant loss of life at sea, especially in the days of long distance passenger travel by sea. While there has been a decrease in the loss of large vessels, recent cyclones have continued to destroy small fishing boats in developing countries as well as recreational vessels.

Storm surge, and associated flooding from the ocean, heavy rainfall and rivers overtopping their banks, frequently bring about more extensive damage than that caused by cyclonic winds, and it is certainly this aspect of tropical cyclones that causes the greatest loss of life. This was the case in all of the recent tropical cyclones, identified in the introduction, that resulted in extensive loss of life. The most vulnerable locations for tropical cyclone surge and flood impacts are low lying coastal plains and beach frontage that have been the focus of residential development, tourist resorts and coastal resource and fishing settlements. Additionally many estuaries and tidal rivers that have experienced significant development are even more vulnerable to surge and flooding. Many of these areas also have evacuation issues of access and egress.

The recovery and long-term viability of tropical cyclone impacted communities is a consequence of tropical cyclone intensity, on top of related and past disasters, such as previous cyclones and accompanying floods. Recovery is additionally constrained by household and community wealth, resources and infrastructure. Communities in less developed countries face much greater recovery constraints, and some places and regions do not recover from their losses in the medium to long term. Even New Orleans in the world's wealthiest nation had not recovered five years after Katrina's catastrophic impact (fieldwork, King 2009).

An additional wind impact is the variability of wind speeds, bringing gusts and vortices that randomly destroy structures. Building codes and community preparations are inevitably for an average set of expected conditions and will frequently fall short of preparation for severe storms.

Frequent catastrophic tropical cyclones lead to a long-term loss of economy and population. Younger people migrate away from the disaster zone to seek opportunities elsewhere (Hunter 2005), while the elderly become particularly vulnerable to sickness and depression. On the other hand while scientists have questioned whether increasing losses from disasters were due to climate change, and also concluding that there is no global trend in tropical cyclones, many, such as Bruce (1999) stressed that mitigation has to proceed on the cautionary principle.

### 9.6.3 Physical impacts upon households and communities

Tropical cyclone impacts on houses range from minor repairs to total destruction. Loss of the household dwelling then leads to temporary migration and relocation (that may last for many months or even years), as well as social and community dislocation, isolation, and in many cases (especially in less developed countries) homelessness. A specific developing country problem is tropical cyclone destruction of the local environment which removes accessibility to resources for rebuilding village houses -- timber, palm, bamboo and roofing thatch. In all societies, both dwellings and personal belongings are spoiled or destroyed by water damage. Outside the immediate losses to the household and its dwelling, community facilities, infrastructure and lifelines are equally damaged, compromising the processes of survival and recovery.

The impact of hurricane Ivan in 2004, assessed in a post-disaster study of Orange Beach, Alabama (Picou and Martin 2006), showed that average damage to each home was $36,000, with 81 percent of the residents of Orange Beach having to be evacuated for an average of 11 days absence. There was no power for an average of 12 days, and no telephone for an average of 9 days. The study showed significant social conflict and loss of trust within the community. The following year, these sorts of impacts were repeated on a greater scale after hurricanes Katrina and Rita (Khoury et al. 2006).

### 9.6.4 Psychological impacts upon households and communities

Psychiatrists and psychologists have developed specific analytical tools to assess the traumatic effects of experiencing a disaster. An extensive range of experiences is involved, both for the victims and responders — fear, shock, bereavement, depression, loss of control, social and psychological isolation which in turn contribute to community and societal impacts which may range from strength, resilience and empowerment to severe loss, disruption and breakdown. Impacts of cyclones and hurricanes generate from enormous losses and widespread disruption to peoples' lives with long term PTSD (Post Traumatic Stress Disorder), relocation and longer term out-migration, economic disruption and decline and unequal impact on the socio-economically disadvantaged and vulnerable groups within the community.

Stein and Preuss (2008) recorded oral histories amongst the victims of Katrina. There were stories of violence, and of police preventing people entering evacuation centres. Drawing on studies carried out with focus groups, interviews and photo-journalism with narratives from a wide diversity of participants, oral histories captured people's awareness of their own misperceptions. For example the oral histories captured the black story of New Orleans, but while the researchers acknowledge that they missed the white story, the highest impact fell upon African-Americans (Spence et al 2007). While the lessons learned from one disaster help prepare for future events, the experience of the events are probably distorted for each individual, as people select and construct their memories, and prioritize their actions, behavior and responses. Any single individual has an incomplete and personal experience of a disaster, which affects the way in which they will interpret future warnings and information.

### 9.6.5 Environmental damage

The damage to the natural environment reduces landscape amenity that contributes to non-quantifiable and non economic impacts that influence community well-being, culture and heritage. There are direct and quantifiable effects on agriculture, tourist attractions, fisheries and construction materials. There are also intangible socio-economic environmental impacts where species are lost, weed species invade an area, and time and labor are transferred from economic activities to recovery of the environment.

## 9.7 Vulnerability and resilience

The vulnerability of people and communities to tropical cyclone risk is measured at levels of the individual, the household and the community. Communities are complex entities, at their simplest consisting of a collection of households at a geographical location — a neighbourhood or a village. In all societies, but especially in urban and industrial settlements, people are members of multiple communities, of family, workplace, educational institution, recreation and interest communities, which include religious, political and cultural groups, and many more. The idea of community also includes intangible networks, like facebook, where relationships and support extend way outside the impact area of a specific tropical cyclone.

Social capital and collective action are central to resilience and will also drive some of the adaptation strategies needed for climate change. Adger (2003) illustrates how social capital operates at different scales from the individual through communities to the state. However, measurements of both vulnerability characteristics and elements and social capital present problems to emergency managers and local governments. Some characteristics of individuals, households and communities can relatively easily be measured from censuses and local government inventories of lifelines and community infrastructure. However, such databases only provide snapshots, or non contextual aspects of human and community characteristics of either vulnerability or resilience. The lack of data makes it difficult to measure the qualitative and intangible aspects of individuals or of communities — things like knowledge, wisdom, community spirit, sense of place and purpose, all of which are extremely important aspects of the social capital that reduces vulnerability and enhances resilience.

There is a problem for all levels of government in influencing or attempting to reduce vulnerability. In defining such demographic characteristics as the very young of the very old as vulnerable groups, there is little one can do about it. The same applies to many other vulnerability characteristics which are structural and fixed in the short to medium term. Vulnerability assessments at the beginning of the IDNDR identified specific population characteristics or elements of structures and infrastructure. These have proved to be useful indicators, but they left out too many of the qualitative and intangible aspects of communities. Models of vulnerability have more recently emphasised broader issues of governance, resilience and education. For example Gopalakrishnan and Okada (2007) list elements for vulnerability assessment:

1. Awareness and accessibility
2. Autonomy
3. Affordability
4. Accountability
5. Adaptability
6. Efficiency
7. Equity
8. Sustainability

Schroter et al. (2005) also presented five criteria for vulnerability assessment that anticipate climate change adaptation:

1. Flexible knowledge base
2. Place based — local scale
3. Interconnectedness of change
4. Differential adaptive capacity
5. The future draws from the past.

They added eight steps towards the achievement of such a vulnerability assessment:

1. Defining the area along with stakeholders
2. Know the place over time
3. Hypothesise vulnerability
4. Develop a causal model of vulnerability
5. Develop indicators for vulnerable elements
6. Operationalise the model
7. Project future vulnerability
8. Communicate vulnerability clearly.

Myers's et al. (2008) study of migration following Hurricanes Katrina and Rita illustrates issues of disadvantage and social class. Out-migration following the hurricanes was particularly concentrated amongst the disadvantaged and those living in densely populated areas. Motivations for migration are complex but economic loss is strongly related to opportunities that exist elsewhere. Housing loss and damage are prompts to migration, but the socio-economically disadvantaged are less likely to have well maintained or protected properties. The loss for the poor is then exacerbated by the loss of jobs.

Hurricane Katrina led to the loss of 1,833 people's lives, but there were many other social impacts. Immediately following the hurricane, 5,088 children were separated from their families, and many adults remained unaccounted for months after the disaster, leading to a considerable separation anxiety and other psychological distress associated with being orphaned. During the subsequent evacuation after the hurricane, a further 300,000 schoolchildren were moved away from their homes and communities. Out-migration includes the impact upon children and young people (Peek and Fothergill 2006; Casserly 2006). Schools were destroyed and the public education system in New Orleans has not recovered. Peek and Fothergill's study records the importance of school in terms of recovery, but they also point out problems for the socio-economically disadvantaged and people of minorities in dealing with relocation.

After Cyclone Larry struck North Queensland in 2006, there were similar issues among schoolchildren in recovering from the psychological trauma of the event. Children stated the importance of the reopening of their schools in helping them to deal with the event as it brought them back to a state of relative normality (King et al. 2006). Cyclone Larry was as severe as Katrina but communities were spared the flooding. There was no loss of life, although 19,000 building insurance claims and 27,000 domestic contents claims were made in an impact area that contained less than 50,000 people. There was immediate short-term out-migration (King et al. 2006) and longer term migration during the recovery period following disruption to the local economy such as the short-term destruction of the banana industry (Glick 2006).

## 9.8 Tropical cyclone hazard mitigation

Mitigation of tropical cyclone risk requires preparatory action from a wide range of institutions and organizations — government at all levels, non-government organizations, private enterprise and community groups. The physical prevention of risk will continue to involve the building of protective barriers, such as sea walls and levees, even if these are short-term and contribute to community complacency. More significantly physical protective measures contribute to the strength of buildings to withstand high winds and localized flooding. Building codes exist, but weak enforcement and non compliance are governance issues that continue to put communities at risk. During the last decade land use planning has been targeted to ensure greater responsibility and vigilance over the suitable siting of new urban developments. Planners are directly involved in hazard mitigation efforts but they also face governance, information and legislative constraints that reduce the effectiveness of appropriate hazard zone planning.

For weather agencies and emergency managers the core business of tropical cyclone mitigation is communication, warnings, awareness, preparedness, and education. Communication extends beyond pre-season education campaigns. It takes place at different stages — mitigation, response and recovery. At all of these levels the media is crucial in transmitting information and warnings and informing the community. Engagement with the media, including the important role of media liaison officers, is a specific hazard mitigation role.

Pielke and Sarewitz (2005) argue that the impacts of climate change are social (although environmentalists might take issue), but that while society has a past history of adaptation, it has no experience in successfully modifying climate. This reinforces the argument that mitigation (including carbon trading and emissions reduction) is much less likely to be successful than adaptation to a changing global climate. Initially, adaptation brings high costs, but in the long-term it might transform into a new sustainability. Seasonal mitigation strategies have been put in place to reduce the hazard risk and to lessen the impact of a tropical cyclone. In practice mitigation has been conservative, oriented towards maintenance of the status quo (Handmer et al. 1999). Climate change has added a new vocabulary to hazard mitigation — specifically the concept of adaptation.

Adaptation is neither static nor protective as it requires change to an uncertain future state. It is the uncertainty of future climate change scenarios that makes adaptation a particularly difficult concept to sell to communities. There is a need for much greater clarity and precision of potential climate change scenarios and changing risk. Tropical cyclone awareness and preparedness strategies are in danger of being devalued by imprecise warnings of more intense and possibly more frequent cyclones, which may not transpire in reality. If we are not certain about these trends we should not confuse the mitigation message but should concentrate on sound preparation and enhance governance to support communities.

## 9.9 Economic impacts of tropical cyclones

Global natural disaster losses have risen dramatically in recent decades and tropical cyclones have contributed significantly to this trend. Tropical cyclones account for nine of the ten most costly inflation-adjusted insurance natural disaster losses (2009 dollars) between 1970 and 2009 (Swiss Re, 2010). Of these nine, eight impacted the US and surrounding areas and one impacted Japan. In original loss values, tropical cyclones account for two of the five most costly economic losses and four of the five most costly insurance losses from natural disasters over the period 1950 to 2009 (Munich Re, 2010). All hurricanes in the top five of both original loss lists impacted the US and Hurricane Katrina tops the original and inflation adjusted loss lists.

The increase in tropical cyclone losses has led to concern that anthropogenic climate change is contributing to this trend. In response to this, numerous studies of databases1 from around the world have been undertaken to examine the factors responsible for this increase. Research has also focused on what role various factors may have in shaping tropical cyclones losses in the future. This report summarizes those efforts.

The significant increase in losses has also made the question of how to better manage tropical cyclones, and natural hazards more generally, even more salient. An important component of catastrophe risk management is the development of adequate and sustainable financial protection for potential victims of future disasters and our report discusses this financial management aspect.

### 9.9.1 Loss normalization

Before comparisons between the impacts of past and recent tropical cyclones can be made, various societal factors known to influence the magnitude of losses over time must be accounted for. This adjustment process has become commonly known as *loss normalization* (Pielke and Landsea, 1998).

Normalizing losses to a common base year is undertaken primarily for two reasons:

1. to estimate the losses sustained if events were to recur under current societal conditions; and,
2. to examine long term trends in disaster loss records.

In particular, to explore what portion of any trend remaining after taking societal factors into account may be attributed to other factors including climate change (natural variability or anthropogenic).

Climate-related influences stem from changes in the frequency and/or intensity of tropical cyclones whereas socio-economic factors comprise changes in the vulnerability and in the exposure — value of assets at risk — to the natural hazard. Socio-economic adjustments have largely been limited to accounting for changes in exposure, although Crompton and McAneney (2008) adjusted Australian tropical cyclone losses for the influence of improved building standards introduced since the early 1980s.

Bouwer (2011) provides a recent comprehensive summary of loss normalization studies. Table 9.6 has been adapted from that study to include only those relating to tropical cyclones.

**Table 9.6. Normalization studies of tropical cyclone disaster loss records (Modified from Bouwer 2010).**

| location | Period | normalization | Normalized loss | reference |
|---|---|---|---|---|
| | | | | |
| **Latin America** | **1944-1999** | **Wealth, population** | **No trend** | **Pielke et al. (2003)** |
| | | | | |
| **India** | **1977-1998** | **Income, population** | **No trend** | **Raghaven and Rajash (2003)** |
| | | | | |

<<Previous

Next>>

| | | | | |
|---|---|---|---|---|
| **United States** | **1900-2005** | **Wealth, population** | **No trend** | **Pielke et al. (2008)** |
| | | | | |
| **United States** | **1950-2005** | **Asset values** | **Increase since 1970; no trend since 1950** | **Schmidt et al. (2009)** |
| | | | | |
| **China** | **1983-2006** | **^GDP** | **No trend** | **Zhang et al. (2009)** |
| | | | | |
| **China** | **1984-2008** | **^GDP** | **No trend** | **Zhang et al. (2010)** |
| | | | | |
| **United States** | **1900-2008** | **^GDP** | **Increase since 1900** | **Nordhaus (2010)** |
| | | | | |
| ***Australia** | **1967-2006** | **Dwellings, dwelling value** | **No trend** | **Crompton and McAneney (2008)** |
| | | | | |
| ***United States** | **1951-1997** | **Wealth, population** | **No trend** | **Choi and Fisher (2003)** |
| | | | | |
| ***World** | **1950-2005** | **^GDP per capita, population** | **Increasing since 1970; no trend since 1950** | **Miller et al. (2008)** |

***Includes other weather hazards besides tropical cyclones.**

**^ Gross domestic product (GDP) is a measure of a country's overall official economic output. It is the market value of all final goods and services produced in a country in a given year.**

In what follows we focus on the more recent tropical cyclone loss normalization studies.

*a) China*

Zhang et al. (2009) examined the direct economic losses and casualties caused by landfalling tropical cyclones in China during 1983-2006 using the data released by the Department of Civil Affairs of China. The economic loss data was estimated by the governments usually at town and county levels and collected by provincial governments and reported to the Department of Civil Affairs. Zhang et al. (2009) show that in an average year, seven tropical cyclones made landfall over the Chinese mainland and Hainan Island, leading to 28.7 billion yuans (2006 RMB) in direct economic losses and killing 472 people. A significant upward trend in the direct economic losses was found over the 24-year period. This trend disappeared after the rapid increase in the annual total Gross Domestic Product (GDP) of China was taken into consideration, a result that

<<Previous Next>>

suggested that the upward trend in direct economic losses was a result of Chinese economic development.

More recently, Zhang et al. (2010) updated the earlier analysis to 2008 and also included a consumer price index (CPI) inflation-adjusted time series of direct economic losses. Over the period 1984-2008, tropical cyclones led to 505 deaths and 37 billion yuan in direct economic loss per year accounting for about 0.4% of annual GDP. The annual total direct economic losses increased significantly due to the rapid economic development over the 25-year period, while the percentage of direct economic losses to GDP (the 'normalization') and deaths caused by landfalling tropical cyclones decreased over this period. Both studies concur that economic development is the primary factor responsible for the increasing tropical cyclone damage in China.

Over the past 25 years, tropical cyclones made landfall on the Chinese mainland and Hainan Island with an average landfall intensity of 29.9 m/s and they retained their tropical cyclone intensity for 15.6 hours over land (Zhang et al., 2010). No significant trends in landfalling frequency and intensity have been found. Rainfall associated with landfalling tropical cyclones is a major contributor to damage in China. Chen et al. (2011) shows a significant increase in the time landfalling tropical cyclones spend over land with tropical storm intensity. By separating the tropical cyclone rainfall from other weather systems, Chen et al. (2011) found that the overall rainfall associated with landfalling tropical cyclones was dominated by significant downward trends over the past 25 years. In the extreme rainfall days, Chen et al. (2011) also did not find an overall increasing trend. These results suggest that the significant upward trend in typhoon damage cannot be explained by changes in tropical cyclone activity.

*b) US*

Schmidt et al. (2009a) discuss two essential differences between their normalization methodology and the Pielke et al. (2008) "PL05" methodology. The first is their use of capital stock at risk (determined from the number of housing units and mean home value) rather than the wealth at risk (determined from population and per capita wealth) employed in Pielke et al. (2008). Secondly, Schmidt et al. (2009a) apply regional figures for mean home value whereas Pielke et al. (2008) use the national average for per capita wealth. Fig. 9.11 shows the different rate of change in these metrics over time (Schmidt et al., 2009a). The wealth at risk factors are higher than the capital stock at risk factors and this difference generally increases back in time.

Green bars show the factors applied based on wealth at risk (population in 177 coastal counties and real wealth per capita). Losses adjusted by wealth at risk will be higher than adjusted by capital stock at risk (source: Schmidt et al. (2009a)).

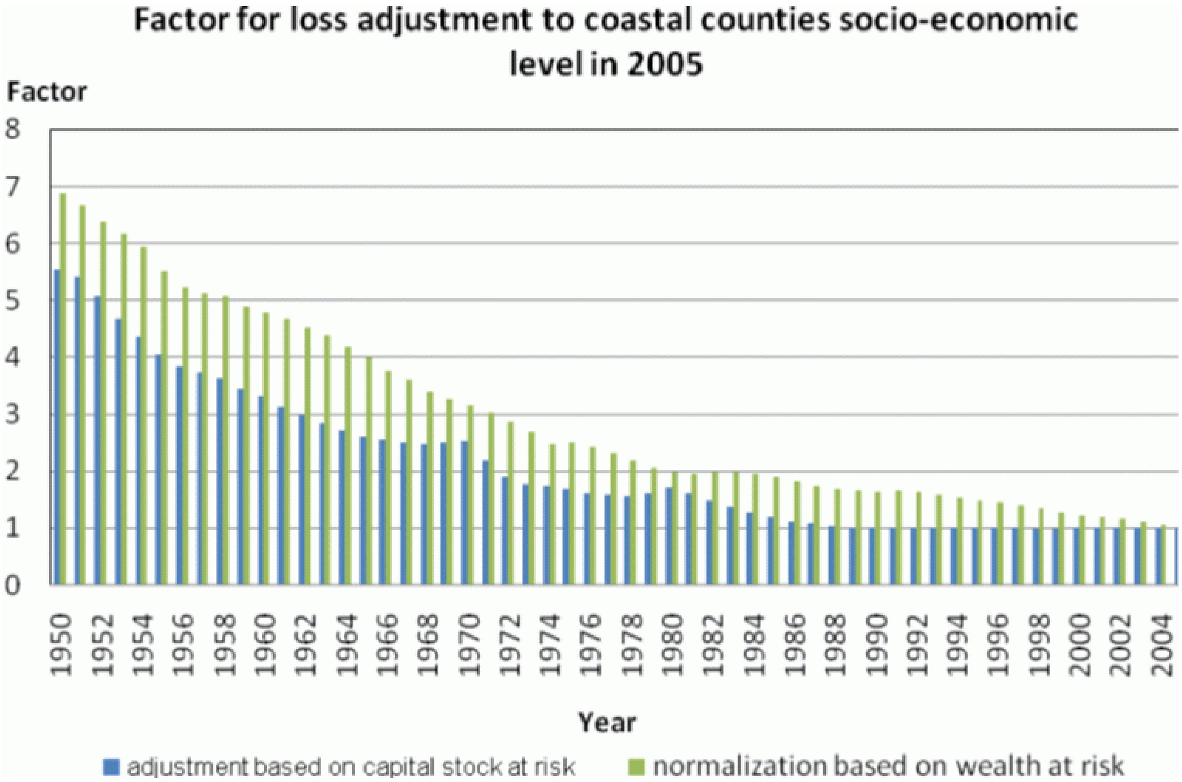


**Figure 9.11.** Blue bars show the factors applied for adjustment of losses to 2005 socio-economic level based on capital stock at risk (e.g. losses in year 1962 will be multiplied by factor of 3).

Here we update the Pielke et al. (2008) analysis to include US hurricane losses from the 2006 to 2009 seasons with all losses now normalized to 2009 values. Fig. 9.12 shows the normalized US hurricane losses for 1900 to 2009. While it is apparent that there is no obvious trend over the entire time series, our emphasis is on the period 1971-2005 for which Schmidt et al. (2009a) report a statistically significant trend. (This trend in the log-transformed annual normalized losses was significant at the 10% level). Schmidt et al. (2009a) also show what effect a single event can have on the result as the trend was no longer significant when the Hurricane Katrina loss was excluded. In what follows, we investigate the effect that accounting for recent seasons has had on resulting trends beginning in 1971.

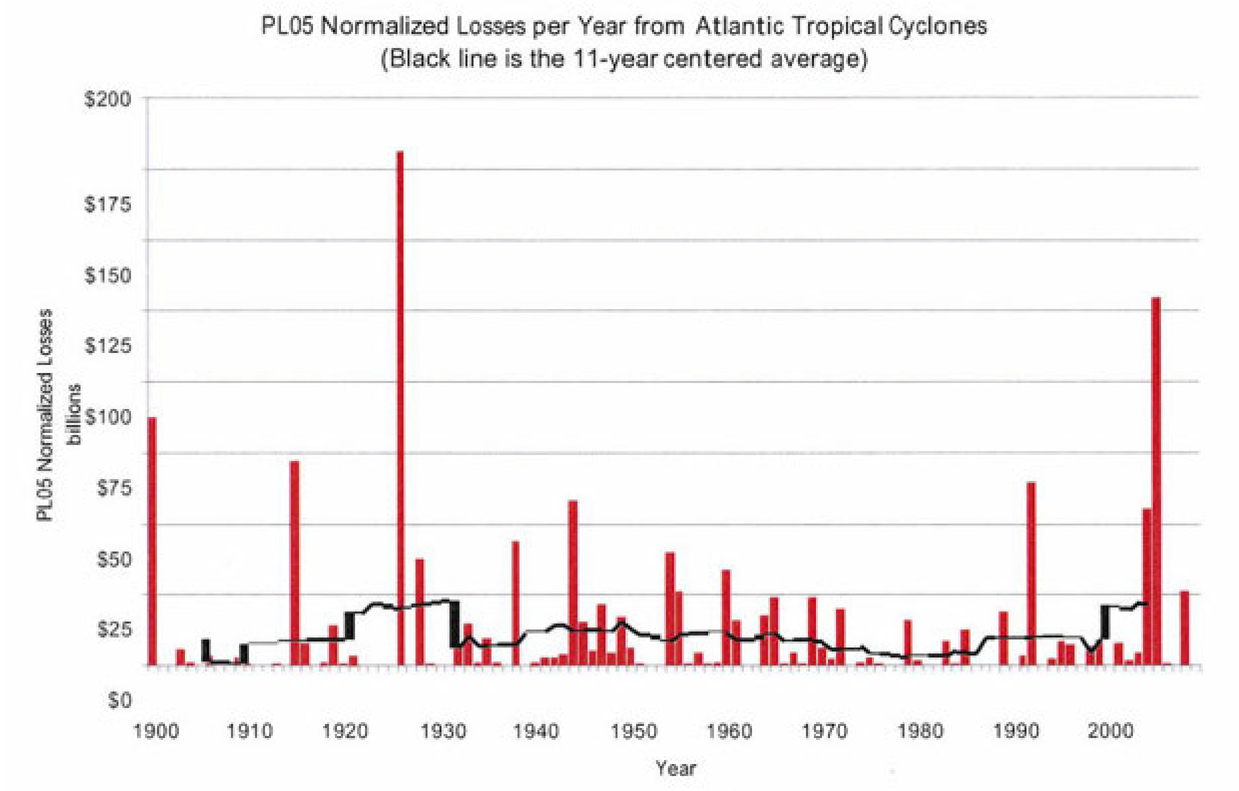


**Figure 9.12.** U.S. Gulf and Atlantic damage, 1900-2005, for total U.S. tropical cyclone losses normalized with a methodology that focuses on population change. An alternate methodology that focuses on housing units was within 2% of the population change methodology. Although the 2004 and 2005 seasons produced high losses, these years are not unprecedented when considering normalized losses since 1900. (From Pielke et al, (2008))

Similar to Schmidt et al. (2009a) we find a statistically significant (at the 10% level) trend (*Pvalue* = 0.091) in log-transformed annual normalized losses (2009 values) during 1971-2005. However the trend is not statistically significant (at the 10% level) when the time series is extended to any year after 2005 (e.g. 1971-2006, etc.). This highlights the difficulty that the large volatility in the time series of tropical cyclone losses poses when estimating trends over short periods of time.

*c) Australia*

Crompton and McAneney (2008) normalized Australian weather-related insured losses over the period 1967-2006 to 2006 values. Insured loss data were obtained from the Insurance Council of Australia (http://www.insurancecouncil.com.au/). The methodology adjusted for changes in dwelling numbers and nominal dwelling values (excluding land value). A more marked point of departure from previous normalization studies was an additional adjustment for tropical cyclone losses to account for improvements in construction standards mandated for new construction in tropical cyclone-prone parts of the country.

Crompton and McAneney (2008) found no statistically significant trend in weather-related insured losses once they were normalized in the manner described above. They emphasize the success improved building standards have had in reducing building vulnerability and thus tropical cyclone wind-induced losses. Due to limited data, they did not analyze the losses from any one particular hazard. In total, only 156 event losses were included in their analysis and this relatively small number results from the combined effect of a short data series and sparse population, especially in tropical cyclone-prone locations of the country.

*d) World*

Miller et al. (2008) compiled a global normalized weather-related catastrophe catalogue covering the principal developed and developing countries and/or regions (Australia, Canada, Europe, Japan, South Korea, United States, Caribbean, Central America, China, India, the Philippines). Various data sources were accessed and losses surveyed from 1950 to 2005, however post-1970 data were more reliable across all countries. Economic losses were normalized to 2005 values by adjusting for changes in wealth (GDP per capita in USD), inflation (national level), and population (national level).

Miller et al. (2008) discuss a number of issues in relation to their methodology including what effect applying a national level population factor has on normalized losses. They state that for those events that impacted certain high growth, coastal regions such as Florida, their national population factor will understate the true population growth rate. A regression of global normalized hurricane losses over the period 1970-2005 found a statistically significant (at the 5% level) trend.

More generally, Miller et al. (2008) found a 2% per year increasing trend in global normalized weather-related losses after 1970. However, their conclusions were heavily weighted by US losses and their removal eliminated any statistically significant trend. Their results were also strongly influenced by large individual events such as Hurricane Katrina. The significance of the post-1970 global trend disappeared once national losses were further normalized relative to per capita wealth (i.e. by multiplying each region's normalized losses by the ratio of US GDP per capita to regional GDP per capita to approximate a homogenous distribution of wealth). They confirm that the principal driver of increasing global disaster losses to date was tropical cyclones in wealthy regions and that there was insufficient evidence to claim any firm link between global warming and disaster losses.

## 9.10 Future and current loss sensitivity

A number of studies have projected US tropical cyclone losses. This has been done to either quantify the effect of anthropogenic climate change (due to a projected change in tropical cyclone frequency and/or intensity) on its own, or to compare the effect of projected changes in both exposure and climate. Future losses will also be sensitive to changes in vulnerability, but this factor is usually held constant. Table 9.7 (from Schmidt et al. (2009b)) summarizes US tropical cyclone loss projection studies and Table 9.8 provides a more detailed account of some of the more recent studies as well as that of Schmidt et al. (2009b). The logic usually employed in these studies to examine the effects over a given time horizon is presented below.

**Table 9.7: Overview of studies to estimate future storm losses in the USA resulting from global warming (source: Schmidt et al. (2009b)).**

| Study | Loss function | Assumed change in intensity | Assumed change in frequency | Result |
|---|---|---|---|---|
| Cline (1992) | Increase in intensity produces a linear increase in losses | Increase of 40–50% with 2.3–4.8°C warming | – | Average loss increases by 50% |
| Fankhauser (1995) | Increase in intensity triggers a 1.5 increase in losses | Increase of 28% with warming of 2.5°C | – | Average loss (global) increases by 42% |
| Tol (1995) | Connection is in the quadratic form $f(x)=\alpha x+bx^2$ | Increase of 40–50% with warming of 2.5°C | constant | Increase in losses of 300 million US$ (1988 values) |
| Nordhaus (2006)a | d= α X windspeed$^3$ | Increase of maximum wind speeds of 8.7% with warming of 2.5°C | constant | Average loss increases of 104% |
| Stern et al. (2006) | d= α X windspeed$^3$ | Increase of 6% with warming of 3°C | – | Average loss increases by 100% |
| Hallegatte (2007)b | Physical storm model to create synthetic storms; loss function in the form d= αx(s) X windspeed$^3$ | Increase of 10% under the expected climate conditions at the end of the 21st century | no change in absolute number | Increase in landfalls and maximum wind speed (+13%); Average loss increases by 54% |
| Pielke (2007) | d= α X windspeed$^3$ (further scenarios with elasticity of 6 and 9) | Increase of 18% by 2050 | constant | Increase in loss of 64%c |

Notes:

a Losses adjusted for economic development using GDP.
b Losses adjusted for population and wealth trends, s for vulnerability index.
c Additional loss increase of 116% from the combined effect of increase in intensity and socio-economic trend.

*Anthropogenic climate change effect:*
Emission scenario → tropical cyclone projection (frequency and intensity) → relationship between tropical cyclone normalized damages and intensity (wind speed) (referred to as "loss function") → projected anthropogenic climate change influence on tropical cyclone losses

*Exposure effect:* (e.g. projected changes in population and wealth)
*Total effect:*

Anthropogenic climate change effect + Exposure effect + Anthropogenic climate change effect X Exposure effect + 1

Despite the various assumptions made in each of the studies in Table 9.8, the estimated changes in future tropical cyclone losses in the US resulting from anthropogenic climate change fall into two broadly similar pairs of studies. The Pielke (2007) lower estimate extrapolated to 2100 is approximately +128%, a figure comparable to the Nordhaus (2010) central estimate of +113%. On the other hand, linearly extrapolating the Schmidt et al. (2009b) estimate to 2090 results in an approximate +20% change in loss, whereas the Bender et al. (2010) ensemble-mean estimate is +28%.

Both Pielke (2007) and Schmidt et al. (2009b) show that exposure growth will have a greater effect than anthropogenic climate change on future US tropical cyclone losses. Pielke (2007) adopted a conservative approach in deliberately selecting upper end estimates for the anthropogenic climate change effect on tropical cyclone intensity. Schmidt et al. (2009b) note that the anthropogenic climate change-induced increase in loss results in an additional loss of wealth in the sense that it increases loss over and above the proportional increase in exposure (capital stock).

Loss functions have also been used by Nordhaus (2010) and Schmidt et al. (2010) to estimate the climate-induced (i.e., resulting from natural variability and any unquantifiable anthropogenic contribution) increase in mean US tropical cyclone damage since 1950. Nordhaus (2010) estimates an 18.4% increase in mean damages since 1950 based on an elasticity of 9 and a 1.9% increase in intensity. The intensity estimate was calculated using the Knutson and Tuleya (2004) intensity / SST relationship assuming a 0.54°C increase in SST.

Schmidt et al. (2010) examined the sensitivity of storm losses to changes in socioeconomic and climate-related factors over the period 1950-2005. They show losses to be much more responsive to changes in storm intensity (as estimated by changes in the basin-wide Accumulated Cyclone Energy (ACE) between successive "warm phases") than to changes in capital stock. Nonetheless capital stock had a greater effect on losses due to its far greater increase over the study period. They determine that the increase in losses was approximately three times higher for socio-economic changes (+190%) than for climate-related changes (+75% based on the 27% increase in ACE between the "warm phases" 1926-70 and 1995-2005 — the authors note that the latter "warm phase" had not ended) and state that the extent to which the climate-related changes were the result of natural climate variability, or anthropogenic climate change, remains unanswered.

## 9.11 Financial management of extreme events

Previous sections have showed that the significant growth in exposure in hazard-prone areas have been the primary reasons for the increase in natural disaster losses (both insured and uninsured) in the US and other parts of the world. This result is consistent with the conclusion from Kunreuther and Michel-Kerjan (2009) that the increase in losses is due to growth in population and assets coupled with a lack of investment in risk reduction measures. Recent catastrophes have highlighted many challenges, including how to best organize systems to pay for the damage caused by natural disasters and how to mitigate their effects.

### 9.11.1 Catastrophe insurance: how it is changing in the US

In most Organization for Economic Co-operation and Development (OECD) countries, insurance penetration is quite high, so a large portion of the economic damage from natural disasters is covered by public or private insurance. For truly catastrophic risks, many countries have developed some type of private sector — government partnerships for certain risks or certain exposed regions (as is the case for example in the UK, France, Spain or Japan). In the US, cover for damage due to floods and storm surge from hurricanes has been available through the federally managed National Flood Insurance Program (NFIP) since 1968 (Michel-Kerjan, 2010). State government programs supplement private sector cover in many US states; in Florida, the state has set up a reinsurer (the Florida Hurricane Catastrophe Fund) and a direct insurer (Citizens) which absorb a considerable proportion of the state's hurricane risk.

Cover against wind damage in the US has typically been offered in standard homeowners' insurance policies provided by private insurers. A number of extremely damaging hurricanes since the late 1980's (including Hugo, Andrew, and others during the intense hurricane seasons of 2004 and 2005) caused substantial instability in property insurance markets in coastal states. High loss activity prompted most insurers doing business in coastal states to seek major price increases; however, state insurance regulators failed to authorize the full amounts requested. Even with the restricted premium increases, rates doubled or even tripled in the highest risk areas in Florida between 2001 and 2007 (Kunreuther and Michel-Kerjan, 2009). Due to their inability to charge adequate premiums many insurers reduced their exposure in coastal regions and in December 2009 State Farm, for example, announced that it would discontinue 125,000 of its 810,000 property insurance policies in Florida (State Farm, 2009).

The combined effect of dramatically increased premiums for private residential wind insurance in coastal states and the decline in access to coverage for those in areas most exposed to wind damage has resulted in increased demand for government programs that provide insurance for residents in high-risk areas at highly subsidized rates. While subsidized rates have short term political benefit they do not encourage investment in risk reduction measures. Moreover, inadequate rates lead to large deficits in government pools over time and excessive growth in high risk areas and thus an even greater potential for large losses. Historically inadequate rates fuelled the dramatic exposure accumulation in the southeastern US where large losses have subsequently occurred.

### 9.11.2 The disaster mitigation challenge

Insurance (public and private) plays a critical role in providing funds for economic recovery after a catastrophe. But insurance merely transfers risks to others with a broader diversification capacity; simply purchasing insurance does not reduce the risk. The insurance system can play a critical role in providing incentives for loss mitigation by sending price signals reflecting risk. Regulatory efforts to limit premium increases in high risk areas can diminish the insurance system's ability to perform this function.

Disaster mitigation measures can offset some of the upward pressure demographic and economic drivers (as discussed in previous sections) exert on tropical cyclone losses. Kunreuther and Michel-Kerjan (2009) shed some light on this aspect by analysing the impact that disaster mitigation would have had on reducing losses from hurricanes in four states in 2005: Florida, New York, South Carolina, and Texas. In their analysis of the impact of disaster mitigation, they considered two extreme cases: one in which no one invested in mitigation and the other in which everyone invested in predefined mitigation measures. A US hurricane loss model developed by Risk Management Solutions (RMS) was used to calculate losses assuming appropriate mitigation measures on all insured properties. The analyses revealed that mitigation has the potential to significantly reduce losses from future hurricanes with reductions ranging from 61% in Florida for a 100-year return period loss to 31% in Texas for a 500-year return period loss. In Florida alone, mitigation is estimated to reduce losses by $51 billion for a 100-year event and $83 billion for a 500-year event.

In a study for the Australian Building Codes Board, McAneney et al. (2007) estimated that the introduction of building code regulations requiring houses to be structurally designed to resist wind loads had reduced the average annual property losses from tropical cyclones in Australia by some two-thirds. Their estimate was based on the likely losses had the building code regulations never been implemented or had they always been in place.

Without regulations, the challenge lies in encouraging residents in hazard-prone areas to invest in mitigation measures and this has been highlighted by many recent extreme events. Even after the devastating 2004 and 2005 US hurricane seasons, a large number of residents in high-risk areas still had not invested in relatively inexpensive loss-reduction measures, nor had they undertaken emergency preparedness measures. A survey of 1,100 residents living along the Atlantic and Gulf Coasts undertaken in May 2006 revealed that 83% had taken no steps to fortify their home, 68% had no hurricane survival kit and 60% had no family disaster plan (Goodnough, 2006). Homeowners, private businesses, and public-sector organizations often fail to voluntarily adopt cost-effective loss-reduction measures, particularly if regulatory actions inhibit the insurance system from providing sufficient economic incentives to do so. In addition, the magnitude of the destruction following a catastrophe often leads governmental agencies to provide disaster relief to victims — even if prior to the event the government claimed that it would not do so. This phenomenon has been termed the "natural disaster syndrome" (Kunreuther, 1996). This combination of underinvestment in protection prior to a catastrophic event and taxpayer financing of part of the recovery following can be critiqued on both efficiency and equity grounds.

### 9.11.3 Global risk financing in coming decades

In coming decades, global trends in population distribution, economic development, wealth accumulation and increasing insurance penetration will place significant strain on the ability to absorb economic losses and undertake post-event reconstruction. The problems that Florida is currently experiencing may develop elsewhere. For example, patterns of urbanization in areas of China vulnerable to typhoons resemble those of Florida in years past.

Musulin et al. (2009) analysed the financial implications of future global insurance losses. Future losses were estimated by using projected values of the variables used to normalize losses and an additional adjustment was made for changes in insurance penetration. Their analysis revealed that new peak zones (those locations that have the largest disaster potential globally) are likely to emerge in several developing nations due to the projected changes in demographics, wealth and insurance penetration. They note that the rapid projected exposure accumulation was similar to that experienced in Florida between 1950 and 1990. Musulin et al. (2009) conclude that the future loss levels will have significant ramifications for the cost of financing disasters through the insurance system, both in the new peak zone locations and in the system as a whole. Their results were independent of any anthropogenic climate change effects on future losses.

Musulin et al. (2009) identify an additional factor that must be considered to correctly assess the proper level of investment in loss mitigation. They refer to three lenses through which loss mitigation activities can be viewed: life safety, protection of individual properties, and management of overall economic impact. While building code development traditionally focuses on the first two, the authors argue that consideration also needs to be given to the current and future potential for large disaster losses in the area where the building code applies.

The management of overall economic impact means that current building code design should also reflect the current and future potential impact of large disaster losses on the overall economy (Musulin et al., 2009). The destruction of a single building can be easily absorbed into the normal building capacity of an economy but the destruction of one million homes by a major hurricane cannot — the required diversion of material and labour to post-event reconstruction from other activities would cause massive stress and disruption. The potential economic damage from tropical cyclones can become very significant at a macroeconomic level as exposure grows disproportionately in high risk areas, particularly when there is a dramatic increase in insurance penetration (Musulin et al., 2009).

Musulin et al. (2009) conclude that the economic value of loss mitigation must reflect the expected cost of risk transfer over the lifetime of the building. Since the cost of risk transfer is affected by the aggregate level of risk in an area, it can change if the surrounding area is subject to significant population growth and wealth accumulation. Loss mitigation should therefore also target areas of high potential future growth (Musulin et al., 2009).

### 9.11.4 Integrating the financial management of disasters as part of a national strategy

In the aftermath of the very destructive 2004/05 US hurricane seasons, increasing the country's resiliency to natural disasters was destined to become a national priority in the US. As other crises occurred locally and abroad, attention was directed away from this issue. The question of how to best organize financial protection and risk reduction against future hurricanes remains largely unanswered.

Other countries that have suffered disasters are faced with similar questions. Outside of the OECD countries, developing countries have started to think about these issues. In many cases, populations are growing fast and assets at risk have increased significantly as a result of decades of economic development. People and businesses are turning to their governments and the private sector for solutions. These solutions will come in the form of micro-insurance (well-developed in India and several African countries today), strong government participation (as is the case in China), traditional insurance, or the transfer of catastrophe exposure directly to investors on the financial markets (e.g. catastrophe bonds of which over 160 have been issued to date) (Michel-Kerjan and Morlaye, 2008).

Each country will have to define and select what solutions make the most sense given its culture, current development of its insurance market, risk appetite and other national priorities. These solutions will also evolve over time as a response to the occurrence of (or absence of) major catastrophes. Higher climate variability and increasing exposure means that the financing of disaster risks and long-term disaster mitigation planning must become a critical element of the national strategy in many countries to assure sustainable development.

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<<Previous Next>>

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