Henry F. Diaz Roger S. Pulwarty (Eds.)

Hurricanes

Climate and Socioeconomic Impacts

With 77 Figures and 30 Tables

Springer

Dr. Henry F. Diaz
NOAA/ERL/CDC
325 Broadway
Boulder, CO 80303, USA

Dr. Roger S. Pulwarty
Cooperative Institute for Research in Environmental Sciences
Campus Box 449
University of Colorado
Boulder, CO 80309, USA

ISBN 3-540-62078-8 Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging-in-Publication Data
Hurricanes : climate and socioeconomic impacts / [edited by Henry F. Diaz, Roger S. Pulwarty].
Includes bibliographical refereces and index.
ISBN 3-540-62078-8
1. Hurricanes—Social aspects—United States. 2. Hurricanes—Social aspects—Caribbean Area. 3. Hurricanes—Economic aspects—United States. 4. Hurricanes—Economic aspects—Caribbean Area. 5. Climatic changes—Atlantic Ocean Region. I. Diaz, Henry F. II. Pulwarty, Roger S., 1960- .
QC945.H89 1997
363.34'922'091821—dc21

Printed in Germany

Cover design: Erich Kirchner, Heidelberg
Typesetting: Camera ready by editor
SPIN: 10526008 32/3136 - 5 4 3 2 1 0 – Printed on acid-free paper

8 Vulnerability to Hurricanes Along the U.S. Atlantic and Gulf Coasts: Considerations of the Use of Long-Term Forecasts

Roger A. Pielke, Jr.[1] and Roger A. Pielke, Sr.[2]

[1]Environmental and Societal Impacts Group
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307-3000, U.S.A.

[2]Department of Atmospheric Sciences
Colorado State University
Fort Collins, CO 80523, U.S.A.

Abstract

The scientific community has demonstrated some skill in long-term forecasts (i.e., inter-annual/decadal) of Atlantic hurricane activity. Long-term forecasts of hurricane incidence are a component of broader political and social processes. Recognition of this broader context of a forecast is central to its utilization for societal benefits. We seek to use the concept of vulnerability to hurricanes along the U.S. Atlantic and Gulf coasts to provide a framework to assess the use/value of long-term forecasts of hurricane activity. Vulnerability provides a common goal that integrates the science and social science of hurricane impacts. Experience suggests that improved long-term forecasts, by themselves, will not reduce society's vulnerability unless accompanied by efforts to use them in processes of preparedness. To the extent that improved forecasts contribute to reduced vulnerability we will have made less serious the threat of hurricanes to coastal communities, supplied a basis of experience for actions in response to other types of extreme weather phenomena, and provided a practical demonstration of a successful connection of scientific research in pursuit of societal objectives.

8.1 Introduction: Defining the Problem

A better understanding of societal vulnerability to hurricanes helps to illuminate at least three complexes of problems facing the United States. First, hurricanes pose a serious threat to the U.S. Atlantic and Gulf coasts. Second, hurricanes are a subset of a broader class of extreme weather events that threaten the nation. And third, societal and political responses to the hurricane threat have potential to contribute to ongoing debate over U.S. science policy concerning the efficacy of research supported with federal funds. In the context of these problems, this paper seeks to (1) expand the problem definitions, (2) define and clarify vulnerability to hurricanes along the U.S. Atlantic and Gulf coasts, focusing on intense hurricanes, and (3) provide general guidance as to how long-term (i.e., interannual/decadal) forecasts of hurricane activity might contribute to reduced societal vulnerability. The paper is targeted at both users (actual and potential) and producers of hurricane information, as well as those interested in a better understanding the role of long-term forecasts in reducing vulnerability to hurricanes.

8.1.1 Intense Hurricanes

About a year after Hurricane Andrew devastated south Florida and parts of rural Louisiana, Director of the National Hurricane Center, Dr. Robert Sheets (whose home suffered extensive damage due to the storm), testified before Congress that "We were lucky" (Sheets 1993, 41). In spite of the $25 billion in damage caused by Andrew, Floridians and the U.S. were lucky because "had Hurricane Andrew been displaced only 20 miles north of its track over South Florida, two different studies show that losses would have exceeded $60 billion in South Florida alone." Indeed, over the past several decades the U.S. Atlantic and Gulf coasts as a whole may be considered fortunate because hurricane activity during this period has been below the climatological average (Gray and Landsea 1992; Landsea et al. 1996; Gray et al., Chap. 2 this volume). Coch (1994), on the other hand, argues that in 1985 residents along the northeast Atlantic coast "were just lucky" to avoid a greater impact from Hurricane Gloria. The trend of below-average hurricane activity is apparent in Figs. 9.1a, b which show the tracks of intense hurricanes for two periods: (a) 1947 to 1969, and (b) 1970 to 1987. Although Hurricane Andrew was not as costly as it might have been, it was the most costly weather-related disaster in U.S. history, and perhaps a warning that our luck with hurricanes may be running out.

Hurricanes, which are a type of tropical cyclone, are classified by their damage potential according to a scale developed in the 1970s by Robert Simpson, a meteorologist and director of the National Hurricane Center, and Herbert Saffir, a consulting engineer in Dade County, Florida (Simpson and Riehl 1981). The Saffir/Simpson scale is now in wide use and was developed by the National Weather Service to give public officials usable information on the magnitude of a storm in progress. The scale has five categories, with category 1 the least intense hurricane and category 5 the most intense. Storms are named when they reach tropical storm strength. Tropical storms are tropical cyclones below category 1 strength and have wind speeds of 39-74 mph. Table 8.1 shows the Saffir/Simpson scale and the corresponding criteria for classification. This paper focuses on intense (or "great") hurricanes, i.e., those classified in categories 3, 4, or 5.

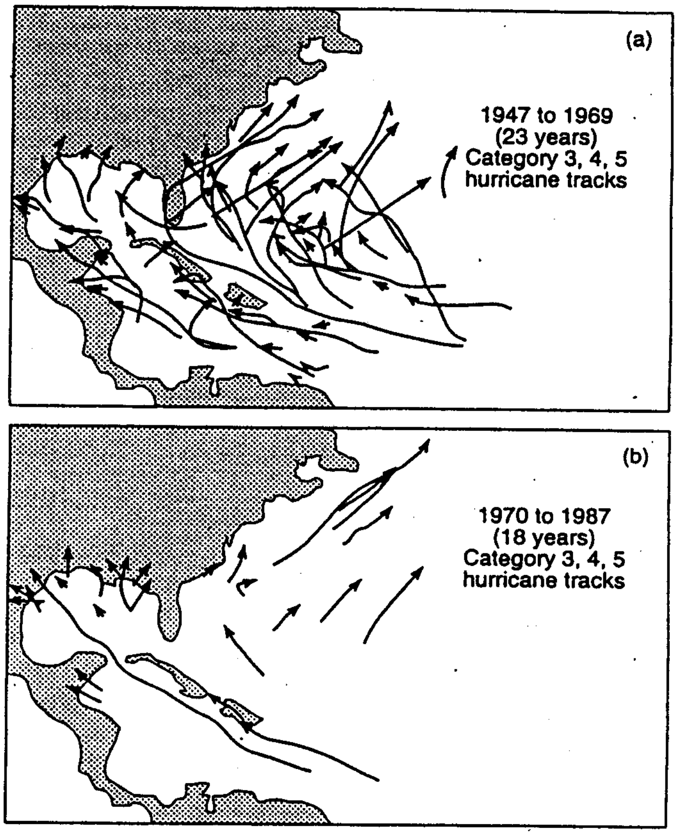

Fig. 8.1. Comparison of intense (Saffir/Simpson categories 3, 4, and 5) hurricane tracks for (a) 1947 to 1969, and (b) 1970 to 1987. Since 1989 there have been two landfalling intense hurricanes, Hugo (1989) and Andrew (1992). Graphic provided by W. Gray.

Hurricanes pose a number of threats to coastal communities including storm surge (e.g., Anthes 1982), high winds (e.g., Golden and Snow 1991), excessive rainfall (e.g., Dunn and Miller 1960), and tornadoes (e.g., Novlan and Gray 1974).[1] A storm

---

[1] Snowfall has occasionally been associated with the inland portion of hurricane circulation. for instance, in 1963 Hurricane Ginny caused more than a foot (30 cm) of snow in northern Maine (Pielke 1990)

surge is a dome-shaped area of water caused by strong hurricane winds and is related to the low surface pressure of a storm. Past disasters have focused attention on hurricane storm surge. For example, in 1900, more than 6000 deaths occurred in Galveston, Texas, primarily as a result of a hurricane storm surge. In 1957 the storm surge of over 20 feet associated with Hurricane Audrey extended as far inland as 25 statute miles and was the major cause of 390 deaths in Louisiana. Winds have also been responsible for significant loss of life. In September 1928, the waters of Lake Okeechobee, driven by hurricane wind, overflowed the banks of the lake and were the main cause of 1836 deaths associated with the storm. Loss of life due to excessive rainfall has primarily been an inland threat, such as that associated with Hurricane Camille (1969), although rainfall also provides economic benefits (Sugg 1968). Hurricane Andrew (1992) has increased attention to damage caused by strong hurricane winds (e.g., Wakimoto and Black 1993).

Table 8.1. Saffir/Simpson Hurricane Scale (after Herbert et al. 1993)

Category	Central (mb)	Pressure (inches)	Winds (mph)	Surge (feet)	Damage
1	980	≥28.94	74-95	4-5	minimal
2	965-979	28.50- 28.91	96-110	6-8	moderate
3	945-964	27.91-28.47	111-130	9-12	extensive
4	920-944	27.27-27.88	131-155	13-18	extreme
5	<920	<27.17	>155	>18	catastrophic

When they strike the U.S. coast, intense hurricanes cost lives and dollars, and disrupt communities. Figures 8.2a-j show U.S. intense landfalling hurricane tracks for each decade this century. Due largely to better warning systems, hurricane-related loss of life has decreased dramatically in the 20th century (NRC 1989). However, the economic and social costs of hurricanes is large and rising. A rough calculation shows that annual losses to hurricanes has been in the billions of dollars (cf. Sugg 1967). Landsea (1991, 62) documents $74 billion (1990 $) in hurricane related damage for the period 1949-1989 (cf. Gray and Landsea 1992, 1356). With the addition of the approximately $25 billion for Hurricanes Andrew (1992) and Bob (1991), the total is about $100 billion over 45 years, or well over $2 billion annually. Approximately 80% of the costs are attributed to intense hurricanes (Gray and Landsea 1992). However, as Landsea (1991), Sheets (1993), and others are quick to observe, this type of calculation is likely to significantly underestimate the magnitude of the actual hurricane threat because data based on past storm damage represents costs incurred prior to most coastal development. Were the same storms to landfall today, in most cases, damage would be significantly higher. Therefore, the $2 billion figure should be considered a lower bound on the annual costs of the hurricane threat facing the united states. Sheets (1993) estimates the annual monetary costs of hurricanes to be on the order of $3 billion.

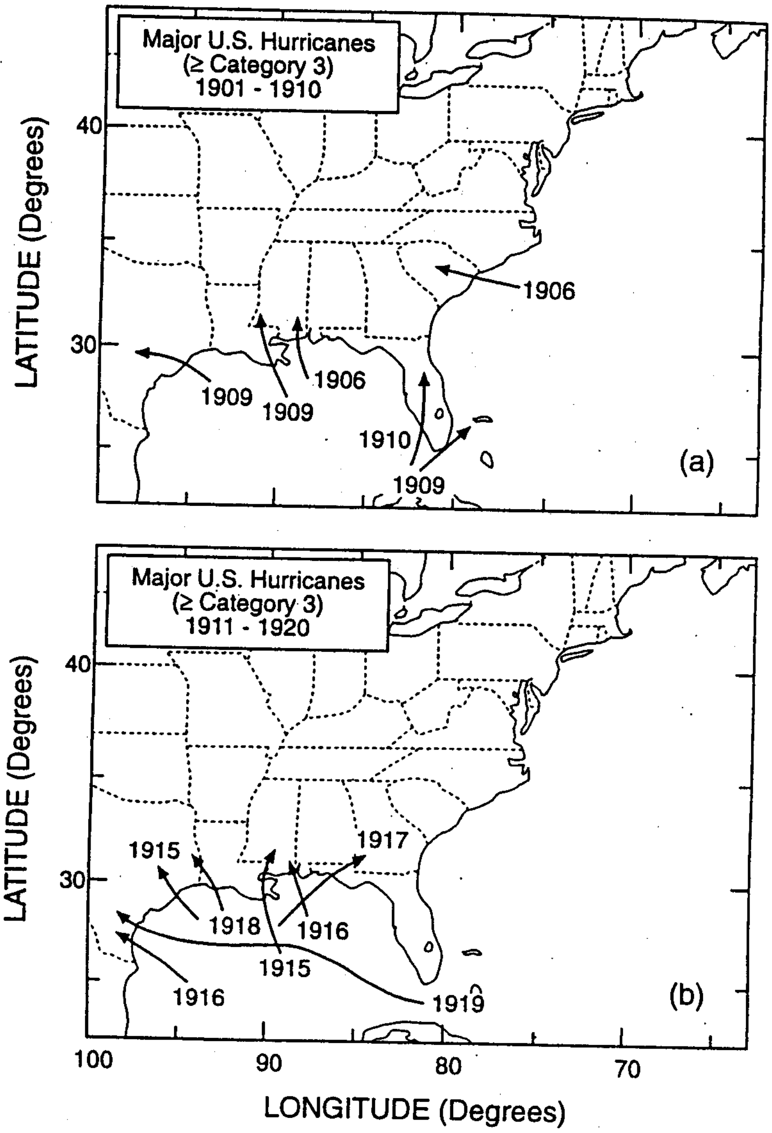

Fig. 8.2. Intense (categories 3, 4, and 5) landfalling hurricanes in the U.S. for (a) 1900s and (b) 1910s. Source: Herbert et al. (1993).

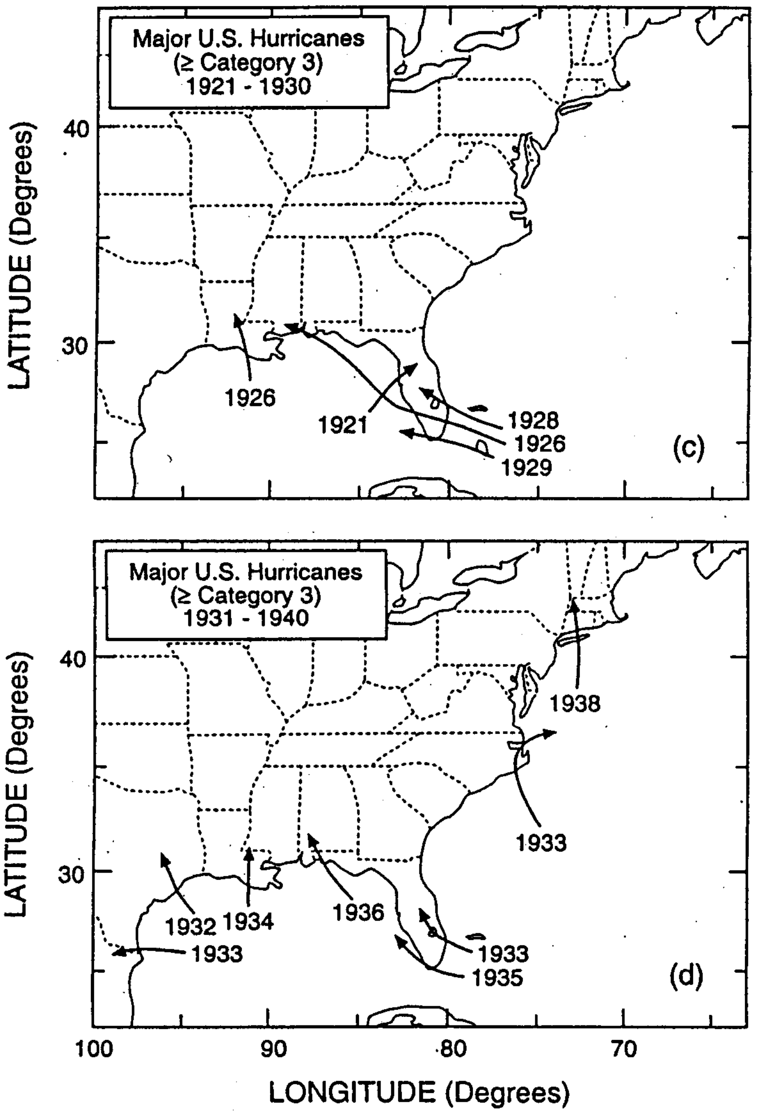

Fig. 8.2. Intense (categories 3, 4, and 5) landfalling hurricanes in the U.S. for (c) 1920s and (d) 1930s. Source Hebert et al. (1993).

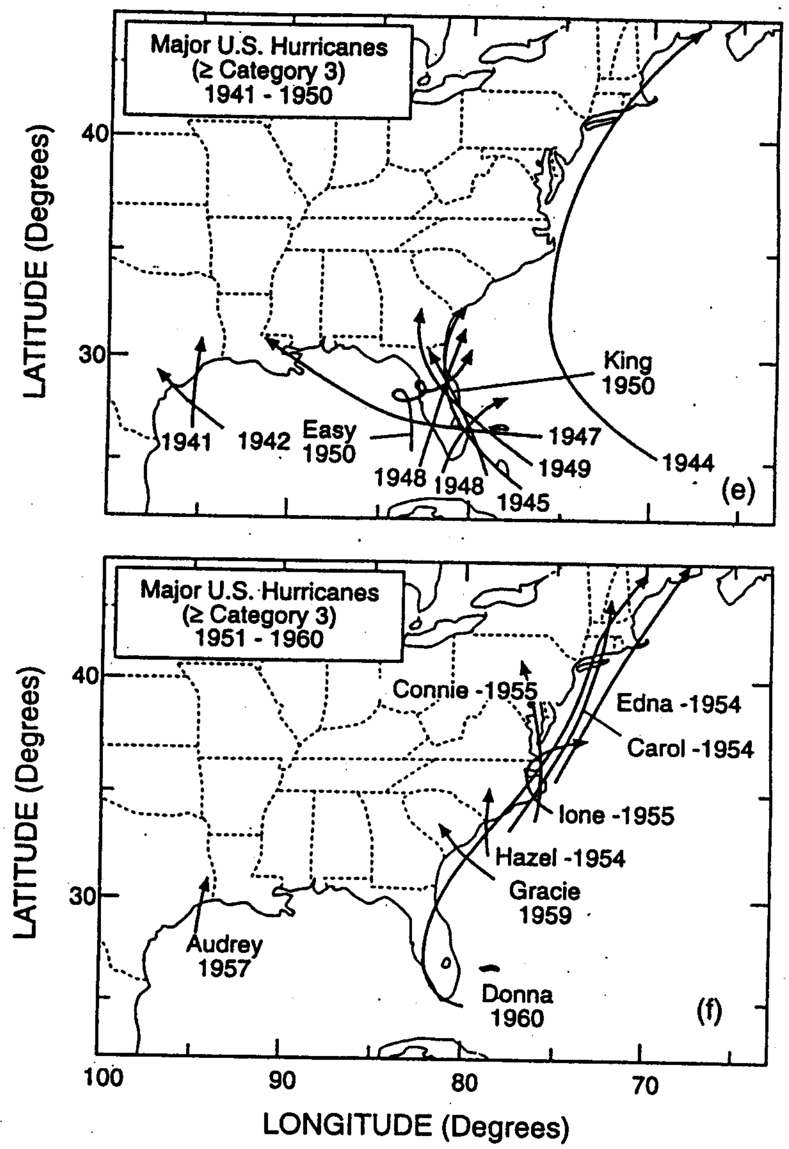

Fig. 8.2. Intense (categories 3, 4, and 5) landfalling hurricanes in the U.S. for (e) 1940s and (f) 1950s. Source: Hebert et al. (1993).

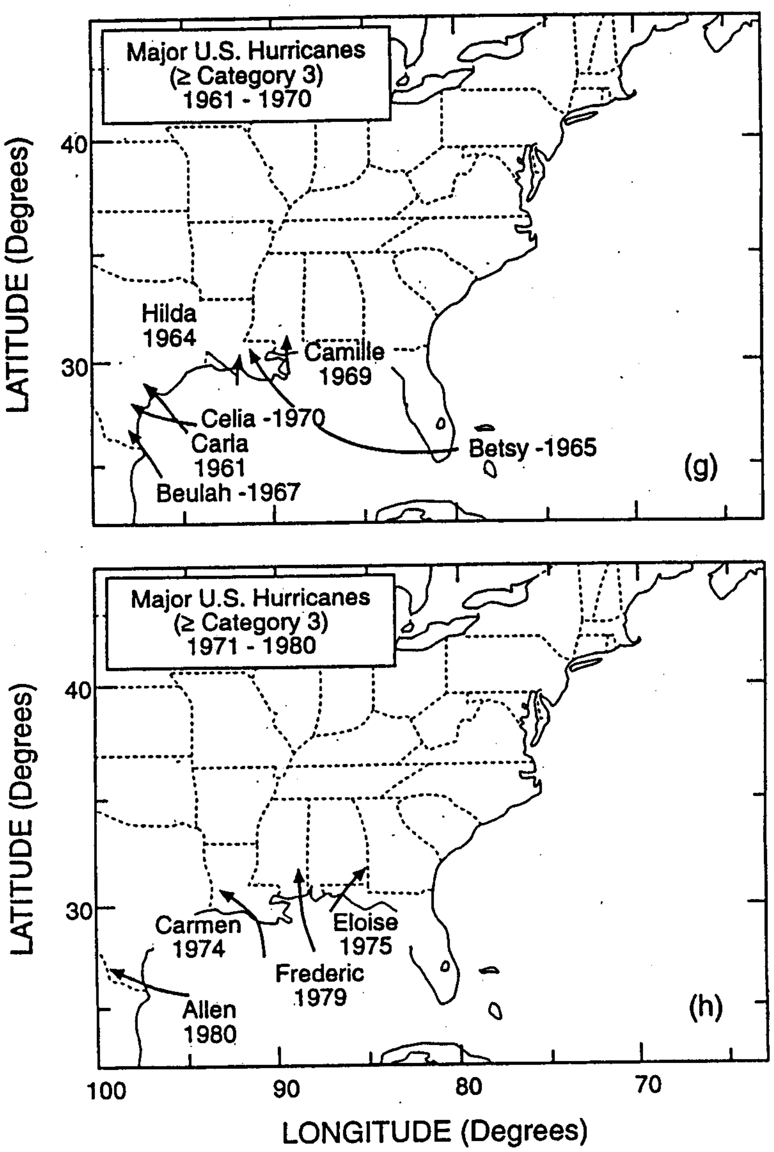

Fig. 8.2. Intense (categories 3, 4, and 5) landfalling hurricanes in the U.S. for (g) 1960s and (h) 1970s. Source: Hebert et al. (1993).

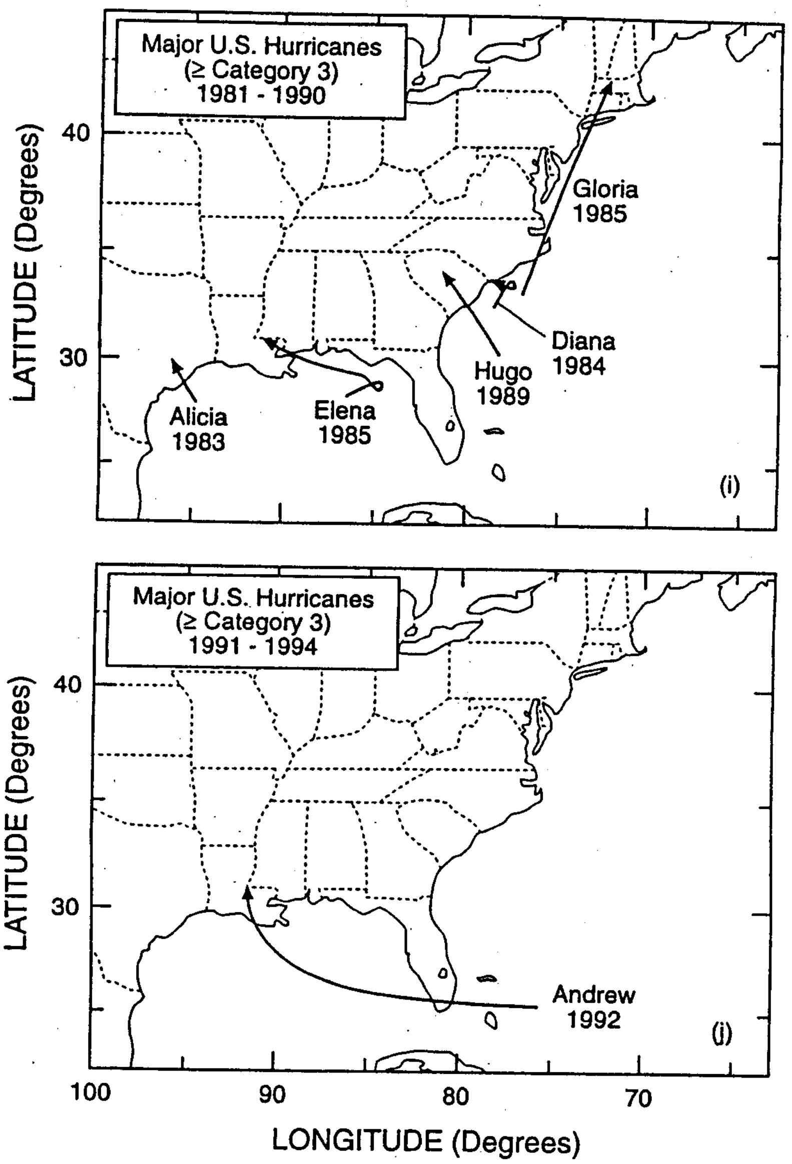

Fig. 8.2. Intense (categories 3, 4, and 5) landfalling hurricanes in the U.S. for (i) 1980s and (j) 1990s. Source: Hebert et al. (1993).

While the hurricane threat to the U.S. Atlantic and Gulf coasts has been widely recognized, only in recent years, following Hurricane Andrew, have many public and private decisionmakers sought to better understand the magnitude of the threat.[2] The U.S. will never escape the hurricane threat, although it is possible that with a better understanding of societal vulnerability to hurricanes, public and private decisionmakers may recognize ways to change behavior in ways that would significantly reduce societal vulnerability.

8.1.2 Extreme Weather Events

The hurricane is part of a broader class of extreme weather phenomena that threaten the United States. Other phenomena include winter storms (e.g., snow, sleet, freezing rain, and freezes), thunderstorms (e.g., tornadoes, heavy rains/floods, lightning, wind, and hail), and windstorms. Changnon and Changnon (1992) report insurance claims due to extreme weather events for the period 1950 to 1989. They find $66.2 billion (1991 $) in insured losses during the 40-year period due to extreme weather events, with about half due to hurricanes. For comparison, Landsea (1991) found *total* monetary losses over the same period due to hurricanes to be about twice the *insured* losses reported by Changnon and Changnon (1992). The difference is attributed to uninsured losses, damage to public infrastructure, federal disaster assistance payments, private contributions, and other costs (Pielke 1995).

In the face of large losses due to weather phenomena in recent years, the U.S. Congress established the U.S. Weather Research Program in Public Law 102-567. The program is justified on the basis that it will save the country "hundreds of lives, thousands of injuries, and billions of dollars" (USWRP 1994, xvi). While implementation of the program awaits congressional appropriations, a 1980 National Academy of Sciences assessment of the National Weather Service gives reason for caution in structuring a program to leverage societal benefits from scientific research:

> For many years the National Weather Service and its predecessor organization apparently operated on the assumption that if they produced a good product someone would come to get it and use it... Users are currently left largely to their own devices in determining what is available and how to use it; many are unaware of the information available. As a result, the potential benefits of the excellent information currently available are not being fully realized (NAS 1980).

While the hurricane threat to the U.S. Atlantic and Gulf coasts remains significant, past successes in reducing societal vulnerability to hurricanes (particularly the threat to human life) provide a significant base of experience to

---

[2] We use the term "decisionmaker" to refer to anyone faced with a decision. The term "policymaker" is reserved for elected officials and administrators at various levels of government.

serve as a prototype of how scientific information can play a more generally useful role in preparation, mitigation, and response efforts to extreme events.

8.1.3 Science for Society

In broader context, a significant aspect of societal responses to extreme weather events is the role of scientific research, particularly forecasts, in the decision processes of public and private individuals and groups. In recent years, in the U.S. as well as in other countries, the institution of science has faced close scrutiny with respect to its ability to contribute to societal problems (e.g., *Nature* 1995; Rensberger 1995). For instance, some members of Congress, both Republicans and Democrats, have called upon science to demonstrate the societal benefits that are often promised in efforts to secure federal funding (Byerly 1995). In light of changes in the environment of U.S. science policy, it is likely that sustained federal support of scientific research, including weather research, will be a function of a particular program's performance with respect to justifications made to Congress by its supporters (Brunner and Ascher 1992).

The case of the hurricane threat to the U.S. Atlantic and Gulf coasts provides the scientific community with an opportunity to demonstrate tangible societal benefits that are directly related to scientific research. Yet, demonstration of benefits is often difficult to achieve in practice as "the path between scientific research and societal benefits is neither certain, nor straight" (Brown 1992). As Glantz (1978) has noted, "adverse weather events by themselves can be devastating for society, but their effects are often exacerbated by economic, political, and social decisions made, in many instances, long before those events take place." Thus, while research holds much potential to contribute results useful to reducing societal vulnerabilities to hurricanes, if potential is to be realized, then care must be taken to understand such results in their broader political and social contexts.

8.1.4 The Challenge

The general challenge facing U.S. science policy is to connect scientific research more directly to societal benefits. In the context of the hurricane threat facing the U.S. Atlantic and Gulf coasts, the challenge is to improve public and private decisionmaking with the aid of science. With the modernization of the National Weather Service, a multi-billion dollar U.S. Global Change Research Program, and a congressionally authorized U.S. Weather Research Program, weather and climate forecasts on various time scales appear to be a growth industry. Yet, as Glantz (1986) has cautioned, "forecasts are the answer, but what was the question?"

The remainder of this paper has two purposes. First, it uses the concept of societal vulnerability to integrate the physical and societal dimensions of hurricanes in order to provide a sense of the broader context of the hurricane threat facing the continental United States. Second, the paper discusses ways in which interannual/decadal forecasts might contribute to reducing societal vulnerabilities to hurricanes, and recognizes both the opportunities and the limitations.

8.2 Societal Vulnerability to Hurricanes

Societal vulnerability (Pielke 1995) to hurricanes is a function of *exposure* and *incidence*. Clearly, if people were not exposed to hurricanes or if hurricanes did not occur (i.e., no incidence), then society would be *in*vulnerable to hurricanes. Exposure refers to the number of people and amount of property threatened by hurricanes. The gross number of exposed people and property can be reduced through preparedness efforts such as evacuation and building fortification. Incidence refers to the climatology of hurricanes -- how many, how strong, and where. Societal vulnerability, then, is determined through the societal and climatic aspects of the hurricane phenomenon.

8.2.1 Exposure to Hurricanes

Exposure is a function of (a) population at risk, (b) property at risk, and (c) preparedness (cf. Brinkmann 1975, 11-20). This section presents data on hurricane exposure at the coastal county level for 168 coastal counties that lie adjacent to the Gulf of Mexico and the Atlantic Ocean from the Mexico-Texas border to the Maine-Canada border. Figure 8.3 shows the coastal counties used in this study. Of course, societal vulnerability to hurricanes extends well inland, beyond the coastal counties. For instance, following Hurricane Andrew's landfall in Louisiana, 29 inland parishes were declared disaster areas in addition to all 11 of Louisiana's coastal parishes (USDOC 1993). The remnants of Hurricane Camille (1969) killed 109 in central Virginia as a result of up to 30 inches (0.76 m) of rain within 6 hours. Coastal counties, however, are a primary component of societal vulnerability to hurricanes.

Population at Risk. Figure 8.4 shows U.S. coastal county population by state for each of the 168 coastal counties from Texas to Maine for the years 1930 and 1990 (U.S. Census). The most readily apparent trend is the growth in population along the Gulf and southern Atlantic counties through North Carolina. For instance, in 1990 the combined population of Dade County, Florida, and its two neighbors to the north, Broward and Palm Beach counties, was more than that of 29 states. About the same number of people now live in Dade and Broward counties, Florida, as lived in *all* the 109 coastal counties from Texas through Virginia in 1930. A second trend is the very low level of growth in the coastal counties of the U.S.

northeast. Some counties north of New York City have actually experienced population decreases in recent decades. However, the population of the Atlantic coast from Baltimore to Boston remains very large.

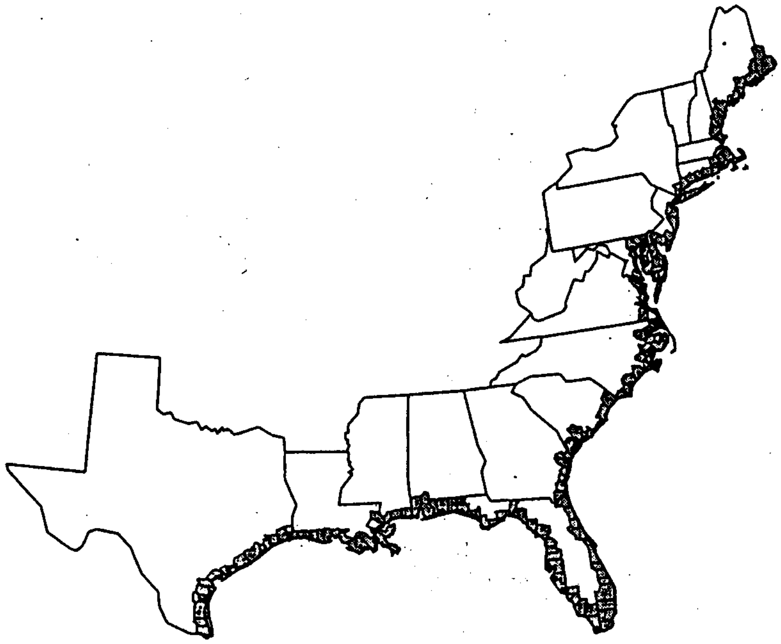

Fig. 8.3. The 168 coastal counties from Texas to Maine used in this study.

Rising population has not only created record densities for areas such as south Florida, but also "filled in" formerly low-population areas. In the 95 coastal counties from Texas through North Carolina the number of counties with populations of more than 250,000 tripled from 1950 to 1970, from 3 (3%) to 9 (10%), and doubled again from 9 to 18 (19%) by 1990. A quarter of a million residents is about the population of Charleston County, South Carolina, where Hurricane Hugo made landfall in 1989 and caused $8.2 billion (1993 $) in damage (Hebert et al. 1993, 10). (Hurricane Hugo, however, made landfall in a relatively unpopulated stretch of South Carolina coast (Baker 1994). Had Hugo directly hit a more populated section, casualties and damage would likely have been significantly higher.) The number of counties with more than 100,000 residents went from 15 (16%) in 1950 to 21 (22%) in 1970, to 36 (38%) in 1990. Hurricane Frederic made landfall in a county of about 100,000 near Gulf Shores, Alabama, in 1979 and caused $3.8 billion (1993 $) in damage (Hebert et al. 1993, 10). Another way to look at population growth is in terms of the dwindling number of counties with very few residents. From Texas through North Carolina, the number of counties with less than 50,000 residents decreased from 75 (79%) in 1950 to 54 (57%) in 1970, and to 38 (40%) by 1990. Hurricane Andrew made landfall across two such relatively low-population counties in Louisiana in 1992 and caused about $1 billion (1993 $) in damage (Cochran and Levitan 1994). According to the U.S. Census Bureau, population growth can be expected to continue in most coastal counties (Campbell 1994).

In aggregate, the 168 coastal counties (out of more than 3,000 nationwide) are home to approximately 40 million people, or about 16% of the total U.S. population. Although the numbers are large, census populations may actually underestimate the number of people in coastal counties during hurricane season. Because the hurricane season overlaps the tourist season in many of these coastal counties, many more people in addition to permanent residents may actually be in the path of an approaching hurricane (cf. Sheets 1993).

Property at Risk. Figure 8.5 shows insured property values in each of the 168 coastal counties from Texas to Maine for the years 1988 and 1993 (IRC/IIPLR 1995). Figure 8.6 shows the increase from 1988 to 1993 as a percentage of the 1988 total. An increase of 100% represents a doubling in value, 200% a tripling, etc. Inflation accounts for 19.5% of the aggregate growth during that 5-year period (Council of Economic Advisors 1994). The remainder of growth can be attributed to expanded insurance coverage and real increases in property values.

The total amounts of insured property are staggering. Over $3.1 *trillion* worth of property was insured in 1993, an increase of 69% (50% excluding inflation) over the 1988 total of about $1.9 trillion. The 1988 total represented an increase of 64% (35% after inflation) over the 1980 total of about $1.1 trillion (Sheets 1993, 47). For comparison, the coastal counties represented about 15% of the total insured property in the United States in 1993, which was about $21.4 trillion. For 1988 the figures are approximately 14% and $13 trillion, respectively.

Compared to rates of population growth, growth in insured property in the last 5 years is startling. After adjusting for the effects of inflation, the aggregate growth in insured property for all coastal counties is 46%. Table 8.2 shows a summary by state of insured property for the coastal counties. Except for Louisiana, Florida had the slowest rate of growth in coastal insured property. Despite its lower rate of growth, the total insured coastal property in Florida exceeds the combined coastal insured property from Texas to Delaware (excluding Florida). Within states, local variations are large. Only one county, Laforche Parish, Louisiana, had property values decrease over the period (compensating for inflation). Over the 5 year period, 24 counties experienced more than a doubling in insured property. Although the amount of insured property is large, it is worth repeating a point made in the introduction that insured property represents only a portion of the total losses due to hurricanes. In addition, uninsured property and public infrastructure makes up a substantial portion of damage due to hurricanes. It is also important to recognize that the "costs" of hurricanes go well beyond those which can be easily expressed in dollars (e.g., Mauro 1992).

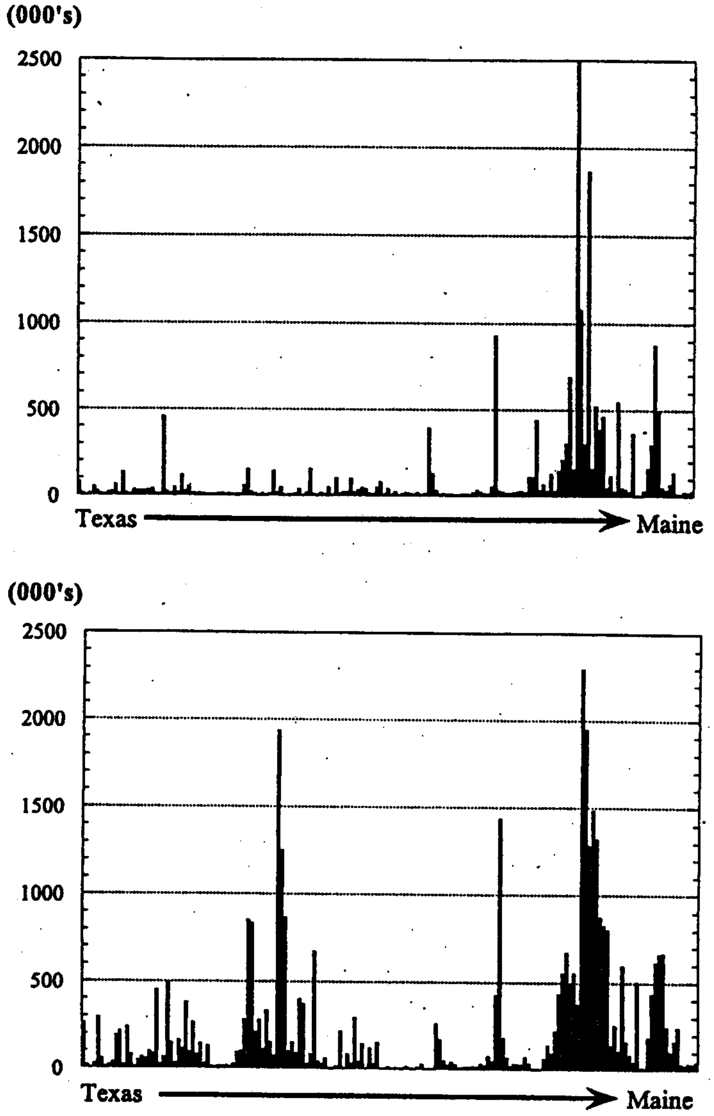

Fig. 8.4. U.S. Coastal county population by county and state for (top) 1930 and (bottom) 1990. Source: U.S. Census Bureau.

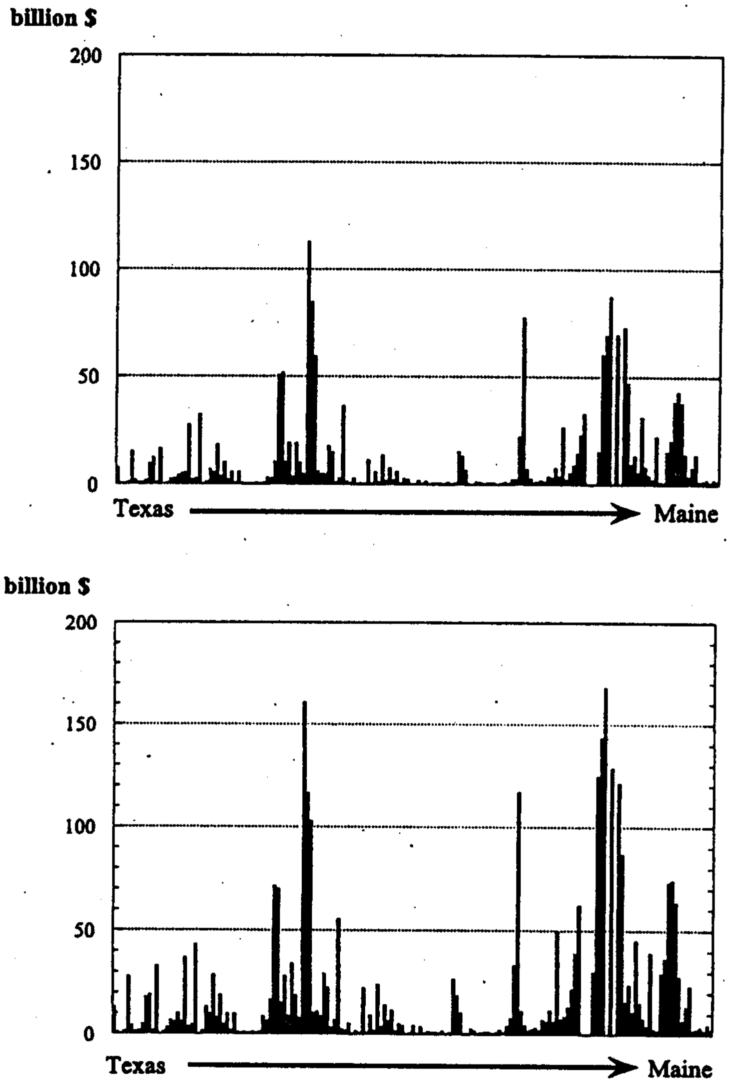

Fig. 8.5. Insured U.S. coastal county property values by county and state for (top) 1988 and (bottom) 1993. Source: Insurance Institute for Property Loss Reduction.

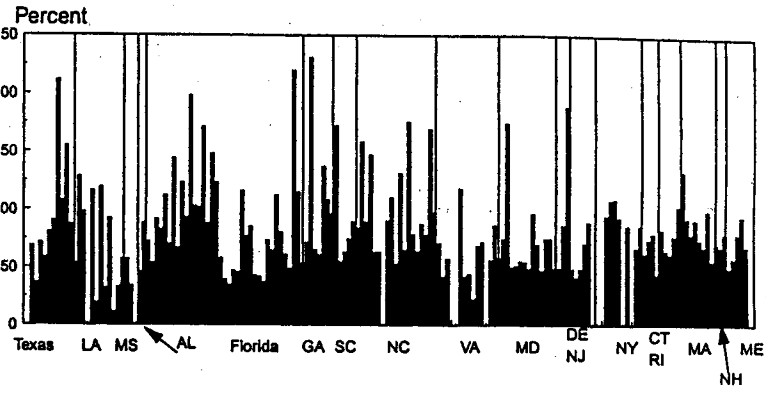

Fig. 8.6. Increase in insured U.S. coastal county property values by county and state from 1988 to 1993 as a percentage of the 1988 total. Source: Insurance Institute for Property Loss Reduction.

Table 8.2. Summary of Coastal County Insured Property by State.

State	1988 Total coastal Insured Property Values (Current billions of $)	1993 Total Coastal Insured Property Values (Current billions of $)	1988-1993 Increase as a Percent of 1988 Value
Texas	70.1	128.6	83
Louisiana	87.5	123.5	41
Mississippi	14.1	25.5	80
Alabama	22.8	36.9	61
Florida	565.8	871.7	54
Georgia	16.5	32.5	96
South Carolina	31.2	54.7	75
North Carolina	22.7	45.0	97
Virginia	42.5	67.8	59
Maryland	129.2	202.6	56
Delaware	38.7	67.7	74
New Jersey	88.5	152.8	72
New York	301.7	595.6	97
Connecticut	143.3	248.1	73
Rhode Island	52.9	83.1	57
Massachusetts	179.8	321.6	78
New Hampshire	18.5	34.9	88
Maine	32.3	54.5	68
Coastal Total	1858.1	3147.0	69
U.S. Total	12967.1	21422.0	65

Source: Insurance Institute for Property Loss Reduction.

Preparedness. Preparedness, as used in this paper, refers to all of the various efforts at various levels of public and private decisionmaking to reduce vulnerability to hurricanes. We use the term "preparedness" in a general sense to refer to the full range of emergency management activities (e.g., planning, mitigation, response, restoration) in full recognition of the significant differences between the various phases of preparedness. Preparedness can be broken down into component phases such as planning, mitigation, response, restoration, etc., and has been widely studied by the natural hazards community (e.g., hazard research centers exist at the Universities of Colorado, Delaware, and Texas, see Burton et al. [1993] for a review of the field). Salmon and Henningson (1987, 2) refer to preparedness as "mitigation planning" and they argue that "it makes excellent sense to do now those things which can reduce or minimize the risks and costs of future hurricanes, and hasten sensible recovery practices after the storm." Mitigation planning has technical, practical, and political aspects which, in large part, are often determined by the idiosyncrasies of and resources available to each community. Therefore, levels of preparedness (and consequently, societal vulnerability more broadly) vary a great deal along the U.S. Gulf and Atlantic coasts.

In general, preparedness activities have short- and long-term components (Salmon and Henningson 1987). Short-term responses focus on a particular approaching storm. Long-term responses focus on the hurricane threat more generally. Many short-term responses related to protection of the exposed population are based upon long-term studies of expected storm surge due to a landfalling hurricane (Sheets 1990; Baker 1991). For example, expected coastal flooding is calculated using the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) storm-surge model (Jarvinen and Lawrence 1985).[3] Evacuation studies are then based upon the areas identified to be at risk from the output of the SLOSH modeling process. Such studies include a behavioral component that seeks to identify "realistic assumptions of how the public will behave when advised or ordered to evacuate" and a transportation analysis which seeks to identify the capacity of routes of escape, points of congestion (Baker 1993; Carter 1993), and places of "last resort refuge" (Sheets 1992). Short-term response is focused on the hurricane forecast. The National Weather Service, National Hurricane Center, local and state officials, and the media coordinate hurricane watches and warnings based upon the forecast tracks of specific approaching hurricanes (Sheets 1990).

The following isolated incident, which occurred in South Carolina during Hurricane Hugo (1989), illustrates the stakes involved with long-term planning for short-term response.

> In the village of McClellanville, the Lincoln High School was used as an evacuation shelter. The evacuation plan listed the base elevation of the school as 20.53 feet National Geodetic Vertical Datum (NGVD). Many of the residents took shelter in this school.

---

[3] The SLOSH model is run for 22 "SLOSH basins" along the U.S. coast from Texas to Maine (Jarvinen and Lawrence 1985). For each basin the model simulates from 250 to 500 different hypothetical storms. The results are maps that depict the "maximum envelope of water" for a family of storms (Sheets 1990). Errors in the forecasts of specific landfalling storms are compensated for because each map represents a composite of maximum storm surges for a range of landfall points, storm movement, and intensity.

> During the height of the storm, water rose outside the school and eventually broke through one of the doors. Water rushed in and continued to rise inside the school reaching a depth of 6 feet within the building. A resident with a videocassette recorder documented people climbing on tables and bleachers to escape the rising water. As the water reached its maximum height, children were lifted onto the school's rafters. Fortunately, everyone survived the event although not without considerable anxiety.
>
> Later examination revealed that the base elevation of the school was 10 feet, not the 20.53 feet listed on the evacuation plan. This school should not have been used as a shelter for any storm greater than a category 1 hurricane (USDOC 1990, 12).

Warning and response to Hurricane Hugo based upon the SLOSH model process has been generally judged successful (e.g., USDOC 1990; Baker 1994; Coch 1994), yet had the evacuees at Lincoln High been less fortunate such judgments would likely have been very different. The incident demonstrates the fine line between success and failure in long-term planning to reduce the hurricane threat. Another example is from Louisiana during Hurricane Andrew, when a number of emergency management officials had difficulty interpreting updated storm surge maps, and consequently relied on older, potentially dated information. Other officials in Louisiana did not have relevant FEMA software available to aid in the evacuation decision process (USACE/FEMA 1993).

The protection of property at risk also has short-term and long-term components. Designing structures to withstand hurricane-force winds is an important factor in reducing property damage (e.g., Mehta et al. 1992). An important aspect in the reduction of property damage is the establishment and enforcement of building codes commensurate with the expected risk. According to John Mulady, an insurance industry official, "a 1989 study of the damage done by hurricanes Alicia and Diana found nearly 70% of damage done to homes was the result of poor building code enforcement. However, in North Carolina, where codes were effectively enforced, only 3% of the homes suffered major structural damage" (Mulady 1994, 4). One insurance official claimed that poor compliance with building codes accounted for about 25%, or about $4 billion, of the insured losses in south Florida due to Hurricane Andrew (Noonan 1993). Other estimates range upwards to 40%, or close to $6.5 billion.

Complacency is the enemy of preparedness. The *New York Times* reported in 1993 that "of 34 coastal areas identified as needing evacuation studies, less than half have been completed, and only $900,000 a year is available for commissioning new ones" (Applebome 1993). A FEMA official complained that the lack of "funding is inhibiting an aggressive and comprehensive approach to hurricane preparedness programming" (Applebome 1993). Complacency led to Dade County's unpreparedness for Hurricane Andrew (Leen et al. 1993). For instance, in 1988 Dade county employed 16 building inspectors to serve a population of well over 1 million. On many occasions in the years preceding Andrew inspectors reported conducting more than 70 inspections per day, a rate of one every six minutes, not counting driving time (Getter 1993). Such anecdotes beg for systematic assessments of hurricane preparedness in the broader context of hurricane vulnerability *before a hurricane strikes*. There is sufficient evidence of complacency along the U.S.

Atlantic and Gulf coasts that future hurricane disasters should not come as surprises when they occur (cf. Sheets 1992, 1993).

With population-at-risk and property-at-risk rising rapidly in many coastal communities, and the rate of growth increasing as well, the key to reduced hurricane exposure lies in improved preparedness. While past responses to reduce the threat to human life have been extremely successful, demographic changes mean that the nature of the hurricane threat is ever changing. The recent experience of Hurricane Andrew in Dade County, previously believed to be among the best prepared locales, suggests that many coastal areas may not be as prepared for hurricane impact as was once thought (Pielke 1995). The worst disasters may lie ahead.

Intensity. The intensity of an Atlantic or Gulf of Mexico hurricane at landfall is directly related to its central pressure and to its speed of movement: The lower the central pressure, the higher the wind velocity (Simpson and Riehl 1981; Anthes 1982; Elsberry et al. 1988). The potential minimum central pressure is limited by sea surface temperature (Merrill 1985, 1987), a warmer sea means lower pressure (and higher winds). For example, based on analysis in Merrill (1985), a potential minimum central pressure of 964 mb (which corresponds to the minimal category 3 storm) requires a sea surface temperature of at least 26.5°C). Hurricane Gilbert (1988), a category 5 hurricane, is the most intense Atlantic hurricane on record, with a central pressure of 888 mb. Since 1899, only two category 5 hurricanes have made landfall on the U.S. coast, Camille in 1969 and an unnamed Labor Day storm that hit the Florida Keys in 1935 (Hebert et al. 1993). Hurricane Andrew (1992) was a category 4 storm.

The speed of a storm is added onto the wind speeds determined by the central pressure. For instance, the Great New England Hurricane of 1938 was travelling over 70 knots at landfall (cf. Coch 1994). Thus, winds parallel to the storm's direction of motion were increased by that amount. The 1938 storm is an example of hurricanes that accelerate out of the tropics ahead of a trough in the westerlies. Hurricanes Hazel (1954) and Carol (1954) are two other examples of such rapidly moving storms. Damage potential due to strong winds is directly related to a storm's central pressure and speed of forward movement.

On average, storms only reach about 55% of their maximum potential intensity (DeMaria and Kaplan 1994). In addition to (a) warm sea surface temperatures, favorable conditions for intensification include (b) weak vertical shear of the horizontal wind (less than about 15 knots between the upper and lower troposphere within a radius of about 4 degrees of latitude from the center), (c) an environment favorable for deep cumulonimbus convection, and (d) an upper tropospheric large-scale anticyclone over the surface low so as to evacuate mass from the region of the hurricane, thereby permitting surface pressure to continue to fall (Pielke 1990).

Under the conditions favorable for hurricane intensification, there are generally two types of maximum intensity hurricanes that threaten the U.S. Atlantic and Gulf coasts. The first type is directly related to the sea surface temperature and is most appropriate for slow moving storms such as usually occur in the Gulf of Mexico and over Florida and the Southeast coasts. The slow movement of these storms means that winds in parallel and in the same direction as the storm's motion will increase on the order of only about 10%. The second type of maximum intensity storm is one that has intensified over a warm sea surface and then is rapidly ejected to higher latitudes. In this scenario the rapid transit over cooler ocean waters does not permit much weakening of the storm prior to landfall. These storms threaten the Northeast Atlantic coast with the storm's high speed resulting in a large magnification of the winds in the storm's right front quadrant (where wind direction is in the storm's direction of motion). Consequently, the area of maximum winds remains offshore in storms that move parallel to the Atlantic coast (with the eye remaining offshore).

Occurrence. Landfalling hurricanes of categories 3, 4, and 5 are irregular events within a decadal and longer time scale, and for particular locations on the coast. Thus, when they do occur, they are intensively studied, e.g., Hurricane Frederic (Powell 1982); Hurricane Hugo (Golden 1990); Hurricane Andrew (Wakimoto and Black 1994).

On the annual time scale, Gray (1994) summarizes a statistical Atlantic Seasonal Hurricane Variability technique based on a number of climatic indices, including factors such as the state of the El Niño/Southern Oscillation (ENSO), the Quasi-Biennial Oscillation (QBO) of 30 mb and 50 mb stratospheric winds, the Caribbean Basin-Gulf of Mexico sea-level pressure anomaly in spring and early summer, the lower latitude Caribbean Basin 200 mb zonal wind anomaly in early summer, the rainfall in Africa's Western Sahel region, and a parameter expressing the trend in west to east surface pressure and surface temperature gradients in February through May in West Africa. Among the forecasts made using this method are Hurricane Destruction Potential, Intense Hurricanes (reaching at least category 3 at some time in a storm's evolution), and Intense Hurricane Days (see Gray et al., Chap. 2, this volume). Because of their record of success, the seasonal hurricane forecasts have received wide attention in user communities (e.g. Morgenthaler 1994).

It has been suggested that time periods longer than a year might be amenable to some level of forecast skill. Landsea et al. (1994) speculate to a connection between decadal variations in the "ocean conveyor belt" and sea surface temperatures, Sahel rainfall, ENSO events, and Atlantic hurricanes. Gray (1992) notes that in only one instance has an intense hurricane been observed to strike the Atlantic coast of the U.S. (Andrew in 1992) in years with simultaneous occurrences of a warm ENSO event and dry Western Sahel conditions. Gray and Landsea (1992) found that category 3, 4, and 5 hurricanes along the U.S. Atlantic coast have a strong correlation with Sahel rainfall (cf. Gray 1990). Lare and Nicholson (1994) discuss dry conditions in the western Sahel and attribute intra-year persistence of anomalous wet or dry periods to land-atmosphere feedbacks.

The track record of seasonal hurricane forecasts appears to demonstrate that some statistical skill in predicting the level of hurricane activity in the Atlantic ocean, at least on an annual basis, and with some suggestion that longer period skill may be achievable (cf. Livezey 1990). However, none of these techniques offers a tool for predicting with skill specific landfall locations at annual or longer time scales (Hess and Elsner 1994). Thus, climatology remains the best tool available to estimate coastal vulnerability to hurricane occurrence for specific locations.

Landfall frequency. Ninety-five percent of category 3, 4, and 5 hurricanes in the Atlantic Basin occur during August to October (Landsea 1993). Over the last several decades there has been an observed decrease in major landfalling hurricanes (Landsea et al. 1995, Landsea 1993). Hurricanes Hugo and Andrew and the active 1995 hurricane season have led many to suggest that annual hurricane activity may be increasing. According to Hebert et al. (1993) a category 4 storm strikes the U.S., on average, every 6 years. Hurricanes Andrew and Hugo are the only category 4 storms to make landfall on the U.S. coast since 1969.

Hebert et al. (1993) also note that on the average two hurricanes strike the U.S. coast each year, with *two intense hurricanes striking the U.S. coast every 3 years.* Climatology suggests that the average damage due to an intense hurricane would only need to be $4.5 billion for annual U.S. exposure to be at least $3.0 billion. Hurricanes Hugo and Andrew suggest, however, that these estimates may be low. If the average damage due to an intense hurricane is $7.5 billion, for example, then annual exposure would be at least $5.0 billion. Such estimates exclude the costs of landfalling tropical storms and category 1 and 2 hurricanes which are capable of extensive economic damage (cf. Landsea 1991). For example, tropical storm Gordon (1994) resulted in more than $200 million in agriculture-related damage in Florida (NYT 1994).

Other climatological information related to landfall frequency includes (a) 35% of all hurricanes have hit Florida, (b) more than 70% of category 4 or 5 storms have hit Florida and Texas, and (c) along the middle Gulf coast, southern Florida, and southern New England half of all landfalling hurricanes have been category 3 and higher.

Jarrell et al. (1992) compile coastal county hurricane landfalls since 1900 and provide the data necessary to compute landfall probabilities by coastal county. One storm which could arguably be added to their compilation include 17-26 August 1933 storm that made landfall at the North Carolina Outer Banks with a central pressure of 960 mb. and moved north along the western side of the Chesapeake Bay (Cobb 1991). Figure 8.7 shows the observed annual probability of a direct hit by an intense hurricane expressed as a percentage for each coastal county from Texas to Maine. The highest probability is for Monroe County, Florida (0.095), immediately to the south of Dade County where Hurricane Andrew (1992) made landfall. The Gulf coast and the Atlantic coast of Florida are particularly at risk to hurricane landfall. In contrast, several counties along the Gulf coast and many along the Atlantic coast have never experienced a direct hit from intense hurricane during the period 1900-1994. Most of New England sees few direct hits from hurricanes because most storms accelerate northward or northeast on a track that typically places the storm either inland or parallel to the coast but offshore. The absence of direct hits to the northern Florida and Georgia coasts, in contrast, is partly a consequence of their orientation with respect to the more typical hurricane track as the storms begin to recurve around the subtropical Bermuda high pressure ridge. Undoubtedly, the absence of direct hits is also partly due to good fortune (cf. Kocin and Keller 1991). A landfall of Hurricane Hugo (1989) just slightly farther south would have altered these statistics. Indeed, Ludlam (1963) reports that a number of hurricanes struck the coast of northern Florida and Georgia in the 18th and 19th centuries. For instance, the Atlantic coast between St. Augustine, Florida, and Savannah, Georgia, was hit by very strong storms in 1824 and 1837.

Table 8.3 shows annual landfall probabilities (percentages) for intense hurricanes, average return period in years, and year of last direct hit by an intense hurricane for selected coastal counties and major metropolitan areas for each state from Texas to Maine through 1994. Table 8.3 also displays for each coastal county insured property values and estimated 1993 population. The return period is simply the inverse of the annual probability and represents the average number of years between direct hits for each location. An observed annual landfall probability of 0.053 for Miami, Mobile, and Galveston corresponds to a greater than 50% chance of at least one intense hurricane within the next 13 years.[4] Similarly, an observed annual landfall probability of 0.021, such as observed in Charleston, South Carolina, Wilmington, Delaware, and Providence, Rhode Island, corresponds to a greater than 50% chance of at least one intense hurricane within the next 33 years.[5] Climatology represents a baseline against which efforts to improve long-term forecasts ought to be measured. Reliable forecasts that improve upon climatology may have value to those decisionmakers who can alter their behavior accordingly.The probabilities shown in Fig. 8.7 for intense hurricane are similar to the findings of Ho et al. (1987) for all types of landfalling hurricanes. Ho et al. (1987, 77) find that:

> Highest frequency of landfalling tropical cyclones on the Atlantic coast is in southern Florida, and a comparatively high frequency appears to the south of Cape Hatteras, North Carolina. The frequency of entries drops off rapidly from Miami to Daytona Beach, Florida and from Cape Hatteras northward to Maine, except around Long Island.

Simpson and Lawrence (1971) report observed landfall probability for 50-mile segments of coast. Differences between Simpson and Lawrence, Ho et al., and the analysis of landfall probability in this paper are primarily due to different levels of analysis -- that is landfall probability percentages are given in this paper for each coastal county, whereas Simpson and Lawrence and Ho et al. give landfall probabilities for equal segments of coastline. Each method has strengths: equal segments of coastline allow for ready comparison between segments, whereas data

---

[4] The calculation which gives the period N, where N equals the number of years from now within which there exists a greater than 50% chance of at least one intense hurricane is, $(1 - P)^N \geq 0.50$, where P is the annual landfall probability based on the historical record and is assumed to be constant, and events are assumed to be independent from year to year.

[5] For Monroe County, Florida immediately to the south of Dade County (Miami) climatology suggests that there is a greater than 50% chance of at least one intense hurricane in the next 7 years.

by county may be more meaningful to decisionmakers at state and local levels. Figure 8.8 shows analyses of landfall probabilities from Simpson and Lawrence and Ho et al. for purposes of comparison. It has been suggested that hurricane intensity, occurrence, and landfall frequency may be affected by anthropogenic global warming. One hypothesis is that the oceans would warm, thereby creating more intense hurricanes over a greater geographic area (Emanuel 1987). But Gray (1990) argues that variability in hurricane incidence is a function of random climatic variability. See also Emanuel, Chap. 3, this volume. On the basis of such scientific hypotheses, a number of groups have argued that the recent impacts of Hurricanes Andrew and Hugo are evidence for global warming (e.g., Leggett 1994). In addition to faulty logic (i.e., the converse of a true proposition is not necessarily true) such arguments, no matter how well intentioned, serve to direct attention away from the documented hurricane threat. In the context of the hurricane threat facing the U.S., such arguments focus attention on responses to global warming (e.g., reducing carbon emissions) rather that on the need for increased hurricane preparedness in individual communities to reduce vulnerability. Increased effort in preparedness is necessary under *any* climate change scenario.

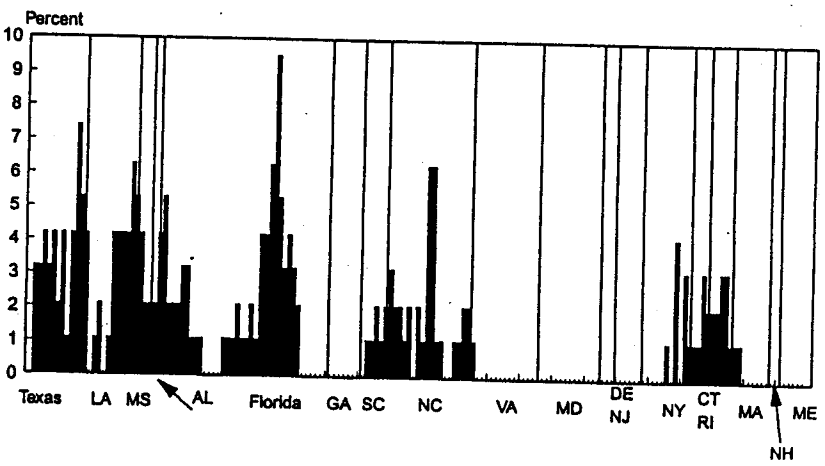

Fig. 8.7. Observed (1900-1994) annual probability of a direct hit by an intense hurricane for U.S. coastal counties from Texas to Maine.

Furthermore, from the standpoint of societal vulnerability to hurricanes, the cause of any increased hurricane occurrence, intensity, and landfall frequency is arguably less important for purposes of action because response efforts necessarily must focus on preparedness and not hurricane prevention. Consider that coastal population has increased by more than 20% over the period 1970 to 1990 and insured property has increased by more than 180% over the period 1980 to 1993. Meanwhile, over the period 1970 to 1990 hurricane incidence was well below the observed climatological average (Landsea et al. 1995). Efforts to reduce vulnerability make sense no matter what the cause of any increase in hurricane incidence. In other words, global warming is largely irrelevant to the need for actions to reduce our vulnerability to hurricanes. History alone dictates that such actions are sorely needed.

Table 8.3. Summary of hurricane statistics for selected locales in Atlantic and Gulf coastal states.

State	City	County	Population 1993 (est)[a] (000s)	Insured Property 1993[b] (billions $)	Observed Intense Landfall Probability[c]	Return Period (yr)	Most Recent Intense Direct Hit[d] (Year, Category, Storm)
TX	Brownsville	Cameron	270	13.182	3.2	31.7	1980 (3) Allen
	Galveston	Galveston	217	19.309	5.3	19.0	1983 (3) Alicia
LA	New Orleans	Orleans	491	43.340	4.2	23.7	1965 (3) Betsy
MS	Gulfport	Harrision	166	13.470	2.1	47.5	1985 (3) Elena
AL	Mobile	Mobile	384	28.606	5.3	19.0	1985 (3) Elena
FL	Tampa/	Hillsbor-	847	69.968	1.1	95.0	1921 (3)
	St. Petersburg	ough?	859	71.283	1.1	95.0	1921 (3)
	Miami	Pinellas	1979	160.844	5.3	19.0	1992 (4) Andrew
	Jacksonville	Dade Duval	689	55.527	0.0	-	1854
GA	Savannah	Chatham	219	22.386	0.0	-	1893
SC	Charleston	Charleston	304	24.118	2.1	47.5	1989 (4) Hugo
NC	Wilmington	New Hanover	125	11.814	2.1	47.5	1960 (3) Donna
VA	Norfolk	Norfolk	261	18.912	0.0	-	1856
MD	Ocean City	Worcester	35	6.269	0.0	-	1933 (3)[f]
	Baltimore	Baltimore[e]	1438	117.128	0.0	-	1850
DE	Wilmingon	New Castle	450	49.794	010	-	1861
NJ	Asbury Park	Monmouth	227	62.038	0.0	-	1861
NY	New York City	Kings	2289	124.887	0.0	-	1821
CT	New Haven	New Haven	803	87.142	1.1	95.0	1938 (3)
RI	Providence	Providence	596	45.305	2.1	47.5	1954 (3) Carol
MA	Cape Cod	Barnstable	187	29.572	1.1	95.0	1954 (3) Edna
	Boston	Suffolk	649	74.299	0.0	-	1869
NH	Portsmouth	Rockinham	243	28.010	0.0	-	1788
ME	Portland	Cumberland	245	23.341	010	-	1830

[a] Source: US Census Bureau.

[b] Source: Insurance Institute for Property Loss Reduction.

[c] Source: Jarrell et al. (1992). Period of record is 1900-1994.

[d] Data for years since 1900 from Herbert et al. (1993), Table 11, 24-25. Estimates for years prior to 1900 are based on descriptions in Ludlam (1963) and Tannehill (1952).

[e] Includes both city and county.

[f] According to data in Cobb (1992) the 1933 storm was a category 3 hurricane.

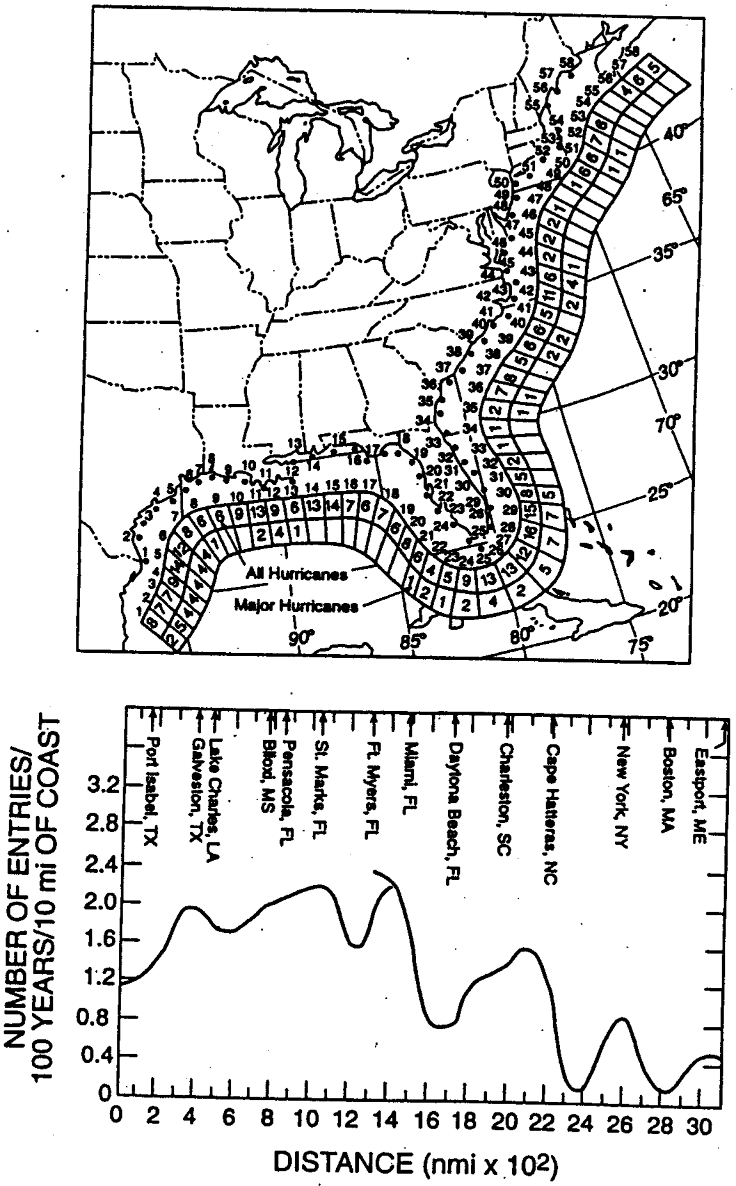

Fig. 8.8. Analysis of landfall probabilities from (top) Simpson and Lawrence (1971) and (bottom) Ho et al., (1987) for purposes of comparison.

8.3 Long-Term Forecasts and Reducing Societal Vulnerabilities to Hurricanes: Opportunities and Limitations

If we assume that for the foreseeable future little can be done to control hurricane incidence (i.e., intensity, occurrence, and frequency), then efforts to reduce societal vulnerability to hurricanes must focus on reducing exposure (i.e., population and property at risk, improving preparedness). Consequently, the value of long-term forecast might be determined through answers to the following question:[6]

> How might long-term (interannual/decadal) forecasts of hurricane incidence be used (directly/indirectly) to reduce exposure (i.e., population at risk, property at risk, unpreparedness) and thus also reduce the societal impacts of hurricanes?

To answer this question a series of assessments might be structured using the methodology applied by Glantz (1976, 1977, 1979). One such study sought to determine:

> How much flexibility decisionmakers in Saskatchewan and in Canada might have, given perfect information about their climate one year in advance. Although such a forecast will never be available, an assessment of the impact of a perfect forecast can be useful in determining the value of a less-than perfect, but feasible, long-range forecast for the Prairie Provinces. It will also enable us to examine options that various types of decisionmakers, from Provincial and Federal government officials to individual farmers, might have to minimize the impact of weather anomalies on agricultural output (Glantz 1976, 1-2).

Glantz (1982) considered the problem in another way and assessed the social costs of an inaccurate forecast. Glantz (1986, 93) concluded from the studies that "the formulation, promulgation, and implementation of a forecast must be carefully assessed, almost on a case by case basis, in order to determine its true value to society." Such assessments of use, misuse, and nonuse of forecasts could illuminate the strong sensitivity of various decisionmaking processes to improved meteorological products, and to define the upper and lower limits on the value of improved long-term forecasts.

To our knowledge, no such assessment of the value of a long-term hurricane forecast has been conducted. The observation of Gray et. al. (1991, 1881) in connection with aircraft reconnaissance and tropical cyclone forecasting has general relevance for understanding the lack of assessments of potential long-term hurricane forecast use and benefits:

> While relying on reconnaissance for more than 40 years, most American [tropical cyclone] forecasters and researchers have not felt the need to make quantitative studies of just how beneficial aircraft reconnaissance has been in order to justify its

---

[6] Clearly, much work needs to be done to reduce vulnerability to hurricanes independent of our ability to make long-term forecasts. However, recent advances in seasonal and interannual forecasts of hurricane incidence may, with proper use, enhance efforts to reduce vulnerability.

continuation. Research is now belatedly beginning to focus on this subject.

The same claim might be said of hurricane research more generally, and indeed much of scientific research as well. Assessments of the potential and actual use and value of long-term forecasts of hurricane activity would be a valuable contribution to understanding the opportunities for and limitations on actions focused on reducing societal vulnerability to hurricanes. Furthermore, in an era where science is increasingly called upon to demonstrate societal benefits, such assessments have potential to explore how to best leverage investments in research for practical ends. The following sections present a number of heuristics for structuring and conducting an assessment of the use and value of a long-term hurricane forecast.

The phrase "integrated assessment" is a "buzz word" out of the global change community, and is generally associated with future scenarios generated by economic models for planning purposes (e.g., Dowlatabadi and Morgan 1993). As we use it, integrated assessment refers to the *integration* of knowledge of climate-related and societal processes in order to *assess* alternative courses of action under the goal of reducing societal vulnerability to hurricanes. Such an integrated assessment of the hurricane problem would focus on processes of decisions and the role of forecast information therein by public and private individuals and groups.

A focus on process is central to realistic determination of the opportunities for and limitations on use of long-term forecasts to reduce societal vulnerabilities to hurricanes (cf. Pielke 1994). To focus on process is to focus on the formulation, promulgation, and execution of particular decisions (Lasswell 1971). Often, both scientists and policymakers alike behave as if the development of scientific information (such as long-term forecasts) is sufficient to lead to better decisions. From a decision maker's perspective, a call for better information from scientists can forestall the need to make difficult decisions while placing the burden of problem solving upon the scientists (Clark and Majone 1985). From a scientist's perspective, a focus on information allows for relative autonomy from the "politics" of decisionmaking and a justification for continued funding. However, it is often the case that scientific information is misused or not used at all because of rigidities in and practicalities of decisionmaking processes (e.g., Feldman and March 1981). Therefore, an integrated assessment "addresses environmental questions and issues which reflect political, societal, regulatory, and management values and expectations, as much as, if not more than, scientific and technical information" (Davis et al. 1994, 1047-1048).

Specific decisions are made in the context of a set of alternative courses of action. For example, in order to better prepare for the hurricane threat, citizens of New Orleans might desire a range of alternative responses to the following questions: How strictly shall we enforce our buildings codes? At what point in time before an approaching hurricane shall evacuation become mandatory? How much, if any, increase in insurance should citizens be required to carry in the face of a long-term forecast of increased hurricane incidence? Alternative actions in response to each question are embedded in a broader context of values, feasibility, and efficacy. For instance, building code enforcement cannot be separated from issues such as the costs to the resident of building a reinforced structure and the tax revenues necessary to hire a sufficient number of building inspectors. In many respects, decisions to which long-term forecasts may be relevant are decisions about how a community wishes to move into the future (cf. Salmon and Henningson 1987).

8.3.1 Quantification of Benefit Requires Attention to Actual and Potential Forecast Use

Demonstration of use or value of long-term hurricane forecasts is a challenging analytical task. Glantz (1986, 93) notes that "one could effectively argue that the value of climate-related forecasts will in most instances be at least as much a function of the political, economic, and social settings in which they are issued than of the soundness of information in the forecast itself." Put another way, the solution to the hurricane problem is potentially very different in Dade County, Florida, from the solution in Worcester County, Maryland, and both of those may be significantly different from the solution in Nueces County, Texas as a result of economic, political, and civic differences between the various communities.

Apart from demonstrating value of improved long-term forecasts, accurate assessment of societal vulnerabilities to hurricanes is a very challenging task. An example of the difficulties in defining the extent and magnitude of the hurricane threat is provided by the response of the insurance industry to Hurricane Andrew. The 1992 event served as a "wake-up call" to the insurance industry. Prior to Andrew the insurance industry largely ignored hurricane climatology and instead kept records of hurricane-related deaths and economic damage, according to Russell Mulder, director of risk engineering at the Zurich-American Insurance group (Wamsted 1993). The insurance industry's records were accurate measures of their losses, but not of hurricanes: they neglected storms that did not make landfall and underestimated the potential impact of storms that made landfall in relatively unpopulated areas. Since Hurricane Andrew, the insurance industry has paid closer attention to the hurricane threat (e.g. Banham 1993; Noonan 1993; Wilson 1994). One would expect the insurance industry to be among the most sensitive to societal vulnerability to hurricanes, however, Hurricane Andrew demonstrated that even when concern exists, accurate definition of the hurricane problem is difficult (see chapters by Roth, Chap. 13, and Clark, Chap. 14, this volume).

8.3.2 Consider Forecast Use and Value in Context

Murphy (1993, 286) states that "forecasts possess no intrinsic value. They acquire value through their ability to influence the decisions made by the users of the forecasts." Yet, because numerous factors contribute to any particular decision "assessing the economic value of forecasts is not a straightforward task" (Murphy 1994, 64). That is, a forecast is, at best, only one of a multitude of factors which influence a particular (potential) user (cf. Torgerson 1985). It is often difficult to identify the signal of the forecast in the noise of the decisionmaking process. Factors external to the forecast may hinder its use.

Murphy (1994) identifies two complementary approaches to assessment of forecast value which can be summarized as use-in-theory and use-in-practice (cf. Camerer and Kunreuther 1989). Murphy (1994) calls these prescriptive and descriptive assessments of forecast value. Glantz (1976) uses the terminology of "what ought to be" and "what is." Use-in-theory refers to efforts to estimate the "value of forecasts under the assumption that the decisionmaker follows an optimal strategy" (Stewart 1995, 40). Generally, economists, statisticians, and decision theorists share expertise in assessment of use-in-theory (e.g., Winkler and Murphy 1985). Use-in-practice refers to efforts, including case studies, to understand how decisions are actually made in the real world and the value of forecast information therein (e.g., McNew et al. 1991). Political scientists, sociologists, and psychologists are examples of those with expertise in assessment of use-in-practice.

It is likely that as long-range forecasts of hurricane incidence demonstrate increased skill that the value of such forecasts will not be self-evident to most users. Hence, it may be worthwhile for producers of long-range forecasts to conduct an ongoing parallel research effort targeted at actual and potential users. Such a parallel program could focus on integrated assessments of use-in-theory and use-in-practice in order to identify opportunities for and constraints on improved and proper use of long range hurricane forecasts. Counties, states, and SLOSH basins would be appropriate levels of analysis for an assessment. Such assessments may find that in some cases a particular decision process may constrain effective use of a long-term forecast. Other assessments may find clear opportunities to leverage forecast information for reduced vulnerability. If long-term forecasts of hurricane activity are justified in terms of their value added to social processes, then the susceptibility of support for such research may depend in large part upon demonstration of actual use or value.

8.3.3 Beware of Overselling the Science

It is generally accepted that modification of hurricane incidence will remain impractical for the foreseeable future, in spite of the mid-century optimism following an intensive series of efforts to "tame" hurricanes in the 1950s and 1960s (Gentry 1974). Experience with hurricane modification does provide one very important lesson: Care must be taken not to "over-promise" expected benefits deriving from research (cf. Tennekes 1990; Namias 1980).

Consider the following statement made in the late 1940s in a talk given by Nobel Laureate Irving Langmuir at the dawn of optimism about hurricane modification: "The stakes are large and with increased knowledge, *I think that we should be able to abolish the evil effects of these hurricanes*" (quoted in Byers 1974, 15, emphasis added). On one level such claims reflect the eternal optimism of science and technology. But at another level, such claims are publicly irresponsible and potentially damaging to the institution of science (Changnon 1975). One can easily imagine a congressional appropriator, excited by the possibilities of Langmuir's claim, making an argument that "preparedness plans for hurricane would no longer be necessary because in weather modification scientists had discovered a magic bullet." Of course, taking the thought a step further, had a hurricane then hit a poorly prepared community blame would have been laid at the feet of the scientist, and not the policymaker. In the context of long-term forecasts of hurricane activity credibility with the public will be difficult to gain, and easy to lose (Slovic 1993).

Weather modification is perhaps an extreme example of the risks involved with overselling science. However, in an era when science is increasingly called upon to contribute to the resolution of many difficult societal problems, demonstration of benefits may become central to sustained federal support of research.

8.4 Conclusion

The hurricane threat facing the U.S. Atlantic and Gulf coasts is constantly changing. Along these coasts population and property vulnerable to hurricanes have increased dramatically over the last several decades. During that period hurricane incidence was well below the observed climatology. Communities that have suffered the force of recent hurricanes, particularly Dade County, Florida, with Hurricane Andrew, give evidence that the U.S. may be more vulnerable to hurricanes than has been recently thought. Furthermore, anecdotal evidence suggests that complacency is the norm in many communities. Such experiences and scattered evidence begs for systematic assessment of societal vulnerability to the hurricane threat in particular coastal communities. Such assessments could establish vulnerability with enough detail so as to provide a baseline against which one might measure the potential use and value of improved forecast capabilities (short- and long-term).

While the hurricane threat to the U.S. Atlantic and Gulf coasts is ever changing, past efforts to reduce societal vulnerability have had many successes (e.g., the relatively few casualties in Hugo [1989] and Andrew [1992]). These successes form a body of practical experience from which lessons might be distilled and used to help guide efforts to reduce vulnerability to extreme weather events more generally. Such efforts will become increasingly important as demographic changes place more people and property in the path of extreme events (themselves part of a constantly changing climate). Future successes in reducing vulnerability to hurricanes have potential to add to the base of experience available to guide action in response to weather threats. However, the lessons of past and future experience depend upon rigorous assessments of the processes of decisionmaking. Absent such assessments, policy failure will likely become apparent only in the aftermath of an extreme event. In the future, anecdotal evidence of the importance of hurricane forecasts will not suffice; for lesson-drawing there is no substitute for rigorous demonstration of use and value of the role of research in practical settings.

In the broader context of U.S. science policy, the use and value of long-term hurricane forecast, and hurricane research more generally, has not found a broad audience. There are at least three reasons why the successes of hurricane research have not reached the broader science policy community. First, as Gray (1991) argues, hurricane researchers in the past have had little incentive to conduct assessments of the use and value of their research. Second, members of the hurricane research community are poorly placed to argue for the worth of their research, as some policymakers may view such arguments as self-serving, no matter how meritorious. Finally, the question of the use and value of hurricane research is a difficult analytical question that involves assessment of the process of decisionmaking well beyond the contribution of scientific research. For these reasons, there exists an opportunity for assessment of the role of forecasts in reducing societal vulnerability to hurricanes, to contribute to recent debate on the efficacy of federally funded research.

Societal vulnerability to hurricanes -- exposure and incidence -- provides a basis for understanding the potential use and value of hurricane research, particularly forecasts, to resolution of the problems of hurricanes, extreme weather, and U.S. science policy. Reducing vulnerability provides a common goal that integrates the science and social science of hurricane impacts. Experience suggests that improved long-term forecasts, by themselves, will not reduce societal vulnerability unless accompanied by efforts to use them in processes of preparedness. To the extent that improved forecasts contribute to reduced vulnerability we will have made less serious the threat of hurricanes to coastal communities, supplied a basis of experience for actions in response to other types of extreme weather phenomena, and provided a practical demonstration of the relationship of scientific research in pursuit of societal objectives. Such progress will not come easy, but with the close interaction of social and physical scientists with actual and potential users of science, meeting these goals is a surmountable challenge.

Acknowledgments

We would like to thank the following individuals for useful comments and suggestions as well as for assistance in the preparation of this manuscript: Radford Byerly, Leighton Cochran, Mark DeMaria, Steve Dickson, Mary Downton, Leslie Forehand, Karen Gahagan, Kevin Gallagher, Michael Glantz, William Gray, William Hooke, Jan Hopper, Richard Katz, Chris Landsea, Steve Nelson, Steve Rhodes, Robert Serafin, Robert Simpson, Ken Van Sickle, and Thomas Vonderhaar. NCAR Graphics and Justin Kitsutaka expertly aided with the figures.

We would also like to thank Henry Diaz and Roger Pulwarty for providing the opportunity to prepare the manuscript and for assistance with the revision. The research in the manuscript was partially supported by a grant from the National Science Foundation. Partial support to attend the workshop was provided by the Cooperative Institute for Research in the Atmosphere at Colorado State University. The views in the paper are those of the authors and should not be construed as representing any of the individuals or institutions with whom either author is associated.

References

Anthes, R.A., 1992. *Tropical Cyclones: Their Evolution, Structure and Effects*. American Meteorological Society, Boston, MA.

Applebome, P., 1993. In the Hurricane Belt, a New, Wary Respect. *New York Times* August 18, p. A12.

Baker, E.J., 1994. Warning and response. In: *Hurricane Hugo: Puerto Rico, The Virgin Islands, and Charleston, South Carolina, September 17-22, 1989*, Natural Disaster Studies Volume 6, National Academy of Sciences, Washington, DC, 202-210.

Baker, E.J., 1993. Empirical studies of public response to tornado and hurricane warnings in the United States. In: Nemec, J., Nigg, J.M., and Siccardi, F. (eds.), *Prediction and Perception of Natural Hazards*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 65-73.

Baker, E.J., 1991. Hurricane evacuation behavior. *International Journal of Mass Emergencies and Disasters*, 9, 287-310.

Banham, R., 1993. Reinsurers seek relief in computer predictions. *Risk Management*, 8, 14-19.

Brinkmann, W.A.R., 1975. *Hurricane Hazard in the United States: A Research Assessment*, Monograph NSF-RA-E-75-007, Program on Technology, Environment and Man, Institute of Behavioral Science, University of Colorado.

Brown, G., 1992. The objectivity crisis. *American Journal of Physics*, 60, 779-781.

Brunner, R.D., and Ascher, W., 1992. Science and social accountability. *Policy Sciences*, 25, 295-331.

Burton, I.R., Kates R.W., and White, G.F., 1993. *The Environment as a Hazard*, 2nd. edition, Guildford Press.

Byerly, R., 1995. U.S. science in a changing context: A perspective. In: Pielke, R.A. (ed.) *U.S. National Report to the International Union of Geodesy and Geophysics 1991-1994*.

Byers, H.R., 1974. "History of weather modification." In: Hess, W.N. (ed.), *Weather and Climate Modification*, John Wiley & Sons, New York, 3-44.

Camerer, C.F., and Kunreuther, H., 1989. Decision process for low probability events: policy implications. *Journal of Policy Analysis and Management*, 8, 565-592.

Campbell, P.R., 1994. Population projections for states, by age, sex, race, and Hispanic origin: 1993 to 2020. Current Population reports, P25-1111, US GPO, Washington, DC.

Carter, T.M., 1993. The role of technical hazard and forecast information in preparedness for and response to the hurricane hazard in the United States. In: Nemec, J., Nigg M., and Siccardi, F., (eds.), *Prediction and Perception of Natural Hazards*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 75-81.

Changnon, S.A., 1975. The paradox of planned weather modification. *Bulletin of the American Meteorological Society*, **56**, 1, 27-37.

Changnon, S.A. and Changnon, J.M., 1992. Temporal fluctuations in weather disasters: 1950-1989. *Climatic Change*, **22**, 191-208.

Clark W.C. and Majone, G., 1985. The critical appraisal of scientific inquiries with political implications. *Science, Technology, and Human Values*, **10**, 3, 6-19.

Cobb, H.D. III., 1991. The Chesapeake-Potomac hurricane of 1933. *Weatherwise*, **44**, 24-29.

Coch, N.K., 1994. Geologic effects of hurricanes. *Geomorphology*, **10**, 37-63.

Cochran, L. and Levitan, M., 1994. Lessons from Hurricane Andrew. *Architectural Science Review*, **37**, 3, 115-121.

Council of Economic Advisors, 1994. *Economic Report of the President*, US GPO, Washington, DC, February.

Davis, W. P., Thornton, K.W. and Levinson B., 1994. Framework for assessing effects of global climate change on mangrove ecosystems. *Bulletin of Marine Science*, **54**, 1045-1058.

DeMaria, M. and Kaplan, J., 1994. Sea surface temperature and the maximum intensity of Atlantic tropical cyclones. *Journal of Climate*, **7**, 1324-1334.

Dowlatabadi, H. and Morgan, M.G., 1993. Integrated assessment of climate change. *Science*, **259**, 1813, 1932.

Dunn, G.E. and Miller, B.I., 1960. *Atlantic Hurricanes*, Louisiana State University Press, Baton Rouge, LA.

Elsberry, R. L., Frank, W.M., Holland, G.J., Jarrell, J.D., and Southern, R.L., 1988. *A Global View of Tropical Cyclones*, Naval Postgraduate School, Monterey, CA.

Emanuel, K.A., 1987. The dependence of hurricane intensity on climate. *Nature*, **326**, 483-485.

Feldman M.S. and March, J.G., 1981. Information in organizations as signal and sign. *Administrative Science Quarterly*, **26**, 171-186.

Gentry, R.C., 1974. Hurricane modification. In: Hess, W.N. (ed):, *Weather and Climate Modification*, John Wiley and Sons, New York, 497-521.

Getter, L. 1993. Inspections: A breakdown in the system. In: Tait, L.S. (ed.) *Lessons of Hurricane Andrew*, Excerpts from the 15th Annual National Hurricane Conference, FEMW, Washington, DC. April, 33-36.

Glantz, M.H., 1976. Value of a reliable long range climate forecast for the Sahel: A preliminary assessment. International Federation of Institutes for Advanced Study, May 15.

Glantz, M.H., 1977. The value of a long-range weather forecast for the West African Sahel. *Bulletin of the American Meteorological Society*, **38**, 150-158.

Glantz, M.H., 1978. Render Unto Weather... -- An Editorial. *Climatic Change*, **1**, 305-306.

Glantz, M.H., 1979. Saskatchewan spring wheat production 1974: A preliminary assessment of a reliable long-range forecast. *Climatological Studies No. 33*, Canadian Government Publishing Centre, Hull, Quebec.

Glantz, M.H., 1982. Consequences and responsibilities in drought forecasting: The case of Yakima, 1977. *Water Resources Research*, **18**, 3-13.

Glantz, M.H., 1986. Politics, forecasts, and forecasting: forecasts are the answer, but what was the question? In: Krasnow, R. (ed.), *Policy Aspects of Climate Forecasting*, Resources for the Future, Washington, DC.

Golden, J.H., 1990. Meteorological data from Hurricane Hugo. *Proceedings of the 22nd Joint UJNR Panel Meetings* -- Winds and Seismic Effects, May 14-18.

Golden, J.H. and Snow, J.T., 1991. Mitigation against extreme windstorms. *Reviews of Geophysics*, **29**, 4, 477-504.

Gray, W.M., 1994. Extended range forecast of Atlantic seasonal hurricane activity for 1995. Department of Atmospheric Science, Colorado State University, Fort Collins, CO.

Gray, W.M., 1992. Summary of 1992 Atlantic tropical cyclone activity and verification of author's forecast. Department of Atmospheric Science, Colorado State University, Fort Collins, CO.

Gray, W.M., 1990. Strong association between West African rainfall and U.S. landfall of intense hurricanes. *Science*, **249**, 1251-1256.

Gray, W.M. and Landsea, C.W., 1992. African rainfall as a precursor of hurricane-related destruction on the U.S. East Coast. *Bulletin of the American Meteorological Society*, 73, 9, 1352-1364.

Gray, W.M., Neumann, C., and Tsui, T.L., 1991. Assessment of the role of aircraft reconnaissance on tropical cyclone analysis and forecasting. *Bulletin of the American Meteorological Society*, **72**, 1867-1883.

Hebert, P.J., Jarrell, J.D., and Mayfield, M., 1993. The deadliest, costliest, and most intense United States hurricanes of this century (and other frequently requested hurricane facts). *NOAA Technical Memorandum NWS NHC-31*.

Hess, J.C. and Elsner, J.B., 1994. Historical developments leading to current forecast models of annual Atlantic hurricane activity. *Bulletin of the American Meteorological Society*, 75, 1611-1621.

Ho, F.P., Su, J.C., Hanevich, K.L., Smith, R.J., and Richards F.P., 1987. Hurricane climatology for the Atlantic and Gulf coasts of the United States. *NOAA Technical Memorandum NWS-38*.

Jarrell, J.D., Hebert, P.J., and Mayfield, M., 1992. Hurricane experience levels of coastal county populations from Texas to Maine. *NOAA Technical Memorandum NWS NHC-46*.

Jarvinen, B.R. and Lawrence, M.B., 1985. An evaluation of the SLOSH storm-surge model. *Bulletin of the American Meteorological Society*, 66, 1408-1411.

Kocin, P.J. and Keller, J.H., 1991. A 100-year climatology of tropical cyclones for the northeast United States. Paper Prepared for the 19th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, Miami, Florida, May 6-10.

Landsea, C.W., Nicholls, N., Gray, W.M., and Avila, L.A., 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters*, (in press).

Landsea, C.W. 1993. A climatology of intense (or major) atlantic hurricanes. *Monthly Weather Review*, **121**, 1703-1713.

Landsea, C.W. 1991. *West African Monsoonal Rainfall and Intense Hurricane Associations*, Colorado State University Department of Atmospheric Science, Paper No. 484, October 7, Fort Collins, CO.

Landsea, C.W., Gray, W.M., Mielke, P.W. Jr., and Berry, K.J., 1994. Seasonal forecasting of Atlantic hurricane activity. *Weather*, **49**, 273-284.

Lare, A.R. and Nicholson, S.E., 1994. Contrasting conditions of surface water balance in wet years and dry years as a possible land surface-atmosphere feedback mechanism in the West African Sahel. *Journal of Climate*, **7**, 653-668.

Lasswell, H.D., 1971. *A Pre-View of Policy Sciences*, American Elsevier, New York.

Leen, J., Doig, S.K., Getter, L., Soto, L.F., and Linefrock, D., 1993. Failure of design and discipline, In: Tait, L.S. (ed.) *Lessons of Hurricane Andrew*, Excerpts from the 15th Annual National Hurricane Conference, FEMA, Washington, DC. (April), 39-44.

Leggett, J. (ed.), 1994. *The Climate Time Bomb*, Greenpeace International, Amsterdam, The Netherlands.

Livezey, R.E., 1990. Variability of skill of long-range forecasts and implications for their use and value. *Bulletin of the American Meteorological Society*, **71**, 300-309.

Ludlam, D.M., 1963. *Early American Hurricanes*: 1492-1870, American Meteorological Society, Boston, MA.

Mauro, J., 1992. Hurricane Andrew's other legacy. *Psychology Today* **93**, 42-45.

Mayfield, M. and Avila, L., 1993. Atlantic hurricanes. *Weatherwise*, **46**, 18-24.

McNew, K.P., Mapp, H.P., Duchon, C.E., and Merritt, E.S., 1991. Sources and uses of weather information for agricultural decision makers. *Bulletin of the American Meteorological Society*, **72**, 491-498.

Mehta, K.C., Cheshire, R.H., and McDonald, J.R., 1992. Wind resistance categorization of buildings for insurance. *Journal of Wind Engineering and Industrial Aerodynamics*, **43**, 2617-2628.

Merrill, R.T, 1985. *Environmental Influences on Hurricane Intensification*, Colorado State University Department of Atmospheric Science, Paper No. 394, Fort Collins, CO.

Merrill, R.T, 1987. An experiment in statistical prediction of tropical cyclone intensity change, *NOAA Technical Memorandum NWS NHC-34*.

Morgenthaler, E. 1994. He's No Blowhard: Dr. Gray can Predict Atlantic Hurricanes. *The Wall Street Journal* August 8, p. A1.

Mulady, J.J., 1994. Building codes: They're not just hot air. *Natural Hazards Observer*, **18**, 3, 4-5.

Murphy, A.H., 1994. Assessing the economic value of weather forecasts: An overview of methods, results, and issues. *Meteorological Applications*, **1**, 69-73.

Murphy, A.H., 1993. What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather and Forecasting*, **8**, 281-293.

Namias, J., 1980. The art and science and long-range forecasting. *EOS: Transactions of the American Geophysical Society*, **61**, 449-450.

National Academy of Sciences, 1980. *Technological and Scientific Opportunities for Improved Weather and Hydrological Services in the Coming Decade*. National Academy Press, Washington, DC.

National Research Council, 1989. *Opportunities to Improve Marine Forecasting*. National Academy Press, Washington, DC.

Nature, 1995. The Year of Utilitarian Science? **373**, 1-2.

New York Times, 1994. In Florida Storm Hits Crops Hard. *The New York Times*, November 20, p. A10.

Noonan, B., 1993. Catastrophes: The New Math. *Best's Review* **83**, 41-44.

Novlan, D.J. and Gray, W.M., 1974. Hurricane-spawned tornados. *Monthly Weather Review*, **102**, 476-488.

Pielke, R.A., 1990. *The Hurricane*, Routledge, London.

Pielke, R.A. Jr., 1995. Hurricane Andrew: Mesoscale Weather and Societal Responses, Environmental and Societal Impacts Group, National Center for Atmospheric Research, June 1.

Pielke, R.A. Jr., 1994. Scientific information and global change policymaking. *Climatic Change*, **28**, 315-319.

Powell, M.D., 1982. The transition of the Hurricane Frederic boundary-layer wind field from the open Gulf of Mexico to landfall. *Monthly Weather Review*, **110**, 1912-1932.

Rensberger, B., 1995. The Cost of Curiosity. *The Washington Post Weekly Edition*, January 16-22, 11-12.

Salmon, J. and Henningson, D., 1987. Prior Planning for post-hurricane reconstruction. Report Number 88, Florida Sea Grant College, January.

Shapiro, L.J., 1989. The relationship of the quasi-biennial oscillation to Atlantic tropical storm activity. *Monthly Weather Review*, **117**, 1545-1552.

Sheets, R., 1990. "The National Hurricane Center -- past, present, and future." *Weather and Forecasting*, **5**, 185-232.

Sheets, R., 1992. Statement before Hearing of the Senate Committee on Banking, Housing, and Urban Affairs, 1992. The National Flood Insurance Reform Act of 1992, before the Subcommittee on Housing and Urban Affairs, 27 July, 102-913.

Sheets, R., 1993. Statement before Hearing of the House Committee on Science, Space, and Technology, 1993. NOAA'S Response to Weather Hazards -- Has Nature Gone Mad? Hearing before the Subcommittee on Space, 14 September, 103-55.

Simpson, R.H. and Lawrence, M.B., 1971. Atlantic hurricane frequencies along the U.S. coastline. *NOAA Technical Memorandum NWS SR-58*.

Simpson, R.H. and Riehl, H., 1981. *The Hurricane and its Impact*. LSU Press, Baton Rouge, LA.

Slovic, P., 1993. Perceived risk, trust, and democracy. *Risk Analysis*, **13**, 675-682.

Stewart, T.R., 1995. Forecast value: descriptive studies. In: Katz, R.W. and Murphy, A.H. (eds.) *Value of Weather and Climate Forecasts*. Cambridge University Press, Cambridge.

Sugg, A.L., 1967. Economic aspects of hurricanes. *Monthly Weather Review*, **95**, 143-146.

Sugg, A.L., 1968. Beneficial aspects of the tropical cyclones. *Journal of Applied Meteorology* **7**, 39-45.

Tennekes, H., 1990. A sideways look at climate research. *Weather*, **45**, 67-68.

Torgerson, D., 1985. Contextual orientation in policy analysis: The contribution of Harold D. Lasswell. *Policy Sciences*, **18**, 241-261.

U.S. Army Corps of Engineers/Federal Emergency Management Agency, 1993. Hurricane Andrew Assessment: Louisiana Version, Review of Hurricane Evacuation Studies Utilization and Information Dissemination, (July).

U.S. Department of Commerce, 1990. Hurricane Hugo September 10-22, 1989, Natural Disaster Survey Report, (May).

U.S. Department of Commerce, 1993. Hurricane Andrew: South Florida and Louisiana August 23-26, 1992, Natural Disaster Survey Report, (November).

USWRP, 1994. United States Weather Research Program: Implementation Plan, Congressional Submission, Committee on Earth and Environmental Sciences, (January).

Wakimoto, R.M. and Black, P.G., 1994. Damage survey of Hurricane Andrew and its relationship to the eyewall. *Bulletin of the American Meteorological Society*, **75**, 189-202.

Wamsted, D., 1993. Insurance industry wakes up to threat of global climate change. *Environment Week*, **6**, 39.

Wilson, N.C., 1994. Surge of hurricanes and floods perturbs insurance industry. *Journal of Meteorology*, **19**, 3-7.

Winkler, R.L. and Murphy, A.H., 1985. Decision analysis. In: Murphy, A.H. and Katz, R.W. (eds.) *Probability, Statistics, and Decisionmaking in the Atmospheric Sciences*, Westview Press, Boulder, Colorado, 493-524.