4

A Method for Reconstructing Historical Hurricanes

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In many coastal areas of the world the historical record provides evidence of land-falling hurricanes over a period of centuries. Using a combination of wind damage assessment and meteorological modeling, this record can be interpreted to reconstruct spatial and temporal patterns of hurricane impacts over the historical period. The resulting information can enhance understanding of natural ecosystems, improve assessment of hurricane risks, and help calibrate techniques for detecting prehistoric hurricanes. This historical-modeling method is discussed with illustrations from earlier studies in New England and Puerto Rico.

Understanding the impacts of hurricanes on natural and human systems requires a long-term perspective and an estimate of the spatial variation in individual storms. For the North Atlantic Basin, the HURDAT (Hurricane Data) database maintained by the U.S. National Hurricane Center currently provides track and maximum wind-speed data for all known hurricanes since 1851 (Jarvinen, Neumann, and Davis 1984; Landsea et al. 2002; Landsea et al., chapter 7 in this volume). These data must, however, be combined with modeling techniques to reveal the spatial gradient of impacts created by a land-falling hurricane. And the period covered (150 years) is not sufficient to study long-term trends or the frequency of the most intense hurricanes. For that purpose much can be learned from the historical record, which, for this basin, covers a period of 300 to 500 years since European settlement (e.g., Mock, chapter 5; García Herrera et al., chapter 6, and Landsea et al., chapter 7 in this volume).

In earlier studies of the ecological impacts of hurricanes on the forests of New England and Puerto Rico (Boose, Foster, and Fluet 1994; Boose, Chamberlin, and Foster 2001; Boose, Serrano, and Foster 2004), we developed an

approach that combines historical research and computer modeling. The resulting historical-modeling method involves six steps:

1. Identify all historical hurricanes with damaging winds in the selected region.
2. Collect wind damage reports and meteorological observations for each storm.
3. Analyze and compile the damage reports into regional maps of actual damage.
4. Parameterize and test a simple meteorological model (HURRECON) with data from selected recent hurricanes.
5. Use the parameterized model to reconstruct each storm.
6. Compile the results of individual storm reconstructions.

The long-term effects of topography on a landscape scale can then be examined with a simple topographic exposure model (EXPOS).

Details of this method are discussed here, with illustrations from our earlier studies of hurricane impacts at two Long-Term Ecological Research (LTER) sites, Harvard Forest in central Massachusetts and the Luquillo Experimental Forest in northeastern Puerto Rico, and their respective regions, New England and Puerto Rico.[1]

HISTORICAL DATA

Most of the time and effort required by this approach are devoted to historical research. The first tasks are to create a list of hurricanes for which there is evidence of wind damage in the study region and to locate historical documents for each storm. In our studies we relied on the works of other scholars to identify significant hurricanes in the early period. Our assessment of the impacts of each storm was based, wherever possible, on contemporary accounts. As expected, the number of historical reports was greater for recent or severe hurricanes. Efforts focused on obtaining good regional coverage for each storm.

For New England, newspapers proved to be the best source of information for hurricanes since 1700 (when newspapers first appeared), especially the *Boston Globe* and the *New York Times* for the period since 1871, and various local newspapers (depending on the area of impact) for the period 1700–1870. Personal diaries and town histories (especially those found at the American Antiquarian Society, Worcester, Massachusetts) provided contemporary evidence for seventeenth-century storms. Sixty-seven hurricanes during the period

from 1620 to 1997 were selected for detailed study, including all hurricanes that approached within 200 km of New England since 1851 according to HUR-DAT, and all earlier hurricanes for which Ludlum (1963) presented evidence of F1+ damage on the Fujita scale in New England.

For Puerto Rico, contemporary Puerto Rican newspapers proved to be the best source of information for hurricanes since 1876. For earlier storms we relied mainly on secondary studies (especially Salivia 1950 and Millás 1968), supplemented wherever possible by contemporary documents (especially from the Archivo de Indias at the University of Puerto Rico in Rio Piedras and the General Archives of Puerto Rico in San Juan). Eighty-five hurricanes during the period from 1508 to 1997 were selected for detailed study, including all hurricanes for which we found historical evidence of F0+ damage on the island.

Wind Damage Assessment

Actual wind damage in each hurricane is then classified using Fujita's (1971, 1987) system for assessing wind damage in tornadoes and hurricanes. This sys-tem has been used by the U.S. National Weather Service for tornadoes since the early 1970s (Grazulis 1993). Fujita's damage classes extend from F0 (minor damage caused by gale or storm force winds) to F5 (extreme damage in the most severe tornadoes). Each F-scale (Fujita scale) class is defined by specified levels of damage to common cultural and biological features of the landscape. The system was designed for rapid application in the field and does not require detailed engineering analysis. Note that this measure of local wind damage is not equivalent to overall hurricane intensity (as measured, for example, by the Saffir-Simpson scale). For example, intense storms that remain offshore may cause lower levels of wind damage over land.

In our studies minor modifications of Fujita's system were required for application to historical materials from New England and Puerto Rico (table 4.1). These changes were based in part on the work of Grazulis (1993) and in part on historical evidence of comparable damage in the hurricanes studied (e.g., town halls in New England tended to suffer damage comparable to churches and barns, in the same location and the same storm). Some modifi-cations were required by the nature of the historical materials. For example, when one or more trees were blown down the damage was classified as F1, even though Fujita regarded the pushing over of shallow-rooted trees as F0. That is because, in most cases, it was impossible to determine the condition of the tree from the historical reports. Similarly, when part or all of a roof was blown off a

TABLE 4.1 The Fujita Scale of Wind Damage Modified for Application to Historical Materials from New England and Puerto Rico

	F0 Damage	F1 Damage	F2 Damage	F3 Damage
Sustained wind speed (m/s)[1]	18–25	26–35	36–47	48–62
Trees	Leaves and fruit blown off, branches broken, trees damaged	Trees blown down	Extensive blowdowns	Most trees down
Crops	Damaged or blown down			
Masonry buildings	Minor damage	Roof peeled, windows broken, chimneys down	Unroofed	Blown down or destroyed
Wood houses[2]	Minor damage	Roof peeled, windows broken, chimneys down	Unroofed or destroyed	3+ blown down or destroyed in same town
Unspecified buildings, wood-zinc houses[3]	Minor damage	Unroofed or damaged	Blown down or destroyed	50% or more blown down or destroyed in same town[4]
Barns, churches, town halls, cottages[5]	Minor damage	Unroofed, steeple blown down, damaged	Blown down or destroyed	
Shacks, sheds, outbuildings, warehouses	Minor damage	Unroofed, blown down or destroyed		
Huts[6]	Damaged	Blown down or destroyed		
Furniture, bedding, clothes	Not moved	Blown out of building		
Masonry walls, radio towers, traffic lights	No damage	Blown down		
Utility poles	Wires down	Poles damaged or blown down, high-tension wires down		

	F0 Damage	F1 Damage	F2 Damage	F3 Damage
Signs, fences	Damaged	Blown down		
Autos	No damage	Moving autos pushed off road	Stationary autos moved or pushed over	Heavy autos lifted and thrown
Trains	No damage	Pushed along tracks	Boxcars pushed over	Trains overturned
Marinas, small airplanes	Minor damage	Destroyed		
Small boats	Blown off mooring	Sunk		
Missiles	None	None	Light objects, metal roofs	

[1] Corresponding sustained wind speed values are derived from Fujita's equations (1971), assuming a wind gust factor of 1.5 over land.
[2] Described as well-constructed or owned by a wealthy person (Puerto Rico [PR]). Also municipal buildings (PR).
[3] Constructed with light wood frame and metal roof (PR).
[4] F2 assigned if buildings described as rural or poor (PR).
[5] Includes schools, sugar mills, commercial buildings, and military buildings (PR).
[6] Constructed of palm leaves or similar materials (PR).
Sources: Adapted from Boose, Chamberlin, and Foster 2001; Boose, Serrano, and Foster 2004.

wood frame house, the damage was classified as F2, even though Fujita required that the entire roof be removed. Again, this is because it was usually impossible to determine exactly how much of the roof was gone. Damage to wood frame houses was assigned to F3 only if at least three houses in the same town were completely blown down, increasing the likelihood that at least one of the three houses was well-built and in good condition. For Puerto Rico, additional changes were required to account for different building practices and higher wind speeds. For example, unless described as well-constructed or owned by a wealthy person, houses were assumed to be constructed with a light wood frame and zinc-plated metal roof (or thatch before the late nineteenth century) and to sustain damage comparable to barns in Fujita's system. When at least half of the wood frame-metal roofed houses were completely blown down in a town, the damage was assigned an F3 category, unless the town was described as rural or poor.

Using the range of wind speeds proposed by Fujita (1971) for each damage

class, the Fujita scale provides a means to quantify the level of wind damage caused by historical hurricanes and a link to the meteorological modeling described later in this chapter (table 4.1). Fujita's values were found to work well for the lower damage classes (F0 to F3) treated in our study, although some engineers have suggested that Fujita's wind speeds may be too high, especially for F3 to F5 damage (e.g., Twisdale 1978; Liu 1993). Much work is still needed to understand the forces generated on buildings in hurricane winds (Powell, Houston, and Reinhold 1994).

For each historical report that references a specific location, the following information is collected, summarized, and entered into a database: (1) hurricane, (2) location, (3) bibliographic source, (4) meteorological observations, (5) storm surge, (6) wind damage, (7) fresh-water flooding, (8) notes, and (9) Fujita scale. We found that nearly all reports referenced one or more individual towns. The town also proved to be a suitable geographic unit for mapping and modeling hurricane impacts. Each report that contains sufficient information is assigned an F-scale value based on the highest level of damage reported (table 4.2). Care must be taken to exclude coastal damage caused by the storm surge, valley damage caused by river flooding, or local damage caused by landslides. In our studies we collected a total of 2,710 reports for New England and 2,699 reports for Puerto Rico. In general, we found that the level of wind damage was consistent within reports and among reports for the same town; for example, if house roofs were blown off (F2), barns were also blown down (F2).

Maps of actual wind damage are then created for each hurricane, using the maximum F-scale value assigned for each town (plate 1). These maps provide a quantitative, spatial assessment of actual damage for each storm. In general, we found the regional patterns to be consistent with meteorological expectations; that is, damage was usually greater to the right of the storm track where wind velocities are normally higher (in the Northern Hemisphere), and the intensity of damage usually lessened along the storm track as the hurricane made landfall. In New England, the most intense hurricanes (Category 3 on the Saffir-Simpson scale) caused widespread F2 damage across southern and coastal areas, with scattered F3 damage. In Puerto Rico the most intense hurricanes (Category 5) caused widespread F3 damage across much of the island.

TEMPORAL VARIATION

Information on actual wind damage can be used to study variation in hurricane impacts over the entire study region on a range of temporal scales, from seasonal to annual to decadal to centennial. For example, the multi-decadal vari-

TABLE 4.2   Historical Examples of F1, F2, and F3 Wind Damage in Puerto Rico

Hurricane Betsy, 1956

Location	San Juan
Source	*El Mundo*, August 13, 1956, pp. 1, 25
Wind	"Along Ponce de Leon Ave. there were many downed trees and fallen power lines. Construction support structures, scaffolding, and zinc plates had fallen and blocked the streets. Showcases were shattered in the New York Department store. Chimneys fell at a bakery in Rio Piedras."
Fujita rating	F1

Hurricane Hugo, 1989

Location	Luquillo
Source	*El Mundo*, September 20, 1989, p. 16
Wind	"In the barrios of Junquito, Pasto Viejo, Manbiche, and Anto Ruiz, where most of the houses were constructed of wood and zinc, everything blew away. The sports complex and a gymnasium lost their roofs and filled with water. In the barrio Canovanillas, several residences were knocked down."
Fujita rating	F2

Hurricane San Ciriaco, 1899

Location	Yabucoa
Source	*La Corresponencia*, August 12, 1899, p. 3
Wind	"The town remains in ruins. Only the church resisted the cyclone, and its walls sheltered many people. One of the houses that fell down was of masonry, and it killed the family and other people who sought shelter within its walls. In the countryside, nothing remained standing. Several haciendas were completely destroyed."
Fujita rating	F3

Sources: Translated from the Spanish by M. Serrano.

ation that is well documented for North Atlantic hurricanes since 1871 was evident in both study regions over the entire historical period (e.g., Neumann, Jarvinen, and Pike 1987; Gray, Sheaffer, and Landsea 1997) (figure 4.1). On a centennial scale, the number of F3 hurricanes in both regions was fairly constant over the historical period, while the number of F1 and F2 hurricanes increased steadily until the nineteenth century. These trends were probably the
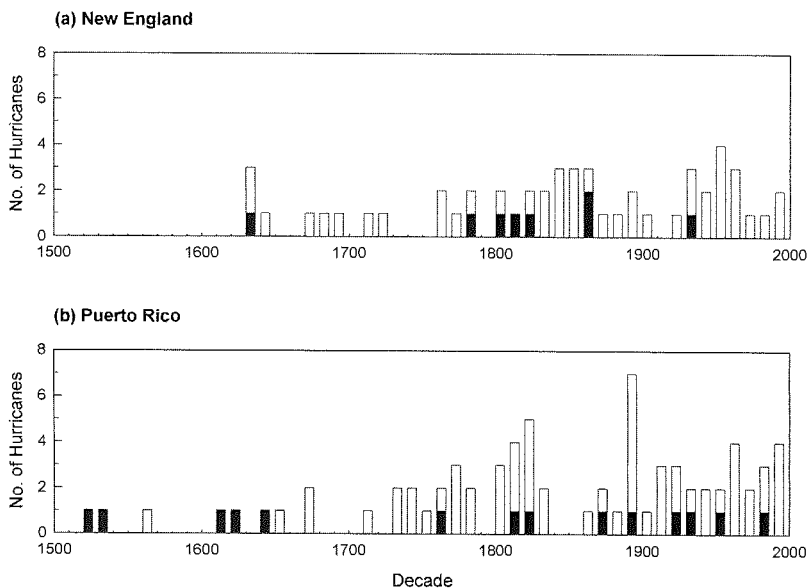
FIGURE 4.1   Number of hurricanes by decade with maximum reported damage equal to F1 to F2 (white) or F3 (black): (*a*) New England, 1620–1997; (*b*) Puerto Rico, 1508–1997 (adapted from Boose, Chamberlin, and Foster 2001; Boose, Serrano, and Foster 2004).

result of improvements in meteorological observations and records, and the natural tendency to retain records of the most damaging storms.

HURRECON MODEL

Individual hurricanes are then reconstructed with a simple meteorological model—HURRECON—based on published empirical studies of many hurricanes (Boose, Foster, and Fluet 1994; Boose, Chamberlin, and Foster 1997; Boose, Chamberlin, and Foster 2001). HURRECON uses information on the track, size, and intensity of a hurricane, as well as the cover type (land or water), to estimate surface wind speed and direction (figures 4.2 and 4.3). The model also estimates wind damage on the Fujita scale by using the correlation between maximum quarter-mile wind velocity (i.e., maximum wind velocity sustained over a quarter-mile distance) and wind damage proposed by Fujita (1971). The model complements actual wind damage assessment by providing informed estimates for sites that lack data as well as a complete regional picture of the impacts of each storm.
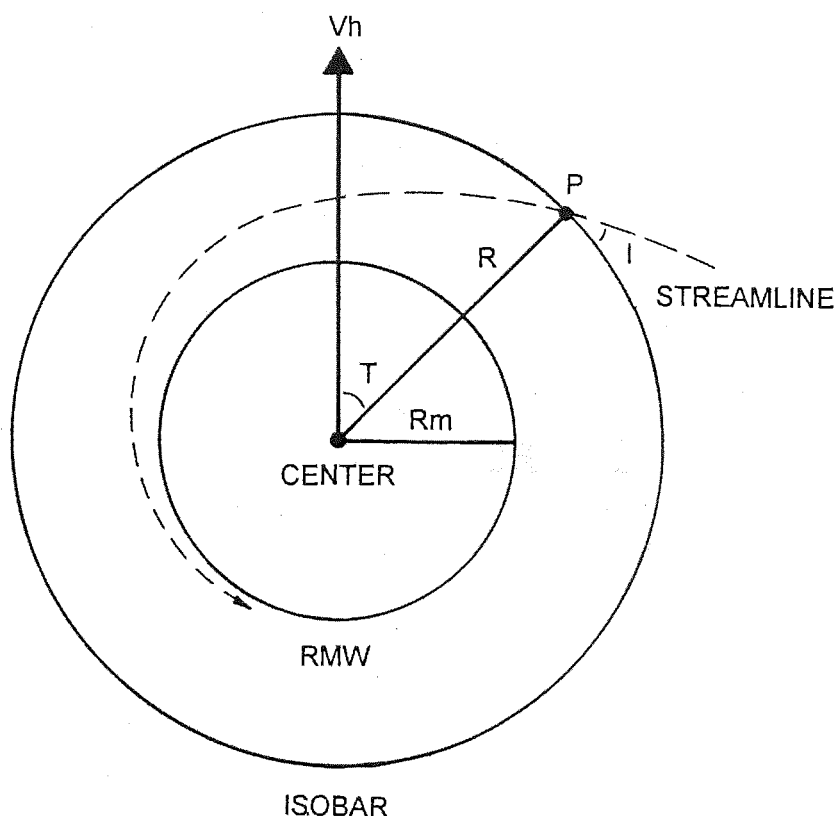
FIGURE 4.2 HURRECON model: wind direction. At the surface, air is drawn into the hurricane along spiral streamlines that cross the nearly circular isobars at inflow angle *I*. The estimated wind direction at point *P* is a function of *I* and the relative positions of *P* and the storm center (adapted from Boose, Chamberlin, and Foster 2001).

In the HURRECON equations provided here wind velocity and direction are measured relative to the Earth's surface, and angles are measured in degrees. Parameter values used for New England and Puerto Rico are given in parentheses. The sustained wind velocity (V_s) at any point P in the Northern Hemisphere is estimated as:

$$V_s = F\,[V_m - S(1 - \mathrm{Sin}\ T)V_h\,/\,2]\,[(R_m/R)^B \exp(1 - (R_m/R)^B)]^{1/2} \qquad (1)$$
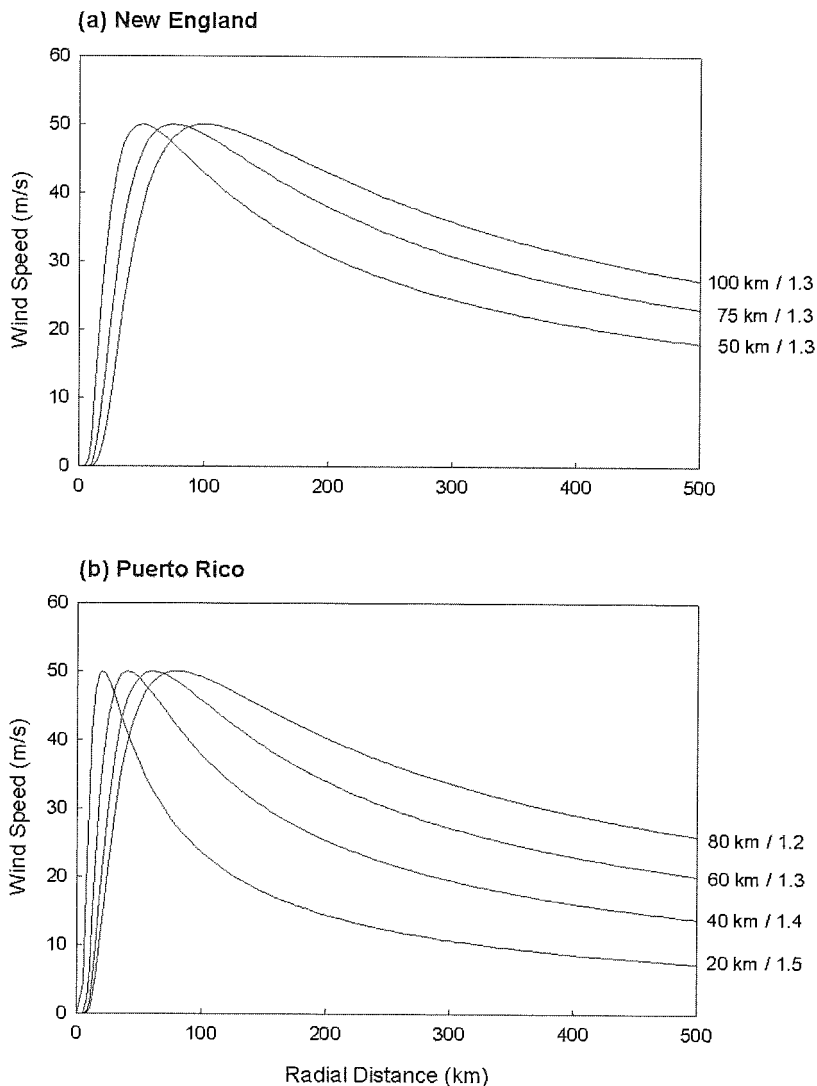
FIGURE 4.3   HURRECON model: wind speed. The estimated wind speed along a radial line outward from the hurricane center is a function of the radius of maximum winds (R_m), the wind speed at that radius (V_{rm}), and the scaling parameter B that controls the shape of the curve. Different combinations of R_m and B were selected to represent typical wind profiles for (a) New England and (b) Puerto Rico, shown here for an arbitrary value of V_{rm} = 50 m/s (adapted from Boose, Chamberlin, and Foster 2001; Boose, Serrano, and Foster 2004).

where F = scaling parameter for effects of friction (water = 1.0, land = 0.8), V_m = maximum sustained wind velocity over water anywhere in the hurricane, S = scaling parameter for asymmetry due to forward motion of storm (1.0), T = clockwise angle between forward path of hurricane and a radial line from hurricane center to point P, V_h = forward velocity of hurricane, R_m = radius of maximum winds, R = radial distance from hurricane center to point P, and B = scaling parameter controlling shape of wind profile curve. This equation was adapted from Holland's equation for the cyclostrophic wind (Holland 1980, equ. 5).

The peak wind gust velocity (V_g) at point P is estimated from V_s as follows:

$$V_g = G\,V_s \tag{2}$$

where G = gust factor (water = 1.2, land = 1.5). The maximum 1/4-mile wind velocity (V_f) is estimated from V_s and G using Fujita's method (Fujita 1971, equ. 12).

Wind direction (D) at point P is estimated as:

$$D = A_z - 90 - I \tag{3}$$

where A_z = azimuth from point P to hurricane center and I = cross isobar inflow angle (water = 20°, land = 40°). In the Southern Hemisphere, where the wind circulation is clockwise around the center, T = counterclockwise angle between forward path of hurricane and a radial line from hurricane center to point P, and $D = A_z + 90 + I$.

The HURRECON model was parameterized and tested for our two regions as follows:

1. Parameters were assigned from the literature and adjusted as necessary in detailed studies of six to seven major hurricanes over the last 100 years. For each storm, model estimates were compared to actual wind damage observations. The goal was to find parameters or a range of parameters that worked well for all storms.
2. The model thus parameterized was tested by comparing actual and reconstructed damage for the remaining hurricanes since 1851, where damage data were independent of the (input) meteorological data.
3. For New England, the model was then applied to hurricanes before 1851, where damage data were used to help determine the (input) storm track and/or maximum wind speed.

Parameter values for F, G, and I were adopted directly from published sources (Dunn and Miller 1964; Fujita 1971; Simpson and Riehl 1981; Powell 1982, 1987); F and G were chosen so that peak gust speeds are the same over water and land. The value $S = 2.0$ reported in the literature (i.e., peak wind speed on right side minus peak wind speed on left side = $2V_h$) was found to consistently underestimate wind speed and damage on the left side of the storm; better results were obtained with $S = 1.0$. The width of the modeled storm (for a given value of V_m) is controlled by the parameters R_m and B. Because direct measurements of the radius of maximum winds (R_m) were unavailable for all but the most recent hurricanes (H. Willoughby, personal communication), and to test model sensitivity to these critical parameters, each storm was modeled for a range of values of R_m and B selected to represent typical wind profiles for each region (figure 4.3). The combination of R_m and B that produced the best agreement between actual and reconstructed regional damage was selected for the final results.

HURRECON provides estimates for individual sites (as tables) and for entire regions (as GIS maps in Idrisi format; Eastman 1997). In our studies model runs for individual sites were made using a time step of 5 minutes; output variables included peak wind speed and direction and maximum F-scale damage for each storm. The cover type for individual sites was assumed to be land. Regional estimates were made at 10-km (New England) or 3-km (Puerto Rico) resolution using a time step equal to the minimum time required for each hurricane to traverse one grid cell in the regional study window. Output maps included peak wind speed and maximum F-scale damage across the region for each storm.

Model reconstructions are tested by comparing actual and reconstructed F-scale wind damage on a regional scale (plate 2). Such comparisons are quantified by creating and analyzing a difference map (reconstructed damage minus actual damage) for each storm (plate 2c). The difference maps provide a measure of the overall accuracy of each reconstruction as well as the spatial pattern of agreement (e.g., reconstructed values might be too high or too low on one side of the track, or along the fringes of the storm).

Reconstructed wind speeds can also be tested against observed wind speeds at surface stations where such data are available (Boose, Foster, and Fluet 1994). Though desirable, we found such tests to be impractical for all but the most recent hurricanes. Accurate comparisons require careful correction of the observed wind speed for various factors including height of the anemometer, surface roughness over the approaching wind trajectory, and duration of measurement (Powell, Houseton, and Reinhold 1994). Such information was diffi-

cult or impossible to obtain in many cases. In addition, peak wind speeds were often missed in all but the most recent storms because observations were only made at fixed, infrequent intervals.

METEOROLOGICAL RECONSTRUCTIONS

The range and quantity of meteorological data in the New World have, of course, increased dramatically since European settlement as a result of a more widely distributed population, better historical records, and steady improvements in technology (Ludlum 1963; Neumann, Jarvinen, and Pike 1987). HURDAT provides an invaluable source of meteorological data for hurricanes since 1851, though the database has known problems (including both systematic and random errors) and is currently under revision by NOAA (Neumann and McAdie 1997; Landsea et al. 2002; Landsea et al., chapter 7 in this volume). At the present time, meteorological data for earlier hurricanes must be estimated from historical records. Though actual measurements of wind speed are not available, early observers often left careful records of wind speed (in qualitative terms) and direction (eight points of the compass), noting the times of peak wind, wind shift, lulls, and changes in cloud cover and precipitation intensity.

In our studies we relied on HURDAT for track and maximum wind speed data for hurricanes since 1851. In most cases there was good agreement between observed and reconstructed F-scale damage. But in a few cases there were significant discrepancies, which were interpreted as stemming from problems with the HURDAT data and resolved by making conservative adjustments to the maximum sustained wind speed (V_m) values in HURDAT (Boose, Chamberlin, and Foster; 2001; Boose, Serrano, and Foster 2004). In addition, maps of actual wind damage in Puerto Rico showed evidence of storm weakening (at least at surface levels) in nearly all cases where hurricanes passed directly over the interior mountains. Such weakening was simulated for landfalling hurricanes by reducing V_m by 1.5 m/s (3 knots) for each hour that the storm remained over land, a rate consistent with empirical observations (Anthes 1982) and recent empirical models (Kaplan and DeMaria 1995).

For hurricanes before 1851 in New England, we used the meteorological observations and wind damage data we collected along with analyses by Ludlum (1963) to reconstruct track and maximum wind speed data for each storm. For Puerto Rico, such reconstructions were not attempted because the spatial coverage of the data collected was too small to create reliable estimates of hur-

ricane tracks. Such estimates, which would require extensive analysis of historical reports from surrounding islands and ships at sea, may become available in the future (C. Landsea, personal communication) but were beyond the scope of our project.

After the individual model runs are completed, maps of reconstructed F-scale damage for each hurricane are compiled to generate maps showing the number of storms at a given minimum intensity (F0, F1, F2, or F3). Each frequency map is divided into several regions by hand, and an average return time is calculated for each region based on the average number of storms and the observation period. For New England, we used three observation periods:

1. F2 maps: the entire historical period (1620–1997).
2. F1 maps: an intermediate period characterized by improvements in meteorological records and newspaper coverage (1800–1997).
3. F0 maps: the modern period beginning with the establishment of the U.S. Signal Corps storm warning system (1871–1997).

This approach was designed to maximize the observation period while minimizing the likelihood that storms of a given intensity escaped historical notice. For Puerto Rico all analyses were based on the entire period covered by HURDAT (1851–1997). In both regions the frequency of F0 events was no doubt underestimated, because F0 damage could have resulted from storms not included in our study; for example, hurricanes that passed farther out to sea or tropical storms that did not attain hurricane strength.

In nearly all cases we found good agreement between reconstructed and actual F-scale damage by town. For New England, reconstructed F-scale damage equaled actual damage in 62% of the cases and was within one damage class in 99% of the cases, with a slight tendency to underestimate actual damage. For Puerto Rico, reconstructed F-scale damage equaled actual damage in 52% of the cases and was within one damage class in 92% of the cases, with a slight tendency to overestimate actual damage.

SPATIAL VARIATION

One advantage to the modeling approach is that it provides complete spatial coverage for the study region. As a result it can be used to study spatial patterns of hurricane impacts, as well as temporal patterns at sites that lack complete historical records. For example, in our two study areas we found significant
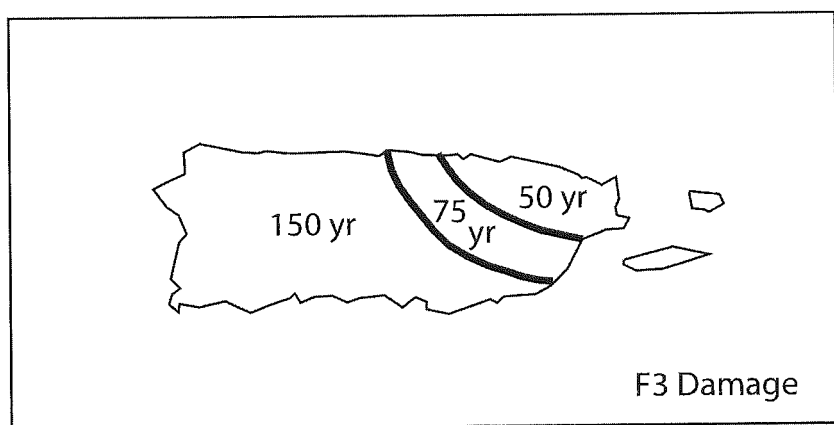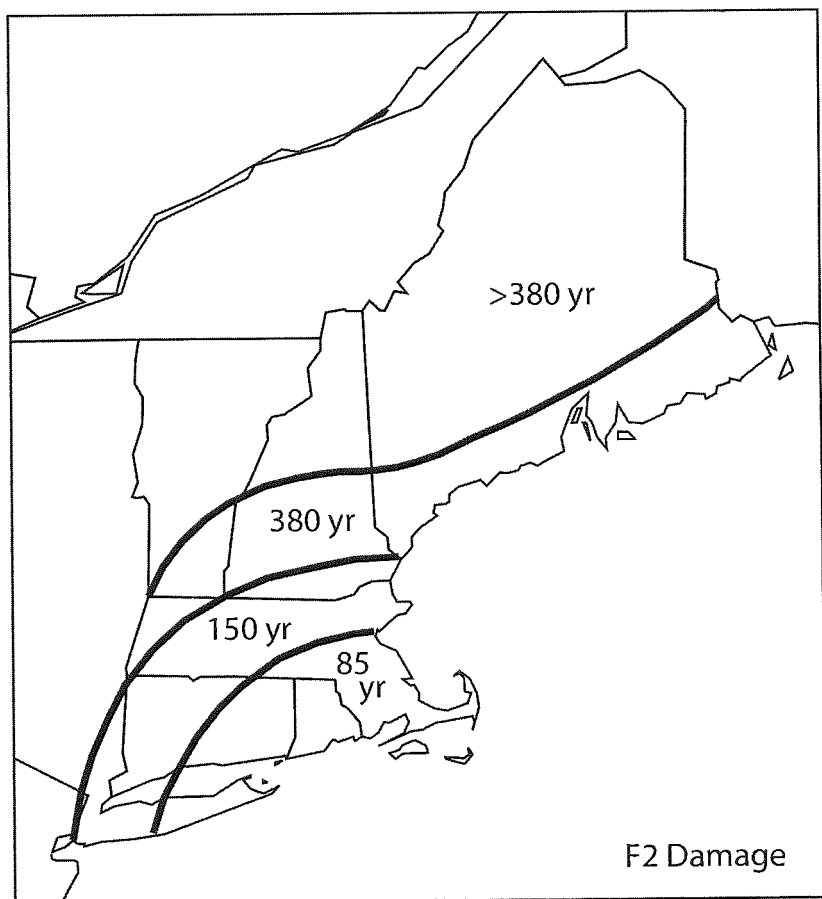
FIGURE 4.4   Regional gradients in reconstructed hurricane damage showing mean return intervals: (*top*) New England, F2 damage, 1620–1997; (*bottom*) Puerto Rico, F3 damage, 1851–1997 (adapted from Boose, Chamberlin, and Foster 2001; Boose, Serrano, and Foster 2004).

regional gradients in hurricane damage that resulted from the consistent direction of the storm tracks and the tendency for hurricanes to weaken as they moved over land or cold ocean water (New England) or over interior mountain ranges (Puerto Rico) (figure 4.4). At the site level there were also significant differences in hurricane frequency and intensity at the two LTER sites (figure 4.5). Topographic effects at a landscape level were studied using a simple exposure model and the reconstructed peak wind direction for each hurricane (Boose, Foster, and Fluet 1994) (figure 4.6). Results showed striking differences in reconstructed impacts on the north and south slopes of the Luquillo Mountains, creating a landscape-level gradient within the larger regional gradient (plate 3). Though none of these results were surprising, the historical-modeling method enabled us to quantify the regional gradients and evaluate site and landscape-level impacts at a level of detail and accuracy not previously possible.
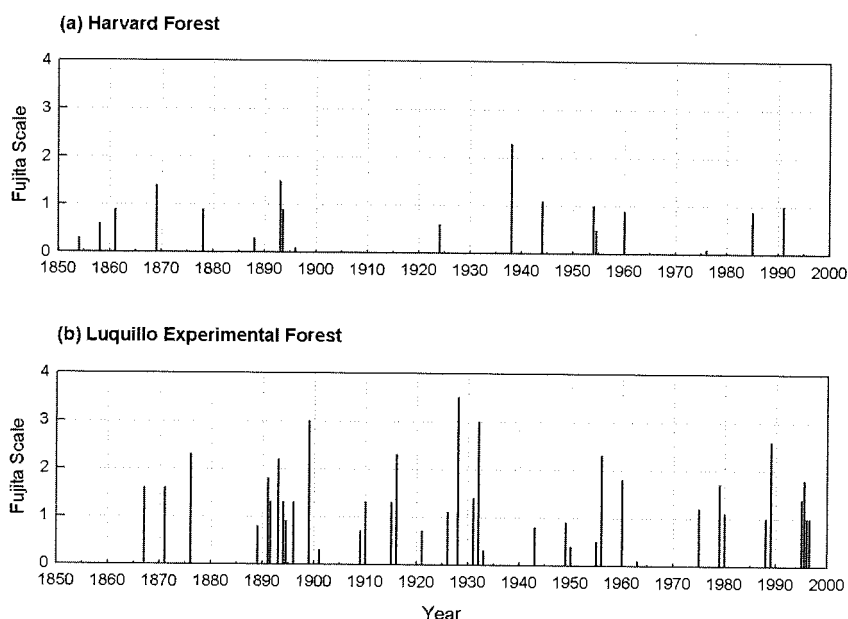

FIGURE 4.5   Reconstructed hurricane damage by year for 1851–1997: (a) Harvard Forest, central Massachusetts; (b) Luquillo Experimental Forest, northeastern Puerto Rico (adapted from Boose, Chamberlin, and Foster 2001; Boose, Serrano, and Foster 2004).
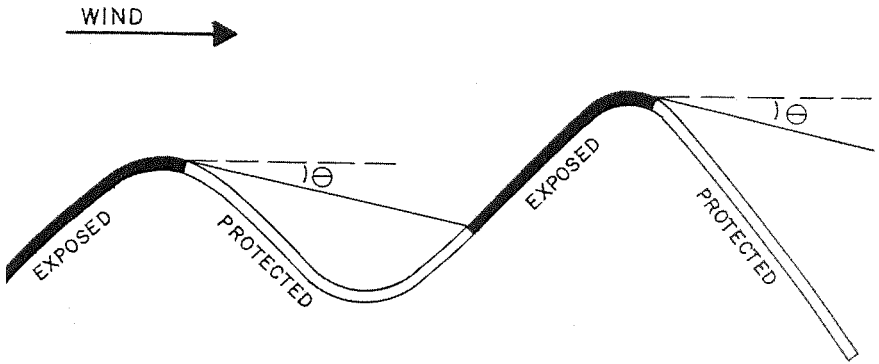
FIGURE 4.6   EXPOS model. For a given wind direction, each point in the study area is classified as protected or exposed, depending on whether or not the point falls within the wind shadow cast by points upwind (adapted from Boose et al. 1994).

HISTORICAL-MODELING METHOD

The approach described here relies on historical documents to assess and reconstruct the impacts of past hurricanes. The most difficult problem in interpreting results is estimating the completeness of the early records. It is quite possible, for example, that all records were lost for a New England storm in the first few decades after settlement, especially if the storm's impacts were not severe or were confined to sparsely populated areas. In both regions a number of early storms that reportedly did cause extensive damage were not included in our analyses because specific examples of damage were not given or the cause (wind, flooding, landslide) was not specified. Valuable information was no doubt overlooked in our studies, because historical searches are necessarily limited by time and resources. For Puerto Rico, especially, there are vast resources in the Archivo General de Indias in Seville that may someday shed more light on hurricanes during the colonial period (Marx 1983; García Herrera et al., chapter 6 in this volume).

One way to compensate for such incompleteness is to use more recent time periods for assessing weaker events, as we did in our analysis of New England hurricanes. Careful study may suggest that the historical record is complete for the most intense storms, at least in certain areas; for example, we concluded that few if any hurricanes that caused F2 damage in New England or F3 damage in San Juan escaped historical notice. This information was used to esti-

mate average return intervals for such storms. It may also be used to examine long-term trends and possible correlations with climate change, though the sample size for such storms is small.

Fujita's system is used to quantify actual wind damage by assigning F-scale values to entire towns based on historical reports. There are a number of potential problems with this approach. For example, damage levels may be overestimated if the object damaged (e.g., a tree or a house) was weak or defective before the storm (which is more likely if two or more severe storms strike over a short period), or if severe damage on a smaller scale (e.g., caused by a tornado embedded in the hurricane) is generalized to an entire town. Failure to exclude damage caused by storm surge, river flooding, or landslides may also lead to overestimation of the level of wind damage in the affected areas. On the other hand, damage levels may be underestimated if suitable objects are not present in the area surveyed (e.g., if only barns and outbuildings are present, then the highest possible level of damage to buildings is F2), if examples of higher damage are not observed and reported (especially in sparsely populated areas), or if news reports are suppressed (as sometimes happened in Puerto Rico). F-scale values may also be higher for larger towns and cities than in the surrounding countryside because there are more observers, more property subject to potential damage, and better records. Systematic errors in damage assessment may occur because of differences in construction practices over time, or from place to place. The susceptibility of a particular building to wind damage is a complex function of building design and construction quality, as well as state of repair, wind direction, topographic position, surrounding wind breaks, and whether or not doors and windows are open, closed, or shuttered (Liu 1993). Such information is generally unavailable from historical sources. Finally, random errors may result from inaccuracies in the historical accounts. These problems arise mainly from the need to rely on written records and photographs for damage assessment.

The basic technique was found to work well for the purposes of our studies, probably because the Fujita damage classes are so broad. The overall tendency for the model to underestimate actual wind damage in New England may have resulted from the inclusion of all tree blowdowns as F1 and even partial roof removals as F2; while the overall tendency to overestimate actual wind damage in Puerto Rico may have resulted from the under-reporting of actual damage, especially from smaller towns.

Meteorological modeling is used to reconstruct a more complete picture of hurricane impacts than can be obtained from wind damage assessment alone. Here, too, there are a number of potential problems. For example, the HUR-

RECON model is based on an idealized wind profile that works best for intense hurricanes and less well for hurricanes that are weak or becoming extratropical storms. The model is not able to reconstruct multiple wind maxima or other mesoscale features (Willoughby 1995). Model estimates of wind damage are also based on peak quarter-mile wind speed following Fujita's method (1971), which assumes that the period of sustained wind required to produce specific damage is inversely proportional to wind speed. This approach yields wind durations appropriate for tree and building damage (e.g., 12 seconds for minimal hurricane force winds), but does not take into account fatigue and stress damage that may occur on a scale of minutes or hours. Nor does it account for damage associated with a shift in wind direction (Powell, Houston, and Ares 1995). Uncertainties in input data (hurricane track, size and intensity) are much greater for early hurricanes, especially in sparsely populated areas. Input data accuracy for New England, for example, was estimated to have increased by an order of magnitude over the historical period (Boose, Chamberlain, and Foster 2001).

Despite these problems, regional maps of actual and reconstructed wind damage were found to agree closely for the hurricanes modeled in both New England and Puerto Rico. This agreement was no doubt enhanced by the small number of predicted damage classes (no damage, F0, F1, F2, F3). A larger number of classes would provide a more robust test of the model but was not practical given the nature of the historical materials.

The historical-modeling method can be applied to any part of the world where good historical records survive. Ecologists can combine information obtained in this way with knowledge of other disturbance events to build a comprehensive disturbance history for a site or region. The same information can used to improve hurricane risk assessment for shoreline and inland areas. The historical-modeling method can also be used to help calibrate and interpret various techniques for studying prehistoric hurricanes, such as the stratigraphic analysis of salt marsh deposits (e.g., Donnelly et al. 2001). These techniques may provide the millennial-scale data needed to better assess long-term trends and correlations with climate change. The main disadvantage of the historical-modeling approach is the time and effort required to locate and interpret historical materials, especially for the early period.

NOTE

1. The HURRECON and EXPOS models and the historical data used in our analyses are available on the Harvard Forest Web site (http://harvardforest.fas.harvard.edu).

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