NISTIR 5987

Hurricane Marilyn in the Caribbean - Measured Wind Speeds and Design Wind Speeds Compared

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

United States Department of Commerce
Technology Administration
al Institute of Standards and Technology

NISTIR 5987

Hurricane Marilyn in the Caribbean - Measured Wind Speeds and Design Wind Speeds Compared

Richard D. Marshall
National Institute of Standards and Technology

John L. Schroeder
Wind Engineering Research Center
Texas Tech University

March, 1997
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati A. Prabhakar, *Director*

ABSTRACT

This report describes the surface wind speeds during the passage of Hurricane Marilyn through the U.S. Virgin Islands on 15-16 September, 1995. Sources of wind speed measurements during this period are described, along with procedures used to adjust these measured speeds to standard conditions, defined for the purposes of this report as the sustained speed (1-minute average) at 10 m above open water. These adjusted speeds provide a basis for the validation of surface wind speeds derived by the surface wind analysis system of NOAA's Hurricane Research Division. It is concluded that the maximum over-water sustained speeds in Hurricane Marilyn were approximately 40 m/s at St. Croix, 46 m/s at St. Thomas, 43 m/s at Culebra, and 26 m/s along the east coast of Puerto Rico. It is probable that locally higher speeds occurred in some over-land locations where topographic features such as hills, ridges or escarpments caused speed-up effects near the ground. In terms of the extreme wind climate for this region of the Caribbean, the maximum over-water sustained speeds at St. Thomas correspond to a mean recurrence interval of about 30 years, or an annual probability of 0.033 of being equalled or exceeded. In view of the fact that traditional practice is to design ordinary buildings and other structures to perform adequately with a comfortable margin of safety when subjected to a 50-year event (about 50 m/s in this case), the resulting wind damage in the affected area must be attributed to poor building practices and inadequate code enforcement rather than to excessively high winds.

Key words: building technology; codes and standards; hurricanes; natural disasters; structural engineering; wind damage; wind engineering; wind loads

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATION

The following symbols are used in this report:

D	nominal dead load
H	height of hill, ridge or escarpment
L	horizontal distance from crest to half-height of hill, ridge or escarpment
kPa	kilo-pascal
R	nominal resistance
V(z)	wind speed at height z
W	nominal wind load
h	hour
km/h	kilometers per hour
m	meter
m/s	meters per second
s	second
x	horizontal distance upwind or downwind of crest
z	height above ground level (m)
z_o	surface roughness length (m)
γ	load factor
ϕ	resistance factor

LIST OF ACRONYMS

ASCE	American Society of Civil Engineers
ASOS	Automated Surface Observing System
AST	Atlantic Standard Time
CUBC	Caribbean Uniform Building Code
FAA	Federal Aviation Administration
HRD	Hurricane Research Division
LRFD	Load and resistance factor design
MRI	Mean recurrence interval
NESDIS	National Environmental Satellite, Data and Information Service

NHC	National Hurricane Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NWSFO	National Weather Service Forecast Office
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTC	Universal Coordinated Time
UVI	University of the Virgin Islands

EXECUTIVE SUMMARY

During a 14-hour period on 15-16 September, 1995, Hurricane Marilyn passed through the U.S. Virgin Islands, causing 8 deaths and damages in excess of $2 billion. Approximately 21,000 homes were damaged or destroyed. At the same time, intense rainfall caused widespread flooding in Puerto Rico, and the island of Culebra suffered extensive wind damage. Wind damage was heaviest on St. Thomas, particularly over the eastern third of the island as well as in the city of Charlotte Amalie. The desalinization plant on St. Thomas was put out of service, and numerous boats were driven ashore by the wind and waves in St. Thomas Harbor. Wind damage on St. Croix was less severe, somewhat the reverse of Hurricane Hugo in 1989 when St. Croix rather than St. Thomas experienced the brunt of the damaging winds.

This report describes the sources of wind speed records obtained during the passage of Marilyn, adjustments/corrections made to these data to obtain a common or standardized basis for comparison, and the use of these adjusted speeds to validate surface analyses based on all available in situ surface observations and flight-level data adjusted to the surface. The basis for comparison used in this report is the sustained speed (1-min average) at a height of 10 m over open water. The maximum sustained wind speeds from the reconstructed surface windfield at selected points along the hurricane track are then compared with the design wind speed specified by the Caribbean Uniform Building Code (1989) and the design wind speed implied by the Virgin Islands Building Regulations (1984).

Based on the reconstructed surface windfield, the maximum over-water sustained speeds in Hurricane Marilyn were approximately 40 m/s at St. Croix, 46 m/s at St. Thomas, and 26 m/s along the east coast of Puerto Rico. According to the Caribbean Uniform Building Code, the wind speed corresponding to a 50-yr mean recurrence interval for this region of the Caribbean is 50.4 m/s. Accounting for load factors or factors of safety used in traditional wind load design, properly designed and constructed buildings should not have exhibited distress at wind speeds of less than about 57.5 m/s. But even if one assumes the wind load provisions of the Virgin Islands Building Regulations in effect at the time of Hurricane Marilyn were adequate (which they were not), minimal damage should have been expected at wind speeds equal to or less than about 50 m/s. Consequently, much of the structural damage must be attributed to poor building practices and inadequate code enforcement rather than to excessively high wind speeds.

If future wind losses in the U.S. Virgin Islands are to be mitigated, there must be significant changes to the wind load provisions of the local building code. An important first step would be to adopt the wind load provisions of the Caribbean Uniform Building Code which are consistent with a sustained speed of 50.4 m/s at 10 m over water, or a sustained speed of 44.4 m/s for flat, open country. In addition, it is critically important that speed-up effects over topographic features such as hills, ridges and escarpments be accounted for, either by simple computation or by microzoning. Finally, it is important to understand that simply increasing the design wind speeds or loads will not solve the problem. Hurricane Marilyn has demonstrated clearly that current building practices and code enforcement in the U.S. Virgin Islands are inadequate and must be improved.

1.0 INTRODUCTION

On 15-16 September, 1995, Hurricane Marilyn passed through the U.S. Virgin Islands, causing 8 deaths and damages in excess of $2 billion (Wernly 1996). Approximately 21,000 homes were damaged or destroyed, and heavy rains triggered extensive flooding in Puerto Rico. Wind damage was heaviest on St. Thomas, particularly the eastern third of the island as well as the city of Charlotte Amalie. The desalinization plant on St. Thomas was put out of service, and numerous boats were driven ashore by the wind and waves in St. Thomas Harbor. Wind damage on St. Croix was less severe, somewhat the reverse of Hurricane Hugo in 1989 when St. Croix rather than St. Thomas received the brunt of the damaging winds. In Puerto Rico, the island of Culebra also experienced extensive wind damage.

Questions arise in the aftermath of extreme events such as Hurricane Marilyn as to the level of performance of buildings and other structures, the adequacy of local building codes, and the adequacy of contemporary building practices. Before these questions can be addressed, however, it is necessary to establish the surface wind field and thus the probable wind loads. Unfortunately, the number of reliable wind speed records obtained during the passage of a typical hurricane usually is small due to the failure of wind sensors (anemometers) or their support structures, power outages, or general indifference on the part of some who are in a position to obtain such records. Nevertheless, the information that can be derived from the reconstruction of these extreme wind events usually is worth the effort.

This report does not address the type, intensity or distribution of structural damage caused by Hurricane Marilyn. The purpose here is to identify and evaluate the wind speed records that were obtained and to estimate the probable maximum speeds at selected locations along the hurricane track. These estimated speeds are then compared with the extreme wind climate for the affected area and the design wind speed(s) implied by the wind load provisions of the local building code.

This report addresses events that occurred on 15-16 September, 1995. All times listed in this report are referenced to Universal Coordinated Time (UTC). Local or Atlantic Standard Time (AST) may be obtained by subtracting 4 hours from UTC (AST = UTC - 4).

2.0 METEOROLOGICAL ASPECTS OF HURRICANE MARILYN

Hurricane Marilyn originated from a tropical wave which traveled across the Atlantic Ocean prior to gaining organization and forming Tropical Depression 15 off the northeast coast of South America on 12 September, 1995. The complete storm track, as established by the National Hurricane Center (NHC) (Rappaport 1995), is shown in Figure 1. The depression continued to strengthen as it moved to the west at approximately 30 km/h. Five hours after being classified a tropical depression, the system reached tropical storm status and became the fifteenth named tropical cyclone of the 1995 Atlantic hurricane season.

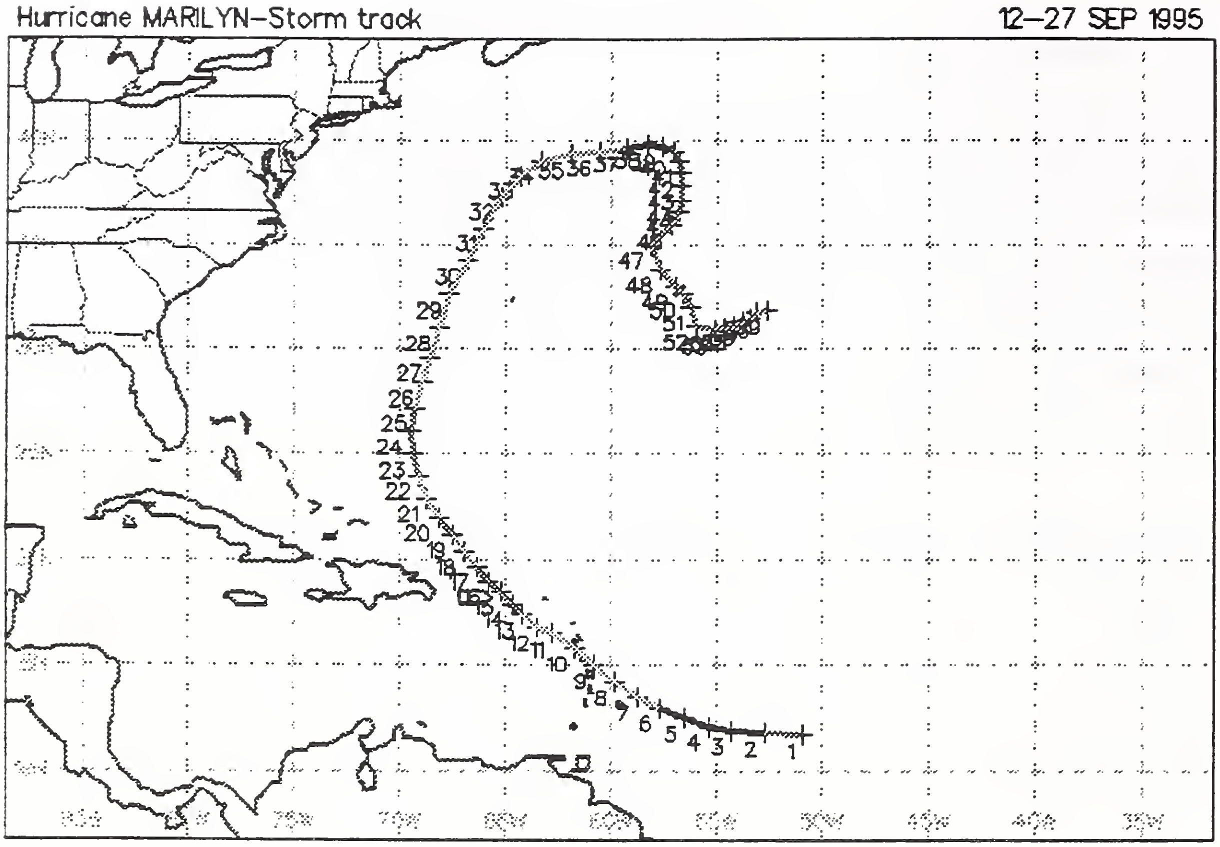

Figure 1. Hurricane Marilyn's complete storm track. Source: Department of Earth and Atmospheric Sciences, Purdue University.

Tropical Storm Marilyn continued to move west, but at a somewhat slower rate of 20 to 25 km/h. The sustained surface wind and pressure, as estimated using satellite imagery, were 22 m/s and 100.0 kPa, respectively, and the storm exhibited good outflow and strong rainbands on its western side. The storm continued primarily on its westward track, but a weakness in a pressure ridge over Puerto Rico began to add a northerly component to the storm's motion. The storm attained hurricane status at 0300 UTC on 14 September, 100 km east of Barbados.

Weakening of the pressure field in the Atlantic allowed the hurricane to slow in pace and turn northward as its center neared Barbados. At 0900 UTC on 14 September hurricane warnings were issued for the U.S. Virgin Islands and Puerto Rico. As Hurricane Marilyn approached St. Croix, it became a strong Category 2 hurricane on the Saffir-Simpson scale (1974) with sustained surface winds of 45 m/s and a minimum central pressure of 97.0 kPa as indicated by the NHC. Hurricane-force winds extended radially 50 km from the center as a 55 km diameter eyewall was broken to the southwest. Approximately, the eastern half of St. Croix experienced the calm of the eye as the hurricane's wind center passed near East Point at 2300 UTC on 15 September. An enhanced infrared satellite picture of Hurricane Marilyn while located just north of St. Croix is shown in Figure 2.

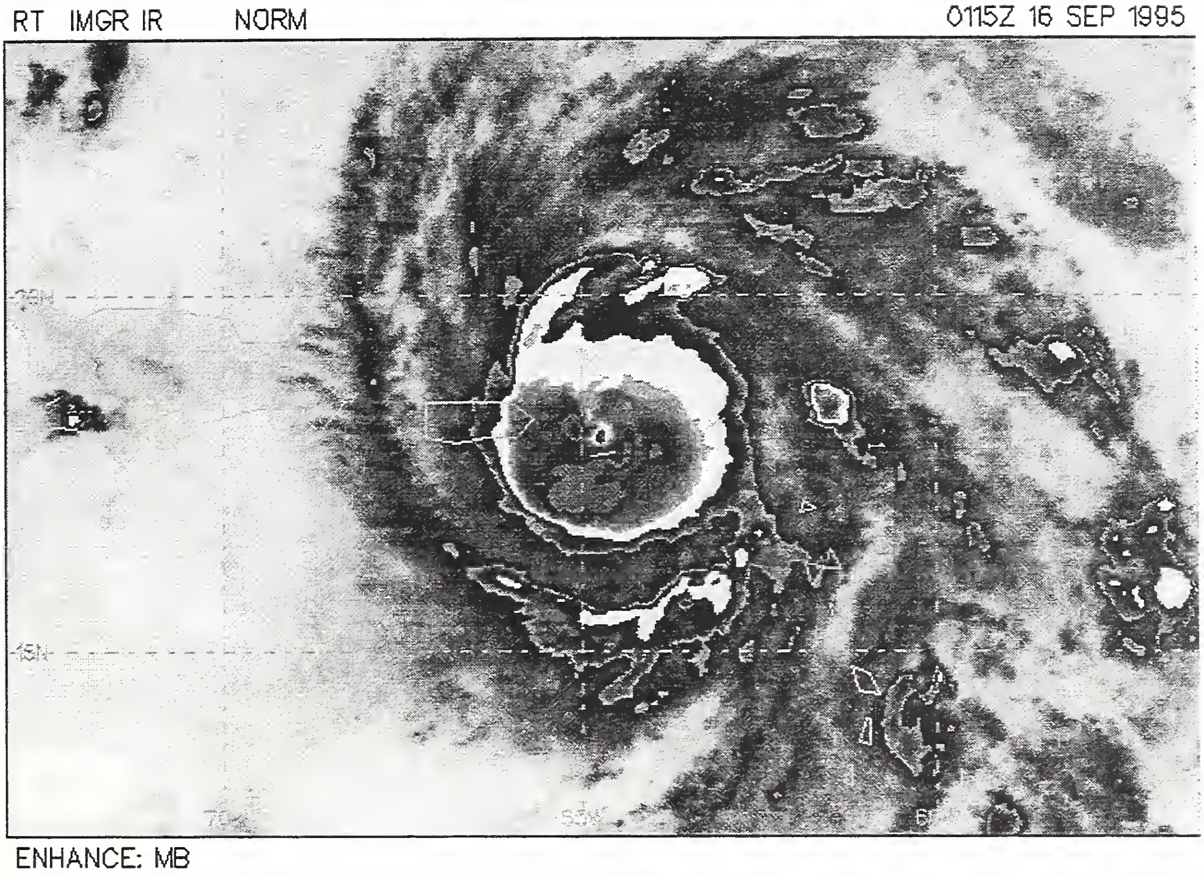

Figure 2. Enhanced infrared satellite photograph of Hurricane Marilyn at 0115 UTC on 16 September with the circulation center located just north of St. Croix, U.S.V.I. Source: NOAA/NESDIS via Dept. of Earth & Atmospheric Sciences, Purdue Univ.

As Hurricane Marilyn affected St. Thomas, Vieques and Culebra around 0300 UTC on 16 September, the central pressure had fallen to approximately 96.0 kPa and the surface winds increased to 47 m/s. The diameter of the eyewall had shrunk to approximately 37 km and was now closed; this along with increased outflow in the upper levels indicated a strengthening hurricane. Hurricane Marilyn continued on a northwesterly track and attained an estimated peak surface wind speed of 51 m/s at 1800 UTC and a minimum central pressure of 94.9 kPa, a Category 3 hurricane, as it exited the Caribbean on 16 September. Under the influence of an upper level low off the eastern coast of Cuba, Marilyn took a more northerly track and eventually turned northeast before becoming extra-tropical. A detailed storm track for the period over which Marilyn was affecting the U.S. Virgin Islands and Puerto Rico is shown in Figure 3. Estimated central pressures and maximum sustained winds over water are listed in Table 1 and are based on a preliminary report issued by the NHC (Rappaport 1995). Hurricane Marilyn had no direct effect on the U.S. Atlantic Coast.

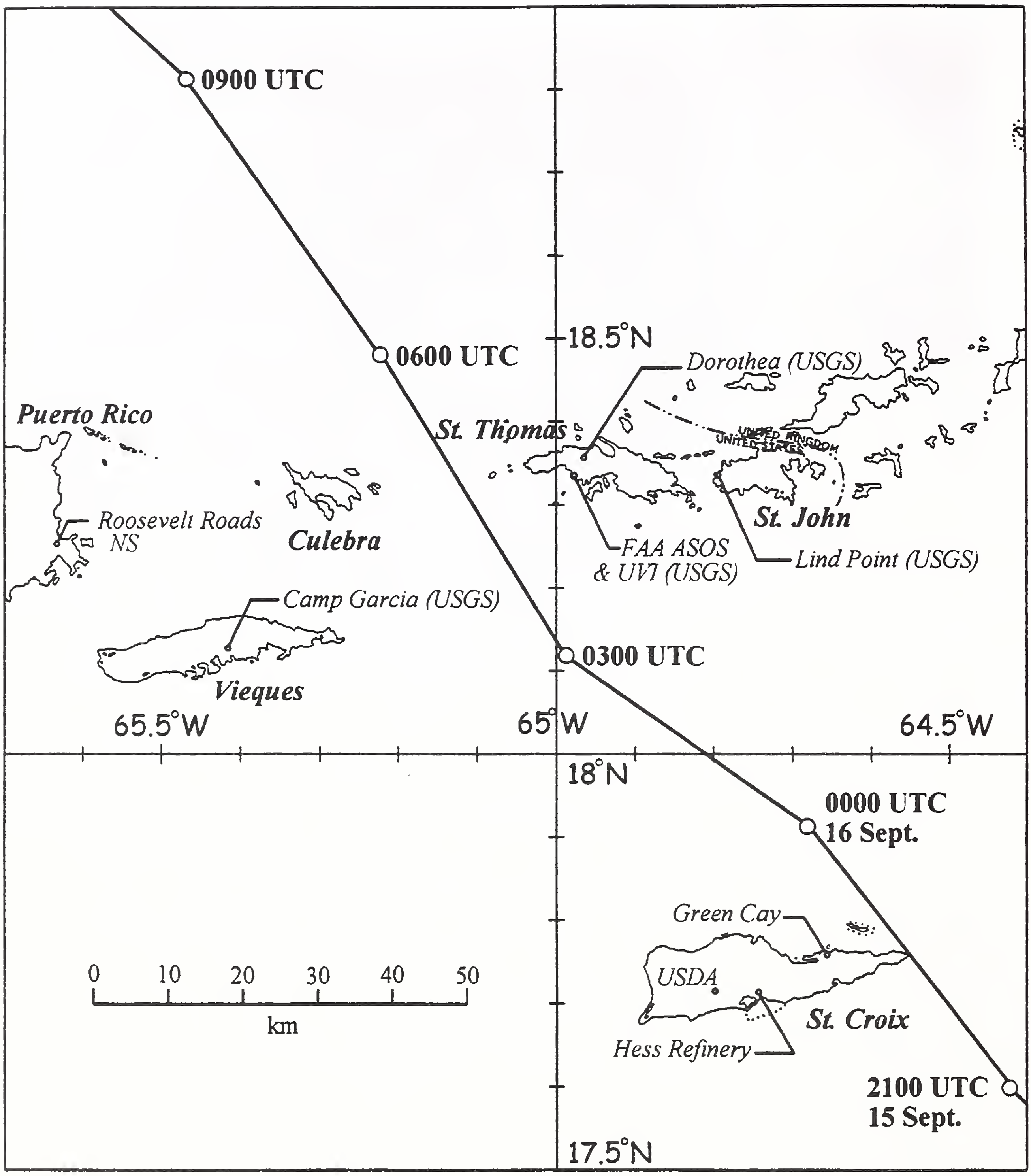

Figure 3. Hurricane Marilyn's storm track for period 2100 UTC 15 September to 0900 UTC 16 September, 1995.

Table 1. Preliminary Estimate of Minimum Central Pressure and Maximum Sustained Speeds Over Water in Hurricane Marilyn (Rappaport 1995).

Date & Time (UTC)	Central Pressure (kPa)	Maximum Sustained Speed (m/s)
15 September, 1995		
1200	97.4	41.2
1800	96.9	43.7
16 September		
0000	96.2	46.3
0600	95.2	48.9
1200	95.1	48.9
1800	95.0	51.4

3.0 SOURCES OF DATA AND ADJUSTMENTS FOR WIND EXPOSURE

As with most hurricane events, the number of verifiable wind speed records obtained during the passage of Hurricane Marilyn is extremely limited. Even when wind speeds have been recorded, adjustments usually must be made to account for variations in anemometer height, averaging time, and terrain roughness. In some situations the effects of nearby buildings and/or topographic features may be so large that it becomes impossible to adjust the wind speeds to standard conditions with any reasonable degree of confidence. The recorded wind speeds described in the following paragraphs were adjusted to standard conditions using traditional boundary-layer models and gust factors (Simiu and Scanlan 1996, ESDU 1995). The accepted definition of standard wind exposure is a 10 m anemometer height in flat, open country characterized by a surface roughness length, z_o, of 0.03 m. However, for the purposes of this report, the wind speeds have been adjusted to correspond to a 1-minute averaging time (sustained speed) and an over-water exposure for which the surface roughness length, z_o, is assumed to be 0.005 m. It can be shown that, for all other conditions being equal, the ratio of the over-water ($z_o = 0.005$ m) to over-land ($z_o = 0.03$ m) sustained speed at a height of 10 m is approximately 1.14.

Records of wind speed, wind direction, and barometric pressure obtained from the affected area in the several months following the passage of Hurricane Marilyn are presented in Appendix A. These records represent the raw data; they have not been adjusted for anemometer height, averaging time, or terrain roughness. These data are summarized in Table 2, along with station ground elevation, anemometer height, wind speed averaging time, and notes on equipment reliability or failure where such information was available. Features of the recording sites and assumptions made in adjusting observed maximum speeds to standard conditions are provided in Appendix B. The following paragraphs provide brief descriptions of the various sources of data used in this post-storm analysis of Hurricane Marilyn's wind speeds and the adjustments made to convert these speeds to a standard wind exposure.

3.1 Hess Oil Refinery - St. Croix

The principal source of wind speed data on St. Croix was the Hess Oil Refinery which is located on the south coast approximately 6.5 km southwest of Christiansted. Wind speed records obtained at this site are reproduced as Figures A-1 to A-6 of Appendix A. Although three of the four anemometers operated by Hess failed during the storm, two of the anemometer sites, East Jetty and Cottage Estate, produced continuous records of wind speed and direction up to or near the time of maximum winds. The wind direction at the refinery shifted counterclockwise from 40 degrees at 0900 UTC on 15 September to 235 degrees at 0200 UTC on 16 September. The strongest winds were observed as the wind direction shifted over the range 330 to 270 degrees from 2215 to 0030 UTC. Note that gust data were not available from the East Jetty site, and there was no permanent record of wind speeds at the refinery fire station.

The maximum 6-minute mean speed at East Jetty was 34.0 m/s. This occurred at 2324 UTC on 15 September from a direction of 291 degrees and at 0018 UTC from a direction of 276 degrees. In addition to mean wind speed, barometric pressure was recorded every 6 minutes at East Jetty, reaching a minimum value of 98.4 kPa at 2324 UTC. However, this same barometer was indicating a pressure of 102.0 kPa at 1000 UTC when the circulation from Marilyn was producing mean wind speeds of about 11 m/s at the recording site, suggesting a downward correction of at least 1.0 kPa. Thus the true minimum pressure at East Jetty probably was closer to 97.4 kPa.

Because it has the simplest and cleanest wind exposure of the four sites at the Hess Refinery, East Jetty was selected for making a comparison with the over-water sustained speeds obtained from the HRD surface wind analysis system described later in this report. For a wind direction of 340 degrees, corresponding to the direction of the first maximum registered by the refinery anemometer sites, the estimated maximum sustained speed at 10 m over water is 41.4 m/s. The corresponding speed for the actual wind exposure at East Jetty is 35.2 m/s. For a wind direction of 280 degrees, corresponding to the direction of the second maximum at East Jetty, the estimated maximum sustained speed at 10 m over water is 37.5 m/s, while the corresponding speed for the actual exposure at the site is 36.4 m/s. Note that for this later direction, the actual wind fetch is primarily over water and smooth terrain.

Table 2. Raw Data Summary for 15-16 September, 1995

Station/Location	Ground Elevation (m)	Anemometer Height (m)	Max. Mean Speed & Direction (m/s)	Averaging Time (minutes)	Peak Gust & Direction (m/s)	Minimum Pressure (kPa)
U.S. VIRGIN ISLANDS						
ST. CROIX						
Hess Refinery:						
East Jetty (1)	3	10.0	34.0 & 291 deg @ 2324 UTC 34.0 & 276 deg @ 0018 UTC Equipment failed @ 0018 UTC	6	--	98.4 @ 2324 UTC
Cottage Estate (1)	24	10.0	30.4 & 330 deg @ 2215 UTC Equipment failed @ 2215 UTC	15	42.5 & 340 deg @ 2145 UTC	--
South Range Finder (1)	3	47.2	30.8 & 340 deg @ 2036 UTC Equipment failed @ 2036 UTC	15	44.3 & 340 deg @ 2036 UTC	--
Fire Station (2)	11	7.6	--	--	44.7	--

Table 2 (Continued)

Station/Location	Ground Elevation (m)	Anemometer Height (m)	Max. Mean Speed & Direction (m/s)	Averaging Time (minutes)	Peak Gust & Direction (m/s)	Minimum Pressure (kPa)
USDA Experiment Station (USGS)	40	9.1	30.4 & 328 deg @ 2315 UTC	30	--	97.7 @ 0015 UTC
Green Cay Marina [(2)] Sailboat Puffin	MSL	12.8	--	--	43.8	96.3
ST. THOMAS						
FAA ASOS [(1)]	3	7.9	46.4 & 066 deg @ 0352 UTC Equipment failed @ 0532 UTC	2	57.7 & 070 deg @ 0400 UTC	95.7 @ 0422 UTC
UVI (USGS) [(1)]	24	9.1	32.2 & 003 deg @ 0315 UTC Equipment failed @ 0330 UTC	30	--	95.7 @ 0345 UTC
Dorothea (USGS)	243	9.1	8.4 @ 0415 UTC Wind speed/direction unreliable	30	--	92.6 @ 0515 UTC

Table 2 (Continued)

Station/Location	Ground Elevation (m)	Anemometer Height (m)	Max. Mean Speed & Direction (m/s)	Averaging Time (minutes)	Peak Gust & Direction (m/s)	Minimum Pressure (kPa)
ST. JOHN						
Lind Point (USGS) (1)	46	9.1	20.2 & 107 deg @ 0315 UTC Equipment failed @ 0335 UTC	30	--	97.5 @ 0315 UTC
PUERTO RICO						
VIEQUES						
Camp Garcia (USGS)	19	9.1	15.6 & 328 deg @ 0345 UTC	30	--	--
CULEBRA (3)	--	--	--	--	56.3 @ 0600 UTC	--
PUERTO RICO						
Roosevelt Roads NS	7	7.0	18.5 & 360 deg @ 0055 UTC	1	25.7 & 020 deg @ 0220 UTC	99.6 @ 0600 UTC
NWSFO San Juan	3	10.0	16.5 & 290 deg @ 0900 UTC	2	20.6 & 300 deg @ 0815 UTC	100.1 @ 0856 UTC

NOTES:
(1) Equipment failure
(2) Observed - no permanent record
(3) Unconfirmed report

3.2 USDA Experiment Station (USGS) - St. Croix

The USDA Experiment Station is located approximately 3 km west of the Hess Oil Refinery and 2 km directly north of Alexander Hamilton Airport at a ground elevation of 40 m. This is one of several meteorological stations operated in the Caribbean region by the United States Geological Survey (USGS). The digital data log for this and other USGS stations affected by Marilyn was updated once each 30 minutes, and it is believed that this interval is close to the effective wind-speed averaging time. This station is of particular interest since it produced the only completely uninterrupted records of wind speed, wind direction, and barometric pressure on St. Croix during the passage of Hurricane Marilyn. The relevant data from this station are plotted as Figures A-7 and A-8 of Appendix A. The maximum mean speed recorded at the USDA Experiment Station was 30.4 m/s at 2315 UTC on 15 September from a wind direction of 328 degrees. Adjusting the averaging time from 30 minutes down to 1 minute at a height of 10 m yields a maximum sustained speed of 37.4 m/s for the actual wind exposure and an over-water sustained speed of 40.5 m/s. The minimum barometric pressure at this site was 97.7 kPa at 0015 UTC on 16 September.

3.3 Green Cay Marina - St. Croix

The only other source of wind speed data on St. Croix considered to be reliable was from the sailboat Puffin at Green Cay Marina. However, no permanent record of wind speed was generated. This site is located on the north coast, approximately 3.2 km east of Christiansted. The site is generally open to the north and northeast and is sheltered by a major ridge to the south and hilly country in all other directions. A peak gust of 43.8 m/s was measured at the mast height of 12.8 m. The corresponding sustained speed at a height of 10 m is 34.4 m/s for both the marina site and an over-water exposure. The minimum barometric pressure registered by the Puffin was 96.3 kPa which is consistent with the value listed in Table 1 for 0000 UTC on 16 September when Green Cay Marina was enveloped by the eye.

Two other potential sources of reliable wind data on St. Croix were the FAA ASOS at Alexander Hamilton Airport and the U.S. Navy Underwater Tracking Range located on the west coast 3 km north of Frederiksted. Unfortunately, the meteorological instrumentation at each of these sites was out of service during the passage of Marilyn.

3.4 Cyril E. King Airport - St. Thomas

The airport is located on the south coast of St. Thomas, approximately 2 km west of Charlotte Amalie. Although the ASOS is located in a flat, open area near the taxiway/runway, the wind exposure from the north around to the southeast is highly complex because of the main east-west ridge and isolated hills on St. Thomas. The maximum 2-minute mean wind speed of 46.4 m/s was logged at 0352 UTC on 16 September from a wind direction of 066 degrees. The minimum barometric pressure was 95.7 kPa at 0422 UTC. Recording ended at 0532 UTC when electrical service to the site was interrupted. Records of the 2-minute mean wind speed, gust speed (5-s mean), wind direction and barometric pressure are plotted in Figures A-9 and A-10. From these plots it is clear that the leading eyewall passed over the site at approximately 0400 UTC, and that the trailing eyewall was over the ASOS site when recording ceased.

Because of the complex wind exposure to the northeast, no attempt was made to adjust the first wind speed maximum to over-water conditions. However, the corresponding sustained speed at a height of 10 m at the site was estimated to be 51.6 m/s. For the second maximum, with the wind directly out of the south, the anemometer height is sufficient to register as an over-water exposure. Therefore, the estimated maximum sustained speeds for a height of 10 m at the site and over water are the same, 43.2 m/s. The true maximum for this direction may have been higher, depending on how well the partial records in Figures A-9 and A-10 describe the passage of the trailing eyewall.

3.5 University of the Virgin Islands (USGS) - St. Thomas

The USGS station at UVI is located in complex terrain on the north edge of the airport, and the wind speed and direction sensors ceased to function at 0330 UTC on 16 September. The maximum mean speed prior to equipment failure was 32.2 m/s from 003 degrees. Minimum barometric pressure prior to system failure was 95.7 kPa at 0345 UTC. Records of wind speed and direction at this site are reasonably consistent with those for the nearby ASOS site up to about 0300 UTC, taking into account the different averaging times for the two sites and the terrain roughness. Because of the complex terrain at the site and the relatively short records no attempt was made to adjust these readings to standard conditions. Records of wind speed, wind direction, and barometric pressure are plotted in Figures A-11 and A-12 of Appendix A.

3.6 Dorothea (USGS) - St. Thomas

This site is located approximately 2 km due north of the east end of the runway at Cyril E. King Airport and about 500 m north of the main east-west ridge on St. Thomas. Ground elevation at the site is 243 m. Both the wind speed and wind direction records for this site are suspect, and no attempt was made to correct the recorded speeds for standard conditions. However, the barometric pressure record does appear to be reliable and indicates a minimum pressure of 92.6 kPa at 0515 UTC. Unadjusted readings of mean wind speed and barometric pressure at Dorothea are plotted in Figure A-13.

3.7 Lind Point (USGS) - St. John

The anemometer mast at Lind Point failed at approximately 0335 UTC on 16 September when the mean wind speed registered 20.2 m/s from 107 degrees. Barometric pressure at the time of this failure was 97.5 kPa. As with the sites at UVI and Dorothea, no attempt was made to adjust the wind speed data to standard conditions because of the complex wind exposure. Mean wind speeds and barometric pressures measured at Lind Point are plotted in Figures A-14 and A-15.

3.8 Camp Garcia (USGS) - Vieques

Mean wind speed and direction for this site are plotted in Figure A-16. The measurements of barometric pressure did not appear to be reliable and are not included in the data plots. The maximum mean speed of 15.6 m/s from 328 degrees was logged at 0345 UTC on 16 September. Based on the available information concerning wind exposure, this mean speed corresponds to an over-water sustained speed of 23.9 m/s. The equivalent sustained speed at a height of 10 m at the site is 19.8 m/s.

3.9 Culebra

A maximum gust speed of 56.3 m/s was reported at the airport on Culebra at approximately 0600 UTC on 16 September. This observation could not be confirmed and no details were available on the anemometer height or characteristics of the surrounding terrain. As this speed is slightly less than that registered by the FAA ASOS on St. Thomas, the adjusted sustained speed of 51.6 m/s at the ASOS site on St. Thomas probably represents a reasonable upper bound on the sustained wind speeds over Culebra.

3.10 Roosevelt Roads Naval Station - Puerto Rico

Verifiable wind speed records were obtained by the U.S. Navy Weather Detachment at Roosevelt Roads Naval Station. The maximum sustained speed recorded at Roosevelt Roads was 18.5 m/s from the north at 0055 UTC on 16 September, and the peak gust was 25.7 m/s from 020 degrees at 0220 UTC. A minimum pressure of 99.6 kPa was recorded at 0600 UTC. Accounting for the terrain roughness between the recording site and the ocean line in a northerly direction, the corresponding maximum over-water sustained speed is 21.5 m/s, and the adjusted sustained speed at a height of 10 m at the anemometer site is 19.6 m/s.

3.11 Other Sources of Data

The NWSFO at San Juan, Puerto Rico, recorded a maximum sustained speed of 16.5 m/s at 0900 UTC and a peak gust of 20.6 m/s at 0815 UTC on 16 September. Minimum pressure was 100.1 kPa. No attempt was made to adjust these wind speeds for standard conditions.

4.0 ESTIMATION OF MAXIMUM NEAR-SURFACE WIND SPEEDS

4.1 HRD Surface Wind Analyses

The primary basis for estimates of maximum wind speeds and corresponding directions at the 10 m level along the path of Hurricane Marilyn is the analysis by NOAA's Hurricane Research Division (HRD) of flight-level data obtained on 15-16 September (Powell and Houston 1997). Typically, the flight-level wind data consist of 10 s means obtained every 30 s along the aircraft line of flight at an altitude of approximately 3 km. For Hurricane Marilyn, the peak 10 s means were adjusted from flight level to the surface (Powell 1980) and were combined with all available *in situ* surface observations using a "nested, scale-controlled objective analysis package" (Powell et al. 1996; Powell and Houston 1996), and the output is a streamline and isotach plot valid for an applicable time period. A typical plot for 0330 UTC on 16 September is shown in Figure 4 when Marilyn was located south of St. Thomas. Data used in this analysis were collected over the period 0029-0330 UTC, and the dotted lines are isotachs of maximum sustained speed (1 minute average) while the solid lines are streamlines. Over the period 13-19 September, HRD conducted 20 real-time surface wind analyses with results similar to those shown in Figure 4. Maximum sustained speeds resulting from the HRD analyses are summarized in Table 3 and are indicated in Figure 5 for selected locations in the U.S. Virgin Islands and in Puerto Rico. Also summarized in Table 3 are the adjusted sustained speeds at selected sites for which reliable surface wind speed measurements were available. Two sets of speeds are included in this second listing; the adjusted sustained speed at 10 m for an over-water exposure, and the adjusted sustained speed at 10 m for the actual wind exposure at the recording site (shown in parentheses). Ideally, the speeds obtained from the HRD analysis and those obtained from the site data for an over-water exposure should be the same.

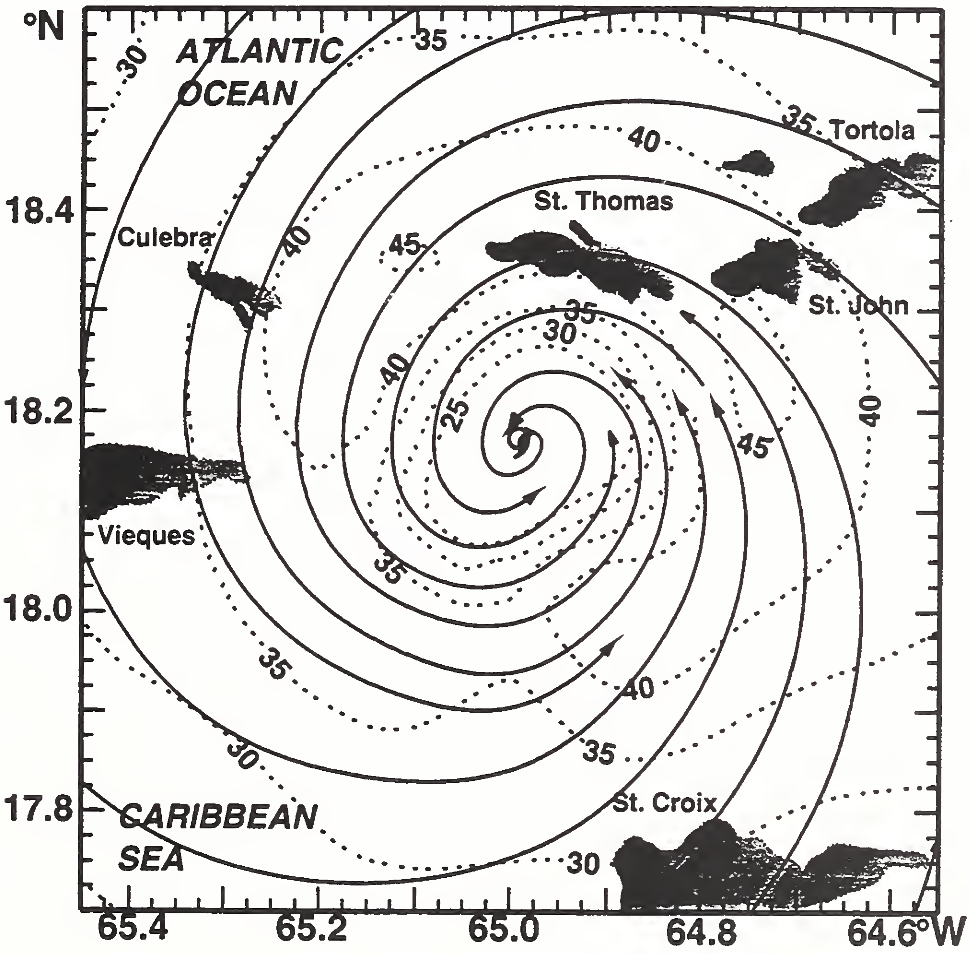

Figure 4. Typical plot of HRD surface wind analysis for Hurricane Marilyn valid at 0330 UTC 16 September 1995. Isotachs (m/s) and streamlines (solid) are shown for maximum 1-minute wind speeds at 10 m over water (Powell and Houston 1997).

Table 3. Estimated Maximum Sustained Speeds at 10 m Height

Station/Location	Minimum Distance To Storm Track (km)	Based on HRD Analysis Over-Water Exposure		Based on Obs. Speeds Over-Water Exposure and (Actual Exposure)	
		Speed (m/s)	Dir. (deg)	Speed (m/s)	Dir. (deg)
U.S. VIRGIN ISLANDS					
ST. CROIX					
Green Cay Marina	8.5	34.3(1)	025	34.4 (34.4)(2)	--
Christiansted	12.5	33.7(1)	020	--	--
Salt River Bay	14.5	33.4(1)	005	--	--
East Jetty (Hess Refinery)	20	32.6	350	41.4 (35.2)	340
		39.4	270	37.5 (36.4)	280
USDA Experiment Sta. (USGS)	22	39.5	285	40.5 (37.4)	330
Hams Bluff	25	39.6	295	--	--
Frederiksted	30	38.4	305	--	--
ST. THOMAS					
West End	8.5	45.0	050	--	--
FAA ASOS	12.5	45.2	075	(51.6)	065
		43.3	180	43.2 (43.2)	180
UVI (USGS)	14	45.1	075	--	--

Table 3 (Continued)

Station/Location	Minimum Distance To Storm Track (km)	Based on HRD Analysis Over-Water Exposure		Based on Obs. Speeds Over-Water Exposure and (Actual Exposure)	
		Speed (m/s)	Dir. (deg)	Speed (m/s)	Dir. (deg)
ST. THOMAS (Continued)					
Dorothea (USGS)	16	44.8(1)	070	--	--
Magens Bay	19	44.5(1)	080	--	--
Mangrove Lagoon	21	46.0	130	--	--
Redhook Point	25	46.1	145	--	--
ST. JOHN					
Lind Point (USGS)	30	45.8	145	--	--
PUERTO RICO					
Camp Garcia, Vieques (USGS)	38	32.0	335	23.9 (19.8)	330
Culebra	17	42.8	235	(56.3 Gust) (3)	
Roosevelt Roads NS	50	25.6(1)	005	21.5 (19.6)	360

NOTES:

(1) Listed value is the maximum onshore wind speed for this site, but not the maximum speed when overland retardation and shielding are neglected.

(2) Values indicated by ( ) are wind speeds corresponding to the actual site exposure.

(3) Insufficient information available for adjustment to standard conditions.

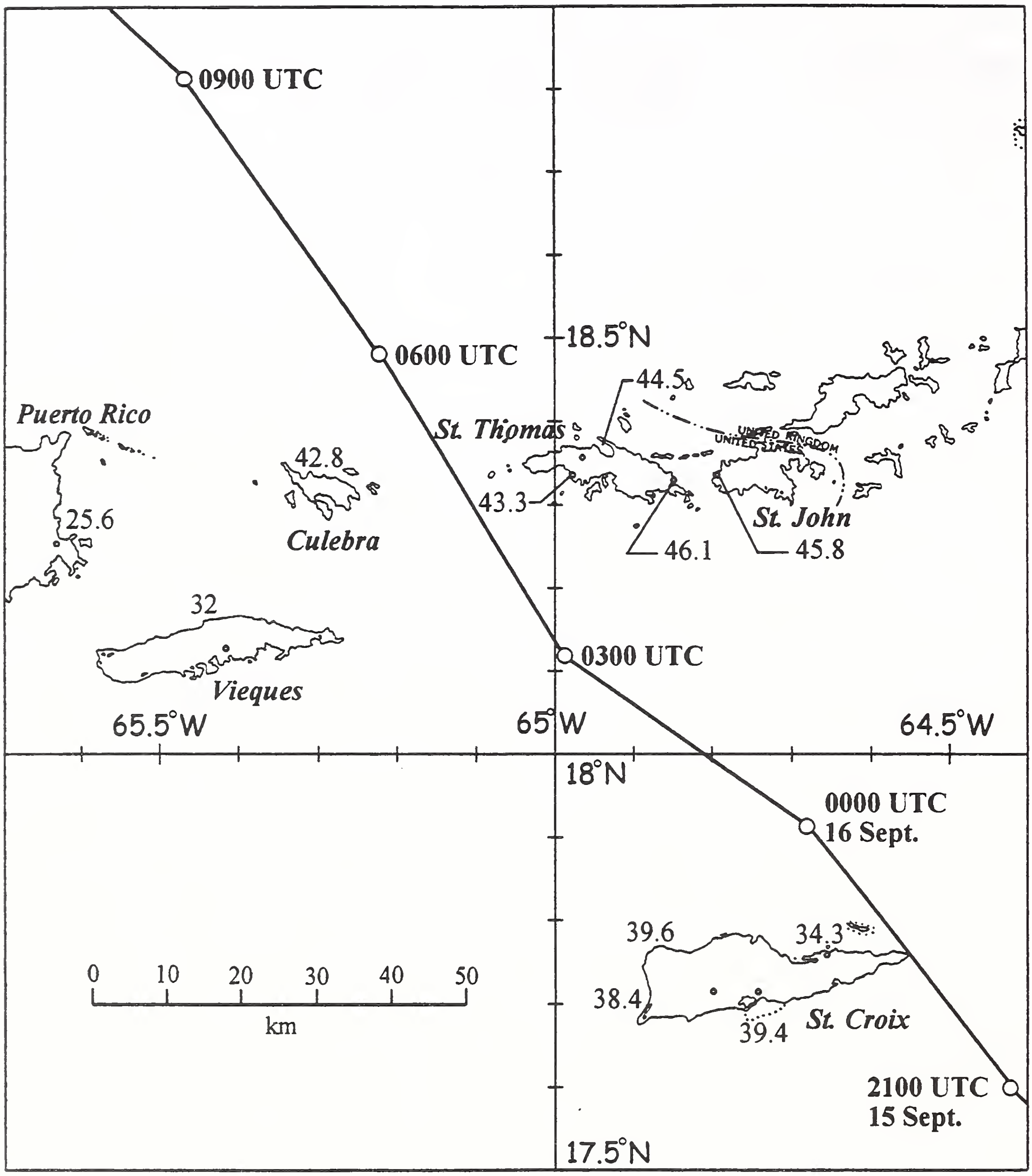

Figure 5. Probable maximum over-water sustained speeds (m/s) in Hurricane Marilyn based on HRD analysis.

4.2 Maximum Sustained Speeds for St. Croix

Maximum sustained speeds for St. Croix are based on the HRD analysis conducted for conditions at approximately 2200 UTC on 15 September. Comparisons of the HRD analysis with adjusted, measured speeds on St. Croix are based on the wind speed records obtained at Green Cay Marina, East Jetty (Hess Oil Refinery), and at the USDA Experiment Station located west of the refinery and directly north of Alexander Hamilton Airport. From Table 3 it can be seen that the HRD analysis indicates maximum speeds for St. Croix ranging from 33.4 m/s to 39.6 m/s. At Green Cay Marina the HRD maximum onshore wind speed of 34/3 m/s is in close agreement with the observed speed, 34.4 m/s when adjusted for anemometer height and averaging time. At East Jetty, the HRD maxima are 32.6 m/s from 350 degrees and 39.4 m/s from 270 degrees. The corresponding measured speeds, adjusted for averaging time and exposure, are 41.4 m/s at 340 degrees and 37.5 m/s at 280 degrees. At the USDA Experiment Station the HRD maximum is 39.5 m/s from 285 degrees, while the adjusted speed based on the actual wind speed record is 40.5 m/s from 330 degrees.

4.3 Maximum Sustained Speeds for St. Thomas and St. John

The maximum sustained speeds listed in Table 3 for selected locations on St. Thomas and St. John are based on the HRD analyses for 0330 and 0438 UTC. Maximum sustained speeds range from 44.5 m/s at Magens Bay on the north coast of St. Thomas to 46.1 m/s at Redhook Point on the east end. These speeds do not account for topographic speed-up effects which are discussed later. Unfortunately, only the wind speed record from the FAA ASOS offers a suitable basis for validation of the HRD analysis for St. Thomas/St. John. The HRD analysis indicates maximum sustained speeds of 45.2 m/s and 43.3 m/s at this site for wind directions of 75 and 180 degrees, corresponding to the leading and trailing eyewalls, respectively. The maximum sustained speed at 10 m over land, based on the actual ASOS record, is 51.6 m/s from 065 degrees. The complexity of the upwind terrain did not permit the reliable estimation of a corresponding over-water speed. As noted earlier in this report, the wind speed for this direction is influenced by blockage effects caused by the main east-west ridge on St. Thomas, and by the terrain roughness over Charlotte Amalie. These influences may be somewhat offsetting, but there is no reliable method other than a wind tunnel model study or a properly validated numerical model to establish the relative amounts. For winds out of the south the ASOS anemometer is responding to a marine boundary layer, and the only adjustments required are for anemometer height and averaging time. This maximum adjusted sustained speed is 43.2 m/s, in good agreement with the HRD value of 43.3 m/s. The true maximum may be slightly higher since system failure occurred at this point. However, both the wind speed record and the barometric pressure record suggest that the last recorded speed was very close to the maximum in the trailing eyewall.

4.4 Maximum Sustained Speeds for Vieques, Culebra and Eastern Puerto Rico

The HRD analysis suggests a maximum over-water sustained speed of 32.0 m/s for central Vieques. This is about 34 percent higher than the value of 23.9 m/s obtained by adjusting the maximum sustained speed observed at Camp Garcia. The most likely reason for this discrepancy is the upwind terrain effects (buildings and ridge) which would require a site visit to evaluate. No attempt was made to compare the HRD analysis with the gust speed observed on Culebra because of insufficient information concerning the anemometer height and wind exposure. However, the reported gust speed of 56.3 m/s for Culebra is only slightly less than the maximum gust speed of 57.7 m/s registered by the FAA ASOS on St. Thomas. Each of these sites should have experienced eye passage.

From the HRD analysis the maximum onshore sustained speed at Roosevelt Roads Naval Station is 25.6 m/s with a corresponding wind direction of 005 degrees. This wind speed is approximately 19 percent higher than the over-water sustained speed of 21.5 m/s based on the measured speed and terrain features for a northerly wind at Roosevelt Roads.

4.5 Topographic Speed-Up Effects

The wind speeds listed in Table 3, even when adjusted for over-land exposure, are not applicable to the upper slopes and crests of significant hills, ridges or escarpments which characterize St. Croix and particularly St. Thomas. The speed-up effect is shown qualitatively by the shaded region in Figure 6. Various procedures are available for estimating speed-up effects due to significant topographic features, and one such procedure (CUBC 1989) has been used to obtain the speed-up factors listed in Table 4. As used in this report, the speed-up factor is the ratio of the actual wind speed at a given height above the crest of a hill or escarpment to the wind speed at that same height above ground in the absence of a hill or escarpment. For example, it can be seen from Table 4 that the wind speed at 5 m above the crest of a 2-dimensional ridge with windward slope of 0.125 and ridge height of 50 m will be about 39 percent greater than the wind speed at a height of 5 m in flat terrain. The speed-up effect increases with increasing hill height and steepness of slope. It reaches a maximum at the crest and decreases with height above ground and distance from the crest.

Because the wind load is proportional to the square of the reference wind speed, it can be seen from Table 4 that speed-up effects can be significant, even for hills and ridges of moderate height and slope. The speed-up effect is only slightly reduced for rougher ground surfaces. For example, the above speed-up factors are based on $z_o = 0.03$ m. For $z_o = 0.1$ m, the factors are reduced by about 2 percent on average.

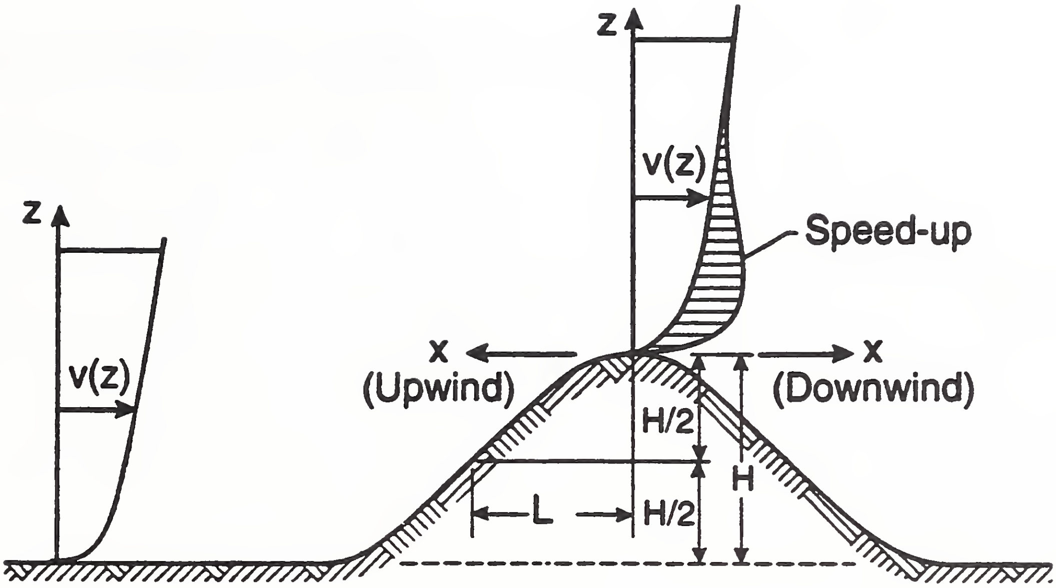

Figure 6. Sketch showing wind speed-up over a 2-dimensional ridge (CUBC 1989).

Table 4. Speed-Up Factors for Wind Directed Normal to a 2-Dimensional Ridge

Height Above Ridge Line (m)	Average Gradient of Upwind Slope		
	0.25	0.125	0.0625
Ridge Height = 20 m			
5	1.59	1.35	1.20
10	1.40	1.29	1.18
20	1.19	1.21	1.15
Ridge Height = 50 m			
5	1.73	1.39	1.20
10	1.64	1.37	1.20
20	1.48	1.32	1.19
Ridge Height = 100 m			
5	1.79	1.41	1.21
10	1.74	1.40	1.21
20	1.64	1.37	1.20

5.0 EXTREME WIND CLIMATE AND WIND SPEEDS IN HURRICANE MARILYN

5.1 Extreme Wind Climate for the U.S. Virgin Islands and Eastern Puerto Rico

Reference wind velocity pressures for various locations in the Caribbean region can be found in the Caribbean Uniform Building Code (CUBC 1989). These pressures correspond to the mean velocity pressure at a height of 10 m above open terrain (z_0 = 0.03 m), averaged over a period of approximately 10 minutes, and their annual extremes are distributed consistent with the Fisher-Tippett Type I distribution. The curve shown in Figure 7 is based on the distribution of extreme velocity pressures for the U.S. Virgin Islands and eastern Puerto Rico as given in the CUBC. In constructing this curve the air density was assumed to be 1.20 kg/m^3, and the ratio of the over-water sustained speed to the over-land 10-minute mean speed at a height of 10 m was taken to be 1.33.

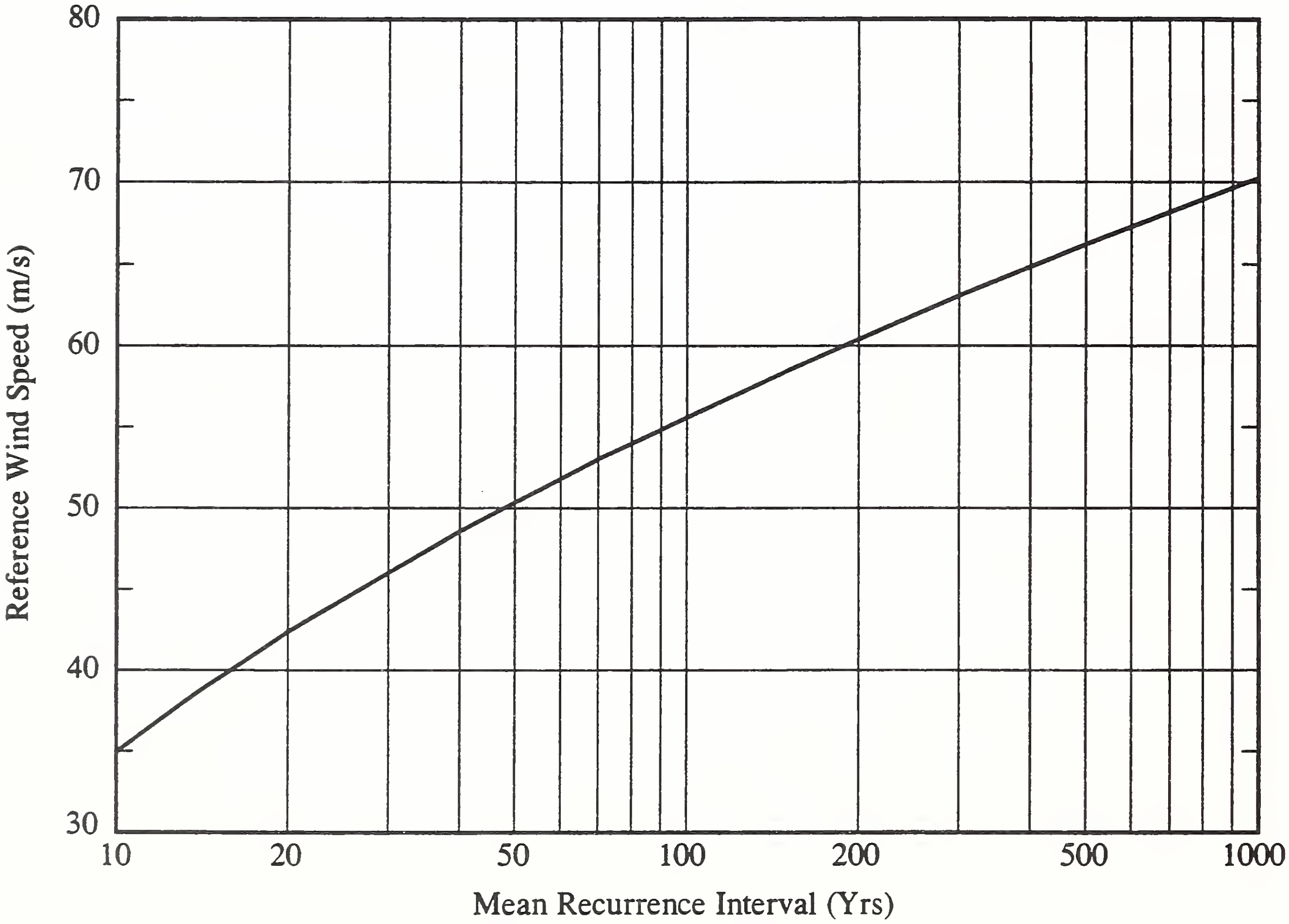

Figure 7. Distribution of extreme wind speeds - U.S. Virgin Islands & Eastern Puerto Rico. (Sustained speed at a height of 10 m over open water)

From Figure 7 it can be seen that the sustained wind speed corresponding to a 50-yr mean recurrence interval (MRI), the wind speed commonly specified for the design of ordinary buildings and other structures, is 50.4 m/s for an over-water exposure. As the annual probability of exceedance is simply the reciprocal of the MRI, there is a 0.02 probability that the maximum over-water sustained speed in any given year will equal or exceed 50.4 m/s. For an over-land exposure (fully-developed boundary layer with $z_o = 0.03$ m), the corresponding sustained speed is (0.88)(50.4) = 44.4 m/s.

5.2 Wind Speeds in Hurricane Marilyn and Associated Mean Recurrence Intervals

In Table 3 are listed the estimated maximum over-water sustained speeds at selected locations along the path of Hurricane Marilyn. Comparing these speeds with the distribution curve plotted in Figure 7, it can be seen that the maximum sustained speed for St. Croix (39.6 m/s at Hams Bluff) corresponds to a mean recurrence interval of about 17 years. For St. Thomas, the estimated maximum over-water sustained speed of 46.1 m/s at Redhook Point corresponds to a mean recurrence interval of about 30 years. Of particular interest in establishing the severity of near-surface wind speeds in Hurricane Marilyn is the FAA ASOS site at Cyril E. King Airport. From Table 3 it is noted that the maximum sustained speed for this site, adjusted to a height of 10 m over land, was 51.6 m/s from 065 degrees. This is slightly higher than the 50-yr over-water sustained speed of 50.4 m/s, but substantially less than what one might expect from topographic speed-up effects as indicated in Table 4. For wind out of the south (trailing eyewall), the sustained speed of 43.2 m/s at the ASOS site corresponds to a mean recurrence interval of about 22 years.

In Puerto Rico to the west of the hurricane storm track the estimated maximum over-water speeds from Table 3 are 42.8 m/s at Culebra, 32.0 m/s near the central part of Vieques, and 25.6 m/s at Roosevelt Roads Naval Station. As noted previously, the adjusted wind speeds at Camp Garcia on Vieques are substantially less than the wind speed obtained from the HRD analysis. Allowing for local terrain roughness, it is likely that the actual sustained speed at the recording site was about 27 m/s. Because it is nearer the storm track and because Hurricane Marilyn continued to strengthen after 0600 UTC on 16 September, wind speeds in northeastern Puerto Rico around Cape San Juan probably were higher than the over-water sustained speed of 25.6 m/s at Roosevelt Roads Naval Station. But even with the high speeds over Culebra, the mean recurrence interval in each case for Puerto Rico is equal to or less than about 20 years. Although Hurricane Marilyn caused considerable damage, it is clear from the wind speed observations and subsequent analyses that Marilyn was less than a 50-yr design event in the U.S. Virgin Islands and in Puerto Rico.

5.3 Wind Speeds Associated With Ultimate Limit States

More relevant to the assessment of structural performance in extreme winds are the wind loads used in load and resistance factor design (LRFD), sometimes referred to as "strength design" or "limit states design." The LRFD format requires that

$$\phi R \geq \gamma L$$

where R is the nominal resistance (strength) of the structure, L is the nominal load effect, and

ϕ and γ are factors that account for the uncertainties associated with resistance and load effect, respectively. Standards such as ASCE 7-95 provide values of γ for various types of loads and load combinations while recommended values of ϕ are provided in materials specifications and standards intended for use with the LRFD format. For main wind force resisting systems, dead load and wind load constitute a critical load combination, and ASCE 7-95 requires that

$$\phi R \geq 0.9D + 1.3W$$

where D and W denote the nominal (code value) dead and wind load, respectively. However, it usually is the case with low-rise buildings that the dead load is a small fraction of the wind load. Accordingly, the dead load is neglected in the following discussion.

Implicit in the load factor of 1.3 is a factor of 0.85 to account for the reduced probability that the maximum wind speed will occur from a wind direction that is most unfavorable to the building response (Ellingwood et al. 1980). Because wind loads are proportional to the square of the wind speed, the ASCE 7-95 factored wind loads correspond to the nominal 50-yr design speed multiplied by the factor $(1.3)^{1/2} = 1.14$. Applying the ASCE 7-95 wind load factor to the CUBC reference wind velocity pressure for the U.S. Virgin Islands, the corresponding wind speed for an over-water exposure would be $(1.14)(50.4) = 57.5$ m/s with a corresponding mean recurrence interval of about 130 years. Because this wind speed is associated with the factored resistance, ϕR, it constitutes a damage threshold, the wind speed at which the weakest structures should begin to fail, assuming they are properly designed and constructed.

5.4 The Need for Improved Building Practices in the U.S. Virgin Islands

An assessment of wind speeds and structural damage following the passage of Hurricane Hugo through the U.S. Virgin Islands in 1989 prompted a comparison of the wind load requirements of the local building code with those of the CUBC (Marshall 1990). In this comparison the nominal design wind loads required by the Virgin Islands building code (1984) were found to be at most some 75 percent of the CUBC-specified loads. Consequently, the over-water sustained speed associated with the factored wind loads of the Virgin Islands building code would be approximately $(0.75)^{1/2}(57.5) = 50$ m/s. In view of the estimated maximum wind speeds listed in Table 3, it is readily apparent that much of the damage caused by Hurricane Marilyn can be attributed to substandard construction rather than to excessively high winds.

An obvious improvement to the Virgin Islands building code would be the adoption of the CUBC wind load provisions which are consistent with a sustained speed of 44.4 m/s at a height of 10 m over flat, open country. Alternatively, a 50.4 m/s sustained speed at 10 m above open water could be specified with appropriate reduction factors for inland exposures. Whatever the approach selected, it is essential that topographic speed-up effects be included in any future revision of the building code. As can be seen from Table 4, these effects are significant, particularly in the case of low-rise buildings. Implementation could be accomplished either through a simple computational approach or through microzoning of the basic wind speeds.

If an LRFD format is included in any future code revision, some care should be exercised in specifying the wind load factor γ. A value of 1.3 is specified by ASCE 7-95, and this same value has been used in this report to derive wind speeds associated with ultimate strength. While this value of γ has been shown to be adequate for most of the continental U.S., recent work by Whalen (1996) indicates that higher values are required along the hurricane-prone Atlantic and Gulf Coast to provide consistent levels of structural reliability.

Finally, there are the issues of building practices and code enforcement in the U.S. Virgin Islands. As noted earlier, it is the intent of this report to address the probable maximum wind speeds in Hurricane Marilyn rather than the specifics of wind damage which ultimately lead to workmanship, quality of materials and code enforcement. Nevertheless, there is sufficient evidence to show that much of what was built prior to Hurricane Marilyn was deficient, even in terms of the inadequate wind load provisions of the Virgin Islands building code. Specifically, the over-water sustained speed corresponding to the factored wind loads is 50 m/s as shown previously. Assuming the local building stock was designed and constructed in strict compliance with the building code, this is the wind speed at which the weakest buildings in that stock should begin to fail. However, from Table 3 it can be seen that nowhere in the U.S. Virgin Islands did the actual over-water sustained speeds reach this level. Therefore, improved construction practices and code enforcement must be a part of any effort to mitigate the wind hazard in the U.S. Virgin Islands. Wind hazard mitigation is an evolutionary process, and some encouraging signs have emerged in the aftermath of Hurricane Marilyn. Notable is the reduced number of outrageous claims of high wind speeds that followed Hurricane Hugo. After that event, numerous claims of gust speeds in excess of 95 m/s appeared in the media while the physical evidence did not support gust speeds in excess of 70 m/s (Marshall 1990).

6.0 MAJOR FINDINGS AND RECOMMENDATIONS

6.1 General

This report has provided a summary of wind speed measurements obtained during the passage of Hurricane Marilyn through the U.S. Virgin Islands on 15-16 September, 1995. As usually happens in extreme natural events such as hurricanes, the number of reliable, verifiable wind speed measurements is quite limited, and those measurements that are available usually require some adjustments/corrections before they can be compared with one another. Sources of data and procedures for adjusting these data have been described. The resulting adjusted speeds are compared with the extreme values for the region, namely the 50-yr speeds recommended for the design of ordinary buildings and other structures. Also, the likely maximum wind speeds in Hurricane Marilyn are compared with the design speeds implied by the wind load provisions of the local building code which were in effect over the decade prior to Hurricane Marilyn.

6.2 Major Findings

Major findings in this study of wind speeds in Hurricane Marilyn can be summarized as follows:

1. The maximum over-water sustained speeds in Hurricane Marilyn were approximately 40 m/s at St. Croix, 46 m/s at St. Thomas and 26 m/s along the east coast of Puerto Rico.
2. According to the Caribbean Uniform Building Code, the design wind speed (50-yr mean recurrence interval or 0.02 annual probability of being equalled or exceeded) for this region of the Caribbean corresponds to a sustained wind speed of 50.4 m/s at 10 m over water.
3. The probable maximum over-water sustained speed of 46.1 m/s at St. Thomas corresponds to a mean recurrence interval of approximately 30 years.
4. Based on an LRFD format and a wind load factor of 1.3, structures designed in accordance with the Caribbean Uniform Building Code should not have exhibited distress at wind speeds less than about 57.5 m/s.
5. Even if one assumes that the wind load provisions of the Virgin Islands building code in effect at the time of Hurricane Marilyn were adequate (which they were not), minimal damage would have been expected at wind speeds equal to or less than about 50 m/s.
6. Hills, ridges and escarpments can have a pronounced effect on the wind speed near the crest of these topographic features. Increases of 50 percent are not uncommon.
7. Given the speeds below which wind damage should have been minimal, the actual wind speeds, and the extensive damage caused by Hurricane Marilyn, it can be concluded that poor building practices and inadequate code enforcement were in large part responsible for the losses experienced.
8. Hurricane Marilyn must be viewed as a continuing learning experience. Even though the damage to St. Thomas appeared to be far greater in Marilyn than in Hurricane Hugo in 1989, there were far fewer outrageous claims of high wind speeds following Marilyn.

6.3 Recommendations

Based on observations made in the affected area immediately following Hurricane Marilyn, and in view of the findings summarized above, the following recommendations are offered:

1. The Virgin Islands building code needs to be revised to reflect the 50-yr (0.02 annual probability) sustained wind speed of 50.4 m/s at 10 m over water with appropriate reduction factors for inland exposures. Alternatively, the sustained wind speed at 10 m over flat, open country should be 44.4 m/s.

2. Because of the hilly terrain, any revision of the Virgin Islands building code should provide for speed-up effects over topographic features such as hills, ridges and escarpments. This may be accomplished either by simple computation or by microzoning.

3. As was clearly demonstrated by Hurricane Marilyn, construction practices and code enforcement in the U.S. Virgin Islands are inadequate and must be improved.

7.0 REFERENCES

American Society of Civil Engineers (1995). *ASCE Standard 7-95, Minimum Design Loads for Buildings and Other Structures.* ASCE, New York, NY, 214 pp.

Caribbean Uniform Building Code (1989). *Part 2 - Structural Design Requirements.* Caribbean Community Secretariat, Georgetown, Guyana.

Ellingwood, B., Galambos, T.V., MacGregor, J.G. and Cornell, C.A. (1980). "Development of a Probability Based Load Criterion for American National Standard A58." NBS Special Publication 577, National Bureau of Standards, Washington, DC, pp 115.

ESDU (1995). *Data Item No. 92032, Computer Program for Wind Speeds and Turbulence Properties: flat or hilly sites in terrain with roughness changes.* ESDU International plc, London, 29 pp.

Marshall, R.D. (1990). "Lessons Learned by a Wind Engineer." *Proceedings, Hurricane Hugo One Year Later,"* ASCE, Charleston, SC, September 13-15, pp 160-169.

Powell, M.D. (1980). "Evaluations of Diagnostic Marine Boundary Layer Models Applied to Hurricanes." *Monthly Weather Review,* 108, pp 757-766.

Powell, M.D. and Houston, S.H. (1996). "Hurricane Andrew's Landfall in South Florida. Part II: Surface Wind Fields and Potential Real-Time Applications." *Weather and Forecasting,* Vol. 11, No. 3, American Meteorological Society, September, pp 329-349.

Powell, M.D. and Houston, S.H. (1997). "Surface Wind Fields of 1995 Hurricanes Erin, Opal, Luis, Marilyn, and Roxanne at Landfall." Accepted for publication, *Monthly Weather Review.*

Powell, M.D., Houston, S.H. and 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, pp 304-328.

Rappaport, E.N. (1995). "Preliminary Report - Hurricane Marilyn, 12-22 September 1995." National Hurricane Center, Miami, FL, November 6, 15 pp.

Saffir, H. and Simpson, R. (1974). "The Hurricane Disaster Potential Scale." *Weatherwise,* August, pp 169-170.

Simiu, E. and Scanlan, R.H. (1996). *Wind Effects on Structures - Fundamentals and Applications to Design, Third Edition.* John Wiley & Sons, Inc., New York, NY, 688 p.

Department of Planning and Natural Resources (1984). *Virgin Islands Zoning, Building and Housing Laws and Regulations.* Virgin Islands Government, St. Thomas, VI.

Wernly, D. (1996). "Hurricane Marilyn September 15-16, 1995." Natural Disaster Survey Report, National Weather Service, NOAA, Silver Spring, MD, pp 38.

Whalen, T.M. (1996). "Probabilistic Estimates of Design Load Factors for Wind-Sensitive Structures Using the 'Peaks Over Threshold' Approach." NIST Technical Note 1418, National Institute of Standards and Technology, 27 pp.

ACKNOWLEDGMENTS

Many individuals contributed to this field study and report, particularly the critical wind speed records referenced herein. The authors were part of a team which visited the affected area within a week of Hurricane Marilyn. Other members of the team included Dr. Dale C. Perry (Texas A&M University), Mr. Chris Austin (Risk Management Solutions, Inc.), and Mr. Edward Sutt, Jr. (Clemson University). Mr. Luther K. Edwards and Mr. Paul Tupper (Hess Oil Virgin Islands Corp.) were instrumental in supplying weather data for St. Croix. Mr. Israel Matos and Mr. Raphael Mojica (National Weather Service Forecast Office, San Juan, PR) provided preliminary storm data and many helpful leads for follow-up data. Mr. Pedro Diaz (Water Resources Division, USGS, San Juan, PR) provided tabulated weather data for the USGS stations affected by Marilyn in the U.S Virgin Islands and Puerto Rico. Dr. Long T. Phan of the Structures Division, NIST, reviewed the manuscript and his comments and suggestions are appreciated. The authors wish to extend special thanks to Dr. Mark D. Powell and Mr. Sam Houston of the Hurricane Research Division (NOAA/AOML) for their real-time data analyses, helpful comments, and encouragement in the preparation of this report.

APPENDIX A

Compilation of Wind Speed and Pressure Records

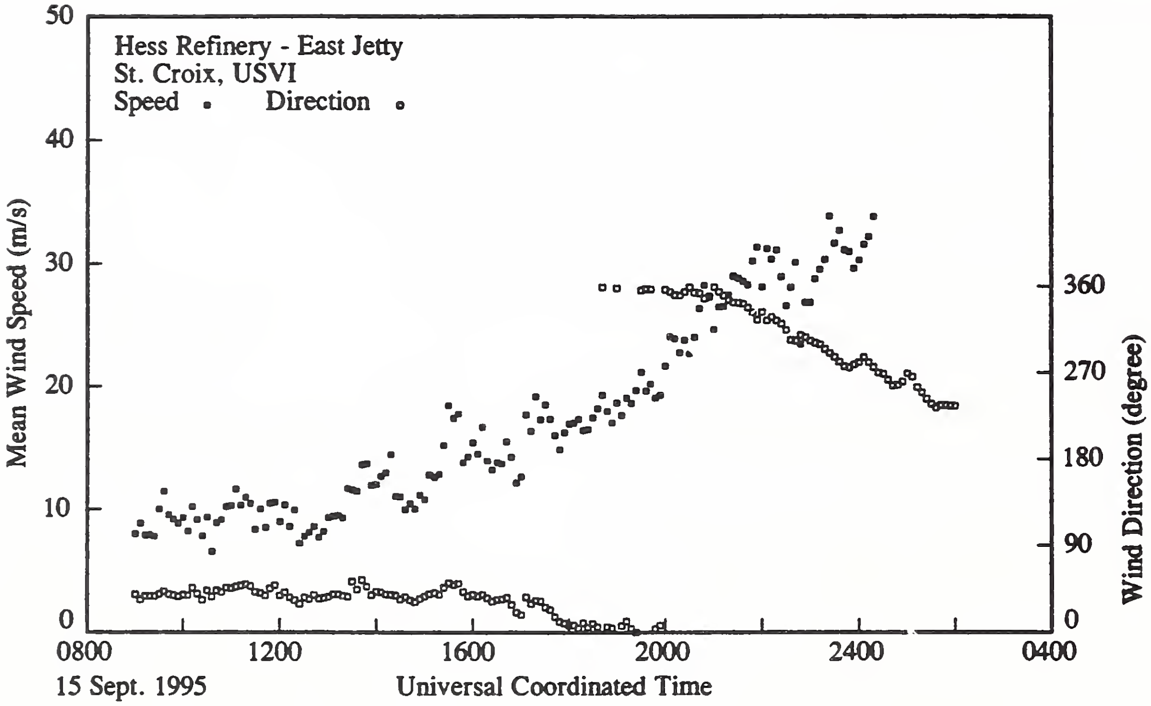

Figure A-1. Record of mean wind speed and direction, East Jetty, Hess Refinery, St. Croix.

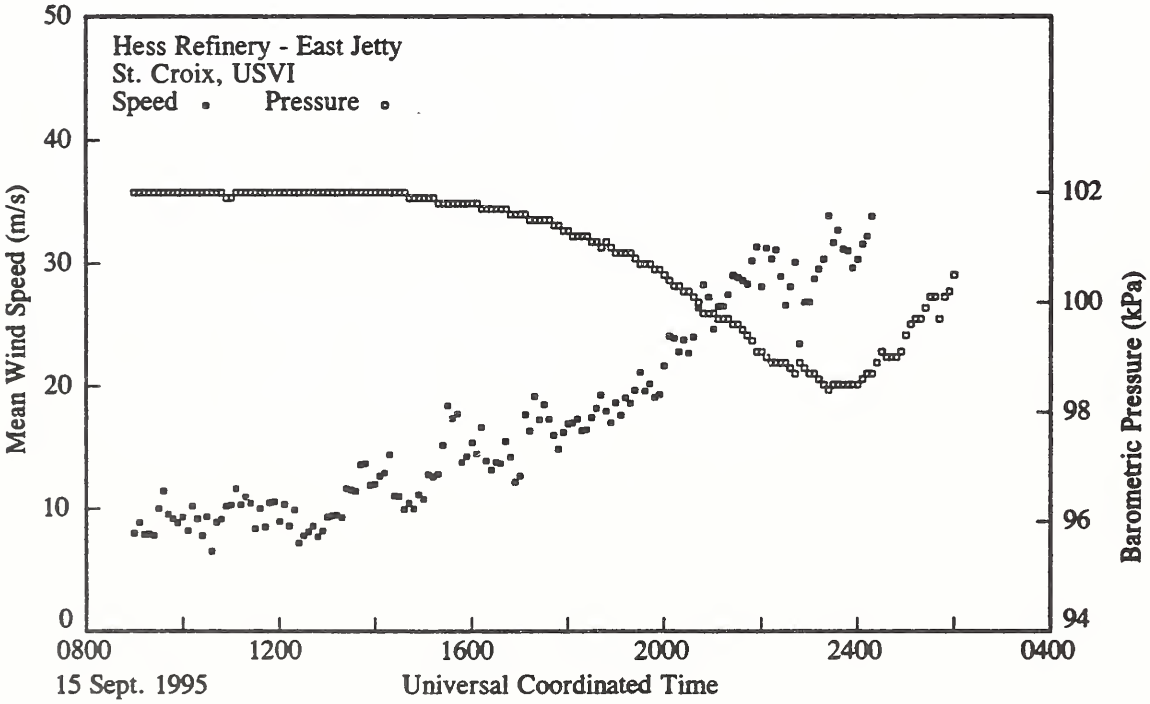

Figure A-2. Record of mean wind speed and barometric pressure, East Jetty, Hess Refinery, St. Croix.

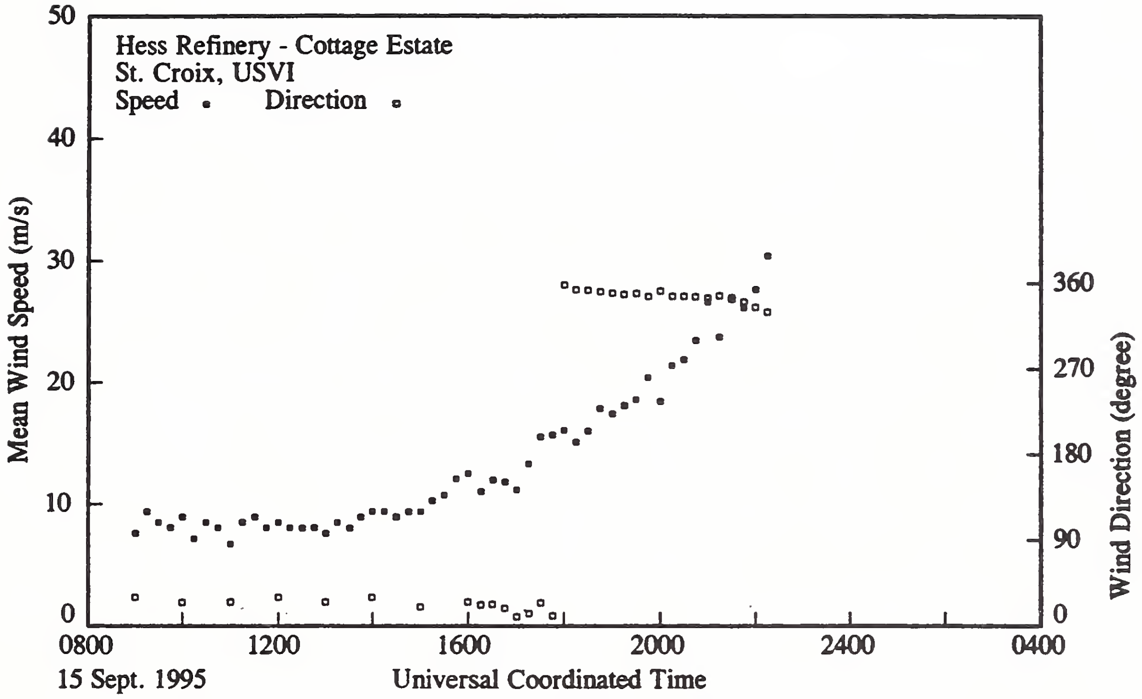

Figure A-3. Record of mean wind speed and direction, Cottage Estate, Hess Refinery, St. Croix.

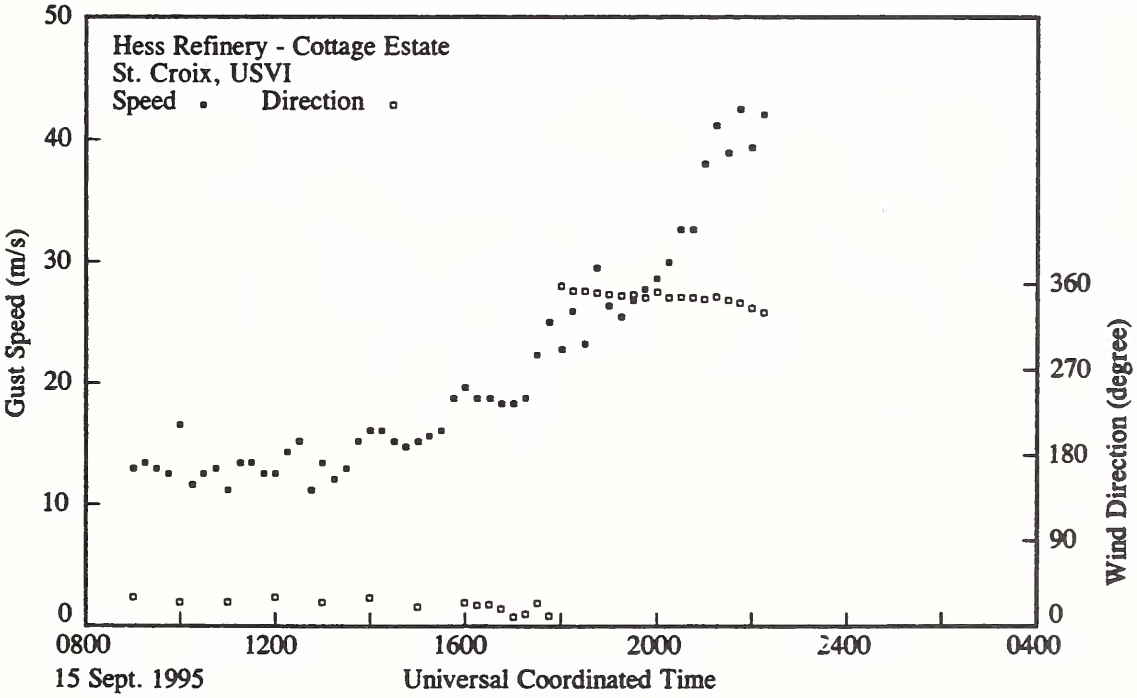

Figure A-4. Record of gust speed and direction, Cottage Estate, Hess Refinery, St. Croix.

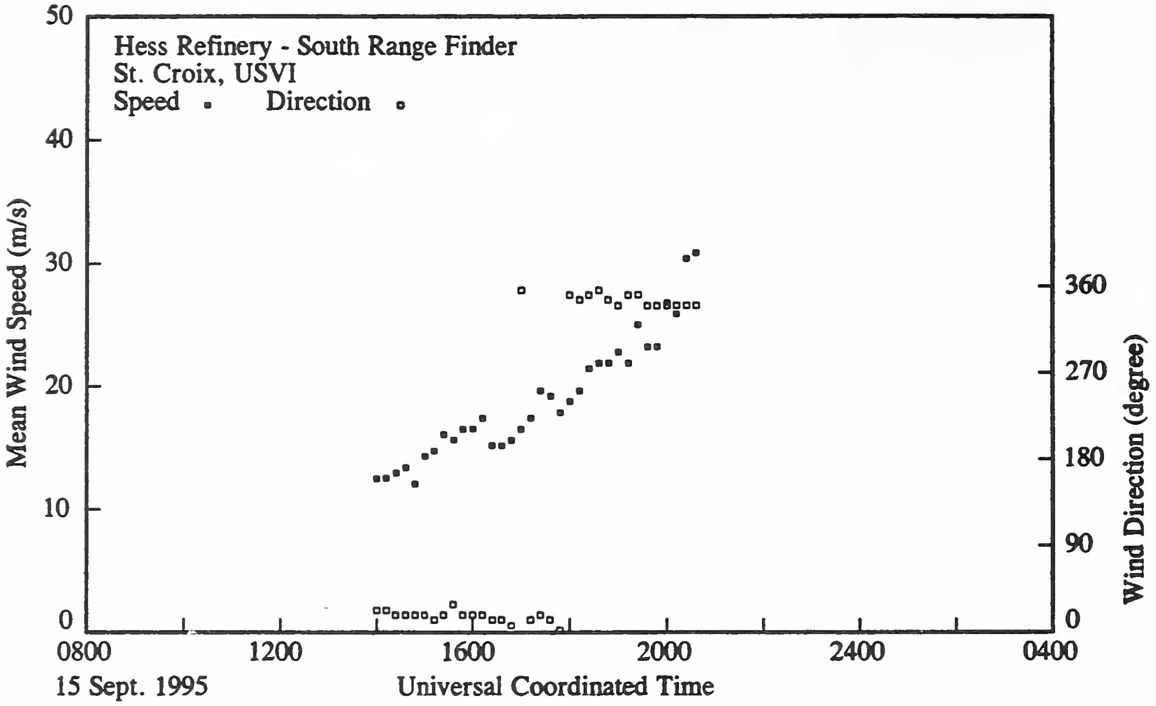

Figure A-5. Record of mean wind speed and direction, South Range Finder, Hess Refinery, St. Croix.

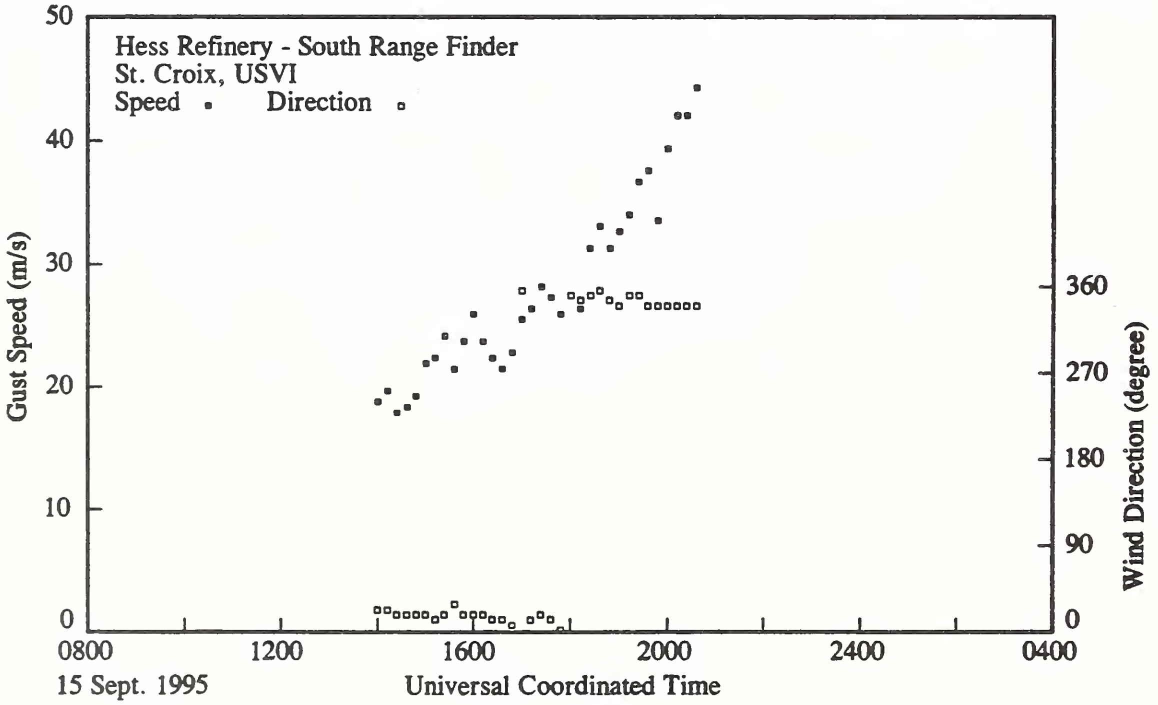

Figure A-6. Record of gust speed and direction, South Range Finder, Hess Refinery, St. Croix.

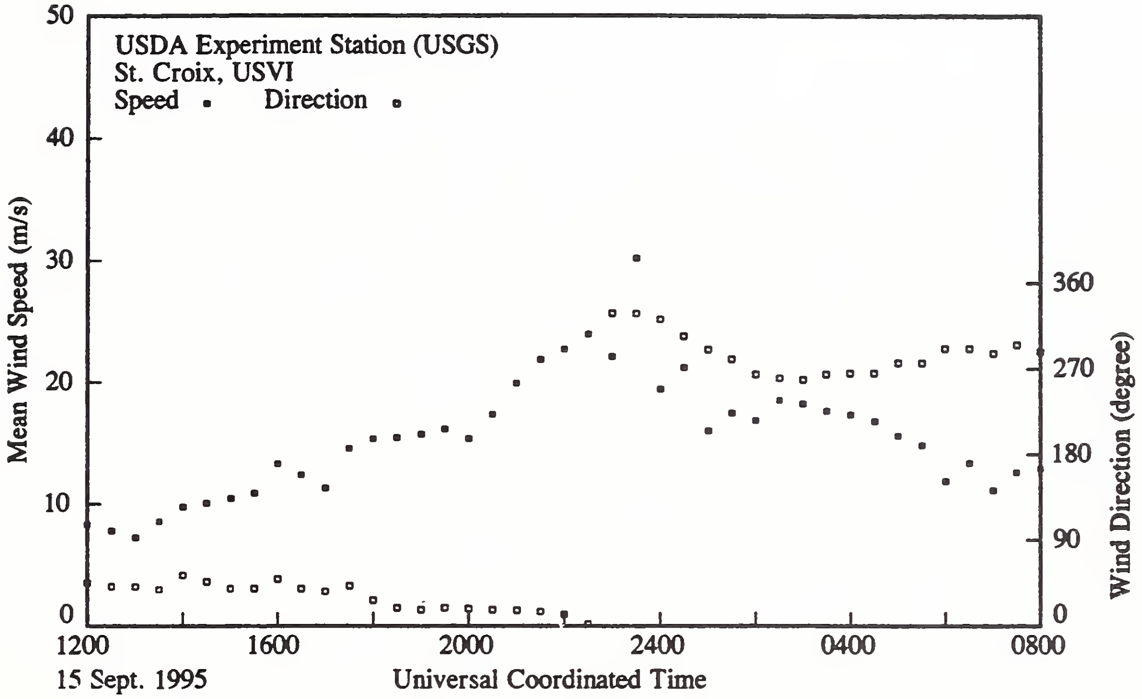

Figure A-7. Record of mean wind speed and direction, USDA Experiment Station (USGS), St. Croix.

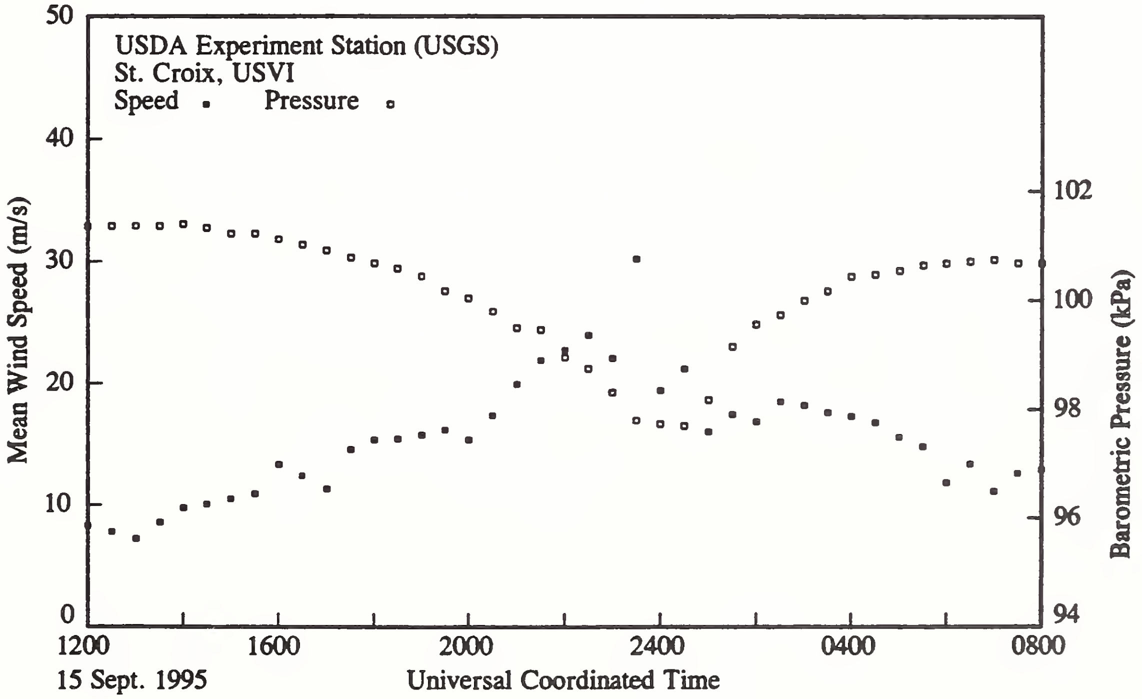

Figure A-8. Record of mean wind speed and barometric pressure, USDA Experiment Station (USGS), St. Croix.

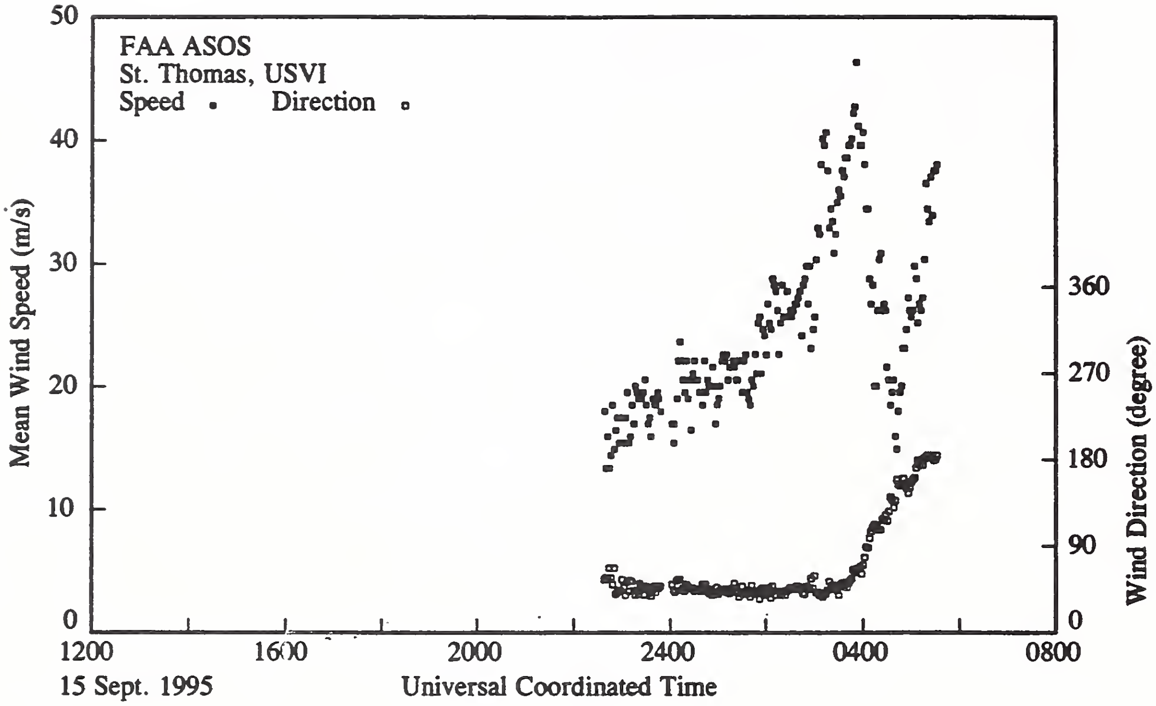

Figure A-9. Record of mean wind speed and direction, FAA ASOS, Cyril E. King Airport, St. Thomas.

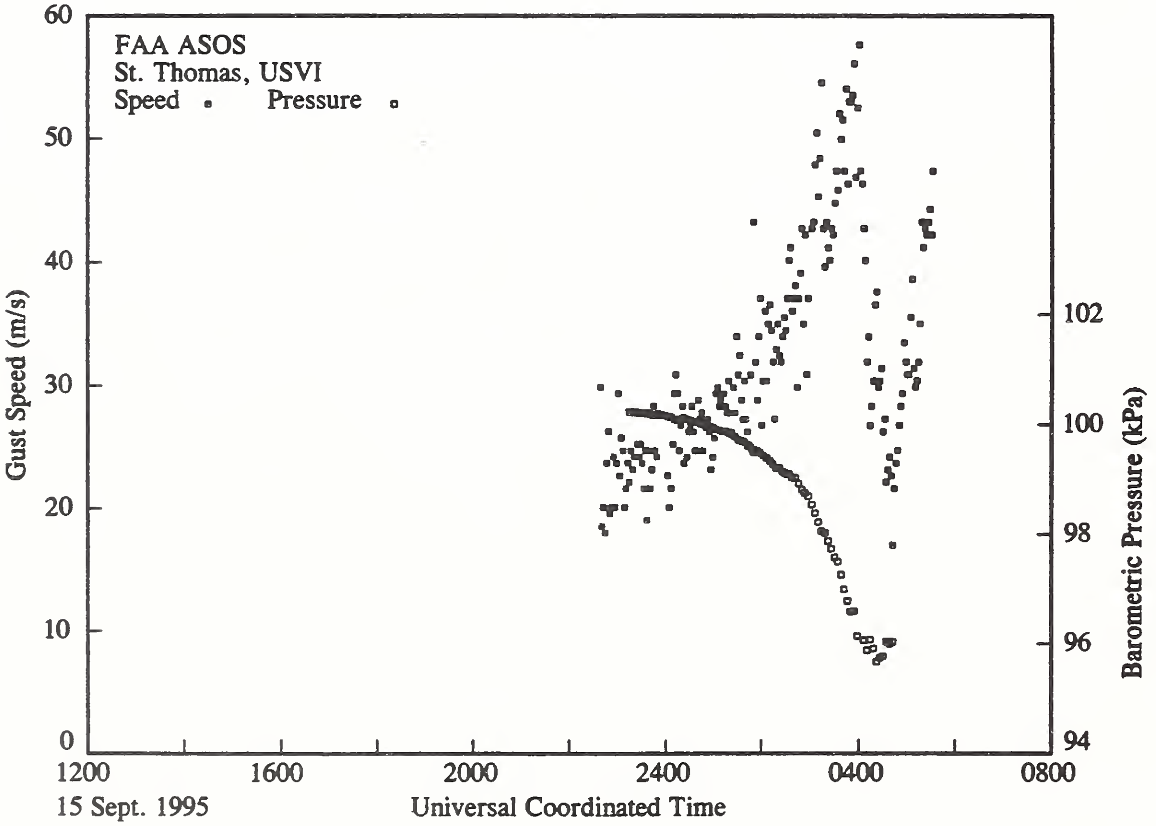

Figure A-10. Record of gust speed and barometric pressure, FAA ASOS, Cyril E. King Airport, St. Thomas.

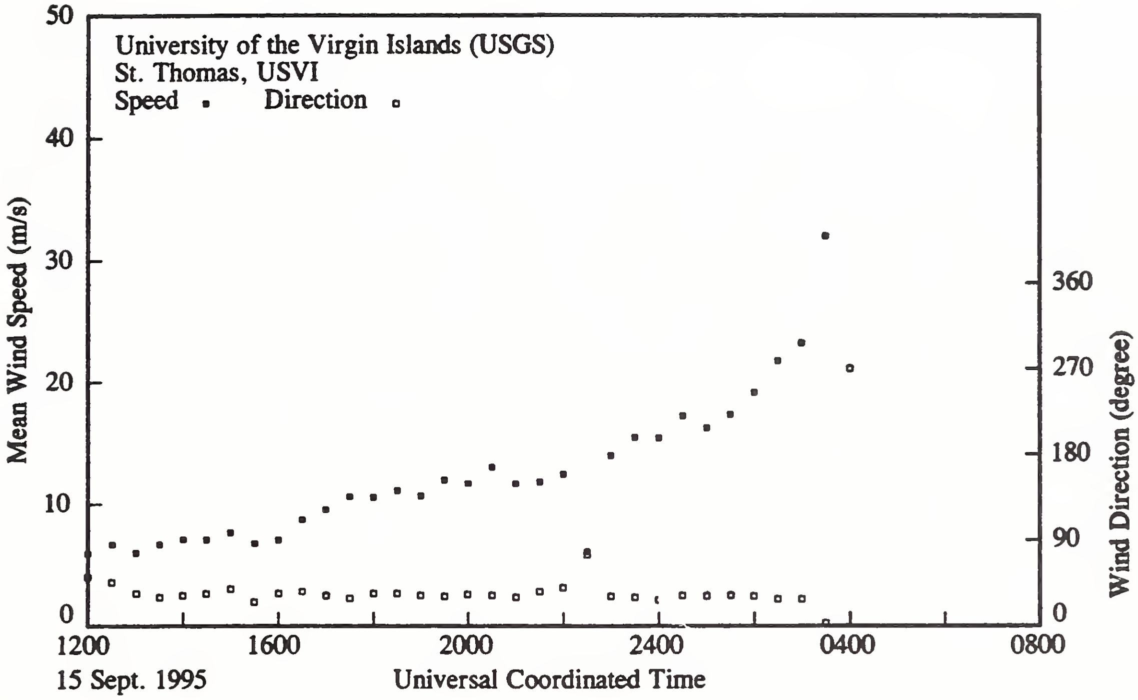

Figure A-11. Record of mean wind speed and direction, UVI (USGS), St. Thomas.

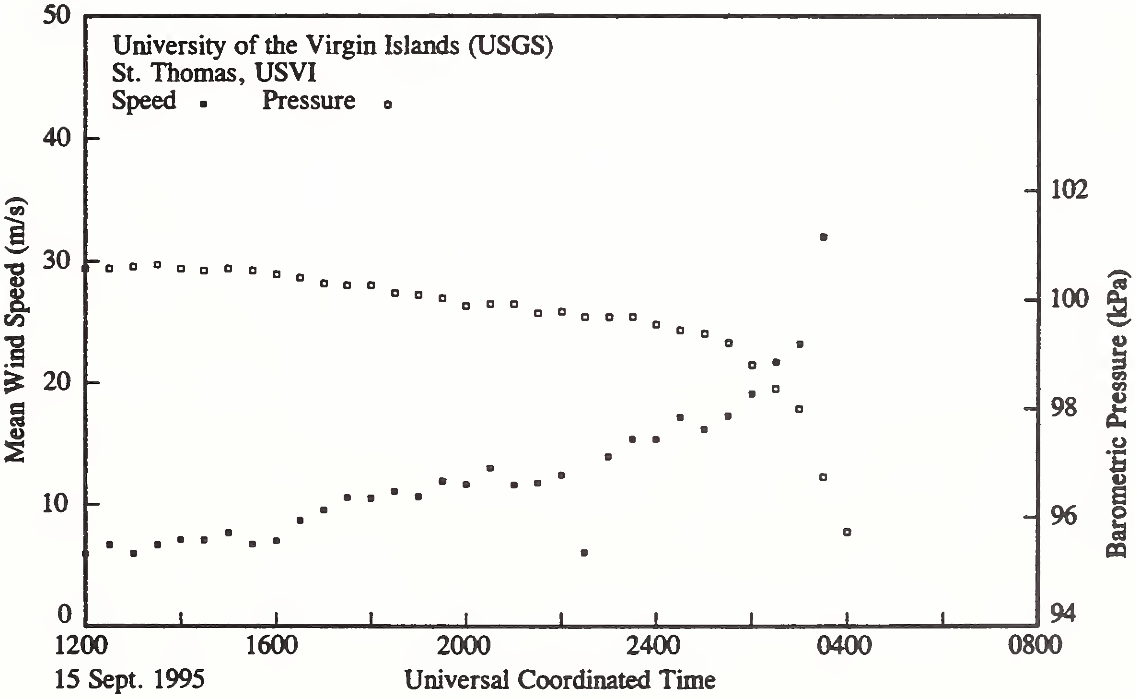

Figure A-12. Record of mean wind speed and barometric pressure, UVI (USGS), St. Thomas.

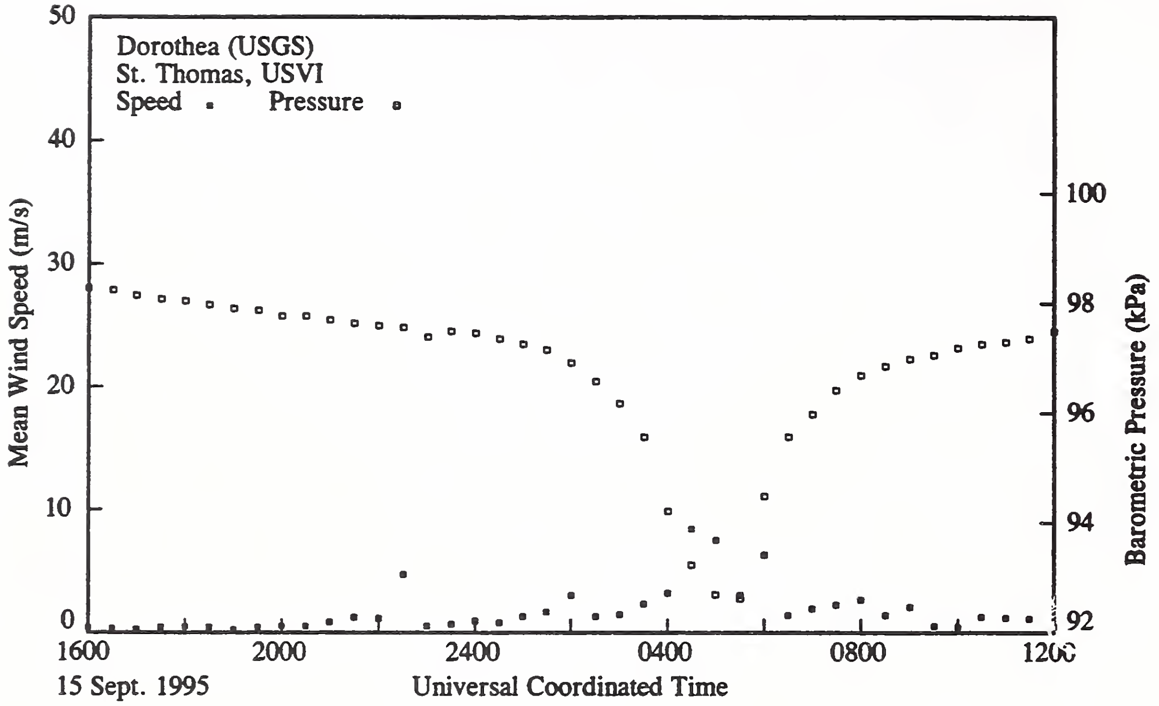

Figure A-13. Record of mean wind speed and barometric pressure, Dorothea (USGS), St. Thomas.

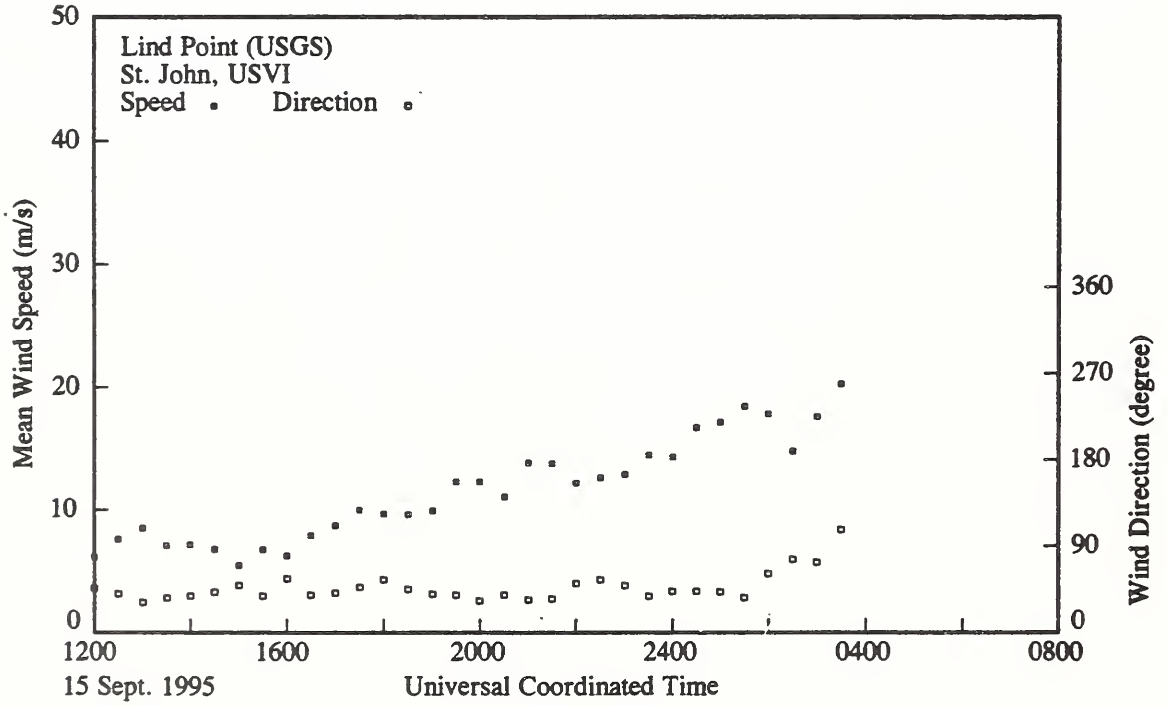

Figure A-14. Record of mean wind speed and direction, Lind Point (USGS), St. John.

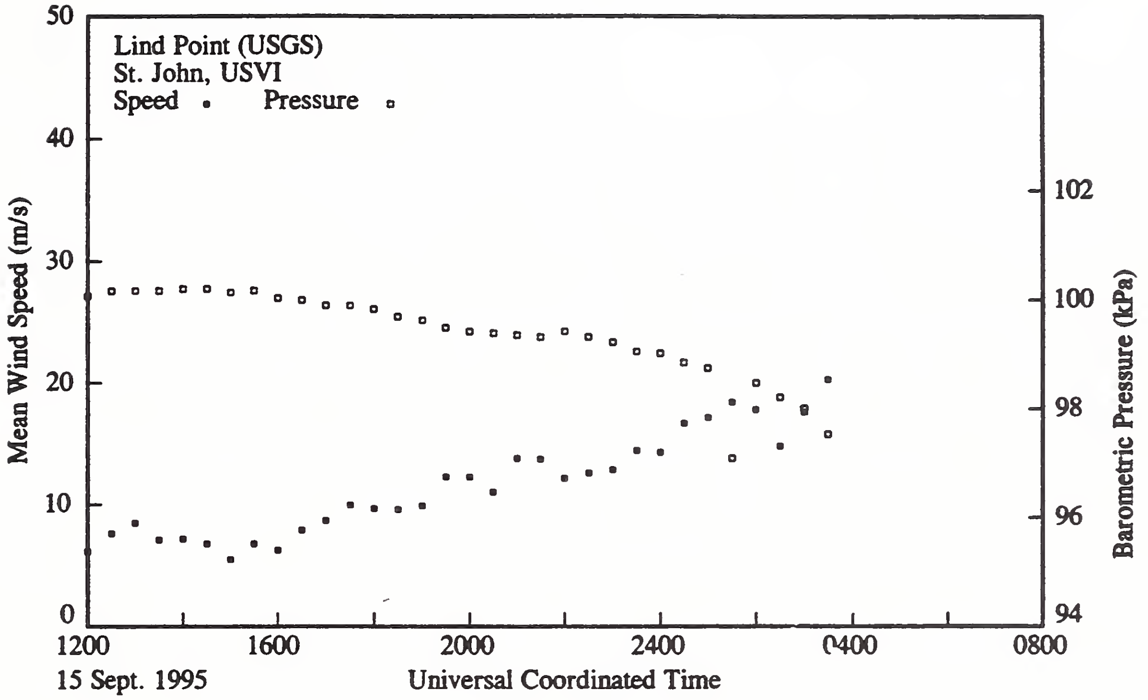

Figure A-15. Record of mean wind speed and barometric pressure, Lind Point (USGS), St. John.

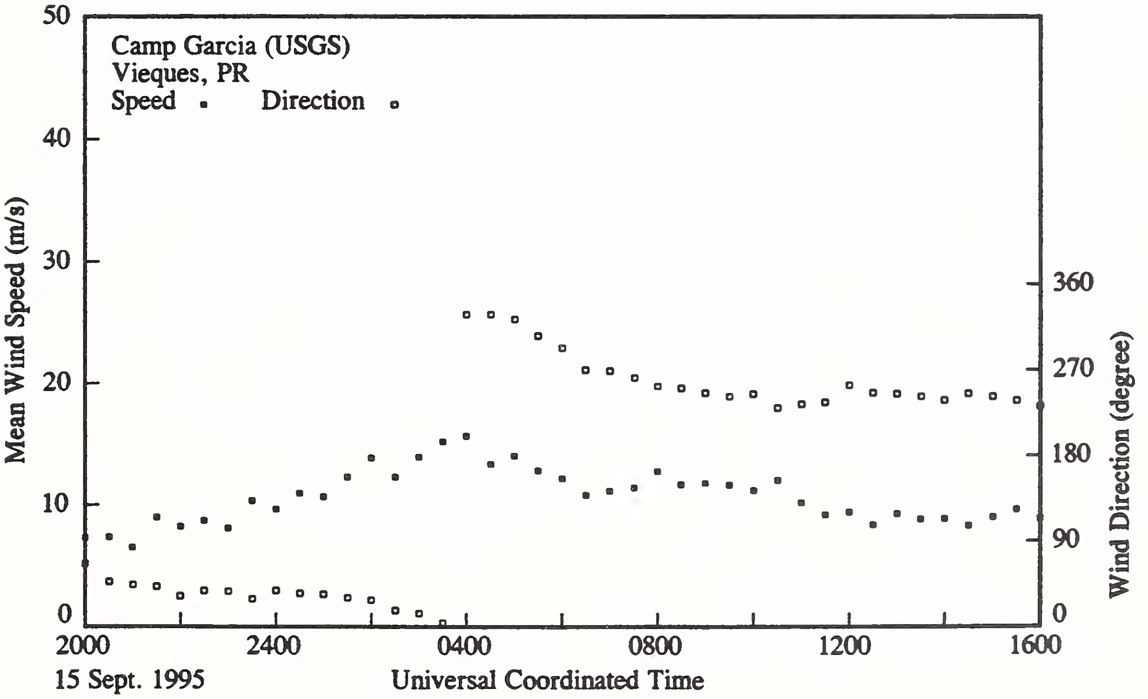

Figure A-16. Record of mean wind speed and direction, Camp Garcia (USGS), Vieques, Puerto Rico.

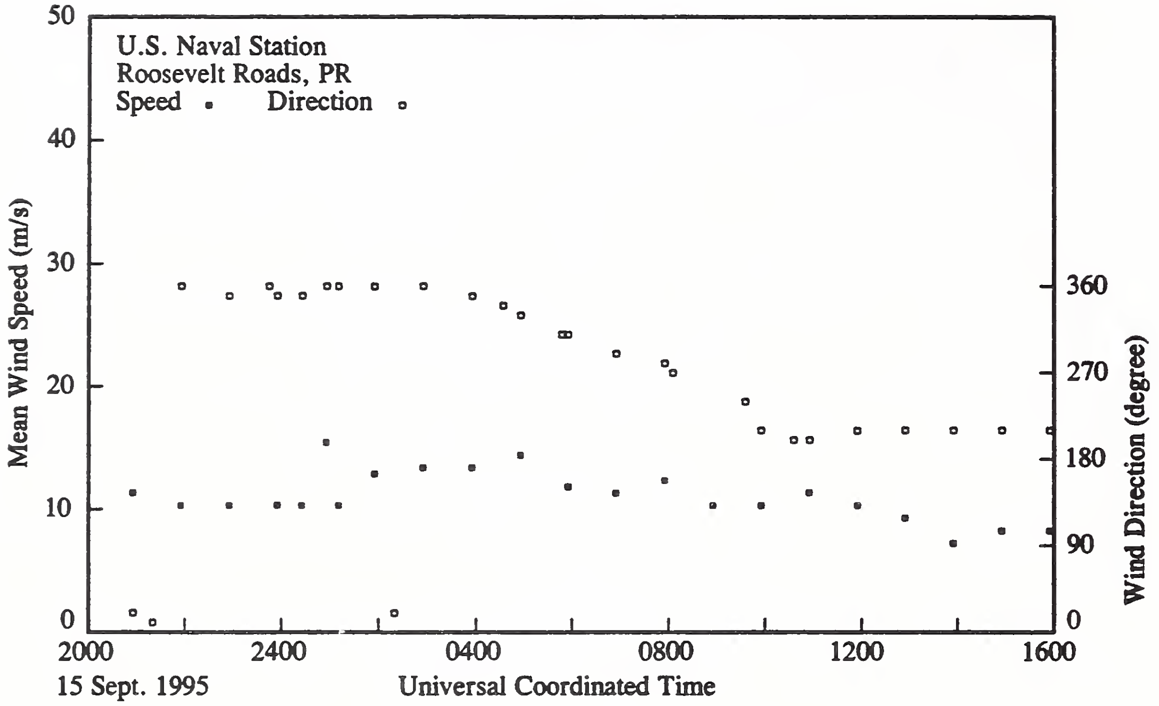

Figure A-17. Record of sustained speed and direction, Roosevelt Roads Naval Station, Puerto Rico.

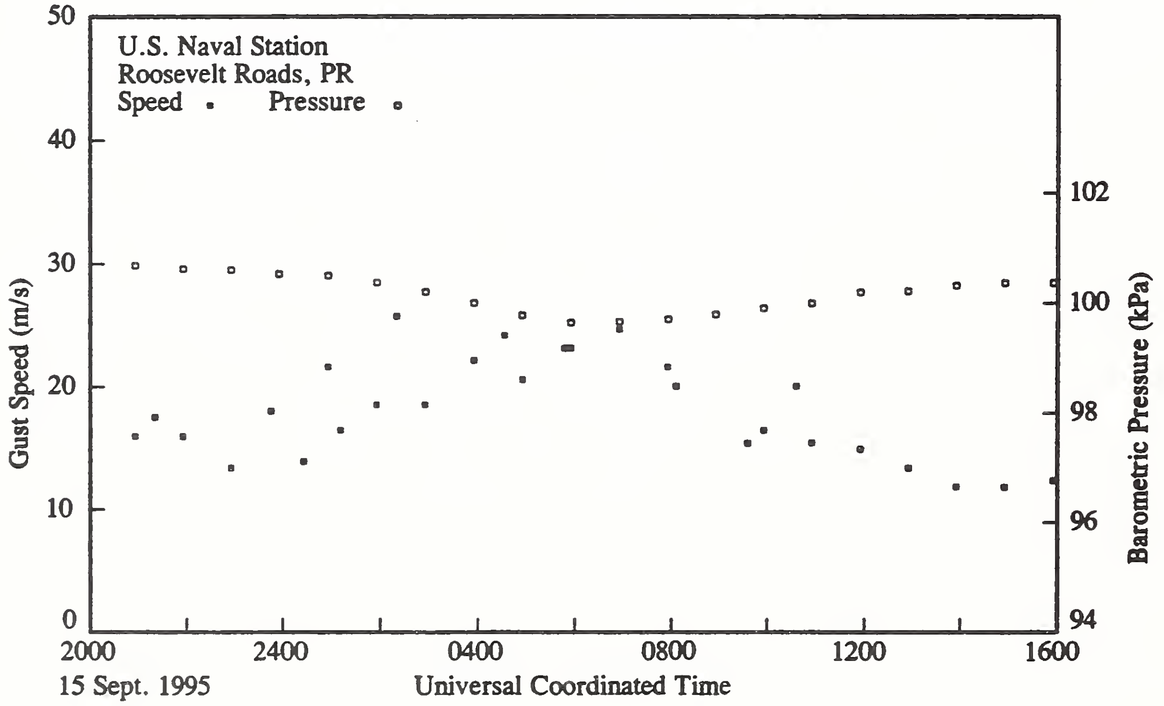

Figure A-18. Record of gust speed and barometric pressure, Roosevelt Roads Naval Station, Puerto Rico.

APPENDIX B

Station Descriptions and Adjustments to Recorded Wind Speeds

U.S. VIRGIN ISLANDS

ST. CROIX

Hess Oil Refinery

East Jetty

Station Coordinates: 17.691 N
64.741 W

Equipment Problems: The last 6-minute mean speed was logged at 0018 UTC on 16 September. The wind direction vane and the barometer continued to function throughout the storm.

Upwind Terrain: The direction of strongest winds at this site shifted counterclockwise from 360 to 270 degrees with the maximum 6-minute means occurring at 290 and 275 degrees. The refinery is located northwest of the site, and the overland distance to the north coast of St. Croix is 10 to 12 km. To the west, the first 8 km of exposure include Limestone Bay, tidal flats and Alexander Hamilton Airport, followed by approximately 7 km of flat, open land with sparse low brush and tidal flats.

Wind Speed Adjustments: Two wind directions were considered when adjusting observed speeds to standard conditions. The first direction of 340 degrees corresponds to events at about 2200 UTC on 15 September when peak gusts were registered by the anemometers at Cottage Estate and at South Range Finder. A constant value of $z_0 = 0.1$ m was assumed for a distance of 11 km to the north coast and $z_0 = 0.005$ m for over-water exposure beyond the coast. A sustained speed of 41.4 m/s at 10 m over water corresponds to a 6-minute mean speed of 31.3 m/s measured at East Jetty at 2154 UTC. The corresponding sustained speed at East Jetty is 35.2 m/s.

The second wind direction considered was 280 degrees which corresponds to events at East Jetty at about 0000 UTC when the 6-minute mean speed was 32.4 m/s. For this wind direction a value of $z_0 = 0.01$ m was assumed for the first 8 km upwind of the site, followed by a value of $z_0 = 0.03$ m for an additional 7 km to the ocean line near Frederiksted. The corresponding sustained speed at 10 m over water is 37.5 m/s, and the sustained speed at the site is 36.4 m/s.

Cottage Estate

Station Coordinates: 17.720 N
64.756 W

Equipment Problems: Both the anemometer and direction vane ceased data transmission at 2215 UTC on 15 September.

Upwind Terrain: This site is located in hilly terrain on the northern perimeter of the refinery, approximately 3.7 km north-northwest of the East Jetty site.

Wind Speed Adjustments: Because of the shorter record and more complex terrain at Cottage Estate, this site was not used to estimate standardized wind speeds. However, the availability of gust data makes this site valuable for future, more detailed analyses.

South Range Finder

Station Coordinates: 17.704 N
64.748 W

Equipment Problems: Both the anemometer and direction vane ceased data transmission at 2036 UTC on 15 September.

Upwind Terrain: This site is approximately 1.5 km northwest of East Jetty and is situated on the south edge of the refinery near the dry cargo dock.

Wind Speed Adjustments: As with the Cottage Estate site, South Range Finder was not used to estimate standardized wind speeds because of its relatively short record and its proximity to major structures in the refinery.

Firehouse

Station Coordinates: 17.717 N
64.761 W

Equipment Problems: No problems reported, but no permanent record of wind speed was obtained.

Upwind Terrain: The anemometer mast is mounted on the southwest corner of the fire station which occupies a single-story metal building located on the north edge of the refinery. Anemometer height above local ground level is 7.6 m. This site is approximately 600 m west-southwest of the Cottage Estate site.

Wind Speed Adjustments: This site is included here since the reported gust speed of 44.7 m/s is the highest gust registered at the Hess Oil Refinery (and on St. Croix) during the passage of Hurricane Marilyn.

USDA Experiment Station (USGS)

Station Coordinates:	17.720 N 64.795 W

Equipment Problems: None reported.

Upwind Terrain: The highest wind speeds registered at this site occurred between 2000 UTC on 15 September and 0200 UTC on 16 September. During this period the wind direction shifted counterclockwise from 020 to 270 degrees. The maximum mean speed was 30.4 m/s at 2315 UTC with the wind from 328 degrees. Terrain at the site is rolling country and open in all directions. To the north it is approximately 6 km to the north coast with ground elevations of 150 to 200 m. Blue Mountain reaches to 335 m. To the northwest the maximum ground elevation is about 200 m, and the distance to the ocean line is about 10 km. In a westerly direction the terrain is relatively flat and open to Frederiksted which is 9 km away.

Wind Speed Adjustments: To estimate the corresponding over-water sustained speed, it was assumed that $z_0 = 0.10$ m over a distance of 6 km and a direction of 330 degrees. For this condition, an over-water sustained speed of 40.5 m/s is consistent with the observed speed of 30.4 m/s at the site and averaged over a period of 30 minutes. The corresponding sustained speed at 10 m above ground at the site is 37.4 m/s.

Green Cay Marina
Sailboat Puffin

Station Coordinates:	17.762 N 64.668 W

Equipment Problems: None reported.

Upwind Terrain: This site is open to the ocean. approximately 500 m to the north and northeast. Low hills surround the site in other directions, and the crest of the main east-west ridge on St. Croix is located 2 km to the south. This data source claimed a maximum speed of 43.8 m/s, but there was no mention of wind direction or time of day. Based on the hurricane track shown in Figure 3, it is likely that the maximum speed was registered when the wind was out of the northeast, corresponding to the most open direction at the site.

Wind Speed Adjustments: It was assumed that the approach to the site could be described with z_0 = 0.03 m for a distance of 500 m, and that the boundary layer was in equilibrium beyond this point with z_0 = 0.005 m (over-water exposure). Given the mast height of 12.8 m, the over-land portion of the exposure has little effect on the observed wind speed. If the observed speed was in fact a gust speed, then the corresponding over-water sustained speed is 34.4 m/s. Also, this is the speed at the 10 m level at the site. If the reported speed was a sustained speed, then the corresponding speed at the 10 m level (at the site and over water) is about 42 m/s.

ST. THOMAS

FAA ASOS

Station Coordinates: 18.339 N
64.977 W

Equipment Problems: The last wind speed and direction readings at this site were logged at 0532 UTC on 16 September when electrical service was interrupted. Fortunately, it was possible to download recorded data several days after the passage of Marilyn.

Upwind Terrain: Wind directions of interest at this site range from 45 degrees clockwise to 180 degrees. Although the local exposure for this site is flat and open (airport runway/taxiway), the terrain beyond the airport boundary is highly complex, except for the southwest quadrant which is an over-water exposure. Ridge elevations to the north and northeast reach 350 m or more, and the city of Charlotte Amalie is located 2 km due east of the airport.

Wind Speed Adjustments: The wind speeds plotted in Figure A-9 are 2-minute mean speeds measured at a height of 7.9 m while the gust speeds recorded by ASOS and plotted in Figure A-10 are averaged over a period of 5 seconds. In adjusting the observed speeds to equivalent sustained speeds for standard wind exposure, it was assumed that the surface roughness length at the site was 0.03 m for all wind directions. The ratios of peak gust speed to the corresponding 2-minute mean speeds were found to support this assumption. The corresponding maximum sustained speed at the ASOS site for a wind direction of 65 degrees is 51.6 m/s. Because of uncertainties regarding topographic effects for this wind direction, no attempt was made to estimate the corresponding sustained speed for an over-water exposure.

For a wind direction of 180 degrees, the direction corresponding to the second wind speed maximum at the airport, the height of the anemometer is sufficient to avoid the effects of the local ground surface on the wind speed. In other words, the actual anemometer exposure is over water, and it is necessary to apply adjustments only for anemometer height and averaging time. The corresponding adjusted sustained speed is 43.2 m/s at 0532 UTC. However, the true maximum may be slightly higher as the wind speed section of the ASOS ceased to function at this time.

UVI (USGS)

Station Coordinates: 18.343 N
64.976 W

Equipment Problems: This site made its last wind speed and direction data transmission at 0315 UTC when the mean wind speed was 32.2 m/s from the north. Minimum barometric pressure was 95.7 kPa at 0345 UTC.

Upwind Terrain: This site is located in complex terrain directly north of Cyril E. King Airport. It is located on a hillside sloping upward to the west. Two-story buildings are located to the southeast and to the northwest at distances of approximately 100 m.

Wind Speed Adjustments: No attempt was made to adjust the wind speed record for standard conditions.

Dorothea (USGS)

Station Coordinates: 18.361 N
64.962 W

Equipment Problems: Both the wind speed and wind direction records for this site are suspect. The barometric pressure record appears to be reliable.

Upwind Terrain: This site is located in complex terrain on the north-central slope of St. Thomas. The station datum is at 243 m, and the main east-west ridge in this part of the island is located approximately 500 m to the south with an elevation of about 370 m. To the east is a valley with heavy vegetation. The maximum wind speed registered at this site was 8.4 m/s at 0415 UTC on 16 September. Minimum barometric pressure was 92.6 kPa at 0515 UTC.

Wind Speed Adjustments: Due to questions about the reliability of the wind speed record and the complex terrain, no attempt was made to make adjustments for standard conditions.

ST. JOHN

Lind Point (USGS)

Station Coordinates: 18.338 N
64.797 W

Equipment Problems: The last data transmission from this site was at 0315 UTC on 16 September. Examination of the site revealed a failure of the anemometer mast which also supported the transmitting antenna.

Upwind Terrain: The site has a clear exposure to the ocean to the north and west with an average slope of 20 percent. To the south is the town of Cruz Bay and the ocean line is about 1 km away. However, the terrain is complex from the northeast clockwise around to the southeast, the direction of greatest interest for this site. Ridges and hills in this sector rise to 200 m or more. The highest recorded mean wind speed was 20.2 m/s at 0315 UTC from 107 degrees. Minimum barometric pressure at the same time was 97.5 kPa.

Wind Speed Adjustments: Because of the complex terrain upwind of this site, no attempt was made to adjust the recorded data to standard conditions.

PUERTO RICO

VIEQUES

Camp Garcia (USGS)

Station Coordinates:	18.122 N 65.416 W

Equipment Problems: None reported. However, the barometric pressure readings appeared to be erratic, and no attempt was made to plot them.

Upwind Terrain: The strongest winds at this site were out of the north at approximately 0400 UTC. The site elevation is 19 m and the distance from the site to the ocean line to the north is approximately 5 km. Between the recording site and the ocean line is a ridge with an elevation of approximately 100 m. Also, the site description provided by USGS indicates the presence of buildings about 500 m north of the anemometer site.

Wind Speed Adjustments: A value of $z_0 = 0.20$ m was assumed for the entire over-land distance between the recording site and the ocean line. No attempt was made to account for the effects of the 100 m ridge or the buildings. For this assumed fetch, an over-water sustained speed of 23.9 m/s is consistent with the measured maximum speed of 15.6 m/s, averaged over approximately 30 minutes. The corresponding 10 m sustained speed at the site is 19.8 m/s.

CULEBRA

Station Coordinates: Unknown. Observation reportedly made at local airport which would suggest coordinates of approximately 18.32 N, 65.30 W.

Equipment Problems: None reported.

Upwind Terrain: Not available.

Wind Speed Adjustments: Because of insufficient information, no wind speed adjustments were made at this site.

PUERTO RICO

Roosevelt Roads Naval Station

Station Coordinates: 18.256 N
65.638 W

Equipment Problems: None reported.

Upwind Terrain: The anemometer is located adjacent to the main runway at Ofstie Field. The strongest winds at this site were from the north and northwest. To the north and northeast, the terrain is relatively flat with scattered trees outside the runway area. Distance to the ocean line varies from about 1.5 km to the northeast to about 4 km to the north. The terrain in the other directions is complex with numerous hills close to the runway area.

Wind Speed Adjustments: The highest sustained speed was measured when the wind was directly out of the north, and this direction was assumed in evaluating the upwind terrain. Starting at the recording site, $z_0 = 0.03$ m for 2,000 m, $z_0 = 0.20$ m for 2,000 m, and $z_0 = 0.005$ m over water. With this assumed fetch and the measured sustained speed of 18.5 m/s, the corresponding over-water sustained speed is 21.5 m/s. The sustained speed at the site with $z = 10$ m is 19.6 m/s.