A Method for Reconstructing Historical Hurricanes

Emery R. Booze

In many coastal areas of the world the historical record provides evidence of landfalling 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 landfalling 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 that approached within 200 km of DAT, and all earlier hurricanes of F1+ damage on the Fujita scale are included.

For Puerto Rico, contemporary sources were the best source of information for hurricanes, which relied mainly on secondary studies supplemented wherever possible by the Archivo de Indias at the University of Puerto Rico General Archives of Puerto Rico. The period from 1508 to 1997 included all hurricanes for which we found documentation.

Wind Damage Assessment

Actual wind damage in each hurricane is assessed using the modified 1987 NWS system for assessing wind damage to buildings. The system has been used by the U.S. Air Force since the early 1970s (Graulich 1993). It does not account for damage caused by gale or storm surge effects (the most severe tornadoes). Each F-scale level of damage is common to a category. The system was designed for rapid, general wind damage assessment. No level of damage is equivalent to overall hurricane damage (e.g., Saffir-Simpson scale). For example, F1 damage indicates lower levels of wind damage.

The system also accounted for local conditions (e.g., town halls in New England, churches and barns, in the same locations were required by the nature of the structures when one or more trees were blown down, though Fujita regarded the push from the historical reports. Simi
Research and computer modeling. The method involves six steps:

1. With damaging winds in the selected area exceeding 64 km/h, meteorological observations for each county are reviewed.
2. Reports into regional maps of actual damage are used.
3. A meteorological model (HURRECON) is used to construct each storm.
4. Storm reconstructions are then examined at the landscape scale.

Here, with illustrations from our earlier Long-Term Ecological Research (LTER) project and the Luquillo Experimental Forest, their respective regions, New England hurricanes from 1620 to 1997 were selected for detailed study, including all hurricanes that approached within 200 km of New England since 1851 according to HURDAT, 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 Salvia 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 system 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 modifications 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>
<thead>
<tr>
<th>Fo Damage</th>
<th>F1 Damage</th>
<th>F2 Damage</th>
<th>F3 Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained wind speed (m/s)</td>
<td>18–25</td>
<td>26–35</td>
<td>36–47</td>
</tr>
<tr>
<td>Trees</td>
<td>Leaves and fruit blown off, branches broken, trees damaged</td>
<td>Trees blown down</td>
<td>Extensive blowdowns</td>
</tr>
<tr>
<td>Crops</td>
<td>Damaged or blown down</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Masonry buildings</td>
<td>Minor damage</td>
<td>Roof peeled, windows broken, chimneys down</td>
<td>Unroofed</td>
</tr>
<tr>
<td>Wood houses</td>
<td>Minor damage</td>
<td>Roof peeled, windows broken, chimneys down</td>
<td>Unroofed or destroyed</td>
</tr>
<tr>
<td>Unspecified buildings, wood-zinc houses</td>
<td>Minor damage</td>
<td>Unroofed or damaged</td>
<td>Blown down or destroyed</td>
</tr>
<tr>
<td>Barns, churches, town halls, cottages</td>
<td>Minor damage</td>
<td>Unroofed, steeple blown down, damaged</td>
<td>Blown down or destroyed</td>
</tr>
<tr>
<td>Shacks, sheds, outbuildings, warehouses</td>
<td>Minor damage</td>
<td>Unroofed, blown down or destroyed</td>
<td></td>
</tr>
<tr>
<td>Huts</td>
<td>Damaged</td>
<td>Blown down or destroyed</td>
<td></td>
</tr>
<tr>
<td>Furniture, bedding, clothes</td>
<td>Not moved</td>
<td>Blown out of building</td>
<td></td>
</tr>
<tr>
<td>Masonry walls, radio towers, traffic lights</td>
<td>No damage</td>
<td>Blown down</td>
<td></td>
</tr>
<tr>
<td>Utility poles</td>
<td>Wires down</td>
<td>Poles damaged or blown down, high-tension wires down</td>
<td></td>
</tr>
</tbody>
</table>

1 Corresponding sustained wind speed value is a wind gust factor of 1.5 over land.
2 Described as well-constructed or owned by buildings (PR).
3 Constructed with light wood frame and metal.
4 F2 assigned if buildings described as rural or poor.
5 Includes schools, sugar mills, commercial buildings.
6 Constructed of palm leaves or similar materials.

Sources: Adapted from Boone, Chamberlin, and others.

For wood frame houses, the damage was often described as rural or poor. It required that the entire roof be removed to the extent that it was impossible to determine exactly how many houses were completely blown down. The three houses was well-built, with additional changes required for higher wind speeds. For example, houses owned by a wealthy person, houses with wood frame and zinc-plated metal roof, and to sustain damage consistent with at least half of the roof being blown down in a town, the damage was also described as rural or poor.

Using the range of wind speeds...
A Method for Reconstructing Historical Hurricanes

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>F2 Damage Description</th>
<th>F3 Damage Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>36–47</td>
<td>48–62</td>
<td>103–130</td>
</tr>
<tr>
<td>Extensive blowdowns</td>
<td>Most trees down</td>
<td></td>
</tr>
<tr>
<td>Unroofed</td>
<td>Blown down or destroyed</td>
<td></td>
</tr>
<tr>
<td>Unroofed or destroyed</td>
<td>3+ blown down or destroyed in same town</td>
<td></td>
</tr>
<tr>
<td>Blown down or destroyed</td>
<td>50% or more blown down or destroyed in same town</td>
<td></td>
</tr>
<tr>
<td>Blown down</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blown down or destroyed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blown down or destroyed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sign, fences</th>
<th>Autos</th>
<th>Trains</th>
<th>Marinas, small airplanes</th>
<th>Small boats</th>
<th>Missiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damaged</td>
<td>No damage</td>
<td>No damage</td>
<td>Minor damage</td>
<td>Blown off mooring</td>
<td>None</td>
</tr>
<tr>
<td>Blown down</td>
<td>Moving autos pushed off road</td>
<td>Pushed along tracks</td>
<td>Destroyed</td>
<td>Sunk</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Stationary autos moved or pushed over</td>
<td>Boxcars pushed over</td>
<td></td>
<td></td>
<td>Light objects, metal roofs</td>
</tr>
<tr>
<td></td>
<td>Heavy autos lifted and thrown</td>
<td>Trains overturned</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 Boone, Chamberlin, and Foster 2001; Boone, 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**

<table>
<thead>
<tr>
<th>Location</th>
<th>Source</th>
<th>Wind</th>
<th>Fujita rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Juan</td>
<td>El Mundo, 1956</td>
<td>&quot;Along Ponces&quot;</td>
<td>F1</td>
</tr>
<tr>
<td>Luquillo</td>
<td>El Mundo, 1989</td>
<td>&quot;In the barrio where most of the houses were shingled, a tree fell at a barrio meeting place and several residents were injured.&quot;</td>
<td>F2</td>
</tr>
<tr>
<td>Yabucoa</td>
<td>La Correspondencia, 1989</td>
<td>&quot;The town rode out the hurricane, and its winds, and its waves were not as bad as they could have been. Some houses were damaged, but most remained standing.&quot;</td>
<td>F3</td>
</tr>
</tbody>
</table>

Sources: Translated from the Spanish by the authors.
A Method for Reconstructing Historical Hurricanes 105

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

<table>
<thead>
<tr>
<th>Hurricane</th>
<th>Location</th>
<th>Source</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Betsy, 1956</td>
<td>San Juan</td>
<td>El Mundo, August 13, 1956, pp. 1, 25</td>
<td>&quot;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.&quot;</td>
</tr>
<tr>
<td>Hugo, 1989</td>
<td>Luquillo</td>
<td>El Mundo, September 20, 1989, p. 16</td>
<td>&quot;In the barrios of Junquito, Pasto Viejo, Manbicre, 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 Canovanas, several residences were knocked down.&quot;</td>
</tr>
<tr>
<td>San Ciriaco, 1899</td>
<td>Yabucoa</td>
<td>La Correspondencia, August 12, 1899, p. 3</td>
<td>&quot;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.&quot;</td>
</tr>
</tbody>
</table>

Fujita ratings: F1, F2, F3

Sources: Translated from the Spanish by M. Serrano.

To quantify the level of wind damage, we used a range of temporal scales, from seasonal to decadal. For example, the multi-decadal vari-
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 hurri-
canes (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.

\[ V_s = F [V_m - S] (1 - \sin T) \]

*Figure 4.1* Number of hurricanes by decade with maximum reported damage equal to F1 to F0 (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).

*Figure 4.2* HURRECON model along spiral streamlines that cross the direction at point P is a function of [a] a (Boose, Chamberlin, and Foster 2001).
constructed with a simple meteorological
and empirical studies of many hurri-
cone, Chamberlin, and Foster 1997;
HURRECON uses information on the
cover type (land or water),
figure (4.2 and 4.3). The model
Fujita scale by using the correlation
d wind velocity
and wind damage proposed by Fujita
wind damage assessment by providing
as well as a complete regional picture

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:

$$V_s = F \left[ V_m - S(1 - \sin T) V_h / 2 \right] \left[ (R_m / R)^\beta \exp\left(1 - (R_m / R)^\beta\right)\right]^{1/2}$$  (1)
where $F$ = scaling parameter for $V_m$, $V_m$ = maximum sustained wind, $S$ = scaling parameter for asymmetry, $T = \text{clockwise angle between forward path of hurricane center to point } P$, $V_g$ = maximum winds, $R = \text{radial distance} = \text{scaling parameter controlling regression}$ (adapted from Holland’s equation, equ 5).

The peak wind gust velocity $V_g = G V_s$

where $G = \text{gust factor}$ (water = 1.2, land = 1.5) and $V_s$ = wind velocity at the radius $R_g$ is estimated from equ. 12.

Wind direction ($D$) at point $P$:

$$D = A_x - 90 - I$$

where $A_x = \text{azimuth from point } P$ to point $I$ (water = 20°, land = 40°). The hurricane circulation is clockwise around the eye of the hurricane. $I$ is the forward path of hurricane eye $m$ and $D = A_x + 90 + I$.

The HURRECON model works as follows:

1. Parameters were assigned in detailed studies of six to ten storms. For each storm, model estimates were compared to existing storm observations. The goal was to find a model that worked well for all storms.
2. The model thus parameterized to accurately reconstruct hurricane damage.
3. Damage data were independent of model parameters. For New England, the maximum wind data were used to parameterize the model. The curve for hurricanes in 1851, where damage data were available, was used to validate the model.

**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 ($V_m$), and the scaling parameter $S$ that controls the shape of the curve. Different combinations of $R_m$ and $S$ were selected to represent typical wind profiles for (a) New England and (b) Puerto Rico, shown here for an arbitrary value of $V_m = 50 \text{ m/s}$ (adapted from Boone, Chamberlin, and Foster 2001; Boone, Serrano, and Foster 2004).
A Method for Reconstructing Historical Hurricane Winds

where $F = \text{scaling parameter for effects of friction}$, $V = \text{wind speed along a radial line}$, $S = \text{maximum sustained wind speed anywhere in the hurricane}$, $T = \text{clockwise angle between forward path of hurricane and a radial line from hurricane center to point P}$. 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 major hurricanes over the last 10 years.

2. The model was tested by comparing actual and reconstructed damage for the remaining hurricanes since 1951, where damage data were used to help determine the input storm track and/or maximum wind speed.

3. For New England, the model was then applied to hurricanes before 1951, where damage data were used to help determine the input storm track and/or maximum wind speed.

$V = CV$, where $C = \text{geostrophic factor}$ ($C = 1.5$), $V = \text{maximum 14-mile wind speed}$.

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

$D = A - 90I$, where $A = \text{azimuth from point P to hurricane center}$ and $I = \text{coefficient of inflow}$.

The maximum 14-mile wind speed ($V$) is estimated from $V$ and $C$ using Fujita’s method (Fujita 1971).

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

$V_g = GV$, where $G = \text{scaling parameter controlling shape of wind profile curve}$ (Holland 1980).
Parameter values for $F$, $G$, and $I$ were adopted directly from published sources (Dunn and Miller 1964; Fujita 1971; Simpson and Richl 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 = $2V_w$) 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, Houelon, and Reinhold 1994). Such information was difficult or impossible to obtain in real time and was often missed in all but the most recent hurricanes made at fixed, infrequent intervals.

**Meteorological Reconstructions**

The range and quantity of meteorological observations, increased dramatically with improvements in technology (Landsea and Hare 1992). HURDAT provides an invaluable listing of storms since 1851, though the database (both systematic and random errors) and is not complete (Landsea and McAdie 1997; Landsea et al. 2004). At the present time, most manual storm tracks estimated from historical records are not available, early observations are qualitative terms) and directions of peak wind, wind shift, lulls, and intensities.

In our studies we relied on historical data for hurricanes since 1851. Between observed and reconstructed there were significant discrepancies in the HURDAT data and the maximum sustained wind speeds of Chamberlin, and Foster; 200 maps of actual wind damage were screened (at least at surface level) directly over the interior and falling hurricanes by reducing storm remained over land, a recent empirical method.

For hurricanes before 1851, observations and wind damage information were used (Landsea 1963) to reconstruct tracks. For Puerto Rico, such reconstruction was not possible due to the lack of coverage of the data collected.
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...
An extensive analysis of historical data, may become available in the future, but were beyond the scope of this analysis.

To facilitate further analysis, maps of reconstructed hurricane data were generated, showing the European region, the Eastern United States, and the Gulf Coasts. Each family of storms was assigned an average return time, while the number of storms and the observed damages were tallied for each observation period:

- For the Eastern United States, the period covered by HURDAT spans the years 1851–1997.
- For the Gulf Coasts, the period covered is 1851–1997.

The observation period while minimizing the number of storms that escaped historical notice. The mean return time of F0 events in the period 1800–1997 was no doubt underestimated, and storms that resulted from storms not reaching land or that passed farther out to sea or over water were not included.

A comparison between reconstructed and reconstructed F-scale damage data showed that the former was within one damage category of the later in 92% of the cases, with a tendency to underestimate actual damage. The reconstructed actual damage in 150 years, 50 years, and 75 years, respectively.

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 Boise, Chamberlin, and Foster 2001; Boise, 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.

![Graph of reconstructed hurricane damage](image)

**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 forest that is protected or exposed, depending on the period, points upwind (adapted from Boose et al.).

**Historical-Modeling Approach**

The approach described here used to reconstruct the impacts of past events is interpreting results is estimating what was possible, for example, that all of the first few decades after settlement were severe or were confined to specific areas of early storms that reportedly occurred in our analyses because specific factors (wind, flooding, landslide) were doubt overlooked in our studies. (limited by time and resources. Further studies in the Archivo General de Indias provide information on hurricanes during the colonial period, see chapter 6 in this volume).

One way to compensate for these limitations is to focus on periods for assessing weaker hurricane impacts. Careful study may reveal the most intense storms, at least to the extent that few of the hurricanes that caused significant damage in San Juan escaped historical records.
resulted from the consistent direction hurricanes to weaken as they (England) or over interior mountain level there were also significant intensity at the two LTER sites level were studied using a simple wind direction for each hurricane. Results showed striking difference and south slopes of the areal gradient within the larger areas these results were surprising, they quantify the regional gradients and level of detail and accuracy not

**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 storm and is less well for hurricanes. The model is not able to capture mesoscale features (Willoughby 1995) and is also based on peak quarter-mile winds, which assumes that the period of time that damage is caused is inversely proportional to the wind duration appropriate for tree and small building damage (e.g., F2 in a tropical hurricane force winds), but not for damage that may occur on a scale of seconds. Damage that may occur on a scale of hours is associated with a shift in the wind direction (Foster 1995).

Despite these problems, regional differences in damage were found to agree closely between New England and Puerto Rico. This agreement in number of predicted damage classes suggests that a relatively small number of classes would provide a reasonable reflection of the nature of the damage and the methods used to assess it. The historical-modeling method uses only those records obtained in this way with knowledge of the comprehensive disturbance history for a location. This method may be used to improve hurricane risk assessment and provide a way to improve hurricane risk assessment. The historical-modeling method can also be used to study the effects of historical events on the modern environment. This approach is the time analysis of salt marsh deposits (e.g., Sibley 1995) and provides information that may be useful in understanding the relationship between climate change and coastal processes.
A Method for Reconstructing Historical Hurricanes

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 scales of minutes or hours. Nor does it account for damage associated with a shift in wind direction (Powell, Houston, and Are 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 be 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.

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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).

REFERENCES


A Method for Reconstructing Historical Hurricanes


Tropical cyclones are commonly seen in the Atlantic Ocean. Examination of the modern historical records from 1851 indicate significant impacts on tropical storm centers within 100 km of Charleston, South Carolina, in the mid-eighteenth century by utilizing weather records. The record is of daily information that allows the general to generally provide more detailed information than plantation records from sources such as planters and the Charleston Board of Health, but sometimes also includes pressure, temperature, wind direction, and other reconstruction of information which are newly documented. The 1778 period. Temporal analysis of a running mean, indicate substantial shifts in the modern record for the northeast Caribbean, with a particularly active year for the entire most active year for the entire affecting South Carolina. The framework for conducting historical reconstructions in locations of the Atlantic Basin.