A1 Hurricane and Earthquake Hazards in the Caribbean

A1.1 The Hurricane Hazard

by Tony Gibbs, BSc, DCT(Leeds), FICE, FIStructE, FASCE, FConsE, FRSA
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1 Formation

Cyclones are formed when an organised system of revolving winds, clockwise in the Southern Hemisphere and anti-clockwise in the Northern Hemisphere, develop over tropical waters. The classification of a cyclone is based on the average speed of the wind near the centre of the system. In the North Atlantic they are called tropical depressions for wind speeds (1-minute average) up to 17 metres per second (m/s). Tropical storms have wind speeds in the range 18 m/s to 32 m/s. When the wind speeds exceed 32 m/s the system is called a hurricane in the Caribbean.

A hurricane is a large-scale, low-pressure weather system. It derives its energy from the latent heat of condensation of water vapour over warm tropical seas. In order to develop, a hurricane requires a sea temperature of at least 26 C which must be maintained for several days for the system to sustain itself. A large expanse of sea surface is required for the formation of a hurricane, about 400 kilometres (km) in diameter. A mature hurricane may have a diameter anywhere from 150 km to 1,000 km with sustained wind speeds often exceeding 52 m/s near the centre with still higher gusts.

A unique feature of a hurricane is the eye. The system of revolving winds does not converge to a point, but becomes tangential to the wall of the eye at a radius of 8 to 12 km from the geometric centre of the disturbance. The eye is an area of light winds, thin cloud cover and the lowest barometric pressure. The eye provides a convenient frame of reference for the system and can be tracked with radar, aircraft or satellite. The illustration at the start of this session shows a computer-generated view of a hurricane from above. Figure 1 shows the variations of wind speed and barometric pressure with distance from the eye of the hurricane.

The normal criterion for the design of buildings to resist hurricane force winds is the 1-in-50-year wind, i.e. a wind which on average is not expected to be exceeded more that once in 50 years. For buildings of a critical nature it is common practice in hurricane-resistant design to cater for a wind speed with a statistical return period of more than 50 years. Depending on the circumstances, a 1-in-100-year hurricane or a 1-in-200-year hurricane may be appropriate. This has the same effect as increasing the "safety factor" or the design wind speed.

Figure 2 illustrates isolines depicting the geographical distribution of tropical storms and hurricanes during the period 1886-1992. It can be seen that as one moves northwards and westwards the frequency increases.

2 Climate Change and its Effects on the Windstorm Phenomena

Much controversy surrounds this subject. There is certainly no unanimity among scientists about the extent of global warming and effect of global warming on the weather patterns of this planet.

2.1 Increases in Frequency and Intensity of Windstorms

There is a general feeling that windstorms have increased in frequency and severity in recent decades. This "feeling" is unreliable as a measure of the facts. Certainly there has been a dramatic and irrefutable increase in economic losses during the past two decades as compared with earlier decades. But this has more to do with demographics than with the weather. The trend is for population shifts towards coastlines which are more vulnerable to windstorms and for greater concentration of populations in urban areas as opposed to dispersed rural agricultural communities. Then there is the much better reporting of disasters through global television networks. As recently as 1976 an earthquake in Tangshan (China) killed several hundred thousand people and yet went largely unreported for months. Much less cataclysmic events are known of instantly around the world today.

Nevertheless, it is worth examining the possible effects of climate change on the frequency and severity of wind hazards.

2.2 The Greenhouse Effect

The main source of energy for our planet is the sun. In spite of the considerable amount of energy provided by the sun (about 20,000 times as much as the total of all man-made power stations on earth) the temperature of the earth would be 30 degrees Celsius colder were it not for the blanketing effect of the atmosphere. This is the so-called greenhouse effect. The atmosphere consists mainly (99.9%) of nitrogen, oxygen and argon. The remaining trace gases are mainly water vapour, carbon dioxide, ozone and methane. An important function of these trace gases is to absorb the thermal radiation emitted by the earth and send it back to the earth's surface thus reducing dramatically the loss of heat. An increase in these greenhouse gases is therefore blamed for global temperature rise. Global temperatures have been measured accurately and reliably for over 100 years. The absolute rise has been quite small (less than 1 degree) during this period. However the rate of rise has increased quite dramatically during the past twenty years, hence the alarm. Figure 3 shows measured and projected mean global temperatures from 1880 to 2040.

On 26 October 2000, CNN reported that pollution was adding to severe global warming. There is new evidence showing that man-made pollution has "contributed substantially" to global warming and the earth is likely to get a lot hotter than previously predicted, according to a UN-sponsored panel of hundreds of scientists. There is stronger evidence of the human influence on climate. The UN report is clearly saying that global warming is a real problem and it is getting worse. There are still some doubters, including Michael Schlesinger - a climatologist at the University of Illinois, who said that despite the new information there is still insufficient knowledge about natural climate to make such assessments. Nevertheless the new estimates of warming pose a risk of devastating consequences within this century.

2.3 Deforestation and Industrialisation

Natural forests covered 35% of the earth's surface as recently as the nineteenth century. Now that figure has been reduced by a third. This has resulted in a significant change in the water and radiation balance of the planet. An even more important development is the use of fossil fuels (coal and oil) for our energy needs. This leads directly to an increase in the carbon dioxide content of the atmosphere. Various models predict a range of temperature rises for the planet. That range is between 1 and 5 degrees over the next sixty years. Two-thirds of this increase is attributable to increases in carbon dioxide and chlorofloro-carbons (CFCs). (CFCs are used as propellants in sprays and in refrigerators and foamed plastics.)

3 Factors Affecting the Wind Speed

3.1 Ground Roughness

The wind near the surface of the earth is very turbulent and is greatly affected by the frictional effect of the ground. The greater this friction the slower the average speed and the greater the turbulence. In order of increasing friction one can move from the ocean; to flat, open countryside; to undulating countryside with trees; to suburban areas with low-rise buildings; to the centre of large cities. Figure 4 illustrates this factor.

3.2 Topography

Experience teaches us that wind speeds are affected by the shape of the land over which it flows. Wind accelerates as it flows upwards and across hills and ridges. On the other hand the leeward sides of such ridges exhibit lower wind speeds due to the sheltering effect of the hill. Wind blowing parallel to narrow valleys accelerate due to the Venturi effect.

An interesting experiment was carried out on a model of the small island of Nevis on this phenomenon in 1985 at The University of Western Ontario Boundary Layer Wind Tunnel Laboratory.

As part of the Caribbean Disaster Mitigation Project wind hazard maps have been produced by TAOS Output System. The 100-year Wind Hazard Map for St Lucia is reproduced as Figure 5. It shows the influence of topography on the wind speed.

3.3 Height above Ground

Wind speeds increase with height above ground up to what is known as the gradient height. At this gradient height (and above) the wind speed is relatively constant. Gradient height varies depending on ground roughness. Over open country gradient height is at approximately 300 metres whereas over the centre of a large city it would be at approximately 500 metres. Figure 4 illustrates this factor.

3.4 Averaging Period for Measurement

Wind speeds vary from place-to-place and from moment-to-moment. There may be such a thing as an instantaneous wind speed but it is not easy to measure nor is it useful for engineering design purposes. In practice reported wind speeds are averages over periods which depend on the type of anemometer and on the traditions in the country. In Australia (and, until 1995, in the United Kingdom) the 3-second gust is the reporting standard for engineering purposes. In the USA, until very recently, they used the unusual concept of "the fastest mile" wind speed because their anemometers measured "a mile of wind" as it passed the instrument. (The USA now uses the 3-second gust.) The International Organisation for Standardisation (ISO) uses a 10-minute average and Canada (and now the United Kingdom) uses a 1-hour average. The Caribbean Uniform Building Code (CUBiC) follows the ISO standard and the Barbados National Building Code uses the 3-second gust. As an example of the effect of this factor, a wind speed of 100 kilometres per hour averaged over one hour would be equivalent to a wind speed of about 150 kilometres per hour averaged over three seconds. Figure 6 illustrates this factor.

4 Factors in Determining the Effect of Wind on Buildings

4.1 Speed (rotational plus forward motion)

The destructive potential of a hurricane is significant due to high wind speeds, in the main.

The Saffir/Simpson scale is often used to categorize hurricanes based on wind speed and damage potential. The following five categories of hurricanes are recognized:

Wind Speed (1-minute average)			
Category	m/s	mph	Damage
HC1	33 - 42	74 - 95	Minimal
HC2	43 - 49	96 - 110	Moderate
HC3	50 - 58	111 - 130	Extensive
HC4	59 - 69	131 - 155	Extreme
HC5	> 69	> 155	Catastrophic

4.2 Direction

Buildings and other structures usually vary in shape and strength depending on the compass direction from which they are viewed. Wind storms may attack from any direction but their effective severity does depend on their angle of attack or their direction. For example the particular location may be shielded by hills or, unfortunately, the location may be in a valley (parallel with the wind direction) causing the acceleration of the wind. Also most destructive winds happen in circular formations which have translational motion as well. In such circumstances the forward speed of the entire system must be added or subtracted from the circular speed to obtain the effective speed. Thus, in most hurricanes in the Caribbean, the north quadrant of a system has higher overall wind speeds than the south quadrant.

4.3 Duration

Tropical cyclones last for days and because of their slow forward motion (15 to 25 kilometres per hour) their impact on a particular community or structure can last for hours. The frequency of gusting in a well-developed hurricane can be as high as 3 hertz. That means about 10,000 cycles of loading in an hour. Fatigue of materials thus becomes an important consideration in determining the vulnerability of structures.

4.4 Collateral Damage from Flying Debris

There is a growing recognition that it is not sufficient to consider only the wind when addressing the damage potential of windstorms. With the increasing use of glass in building envelopes, and relative increase in the value of contents over the value of buildings, damage from flying debris has become an important factor. Conscious attention to this issue has its identifiable start about 30 years ago. The building industry has been reluctant to embrace the need for protection against missiles however and the regulatory authorities have not, generally, been sufficiently bold to impose such protection on the industry. In a well-developed windstorm the air is laden with all manner of loose objects which serve to intensify the hazard.

4.5 Collateral Damage from Rainfall

Breaches to building envelopes by impact damage or wind-pressure failure make the contents vulnerable to water damage from the heavy rains which often accompany windstorms. Even when there is no clear breach in the envelope, wind-driven rains are able to enter otherwise secure buildings.

4.6 What is a Hurricane?

The following quotation describes the reality of a hurricane:

> *"The real environment in a hurricane consists of strong, turbulent winds (sustained for many hours), that change slowly in direction as the storm passes, and carry large amounts of debris while accompanied by torrential rains."*

Prof Joseph Minor (modified by Tony Gibbs)

5 Examples of Failures

5.1 Catastrophic Failures

Photo 1 shows a foundation failure. The uplift forces from hurricane winds can sometimes pull buildings completely out of the ground. In contrast to designing for gravity loads, the lighter the building the larger (or heavier) the foundation needs to be in hurricane resistant design. Ignoring this precept has led to some dramatic failures of long-span, steel-framed warehouses as well as conventional schools.

Steel Frames are often damaged by hurricanes, as illustrated by Photo 2. A common misconception is that the loss of cladding relieves the loads from building frameworks. There are common circumstances where the opposite is the case and where the wind loads on the structural frame increase substantially with the loss of cladding. Usually the weakness in steel frames is in the connections. Thus economising on minor items (bolts) has led to the overall failure of the major items (columns, beams and rafters).

Masonry buildings are usually regarded as being safe in hurricanes. There are countless examples where the loss of roofs has triggered the total destruction of un-reinforced masonry walls, as illustrated in Photo 3.

The key to safe construction of timber buildings is in the connection details. The inherent vulnerability of light-weight timber houses coupled with poor connections is a dangerous combination which has often led to disaster, as illustrated in Photo 4.

The design of reinforced concrete frames is usually controlled by the seismic hazard. In countries where this is not an issue care still needs to be exercised to ensure that the concrete frames can accommodate the wind forces. There have been a few isolated examples where ignoring this has led to disaster, as illustrated in Photo 5.

5.2 Component Failures

Roof sheeting is perhaps the commonest building component subject to failure in hurricanes. (see Photo 6.) The causes are usually inadequate fastening devices, inadequate sheet thickness and insufficient frequencies of fasteners in the known areas of greater wind suction.

Of particular interest in recent hurricanes was the longitudinal splitting of rafters with the top halves disappearing and leaving the bottom halves in place. (See Photo 7.) The splitting would propagate from holes drilled horizontally through the rafters to receive holding-down bars.

After roof sheeting, windows and doors are the components most frequently damaged in hurricanes. (See Photo 8.) Of course, glass would always be vulnerable to flying objects so that hurricane shutters are indicated. The other area of vulnerability for windows and doors is the hardware - latches, bolts and hinges.

It is not uncommon for un-reinforced masonry walls to fail in severe hurricanes. (See Photo 9.) Cantilevered parapets are most at risk. But so are walls braced by ring beams and columns.

6 Effects of Windstorms on Agriculture and Forests

Some economic crops have virtually no resistance to the wind. These usually are crops with very short life cycles. A prime example of such crops is the banana plant. A storm with 50-kilometre-per-hour winds would wreak havoc in a banana plantation. Decorative palms grown specifically for sale also come into this category.

Bamboo plants, palms in their natural state and sugar cane can resist winds fairly successfully. But even these relatively strong trees are damaged and destroyed by severe winds.

In regions where windstorms are infrequent even very large and old species of trees have inadequate roots to resist severe windstorms.

In cases where trees have been strong enough to resist the force of the wind there has nevertheless been the loss of forests because of the stripping of the protective barks from the trees. The appearance of a tropical forest after a major hurricane is not dissimilar to that of a forest fire.

In the 1960s the United States embarked on a series of experiments named Project Storm Fury. The idea was to reduce the strength of hurricanes by seeding them during the early stages of development. This project was blamed for the droughts in some Caribbean islands at the time. This points to one of the beneficial effects of tropical storms being the production of rain. Hurricanes also serve to dissipate excess heat from the lower latitudes.

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Variations of wind speed and barometric pressure with distance from the eye of a hurricane
(Shell)

Figure 1

Isolines depicting the geographical distribution of category-3 hurricanes in the Caribbean (1886 to 1992)
(The University of the West Indies)

Figure 2

Mean global temperatures measured from 1880 to 1990 and projections to 2040

Curve 1assumes a further increase in the release of greenhouse gases

Curve 2assumes the volume of greenhouse gases remaining at the current level

Curve 3assumes a substantial decrease in the volume of greenhouse gases

(Munich Re)

Figure 3

Variation of relative wind speed with height above the ground and different ground-roughness characteristics

1 represents the open ocean
2 represents open countryside
3 represents small towns and villages
4 represents the centres of large cities

Figure 4

Topographic effects on wind speeds on the island of St Lucia in the Caribbean

(TOAS for OAS-USAID)

Figure 5

Ratio of probable maximum speed averaged over *t* seconds
to hourly (3,600 seconds) mean speed
(C S Durst and William R Krayer & Richard D Marshall)

Figure 6

A1.2 The Earthquake Hazard

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1 The Tectonic Setting of the Caribbean

The Tectonic Setting of the Caribbean[1] is illustrated in *Figure 1*. It shows the Approximate Caribbean Plate Boundaries. As can be seen, all of the Commonwealth Caribbean countries, with the exceptions of Bahamas and Guyana, lie close to these boundaries. The Caribbean Plate is moving eastward with respect to the adjacent North American and South American Plates at a rate of approximately 20 millimetres per year. A moderate level of inter-plate activity is generated along these boundaries. Along the northern margin, including areas in the vicinities of Jamaica and the Virgin Islands, moderate earthquakes of shallow depth are generated. Near the plate boundaries there are also intra-plate earthquakes. In the northern Caribbean these intra-plate earthquakes are caused by internal deformation in a slab of the North American Plate. Concentrations of these earthquakes occur at depths of up to 200 kilometres.

F J McDonald and J Turnovsky[2]:
"The Cayman Fracture Zone which extends eastward from Honduras to Hispaniola is the boundary between the Caribbean and North American Plates in the area and is a tectonically active feature along which future seismic events may be expected."

Drs John B Shepherd and W P Aspinall[3]:
"All three segments of the Cayman Trough are seismically active but the number of fault-plane solutions obtained to date is small."
"All of these solutions are consistent with the idea that the Cayman Trough forms part of the northern boundary of the Caribbean lithospheric plate ...."

John B Shepherd[4]:
"The mid-Cayman Rise is a currently-active spreading centre opening at a rate of 20 mm per year ..."
"Historically no great earthquake is known to have originated in the mid-Cayman rise and, worldwide, earthquakes in sea floor spreading centres rarely exceed magnitude 5 ..."

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[1]This is an often-published document originally prepared by the researchers Molnar and Sykes in 1969.
[2]both of Mines and Geology Division, Ministry of Mining and Natural Resources, Jamaica
[3]"Estimating Earthquake Risk in Jamaica", Seismic Research Unit, UWI, Trinidad
[4]"Seismicity of the Greater and Lesser Antilles", Seismic Research Unit, UWI, Trinidad

"This (mid-Cayman to Haiti) is one of the more complex sections of the circum-Caribbean plate boundary."

Seismic events in the Eastern Caribbean are principally associated with a subduction zone at the junction of the Caribbean Plate and the North American Plate. The North American Plate dips from east to west beneath the Caribbean Plate along a north-south line just east of the main island arc. This leads to a moderate level of inter-plate seismicity. Superimposed on this is a pattern of intra-plate activity. There is a concentration of such activity in the Leeward Islands where the subduction of the Barracuda Rise imposes additional stresses on both the "subducted" North American Plate and the overriding Caribbean Plate. The earthquakes there are generally shallow. In the region north-west of Trinidad there is another concentration of earthquake activity where the strike of the plate boundary changes direction. These earthquakes are of intermediate depth.

In addition *Figure 9* shows the Main Features of the Eastern Caribbean and *Figure 10* shows the structure in the region of Barbados.

2 Seismic Research Unit of Uwi and the Engineering Community

Over the past forty-seven years a considerable amount of research has been carried out on the seismicity of the Caribbean by the Seismic Research Unit (SRU) of The University of the West Indies (UWI). The engineering community has been requesting more and more assistance from the SRU in interpreting the fundamental research and developing "code" values for seismic forces for use in structural design. The most recent published work in this field is that of SRU's head, Dr John Shepherd.

3 The Pan-american Institute of Geography and History Project

The Pan-American Institute of Geography and History (PAIGH) is based in Mexico City. The Geophysical Commission of PAIGH was the executing agency for a major project (funded by IDRC) for preparing Seismic Hazard Maps for Latin America and the Caribbean and headed by Dr J G Tanner. Dr John B Shepherd participated in this project as the Caribbean specialist. The final report and mapping from this project was issued in 1997. Some of the information is available on the Internet on the OAS site. Reproduced as *Figure 2* is a regional iso-acceleration map for the Eastern Caribbean.

4 The USAID/OAS-CDMP Project Results and Derived "Code" Values

The Caribbean Disaster Mitigation Project has taken the results of the PAIGH study and put them in a form to be more usable by the Caribbean. The scale for the resulting hazard maps is larger and more related to the islands.

Work on interpreting the hazard maps for use in the various earthquake loading standards in use in the Caribbean continues.

5 Seismic Events in the Caribbean

Several earthquakes have caused severe damage throughout the Caribbean archipelago in post-Columbian historic times. The seventeenth century earthquake in Jamaica and the nineteenth century earthquake in Guadeloupe are particularly well known. The researcher, Dorel, has constructed iso-seismal maps of several events of the nineteenth and twentieth centuries. Some of these are reproduced as *Figures 3 to 8.*

Dr John Tomblin[5]:
"...there are several significant seismicity gaps in the circum-Caribbean belt, including one of spectacularly large dimensions, from the Cayman Islands through Jamaica to Haiti." This 1,200 km long segment of the tectonic belt has had no earthquake of magnitude greater than 5.4 since 1964, and the elastic strain energy now accumulated in this segment, calculated on the space and time length of the gap and the mean rate of energy release around the Caribbean borders, amounts to a single event of Richter magnitude 8?, ..."
"....(this area) showed normal activity between 1898-1952, ..."

The previous subsections talked about the Cayman Trough. This has been recognised as a potential source of earthquakes since the early part of the century. The Cayman Islands sit on a submarine ridge running east-west and about 50 km north of the Cayman Trough (known as the Oriente Fracture Zone in this area). The Oriente Fracture Zone is a strike-slip fault intersecting a spreading centre (the mid-Cayman Rise) and is thus called a transform fault. Such faults are known to be potential sources of major earthquakes.

The Swan Fracture Zone is another strike-slip fault intersecting the mid-Cayman Rise about 200 km south of the Cayman Islands and is thus another transform fault.

Finally, the level of seismicity in most of the Caribbean is considered to be moderate to severe. It is certainly sufficiently important not to be ignored.

6 Regional Conferences

The First Caribbean Conference on Earthquake Engineering was held in Trinidad in January 1978. At that event several papers were presented by seismologists (and other interested professionals) from the Caribbean, Europe and the Americas on the seismic hazard in the region.

The CCEO Regional Seminar on Earthquake and Wind Engineering took place in Trinidad in February 1983.

[5] "Earthquake Parameters for Engineering Design in the Caribbean" by Dr John Tomblin, Head, Seismic Research Unit, The University of the West Indies (UWI), Trinidad

The First Caribbean Conference on Natural Hazards took place in Trinidad in October 1993. The Second took place in Jamaica in 1996. The Third took place in Barbados in 1999.

The proceedings of all of these conferences make useful and interesting background reading on the subject.

7 Volcanic Activity

Several of the islands of the Eastern Caribbean are volcanic in origin. The volcanos there are considered to be either active or dormant. The principal locations of volcanic centres in the Lesser Antilles are shown in *Figure 11*.

Grenada has the only known submarine volcano (Kick 'em Jenny) in the region. It is located just north of mainland Grenada. The first recorded eruption reportedly occurred in 1939. Studies dating back to 1972 indicate that minor eruptions have been occurring on a fairly regular basis and that the summit of the volcano is growing at a rate of approximately 4 metres (13 feet) per annum.

The potential hazard of Kick 'em Jenny to Grenada and the rest of the Eastern Caribbean lies in the form of tsunamis, should a major under-water volcanic eruption occur.

8 Tsunamis

A tsunami (or seismic sea wave or tidal wave) is a series of ocean waves generated by any large-scale, short-duration disturbance of the free surface of the ocean. The majority are related to tectonic displacements associated with earthquakes at plate boundaries. However, tsunamis can also be generated by erupting volcanos, landslides or underwater explosions. In the open ocean, tsunamis may have wavelengths of up to several hundred miles but heights of less than 1 metre. Because this ratio is so large, tsunamis can go undetected until they approach shallow waters along a coast. Their height as they crash upon the shore mostly depends on the geometry of the submarine topography offshore, but they can be as high as 30 metres.

A tsunami travels at an average velocity of 500 to 600 kilometres per hour rising to a maximum of 800 km/h. Therefore within one hour of a major occurrence at Kick 'em Jenny, many of the islands of the Eastern Caribbean will be affected. *Figure 12* indicates the travel times from Kick 'em Jenny and *Figure 13* gives the wave heights at the various islands resulting from a "realistic" scenario for a volcanic event at Kick 'em Jenny.

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Tectonic Setting of the Caribbean
(after Molnar and Sykes, 1969)

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Main Features of the Eastern Caribbean
(based on compilation by JE Case and TA Holcomb USN00
and from Peter and Westbrook, 1976)

Figure 9

Structure in the Region of Barbados
(Westbrook, 1970)

Figure 10

Outline map of the Lesser Antilles
showing locations of main volcanic centres
(Martin S Smith and John Shepherd, Dec 1992)

Figure 11

Tsunami Travel Times from Kick'em Jenny Source
(Martin S Smith and John Shepherd, Dec 1992)

Figure 12

Final run-up values in metres for a 'realistic' scenario event at Kick'em Jenny (VEI = 3)
(Martin S Smith and John Shepherd, Dec 1992)

Figure 13