New Technology for Improved Storm Risk Assessment in the Caribbean

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Abstract

The effects of tropical storms on Caribbean island states are reviewed, and their potential for destruction from coastal flooding and extreme winds are highlighted in the context of sea-level rise and increasingly dense coastal development. The Caribbean Disaster Mitigation Project (CDMP) is applying new technology in modelling these effects. The model used by CDMP relies on a generic database structure using available 'off the shelf' data sources such as satellite imagery and the National Hurricane Center database. The model provides probable maximum values for wind at surface, and for still-water elevation and wave height at the coastline. Model outputs are in Geographic Information Systems (GIS) format for ease of use by planners and emergency managers. Applications in the areas of land use planning, design of coastal works and disaster preparedness are presented. The results of this model compare favourably to those of existing storm surge models such as the WHAFIS model of the Federal Emergency Management Agency (FEMA), and the SLOSH model of the National Oceanographic and Atmospheric Agency (NOAA)

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Introduction

In September 1993, the Department of Regional Development and Environment of the Organization of American States (OAS) started implementing the Caribbean Disaster Mitigation Project (CDMP), a five year technical co-operation project funded by the Office of Foreign Disaster Assistance of the US Agency for International Development. One of the objectives of the CDMP is to improve the understanding and management of the risk posed by tropical storms and hurricanes to population, housing, infrastructure and economic activity in the Caribbean.

For this purpose, the CDMP has developed a computer-based model that produces estimates for the maximum sustained wind vectors at surface, and for storm surge height and wave height at the coastline. The model relies on a generic data base structure using available 'off the shelf' data sources such as satellite imagery, existing digital terrain data, and the National Hurricane Center data base. The authors believe that this model represent a significant advance over existing storm models such as the WHAFIS model of the US Federal Emergency Management Agency (FEMA), and the SLOSH model of the US National Oceonographic and Atmospheric Agency (NOAA).

The Effect of Storm Hazards

By their location and physical characteristics, the Caribbean island nations are subject to strong meteorologic, hydrologic and geologic extremes. Although earthquakes and volcanic eruptions have been responsible for the greatest loss of life in the Caribbean,[1] meteorologic hazards such as tropical storms and hurricanes pose the most frequent and visible threat, and cause the overwhelming part of the economic losses.

Hurricanes can have a particularly devastating effect on the economies of Caribbean countries, as was demonstrated by Gilbert in 1988, affecting the Dominican Republic, Haiti and especially Jamaica, Hugo in 1989, affecting Dominica, Antigua and Barbuda, Guadeloupe, Montserrat, St Kitts and Nevis, the US Virgin Islands and Puerto Rico; and Andrew affecting the Bahamas in 1992. Total losses suffered from these hurricanes ranged from approximately one third of GDP in the case of Gilbert in Jamaica,* to nearly five years of GDP in the case of Hugo in Montserrat.[†]

*As estimated by the Planning Institute of Jamaica
†As estimated by UNDRO/PCDPPP

Non-hurricane storm events can also cause substantial losses. The yearly procession of tropical depressions and winter storms, with accompanying heavy rains, afflict countries in the region with localised flooding, landslides, and damage to crops, housing, roads and other infrastructures. Losses resulting from these events go largely unreported since formal damage reports are compiled only in cases where a country declares a national disaster. The cost of repairs however does show up in places such as the high recurrent costs of public works departments and insurance claims.

A significant factor in the growing losses caused by meteorological hazards is the concentration of population and economic activity in coastal plains and low-lying areas that are subject to storm surges and land-borne flooding. Furthermore, the rapid growth of the tourism industry over the last decade has greatly increased the insured value of the coastal properties in the Caribbean and, associated with it, the storm related risk

Although the concentration of population in vulnerable coastal areas is not an exclusively Caribbean phenomenon, the region represents a significant level of risk to its high population densities. Population density in the coastal area from Florida to North Carolina (considered by the insurance industry the highest risk area for catastrophe losses from hurricanes) has grown from 107 persons per square mile in 1960 to 245 in 1990. In Guam, which was affected by five typhoons in 1992, the population density in 1990 was 640 per square mile. In Barbados, where the entire island can be considered high risk, population density in 1970 was 1,420 per square mile, and grew to 1,570, or more than six times the US Southeast Coast density, by mid 1990.

The rapid increase in population density in high risk coastal areas during the 1970s and 1980s coincided with an unusually low frequency of severe hurricanes in the Caribbean and along the Atlantic Coast from 1970 to 1989. During that period, reinsurance was readily available and inexpensive, and the insurance industry in the region had little or no incentive to accurately price risk or promote loss reduction measures. As a result, insurance underwriters in the Caribbean became overexposed to hurricane catastrophe.

When a series of severe weather occurred, beginning in 1988 in the Caribbean with hurricanes Gilbert and Hugo in 1989, followed by severe winter storms in Europe in 1990, and by super typhoon Iniki in Hawaii in 1992, the reinsurance industry reacted to its record losses be re-evaluating its portfolios, increasing prices and reducing capacity This in turn has led to a dramatic increase in the cost of property and casualty insurance in the Caribbean region. As a consequence, property owners and developers have greater incentives to consider other mechanisms of risk reduction such as retrofitting or avoiding high risk areas.[2]

Global Climate Change and Storm Hazards

The scientific debate on global climate change, which over the past few years has received wide dissemination beyond the scientific community, has generated serious concerns among governments and private sector interests, in the Caribbean and worldwide

Whereas the evidence of climatic change is still being contested in the scientific community, there are clear signs that the reinsurance community, battered by record losses from windstorms worldwide, is taking a closer look at the possible link between climate change and increased storm activity In the Caribbean, this has been felt by a significant rise in the cost and shrinking availability of reinsurance, with a consequent escalation of property insurance premiums.

In response to these growing concerns, the Caribbean Environment Program of UNEP and the Intergovernmental Oceanographic Commission of UNESCO undertook a study of the implications of climatic changes in the Wider Caribbean. The task team for the study adopted a scenario of a 1 5°C rise in temperature, and 20cm rise in sea level by the year 2025 as baseline scenario (*CEP Technical Report No. 22,* 1993). This scenario represents in fact a fairly conservative first step consistent with several longer term projects, like the UNEP-WMO Intergovernmental Panel on Climate Change projection of sea level rise between 50 and 100cm by the year 2100, (IPCC, 1990), and the Second World Climate Conference, held in Geneva in 1990, which predicted a global warming of 2°C to 5°C and sea level rise of 65cm ±35cm over the next century (*CEP Technical Report No. 22,* 1993).

The problem with global projections of this nature is the additional uncertainty introduced by their application at the regional or local levels, as in the Caribbean Basin. Furthermore, the SLOSH model, commonly used to estimate peak surge values accompanying tropical storms, has a margin of error of approximately 20 per cent, or equivalent to the 20cm rise in sea level for a surge prediction of 1m.[3] The same author therefore concludes that the direct effect of sea-level rise (of the order of 20cm) on storm surge modelling in the region will have little practical effects, but that indirect effects – such as shoreline displacement due to increased shoreline erosion – will introduce the need to frequently update coastal maps and other input data to the modelling process.

Given the uncertainties introduced by a possible global warming, storm hazard models will need to be capable of frequent updating of their bathymetric and topographic data, of producing high resolution output, and of dynamic coupling of the wind and water components of the model.

The Forces of Destruction. Wind

The sustained wind speed for a Category 5 hurricane exceeds 155mph in the wall of the eye, with higher gusts occurring in the turbulent interaction of the boundary layer and surface obstacles. Any element which cannot resist the forces exerted by the wind acting on it is bent, broken, lifted or otherwise deformed. Wind damage is not simply a function of the maximum sustained surface wind, defined as the mean wind speed as measured by an anemometer over a one minute interval at an altitude of 10 metres over open terrain Factors such as maximum wind speed in gusts, duration of high sustained wind speeds, and variations in the direction of the wind, can subject different elements of a structure to different loadings with cumulative effects, and are therefore important determinants of the damage suffered by structures in a hurricane.

An important consideration in the design of structures is their response to gusts, or extreme winds. Smaller and lighter elements of a building such as roof sheeting and their support, windows, doors and cladding, respond more rapidly to wind loading and are therefore more vulnerable to damage by wind gusts Since the destructive force of wind increases with the square of its speed, it is very important to be able to accurately determine the maximum wind speed The measurements of wind speed in short wind bursts is difficult, however, since most wind instruments are not equipped to record short period observations.

The relationship between the maximum gust speed and the mean hourly wind speed is defined as the 'gust factor', and has been well-established for non-tropical storms, but may not be appropriate for tropical storm climatology [4] In his study of wind statistics of four different hurricanes, including Hugo in 1989, Krayer defines a tropical storm gust factor as the ratio of the two second peak gust over the ten minute mean wind speed. Analysis of wind instrument data for these four hurricanes resulted in a mean gust factor of nearly 1.6 The author also mentions observing abnormally high gust factors over inland areas, ie areas subject to significant turbulence, and suggests that further study is needed to understand this phenomenon.

The gust factor was also a topic of discussion at the most recent National Hurricane Conference[1], which dedicated one of its sessions to determining what the winds were in hurricane Andrew over South Florida. Based on observations made by a variety of instruments located near the landfall of hurricane Andrew, a consensus estimate of 145mph was calculated for the maximum sustained surface wind.[5] Some of the damage, however, could only be explained by shorter period wind gusts reaching speeds of at least 175mph, a value which was arrived at on the basis of an exercise that consisted in analysing specific structural failures, and calculating what wind speed would have caused such failures.[6]

Two more factors need to be taken into account in assessing wind hazard. The first is the influence of topography on wind speed. This effect is well-known, as evidenced by housing and urban settlements seeking shelter by building on the leeward side of mountains and hills from prevailing winds. With the objective of quantifying this effect, the Boundary Layer Wind Tunnel Laboratory of the University of Western Ontario, Canada, undertook a physical model wind simulation of the island of Nevis.[7] The study confirmed the shelter effect of mountains and hills, with surface wind speeds (at 10m elevation) dropping to less than 50 per cent of the gradient wind speed (at 500m). It also identified the increase in wind speed over crests in the terrain, an effect that can increase the gradient wind speed by up to 20 per cent.

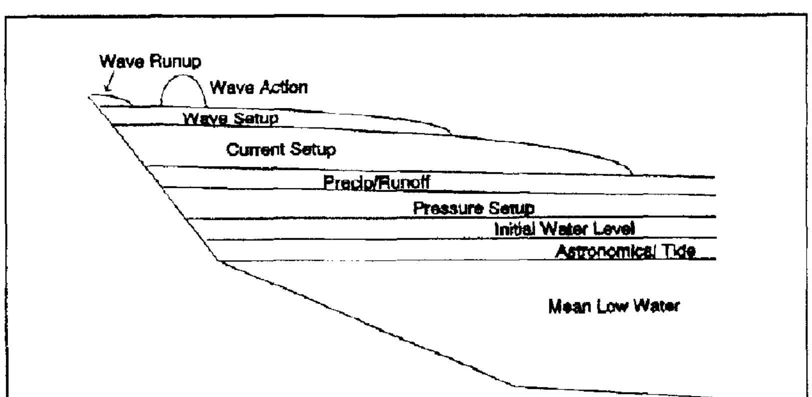
The last, but not necessarily least, factor is that a substantial part of wind damage in an urban environment can be caused by flying debris, ie those materials resulting from already failed structures which may become wind-borne and can in turn inflict damage on surrounding properties. Buildings designed for the proper maximum wind loading may still fail due to the direct impact of debris.

The Forces of Destruction: Water

Historically, 90 per cent of the fatalities and much of the property damage due to storms is as a result of 'storm surge'.[8] In mountainous regions, such as many of the Caribbean islands, rainfall-induced slope failures are another source of damage and loss of life What is commonly referred to as the storm surge is actually a complex phenomenon consisting of many components. A regional risk assessment process can be reliable only by taking into account all of these phenomena, as the various components interact differently on different shorelines. Figure 1 shows these components, which are described below:

- *Astronomical Tide.* Tide levels are especially important for hindcasting, and are important for setting upper and lower bounds for planning purposes Throughout most of the Caribbean, tidal variations are small but can be significant in some locations
- *Initial Water Level.* Some large storms, or storms embedded in larger scale systems, can elevate basin wide water levels. This aspect is especially difficult to model in a forecast mode, and impossible to predict more than 72 hours before storm arrival.
- *Pressure Deficit (or Pressure Setup)* The extremely low pressures associated with the passage of storm systems result in elevated water levels.
- *Precipitation/Run-off/Rivers.* Some storms produce large amounts of rainfall, which contribute to the overall water levels If the rainfall begins before the arrival of the surge, or if the storm is slow moving, this effect can be significant.
- *Current Surge (or Wind Set-up).* The high winds circulating around storms impart momentum to the surface of the ocean, inducing a current. Shallow water slows this movement, resulting in water piling up This effect can result in huge water levels on a continental shoreline, such the 6.7 metre water level at Bulls Bay, South Carolina, as a result of Hurricane Hugo.[9] This effect is usually much lower on islands, as the water can usually flow around the island, and shelf widths are much smaller.

Figure 1: Components of the Storm Surge (After USACERC, 1973)



[1]New Orleans, March 8-11, 1994.

● *Wave Set-up* Continuous trains of waves striking the shoreline over a period of time can result in elevated water levels. This effect is usually more pronounced on shorelines with narrow shelves such as are found in the Caribbean, since higher amplitude waves can reach the shore.

● *Wave Action and Run-up.* The actual waves themselves ride on top of all of the above factors. This can result in quite large waves striking coastal structures. In addition, waves travel far beyond the immediate effects of a storm. On steep shorelines wave run-up can be impressive, as the breaking waves force water far up the shore. This creates the impression that the surge is much larger than it really is. Hurricane Allen, which passed over 80km north of Jamaica, caused flooding at elevations of 12 metres above sea level. This was almost entirely due to wave action and run-up striking a steep foreshore with cliffs (Personal communication with the Jamaica Office of Disaster Preparedness [ODP] and Geological Survey Division [GSD], 1994).

Precipitation can affect inland areas as well as the immediate shoreline. For example, the storm surge has the effect of blocking the outlets of normal drainage systems such as rivers, streams, and man-made drainage control systems. As mentioned previously, the large impulse of rainfall associated with some storms can trigger landslides and cause inland flooding.

The modelling process being used by CDMP for risk assessment incorporates all of the above factors in calculating storm surge. In the Caribbean basin many of the above factors are of roughly equal magnitude. For example, wave set-up and current surge are roughly equal, whereas on the east coast of the United States, the current surge is usually the dominant force by a factor of three or more.

The Storm Modelling Process

Severe storms are relatively rare occurrences in any given location, yet such storms occur with a fairly high frequency throughout the Caribbean Basin. The risk inherent in any location can therefore not be determined solely based on the historical data on storm events that have affected such locations, but needs to be determined by statistical means

The probability of a storm of a certain category striking any location is estimated based on a statistical analysis of historic storm patterns. Numerical techniques and computer based models are needed to carry out such analysis and to determine the probable impact of storm winds and surge

The storm's impact and its effect on a particular site are the result of a very complex and dynamic process, governed by the storm's characteristics and by the interaction of wind and water with land based obstacles. Small changes, such as clearing of land or the construction of a sea wall, may cause large changes in wind or storm effects. Any risk assessment model therefore must be both faithful to the physical processes involved and dynamic enough to incorporate real or projected changes to the study area

CDMP is using a modelling process developed by Charles Watson, called The Arbiter Of Storms (TAOS) system. Traditional approaches to modelling the effects of storm systems have relied on custom data bases and computer code. In addition, the effects of wind, waves, and storm surge are rarely modelled simultaneously using the same data structures or algorithms For the emergency planning community this results in having to use different, complex, often conflicting, difficult to update sources of information. In addition, output products are often in formats not designed for use with planning support systems such as Geographical Information Systems.[10] TAOS attempts to address all of these problems. The three major aspects of TAOS are the data model, the physical storm models, and the output products.

The first question one must answer when beginning a storm modelling process is simple: Which storms to model? It may seem to be an easy question, and for disaster preparedness and evacuation purposes it has a simple answer: run the model once for each Saffir/Simpson storm category from every possible direction to create a map of maximum water and wind levels for each storm type. But if one seeks to establish return times for planning and engineering design purposes, the answer quickly becomes less clear. Recent research, especially by Dr. William Gray of the Colorado State University, indicates that hurricane generation in the Atlantic and landfall in the US occurs in 20 to 25 year cycles. Analysis of the hurricane tracks provided by the National Center for Atmospheric Research shows various patterns in time and space for the Caribbean. Simple statistical analysis of storm tracks can create false return times. For example, during a 'strong' cycle, an area may be hit by two Category 3 storms in 15 years, but none during the following 'weak' cycle. During the 50 year period, is a Category 3 storm a 50 year storm or a 10 year storm? The TAOS system calculates statistics based on the assumption that there are cycles in storm generation for intense storms. When calculating return times, it is assumed the period in question begins in a 'strong' period. While this may seem to be an overly conservative approach, consider that we are most likely entering a period of 'strong' storms.[11]

TAOS was designed from the start to interact with GIS packages such as Arc/Info, GRASS, and Idrisi, obviating the need for creating special purpose data structures. For CDMP, the input data bases are created using Idrisi, a raster-based GIS package from Clark University. Surface characteristics are determined from the results of processing satellite images, using the image processing capabilities of Idrisi. Near shore bathymetry is also determined from the imagery.[12] Topographic data is often available in various GIS or CAD formats. By using a standard GIS package which provides conversion modules, costly and time consuming data input and conversions are avoided. For example, the Caribbean base map created for CDMP is based on the *Digitial Chart of the World*, a public domain data set created by the US Defense Mapping Agency Since the models work from a standardised GIS database, updates or improvements to the database are available for the next model run without further effort.

The second, and most critical, aspect of TAOS is the modelling of the physical storm processes. The primary difference between TAOS and other storm modelling efforts is the integration of the various processes. Comparisons of TAOS to existing storm models are difficult. Most models address only single components of the storm hazard problem For example, SLOSH only deals with the water height caused by momentum, and does not give wave height or wave run up. SLOSH does not include precipitation, or accurately model surface winds over land.[13] WHAFIS, the model used to create the FEMA coastal flood hazard maps, requires the input of a storm surge model and generates wave height, but only for specific transects which must be manually compiled. Other effects must be calculated separately, such as wave run-up. In addition, the results must be manually compiled to create maps.[14] Water and wave levels calculated by traditional 'single transect/wave window' engineering methods are extremely suspect, as they fail to account for many of the physical processes involved in storm wave and surge generation, such as wave set-up and run-up, the effects of surface characteristics, or cross-shore flow. The storm surge is a three-dimensional problem which does not lend itself well to two dimensional solutions. Single transect methods can only be used on well-behaved open shorelines, and should never be used on islands.[15]

The TAOS storm model itself consists of three modules: wind/atmosphere, water flow, and wave generation. The model relies on solving flow equations for air and water via coupled finite difference solutions.[16] The code is heavily optimised to run on either Intel 486 or Pentium-based computers, with the option to parallel up to three machines, each running a single module and communicating via ethernet.[17] Meteorological input parameters may be from three sources: historical storms, hypothetical storms, or directly from the NMC/NHC model outputs for real-time forecasting. TAOS is not designed to be a 'hurricane specific' model, but to be able to model a variety of storm systems. The wind module uses topography and surface characteristics to calculate the wind vectors for each (nominally) 50 metre cell at 30 second intervals. The wind vectors generated by TAOS are at the five metres above grade level to more realistically model the effects of wind on structures Meteorological parameters generated by the wind module, such as pressure, are made available to the other modules. Wind stress, bottom stress, topography, pressure deficit, tidal effects, and precipitation all come together in the water flow module to calculate water movements and levels. The wave generation module calculates the probable wave fields generated by the storm passage and propagates them outward, and calculates wave set-up and run-up It should be noted that the modules are fully coupled: for example, as the surface characteristics of the water changes due to waves, the wind stress is affected.

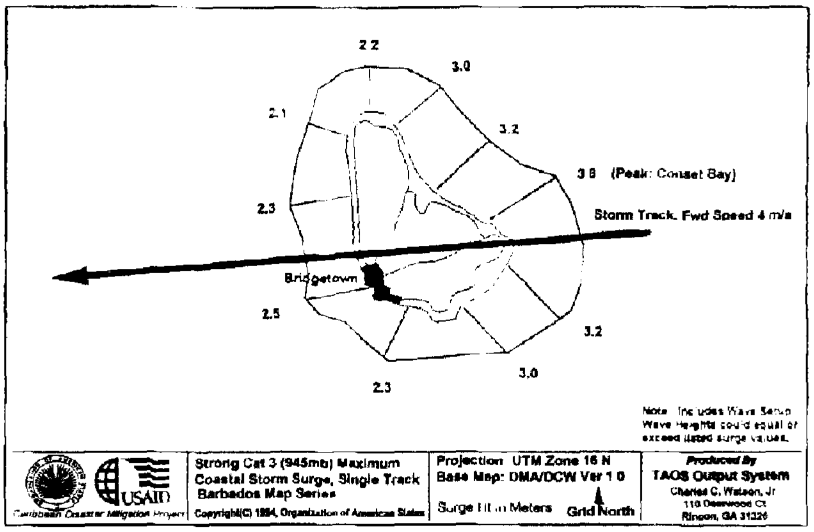


Figure 2: Sample TAOS Coastal Surge Map.

Model runs result in output GIS data bases for the parameters of interest, such as maximum wind at surface, maximum still water height, maximum wave height, etc (see Figure 2). As the outputs are in a format easily exportable to various GIS packages, non-technical users may quickly access model output products and create maps for their particular applications. One important aspect of the model is its high resolution. The nominal grid resolution of TAOS is 50 metres per cell. This results in the ability of the model to produce site specific outputs at virtually the single structure level. For more general results, or for runs across large areas, cell sizes of up to 1,000 metres can be used. Through the use of data compression techniques, it is possible to model very large areas at this level. For example, a calibration run for Hurricane Hugo modelled the entire storm track from Guadeloupe through Puerto Rico, to the final landfall in the US on the South Carolina coast at the 1km/cell level The results compared well with the observations of both surge and wave activity.[16] The ability of the model to cope with both continental shorelines and islands in the same run greatly increases the confidence that the model is producing valid data for a wide variety of shorelines.

Applications of the Storm Assessment Model

The primary objective of the storm hazard studies of the CDMP is to promote safer development location and building practices by producing reliable information on storm risk. The project therefore supports a variety of applications of the information in the context of emergency management and development decision making. User groups in the private and public sector are directly involved in the development of the applications to ensure effective dissemination and use of the hazard and risk information

Hazard maps produced by the project will enable emergency management offices to identify high risk areas from storm surge, and to prepare appropriate evacuation plans. Similar maps can be used by the physical planning departments to locate safe housing and urban expansion areas.

Storm surge and wind hazard maps can be used by builders and individual homeowners to retrofit existing structures to an acceptable level of risk, or to build new structures according to appropriate design standards. Reliable information on maximum probable wave height and storm surge for a given return period, and with sufficiently high resolution to show variation along a coastline, is essential for the cost-effective design of public works projects such as sea walls, bridges and roads.

An important user of storm hazard and risk information in the private sector is the Caribbean insurance industry Site specific hazard information is needed for an underwriter to be able to accurately estimate the risk for a property and to set rates that differentiate by risk level. Hazard information at the regional or country level is an essential input for portfolio risk analysis and management with a company, or to determine the probable maximum loss associated with a catastrophic event affecting a country

Conclusion

Natural hazard mapping is a technique for synthesising and displaying physical and locational characteristics of natural hazards, in combination with physical and socio-economic data on what can be affected by the hazards. If properly designed, hazard maps can be effective tools for risk assessment and analysis. They also are an essential input for emergency management and mitigating planning.

The process of hazard assessment and the maps resulting from that process can also be very effective tools for fostering communication and collaboration between disaster co-ordinators, development planners, local communities and the private sector on all aspects of disaster management. Effective collaboration between these groups is needed in identifying opportunities for vulnerability reduction and in setting priorities for their implementation.

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