Impact of Hurricane Ivan in Grand Cayman

A technical review of the hazards
and their effects

Simon Young & Tony Gibbs

GeoSY Ltd

Impact of Hurricane Ivan in Grand Cayman

A technical review of the hazards and their effects

Prepared by:

Dr Simon R Young
Principal Consultant, GeoSY Ltd
1925 Valleywood Rd & PO Box 224
McLean, VA 22101 Brades, Montserrat
Tel/Fax: 703 532 5788
Mobile: 727 709 0008
Email: simon@geosy.com

and

Tony Gibbs, CEng
Consulting Engineers Partnership Ltd
PO Box 715
Bridgetown, Barbados
Tel: 246 426 5930
Fax: 246 426 5935
Email: tmgibbs@caribsurf.com

under contract to:

UK Department for International Development

For Roger Bellers
Disaster Management Advisor for the UK Overseas Territories
South Base, Grand Turk
Turks & Caicos Islands

Submitted: 18 February 2005

GEOSCIENCE AND NATURAL HAZARDS
CONSULTANCY THROUGHOUT THE CARIBBEAN

EXECUTIVE SUMMARY

Hurricane Ivan passed within 30 miles of George Town, Grand Cayman, as a severe Category 4 storm on 12 September 2004. Although spared a direct hit from Ivan at its worst, Grand Cayman encountered winds of 130-135 mph, gusting to at least 165 mph, and hurricane winds were felt somewhere on Grand Cayman for almost 18 hours. Accompanying the winds was a storm surge of 6-9 ft above mean sea level, waves of 15-20 ft and heavy rain (in excess of 15 inches).

As with most hurricanes, it was a combination of the hazardous phenomena which caused the massive damage rather than one or other in isolation. Winds compromised building envelopes and, occasionally the building structure itself. Rain ingress through a variety of wind-induced breaches in the envelope allowed substantial internal water damage. Storm surge flooding, aided by the heavy rain, caused widespread damage to ground floors. Wave damage to coastal properties unprotected by shallow offshore reefs was extensive on its own, but made worse by further wind damage.

This study, commissioned by DFID's Disaster Management Advisor to the Overseas Territories, aims to provide a comprehensive analysis of the hazardous conditions encountered during Hurricane Ivan's passage past Grand Cayman and the effects that those hazards had on infrastructure. Unsubstantiated rumours abounded in the Cayman Islands and its overseas diaspora as to the level of hazards encountered and the damage those hazards did. The true picture reveals a nation well prepared and with many effective strategies to reduce vulnerability to tropical cyclones, but still severely affected by a bad (but not worst-case) storm. The lessons that can be learned based on this realistic analysis of cause and consequence are numerous, both for the Cayman Islands and for the wider Caribbean.

Perhaps the greatest lesson that can be learned from Ivan's impact on Grand Cayman is that effective disaster management can greatly reduce loss of life in hurricanes, but that reduction of economic impacts are much more difficult to achieve. In Grenada, where Ivan also had a devastating impact and whose disaster management capabilities were not as well developed as those in the Cayman Islands, loss of life was almost 20 times higher than in Grand Cayman (for a similar at-risk population and a similar hazard level) while economic loss as a proportion of GDP was the same. This highlights the need, in small-island nations undergoing rapid economic growth, for continued development of disaster management capabilities with an increased focus on mitigating economic impact. The prevalence of insurance coverage in Grand Cayman greatly reduced the financial burden of Ivan's impact on the government and on individuals. However, long-term sustainable development of an economy dependent on coastal tourism and with large amounts of infrastructure at low elevations near the coast will only be successful if natural hazards are integrated more effectively into all elements of public and private sector development activities.

This page intentionally left blank.

SUMMARY OF RECOMMENDATIONS

i) Hardening of existing meteorological instrumentation and installation of a data gathering network specifically for hazardous meteorological conditions in the Cayman Islands and across the region.

ii) Completion of a comprehensive high resolution hazard assessment of the Cayman Islands for tropical cyclones, with particular emphasis on storm surge and wave action.

iii) Development of infrastructure vulnerability models for tropical cyclones.

iv) Completion of a quantitative risk analysis (QRA) of tropical cyclones to better inform discussion of improved long term development planning aimed at more effective risk reduction.

v) Continuation of data gathering in Grand Cayman, especially of flood levels, to better constrain the surge flooding event, and of human experiences, to act as an educational resource for future generations of Caymanians faced with similar, or growing, risks from tropical cyclones.

vi) Revisiting the use of forecasts and the understanding of forecast uncertainties in planning for tropical cyclone impacts. In particular, public education regarding the hurricane warning system must be continued in order to maintain trust in forecasts.

vii) Hardening of infrastructure in support of the emergency services in order to create a better environment for post-disaster recovery.

viii) Harmonisation of building codes across the Anglophone Caribbean.

ix) The CIG Building Control Unit's relative success with building structures must now be replicated with building envelopes.

x) Greater use should be made by the Building Control Unit of external review consultants for projects outside of the regular experience of its staff.

xi) In addressing the pressing issues brought about by Hurricane Ivan, the seismic hazard must not be swept under the carpet.

xii) Better integration of natural hazards risk into all elements of sustainable development planning and project implementation in the Cayman Islands. Developing a better understanding of and effective strategies to mitigate against economic impacts must be a priority if rapid growth is to be sustainable.

This page intentionally left blank.

1 INTRODUCTION

Hurricane Ivan wrought havoc to the Cayman Islands during September 2004, impacting most severely on Grand Cayman. This report provides a summary of a project undertaken by the authors at the direction of Mr Roger Bellers, DFID Disaster Management Advisor for the Overseas Territories and in conjunction with the Cayman Islands Government (CIG). The aim of the project was to document and analyse the physical impact of the various hazardous phenomena encountered during Hurricane Ivan in order to better understand the nature of the hazards themselves and the variations in impact of those hazards on the built environment.

The project has produced three main reports and a comprehensive set of quantitative data and photographs. This report is a final project summary; it is brief, comprehensively illustrated and aims to enable a wide variety of users, both in the Cayman Islands and throughout the Caribbean region, to better understand what happened in Grand Cayman during Ivan, and learn lessons for mitigation against the damaging effects of future tropical cyclones both locally and across the region. It includes a large insert poster summarising the findings of the project which can be even more widely distributed than this summary report.

Hurricane Ivan was a severe tropical cyclone which sustained maximum winds of over 130 mph throughout its 7-day passage across the Caribbean Sea. Towards the end of this passage, Ivan passed close to Grand Cayman island, producing winds in excess of 130 mph across the western half of the island, storm surge of 6-9 ft and waves 15-20 ft high breaking on unprotected stretches of the south and west coasts. The damage estimate for Ivan in Grand Cayman, at the time of writing, is ~US$3.5 billion, equating to almost 200% of GDP (ECLAC report, 10 December 2004). Despite widespread damage to infrastructure, loss of life was very low, with only 2 deaths officially attributed to Ivan.

Given the severe nature of the storm and the variety of hazardous effects, this low loss of life must be credited to strong short-term emergency preparedness and long-term disaster planning. While there were a number of short-comings exposed by Ivan in the existing mechanisms for disaster management in the Cayman Islands, most of the lessons for the wider Caribbean region are related to things that Cayman did right.

1.1 Acknowledgements

This study was greatly assisted, especially during the field visit in October 2004, by a number of persons and organisations in the Cayman Islands and elsewhere. A full list of acknowledgements is provided below. We especially wish to acknowledge the support of Roger Bellers, whose input in commissioning the project, supporting the field visit and reviewing the final reports, added greatly to the successful completion of the work.

Cayman Islands Government:
National Hurricane Committee, especially Deputy-Chairman Donnie Ebanks and Coordinator Kirkland Nixon
Civil Aviation Authority, National Meteorological Service, especially John Tibbets
Lands & Survey Department, especially Nigel Bates, Garry Green, John Phillips and Mike Whiteman
Department of Environment, especially Gina Ebanks-Petrie and Tim Austin
Public Works Department, especially Max Jones
Planning Department, Building Control Unit, especially McCleary Frederick
Health Department, especially Ellen Connolly and Derrick Tibbetts
Audit Department, especially Georgena Seymour
Governor's Office:
HE Governor Bruce Dinwiddy and staff
Cayman Water Authority, especially Tom van Zanten
Cable & Wireless, especially Vincent Ramgeet and Edward Scott
APEC Consulting Engineers, especially Pearse Murphy
OBM International, especially Cindy O'Hara

Hurricane Research Division (HRD), US National Weather Service (NWS, a division of NOAA), especially Mark Powell and Mike Black
University of Wisconsin – Madison, especially Chris Velden and Tony Wimmers
University of California – Los Angeles, especially George Waldenburger and Robert Fovell

1.2 Report structure

The electronic version of this report is provided in Adobe Acrobat (.pdf) format. Hotlinks within this document will open animations (when clicking on the blue highlighted text) or full resolution versions of figures (when clicking on the figure itself). Associated data, imagery and other information are provided on the main project CD-ROM (which can be found in the back pocket of the printed version of this report). A comprehensive Geographical Information Systems (GIS) dataset is also provided on the CD-ROM, and a summary GIS-based poster (A0 size) is provided as a separate .pdf document and as an insert at the end of the printed version of this report. The GIS data can be integrated into the well-established Cayman Islands Government (CIG) GIS database for future use in a wide variety of project applications.

Units in this report are generally those widely used in the Cayman Islands (miles, feet, inches etc). Times are local time unless stated. Cayman time is Eastern Standard Time throughout the year (GMT/UTC –5 hours).

This summary report has three further chapters. Chapter 2 presents the meteorological data, a model of hazardous phenomena encountered during Ivan based on available data, and a review of short- and long-term hazards forecasting in the light of the estimated hazard levels for Ivan. Chapter 3 presents an assessment of the damage to built infrastructure in Grand Cayman. Chapter 4 provides a discussion of the findings, key lessons to be learnt both locally and regionally, and a series of recommendations.

For more detailed information on the study area covered in Chapter 2, the reader is referred to the companion report by Young (2004).

2 METEOROLOGICAL DATA, HAZARDS AND FORECASTING

This chapter presents the meteorological data pertinent to assessing the hazards encountered on Grand Cayman during the passage of Hurricane Ivan, quantifies the hazardous phenomena and analyses the short-term forecasting for Ivan and the available long-term hazards assessments for tropical cyclones in the Cayman Islands.

2.1 Meteorological data

Meteorological information (which in this case includes storm surge and wave height information which would more accurately be termed oceanographic data) falls into two main classes; remotely sensed data and directly measured data. The former includes data from satellites and aircraft (as well as dropsondes released from aircraft) and the latter includes measurements made on the ground either during or after the storm's passage.

During the course of this project a wide variety of meteorological data has been collected and analysed. Remotely sensed data includes satellite imagery (visible, infrared and microwave), reconnaissance aircraft data and dropwindsonde data. Routine and research-driven processing of these data produces a refined product; in some cases that refined product is used directly (*e.g.* animated morphed microwave imagery) and sometimes it is used as input to further processing and analysis (*e.g.* H*WIND product from Hurricane Research Division (HRD) of the National Oceanographic and Atmospheric Administration (NOAA), best track product from the National Hurricane Center (NHC) of the National Weather Service (NWS) in Miami). Ground based data for Ivan's passage past Grand Cayman is limited to a single partial anemometer record, a rain gauge record, a partial barometer record and post-hoc survey data of flood heights and hazard impacts.

The companion report by Young (2004) fully describes the collection and assessment of the disparate meteorological data sets. A summary of the pertinent results is provided below.

Hurricane Ivan was a classic 'Cape Verde' cyclone, particularly notable for its southerly track and its persistent high intensity. Figure 2.1 shows the track, with colour coding showing the intensity of the hurricane (measured by the maximum estimated wind speed within the storm). A hotlink from Figure 2.1 plays an animation of GOES-IR imagery for Ivan's track past the Cayman Islands. Ivan began as a large, though poorly formed tropical wave off the west African coast on 31 August, attaining Tropical Depression status on 2 September and Tropical Storm status early on 3 September. Despite maintaining a westerly course south of 10°N (the accepted southern limit of the hurricane strengthening zone), Ivan continued to strengthen, achieving Hurricane status at 0600 UTC on 5 September and becoming the most southerly severe hurricane on record during a dramatic intensification phase over the next 24 hours.

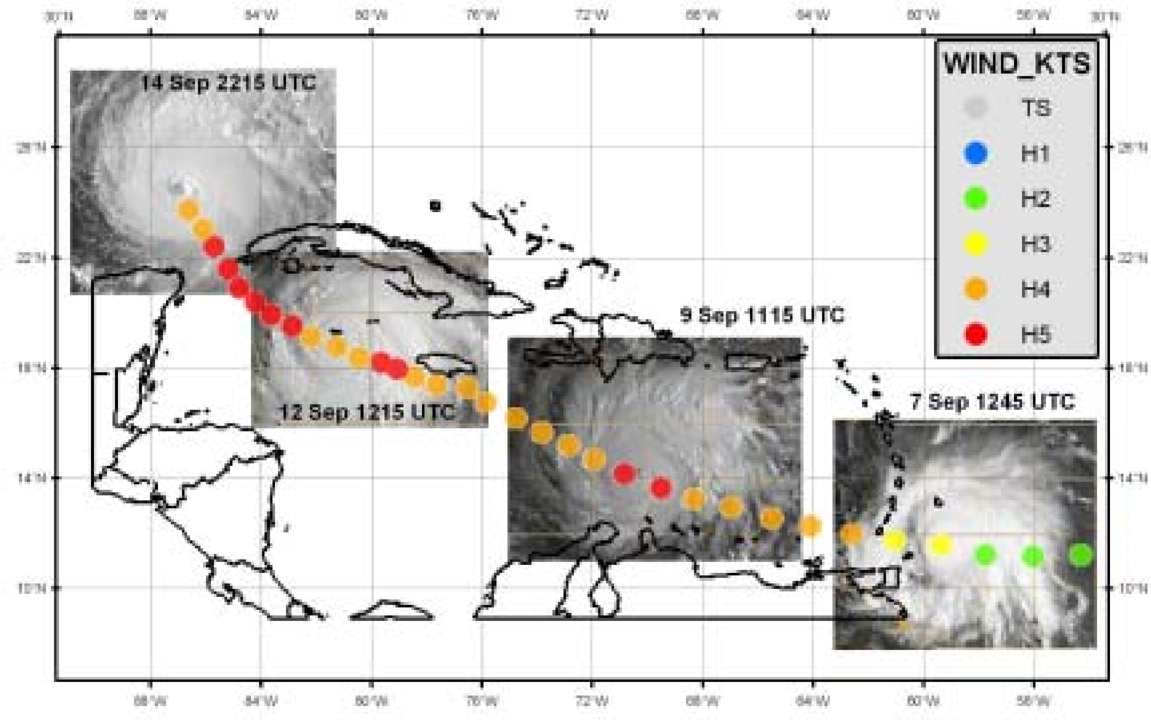

Figure 2.1 Full official track of Hurricane Ivan from passing Barbados on 6 September to its exit from the Caribbean Sea through the Yucatan Passage on 14 September. Selected GOES-12 satellite images illustrate the state of the storm. Note that the hurricane intensity key colours are the same for all figures in this report. Click here for an animated series of GOES-IR imagery for Ivan as it passed Grand Cayman.

After a brief de-intensification, Ivan regained severe hurricane status (Category 3, winds greater than 110 mph) as it passed south of Barbados into the Caribbean Sea around midday (UTC) on 7 September. According to the NHC post-storm best track data, Ivan attained Category 4 status as it passed Grenada late on 7 January and was at Cat 4 or above (winds greater than 130 mph) throughout its passage across the Caribbean Sea, exiting into the Gulf of Mexico on 14 September. While crossing the Caribbean Sea, Ivan achieved Category 5 status (winds greater than 155 mph) on three different occasions, the final two being immediately before and immediately after the 18 hours when the storm was closest to Grand Cayman.

Ivan's passage past Grand Cayman occurred on Saturday 11, Sunday 12 and Monday 13 September, during which time it achieved its highest measured wind speed (flight level (~10,000 ft) wind of 161 kt (185 mph) at 1917 UTC on 11 September) and its lowest pressure (910 mb extrapolated from flight level at 0005 UTC on 12 September). During this same period, Ivan underwent an eyewall replacement cycle which led to a lowering of peak wind speeds between 0600 UTC on 12 September and 0000 UTC on 13 September. This eyewall replacement cycle was the key element in controlling the wind speed encountered on Grand Cayman; it led to a decrease in the peak wind speed encountered on the island, but an increase in the duration of strong winds, especially after the storm had passed its closest approach.

The intensity of the storm and its position relative to Grand Cayman influenced not only the winds felt on the island, but also the nature of the wave and storm surge hazards. Early winds came out of the northeast and produced a high storm surge in North Sound; later winds from the southeast produced a second surge peak from South Sound and also heavy wave action along the South coast and along the south-facing coastal stretch of West Bay. Rainfall was sporadic but heavy and lasted well beyond the period of most intense wind.

The post storm analysis of windfield presented here uses, as a starting point, the NHC official 'best track' intensity and position estimates and a near real time HRD windfield product, H*WIND. Some discrepancies between the official forecast, ground measurements and the H*WIND output (Figure 2.2) prompted a more thorough investigation that might usually be necessary. The H*WIND output gives estimated wind speeds on Grand Cayman considerably below those recorded by anemometer (even allowing for the likely overestimation in those anemometer records) and somewhat below those that would be expected from simple modelling of the best track information.

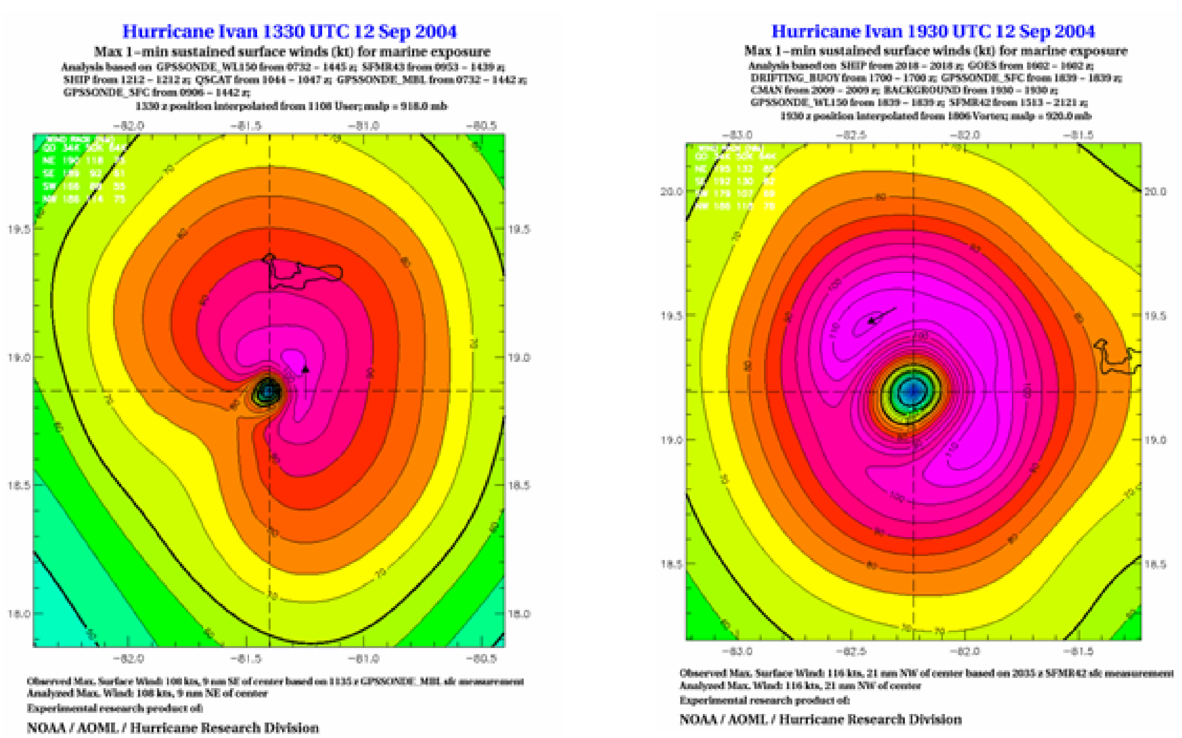

Figure 2.2 H*WIND analysis for Ivan at 1330 and 1930 UTC on 12 September. Although the likely peak in winds on Grand Cayman occurred midway between these times, the overall trend of these H*WIND analyses is to underestimate the wind speed.

The key meteorological phenomenon causing most of the discrepancies is known as an eyewall replacement cycle. Such cycles occur in all powerful hurricanes and provide the mechanism for sustaining hurricanes at Category 4 or 5 for prolonged periods. The details of eyewall replacement will not be discussed here; instead, Figure 2.3 provides a superb illustration of a classic eyewall replacement cycle which just happened to occur as Ivan was passing Grand Cayman. The images and movie in Figure 2.3 are the product of the Morphed anImated Microwave Imagery (MIMI) research project at the University of Wisconsin – Madison, where a diverse set of microwave satellite images are merged together and animated into a succession of images at 15 minute intervals. Microwaves are particularly useful in hurricane research as they are able to see through the upper clouds into the heart of the hurricane, and image the eyewall of a storm particularly well.

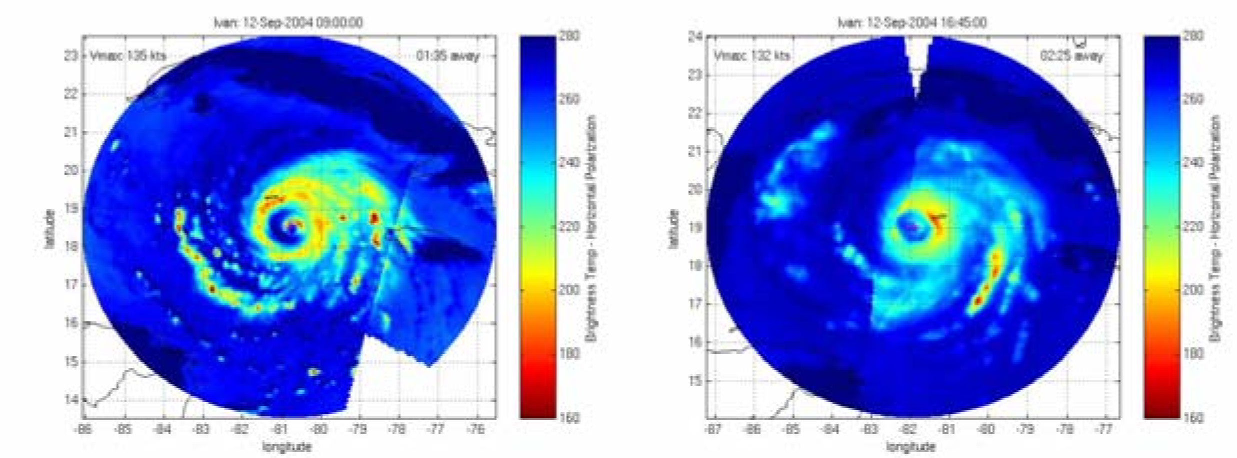

Figure 2.3 Morphed microwave imagery for 0900 (left) and 1645 UTC (right) on 12 September. Click here to play the animation, which covers the period 0700 UTC on 12 September to 0000 UTC on 13 September.

The 0900 UTC (4 am local) MIMI image shows a small, tight eyewall to the SSE of Grand Cayman with highest winds in the northeastern quadrant of the eyewall (red colours in a semicircle to the northeast of the centre). Over Grand Cayman itself is an intense rainband which is starting to form a closed circle. Ivan is waning in intensity at this point at 155 mph, having peaked a few hours earlier at 167 mph maximum sustained wind. The waning is due to initiation of eyewall replacement, where peak winds are falling in the inner eyewall but rising in the intense rainband. Over the next 8 hours or so, the inner eyewall breaks down and the intense rainband develops into first an outer eyewall and then the main eyewall, as shown in the 1645 UTC (11.45 am local) MIMI image. In this later image, it can be seen that Grand Cayman is within this outer eyewall as it becomes dominant, even after the centre of the storm has made its closest pass. The outer eyewall is intensifying as it clears Grand Cayman, reaching 161 mph a few hours later at 7 pm local on 12 September. Another consequence of the eyewall replacement cycle was the slowing of forward speed of the hurricane, from about 11 kt early on 12 September to around 5 kt late on 12 September.

With this basic meteorological model as a foundation, the re-analysis incorporated airborne and dropwindsonde data to act as control points on the windfield. Figure 2.4 shows two sets of key eyewall dropwindsonde profiles taken in locations close to Grand Cayman during the period of eyewall replacement. These profiles are used to extrapolate flight level data to ground level; it is in this extrapolation that most of the uncertainty regarding true surface wind speeds is introduced.

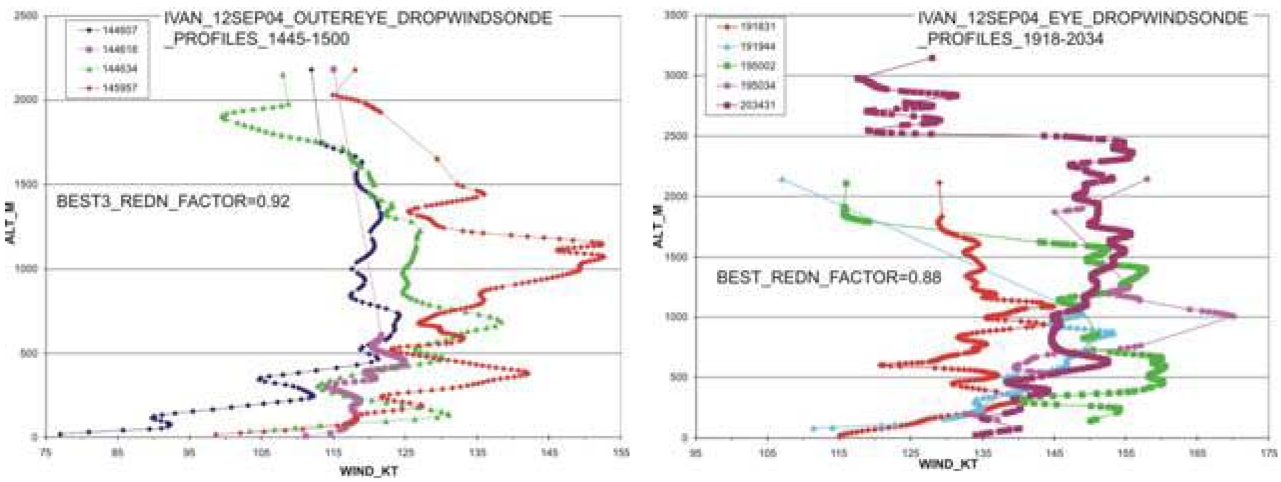

Figure 2.4 Representative eyewall dropwindsonde profiles for 10 am (left) and 2.45 pm (right) on 12 September.

All available data were brought together within a GIS to produce a series of data snapshots representing Ivan's passage past Grand Cayman. The various parameters required to reproduce the windfield, and thus the likely wind speed profile on Grand Cayman, were deduced from these data snapshots. Figure 2.5 provides the data snapshot plots for 10 am local time on 12 September, when the centre of Ivan was closest to Grand Cayman.

In addition to affecting the 'headline' wind speed encountered on Grand Cayman, the location and intensity of the hurricane also affects the storm surge and wave action. Wind direction was especially important in controlling storm surge flooding and wave damage; the effective expansion and intensification of the eyewall after the storm had made its closest pass of Grand Cayman brought strong onshore winds around to the south coast of the island increasing storm surge flooding and causing extensive wave damage after the peak winds had passed. The actual status of wind, surge and wave hazards are described in the next section.

The evolution of the storm as it passed Cayman did not greatly affect the rainfall pattern; however, the slowdown in effective forward speed meant that the total rainfall was significantly higher than would be normal for a similar storm.

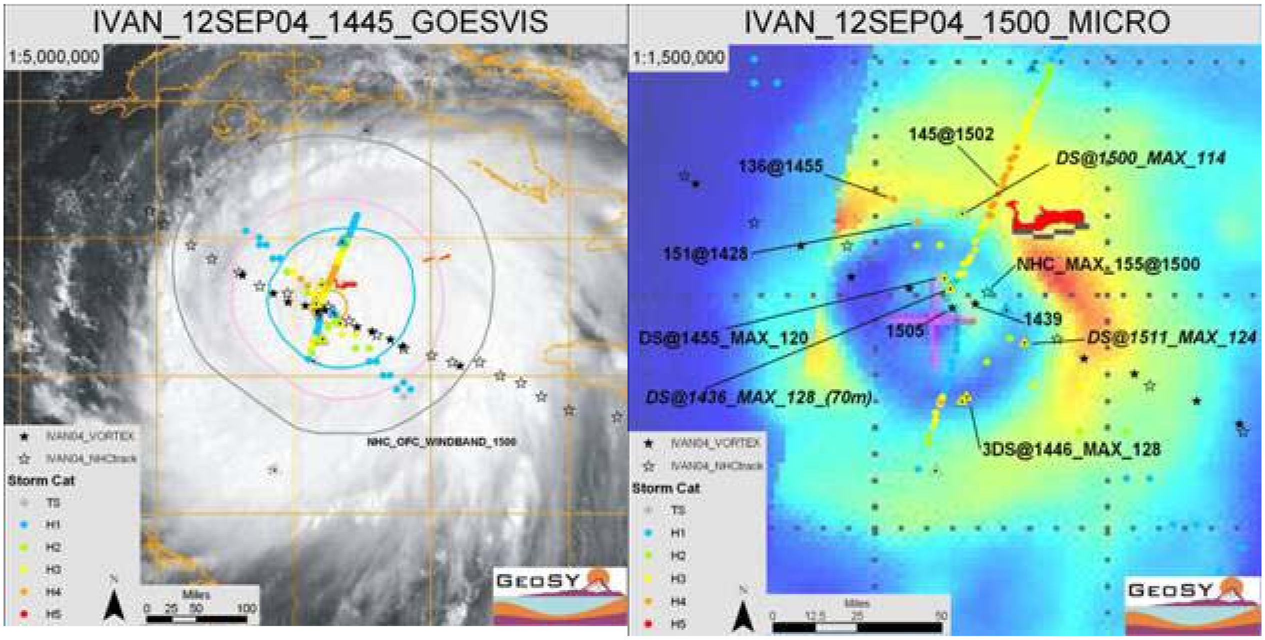

Figure 2.5 GOES visible (left) and morphed microwave (right) imagery for the period around 1500 UTC (10 am local time) on 12 September. The centre of the storm has just passed its closest approach to Grand Cayman, and strongest winds are in the northern outer eyewall close to the island.

2.2 Quantification of hazardous phenomena

This section details the best estimate of actual hazardous conditions felt on Grand Cayman for Hurricane Ivan. Using the analysis described above, the wind speed and direction themselves are modelled using the relatively simple approach of Holland (1980) as performed in HurrTrak EMPro (PC Weather Products software). The temporal evolution of surge and wave hazards are controlled by the same model, although surge flooding levels are estimated only from ground-based measurements. Rainfall is obtained from satellite imagery. Both modelled rainfall and wind speed are compared with the scant real-time measurements.

2.2.1 Wind speed and direction

Peak wind speed measurements on Grand Cayman were limited to a single anemometer in West Bay, which recorded a 1-minute sustained wind of ~150 mph around 10 am local time on 12 September. The various other reports of peak wind speeds and gusts are not based on actual recordings of wind speed and all can be discounted as unsubstantiated rumour. Figure 2.6 shows the temporal evolution of wind speed from 1 pm local on 11 September to 7 am local on 13 September in 3 locations on Grand Cayman as deduced from the hurricane windfield model described above. For comparison, Mike Whiteman's anemometer data are also plotted.

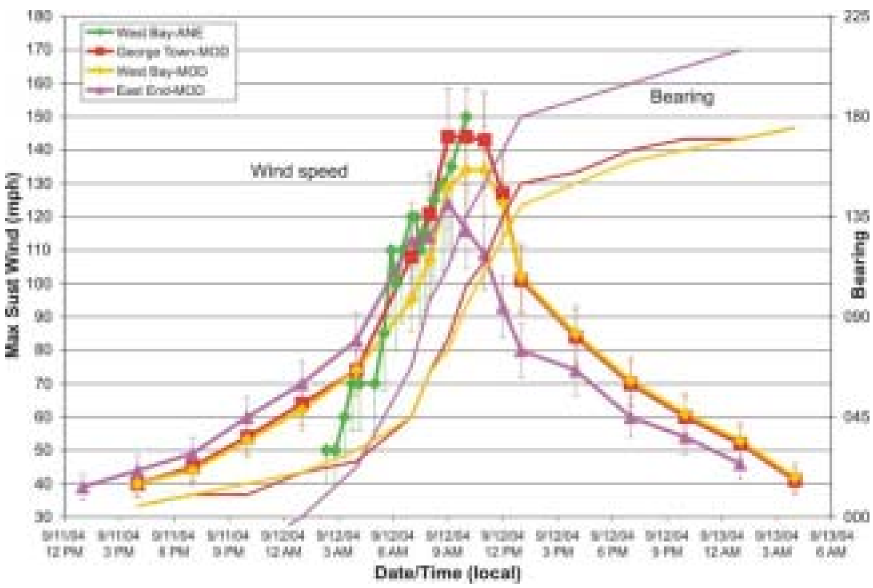

Figure 2.6 Temporal evolution of modelled peak wind speed and bearing for 3 locations on Grand Cayman, and for the anemometer at West Bay. Error bars are ±10% for modelled wind speed and -20% for anemometer wind speed. Time axis is local time.

A tabulation of key data is provided as Table 2.1. The peak wind speed for West Bay from the model is about 10% lower than that recorded by the anemometer; this discrepancy is well within the likely errors in the anemometer data. The distribution of peak winds across the island is consistent with damage levels on a gross scale (*i.e.* much more damage in the west than the east); however, local conditions related both to perturbations in the windfield and to design and quality of buildings dominate variations in damage on a local scale. All indicators show that peak winds were out of the east across the entire island (Figure 2.7), and the model is entirely consistent with this observation.

Location	***Peak wind (mph)***	***Peak Gust (mph)***	***Time of peak (local)***	***Time at Cat 3 or above (>110 mph)***
George Town	140-145	178	9.30 am	7.15 am – 12.35 pm
West Bay	130-135	165	10.30 am	8.10 am - 12.35 pm
East End	120-125	153	9.00 am	7 – 11 am

Table 2.1 Key parameters for winds on Grand Cayman during Ivan from the wind model. Note that the model has an error estimated to be ±10%.

Figure 2.8 shows snapshots of the windfield of Ivan at 1500 and 1800 UTC on 12 September and the associated animation shows the full sequence of windfield plots from 1500 UTC on 11 September to 1200 UTC on 13 September.

Figure 2.7 A clear indicator of Ivan's peak wind direction.

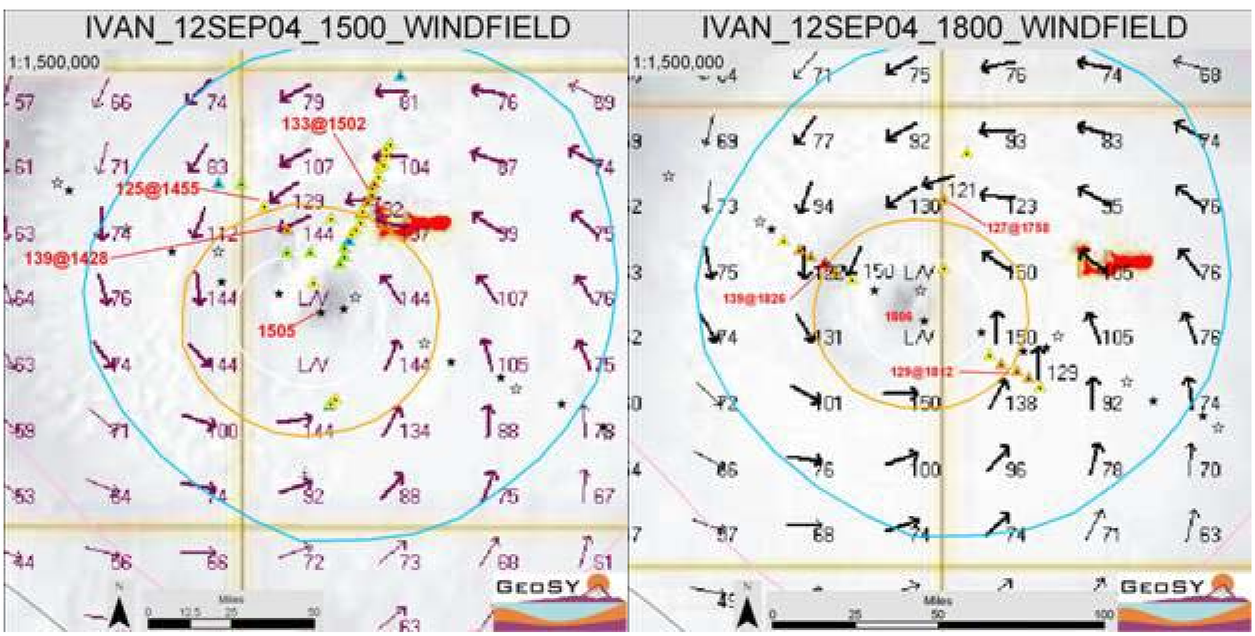

Figure 2.8 Windfield plots superimposed on visible GOES imagery and airborne reconnaissance data (adjusted to surface winds) for 1500 and 1800 UTC on 12 September. The 1500 UTC (10 am local time) image depicts near peak conditions in George Town; note the excellent fit of modelled with actual winds for both time windows. Click here to play an animation of the windfield from 1500 UTC on 11 September to 1200 UTC on 13 September.

Key estimates from the wind profile data are:

- Category 4 winds were sustained over the George Town area for almost 4 hours, peaking at 140-145 mph between 9 and 11 am local time.
- Category 4 winds were sustained in the West Bay area for around 3 hours, peaking at 130-135 mph between 10 and 11 am local time
- Category 3 winds were sustained over the East End area for 4 hours, peaking at 120-125 mph at around 9 am local time
- Using a standard conversion factor, wind gusts likely reached 175-180 mph over George Town
- Tropical storm force winds (39-73 mph) started in East End at around 1 pm local time on 11 September and ended around 5 am local time on 13 September, a total period of 40 hours. Hurricane force winds (>73 mph) were sustained somewhere on Grand Cayman for almost 18 hours.

2.2.2 Rainfall

The Cayman Island's National Weather Service recorded rainfall of 12.1 inches (~300 mm) for Grand Cayman during Ivan (between 0000 UTC on 12 September and 1200 UTC on 14 September). This compares with satellite-based data indicating rainfall of 450-500 mm (18-20 inches) for the same period. The discrepancy can be accounted for by the poor accuracy of satellite rainfall measurement techniques and by the inability of rain gauges to accurately record rainfall during strong winds. A reasonable compromise of 15-18 inches (400-450 mm) is provided as the best estimate of total rainfall.

Detailed rainfall rate data were unavailable from ground-based measurement; satellite data indicates peak rainfall of around 1 to 1.2 inches (25-30 mm) per hour for the period between 9 and 11 am local time on 12 September (Figure 2.9). Rainfall from Ivan started in Grand Cayman around 1 pm on 11 September and cleared around 7 pm on 13 September (although there were some further rain showers throughout 14 September.) The animation in Figure 2.9 depicts the changing rainfall rate as Ivan passed Grand Cayman.

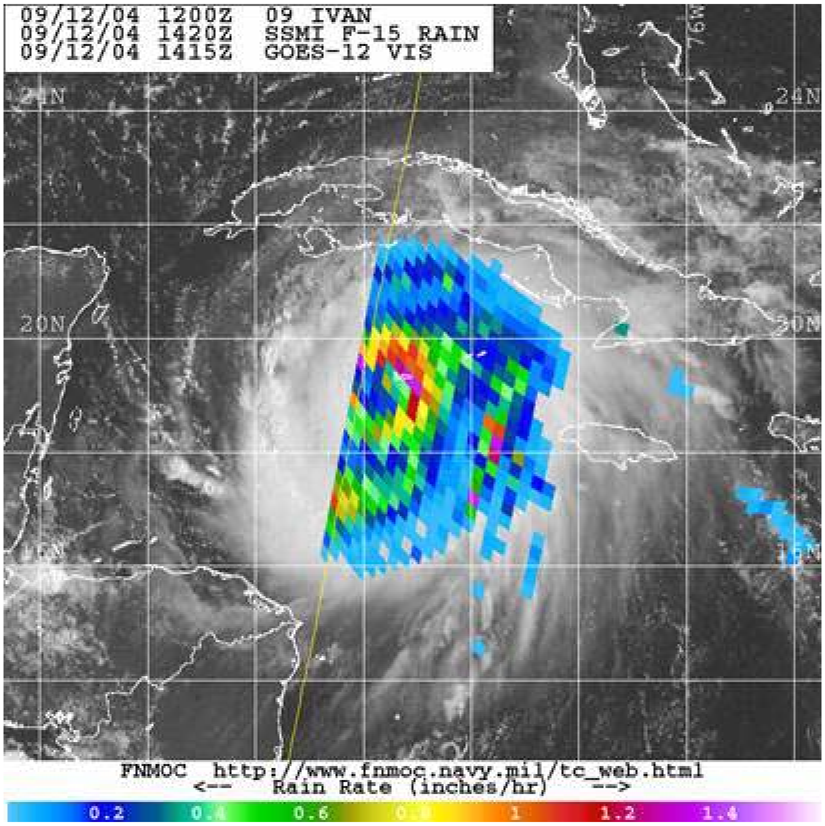

Figure 2.9 Rainfall rate estimated from the SSMI microwave sensor onboard the DMSP-15 satellite. Image at 9.20 am on 12 September. Click here to play an animation of average hourly rainfall rate (image timed at the end of each 3 hour period) from various microwave sensors for the 54 hour period starting at 1 pm on 11 September.

2.2.3 Storm surge and wave action

Both storm surge flooding and wave action were strongly influenced by the evolution of Ivan's windfield as it passed Cayman. While in some respects Grand Cayman was on the bad, northern side of Ivan, there was some good fortune in that onshore winds were not a factor on the most developed, western coastline of the island. Elsewhere, onshore winds produced a storm surge of 6-9 ft and wave heights of around 20 ft.

The geometry of North Sound (Figure 2.10) caused the unanticipated, though not unpredicted nor unprecedented, storm surge flooding through the Red Bay-Prospect neck and across the western peninsula. Similar breaching of the Red Bay-Prospect area has occurred on a number of occasions in recorded history on Grand Cayman (*e.g.* hurricanes in 1731, 1751, 1846, 1915, 1932, 1933, 1944 and 1988, see section 4.4 in Young, 2004), although the extent of flooding was perhaps greater than on any previously recorded occasion.

A key to understanding the unique bathymetry of North Sound and its influence on storm surge is the observation that storm surge flooding in Cayman Kai, seemingly highly exposed at the northern entrance to North Sound, was just 1-2 ft. This proves that there was a substantial slope in the water surface of North Sound, up towards the southwest, achieving a height difference of at least 6 ft from northeast to southwest around 6 am on 12 September.

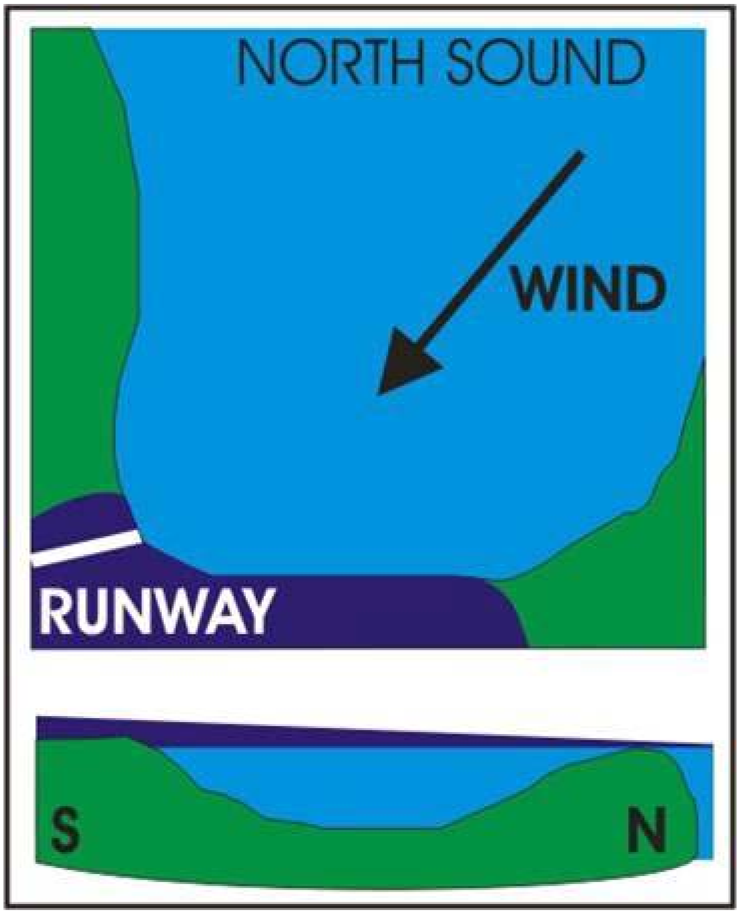

Figure 2.10 Cartoon of the southern part of North Sound in plan (top) and cross-section views. Light blue is the normal water level, dark blue represents the wind-blown surge element.

The early northerly and northeasterly winds, though not the strongest, began to push water into the southern parts of North Sound, causing the first extensive flooding (as recorded at the airport) at between 5 and 6 am local time, coincident with the high tide (1.3 ft at 5.22 am). This surge flooding receded as the tide turned. As the winds swung around to the east, water began to inundate the western shore of North Sound and, in places, pushed right across the western peninsula to Seven Mile Beach.

At the peak of the storm, between 9 and 11 am on 12 September, easterly winds over western Grand Cayman and southeasterly winds over eastern Grand Cayman (see Figure 2.8) caused storm surge inundation from both the western side of North Sound and from South Sound simultaneously. The main storm surge flooding peak was recorded along South Sound at around 11 am, likely the result of winds having swung to onshore in that area. The continued onshore winds at South Sound prevented draining of flood waters until the late afternoon; backflow into North Sound occurred somewhat earlier than that, although southerly winds prevented draining of water over Seven Mile Beach late into the evening.

During this project, there was insufficient time to collect and process a fully representative set of water height estimates. It is recommended that personal memories and actual measurements are collected systematically on Grand Cayman so that a fuller picture of flood levels can be gathered. Table 2.2 summarises a few key measurements of water height during the surge-induced flooding.

Location	*Depth of flooding (inches)*	*Height of floor (ft amsl)*	*Flood height (ft amsl)*
Met Office, Airport	18	7	8.5
Grand Caymanian, Welch Point	24	4	6
Bayshore Drive, The Shores	18	8	9.5
Secret Gardens, South Sound	45	4	8
Bodden Town Police Station	12	6	7
Cayman Kai	12	2	3

Table 2.2 Summary of surge-induced flood heights. Note that floor heights, and thus total flood heights, are approximations only. Accurate elevation data is required to better constrain these numbers.

Storm surge flooding, although damaging, is somewhat of a passive process. Water levels tend to rise relatively slowly (although true 'surges' of water certainly do occur, usually related to surge height reaching above key retaining structures), and damage is done not through active erosion but by everything getting wet. Several cases were noted on Grand Cayman where rising or falling flood water along a confined area caused significant erosion and damage (Figure 2.11) but, in general, erosional water damage was caused by wave action.

Figure 2.11 Damage at this location on Seven Mile Beach was due to erosion by fast-moving storm surge flood water confined to a narrow passageway between buildings.

Wave damage along the coast of Grand Cayman was highly variable in its nature. The variability in damage levels was entirely controlled by the presence or absence of shallow offshore coral reefs and the presence or absence of onshore winds during the storm. Waves break in shallowing water; even with the storm surge, the reefs which surround most of the south, east and north coast of Grand Cayman were sufficiently shallow to cause waves to break, thus dissipating almost all of their energy. The relatively unprotected west coast (where reefs are deeper) was fortunately not subject to onshore winds. Thus severe wave damage occurred only in a few places where onshore winds and no reef protection came together. These areas are shown in Figure 2.12.

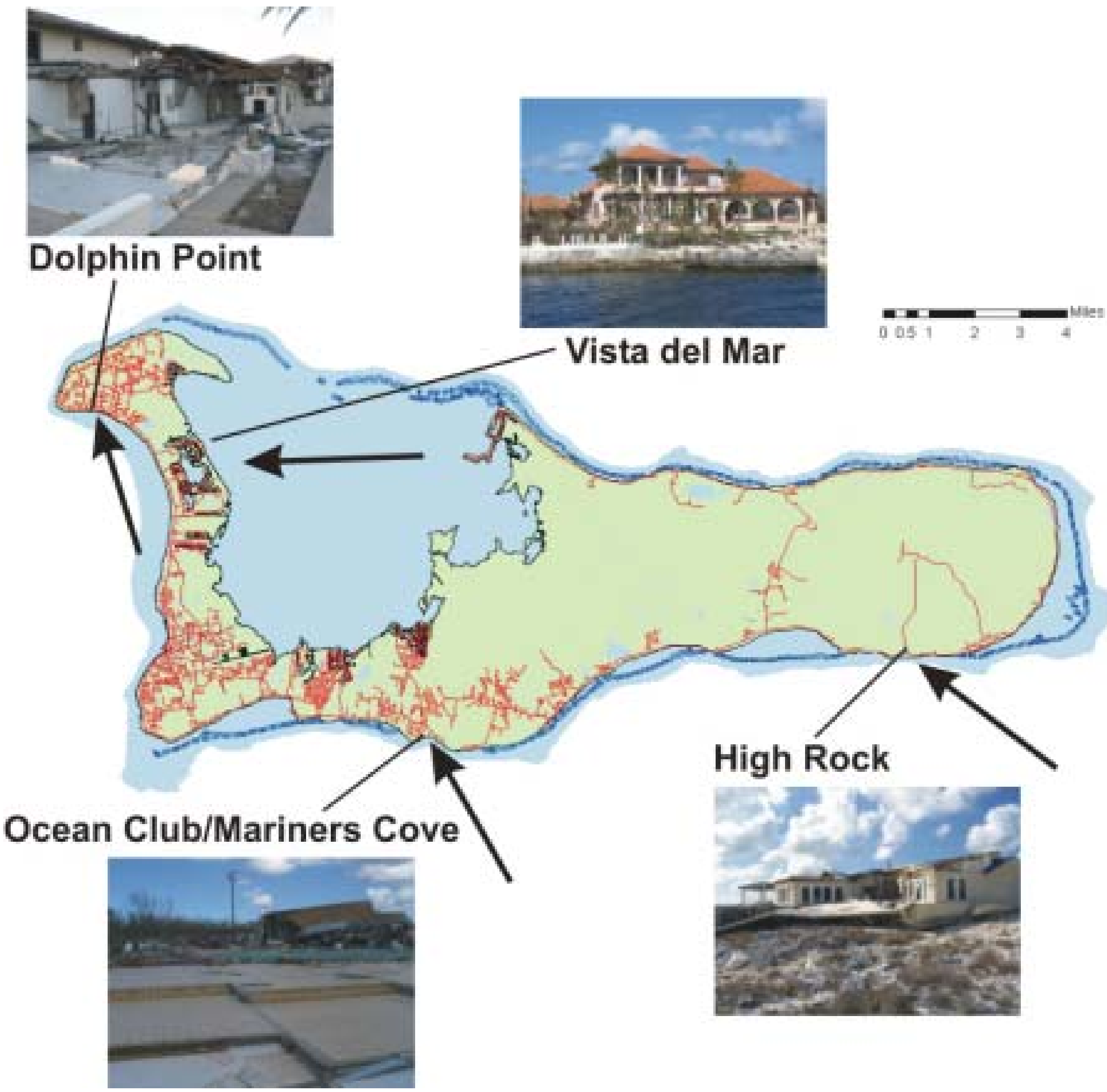

Figure 2.12 Key elements of wave damage around the coast of Grand Cayman. Large arrows indicate wind direction when damage was initiated.

The east-facing coast of North Sound is in the process of being developed; this area received minor wave damage from water driven across the longest reach of North Sound during the peak of the storm. High Rock has a history of exposure to strong waves once winds are out of the southeast; large boulders at ~30 ft above sea level were reportedly carried there during the 1932 hurricane. In this area, houses ~25 ft above sea level received extensive wave damage. At Ocean Club/Mariner's Cove, onshore winds came around 11 am on 12 September and quickly devastated these two resorts. They had no protection from either reefs or from any significant height above sea level. Wave heights here were probably lower than at High Rock, with erosion by waves occurring up to about 15 ft above sea level. The final area of damage was on the south-facing stretch of West Bay, where onshore winds late in the storm drove waves into Dolphin Point and other resorts in this area, causing widespread damage. Estimated wave heights here were 10-15 ft.

As previously mentioned, the main stretch of developed coastline, and Grand Cayman's primary tourist attraction, is the west-facing Seven Mile Beach. The west coast of the island has no shallow reef protection, and strong onshore winds during future storms may cause much more extensive damage from wave action than resulted from storm surge flooding on this occasion.

2.3 Comparison with forecasts and hazard assessments

This section assesses the adequacy of both short term, real-time forecasts for Hurricane Ivan on the basis of which emergency management decisions were taken, and long term, probabilistic-type forecasts for tropical cyclone hazards on the basis of which development planning decisions are taken.

Short term forecasts, issued by the National Hurricane Center (NHC) in Miami, have improved dramatically over the past decade or so, but this rapid improvement is likely to slow substantially as forecasting approaches the limit of its powers. The demonstration of the inherent uncertainties in hurricane forecasting provided below provide a foundation for better integration of forecasting and uncertainty into emergency management planning and decision-making.

Long-term forecasting for Grand Cayman, in the form of probabilistic hurricane hazard analysis, has substantial room for improvement, and improved maps may have key implications for development planning in the Cayman Islands. Although the occurrence of a 'rare' storm does not invalidate probabilistic assessments of the likelihood of such events, some of the consequences of the 'rare' storm appear to have been significantly underestimated in previous hazards assessments for the Cayman Islands. Section 2.3.2 presents an analysis of the two quantitative, model-based studies available, from the Organisation of American States (OAS) Caribbean Disaster Mitigation Project (CDMP) and from a Cayman PWD-commissioned study, and compares them with some simple statistics from the historical record for Grand Cayman.

2.3.1 Short term forecasting

Analysis of the NHC forecasts for Ivan suggests that they were of moderate accuracy for most of its track across the Caribbean Sea, although for the 12 hour period in which Grand Cayman was most severely affected, the forecasts were actually better than for most of the previous 10 days.

For the period between 0300 and 2100 UTC on 12 September, the average forecast position error was around 60nm/day. The key forecast times for the emergency management preparation activities in the Cayman Islands are those at 48 hours (Alert level), 36 hours (Watch level) and 24 hours (Warning level). For those time periods specifically, the position errors for Ivan averaged 127 nm, 100 nm and 53 nm.

Intensity forecasting for Ivan in Cayman was also good, thanks to the temporary reduction in peak intensity during the eyewall replacement cycle. For the key forecast times at 48, 36 and 24 hours, the average intensity errors for Ivan were -7, -2 and +3 kt (negative meaning that the forecast overestimated the intensity).

As an illustration of what these forecast errors mean in reality, Table 2.3 shows the range of possible peak conditions in Grand Cayman from Ivan based on the 48, 36 and 24 hour forecast errors described above.

	Actual	***48-hr forecast***	***36-hr forecast***	***24-hr forecast***
Position (7am local time)	18.8N, 81.2W	20.5N, 80.2W	20.4N, 80.4W	19.6N, 81.0W
Intensity (7am local time)	135 kt	125 kt	140 kt	135 kt
Best case wind George Town	144 mph	< 39 mph	< 39 mph	60 mph
Worst case wind George Town	144 mph	152 mph	163 mph	159 mph

Table 2.3 Illustration of the range of peak wind conditions which were 'predicted' from the NHC forecasts, using calculated errors, at 48, 36 and 24 hours averaged for the period 0300-2100 UTC on 12 September.

As can be seen from Table 2.3, even with 24 hours notice, the range of possible wind speeds which could have, within the error of the forecast, affected George Town was huge, from 60 mph (which would have caused almost no wind damage) to 160 mph, which would have been catastrophic. Similar ranges in storm surge and wave action are likely, although time constraints have limited the ability to model these phenomena.

2.3.2 Long term hazards assessments

As far as has been ascertained by the authors, only two tropical cyclone hazards assessments with relevance to Grand Cayman have been undertaken.

The TAOS (The Arbiter Of Storms) model developed under the auspices of OAS-CDMP (OAS 1999) did not officially cover the Cayman Islands in its outputs; however, regional maps obtained by one of the authors (SRY) do include the islands. The TAOS model produced probabilistic assessments of wind, wave and surge hazards for return periods of 10 to 100 years.

A second study, undertaken by Applied Research Associates under contract to the Public Works Department of the Cayman Islands Government (Minor & Murphy, 1999), uses a slightly different approach to model just peak wind speeds expected at a variety of return periods. This study was commissioned to guide design and construction of new dual-use public buildings such as schools which would double as hurricane shelters. It should be noted that this study recommended a detailed analysis of storm surge and wave hazards.

The results of the two studies are presented in more detail in the companion report (Young, 2004). Major discrepancies were noted between the two models, so some simple statistical and modelling work was undertaken by one of the authors (SRY) in order to gain some insight into the potential weaknesses in the complex models.

TAOS output in this case was in the form of hazard maps, examples of which are provided in Figure 2.13. The ARA output was in tabular form, and refers only to the maximum wind speed expected anywhere on the island (and in fact Little Cayman and Cayman Brac also) at the given return period.

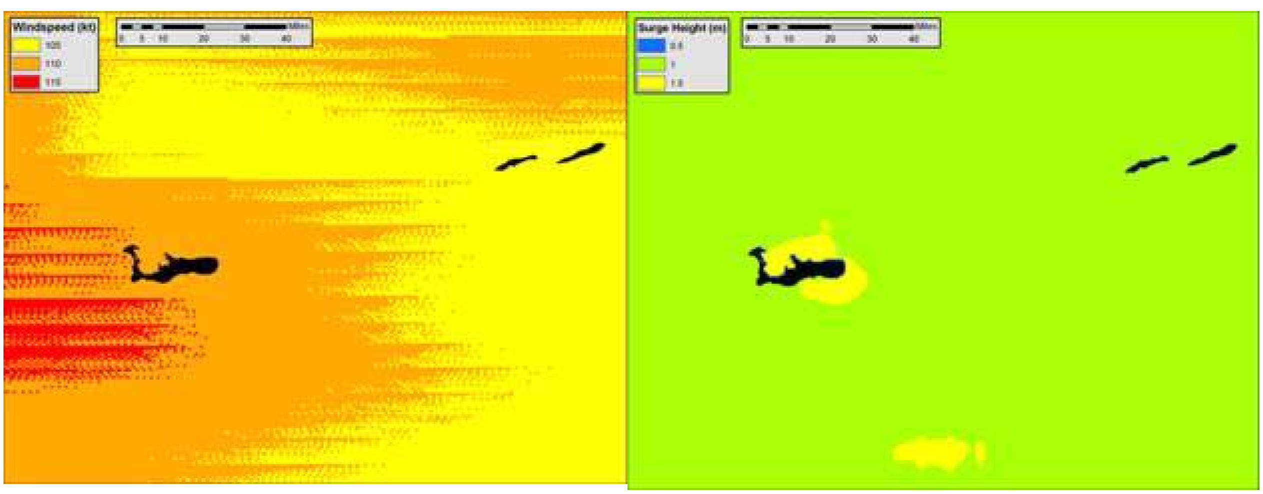

Figure 2.13 Probabilistic wind (left) and surge (right) hazard maps at 100 year return period for Cayman from TAOS-CDMP. Note units are knots in the wind map and metres in the surge map.

Table 2.4 shows a comparison of the results of the two hazard models for wind, along with an approximate estimate made from the simple analysis undertaken as part of this project. As is clear, the two complex hazard models differ significantly, with the simple model giving results between the two, but closer to the TAOS results. The simple model comprises an analysis of all of the tropical cyclones passing close to Grand Cayman, approximating the peak wind in George Town for each (based on the peak intensity of the storm and using an empirical windfield relationship established from NHC records for the past 14 years where good windfield data is available). A comparison between the data for Ivan and the simple model run for Ivan suggests that the simple model has an error of 10-15% and is biased towards underestimating the peak wind speed.

Return Period	***TAOS peak wind (mph)***	***ARA peak wind (mph)***	***SRY peak wind (mph)***
10	75	59	74
25	100		
50	115	91	110
100	130	105	
500		130	
1000		141	
2000		154	

Table 2.4 ARA, TAOS and SRY (simple) model outputs for tropical cyclone peak sustained winds for George Town at various return periods.

For surge and wave height, the TAOS model is known to have significant errors due to the low resolution bathymetrical data used in the model. A model run of Ivan on TAOS using the NHC position and intensity data severely underestimated the surge height for Ivan, and it is thought that the TAOS model does not deal with the special situation of North Sound effectively. Open water wave heights in the TAOS hazard model appear reasonable, but they are not representative of wave damage as the model does not account for waves breaking on the surrounding reef (due to the low resolution of the model).

In summary then, the two available models for wind hazards vary significantly, with a simple analysis of historical data suggesting that the TAOS model is closer to reality. This model, and the historical data, suggest that Ivan's winds, as estimated from the available meteorological data were a 1 in 100 to 1 in 200 year event.

There is currently no good model available for estimating wave and storm surge hazards in Cayman; however, historical data suggest that the wave damage and surge flooding events were probably a little less rare than the wind event, perhaps a 1 in 75 to 1 in 100 year event.

Even though these events are thus quite rare, Ivan does not represent a worst-case scenario for Grand Cayman. A storm passing across the eastern side of the island would produce the strongest winds blowing onshore at Seven Mile Beach; without shallow reef protection, surge and especially wave damage could be far more destructive, given the value of property at risk, than was Ivan's.

3 CIVIL AND STRUCTURAL ENGINEERING ASSESSMENT OF IMPACTS

This chapter summarises the context in which the built environment was prepared for tropical cyclone hazards and reviews the actual impact in various sectors. Illustrative photographs are provided.

3.1 Public Works Department and the Building Control Unit

The built environment in Grand Cayman falls under the wings of both the Planning Department and the Public Works Department, headed for the past 18 years by Director Crawford Scott and Deputy Director (currently Acting Director) Max Jones. PWD is the commissioning and maintenance agent for all public buildings and considerable other infrastructure and has had oversight of other key infrastructure such as roads (now under the National Roads Authority), communications and ports (now both under individual engineers). Oversight of planning and building control is under the remit of the Building Control Unit (BCU), part of the Planning Department.

3.1.1 PWD in the National Hurricane Committee

Over the past decade or so, PWD has become increasingly attuned to the requirements of the disaster management community for shelter accommodation and other critical infrastructure safe and secure during hurricanes. This has led to an ongoing effort to increase and harden available public shelter and to harden healthcare and other critical facilities within the public sector. A report commissioned by PWD (Minor & Murphy, 1999) provided information concerning the level of wind hazards likely to be encountered in Cayman and recommended appropriate building standards for new critical infrastructure and for retrofitting of existing infrastructure.

As a direct result of PWD's initiatives, design criteria for the new General Hospital in George Town (Figure 3.1) were set at a very high level, as were design criteria for a number of new schools (which would double as hurricane shelters, Figure 3.2) as well as local health clinics and police posts (which would function throughout a hurricane emergency and act as a local base for post-disaster action).

The low loss of life in Ivan (official death toll of two) is due, in no small part, to the efforts of PWD in providing shelter and critical facilities which stood Ivan's test. Although there were problems with some shelters and other infrastructure, most of these problems were not critical. Other problems were not foreseen, and will need attention. However, most of the lessons to be learnt from PWD's actions, over an extended period of time, are positive.

Figure 3.1 Minor loss of roof covering was the only damage inflicted by the wind on the new Cayman General Hospital; flooding damage was more extensive.

Figure 3.2 No damage was inflicted at the new Prospect Primary School, which served as a shelter for 700 people.

3.1.2 Planning Department in the development process – the Building Control Unit

The BCU has been in operation for approximately two decades. Over the past decade it has implemented the Cayman Building Code which is a country application document based on the Standard Code. (The Standard Code is published by the Southern Building Code Congress International, SBCCI). It is the model code most popular in the south and southeast of the USA. SBCCI is now part of the International Code Council and, therefore, the Standard Code will be replaced by the I-Codes of which the principal one is the International Building Code.

By and large Ivan was a success story for the CIG Building Control Unit headed by Mr McCleary Frederick. There was only moderate structural damage to buildings designed and constructed after the introduction of the Cayman Building Code. Older buildings were noticeably more vulnerable from a structural point of view and, indeed, suffered more damage (Figure 3.3).

Figure 3.3 Severe damage to the upper level of a pre-code un-reinforced masonry building by wind during Ivan.

The failures in newer buildings were mainly of non-structural components and, additionally, due to siting issues. There was loss of roof covering, surprisingly few cases of broken windows, a considerable amount of leakage due to inadequately detailed window assemblies and installations, some damage to non-traditional external wall coverings, loss of boxed-eave ceilings (Figure 3.4), considerable water damage of internal ceilings and partitions and floor coverings, flood damage and wave-related destruction of coastal properties.

Figure 3.4 Boxed-eave coverings suffered extensive damage and allowed major water ingress to many residential and hotel properties.

It is clear that the Building Control Unit is absorbing the lessons from Hurricane Ivan. The care and attention previously given to structural aspects of design and construction will now be replicated for non-structural components. Siting regulations will be reviewed. Materials and applications which fared particularly poorly may be embargoed in the rebuilding process; however, it is not recommended that a prescriptive standards approach be taken in this case.

In the aftermath of Ivan the requirements for approvals of designs will not be relaxed as an expedient measure. The repair of badly-damaged buildings will be subject to the formal approval process.

3.2 *Overview of the damage*

3.2.1 Roads

Damage to the road system occurred mainly on the south coast due to a combination of storm surge and waves (Figure 3.5). In the immediate aftermath of Hurricane Ivan many of the main roads were completely covered with sand (Figure 3.6), attesting to the enormity of marine actions during the event. The clearing of the sand revealed significant damage to coastal roads in the south. In some cases only the wearing courses (asphalt surfacing) were removed. In a few cases the destruction was deep-seated, extending to the base and sub-base of the road.

Repairs are in progress and in some areas the opportunity is being taken to realign the road further inland.

Figure 3.5 Severe road damage along the south coast west of East End.

Figure 3.6 West Bay Road adjacent to Seven Mile Beach, where storm surge flooding carried and deposited sand across the roadway.

3.2.2 Telecommunications

Cellular telecommunication services from one of the providers, Cable & Wireless, were maintained throughout the passage of Ivan. The C&W landline network and all other cellular systems were disrupted by Ivan, often due to flood-induced failure of system power supplies (both mains and standby). Radio and television services were also disrupted.

There was damage to a very few telecommunications towers (Figure 3.7). Overhead landlines are typically carried on the same poles as the electricity distribution cables. The loss of distribution poles was about 10 to 15% (see details below).

Figure 3.7 Upper segments of tall communications tower blown of by Ivan

Fibre optic cables were affected where the roads in which they were buried suffered marine damage. The cables themselves were not broken but the ducts enclosing them were. These uncovered cables are being relocated further away from the coastline (Figure 3.8).

Figure 3.8 Fibre-optic cables exposed by erosion of the south coast road.

3.2.3 Water Supply

Two water companies produce desalinated water for potable consumption in Grand Cayman. The water distribution is common to both producers.

Production was temporarily halted to protect the systems during the passage if the hurricane. The supply was put back on stream soon after the end of the event. However, some mains were damaged where they were located in destroyed coastal roads.

3.2.4 Electricity

The main power generation plant was virtually undamaged by Hurricane Ivan (Figure 3.9).

Figure 3.9 Main generating plant on Grand Cayman, largely undamaged by Ivan.

As indicated above, distribution poles were lost in a significant number of cases. A few pre-stressed concrete transmission poles broke along the long north-south leg of the distribution system at West Bay (Figure 3.10) and at least one broke in a relatively low-wind setting (Figure 3-11; likely due either to a pole flaw at a bolting point or to poor installation of fitments at the bolting point). This does not indicate a negative view of their continued deployment for this purpose.

Figure 3.10 Failure of concrete distribution poles in the West Bay area.

Figure 3.11 Failure of concrete pole at a bolting point. Along south coast road near Bodden Town.

Large numbers of wooden poles were damaged along West Bay Road (a long stretch of north-south running cabling) due to a combination of across-wind spans, multiple cables and frequent up-pole transformers. In other areas, up-pole transformers were the dominant reason for pole failure (Figure 3.12).

Figure 3.12 Uppermost part of wooden distribution pole broken by wind due to increased total wind pressure (due to higher surface area resisting the wind) and increased gravitational load (weight of the transformer).

In addition to damage to the overhead wiring, other elements of the transmission and distribution system were compromised by flooding, and at least one sub-sea cable was damaged.

Many street lights were also damaged, both up electricity distribution poles (Figure 3.12) and on stand-alone poles (Figure 3.13). Many traffic signals were also damaged.

Figure 3.13 Street lights lost from stand-alone poles.

3.2.5 Ports and Jetties

The main port suffered little and was quickly back in operation to cargo and cruise ships. A jetty on the south coast was completely uprooted and deposited on the land side of the coastal road, and other small wooden jetties along all of the coasts were damaged.

The heavy storm surge flooding coming from North Sound badly affected the newly developing marina areas on the western side of the sound (Governor's Harbour, Snug Harbour and The Shores); many pleasure boats came aground in elevated positions (Figure 3.14).

Figure 3.14 Boat aground at Foster Bay Villas.

3.2.6 Hotels

The hotels, typically, were not able to operate to full capacity for several months after Ivan. Although most fared well with respect to their structures, water ingress from various sources, along with the lack of full air conditioning, meant that conditions were unsuitable for receiving guests.

Almost all of the hotels along the south and east coasts and many along the west coast suffered flood water damage to some extent, with all ground floor rooms in most properties having to be stripped of all contents and re-finished (Figure 3.15). Most other damage came from water ingress through windows, doors, compromised cladding (Figure 3.16) or roofing (Figure 3.17) and boxed-eave coverings (Figure 3.4).

While the structural integrity of recently designed and built properties was not compromised during Ivan, huge losses were incurred through extensive breaching of the building envelope and ingress of rain. Whether or not these losses will be sufficient to cause a re-think in the use of lightweight cladding and roofing is not known; certainly our findings were that interior damage from rain ingress to the upper floors of multi-storey hotel buildings was far more costly than was initially apparent.

Figure 3.15 Storm surge flooding caused extensive damage to ground floor rooms in most beachside properties around Grand Cayman. This is the Morritt's Tortuga Club at the north end of the east coast.

Figure 3.16 Extensive damage to cladding at the eastern end of north-facing walls at the Holiday Inn on West Bay Road.

Figure 3.17 (below) Major roof covering damage to Indies Suites on West Bay Road (left) and minor damage to the much newer Morritt's Tortuga Club (right).

Several villa-type hotel properties were severely damaged by wave action in two particular places. The principal factor controlling wave damage was the absence of offshore reefs shallow enough to induce breaking of waves. Once onshore winds occurred in these areas, extensive wave damage took place. The two areas most severely affected were along South Sound at Milford's Bay (Ocean Club and Mariner's Cove properties, Figure 3.18) and along the south-facing coast of West Bay (Bonnie's Arch, Dolphin Point, Oceanside Plantation and other properties, Figure 3.19). Onshore winds did not, fortunately, occur along the unprotected Seven Mile Beach during Ivan. Wave damage to beachside properties here during future storms with a more easterly track than Ivan could be very substantial.

Figure 3.18 Ocean Club along South Sound; next door, the wooden structures of Mariner's Cove were completely destroyed. Note parts of the sea wall used as a battering ram causing severe structural damage.

Figure 3.19 Dolphin Point, West Bay. Onshore winds late in the storm drove heavy waves into this and adjacent properties, causing massive damage, even to well-built reinforced masonry structures.

3.2.7 Golf Courses

The authors were not able to visit golf courses. Interviews revealed that damage from sea inundation would be of a temporary nature. The salt content of the soils would soon be leached out by normal processes. Other landscaping repairs would not be extensive. The lack of fresh water for the first several days after flood waters receded may have exacerbated the situation somewhat, but does not appear to have been fatal to most of the grasses.

3.2.8 Residential housing

Damage to the single-family housing stock was mainly caused by flood waters.

There was loss of roof coverings. The old, arc-tangent (corrugated), galvanised steel sheets did surprisingly well (Figure 3.20). This is probably due to the thicker gauge metal that was common in less competitive times. Asphalt shingles were the worst-performing covers. The manufacturers' trade association in the USA do not recommend their use in high-wind areas and most newly fitted shingles actually significantly outperformed their stated limits (Figure 3.21). Concrete and clay tiles were lost from many roofs (Figure 3.22). They are usually fixed only at the rear (upper ends) of the tiles. This method of fixing provides inadequate lever-arm resistance. In addition, the smaller the element the higher the wind pressure (force per unit area) to which the element would be subjected in a hurricane. The best-performing roof covering was standing seam metal roofing (Figure 3.23).

Figure 3.20 Traditional arc-tangent roofing fared well in Ivan, much well-installed roofing cover remaining fully intact.

Figure 3.21 New housing in Windsor Park, George Town. Most of the asphalt shingles stayed on despite the strong winds.

Figure 3.22 Clay tiles removed from the east-facing roof and from ridges on this house in Governor's Harbour.

Figure 3.23 Standing seam roofing did very well in Ivan.

The use of hurricane shutters is much more common in the Cayman Islands than in the Eastern Caribbean. This resulted in much less window damage than would otherwise have been the case. Very few residential structures in Grand Cayman have gable roofs, which were found to be highly unstable in strong winds when Hurricane Andrew hit South Florida in 1992. Several gables were seen in a compromised state, re-enforcing the vulnerability of such structures (Figure 3.24).

Many residential structures along the south coast suffered from removal or addition of sand and strong storm surge ingress (Figure 3.25). A few others suffered severe wave damage in the exposed High Rock area along the south coast (Figure 3.26).

Figure 3.24 Compromised gable end in a house under construction.

Figure 3.25 Ingress of sand and flood water was very severe in many areas along the south coast beaches. This property is in Bodden Town.

Figure 3.26 Extreme wave damage at High Rock; this property is about 25 ft above sea level and several hundred feet from the shoreline.

3.2.9 Offices and Banks

Some of the best designed and constructed buildings in Grand Cayman are the newer offices for the financial services sector. In a few cases there were clearly-articulated directives from owners to their design teams to produce buildings which would function seamlessly throughout, and immediately after, severe hurricanes. Even these precautions did not result in seamless services after Ivan because the homes of employees were not as invulnerable as the offices.

Window protection against flying debris is becoming more usual. Either shutters fixed to buildings (integrated in the original design of buildings) are used or laminated glazing is installed (Figure 3.27). These strategies worked satisfactorily.

Figure 3.27 Laminated glass performed very well in office buildings throughout Grand Cayman.

Several of the newest buildings used lightweight, external wall-cladding materials similar to those used in many new hotel buildings (see Figure 3.16). These did not fare well in some instances and would not provide confident, weather-excluding envelopes in hurricanes which are routinely accompanied by flying debris.

There were cases where the buildings appeared to be virtually undamaged but where the normal functioning of the offices was not possible after Ivan because of significant internal damage (Figure 3.28). The detailing of window assemblies, the detailing of the installation of window assemblies in external walls, the detailing of external doors and the fixing of waterproofing membranes on concrete roofs are all areas requiring more care in the design and construction phases of projects. It was surprising how much rain water could enter a buildings which suffered no visible external damage.

Figure 3.28 Significant internal damage was caused by rain ingress through minor breaches in the building envelope.

3.2.10 Commercial buildings

Smaller commercial and retail buildings generally did not perform well during Ivan. A number of flaws in design and/or construction were highlighted by the high winds. A number of 'strip-mall' type buildings were destroyed or severely damaged (Figure 3.29), and long-span galvanized arc-tangent sidings and roofs were ripped off (Figure 3.30) and became damaging debris (Figure 3.31).

Figure 3.29 Loss of long-span galvanised roofing and subsequent destruction of the entire property was frequent around George Town.

Figure 3.30 Long-span galvanised siding blown out and subsequent loss of a large part of the building.

Figure 3.31 The roof from a neighbouring building caused significant damage to this otherwise well-protected residential home.

3.2.11 Shelters

Most public shelters performed extremely well during Ivan, and almost 4,000 people safely rode out the storm. The newest shelters were almost undamaged and all systems operated as planned (e.g. back-up generators running air conditioning). Other older, retrofitted shelters sustained minor damage or some loss of function. Only two buildings which were being used as shelters were badly compromised; the Isley Conelly Hall at John Gray High School and the Bodden Town Civic Centre (Figure 3.32), which had to be rapidly evacuated in the height of the storm. Two other buildings on the original list of 18 designated shelters were not opened due to their likely failure in the high winds forecast for Ivan (and both did in fact fail). Both the Isley Conelly Hall and the Civic Centre were known to be somewhat vulnerable to winds of Ivan's strength, and both were due for replacement as shelters. It is interesting to note that the Isley Conelly Hall roof apparently failed due to compromise of a main truss during installation of air conditioning, required for it to become an official shelter.

Figure 3.32 Extensive roof damage at Bodden Town Civic Centre, which at the time was being used as a shelter.

3.2.12 Healthcare facilities

Four local health clinics and the General Hospital in George Town comprise the key elements of the healthcare system. All of these buildings are relatively new and were designed to high specification. All performed well during Ivan, although some damage from flooding occurred at the Bodden Town clinic and from flooding and rainfall ingress at the General Hospital.

The Bodden Town clinic sustained damage from flood-carried debris to doors and external air-conditioning units, from sea water to internal sheet-rock panels and internal fixtures, and from minor rainwater ingress to parts of the ceiling through the loss of small areas of roof covering.

The General Hospital sustained minor roof damage (Figure 3.1) which allowed localised rainwater ingress and subsequent damage. The major damage to the General Hospital was due to flooding; although this was not, economically, particularly significant, the loss of operation of the standby generator did compromise the operational capacity of the hospital during the critical hours during and immediately after the peak of the storm. Access to the hospital was also severely hampered by high flood water in the area; credible reports of people swimming towards the hospital demonstrate a serious flaw in the operational design of this critical facility.

3.2.13 Other critical facilities

Other critical facilities functioned adequately; flooding and rainwater ingress through minor building envelope breaches did not impact on the functionality of most of these facilities. The efficacy of the Emergency Operations Centre (co-located with the main fire station close to the airport) was restricted by space, security and concern about its structural integrity. A more appropriate centre of operations could only have helped emergency operations in the rescue and recovery phases. Any new facility should be designed with more redundancy in inter-agency communications; as is often the case in such situations, poor communications hampered rescue operations. The main police HQ in George Town was evacuated due to partial roof failure, hampering the ability of the police to play their full part in rescue and recovery operations. Again, a more robust base location and communications systems are required for all sectors of the critical emergency services.

3.2.14 Accommodation and support for critical workers

As is the case in many emergency situations, critical workers in Grand Cayman were called upon to make enormous sacrifices of time and effort. Often, personal needs were not addressed due to the greater need of the general population. In an event such as Hurricane Ivan, where damage was widespread and almost all of the population affected in some way, stress and fatigue among the critical workers was exacerbated by their concerns for the well-being of themselves and their families. Better planning for and management of the needs of critical workers before and during an emergency, including provision of appropriate accommodation, fast-tracking of insurance claims etc. is a vital part of improving disaster preparedness and response.

3.3 *Factors affecting vulnerability*

3.3.1 Construction quality

The quality of construction in Grand Cayman is generally good. The construction industry was well organised and adequately supplied with professional architects, engineers and builders. This refers to the normal state of affairs. In the aftermath of Hurricane Ivan the situation is materially different, as it would be in any small society. The present situation poses a considerable challenge as Cayman embarks on repairs and reconstruction over a 2-year period equivalent to several more years of normal activity. In these circumstances the control of quality would have to be carefully monitored.

During this project, there was insufficient time to undertake a detailed analysis of specific design or construction elements which may or may not have contributed to reduced vulnerability. Such an analysis would be most worthwhile, especially in the residential sector. Cursory inspections indicate that both hurricane straps and window shutters were effective in reducing wind-related damage; however, it is notable that similar low-cost techniques for reducing vulnerability to water ingress (both from rainfall and from flooding) have not been developed and would have had much greater impact in this case.

3.3.2 Maintenance

Maintenance in Cayman was fair to adequate. The main concern would be the aggressive saline atmosphere and the consequent corrosion of metal connectors.

Galvanised hurricane straps and galvanised connector plates in roof trusses are widely used in Grand Cayman (Figure 3.33). This is good. However, many of these devices are 'out of sight and out of mind'. Galvanised, light-gauge straps and plates have finite lives much shorter than the buildings they serve. Maintenance and replacement of these components would require deliberate planning not usually found in these communities. The safer alternative would be to use stainless steel. It is a question of high first costs versus high maintenance costs.

Figure 3.33 Galvanised connector plates on roof trusses kept the roof structure intact, although the roof covering was lost.

In the residential sector, older roof coverings of all types fared worse than their new counterparts. This is essentially a maintenance issue; degradation of asphalt shingles and galvanised roof covering is significant in the Caribbean climate, and such coverings require replacement earlier than is commonly the practice if they are to prevent water ingress or worse during hurricanes.

4 CONCLUSIONS AND RECOMMENDATIONS

This chapter discusses the conclusions of this study, highlights the lessons which should be learnt and provides recommendations for action both in the Cayman Islands and in the wider Caribbean region.

4.1 Conclusions

Hurricane Ivan was an unusually strong hurricane which produced high winds, storm surge flooding, heavy rain and strong wave action on Grand Cayman. Ivan was sustained as a severe hurricane throughout its passage across the Caribbean Sea; for all seven days of its Caribbean life, Ivan had peak winds in excess of 130 mph. Few hurricanes sustain such intensity for so long, and none has done so with such a southerly track since reasonable records began 150 years ago.

The physical impact of Ivan on Grand Cayman was somewhat short of devastation. However, this study shows that the meteorological conditions encountered were certainly capable of causing severe damage, and it was only because of the high standard of built infrastructure, especially shelter accommodation and other critical infrastructure, that loss of life and injuries were kept so low. The economic impact, however, appears to have been unprecedented, and serves as a salutary lesson to the region as to the fragility of rapid development in the face of natural catastrophe, even where mitigation measures were relatively strong.

Analysis of wind damage to built infrastructure suggests that peak wind speeds in Ivan were at the lower end of the range deduced from the meteorological data. A headline peak wind speed of 130-135 mph (1 minute sustained) with 3 second gusts to 165 mph are our best estimate, making Ivan a minimal Category 4 storm in western Grand Cayman. Storm surge was 6-9 ft, which caused flood water depths of up to 5 ft in some areas. Wave heights were of the order of 15-20 ft in the High Rock area, breaking several hundred feet on shore.

Although wind speeds were sustained around 130 mph for 2-3 hours across much of western Grand Cayman, it was water that did most damage, in the form of storm surge flooding (aided somewhat by heavy rain) and wave action in exposed coastal areas. Although water damage appeared to have come as something of a surprise to many residents of Grand Cayman, the conditions were not unusual for such a strong hurricane and, in fact, there is evidence to suggest that the extent of flooding and wave damage was not as unusual as the ferocity of the winds.

Analysis of the short term forecasting and of the few hazard assessments for Grand Cayman suggest that neither performed very well for Ivan. The conditions of wind encountered in Ivan were within the limits of the uncertainty in the forecasts for all time periods, but those uncertainties gave a range of possible peak wind speeds, even at 24 hours notice, of almost 100 mph. This translates to projected damage levels covering the entire range from no damage to catastrophic damage.

The different probabilistic models cannot be assessed on the basis of one storm, but there are clearly major differences and problems in model performance, and these must be addressed and resolved, and improvements made in surge modelling, for the hazard assessments to be regarded as useful. The results of this project will serve as a critical data set for verification of future hazards studies.

It appears, on the balance of meteorological evidence, that Ivan was about a once in 100 year storm. Wind speeds were a little stronger and surge/wave impact perhaps a little less than that, but overall, the impact was probably that of a 100-year event. However, it should be noted that, firstly, two 100-year hurricanes can occur in successive years; the fact that Ivan occurred in 2004 does not give Grand Cayman a guaranteed 99 years without a similar storm, and secondly, that Ivan was somewhat short of a worst case scenario for Grand Cayman.

The built environment performed admirably during Ivan. The effective enforcement of a strong building code ensured minimal wind damage to most large structures. However, relatively minor flaws, either in design or construction, led to substantial damage or loss of function across a wide range of building types. The loss of use of the generator to flooding at the General Hospital and at other critical facilities, rainwater ingress into many commercial and residential structures through poorly fitted windows and minor roof covering breaches are examples of the accuracy of the adage “the devil is in the detail.”

Flooding of ground floors was widespread, especially in coastal property and in the western part of the island. Given the low altitude of most of Grand Cayman, there is no easy fix to the storm surge flooding problem. However, the economic impact of the flooding appears to have exceeded all expectations, and there may be a change in thinking in the design and use of ground floors in some areas.

Wave damage, by contrast, was confined to a limited number of locations, but the damage was uniformly catastrophic. Waves are an extremely damaging agent, especially when given the extra potency of a raise in base level (by storm surge), large heights (15-20 ft for Ivan) and an unprotected coastline. The role of coral reefs in protecting the coastline from breaking waves was highlighted especially effectively in Ivan; the small breaks in reef protection along the south coast of Grand Cayman exactly coincide with the areas of wave destruction. Without major protective structures at the shoreline, it is very difficult to protect property from wave destruction except by avoiding these exposed locations entirely.

Several building designs or materials proved to be no match for Ivan’s winds and rain. Lightweight cladding used in many large hotel and other buildings in Grand Cayman was easily breached, and exposed the interior to major water damage. Plastic boxed-eave covers were often blown out by winds, especially when in place over balconies. This gave rain access to the roof space, causing major interior damage in many cases, even where no other roof breaches occurred. Clay tile performed quite poorly, as did asphalt shingles, although in both cases, well-installed roofing generally performed significantly better than manufacturers guidelines.

Long-span galvanised steel sidings and roofs were often removed, as were poorly constructed residential roofs. However, the widespread use of hurricane straps and the predominance of shuttered windows, especially in residential properties, meant that widespread structural roof loss was largely avoided, greatly mitigating the impacts of Ivan in both social and economic terms.

The socio-economic impacts of Ivan have still been very severe, and perhaps have added to the local perception that Ivan was a Category 5 storm and as bad as it is going to get on Grand Cayman. The evidence suggests that this is not the case, and that the severe economic impact especially is due mainly to the phenomenal growth in population and infrastructure at risk in Grand Cayman. That population growth has been housed, both residentially and commercially, in well-built structures which generally stood up well to the wind, but were within 10 ft of sea level and thus prone to some degree of flooding. Without a comprehensive revision of building practice for low-lying areas, it is difficult to see how storm surge flooding can be effectively mitigated. In contrast, wave damage occurred only in a few exposed locations, where action could be taken to ensure better structures (or no structures at all) in these areas.

One major issue to come out of this study is the possibility of severe wave damage to the exposed west coast of Grand Cayman during a storm tracking over the eastern side of the island. Even a milder storm than Ivan, if taking such a track, could cause severe wave damage as well as surge flooding along Seven Mile Beach and in George Town. Any future hazard assessment work commissioned for the Cayman Islands should include a specific element looking at worst-case scenario storms.

Early estimates of the economic impact of Ivan on the Cayman Islands were of the order of US$1 billion (*e.g*. Risk Management Solutions press release, 21 October 2004). The most recent estimate of US$3.5 billion (ECLAC, 10 December 2004) is probably closer to the truth, but the huge range in estimates highlights the difficulty in making such estimates in the Caribbean due to the lack of insurance and public sector data available to verify models. The importance of more accurately estimating future economic impacts of natural catastrophes cannot be overemphasised, and it is strongly recommended that the substantial data set for the impact of Ivan in Grand Cayman be expanded through the incorporation of insurance data, and then used to control and verify quantitative risk assessment models which are available for future use.

4.2 Lessons for the Cayman Islands and the Caribbean region

i) Ivan demonstrated the vulnerability of island nations in the southeastern Caribbean to severe tropical cyclones. Although the factors controlling tracking of storms across the Atlantic are complex, there is strong evidence suggesting that more hurricanes taking southerly tracks are likely in the next 10-25 years than occurred during the 40 years prior to 1995. As Ivan demonstrated, southerly tracking Atlantic storms are more likely to hit the Cayman Islands than those which cross the Lesser Antilles north of Dominica. There is other evidence to suggest that global climate change may facilitate more southerly tracking of tropical cyclones across the Atlantic Ocean.

ii) Ivan demonstrated the vulnerability of the Caribbean region to multiple strikes from a single storm. In total, six separate island nations encountered at least tropical storm force winds during Ivan's passage across the Caribbean Sea, and three were affected by winds greater than 100 mph.

iii) The low loss of life and injuries sustained in the Cayman Islands is testament to the effectiveness of a strong built infrastructure (especially critical facilities), substantial secure and safe shelter accommodation, good preparedness planning and public education, and effective disaster management. The foundation of strong infrastructure is the effective enforcement of appropriate building codes.

iv) The enormous financial losses sustained on Grand Cayman, especially relative to the loss of life, is strong evidence supporting the supposition that development in the Caribbean is increasingly linked to the coastal areas most at risk in tropical cyclones. So, while loss of life and injury can be reduced very effectively through a number of mitigation mechanisms, economic impacts are much more difficult to mitigate against. As the wider Caribbean strives for economic well-being such as predominates on Grand Cayman, so the sustainability of economic conditions becomes more vulnerable to tropical cyclone disasters. The direct economic impact on the Cayman Islands Government and on individuals was significantly mitigated by the widespread insurance coverage in both the public and private sectors. This allowed a large proportion of the losses to be recouped from the global re-insurance markets.

v) Despite ferocious winds sustained across much of western Grand Cayman, it was sea water flooding which did most damage (in economic terms). Wave damage was also significant, though limited to small areas. Heavy rain led to major internal damage, even where breaches in the building envelope were minor. Although Cayman's flatness reduces elements of the wind hazard associated with altitude and topography, even on the more mountainous islands, water hazards are often more severe and costly during a tropical cyclone disaster than are wind hazards.

vi) The uncertainties in NHC forecasts for Ivan as it approached Grand Cayman were about average, and the uncertainties in position and intensity estimates are unlikely to improve significantly over the coming years. This meant that, even at only 24 hours notice, the

NHC forecast allowed for a range of wind speeds from 60 to 160 mph, with similar large ranges on rainfall, storm surge and wave height estimates. Public education and preparedness planning in the Caribbean must become more attuned to the uncertainties in forecast information so that the public does not lose trust in the warning systems.

vii) The large uncertainties in the forecast as Ivan approached Grand Cayman did not hinder official preparations nor, apparently, public preparations. There are many lessons to be learnt throughout the region from the sustained efforts in the disaster management sphere in the Cayman Islands.

viii) Hazard maps for Grand Cayman proved to be only moderately useful. Ivan appears to have been a 1 in 100 year storm, but different models of the wind hazard diverge hugely in this regard. The only model of surge and wave height proved to be highly inaccurate, apparently due to its low resolution. Many of the problems faced by the Cayman Islands in its hazard mapping are mirrored throughout the region, and high resolution maps of storm surge inundation and coastal erosion are needed everywhere.

ix) Given the excellent infrastructure resilience and disaster preparedness of Grand Cayman prior to Ivan, the impacts there were significantly lower than had the same storm hit with the same severity almost anywhere else in the region. Planning for post-disaster recovery in the region must take account of the potential for disasters substantial worse (especially in human impact) than was experienced on Grand Cayman from Ivan.

x) Although Ivan dealt a severe blow to Grand Cayman, it cannot be regarded as a worst-case storm there. The development and economic hub of Grand Cayman, Seven Mile Beach, is highly exposed to storm surge and especially wave damage during storms crossing the eastern half of the island, which would produce onshore westerly winds at the peak of the storm. Long-term developmental planning, both in Cayman and elsewhere, should take full account of the worst-case scenario storm.

4.3 Recommendations

i) Hardening of existing meteorological instrumentation and installation of a data gathering network specifically for hazardous meteorological conditions in the Cayman Islands and across the region, to include multiple wind sensors, rain gauges and barometers and, where feasible, offshore and coastal tide/surge monitoring through fixed tide gauges and ocean-bottom pressure sensors.

ii) Completion of a comprehensive high resolution hazard assessment of the Cayman Islands for tropical cyclones, with particular emphasis on storm surge and wave action. Such a study must be of sufficiently high resolution so as to be able to model variations of surge and wave action on the scale of tens of metres, and also must meet a standard of being able to accurately model the impacts of Hurricane Ivan. Similar high resolution studies are required across the region, especially for built-up areas close to sea level. Such hazard assessments must form the foundation of quantitative risk analysis.

iii) Development of infrastructure vulnerability models for tropical cyclones. The Cayman Islands provides an ideal location for such studies, with data gathered during this project, by the Cayman Islands Government and ECLAC and by the insurance industry (if made available) enabling unprecedented verification of such models for the Caribbean. Such data are not currently available for Caribbean building types except for wind vulnerability of a very limited range of structures.

iv) Completion of a quantitative risk analysis (QRA) of tropical cyclones to better inform discussion of improved long term development planning aimed at more effective risk reduction. The economic impact of storm surge flooding in particular is something which the region needs to pay more attention to. QRA guides mitigation and preparedness planning through identifying the most critical needs and the cost-benefit relationships for all mitigation measures. Using the results of items (ii) and (iii) above, a well-constrained QRA can be undertaken relatively easily and can be repeated either en-masse or for individual projects.

v) Continuation of data gathering in Grand Cayman, especially of flood levels, to better constrain the surge flooding event, and of human experiences, to act as an educational resource for future generations of Caymanians faced with similar, or growing, risks from tropical cyclones.

vi) Revisiting the use of forecasts and the understanding of forecast uncertainties in planning for tropical cyclone impacts. In particular, public education regarding the hurricane warning system must be continued in order to maintain trust in forecasts. Consideration should be given to the benefits of using a 72-hour rather than 48-hour alert; in a multi-island state, an additional day of time to prepare may be more beneficial than the limited decrease in uncertainty obtained by waiting.

vii) Hardening of infrastructure in support of the emergency services in order to create a better environment for post-disaster recovery. In particular, Police and EOC buildings and communications systems did not fare well in Ivan, and minor problems in other critical infrastructure reduced their effectiveness.

viii) Harmonisation of building codes across the Anglophone Caribbean. It is understood that the Cayman Building Code will be moving from a reliance on the Standard Code of SBCCI to the I-Codes (including the International Building Code) of the ICC. This move will bring the Cayman Islands in line with most of the rest of the Commonwealth Caribbean.

ix) The CIG Building Control Unit's relative success with building structures must now be replicated with building envelopes. The operational effectiveness of BCU should be used as a demonstration to most of the rest of the region.

x) Greater use should be made by the Building Control Unit of external review consultants for projects outside of the regular experience of its staff. It is not sufficient to rely on competent designers. Independent oversight is valuable even with the best of designers. With the international nature of development in the Cayman Islands, designs are often developed off-island with teams of highly specialised professionals. Such designs require a greater level of oversight expertise than can reasonably expected to be maintained in a small island developing state.

xi) In addressing the pressing issues brought about by Hurricane Ivan, the seismic hazard must not be swept under the carpet. There are situations where the requirements of safe wind-resistant design are inconsistent with safe earthquake-resistant design. Fortunately this does not preclude safe multi-hazard designs.

xii) Better integration of natural hazards risk into all elements of sustainable development planning and project implementation in the Cayman Islands. The Comprehensive Disaster Management strategy employed by CIG was highly effective in reducing loss of life during Ivan, but overall economic impacts were not effectively reduced by elements of this strategy (although widespread insurance coverage mitigated the direct economic consequences). Developing a better understanding of and effective strategies to mitigate against economic impacts must be a priority if rapid growth is to be sustainable.

This page intentionally left blank.

5 REFERENCES

Holland, G J. 1980. An analytic model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, **108**, 1212-1218.

Landsea, C W, Franklin, J L, McAdie, C J, Beven, J L, Gross, J M, Jarvinen, B R, Pasch, R J, Rappaport, E N, Dunion, J P and Dodge, P P. 2004. A Reanalysis of Hurricane Andrew's Intensity. *Bulletin of the American Meteorological Society*, **85 (11)**, 1699–1712.

Minor, J E & Murphy, P. 1999. *The hurricane risk for the Cayman Islands, British West Indies*. Technical Brief to CIG Public Works Department.

Organisation of American States. 1999. Caribbean Disaster Management Project, Final CD-ROM.

Powell M D, Houston, S H & Reinhold, T A. 1996. Hurricane Andrew's Landfall in South Florida. Part I: Standardizing Measurements for Documentation of Surface Wind Fields. *Weather and Forecasting*, **11**, 304-328.

Young, S R. 2004. Impact of Hurricane Ivan in Grand Cayman: Understanding and quantifying the hazards. Project report to DFID.

This page intentionally left blank.

APPENDICES

1 *Enclosure poster* "The Impact of Hurricane Ivan in Grand Cayman"

2 *Enclosure CD-ROM* Project data

This CD-ROM contains three folders:

Report and Figures contains the Adobe Acrobat (.pdf) version of the full report, along with all figures and animations. In order for the hotlinks within the report to work, the figures and animations must be in the same folder as the report itself. This folder also includes a .pdf version of the insert poster.

GIS Data contains shapefiles and geotiffs of key data sets. There is also an ArcView 8 map file (Cayman Ivan Photos.mxd) which, when opened, has hotlinks to 48 key photographs of damage and impact.

Imagery contains miscellaneous satellite imagery sets.