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HURRICANES AND THEIR EFFECTS ON BUILDINGS AND STRUCTURES IN THE CARIBBEAN

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1 HURRICANES

1.1 The Natural Phenomenon

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 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.

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. Figure 1 shows the variations of wind speed and barometric pressure with distance from the eye of the hurricane.

1.2 The Historical Record

1.2.1 Post-Columbian History

It is estimated that over 4,000 tropical storms have occurred in the North Atlantic region (including the Caribbean) in the 500 years since the advent of Columbus. About half of these have developed into hurricanes. Of course the European did not bring hurricanes to the Caribbean. Indeed the very name is derived from the Mayan storm god *Hunraken* and the Arawak word *hurican*, which meant the devil wind. The greatest of all recorded hurricanes occurred from 10th to 18th October 1780. Nearly 20,000 people perished as the storm hit virtually every island from Tobago in the south-east through the Windward and Leeward Islands and across to Hispaniola and Cuba. In the last 60 years in the Caribbean another 20,000 people have lost their lives because of hurricanes.

The pattern in recent times has been a reduction of deaths and injuries (because of better warning systems and other preparedness activities) and an increase in property damage (because of commercially-driven unsuitable building practices and locations)

The Caribbean lies in the North Atlantic Ocean, one of the six main tropical areas of the earth where hurricanes may develop each year. Of the 4,000 tropical storms which have occurred in the region within the past 500 years, half have developed into hurricanes. A graphical representation of the occurrences of those hurricanes in Category 3 for the last hundred years is shown in Figure 3. It can be seen that as one moves northward and westward the frequency increases.

During the past fifteen years there have been several memorable hurricanes in the Caribbean. Four have been selected to illustrate the effects of such storms on buildings and other structures.

1.2.2 Hurricane David (Figure 2)

David swept through the Caribbean and into North America during the period 27th August to 4th September 1979. In the Caribbean the devastation was particularly severe in the Commonwealth of Dominica and the Dominican Republic.

The damage illustrations from this event accompanying this paper were all taken in the Commonwealth of Dominica where the losses amounted to more than 100% of GDP.

1.2.3 Hurricane Gilbert (Figure 2)

Gilbert caused severe structural damage in the Caribbean and North America during its passage from 11th to 19th September 1988. The countries most affected were Jamaica, Mexico (Cancun, Yucatan) and the USA (Texas). It was the first Category 5 hurricane to make landfall since Camille in 1969.

The damage illustrations from this event accompanying this paper were all taken in Jamaica where the losses amounted to about 65% of GDP.

1.2.4 Hurricane Hugo (Figure 2)

Hugo was the sixth hurricane of the 1989 Atlantic season. It hit the Leeward Islands in the Eastern Caribbean causing serious damage to Dominica, Guadeloupe, Montserrat, Antigua, St Kitts, Nevis and The British Virgin Islands. The storm went on to wreak havoc in United States territories in the Caribbean and in continental USA. Hurricane force winds lasted from 14th September to 23rd September. Eighty-two deaths were attributed to the storm and property damage was estimated at US$ 8 billion in 1989 dollars.

The damage illustrations from this event accompanying this paper were all taken in Montserrat where the losses amounted to about 200% of GDP.

1.2.5 Hurricane Andrew (Figure 2)

Andrew was a fast-moving, compact storm of great intensity (category 4) which impacted on The Bahamas, Florida and Louisiana in late August 1992. Total damage amounted to approximately US$ 30 billion.

The damage illustrations from this event accompanying this paper were taken in Florida and in the Bahamas (Cat Cay, where the losses amounted to about 50% of the property values).

2 DAMAGE TO BUILDINGS AND STRUCTURES

2.1 Saffir/Simpson Scale

The destructive potential of a hurricane is significant due to high wind speeds, potential torrential rains which produce flooding, and occasional storm surges with heights of up to 8 metres above normal sea level, although such heights are unlikely to be experienced in most of the Caribbean islands.

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 (fastest mile)			
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

2.2 Catastrophic Failures

2.2.1 Foundations (Photo 1)

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 failure of long-span, steel-framed warehouses.

2.2.2 Steel Frames (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 increases 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).

2.2.3 Masonry Houses (Photo 3)

These 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.

2.2.4 Timber Houses (Photo 4)

The key to safe construction of timber houses 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.

2.2.5 Reinforced Concrete Frames (Photo 5)

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.

2.2.6 Telecommunication Towers and Masts (Photo 6)

These are almost always consciously-engineered structures. There is no good reason why so many of them fail in hurricanes. The bad reason is usually inadequate procurement procedures. Specialist advice is not often sought in specifying design criteria for suppliers or in checking that specified criteria have been met. The most common destruction of engineered structures in Caribbean hurricanes is in this class of facility.

2.3 Component Failures

2.3.1 Roof Sheeting (Photo 7)

This is perhaps the commonest area of failure in hurricanes. The causes are usually inadequate fastening devices, inadequate sheet thickness and insufficient frequencies of fasteners in the known areas of greater wind suction.

2.3.2 Roof Tiles (Photo 8)

These were thought to have low vulnerability in storms before Hurricane Andrew exposed the problem of unsatisfactory installation practices. The South Florida method of relying on mortar bonding proved to be woefully inadequate.

2.3.3 Rafters (Photo 9)

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

2.3.4 Windows and Doors (Photo 10)

After roof sheeting, these are the components most frequently damaged in hurricanes. 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.

2 3.5 Walls (Photo 11)

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

3. PREVENTION OF DAMAGE

3.1 Hazards versus Disasters

Hurricanes are not natural disasters, they are natural events which sometimes lead to manmade disasters. In these days of widespread technological education, sophisticated research, reliable building materials, computer-based geographical information systems and satellite-assisted warning programmes, hurricanes in the Caribbean should not lead to disasters. The one exception to this would be vulnerable agricultural crops such as bananas.

Disasters are often seen as unpredictable acts of God or having to do with luck and part of the risks of everyday living. Surely we have progressed beyond the stage when superstition, mythology and fatalism were the public responses to (incorrectly called) "natural disasters". It is now evident that disasters due to natural hazards are largely preventable and soon the public will demand deliberate actions to protect communities against such hazardous events. Disaster mitigation must therefore be made an essential ingredient in development planning and capital works projects. In the same way that environmental impact assessments have now become routine, so too should natural hazard impact assessments be a standard requirement in the planning of projects.

3.2 Codes and Standards

The development of a building code for the Commonwealth Caribbean has been in progress for over two decades. In 1968, an informal meeting of a few senior engineers from different Commonwealth Caribbean territories was held in Guyana. The purpose was to discuss matters of mutual interest to the profession. Out of that meeting came the Council of Caribbean Engineering Organisations (CCEO). The mandate of the CCEO included the development of building codes and the co-ordination of such activities among its various constituent member organisations.

Regional seminars were held in Jamaica in 1970, 1973 and 1974 with the aim of developing and finalising a Caribbean building code. A major conference was held in Trinidad in 1978 devoted entirely to the seismicity of the Caribbean region and earthquake-resistant practices therein. In the 1980s the preparatory activities of the 1970s gelled into the development of CUBiC - the Caribbean Uniform Building Code.

In 1986 the Code was formally accepted by the Caricom Council of Ministers of Health (the sponsors of the project). Since then progress has been frustratingly slow. It was only in 1990 that copies of CUBiC became available for purchase by the general public. To date no Caribbean country has made the use of the Code mandatory.

In the meanwhile the most commonly used standard for wind loading in the Caribbean has been the CCEO-sponsored Code "Wind Loads for Structural Design" first published in 1970 and substantially revised in 1982. This was prepared by the Barbados Association of Professional Engineers (BAPE). This CCEO/BAPE Wind Code sets out the basic wind parameters for the design of buildings in the Commonwealth Caribbean. The normal requirement is the 1-in-50-year wind, ie a wind speed which on average is not expected to be exceeded more than once in 50 years In the Caribbean this produces a basic 3-second gust wind speed of between 45 m/s in Trinidad in the south-east and 64 m/s in the north and west. This represents hurricanes of categories 2 and 3. For a category-4 hurricane, a wind speed is experienced which on average is not expected to be exceeded more than once in 100 years in most of the Caribbean. The 1-in-200-year wind is experienced in a category-5 hurricane.

3.3 Education and Training

Clearly, the construction industry has an important role to play in mitigating losses due to natural hazards such as hurricanes. First, however, there is the need for the communities to be aware of the hazards and to accept, indeed demand, that deliberate measures be taken to reduce the adverse effects of such events. Then there is the need for more education and training of the designers and builders in the well-established techniques that are available for eliminating or reducing property losses due to hurricanes and earthquakes.

There is the need to strengthen the undergraduate curriculum at the University of the West Indies (UWI) in this area of designing against hurricane winds. At post-graduate level the UWI is just coming to the end of an important project on the subject of cyclone-resistant housing in the Caribbean. This should give an impetus to research in this field. UWI also conducts a series of continuing education programmes for practicing engineers, including topics relating to hurricane-resistant design.

The CCEO was very active in the field of continuing education during the 1970s and 1980s. However the level of activity of CCEO has dropped noticeably in the 1990s. A revival of CCEO activities, particularly as they relate to disaster prevention issues, is needed.

3.4 The regulatory environment

3.4.1 Codes and Standards

At present there are no laws or regulations requiring any structure in a Caricom state in the Eastern Caribbean to be designed and built to be resistant to any specified level of cyclonic activity. The Northern Caribbean is better served in this respect. Some government agencies adopt an *ad hoc* approach to this issue based, principally, on the particular individuals involved in the specific projects. In most cases the administrators tacitly assume that their designers and builders would do what is right without being told. In other cases the administrators adopt the approach of not objecting to safe design and construction, provided that these attributes do not interfere with their other aims for the projects.

Many government capital works projects are funded by international lending agencies - the World Bank, the Inter-American Development Bank, the European Investment Bank, etc. Typically there is a reluctance on the part of the banks to impose structural design criteria on their projects. The funding agencies leave it up to the governments and the governments leave it up to their designers and builders. This *laissez-faire* approach leads to inconsistent performance, lack of reliability and, arguably, to higher overall life-cycle costs for our built environment.

Building codes must be adopted immediately (ie today) in all Caricom states. Sufficient technical documentation exists. The fact that such documentation has deficiencies should not be an excuse for non-implementation. Codes and standards can be improved only through usage, which leads to inevitable revisions. (California revises its earthquake code every three years. The current edition is always "out of date".)

3.4.2 Checking Compliance

There is no need to wait for the setting up of an elaborate inspectorate before mandating building codes. The Singapore model, with modifications, could be a good guide. There is a considerable degree of self-regulation with registered professional engineers having to certify, explicitly, that design and construction are in compliance with the codes and standards. Then there are in-depth audits on a few randomly-selected projects with bad work leading to dire consequences. So everyone is kept on their toes. Such in-depth audits are sometimes contracted out to private firms when the public works department lacks the resources.

Several of the Commonwealth Caribbean states have enacted registration laws for professional engineers (Barbados was the first to do so (in 1975), triggered by the collapse of stands at the Garrison during the Mexico/West Indies Davis Cup tie in 1971). Registration of engineers should be extended to all states.

3.5 Insurance

Apart from government action, the most effective influence on the improvement of the security of buildings against hurricanes can be wielded by the general insurance industry. Insurance companies have a vested interest in this subject and could provide a strong incentive for the improvement of standards of design and construction.

Most insurance companies provide hurricane cover at the same rates for most buildings, irrespective of their relative abilities to withstand natural hazards. In this system "Peter pays for Paul". Graduated premiums, based on design type, materials and quality of construction would be a meaningful step in the right direction. With the recent difficulties being experienced in obtaining reinsurance cover, Caribbean insurance companies may well be forced to move in this direction.

3.6 Better Buildings

So what can be done for new construction as well as for the large existing stock of buildings? Quite a lot. Listed below, in very general terms, are some issues which should be addressed for new construction and then for the strengthening of existing buildings.

3.6.1 Location

The location of the building is important. We often have little choice in the matter, perhaps because of financial constraints. It is as well, therefore, to recognise when a building is being located in a more vulnerable area. The rational response would be to build a stronger-than-normal house. Such vulnerable areas include open-ended valleys, which act as funnels for the wind, and exposed hill crests. Both conditions lead to acceleration of wind speeds with the corresponding increase in damage potential.

3.6.2 Shape (Photo 12)

We do have control over the shape of new buildings and shape is the most important single factor in determining the performance of buildings in hurricanes. Simple, compact, symmetrical shapes are best. The square plan is better than the rectangle. The rectangle is better than the L-shaped plan. This is not to say that all buildings must be square. But it is to say that one must be aware of the implications of design decisions and take appropriate action to counter negative features. Even more important than plan shape is roof geometry. For lightweight roofs it is best that they be of hipped shape (sloping in all four directions, usually), steeply pitched (30 to 40 degrees), with little or no overhangs at the eaves (with parapets if possible) and with ridge ventilators where these are practicable.

3.6.3 Windows and Doors

Apart from roofs, the elements requiring the most attention are windows and doors. Sadly, these are often neglected even when buildings are formally designed by professionals. Glass windows and doors are, of course, very vulnerable to flying objects. And there are many of these in hurricanes There are only two solutions: use impact-resistant glass (very expensive) or cover the glass with storm shutters (inconvenient?). For new buildings the challenge is to design storm shutters which are integrated into the permanent structure, have another role which they could play every year (eg sun shading, burglar proofing during long absences from home) and enhance the appearance of the building. It is not sufficient to protect fragile glass however. Attention must also be paid to securing doors with strong bolts or braces and to fixing door and window frames firmly to the walls

3.6.4 Connections

The famous German architect, Mies van der Rohe, used to preach to his students that "God is in the details". For anti-hurricane construction this could be rewritten "God is in the connections". It is imperative that all the components of a building envelope be securely interconnected. For timber construction, screws are better than nails and bolts are better than screws.

3.6.5 Drainage

Heavy rains often accompany hurricanes. Flooding has been the cause of many of the deaths in hurricanes and of much property damage too. We spoke earlier about the effect of location on wind speed. Clearly location is critical when it comes to flood risk. Low-lying lands, river banks and lands adjacent to gullies are to be avoided if possible. If not, deliberate drainage measures must be taken. Usually this is a municipal responsibility, at least in terms of overall control, since what happens to one property can easily be affected by a neighbour's actions.

3.6.6 Retrofitting

But what is to be done about the huge stock of existing buildings? Nothing must not be done. Any improvement is worthwhile. It won't be easy (it may not even be possible) to protect many existing buildings from major damage in another David, Gilbert, Hugo or Andrew. But all hurricanes are not great ones. The more severe the storm the less frequent its occurrence. Conversely, the less strong the hurricane the greater the likelihood of it visiting any particular community. Small improvements would be needed more frequently than major strengthening so, at least, a start should be made with the small things. Add to and improve the connections of lightweight roofs to purlins, purlins to rafters and rafters to walls; invest in storm shutters; add bolts to external doors; increase the connections of door and window frames to walls; pay attention to the maintenance of buildings.

3.7 Costs

3.7.1 Economic Considerations

Collection of data on property damage in disasters is not straightforward and the quality of data is considerably lower than for deaths and injuries. In disasters, like wars, truth is an early casualty. Cost estimates of property damage in Montserrat due to Hugo varied from US$ 130 million to US$ 370 million. Even the lower estimate means a loss of twice the gross domestic product (GDP). Only the small size and population of Montserrat, even in the context of the Caribbean, masked the enormity of the event. An equivalent event in Barbados (with a population of only 250,000) would produce losses of US$ 3 billion! Clearly it is essential to do a lot to reduce the impact of future hurricanes. This is especially important now that insurance is very expensive, increasingly not available in the amounts desired and, sometimes, not available at all. Referring again to Montserrat, by the most conservative of estimates, there were about US$ 100 million worth of uninsured losses or 150% of GDP. Grant aid to Montserrat as a direct result of Hugo is not likely to exceed US$ 50 million. The result of this is a net loss to Montserrat of not less than US$ 50 million or US$ 3,500 per head of population.

It is true that Hugo was an uncommon event. It is also true that the standard of building construction in Montserrat was at least as good as anywhere else in the Caribbean; and there are no guarantees against the occurrence of future Hugos.

3.7.2 Public Awareness

During the past 100 years a total of approximately 800 tropical storms and hurricanes have been recorded over the North Atlantic area. Of these, about 50 percent were hurricanes in the general area of the Caribbean. With such a record, it is not surprising that everyone in this region accepts that hurricanes are a fact of life. However, the frequency of direct hits by hurricanes on any one territory is low. This has led to a considerable lack of consciousness amongst Caribbean people as to the dangerous risk to their own properties. Few believe that their island would be hit. Few believe that their own home would suffer.

The way forward would be led by more public awareness programmes, continuing education, intervention of the insurance industry and government legislation.

3.7 3 Impact of Mandatory Regulations on Conceptual Designs

The official implementation of the Caribbean Uniform Building Code would lead to a significant change in the strategies of designers. At present much time is spent debating the extent to which designers and builders must provide against hurricanes. Since there are no official regulations in most Caribbean countries to provide against natural hazards, hurricane resistance tends to be ignored at the conceptual design stage. This leads to the majority of buildings being of inappropriate shapes for resisting this hazard. Making such buildings safe can be expensive. On the other hand, providing against hurricanes, where the design concept is appropriate, adds little to the cost. Thus the mandatory implementation of CUBiC is likely to lead to the reduction in the cost of safe buildings by encouraging more appropriate conceptual designs.

3.8 Support from Funding Agencies

It is normal for most funding agencies to adopt a *laissez-faire* attitude to codes and standards They often take the view that standards are up to the borrower. It would be a big step forward if CDB, EEC, EIB, IDB, IBRD, ODA, CIDA and KDF would insist on the compliance with stated (Caricom) standards for all their projects.

The trend these days is for environmental impact assessments (EIAs) to precede most important infrastructural projects. This is laudable. Funding agencies must now be urged to require natural hazard impact assessments (NHIAs) to become a standard companion exercise

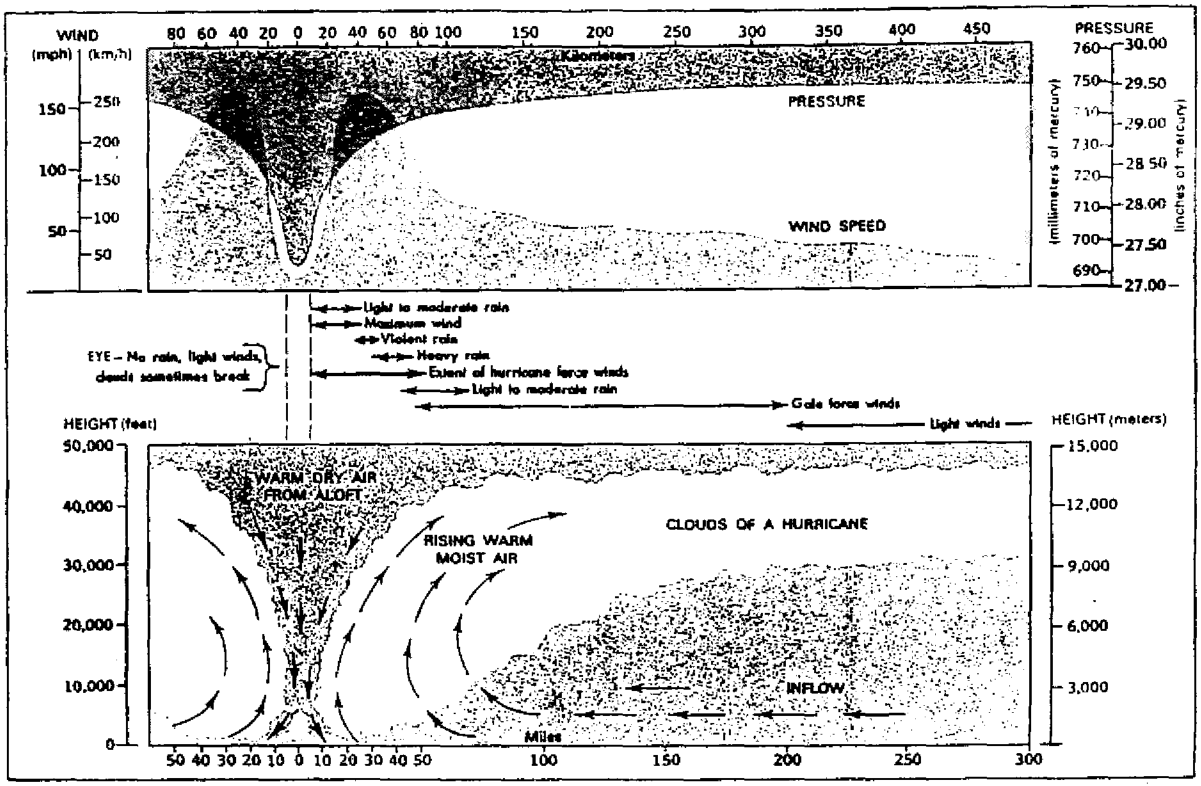


Figure 1 - Variations of wind speed and barometric pressure with distance from the eye of the hurricane

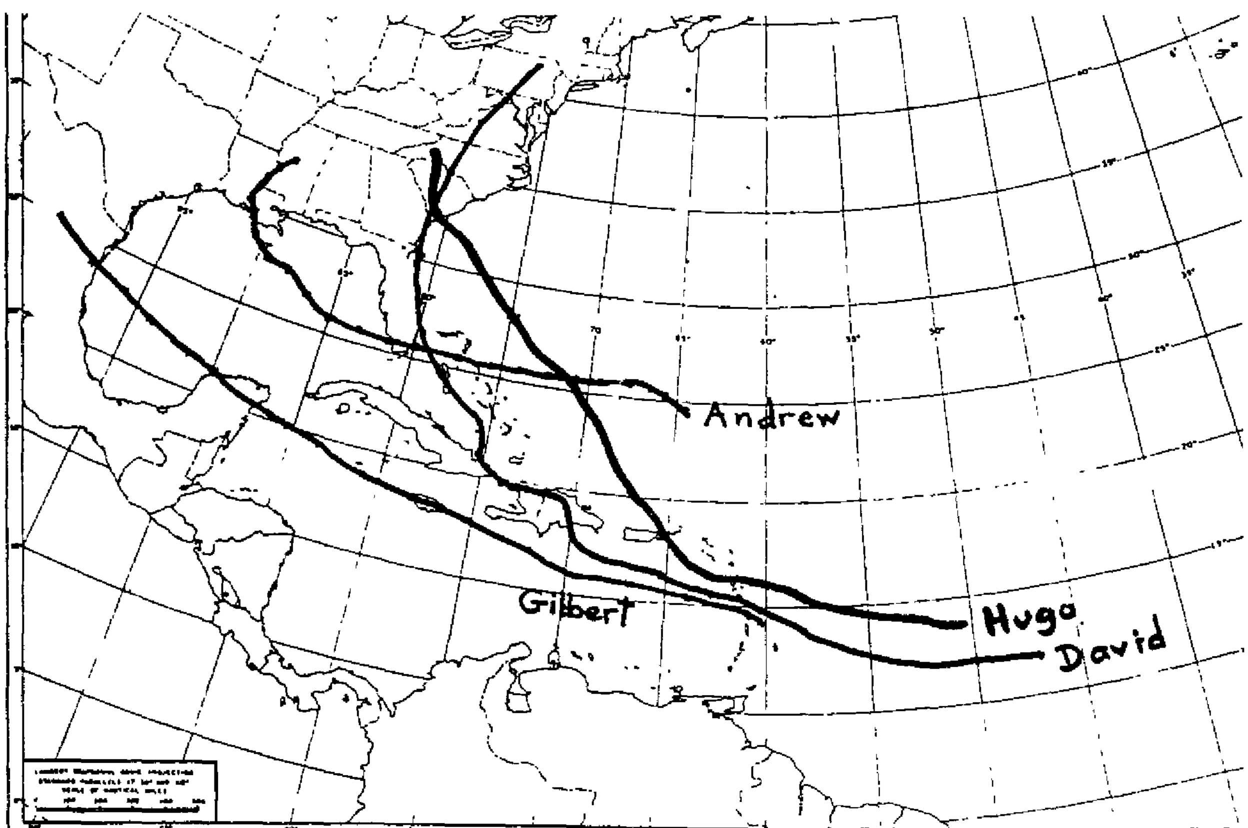
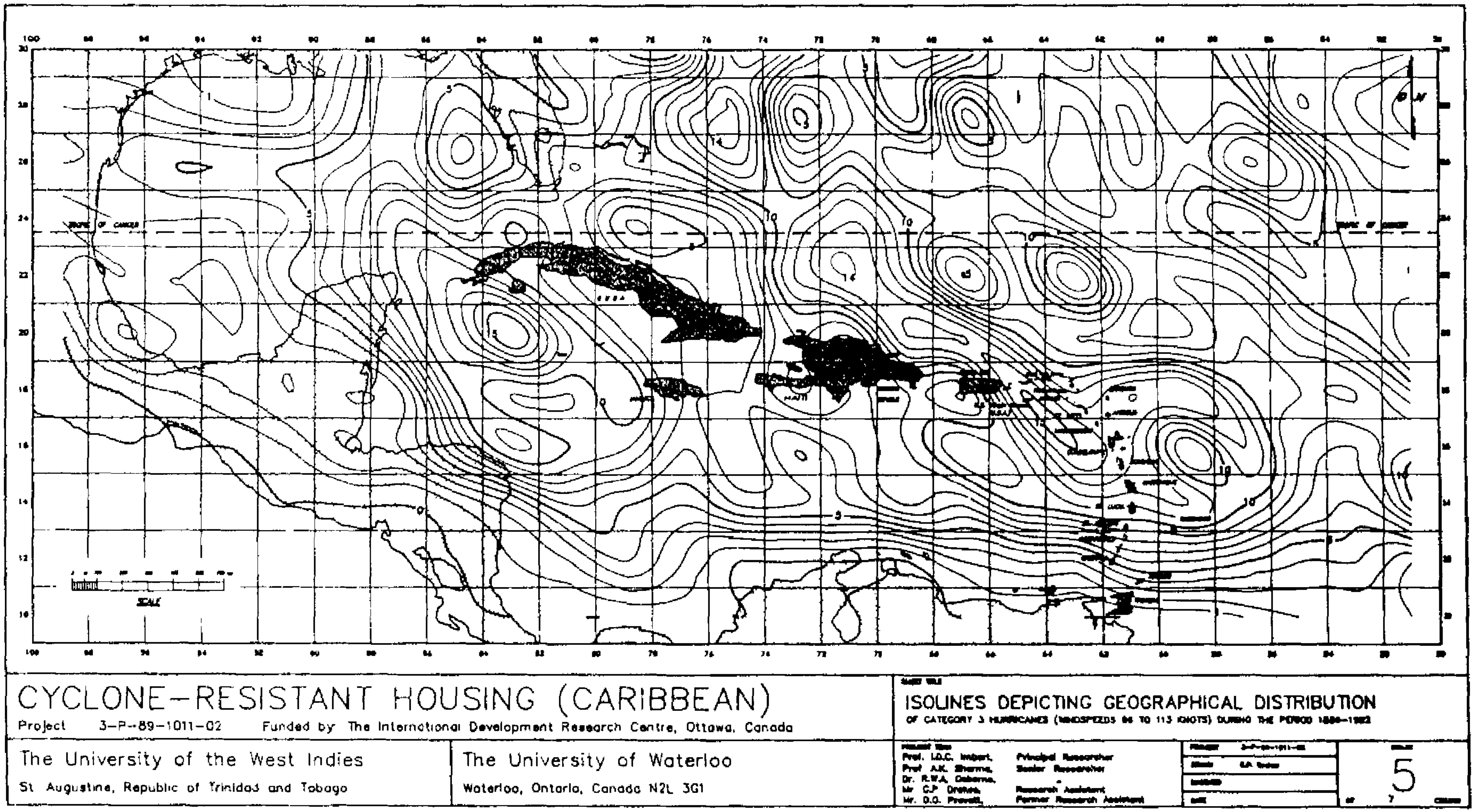


Figure 2 - Tracks of hurricanes David, Gilbert, Hugo and Andrew



The Chart shown here is derived from a detailed study of the frequency of occurrence of Category 3 Hurricanes during the period 1886–1992. The isolines shown above are lines which connect points representing a particular frequency of occurrence of Category 3 Hurricanes. These lines are similar to contour lines on a topographical map, the interval representing one frequency of occurrence. The heavy coloured lines represent 3 frequencies of occurrence in ascending order, as shown by the numbering on the Chart. The isolines are used to determine the average number of Hurricanes which have affected the location during the period. Thus a two–degree square box appropriate to that location is chosen and the isoline(s) nearest to that location is(are) found. The numbers appropriate to those isolines provide the average number of Category 3 Hurricanes which have affected the location during the period. For example, the islands of St. Kitts/Nevis are located within a box bounded by 17 to 19 degrees latitude and 62 to 64 degrees longitude and have an isoline with the number 13 going through them. Thus, the average number of Category 3 Hurricanes affecting these islands during the period was 13, giving a return period of approximately 8 years.

Figure 3