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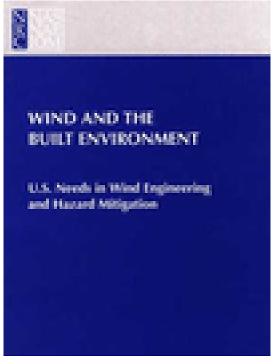

Wind and the Built Environment: U.S. Needs in Wind Engineering and Hazard Mitigation

Panel on the Assessment of Wind Engineering Issues in the United States, Committee on Natural Disasters, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

WIND AND THE BUILT ENVIRONMENT

U.S. NEEDS IN WIND ENGINEERING AND HAZARD MITIGATION

Panel on the Assessment of Wind Engineering Issues in the United States
Committee on Natural Disasters
Commission on Engineering and Technical Systems
National Research Council

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POEM DISPLAYED FOR KINDERGARTNERS AT BELLS MILL ELEMENTARY SCHOOL, POTOMAC, MARYLAND*

Wind is air that is moving fast
Wind may be helpful.
It can turn windmills.
It can dry clothes on a line.
It can push a sailboat.
It can fly kites and balloons.
It can help seeds grow.
It can help frisbees fly.
Wind may be harmful.
It can blow off your hat.
It can blow your hair.
It can blow a house or car.
It can also blow trees.

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* Words and ideas for this class "experience story" were contributed by the kindergartners. Recorded by Mrs. S. Reiss, kindergarten teacher.

Preface

Winds swirl about our planet driven primarily by solar radiation and the rotational effects of the earth. Perhaps more than any other aspect of nature, wind is both friend and foe. It grants us quiet joys as well as many practical benefits—from crop pollination to energy production. Yet these life-giving aspects are counterbalanced by fierce assaults on our lives and property in the form of extreme wind events such as hurricanes, tornadoes, severe thunderstorms, and downslope winds.

Wind-caused disasters affect every sector of society and every inhabited region of the earth. This report examines the need for fundamental research in wind engineering, meteorology, emergency planning, and disaster response in light of these catastrophic wind events. It treats also the need for better education and training in wind engineering and related disciplines, and considers the opportunities that exist for cooperative research with other nations facing similar wind threats.

Responding to a request by the National Science Foundation for direction in addressing the nation's vulnerability to windstorms, the National Research Council's Committee on Natural Disasters assembled a panel consisting of some of the foremost experts associated with wind engineering in both industry and academia—a group drawn from a wide geographic base and possessing broad experience. Their task was to provide a framework of background information, analysis, and recommendations so that the many hard decisions now facing policy makers regarding the wind hazard can be made with confidence and understanding.

The panel set out to make this a readable document, accessible to readers from a wide variety of backgrounds. While the report will likely find its way most frequently onto the desks of administrators of disaster relief and mitigation programs and into the libraries of researchers in the field, it will be useful also to those in the media and to practicing engineers, meteorologists, and scientists from related fields. Political decision makers, too, will find a wealth of knowledge here as well as solid recommendations of importance to their constituencies.

Certainly, the most critical and far-reaching of the recommendations contained in this report is that Congress should act quickly to establish a National Wind Science and Engineering Program, backed by a sustained budgetary commitment, to coordinate and revitalize wind-hazard research.

Chapter 1 sets forth the rationale and general outlines of this proposed program. Here the panel details the magnitude of potential wind-related losses, outlines the inadequacies of the current national response to this substantial risk, and proposes a measured program of mitigation research and local outreach. This program should allow advances in wind science and engineering to translate quickly into improved designs for wind-resistant structures and should encourage better disaster planning and response to the wind hazard.

In subsequent chapters, the panel has evaluated the various facets of the wind hazard, from the difficulties of measuring and predicting extreme winds to the challenge of updating local building codes and standards. These focused discussions are meant to provide the grist from which a National Wind Science and Engineering Program can be refined. Each of these chapters concludes with a discussion of specific research needs and recommendations aimed at meeting these needs. In Chapter 7, the panel recapitulates for easy reference the most critical of these conclusions and recommendations.

Year by year, the nation's wind vulnerability rises as the built environment expands. Yet, as this report demonstrates, wind research in the United States has dwindled over time to a level wholly inadequate to meet this challenge. A direct consequence of this neglect is an increased risk to personal safety as well as to the inventory of structures that provide us with both shelter and livelihood.

To reduce this risk, we must breathe new life into the nation's wind research program. This can only be done by constructing a coherent plan that enlists both industry and academia in an interdisciplinary effort to understand and mitigate the ill effects of the wind. This report outlines the essential first steps in formulating that plan.

Leslie E. Robertson, Chairman

Arthur N. L. Chiu, Vice Chairman

Panel on the Assessment of Wind Engineering Issues in the United States

Contents

Acronym List

ABL	atmospheric boundary layer
ASCE	American Society of Civil Engineers
ASOS	Automated Surface Observing System
CLASS	Cross-Chain Loran Atmospheric Sounding System
EMS	Emergency Medical Services
FEMA	Federal Emergency Management Agency
ICS	Incident Command System
IDNDR	International Decade for Natural Disaster Reduction
KBES	knowledge-based expert system
NAWSEP	National Wind Science and Engineering Program
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
SLOSH	Sea, Lake and Overland Surge Heights
WERD	*Wind Engineering Research Digest*

Executive Summary

RECOMMENDATION

The Panel on the Assessment of Wind Engineering Issues in the United States recommends the establishment of a national program to reduce wind vulnerability—a National Wind Science and Engineering Program. Such a program, enacted by Congress and backed by a sustained budgetary commitment of $20 million per year for the first five years (as outlined later in Table 1-5), would catalyze the formulation of clearly articulated national goals regarding wind engineering and forecasting and establish responsibility among the federal agencies for achieving these goals.

INTRODUCTION

Wind—the motion of air relative to the earth's surface—affects a wide variety of human activities and can be both beneficial and harmful. One benefit, for example, has come with the evolution of wind-turbine technology, which has begun to make wind a viable energy source with the potential to contribute perhaps 10 percent of the nation's energy needs. Wind also plays an essential role in agriculture and silviculture, acting as a pollination agent for grain crops and several commercially valuable timber species.

The focus of this analysis, however, is not on wind's benefits, but on the hazard resulting from extreme winds such as hurricanes and tornadoes. In this respect, the influence of near-surface winds is pervasive and increasing in scope as the global population and the built environment expand.

Near-surface winds are the most variable of all meteorological elements, making their prediction and the control of their impacts all the more challenging. In the United States, the mean annual wind speed (for the contiguous 48 states) is 8 to 12 mph (4 to 6 m/s), but wind speeds of 50 mph (22 m/s) occur frequently throughout the country, and nearly every area occasionally experiences winds of 70 mph (31 m/s) or greater. In coastal areas of the East and Gulf coasts, tropical storms may bring wind speeds of well over 100 mph (45 m/s).

WIND LOSSES: A PERSPECTIVE

Many states in the United States are vulnerable to extreme weather, with hurricanes, tornadoes, severe thunderstorms, and downslope winds inexorably exacting their tolls. Hurricane Hugo, which struck the Virgin Islands, Puerto Rico, and South Carolina in September 1989, caused more than 100 deaths and disrupted the lives of millions, inflicting over $4 billion in insured losses in the process. During the 35-year period from 1953 to 1989, tornadoes claimed 3550 lives—an average of 96 deaths per year. The May 22, 1987, Saragosa, Texas, tornado, alone, caused 30 deaths, mostly of young children. Each year, the nation suffers several billion dollars in wind-related property and economic losses and assumes the direct costs of disaster relief and recovery efforts. The Federal Emergency Management Agency (FEMA) alone has spent an average of nearly $400 million per year for disaster relief during the past 20 years, with a significant portion of this used for wind-related events. From 1981 to 1990, the insurance industry spent nearly $23 billion on wind-related catastrophic events in the United States.

Globally, windstorm-related events cause an annual average of 30,000 deaths and many billions of dollars in direct losses (National Research Council, 1987). United Nations statistics covering about 400 disasters since the beginning of the century indicate that roughly 15 percent of these events are windstorms, and lists of major disasters since the 1960s indicate that over half are due to extreme winds.

LOOKING AHEAD

Worldwide, vulnerability to natural disasters is rising as a result of several factors, including rapid population growth concentrated in urban areas, especially along coastlines; increasing capital outlays for buildings and lifelines; deteriorating infrastructure systems; and growing interdependence among local, national, and global communities. These factors are particularly pertinent to the communities along the east coast of the United States.

For example, national estimates of the population per mile of coastline suggest that by the year 2010 the population density on Florida's east and west coasts will have increased about 130 percent from the 1988 level. Moreover, as the national population ages, an increasing percentage of coastal immigrants will probably be older individuals, a group more likely to inhabit manufactured houses, which are more vulnerable to extreme wind hazards. The Bureau of the Census estimates that by the year 2030, over 22 percent of the population will be 65 or older, compared with 12 percent in 1987. Millions of these individuals will undoubtedly make their way to the Sun Belt coastal states.

Growing affluence, the development of attractive communities, good career opportunities, and the freedom of movement facilitated by low-cost transportation have resulted in the growth of residential and commercial construction in vulnerable, coastal regions. A 1989 study by the All-Industry Research Advisory Council indicates that these construction activities resulted in a 64 percent increase in insured property exposures during the period 1980 to 1988. The combined structural value of these residential and commercial properties—$1.86—trillion is a staggering indicator of the catastrophic damage potential.

Adding to the disaster potential is the gradual deterioration of many elements of the transportation infrastructure. For example, the compromise of critical transportation links, such as coastal bridges and overpasses essential to emergency evacuation and response, could measurably increase the vulnerability of the populations that these elements serve.

Moreover, some climatologists predict increases in the frequency and severity of intense tropical cyclones in the next few decades. It has been suggested that, given the multi-decadal cycle of West African precipitation and its apparent linkage to the weather cycle, an increased incidence of intense hurricanes in the United States during the 1990s and the early twenty-first century is likely.

A combination of the above-mentioned factors would make all communities in coastal regions more vulnerable to extreme wind hazards, including such cities as New Orleans, Tampa Bay, Miami, and others, which are particularly susceptible to mass inundation by storm surge because of the shape of their bays and coastlines. Nor will inland areas be spared; these regions can also expect rising wind vulnerability—though perhaps not to the extent expected for coastal areas—as structure density and value gradually increase.

CREATING A NATIONAL WIND SCIENCE AND ENGINEERING PROGRAM

Today, the sciences of meteorology and wind engineering are central to predicting and managing wind forces and their effects. Continued improvements in the ability to forecast severe weather have led to longer lead times for responding to the disaster threat. The application of wind-engineering principles to accommodate wind loads has become an important aspect of modern construction practice. Research using modern boundary-layer wind tunnels and sophisticated computer modeling has greatly enhanced the designer's ability to ensure the safety and comfort of structures for the least cost. Design provisions based more directly on wind-engineering research than on traditional, empirical guidelines are also gradually finding their way into local building codes.

In spite of these advances over the past 20 years, losses from wind-related hazards are mounting, particularly economic losses. The need for accelerated progress remains acute, especially in light of the expansion of the built environment and the rising exposure to wind-related events. Since the 1970s, the pace of this progress has faltered for lack of funding and the absence of a cohesive, national program of wind research and application.

As indicated in the 1989 National Research Council report, *Reducing Disasters' Toll*, one major reason for the nation's inability to deal with mounting losses is that U.S. efforts in hazard mitigation have evolved slowly over many decades and are fragmented. Responsibility for these efforts is shared among federal, state, and local governments, as well as with the private sector, professional organizations, voluntary organizations, the insurance industry, and the public. This diffusion of responsibility stems from two factors. The first is the historic role in government reserved for states and localities. The second factor comes from the traditional perspective that views natural hazards as acts of God for which little anticipatory action is possible and to which postdisaster humanitarian relief is the most important response as well as a much-publicized noble cause.

The nation's efforts in hazard management lack coordination and a coherent focus. At the federal level, for instance, the present research and implementation program reflects a piecemeal accumulation of activities initiated incrementally by Congress. Examples are the 1968 Flood Insurance Program and the 1977 National Earthquake Hazards Reduction Program, which address specific areas of concern.

Wind-hazard efforts are typical examples of the nation's inadequate and fragmented management capability, which is focused mostly on near-term and postdisaster activities. The United States as a whole spends no more than $4 million each year on wind-hazard mitigation, most of which is for storm warning capability (National Research Council, 1989). Through its National Weather Service, the National Oceanic and Atmospheric Administration is responsible for meeting the nation's needs in weather forecasting. It also conducts research relevant to hurricanes, tornadoes, floods, and droughts. The National Science Foundation, the nation's primary agency supporting science and engineering research, allocates no more than $750,000 each year to wind-engineering mitigation research. The FEMA's efforts are almost exclusively in disaster relief. Other agencies, such as the Departments of Energy and Defense, which own and operate numerous facilities nationwide, often suffer significant damage from extreme wind events. Nonetheless, their support for the wind-engineering and wind-hazard research aimed at reducing these losses is almost nonexistent.

Although the National Weather Service is undergoing a slow, steady modernization program to advance its forecasting capabilities, the wind-engineering discipline has suffered a period of stagnation, even disintegration, over the past decade. No U.S. organization is willing to spearhead the drive to advocate wind-hazard mitigation. From time to time—immediately following a major hurricane or tornado—a surge of interest stirs policymakers to debate what should be done in the future, but it withers rapidly because of the urgency of addressing the short-term needs of communities.

The United States needs the political will to develop long-term goals and objectives to deal effectively with wind-hazard issues. The threat from extreme winds is real and dramatic for all Atlantic and Gulf coast states; for Hawaii, Puerto Rico, and the Virgin Islands; and for inland states as well. The nation's apparent indifference to this threat is astonishing and perplexing.

How can this be rectified? Advocates must arise from within the affected communities, and they must be augmented by a strong voice from the professional community that addresses wind-hazard issues. Perhaps the Wind Engineering Research Council could serve as this voice, in a role similar to that played by the Earthquake Engineering Research Institute for its constituents.

Through these advocates, communities must then approach Congress to establish a National Wind Science and Engineering Program (NAWSEP).

Such a program, which would provide the needed focus to address the nation's wind vulnerability, should include:

- a coordinated program of wind research that draws upon expertise in both academia and industry, and addresses both structural and nonstructural mitigation measures;
- an outreach program to educate state and local governments on the nature of the wind risks they face, especially along vulnerable coastlines, and to transfer state-of-the-art wind mitigation measures, from improved building codes to computer-based expert systems that offer guidance in a variety of areas such as disaster preparation or structural design;
- a conscious effort to improve communication within the wind community and to foster renewed interest in this field through undergraduate and graduate curriculum development and through support for graduate study; and
- a commitment to international cooperation in wind-engineering work through the support of selected, joint studies with other nations sharing similar wind-hazard and engineering concerns.

Once the concept of a NAWSEP is accepted, the process of formulating its specific structure may benefit from the convening of one or more national workshops to arrive at appropriate working agendas for wind research and for mitigation and outreach activities to be undertaken as part of the NAWSEP.

Chapter 1 of this report provides an overview of wind's impact on the built environment. It is followed by detailed presentations of the issues critical to the establishment of a sound and long-term national wind program. Chapter 7 then summarizes the panel's key conclusions and recommendations concerning the critical issues that have been identified.

1

Wind Hazards and Related Issues

THE POWER OF WIND

Wind in the lower atmosphere affects a wide variety of human activities and can be both harmful and beneficial. Globally, windstorm-related events cause an average of 30,000 deaths and several billion dollars in direct losses annually (National Research Council, 1987). In the United States alone, the insurance industry spent nearly $23 billion on wind-related catastrophic events from 1981 to 1990 (Insurance Information Institute, 1992). Every year, residents along the Atlantic Coast face the threat of severe windstorms, some of which develop into hurricanes. Hurricane Hugo, which struck the Virgin Islands, Puerto Rico, and South Carolina in 1989, inflicted over $10 billion in total losses, causing over 100 deaths and disrupting the lives of millions. New Orleans, Tampa Bay, Miami, and other cities along the Atlantic and Gulf coasts are notably susceptible to mass inundation by storm surge because of the shape of their bays and coastlines.

Tornadoes and severe thunderstorms also constitute major wind hazards over much of the United States, often occurring unexpectedly and with devastating effect. For instance, the May 1987 tornado in Saragosa, Texas, killed 30 people—most of them children—within seconds (National Research Council, 1991b).

Worldwide, vulnerability to natural disasters is rising due to the conjunction of several factors: rapid population growth concentrated in urban areas, especially in housing developments along coastlines; increasing capital outlays for buildings and lifelines; deteriorating infrastructure systems; and a growing interdependence among local, national, and global communities. This rise in vulnerability is particularly marked in the case of windstorm-related catastrophes. United Nations statistics covering about 400 disasters since the beginning of the century indicate that roughly 15 percent of these events are windstorms, and lists of major disasters since the 1960s indicate that more than half are due to extreme winds.

But wind is not always an agent of disaster; it can be a boon as well. For instance, wind is a natural energy producer with the potential to contribute significantly to the nation's energy security. In 1989, wind power plants in California provided a capacity of 1335 MW, equivalent to a medium-sized utility power plant (National Research Council, 1991a). Indeed, with the passage of the Clean Air Act and later amendments, wind engineering for energy production activities and industrial development was acknowledged as a key factor in economic progress. However, the conversion of wind energy to usable forms remains in the early stages of development.

Wind is also a beneficial, natural transport medium that can be used to advantage in several ways. For instance, management of snow deposition over the nation's central and northern plains could improve grain production significantly. In these areas, where snow accounts for 15 to 45 percent of the annual precipitation, the use of stubble, rows of tall wheat grass, or level benches to deposit wind-driven snow could bring about a moisture distribution more favorable for plant growth. Much research remains to be done in the area of agricultural meteorology.

Wind also transports and dilutes air pollutants, thus controlling air quality. This can be either advantageous or disadvantageous for the local populace, depending upon wind direction, distance from the pollution source, source strength, and height of release. Management for optimum air quality requires careful analysis of wind characteristics in the area and control methodologies for sources, followed by well-planned and enforced zoning for industrial, residential, and business development.

Wind has a host of other effects as well. For instance, wind can remove heat from buildings during cold weather and, thus, increase heating costs. Wind also contributes to high rates of soil erosion and evaporation during dry periods and, therefore, impacts drought conditions.

WIND ENGINEERING

Given the widespread impacts of wind, it is not surprising that wind engineering for human safety and comfort is of increasing concern. As the number of tall buildings has increased in cities throughout the United States, wind impacts have grown more visible. High winds induced at street level between high rises have caused numerous injuries (McKean, 1984), and wind-excited building motion has resulted in the evacuation of tenants in some buildings.

Wind engineering derives largely from the traditional disciplines of fluid mechanics, meteorology, and structural mechanics. Wind includes flow associated with a variety of meteorological phenomena: tornadoes, hurricanes, downslope flows, thunderstorms, boundary-layer flows, and near-calm conditions. Interactions of wind with buildings, towers, bridges, transmission lines, transport vehicles, plants, people, pollution sources, and other terrestrial objects provide a multitude of challenge for wind engineering in the areas of planning, analysis, design, construction, and maintenance.

The goals of wind engineering are to minimize wind's adverse effects and to maximize its beneficial ones. Only through a planned, long-range program of wind-engineering research and development can the knowledge and information necessary to attain these goals be developed. Such a program will require an integrated effort by meteorologists and engineers backed by a parallel effort to develop the economic analyses and political tools necessary to implement the results of this research.

THE CRITICAL ROLE OF STRUCTURES

Proper design and construction of structures and lifeline systems are critical elements in the effort to minimize losses from all natural disasters, including extreme winds. Partial or total collapse—with the consequent financial and personal losses—may result when structures are poorly designed or constructed. Nor are wind-induced losses confined to total or partial collapses. Other forms of structural damage, such as the compromise of roof systems or walls, can also render a structure useless after an intense windstorm. Further, past case studies show that, in many cases, structural damage is caused by flying glass or debris from neighboring structures. Thus, improperly built structures can cause negative impacts beyond their own direct losses (National Research Council, 1984).

Indirect losses can far exceed direct losses in many cases. For example, damage to a building's contents could idle a business located there—a potentially fatal blow, especially for a small business. In the case of large corporations and factories, a few days closure could seriously impact the local economy, which often depends heavily on those large businesses for survival. In addition, economic losses are not limited to the built environment (buildings, structures, and lifeline systems) but can affect agriculture, forestry, and tourism as well, as occurred on the Cancun Peninsula after Hurricane Gilbert in 1988 and in South Carolina after Hurricane Hugo in 1989.

Tornado sheltering is a special issue for engineers. These violent events often confound modern meteorological prediction and can cause sudden loss of life and property. It is not feasible, nor is it economical, to build structures to withstand the highest tornado wind speeds. However, affordable in-residence tornado shelters have been designed by wind engineers and can be retrofitted to existing homes.

The safety of emergency shelters and the functionality of critical facilities such as hospitals, fire stations, and communication systems are of paramount importance for a community's survival in the wake of a major wind or any other natural disaster. In this light, the use of school buildings as emergency shelters should be addressed. In many jurisdictions, the design and construction of school buildings are exempt from local building code requirements, in spite of the fact that many of these buildings, especially gymnasiums, are designated as public shelters during natural disasters. Unfortunately, these buildings sometimes become death traps because of their inadequate design and construction, as happened at the East Coldenham Elementary School in Newburgh, New York, in November 1989. It is absolutely necessary to apply proper building codes to the design and construction of school buildings. Further, the building code provisions applied to them should be strictly enforced by inspection because of their use as safe havens during major windstorms.

In recent years, engineers have emphasized the better design and construction against seismic loadings of hospitals, fire stations, and some communication systems (such as towers and switchboard buildings) located in earthquake-prone areas, especially in California. However, the same is not true for facilities in wind-hazard-prone areas in the United States, and their functioning after a wind event is often compromised by damage to nonstructural components. These facilities are a major community investment and should perform dependably in both normal and emergency situations; therefore, it is vital that they be designed and built accordingly.

WIND-INDUCED LOSSES: VICTIMS AND COSTS

Society as a whole bears the burden of wind loss. Individuals; renters; homeowners; farmers; businesses; and federal, state, and local governments are all called upon to pay the price of losses attributable to hurricanes; tornadoes; severe, local winter storms; and other wind hazards. In human terms, this price includes death, injury, and personal suffering. The monetary cost of this personal suffering cannot be finitely measured and, generally, is not indemnified. In the event of death or injury, medical and funeral expenses are borne directly by the victim or the victim's family and, in many instances, borne indirectly by insurers or government. The costs are thus redistributed to the purchasers of insurance or absorbed by taxpayers.

Economic losses–the monetary value of the property, goods, and services destroyed, damaged, or interrupted by a wind event–can be quantified and are redistributed in several ways: they can be carried directly by the victim; redistributed through the insurance mechanism; or borne by federal, state, and local governments and, ultimately, the taxpayer (Haas et al., 1977).

Those individuals and businesses in the path of the wind event are its victims and directly bear any loss attributable to the event. To the extent that they are not insured, or are not eligible for government-funded relief, they bear the direct impact of the economic losses incurred.

Insurance represents a means by which victims of the wind event may be indemnified if they purchased coverage. Insurance also provides a means whereby the losses of a few are distributed among the many. Losses incurred are redistributed through the pricing mechanism for the coverage purchased.

In the case of hurricanes, the event is likely to occur in a relatively restricted geographic area and involve a massive exposure to an unpredictable occurrence. In turn, the losses may result in a market failure among insurers, at least regionally. In these cases, insurers have been called upon to provide coverage through mandated pools. Losses are distributed to the insurance community within the affected state and, through the rate-making mechanism, back to the policyholders in the state.

Federal, state, and local governments provide additional services and relief to victims when a catastrophic event occurs. Governments also bear the cost of repairing damage to or replacing the infrastructure and government property. Additionally, governments are generally responsible for the cost of debris removal and for emergency police, fire, and medical services. Ultimately, all government costs are borne by the taxpayer.

Although it is not possible to place a value on the pain and suffering caused by wind events, it is possible to present data on the direct economic impact of these events. Table 1-1, based on data developed by the Natural Hazards Research Program of the Travelers Insurance Company (Friedman, 1989), displays the dollar costs for hurricanes, severe local storms, and winter storms during 1980–1989. For this 10-year period (in 1990 dollars and projected market), the insurance industry spent over $23.8 billion on wind-related catastrophic events. Of this total, 30.4 percent was spent on hurricanes, 51.3 percent on severe local storms, and 18.3 percent on winter storms. It must be emphasized that these totals do not reflect all wind-related losses. Rather, they detail the cost to the insurance industry for events that were designated *catastrophes* during the period. To be designated a catastrophe, an event must cause at least $5 million in insured loss and involve a significant number of individual claims. The insured-loss payment figures for the 10 most costly hurricanes in the United States since 1950 are presented in Table 1-2.

Every year, the nation also assumes the direct costs of disaster relief and recovery efforts. Expenditures related to these activities are not easy to estimate. The Federal Emergency Management Agency (FEMA) alone has spent an average of close to $400 million per year for disaster relief during the last 20 years (National Research Council, 1989). This represents only a small portion of the total federal costs incurred in coping with natural disasters. Simply restoring vital transportation links destroyed by natural disasters costs the Department of Transportation about $160 million annually.

The expenditure breakdown of losses attributed to wind hazards is even more difficult to estimate. Hurricane Hugo, a recent wind hazard that had dramatic impact on the United States, serves as an example. In addition to insured damages exceeding $4.1 billion, government financial support reached staggering proportions. In the *Interagency Hazard Mitigation Team Report for Hurricane Hugo* (FEMA, 1989), it was reported that in South Carolina alone, relief needs in the amount of half a billion dollars were identified a month after the event. These included:

- $179 million in public assistance;
- $115 million in project applications;
- $90 million for debris removal;
- $20 million for protective measures;
- $15 million for roads and bridges, water control facilities, and other purposes; and
- $80 million for use on repair or replacement of public buildings.

The final tally has not been made for Hurricane Hugo, but these early figures–for South Carolina only–are alarming indicators of the potential future costs resulting from catastrophic wind events.

TABLE 1.1 Insured Losses Due to Hurricanes, Severe Local Storms, and Winter Storms During the Period 1980-1989

	HURRICANE			SEVERE LOCAL STORM			WINTER STORM			COMBINED			COMBINED (AS A PERCENT OF TEN YEAR EXPERIENCE)		
Ten Years (1980-1989)	Original Dollar; Original Market	1990 Dollar; Original Market	1990 Dollar; Original Market	Original Dollar; Original Market	1990 Dollar; Original Market	1990 Dollar; 1990 Market	Original Dollar; Original Market	1990 Dollar; Original Market	1990 Dollar; 1990 Market	Original Dollar; Original Market	1990 Dollar; Original Market	1990 Dollar; 1990 Market	Original Dollar; Original Market	1990 Dollar; Original Market	1990 Dollar; 1990 Market
1990	$57,911	$89,368	$129,887	$794,361	$1,225,849	$1,375,651	$58,000	$89,505	$95,060	$910,272	$1,404,722	$1,600,598	4.8%	6.3%	6.7%
1981	0	0	0	588,282	843,447	984,073	64,000	91,760	98,505	652,282	935,207	1,082,578	3.4	4.2	4.5
1982	137,000	185,927	226,275	691,920	939,023	1,082,866	601,500	816,314	919,002	1,430,420	1,941,264	2,228,143	7.5	8.8	9.4
1983	675,520	865,016	1,071,305	654,245	837,771	935,476	910,000	1,165,272	1,207,891	2,239,765	2,868,059	3,214,672	11.7	12.9	13.5
1984	36,000	43,735	46,398	1,259,757	1,530,417	1,669,794	242,500	294,601	318,968	1,538,257	1,868,753	2,035,160	8.1	8.4	8.5
1985	1,133,754	1,290,481	1,368,025	1,099,585	1,251,588	1,346,742	550,000	626,030	650,316	2,783,339	3,168,099	3,365,083	14.6	14.3	14.1
1986	28,269	31,558	35,179	718,747	802,369	863,064	124,500	138,986	150,271	871,516	972,913	1,048,514	4.6	4.4	4.4
1987	0	0	0	715,000	782,540	821,256	160,000	175,114	183,087	875,000	957,654	1,004,343	4.6	4.3	4.2
1988	80,000	85,360	90,706	1,148,000	1,224,916	1,269,747	81,000	86,427	88,894	1,309,000	1,396,703	1,449,347	6.9	6.3	6.1
1989	4,059,000	4,184,829	4,257,132	1,787,000	1,842,397	1,872,213	625,000	644,375	651,900	6,471,000	6,671,601	6,781,245	33.9	30.1	28.5
10 YEAR TOTAL	$6,207,454	$6,776,274	$7,224,907	$9,456,897	$11,280,317	$12,220,882	$3,416,500	$4,128,384	$4,363,894	$19,080,851	$22,184,975	$23,809,683	100.0%	100.0%	100.0%
% OF COMBINED	32.5%	30.6%	30.4%	49.6%	50.8%	51.3%	17.9%	18.6%	18.3%	100.0%	100.0%	100.0%			

Source: D.G. Friedman, Travelers Insurance Company, 1989

TABLE 1-2 Insured Loss Payment Figures for the Ten Most Costly Hurricanes

	Date	Place	Estimated Insured Loss (dollars)[a]	Constant 1982– 1986 Dollars[b]
Hugo	Sept. 17–18, 21–22, 1989	U.S. Virgin Islands, Puerto Rico, Georgia Virginia, North Carolina, South Carolina	4,195,000,000	3,383,060,000
Betsy	Sept. 7–10, 1965	Florida, Louisiana, Mississippi	715,000,000	2,269,840,000
Frederic	Sept. 12–14, 1979	Mississippi, Alabama, Florida, Louisiana, Tennessee, Kentucky, West Virginia, Ohio, Pennsylvania, New York	752,510,000	1,036,520,000
Celia	Aug. 3, 1970	Southeastern Texas	309,950,000	798,840,000
Alicia	Aug. 18, 1983	Southeastern Texas	675,520,000	678,230,000
Camille	Aug. 17–18, 1969	Louisiana, Mississippi, Alabama, Florida Panhandle	225,000,000	613,080,000
Elena	Aug. 30–Sept. 3, 1985	Louisiana, Mississippi, Alabama, Florida	543,300,000	504,930,000
Carol	Aug. 30–31, 1954	New York, Connecticut, Rhode Island, Massachusetts, Maine, New Hampshire, New Jersey	129,700,000	482,160,000
Gloria	Sept. 26–27, 1985	North Carolina, Virginia, Maryland, Delaware, Pennsylvania, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, Vermont, Maine	418,750,000	389,170,000
Iwa	Nov. 23–24, 1982	Hawaii	137,000,000	141,970,000

[a] Source: Property Claim Services Division, American Insurance Services Group, Inc.
[b] 1982–84 = 100; deflated by Consumer Price Index.

WHAT DOES THE FUTURE HOLD?

Several trends with the potential to affect the frequency, severity, and toll that wind events take in both human suffering and economic terms are apparently now converging. Taken together, these trends must have significant bearing on the path society sets for the preparation, mitigation, recovery, and response to wind events. Although not all of these trends are universally accepted, they cannot be overlooked in any reasonable analysis of the nation's future wind peril.

First, some climatologists predict increases in the frequency and severity of intense tropical cyclones in the next few decades. For example, it has been suggested that, given the multi-decadal cycle of West African precipitation and its apparent linkage to the weather cycle, it is likely that we will see a return to an increased incidence of intense hurricanes in the United States during the 1990s and the early twenty-first century. Should this higher incidence of hurricanes occur, the increased coastal development that has taken place will bring greater property damage than has ever before been experienced (Gray, 1990).

In addition, recent computer simulations comparing the damage impact of hurricanes of the present climatic regime with those that may occur in a greenhouse-caused transitional climate indicate that the sea-surface temperatures will likely increase, bringing an earlier beginning and later ending of the hurricane season. Some investigators believe this could translate into an additional period of about 20 days when landfalling storms could occur (Friedman, 1989).

Further, the National Oceanic and Atmospheric Administration (NOAA) has released statistics regarding projected population growth along selected state coastlines (Table 1-3) that graphically illustrate the significant population increases expected along the Gulf and southern Atlantic coasts. Estimates of the population per mile of coastline suggest that, by the year 2010, the population density on Florida's east and west coasts will increase about 130 percent from 1988 levels. This increase in coastline population density will occur during the same time frame in which increases in the frequency and intensity of landfalling hurricanes are predicted.

Still another trend with implications for wind-induced losses shows that the nation's population is aging. The U.S. Bureau of the Census estimates that by the year 2030, over 22 percent of the population will be 65 or older, compared with just 12 percent in 1987. The special concerns of an older population migrating toward the Sun Belt coastal states, with many of them concentrating in manufactured houses during a period in which wind events are predicted to increase, must thus become a factor in future disaster planning.

TABLE 1-3 Projected Population Growth Along State Selected Coastlines

State	Estimated Coastal Population	Population per Mile of Coastline		Increase (percent)	2010 Projection
	(percent)	1960	1988		
Florida (East Coast)	100	824	2075	152	2689
Florida (West Coast)	100	433	1064	146	1411
Texas	31	798	1517	90	1956
Mississippi	13	527	928	76	1102
Alabama	12	599	800	34	886
Louisiana	62	248	352	42	420
South Carolina	25	176	303	72	365
North Carolina	11	140	202	44	234
Georgia	6	144	158	10	179

Source: National Oceanic and Atmospheric Administration

Growing affluence, the development of attractive communities, numerous career opportunities, and the freedom of movement facilitated by low-cost transportation have served as magnets to draw the U.S. population into harm's way. Table 1-4 shows that the growth of residential and commercial coastal construction in the first tier of coastal counties of the Gulf Coast and the Atlantic states resulted in a 64 percent increase in insured property exposure during 1980–1988 (All-Industry Research Advisory Council, 1989). The $1.86 trillion in the structural value of this residential and commercial property is a staggering economic indicator of the catastrophic damage potential.

Adding to the disaster potential is the gradual deterioration of many elements of the nation's transportation infrastructure. For example, the compromise of critical transportation links, such as coastal bridges and overpasses essential to emergency evacuation and response, could measurably increase the vulnerability of the populations served by these elements.

Yet despite the well-documented need for infrastructure improvement–calculated at roughly $18 billion per year (Office of Technology Assessment, 1990)–the actual funding for such essential maintenance has steadily declined. Coupling an increasingly frail transportation system with an aging population concentrated in a geographic zone predicted to experience more severe wind events in the future is a likely recipe for disaster.

THE CRITICAL ROLE OF DESIGN STANDARDS, CODES, CODE ENFORCEMENT, AND PLANNING REGULATIONS

The development of design standards and the adoption and enforcement of building codes are deliberate and time-consuming processes. Yet they are the most powerful and direct tools available to reduce the impact from wind hazards. The Committee on Natural Disasters has repeatedly observed in its postdisaster reports over the past 20 years that communities that have adopted and enforced certain building codes are less affected by the occurrence of wind events than those with no such requirements (e.g., National Research Council, 1985).

Development of codes and standards is a continuous process. It demands a sustained level of effort to conduct the research needed to improve the state-of-the-art practice of wind engineering. This requires adequate funding, which has been lacking in the last two decades. Code development also requires an efficient means of transferring the results of research to those responsible for formulating local codes–an effort that must be multidisciplinary in nature to be effective.

More importantly, a strong political base is needed to promote wind-disaster-reduction issues. This base is particularly critical to the issues of code implementation and enforcement. Local governments must be informed of the importance of wind engineering so that they develop the political will to ensure that building codes, once adopted through the legislative process, are effectively implemented and enforced during the design and construction of community facilities. Qualified individuals must be brought into local building inspection departments, given the authority to

TABLE 1.4 Total Insured Coastal Property Exposure by State

STATE	RESIDENTIAL ($000s)		COMMERCIAL ($000s)		TOTAL ($000s)		PERCENT CHANGE 1980-88		
	1980	1988	1980	1988	1980	1988	RES.	COM.	TOTAL
Alabama	$ 7,506,048	$10,766,361	$7,689,400	$12,034,794	$15,195,488	$ 22,801,155	43%	57%	50%
Connecticut	54,071,915	82,862,183	36,443,194	60,391,856	90,515,109	143,254,039	53	66	58
Delaware	12,453,050	19,053,924	9,059,654	19,655,746	21,512,705	38,709,670	53	117	80
Florida	177,709,426	278,574,660	155,213,287	287,251,863	332,922,713	565,826,523	57	117	80
Georgia	4,262,578	6,564,667	5,150,122	9,949,177	9,412,700	16,513,844	54	93	75
Louisiana	26,358,420	35,336,933	38,957,144	52,173,736	65,315,564	87,510,669	34	34	34
Maine	11,692,564	17,749,505	7,901,399	14,545,203	19,593,961	32,294,711	52	84	68
Maryland	40,969,895	62,716,633	36,101,614	66,439,027	77,071,508	129,155,661	53	84	68
Massachusetts	54,109,154	82,815,880	50,354,124	96,950,677	104,463,277	179,766,558	53	93	72
Mississippi	4,644,828	6,701,901	3,531,034	7,396,493	8,175,861	14,098,394	44	109	72
New Hampshire	6,072,027	10,076,325	3,943,331	8,456,563	10,015,358	18,532,887	66	114	85
New Jersey	35,614,156	56,006,009	15,477,539	32,483,258	51,091,693	88,489,267	57	110	73
New York	11,997,023	161,038,983	76,278,532	140,656,035	188,275,555	301,695,017	44	84	60
North Carolina	7,441,513	11,733,269	5,713,113	11,008,177	13,154,628	22,741,449	58	93	73
Rhode Island	17,296,893	25,806,754	15,460,444	27,093,376	32,757,338	52,900,131	49	42	44
South Carolina	9,399,383	15,255,815	7,608,740	15,933,971	17,008,122	31,189,786	62	109	83
Texas	20,355,288	30,035,912	28,271,910	40,047,026	48,627,196	70,082,938	48	42	44
Virginia	13,643,584	20,402,392	10,912,406	22,086,657	24,555,988	42,489,049	50	102	73
Coastal Total	$615,597,745	$933,498,106	$514,066,987	$924,553,635	$1,129,664,732	$1,858,051,741	52%	80%	64%
U.S. TOTAL	$4,240,948,850	$6,270,243,310	$3,807,860,750	$6,696,858,550	$8,048,809,600	$12,967,101,860	48%	76%	61%

Source: All-Industry Research Advisory Council, 1989 enforce the codes, and be provided with continuous educational opportunities to stay abreast of progress made in standards and codes development.

Design and construction using proper standards and building codes would enable new buildings to perform satisfactorily during wind events. However, they would not solve the problem of existing buildings. To retrofit or strengthen existing buildings cost effectively is one of the most challenging tasks faced by wind engineers today. Often, the solution lies in the perceived financial acceptability of the retrofit from the owner's viewpoint, rather than in the difficulties encountered in finding technical solutions to remedy the situation.

Proper land-use planning can also be a powerful tool to reduce the impact of extreme winds on a community, but the community must often be ready to pay a price for the use of this tool, since lands subject to wind hazards, such as the coastal zones, almost invariably are the best real estate properties in the community. For this reason, legislated policies on land-use planning are perhaps some of the most difficult and unwelcome pieces of news for a community. As a consequence of this unpopularity, beachfront houses have almost always been rebuilt in the same location immediately after wind disasters, in spite of the best technical advice.

Community emergency preparedness, which is largely a local or state government effort, must be viewed as an integral part of a community's strategy for coping with extreme wind events. Proper emergency preparedness should include the planning and use of evacuation routes, the provision of safe buildings as emergency shelters, and an emphasis on the functioning of hospitals, fire stations, and emergency power supplies after the event. Emergency preparedness planning should occur in close consultation with the wind-engineering community, which can provide technical information to make the overall plan more comprehensive and effective.

STRATEGIES AND INCENTIVES

Losses from wind-related hazards are mounting, especially in the United States. As indicated in *Reducing Disasters' Toll* (National Research Council, 1989), one major reason for the nation's inability to deal with these mounting losses is that U.S. efforts in hazard mitigation have evolved slowly over many decades and are fragmented. Responsibility for those efforts is shared among federal, state, and local governments, and with the private sector, professional organizations, voluntary organizations, the insurance industry, and the public. This fragmentation stems partly from the historic role in government reserved for states and localities, and partly from the traditional perspective that natural hazards are acts of God for which little anticipatory action is possible and to which postdisaster humanitarian relief is the most important response as well as a much-publicized noble cause.

U.S. efforts in hazard management lack coordination and a coherent focus. At the federal level, the present research and implementation program reflects a piecemeal accumulation of activities initiated incrementally by

Congress. Examples are the 1968 Flood Insurance Program and the 1977 National Earthquake Hazards Reduction Program, which address specific areas of concern.

Wind-hazard efforts are a typical example of the nation's inadequate and fragmented management capability, which is focused mostly focused on near-term and postdisaster activities. The United States as a whole spends no more than $4 million each year on wind hazard mitigation, most of which is for storm warning capability (National Research Council, 1989). Through its National Weather Service, NOAA is responsible for meeting the nation's needs in weather forecasting. It also conducts research relevant to hurricanes, tornadoes, floods, and droughts. The National Science Foundation, the nation's primary agency supporting science and engineering research, spends no more than $750,000 each year in wind-engineering mitigation research. FEMA's efforts are almost exclusively in disaster relief. Other agencies, such as the Departments of Energy and Defense, which own and operate a number of facilities nationwide, often suffer significant damage from extreme wind events. Nonetheless, their support for the wind program—especially wind engineering—aimed at reducing these losses is almost nonexistent.

Although the National Weather Service is undergoing a slow, steady modernization program to advance its forecasting capabilities, the wind-engineering discipline has suffered a period of stagnation, even disintegration, over the past decade. No U.S. organization is willing to spearhead the drive to advocate wind-hazard mitigation. From time to time—immediately following a major hurricane or tornado—a surge of interest stirs policymakers to debate what should be done in the future, but this interest dissipates rapidly because of the urgency of addressing the short-term needs of communities.

The United States needs the political will to develop long-term goals and objectives to deal effectively with wind-hazard issues. The threat from extreme winds is real and dramatic for all Atlantic and Gulf coast states, for Hawaii, Puerto Rico, and the Virgin Islands, and for inland states as well. The nation's apparent indifference to this threat is astonishing and perplexing.

How can this be rectified? Advocates must arise from within the impacted communities, and they must be augmented by a strong voice from the wind-related professions. Perhaps the Wind Engineering Research Council could serve as this voice, in a role similar to that played by the Earthquake Engineering Research Institute for its constituents.

Through these advocates, communities must then approach Congress to establish a NAWSEP (National Wind Science and Engineering Program). Such a national program will allow the relevant agencies with responsibilities for sponsoring research, conducting research, and transferring technology to develop comprehensive programs to meet the mandates set forth in the national program.

The NAWSEP would seek to emulate the most successful aspects of such programs as the National Earthquake Hazard Reduction Program and the National Flood Insurance Program. It could help to integrate wind-disaster planning into local codes and land-use policies. It could also foster a collaborative approach to wind research and raise public awareness of wind vulnerability.

As part of the NAWSEP, partnerships should be established between the federal government and local and state governments for the implementation of wind-hazard mitigation strategies. These partnerships should also be extended to the private sector so that wind-mitigation measures can be developed on a fair, affordable, and effective basis.

Better financial support to meet research needs must also accompany a NAWSEP. The current debate over national funding priorities in light of a possible "peace dividend" offers an excellent opportunity to present the case for supporting such a program. A higher level of funding will allow the nation as a whole to develop a long-term strategy in the area of wind-hazard research. It will rekindle the interest of the research community, especially at universities, and allow work to proceed on critical research topics that remain unfunded today. Such an action will undoubtedly trigger many educational initiatives vital to the nation's ability to deal with wind hazards in the future. To ensure the success of the NAWSEP, an annual budget of $20 million for the first five years is projected as necessary. Table 1-5 provides a preliminary breakdown of this proposed budget.

TABLE 1-5 Proposed Annual Budget (first five years) for a National Wind Science and Engineering Program (NAWSEP)

		Cost (million dollars)
1.	Conduct of post-wind-disaster investigations and longer-term research into nonstructural factors, such as code implementation, interorganizational communication, and evacuation planning, that directly affect the preparation for response to, and recovery from wind events	3.0
2.	Research in developing or improving analytical, numerical, and experimental methodologies, including both laboratory wind tunnel and full-scale field tests	12.0
3.	Educational development in wind engineering, including establishment of undergraduate fellowships to attract young talents into wind engineering; curriculum development at undergraduate and graduate levels; and institution of continuing education programs such as seminar series and short courses	1.0
4.	Data archiving, particularly by taking advantage of new weather forecasting systems to develop a comprehensive wind-speed data base for upgrading the guidelines, standards, and codes used in the design and construction of wind-resistant structures	2.0
5.	Development of effective technology transfer techniques to apply research results to the design of wind-resistant structures and building components, and to update local building codes.	2.0
	TOTAL	20.0

2

The Nature of Wind

A WIND PRIMER

Wind is air in motion relative to the earth. It is, in general, three dimensional, with both horizontal and vertical components. However, the vertical component normally is small, so the term *wind* is usually taken to refer only to the horizontal component. Winds near the earth's surface—as opposed to upper-air flows—impinge most directly on human activities. The prevailing wind direction at a site may suggest the orientation of a building to enhance natural ventilation and prevent the development of undesirable winds at street level. Strong wind gusts buffet buildings and can lead to occupant discomfort and eventual fatigue of building components. A knowledge of probable, extreme wind speeds is required so that buildings may be designed to resist these wind effects. Wind direction information is used to select runways for aircraft takeoffs and landings. To ensure that chemicals are not missing the target field, farmers must consider both strength and direction of the wind before spraying crops. Provided they are not too strong, winds also represent an energy source for windmills and wind generators.

The Near-Surface Wind

Near-surface wind is the most variable of all meteorological elements. Due to friction, the wind speed always vanishes at the ground. Approximately 50 percent of the transition in wind speed due to frictional effects takes place in the first 6 ft (2 m) above the surface. The adjustment in wind direction takes place over a 1- to 2-km depth (0.6 to 1.2 miles). These adjustments give rise to the wind profile; the profile of wind speed in particular must be taken into account when tall buildings or stacks are being designed.

At elevations greater than 1 or 2 km (0.6 or 1.2 miles) above the surface, the wind on most days will be more or less uniform in height and will blow steadily at moderate speeds (10–20 knots or 12–23 mph; 1 knot = 1.15 mph = 0.5 m/s). Wind at these elevations is usually almost normal to the local pressure gradient (with lower atmospheric pressure to the left in the Northern Hemisphere) and so tends to flow parallel to the height contours of isobaric surfaces. There are narrow bands of high-speed air very high in the atmosphere, at 30,000 to 40,000 ft. These jet-stream winds can have speeds up to 200 mph (90 m/s).

Under most conditions, wind varies continuously in the near-surface layer. However, it usually can be expressed by a superposition of high-frequency oscillations of small amplitude in both speed and direction around a much more slowly varying sustained speed and a prevailing direction, respectively. Both high-and low-frequency variations play an important role in mixing and dispersing pollutants in the atmosphere. As wind speeds increase, some of the variations can become more abrupt and of greater amplitude—these are called wind gusts.

Measured wind speed is a function of anemometer height, averaging time, and terrain upwind of the measurement site. The variations of wind with respect to height and time make it difficult to obtain values that are representative of the conditions over large regions. Near-surface winds are conventionally measured at a point some distance above the ground in flat, open terrain typical of an airport exposure. Although the recommended height is 33 ft (10 m), which is also the reference height for wind speed designated in building codes, actual measurement heights vary widely due to the peculiarities of each observing site.

Temporal variations must be smoothed out by averaging speed and direction over time. The averaging can be done in a variety of ways, depending on the application. In the United States, 1-minute averages are used to specify the sustained wind, whereas extreme or peak wind speeds are averaged over 2 to 5 seconds. From a practical point of view, this average time may range from 1 to 5 seconds depending on the response time of the anemometer and/or the recorder. Internationally, 10-minute averages are used to specify the sustained wind; however, adherence to this standard is not universal.

To ensure comparability of readings of the mean wind from different locations, heights of measurement and averaging procedures must be standardized or the data from each station must be "adjusted" to standard conditions. If characteristics of gusts are to be compared, then the response characteristics of the measuring instruments must also be matched. In the United States, climatological wind speeds are usually adjusted to 10-m, 1-minute averaged sustained winds. However, adjustment procedures usually entail assumptions about the variation of wind with time and height; these can lead to biases in the climatological values.

The Wind Climatology of the United States

The mean annual wind speed for the contiguous 48 states is 8 to 12 mph (4 to 6 m/s). In sheltered areas, mean speeds tend to be lower; on mountain ridges, in passes, and along coasts they are considerably higher. At most locations throughout the United State, winds speeds of 50 mph (22 m/s) occur frequently. As shown in Figure 2-1, nearly every area of the country will occasionally experience wind speeds over 70 mph (31 m/s). Many coastal regions can expect speeds of more than 100 mph (45 m/s). In the central one-half of the United States, most of these high wind speeds can be associated with frontal passages or thunderstorms (the latter either isolated or in a grouping such as a squall line). In the western mountain states, downslope winds account for many extreme reports (e.g., gusts to 135 mph (60 m/s) in

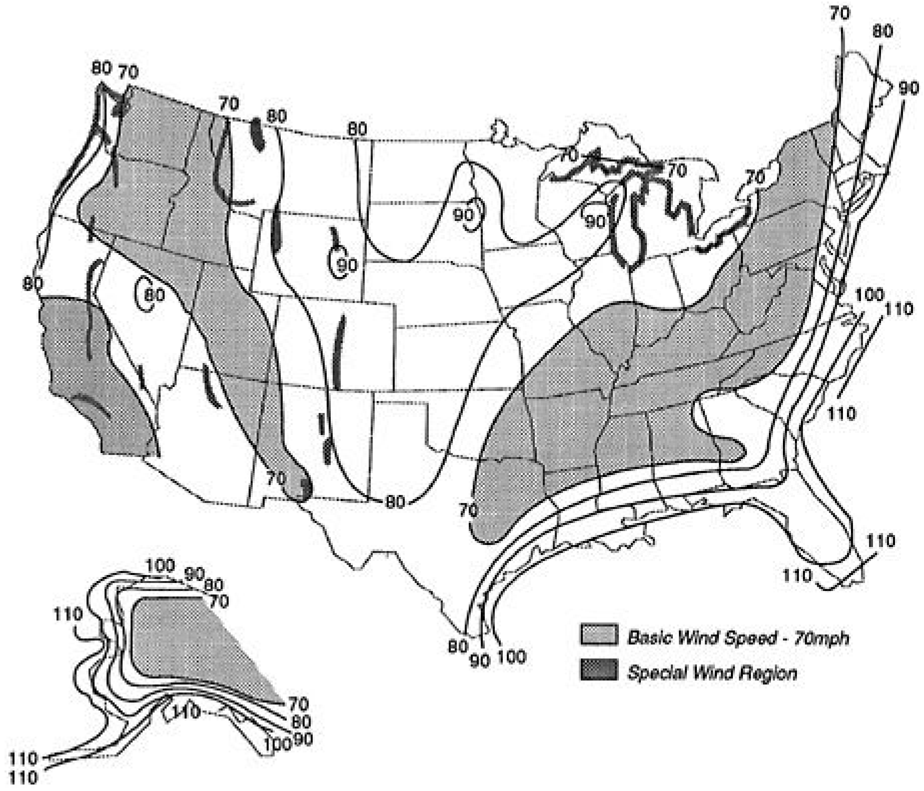

FIGURE 2-1 The current wind climatology for the United States used by the wind community. Contours are in units of "fastest mile speeds at 33 ft. above ground to be encountered at a point once in fifty years." Broadly hatched areas are regions where the fastest mile speeds of 77 mph (31 m/s) or greater recur at intervals less frequently than once in fifty years. Tightly hatched areas are regions subject to particular high wind hazards. Source: American National Standards Institute (1982).

Boulder, Colorado). Along the eastern and Gulf coasts, thunderstorms and hurricanes are the main producers of strong, near-surface winds.

Although the highest, near-surface wind speeds likely occur beneath thunderstorms and in hurricanes, very high wind speeds can also be associated with deep extratropical cyclones developed from winter low-pressure systems. In these weather systems, strong winds may be found both swirling around the center of lowest pressure and in association with the steep gradients of temperature and pressure that characterize the attendant cold frontal zones.

The strongest officially recorded winds observed in the United States, listed in Table 2-1, have all occurred at the summit of Mt. Washington, New Hampshire. These record values illustrate what the atmosphere is capable of producing and provide estimates of the maximum speeds that on rare occasions may be encountered elsewhere in the United States (see Riordan and Bourget, 1985, for additional discussion of extreme winds).

TABLE 2-1 Extreme (nontornadic) Wind Speeds in the United States–All Set at Mt. Washington, New Hampshire (elevation 4800 ft, mean sea level)

PEAK GUST SPEED

Highest Peak Gust: 231 mph (103.6 m/s)
April 12, 1934 (also the world record)

SUSTAINED WIND

Highest 5-Minute Speed: 188 mph (84.2 m/s)
April 12, 1934 (also the world record)

Highest 24-Hour Speed: 128 mph (57.2 m/s)
April 11–12, 1934

Highest Monthly Speed: 70 mph (31.1 m/s)
February 1939

Highest Annual Speed: 35 mph (15.6 m/s)
1934 to 1983

Source: Riordan and Bourget, 1985

Thunderstorms

About 100,000 thunderstorms occur in the United States each year. Most develop in the spring and summer months, though they can occur every month of the year. Figure 2-2 shows that thunderstorms occur in every state

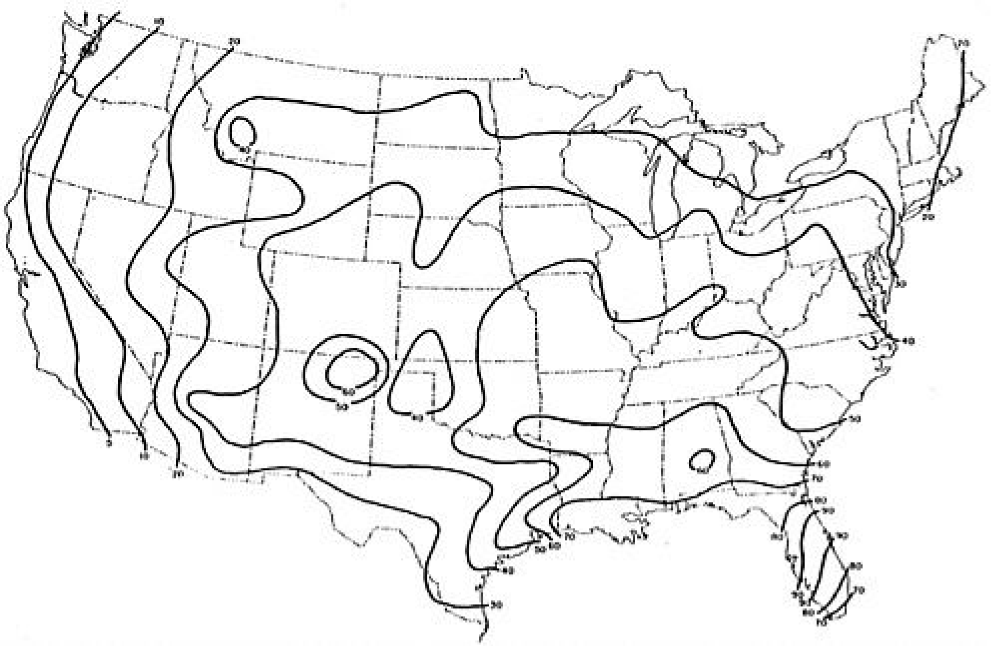

FIGURE 2-2 Distribution of thunderstorms in the United States, with mean number of days based on summaries for 266 stations through 1951. Contours are in units of "numbers of days per year thunder is heard at least once by a weather observer." Source: National Weather Service, National Oceanic and Atmospheric Administration (NOAA).

but are concentrated in the central Great Plains and the southeastern coastal states. Thunderstorms are most frequent in Florida and most infrequent in upper New England, the western states, and along the West Coast (Easterling and Robinson, 1985).

A variety of mechanisms give rise to thunderstorms; therefore, storms behave somewhat differently in the various climatological regions of the nation. All types can occasionally become severe. A thunderstorm is officially considered severe if it produces a tornado, winds in excess of 58 mph (26 m/s), or surface hail greater than 0.75 inch (20 mm) in diameter. About 10,000 severe thunderstorms are reported in the United States each year, resulting in property losses exceeding $1 billion annually.

On occasion, thunderstorms occur as organized elements of larger systems. Such systems can persist for hours, travel distances up to 625 miles (1000 km), and produce a variety of severe weather phenomena. The *squall line*, a linear pattern of thunderstorms, has long been recognized. More recently, *mesoscale convective systems*–large areas of interacting thunderstorms–have been identified.

Thunderstorms can produce large variations in surface wind over a small region. In a severe thunderstorm, air flowing into the storm base can reach speeds of 45 mph (20 m/s), while less than half a mile away, air flowing from the region of heavy rain can reach speeds greater than 145 mph (65 m/s). At the same time, winds in unaffected regions around the storm can be nearly calm. An observer on the surface experiences rapid changes in wind speed and direction as a system of thunderstorm winds moves past. As implied in Figure 2-3, gusts exceeding 50 knots are frequently reported in nontornadic, severe thunderstorms (Kelly et al., 1985). In the exceptionally severe thunderstorm, one or more tornadoes and downbursts may be produced. (A complete discussion of winds in and around thunderstorms can be found in Kessler (1986).)

Outflows

A thunderstorm produces tremendous quantities of rain. The falling raindrops induce a strong downdraft within the storm by aerodynamic drag and evaporation in the dry air that enters the storm at midlevel. A downdraft, as it approaches the earth's surface, begins to spread out beneath the storm. The leading edge of this outflow, the thunderstorm *gust front,* can contain moderately high sustained winds (speeds of 30–50 mph (13–22 m/s) are common). It is a region of strong *wind shear* (where the wind changes rapidly in speed or direction or both) and so constitutes a hazard to low-flying aircraft. If the parent thunderstorm is moving rapidly, then near-surface, peak gusts can be expected that are roughly equal to the sum of the sustained outflow winds and the storm speed. The flow in the gust front and in the current behind it has been investigated by Charba (1974), Goff (1976), and Wakimoto (1982). A conceptual model based on these findings is shown in Figure 2-4.

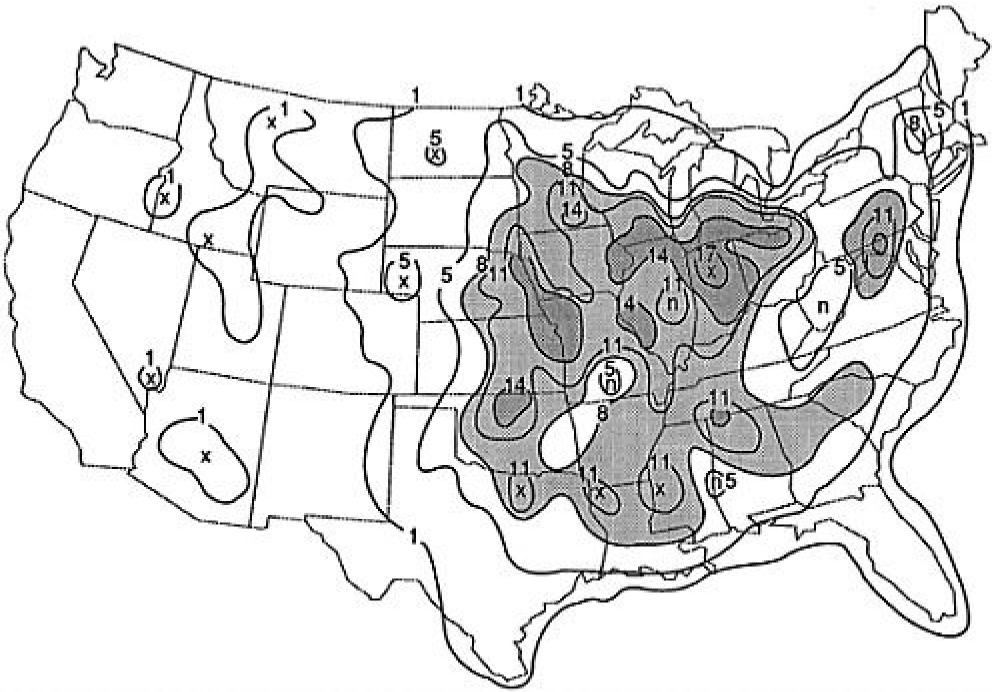

FIGURE 2-3 Frequency of any severe thunderstorm wind occurrence per 26,000 km^2 per year. Source: Kelly et al., 1985.

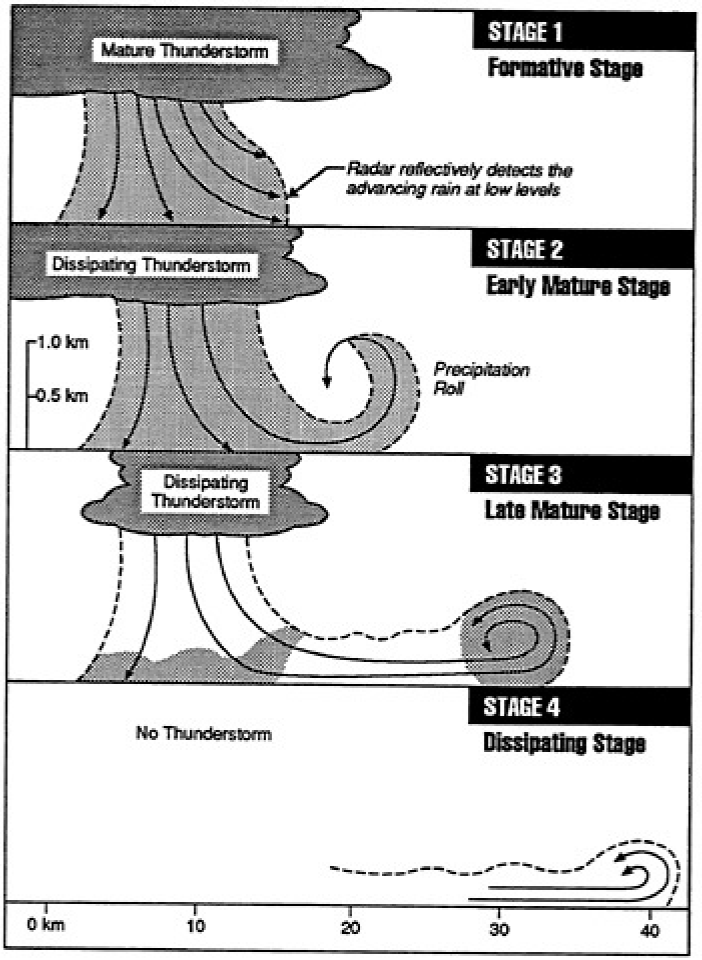

FIGURE 2-4 A conceptual model for the evolution of the flow in a thunderstorm gust front and the following current. Stipling denotes rain (and in later stages, dust and small debris) carried along with current. Source: Wakimoto, 1982

Small tornadoes can form along a gust front. These small, gust-front vortices have recently been investigated by Wakimoto and Wilson (1989); they may account for the majority of all weak tornadoes reported.

Downbursts and Microbursts

Fujita (1976, 1981, 1985) was the first to describe the strong, localized downdrafts, termed downbursts, that are produced by some thunderstorms. Although similar to and resulting from the same processes that produce the thunderstorm downdraft, downbursts are smaller and much more concentrated. They can induce an outburst of damaging winds near the ground, with near-surface speeds up to 125 mph (56 m/s). The strong winds tend to flow radially outward from where the descending current strikes the earth. Very strong wind shears occur at the leading edge of the downburst. The typical area of damaging winds is 3.8 to 5 miles (6 to 8 km) across. At a point beneath the thunderstorm, these strong winds may persist for up to 30 minutes.

Beneath a traveling mesoscale convective system, the individual outflows of the component storms may merge to produce a *derecho* (Johns and Hirt, 1987). As the combined outflow passes a location, very strong, gusty winds can occur for several hours. In addition, such a system can produce a widespread pattern of strong downbursts, both as *downburst families* (produced in sequence by the same thunderstorm cell) and as *downburst clusters* (produced by adjacent thunderstorms in the same general area).

Microbursts are small, very concentrated downbursts, about 2 miles (3 km) or less in horizontal extent. They can contain very high winds; the record observed wind speed in a microburst is 150 mph (67 m/s) reported by Fujita (1985) from an analysis of a microburst at Andrews Air Force Base, Maryland, on August 1, 1983. A microburst may last only 5 to 7 minutes, yet these events pose an especially serious hazard to aircraft during takeoff and landing because of the exceptionally strong wind shears that occur. Both "wet" and "dry" microbursts have been identified: the former appears as a descending shaft of rain and so may be avoided, whereas the latter is nearly invisible and so may not be recognized by pilots until too late.

Tornadoes

A tornado can produce the highest wind speeds known. This swirling column of air is usually associated with a severe thunderstorm, though its location beneath the storm can vary. A worldwide phenomenon, tornadoes occur most often in the United States. From 1953 through 1989, about 27,000 tornadoes were documented in the United States. The distribution of these events by year is shown in Figure 2-5. On average, tornadoes were reported in the United States on 169 days per year during this period. As indicated in Figures 2-6, 2-7, 2-8, and 2-9, tornadoes are concentrated in the central half

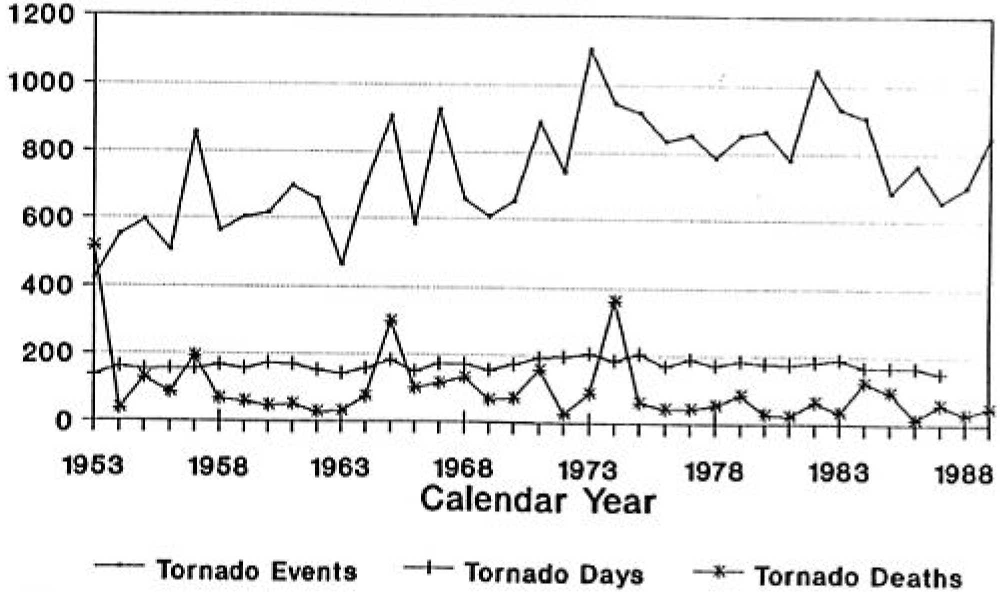

FIGURE 2-5 The annual number of tornadoes, tornado days, and tornado deaths in the United States, based on data from 1953-1989. Figure was created by J. T. Snow and students using data providedby J. H. Golden, NOAA.

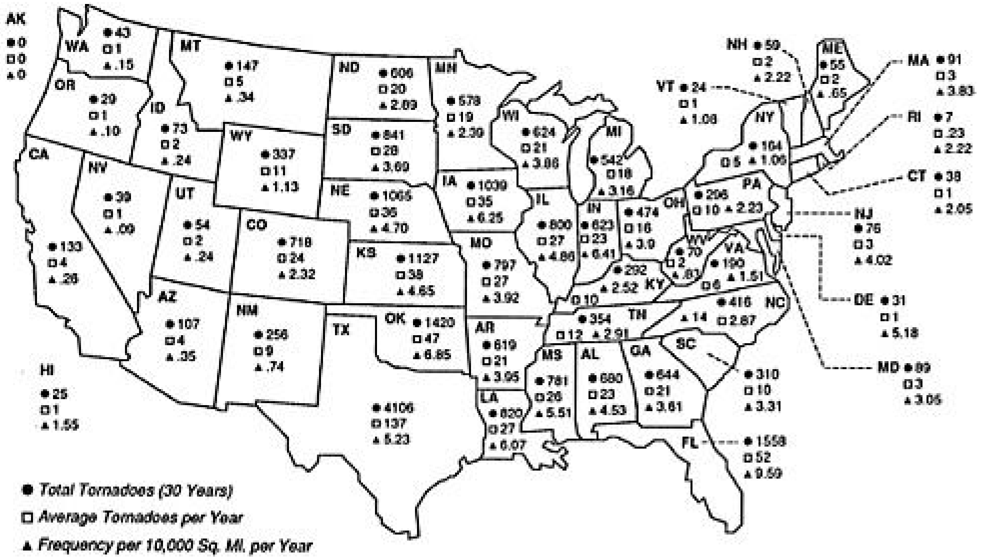

FIGURE 2-6 Tornado occurrence statistics by state, based on reports from 1959 through 1988. The statistics are for an entire state; within many states, there are great local differences. Source: L.A. Grenier,National Severe Storms Forecast Center, National Weather Service,NOAA, 1991.

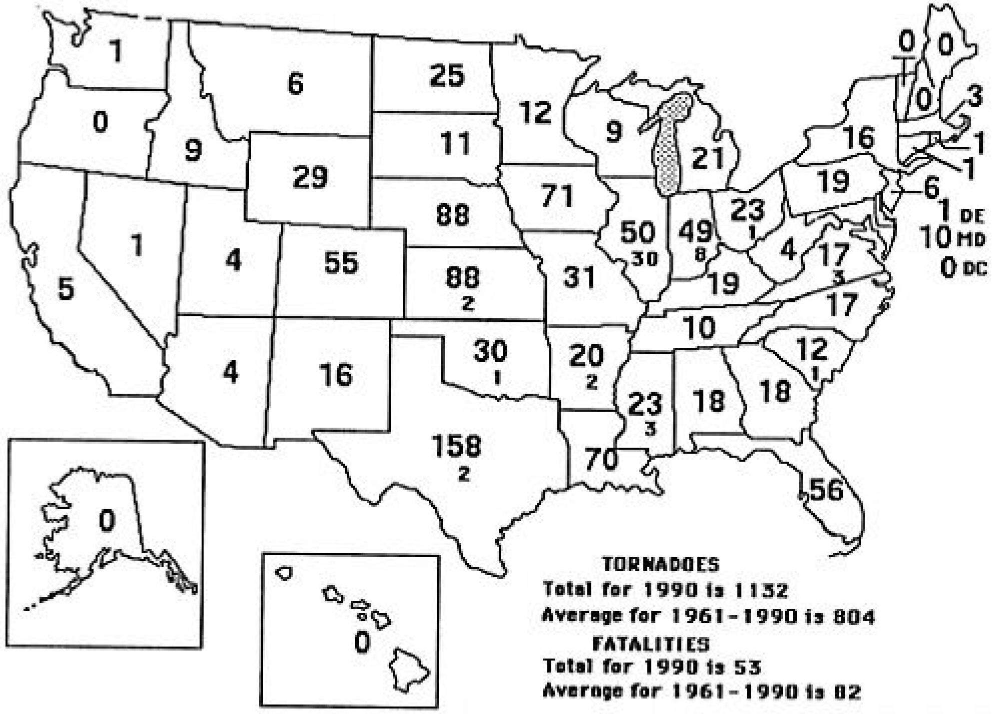

FIGURE 2-7 Tornado occurrences (upper, large numbers) and reported deaths (lower, small numbers) by state, based on reports for 1990. The occurrence statistics shown are for an entire state; within many states, there are great local differences. Source: L. Grenier, National Severe Storms Forecast Center, National Weather Service.

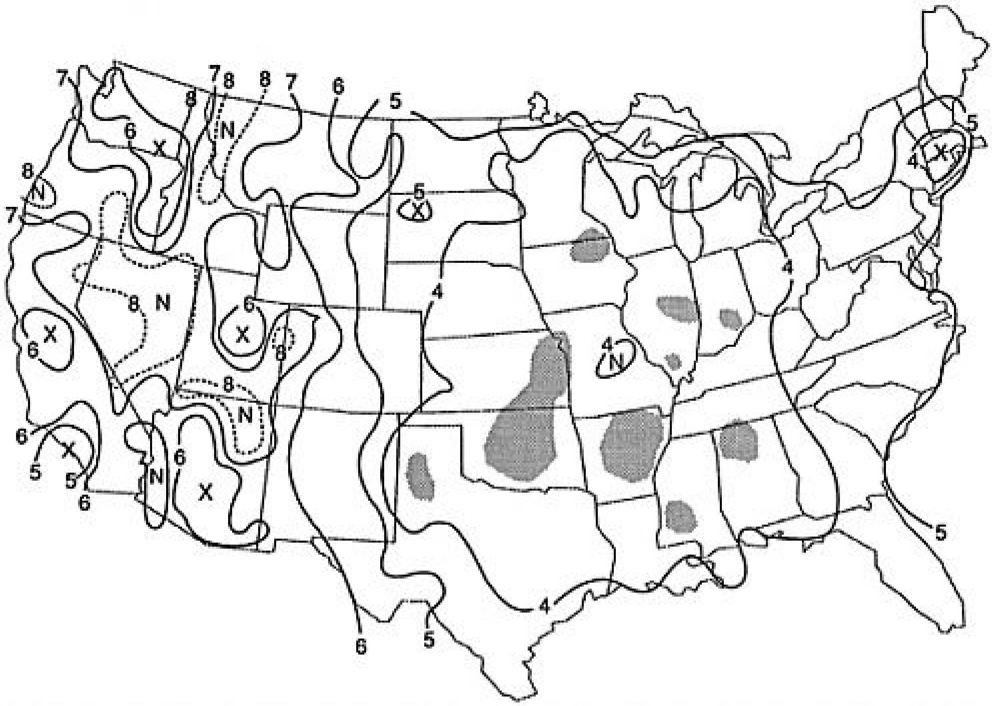

FIGURE 2-8 Probable annual tornado hazard from any tornadoes. Contours are labeled in negative powers of 10 per year (i.e., 4 indicates 10^{-4}). Maxima denoted by X, minima by N. Stippled area has hazard greater than 4×10^{-3} per year. Dotted line indicates 10^{-8} or less.

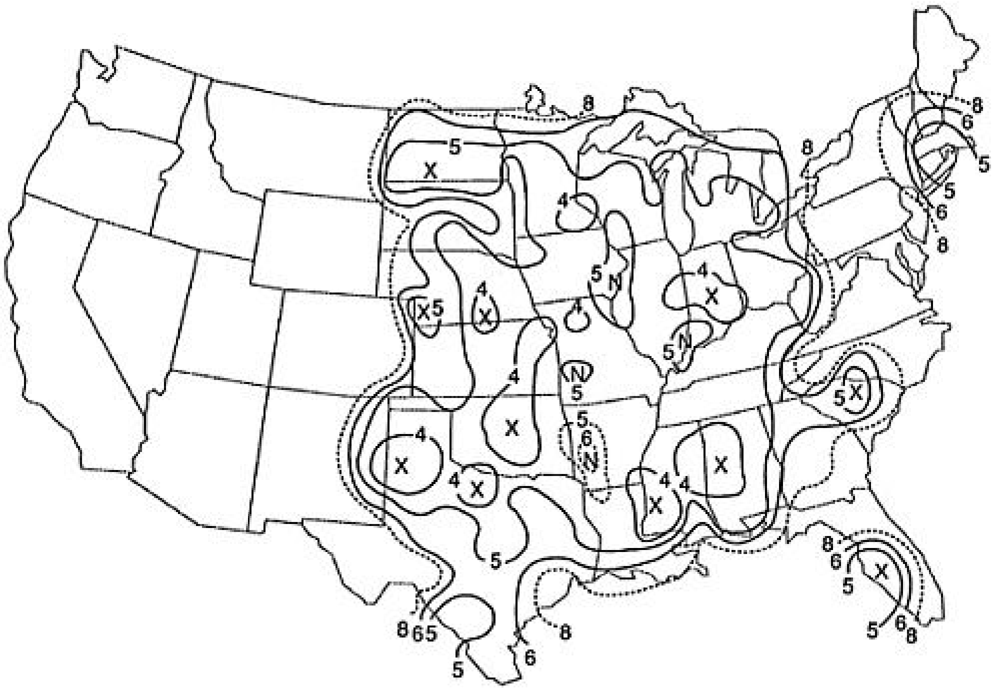

FIGURE 2-9 Probable annual tornado hazard from F4 and F5 tornadoes–labels similar to Figure 2-8. The 10^{-7} contour has been omitted.

of the country and are most prevalent in parts of the states of Texas, Oklahoma, and Kansas (though on a whole-state basis, Indiana ranks ahead of Kansas).

During 1953–1989, tornadoes claimed 3550 lives–an average of 96 deaths per year. Figure 2-10 shows tornado-related deaths to be concentrated in Mississippi, Arkansas, and Indiana (Alabama and Ohio also have had large numbers of deaths due to tornadoes). Inspection of Figure 2-5 shows that three years contribute disproportionately to the total number of deaths: 1953 (516 deaths), 1965 (298) deaths), and 1974 (361 deaths). The deaths in 1953 were due to strong tornadoes striking three urban areas: Waco, Texas on May 11, 1953 (114 dead, 597 injured); Flint, Michigan on June 8, 1953 (116 dead, 867 injured); and Worchester, Massachusetts on June 9, 1953 (90 dead, 1288 injured).

The high death counts in 1965 and 1974 were the result of an extensive tornado outbreak in each of these years. A tornado outbreak is defined as the occurrence of several tornadoes over a region, usually all by thunderstorms embedded in the same extratropical cyclone. Although infrequent, outbreaks strongly affect all tornado statistics.

Tornado wind speeds are especially threatening to human activities because the speeds apparently maximize only a few tens of meters off the ground. Current estimates of tornado wind speeds are based on postevent analyses of damage to engineered structures, on photogrammetric determination of the motion of objects (such as dust packets, pieces of vegetation, and building debris) documented on film and videotape, and on measurement of speeds of objects with Doppler radar. The observation of a tornado with Doppler radar is a fortuitous event, because until very recently, the only such radars available were large, fixed-station systems. This meant that the tornado had to occur within 25–30 miles (40–50 km) of the radar site for it to be observed. Each of the wind-speed estimation techniques has its shortcomings, but taken together, they produce results suggesting that the maximum probable net speed occurs 100 to 165 ft (30 to 50 m) above the ground and is in the range of 250 to 310 mph (110 to 135 m/s), with some likelihood that the actual value is near the lower end of this range (Davies-Jones, 1983). Vertical speeds may be as high as 180 mph (80 m/s), whereas radial speeds have been estimated to reach 112 mph (50 m/s). The speed of translation of a tornado–roughly the same as that of its parent thunderstorm–can exceed 56 mph (25 m/s). It should be emphasized that all of these values are based on indirect measurements as described above. Very little detail is actually known about the airflow in tornadoes.

Tornado wind speeds are categorized by using the Fujita Tornado Scale (commonly called the F-scale) given in Table 2-2. This scale, which was established by Fujita (1971, 1981; also Fujita and Pearson, 1973), was based primarily on the study of damage produced by the 1970 Lubbock, Texas, tornado. A subjective scale value is assigned based on visual assessment of damage severity; this in turn fixes a speed range (note that the ranges in the scale do not overlap). Table 2-2 shows that extreme speeds are usually attained in only a few tornadoes each year, in what are referred to as "F5"

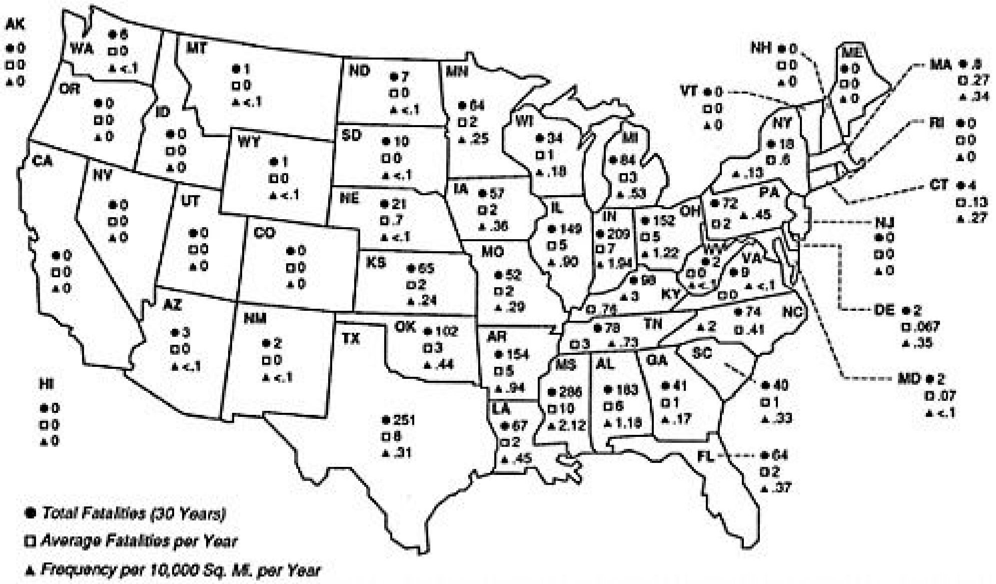

FIGURE 2-10 Tornado deaths by state, based on reports from 1961 to 1990. Source: L. A. Grenier, National Severe Storms Forecast Center, National Weather Service, NOAA, 1991.

tornadoes (Fujita, 1987). In 98 percent of all tornadoes, speeds near the ground are considerably less than 200 mph (90 m/s). Also, since flow configurations vary considerably with overall intensity, extremes in vertical speeds may not occur in conjunction with extremes in tangential speeds. In 50 percent of all tornadoes, speeds are less than 100 mph (45 m/s) and should cause only minor damage to structures.

TABLE 2-2 Fujita Tornado Scale

	Wind-Speed Range[a]			
Scale Value	(m/s)	(mph)	Description of Damage	Average Number per Year (1953–1989)
0	18–33	40–72	Light	218 (29%)
1	33–50	73–112	Moderate	301 (40%)
2	50–70	113–157	Considerable	175 (23%)
3	70–92	158–206	Severe	43 (6%)
4	92–117	207–260	Devastating	10 (1%)
5	117–143	261–318	Incredible	1 (0.002%)
			Total	748

[a] Wind speeds in the ranges given for the scale values are defined by Fujita to be the "fastest 1/4-mile wind". For an F4 wind speed of 200 mph, the duration of the damaging wind at a point would thus be about 4 seconds.

Source: Fujita, 1971.

As discussed in Doswell and Burgess (1988), the F-scale is essentially a damage severity scale and not a true "tornado intensity" scale. In particular, the wind-speed ranges of the F4 and F5 categories have not yet been calibrated by independent observations near the surface. Indeed, wind-speed assessments based on analyses of damage to engineered structures have consistently indicated wind speeds lower than the ranges given by Fujita. These later assessments also suggest that there should be an overlap of wind speeds between the F4 and F5 categories to allow for variability in construction materials and practices (Minor et al., 1977).

Results from laboratory modeling coupled with results from photogrammetric measurements of actual events show that the distribution of wind in a tornado is highly complicated (e.g., Snow, 1987). These findings suggest that in small, generally low-intensity tornadoes, the maximum tangential speeds are contained in a toroidal volume very close to the ground. Maximum vertical speeds are contained in an upward jet through the central hole of this toroid, whereas maximum radial speeds occur in an inflowing surface layer beneath the toroid.

Large, generally high-intensity tornadoes appear to have a more complicated structure, with embedded secondary or "suction" vortices circling a clear, perhaps nearly stagnant central core. These secondary vortices are very intense and usually short-lived, and give rise to the maximum wind speeds cited above (Blechman, 1975; Forbes, 1978). In addition to suction vortices, other asymmetric flow configurations have been documented in tornadoes (e.g., an accelerating radial inflow appearing as a dust band has been described by Golden and Purcell (1977)).

Pressure falls associated with tornadoes are generally fairly small, probably reaching around 100 millibars (mb) in extreme events. Normal sea-level pressure is about 1013 mb (29.91 inches Hg). The local time-rate-of-change of pressure experienced at a point on the surface depends on several factors; for an intense, fast-moving, small vortex, this may approach 100 mb/s. Although this change is large, recent engineering studies have shown that the "explosion" of structures due to an extreme pressure difference developing between inside and outside is an unusual occurrence. Most structures are sufficiently leaky that even with the high rates of pressure change encountered in tornadoes, interior pressures can adjust quickly enough to prevent an explosion. Parallel studies have shown that almost all of the devastating damage caused by tornadoes can be attributed to wind-induced forces tearing structures apart from the outside. Evidence gathered during postevent damage surveys also suggests that a "domino effect" (i.e., large debris elements, such as roofing materials, becoming airborne and then impacting nearby structures) plays a key role in much tornado damage.

Extratropical Cyclones

The passage of a midlatitude low-pressure system (perhaps over a period of several days) and its associated fronts produces a characteristic pattern of shifts in wind direction and variations in wind speed. Such systems (extratropical cyclones) tend to be strongest in late winter and early spring when the north-south temperature contrasts are greatest. There is some tendency for low-pressure systems to follow certain preferred paths across the globe. Thus, in many areas, systematic changes in the wind have long been recognized and used to formulate rules of thumb for forecasting local weather.

Patterns of wind that have unusual characteristics and that occur in the same region with certain frequency are often given descriptive names by local people. For instance, in New England one may hear reference to a *nor'easter*. This wind blows onto the New England coast from the northeast with moderate to strong force and is generally wet and cold.

Topography can compress and funnel the strong air flows accompanying extratropical cyclones to produce very high wind speeds locally. Examples of this effect are provided by the extreme winds cited in Table 2-1 for Mt.

Washington, New Hampshire; the records for April 11–12, 1934, were set during the passage of a strong extratropical cyclone. Winds are stronger at the top of this peak–as they are on the summits of most mountains–than they are at the same elevation in the free air because of the air being forced over the mountain, which presents an obstacle to the wind flow.

Another example of a topographic effect is the *chinook* or *foehn wind* of the eastern slopes of the Rocky Mountains. This is a dry, warm wind that blows down the mountains and has been known to produce near-surface winds in excess of 100 mph (45 m/s) accompanied by temperature fluctuations of up 22°C (40°F) in half an hour (Lilly and Zipser, 1972; Bedard and LeFebvre, 1983). Gusts may reach 140 mph (62 m/s).

As examples of extreme winds that can be produced by these systems, consider that during the storm of November 24–26, 1950, a fastest-mile wind speed of 82 mph (37 m/s) was measured at Newark, New Jersey, and a 110-mph (49-m/s) gust was observed in Concord, New Hampshire. This storm caused 200 deaths and $1 million in property damage. Damage throughout New Jersey, eastern Pennsylvania, and interior and southeastern New York was more severe than in the hurricane of 1938 that struck these same regions.

More recent examples of the high winds that can be produced by extratropical cyclones are provided by the violent storms that struck the United Kingdom and Western Europe on October 16, 1987, January 25, 1990, and February 27, 1990; these storms produced near-surface winds well over 100 mph (45 m/s), resulting in 47 deaths and over $1.5 billion in damage, with thousands of large trees uprooted.

Tropical Cyclones

A few times each year, from early June through October, low-pressure systems termed *tropical cyclones* form over warm ocean waters in the tropics. Occasionally, where sea-surface temperatures are greater than 22°C (72°F) and when winds high in the atmosphere are supportive, one of these systems will become more organized and intensify to become a *hurricane* (wind speeds exceeding 73 mph (64 knots) or more (Anthes, 1982)). When fully developed, a hurricane has a calm, central core, or eye, surrounded by very strong winds concentrated in a doughnut-shaped region of heavy rain, termed the eyewall. A pattern of *rainbands*, each consisting of many thunderstorm cells, spirals inward to merge with the eyewall. These violent tropical cyclones tend to be self-sustaining until they move either into a region of sea-surface temperatures less than 26.5°C (80°F) or over land. In either case, the system is cut off from its main energy source, the warm sea surface.

The eastern and Gulf coasts of the United States are threatened by tropical cyclones that form in the tropical Atlantic and in the Gulf of Mexico (Figures 2-11, 2-12, and 2-13). From 1931 through 1987, 551 tropical storms were observed in these areas; 314 of these reached hurricane status. In an average year, about four tropical storms will make landfall in the continental United States; on average, two of these will be hurricanes. The actual number

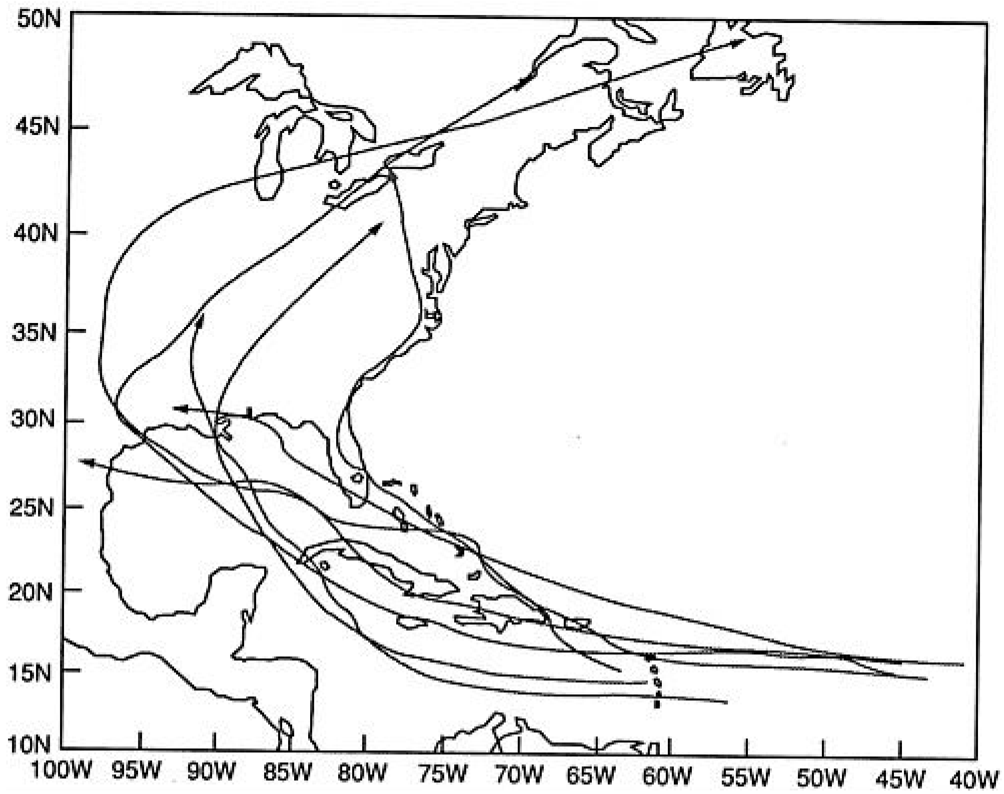

FIGURE 2-11 Distribution of the Saffir-Simpson category 4 or 5 hurricanes that struck the United States from 1900 to 1930. Source: National Hurricane Center, National Weather Service, NOAA.

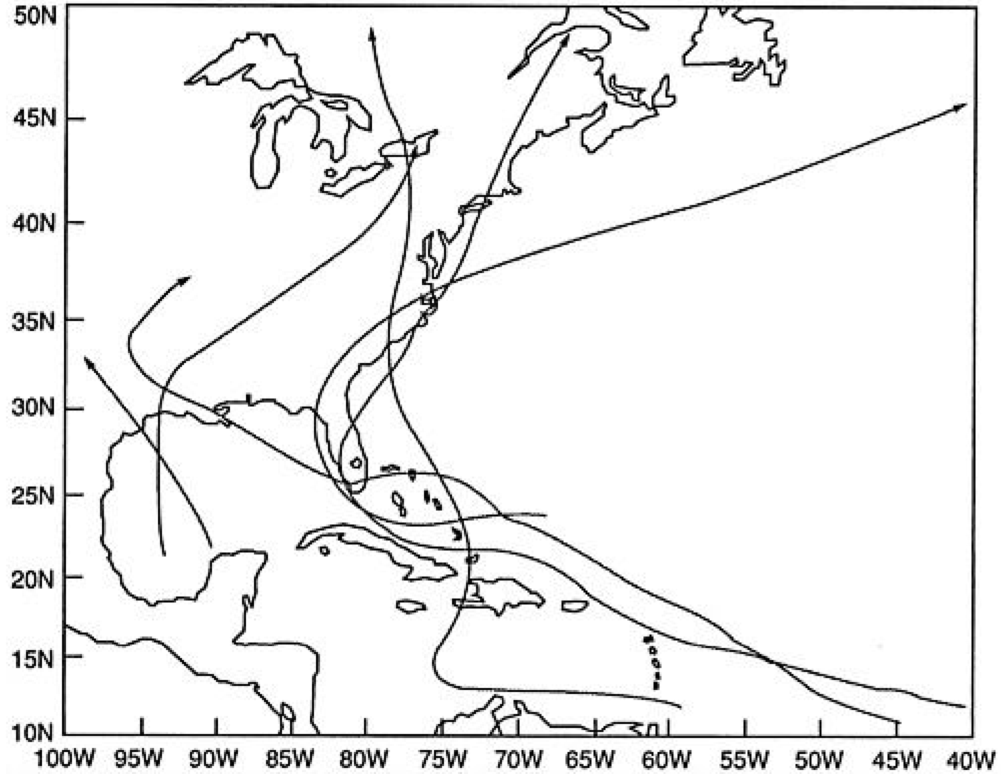

FIGURE 2-12 Distribution of the Saffir-Simpson category 4 or 5 hurricanes that struck the United States from 1931 to 1960. Source: National Hurricane Center, National Weather Service, NOAA.

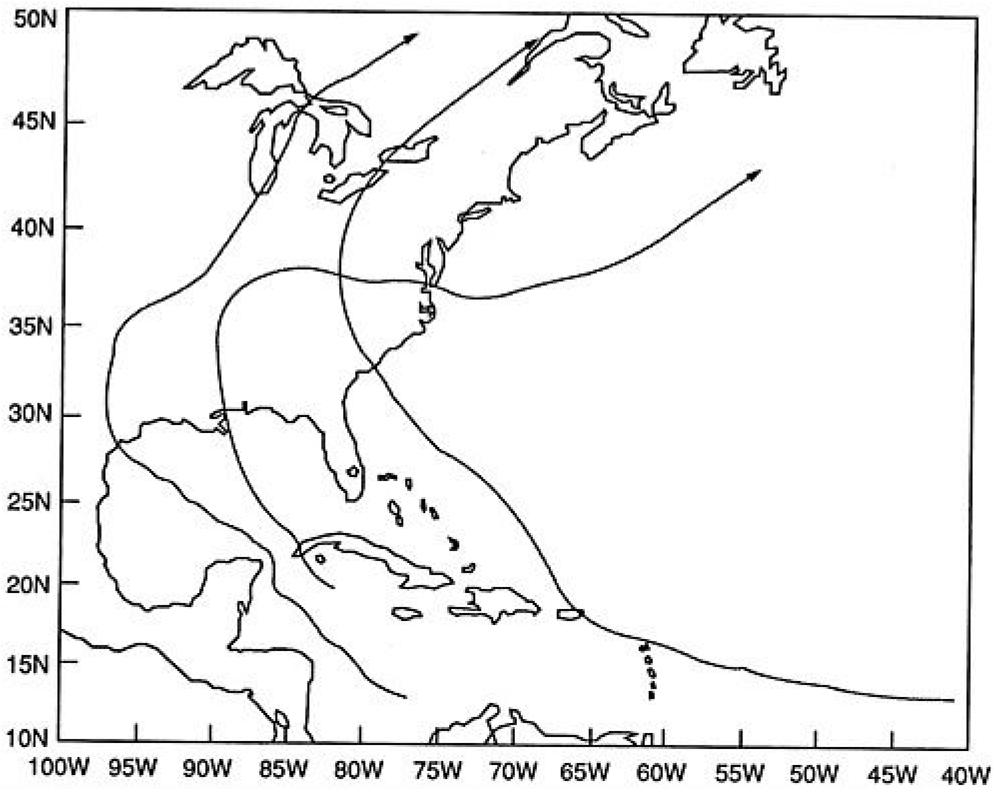

FIGURE 2-13 Distribution of the Saffir-Simpson category 4 or 5 hurricanes that struck the United States from 1961 to 1990. Source: National Hurricane Center, National Weather Service, NOAA.

of hurricanes per year in the subtropical northern Atlantic, Caribbean, and Gulf of Mexico has shown wide variability, ranging from 2 (1931, 1983) to 12 (1969).

Tropical cyclones and hurricanes also pose a serious threat to Puerto Rico and the other islands of the Caribbean. Hurricane Donna passed close to Puerto Rico on September 5, 1960, causing 107 deaths and millions of dollars of property damage. The eye of Hurricane Hugo passed directly over St. Croix and northeast Puerto Rico early on September 18, 1989, with a lowest pressure of 946 mb and peak gusts to 120 mph (104 knots; 52 m/s).

The West Coast and the islands of Hawaii are occasionally threatened by tropical cyclones forming off the western coast of Mexico. These seldom produce strong winds along the California coast, but can lead to very heavy rains along the Pacific coast and in the southwestern states. Hawaii receives moderate to strong winds from a tropical cyclone about once every four years; it was affected by hurricanes only five times from 1904 to 1972. The only storms to pass directly over one of the major islands were Hurricane Dot, which passed over Kauai in August 1959, and Hurricane Iwa, which passed over Kauai in November 1982.

As suggested in Figures 2-11, 2-12, and 2-13 hurricanes make landfall most often in Florida. However, historically these tropical systems have come ashore all along the coast, from Texas to Massachusetts. The northerly landfalls are a consequence of the Gulf Stream that transports warm water northward along the eastern seaboard. Over this current, these cyclones can maintain their tropical characteristics much farther north than they can over the central North Atlantic.

When a hurricane makes landfall in a populated area, the potential is great for significant loss of life and enormous property damage from both high winds and the *storm surge*. The storm surge is the rise of the sea in advance of an approaching tropical storm. The degree of rise is related to both the central low pressure and the overall wind field in the storm; it also depends on coastline bathymetry. The sea experiences its maximum rise in the storm's right-front quadrant taken relative to the storm's track.

The Saffir-Simpson Scale (Simpson and Riehl, 1981) shown in Table 2-3 has been developed to express the severity of these storms in terms of their maximum wind speed (usually estimated from ship and aircraft data) and depth of the storm surge. Of the 138 hurricanes to reach the continental United States in the period 1899–1980, 82 had maximum sustained winds from 74 to 110 mph (33 to 49 m/s)—categories 1 and 2 on the Saffir-Simpson Scale. Of the remainder, 54 were major hurricanes, falling into categories 3 and 4. Only two category 5 hurricanes have hit the mainland this century: the Labor Day hurricane at Matecumbe Key, Florida (September 2, 1935), and Hurricane Camille on the coasts of Louisiana and Mississippi (August 17, 1969).

TABLE 2-3 Saffir-Simpson Hurricane Scale

Category	Wind-Speed Range (sustained)		Storm Surge Depth Above Normal Tide		Storm Description
	(m/s)	(mph)	(m)	(ft)	
1	33–43	74–95	1.2–1.6	4–5	Weak
2	43–49	96–110	1.7–2.5	6–8	Moderate
3	49–58	111–130	2.6–3.8	9–12	Strong
4	58–69	131–155	3.9–5.5	13–18	Very Strong
5	>69	>155	>5.5	>18	Devastating

Source: Simpson and Riehl, 1981.

Hurricane Hugo was the second most costly–though not the most deadly–hurricane in U.S. history. The total number of deaths attributed to Hurricane Hugo during its nine-day life (September 13–22, 1989) is estimated at 49, with 21 on the mainland. It inflicted direct damage estimated at nearly $10 billion, with about $7 to 8 billion occurring on the mainland.

Paths and changes in intensity of tropical cyclones have proved difficult to predict. In the Atlantic and the Caribbean, these systems usually move slowly westward initially, gradually increasing in strength. Often they recurve, turning first to the north and then to the northeast. Detailed studies using aircraft reconnaissance and satellite observation (the latter has been available since the mid-1960s) confirm that hurricane movement is often erratic: a hurricane on the move can slow down, remain nearly stationary, speed up, or change direction. The track of Hurricane Hugo, shown in the map of Figure 2-14 for the 10 days from 1800 GMT September 12, 1989 to 1800 GMT September 22, 1989, illustrates many of these features. However, large-scale mappings of storm-center motion as derived from a mixture of aircraft and satellite data can be misleading because many details are smoothed out. As illustrated in Figure 2-15, the actual hour-by-hour track of Hurricane Hugo's eye, when observed by radar, is much more complex and illustrates the problems of predicting landfall time and location.

Although satellite observations have proved invaluable in continuously monitoring the overall development and motion of a storm system, most of our detailed knowledge of the inner workings of hurricanes has come from aircraft reconnaissance flights by the National Oceanic and Atmospheric Administration (NOAA) and the military services. These flights penetrate the swirling clouds to collect data on wind, temperature, and pressure from about 1500 ft (450 m) to 25,000 ft (7500 m) above the sea surface. Over the ocean, expendable packages are dropped from the aircraft to measure sea-surface temperatures and vertical profiles of winds and other atmospheric parameters.

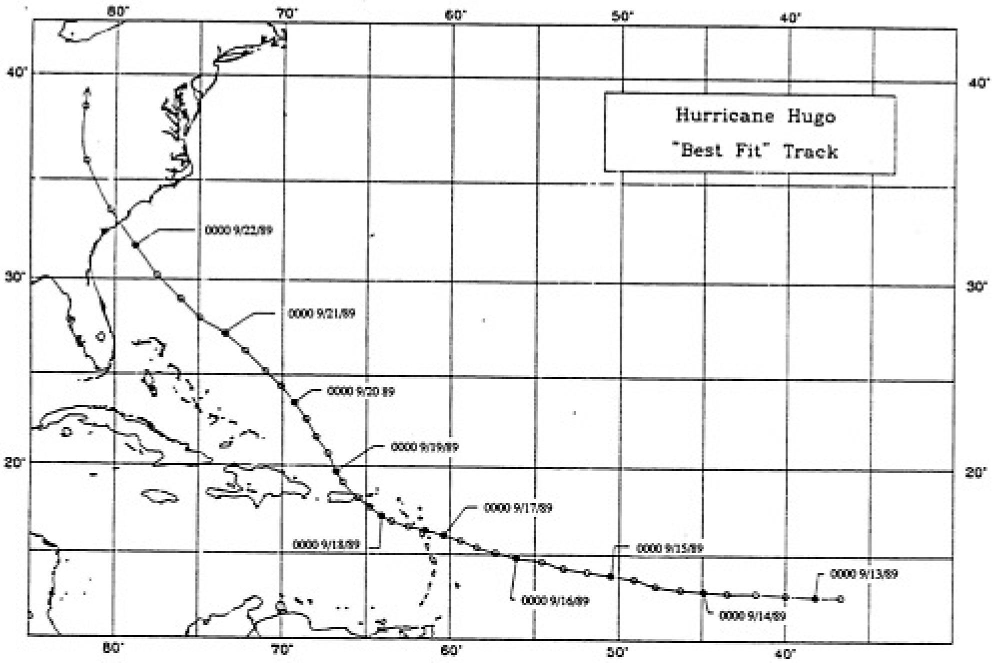

FIGURE 2-14 The track of Hurricane Hugo over a ten-day period, 1800 GMT September 12, 1989 to 1800 GMT September 22, 1989, as determined from composited aircraft, satellite, and other observations.

Most frequently cited extreme wind speeds in hurricanes were measured at aircraft altitude. Using aircraft data, Riehl (1979) has estimated that over the open ocean, the strongest winds are found at about 1000 ft (300 m) above the sea surface in the eyewall region of the storm. The annulus of strong winds extends upward to more than 10,000 ft (3500 m). Aircraft and radar studies have shown that some of the more intense hurricanes have contained a double concentric eyewall structure and a related double maximum in wind speeds, as was the case with Hurricane Alicia in 1983 (Willoughby et al., 1982).

Aircraft measurements provide limited spatial and temporal coverage of weather systems as large and as long-lived as hurricanes. Most seriously, airborne instruments provide no direct measurements of the quantity of greatest interest: near-surface wind speeds as a storm comes onshore. As a consequence, various indirect methods have been devised for estimating near-surface speeds from composite aircraft (usually taken at 10,000 ft (3500 m)) and satellite data.

Because of the physical relationship between the winds circling the eye and the pressure gradient, an inferred central pressure is often used to

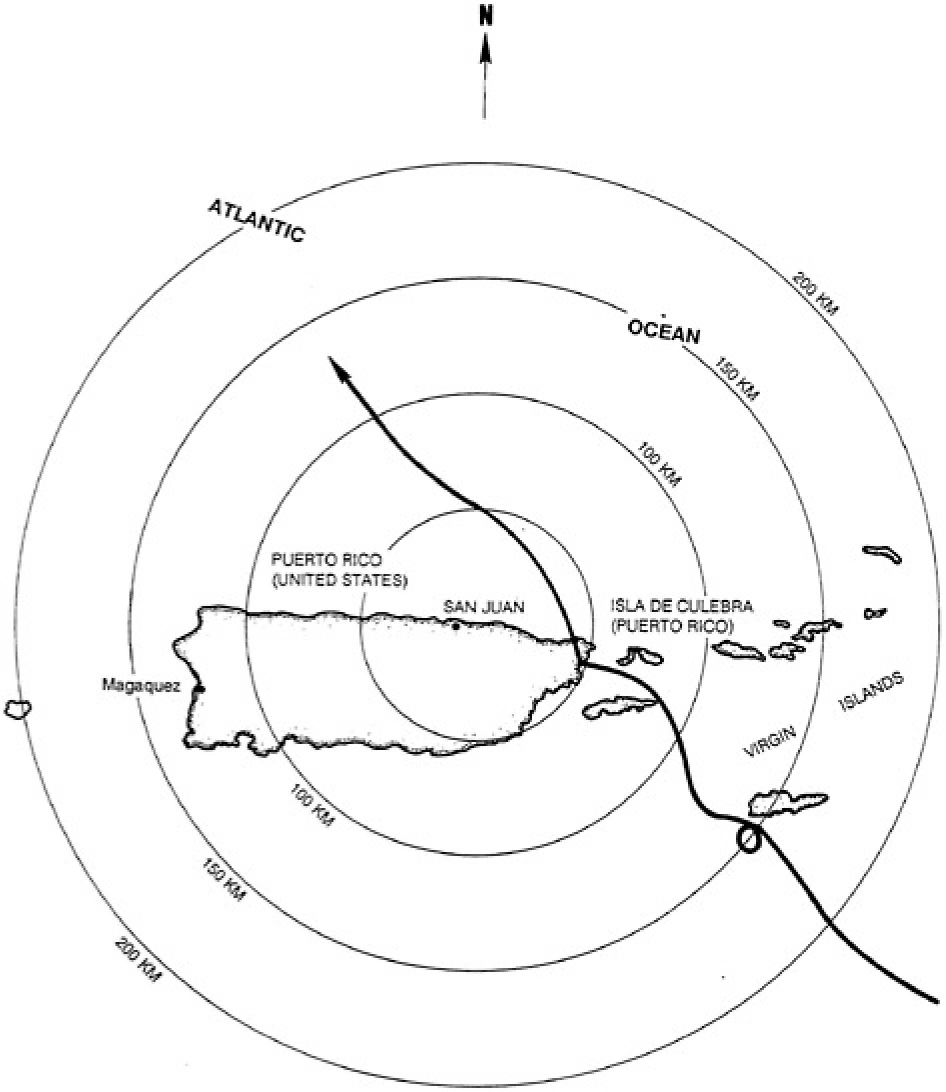

FIGURE 2-15 A detailed mapping of the track of the center of the eye of Hurricane Hugo as it swept past the Virgin Islands and Puerto Rico September 18, 1989. This track was determined by continuous monitoring of the storm system by the NWS radar at San Juan, Puerto Rico.

estimate near-surface, peak wind speeds (neglecting surface friction). By this means, crude estimates of maximum sustained winds of about 200 mph (90 m/s) were made from the two strongest hurricanes to make landfall in the United States in modern times, the Labor Day Hurricane of 1935 (26.35 inches Hg/892.3 mb; McDonald, 1935) and Hurricane Camille in 1969 (26.73 inches Hg/905 mb).

In a hurricane, high near-surface winds affecting land occur as the major rainbands, and especially the eyewall, come onshore. Although winds have been measured at the ocean shore during hurricane landfalls, most observations have been made some distance inland from the coast. Because of poor mast design or inadequate maintenance, anemometers positioned at the shore have usually failed before peak wind speeds are suspected to have occurred, particularly in the extreme storms of most interest. Figure 2-16 shows a trace of wind speed typical of the passage of a hurricane eye by a near-shore station, in this case from Hurricane Hugo, October 22-23, 1989.

The active storm clouds in the rainbands can produce tornadoes (Novlan and Gray, 1974; Gentry, 1983; McCaul, 1987). Although most of these are small and short-lived, occasionally one produces significant damage. Hurricanes Carla (September 10–13, 1960), Beulah (September 20, 1967) and Gilbert (September 11–19, 1988) are known for the destructive tornadoes that accompanied them.

It is important to recognize that wind speeds collected by weather reconnaissance aircraft are estimated values applicable at aircraft altitude. The lower limit for safe flight is around 450 m (1500 ft). Knowledge of the vertical distribution of wind speed in hurricanes, particularly as they are making landfall, is very limited (e.g., Black et al., 1988). Speeds near ground are modified by the roughness of the terrain and trees. The increased friction encountered by the swirling flow after it moves inland quickly reduces the speed of the winds at near-ground level. For example, a wind of 160 mph (71 m/s) at 500 ft (150 m) will typically translate into a fastest-mile wind speed of 120 mph (54 m/s) at 33 ft (10 m) over open seas and into just over 100 mph (45 m/s) in open terrain near the coast. Winds 300 to 400 ft (100 to 125 m) above ground may be little changed for some distance inland. Very strong (though generally less than hurricane force) near-surface winds can persist well inland, particularly in fast-moving storms. On October 15, 1954, Hurricane Hazel, with a forward speed of 50 mph (22 m/s), produced 100-mph (45-m/s) winds in Buffalo, New York. In 1985, Hurricane Gloria, also moving at 50 mph (22 m/s), produced wind gusts to 70 mph (31 m/s) in New Hampshire. As shown in Figure 2-17, Hurricane Hugo (1989) produced winds of hurricane or near-hurricane force over a large inland area; wind damage was reported as far as 150 to 250 miles from the coast.

For reasons not yet understood but probably related to decade-long trends in the Earth's overall climate, yearly hurricane activity has varied extensively over the last century. For example, since 1950 there have been 39 Atlantic hurricanes in categories 1 and 2 of the Saffir-Simpson Scale. Thirty-three, or 85 percent, of these occurred during the "very active period" of 1950 to 1969; only 6, or 15 percent, occurred during the "quiet period" (1970 to

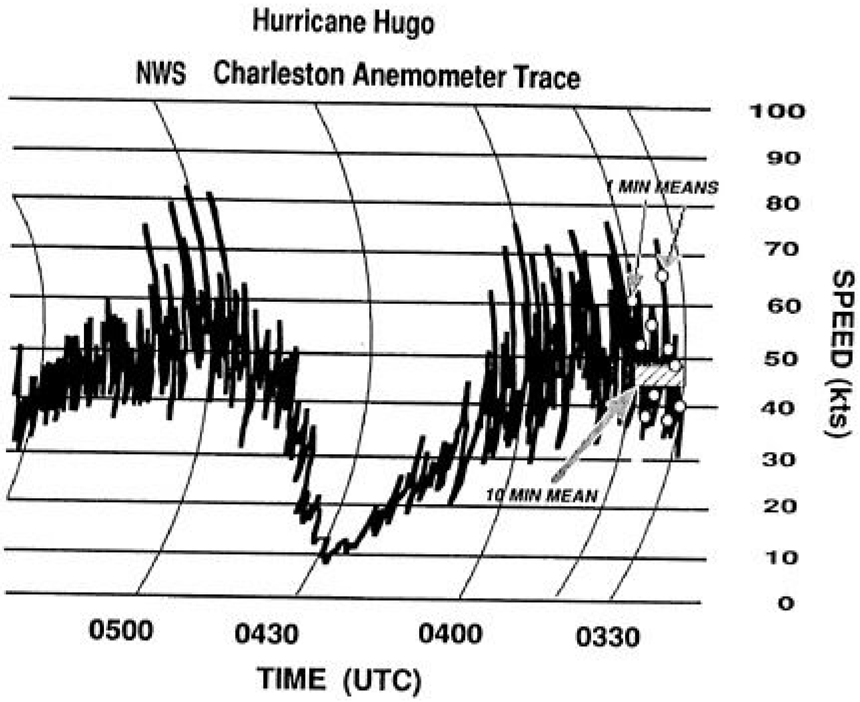

FIGURE 2-16 A portion of the trace of the wind speed observed at the National Weather Service Office, Charleston, South Carolina, during the passage of Hurricane Hugo, 10:10 p.m. EST October 22 to 1:15 a.m. EST October 23, 1989 (note that time advances from right to left; UTC = GMT = EST + 5 h). The relatively calm central eye was over the station for about an hour centered around 11:28 p.m. Maximum sustained surface winds at this somewhat sheltered inland location were around 55 mph (25 m/s) for about 20 minutes both before and after the passage of the eye center. The peak gust of 84 mph (38 m/s) occurred at 11:58 p.m. Courtesy of Mark Powell, Hurricane Research Division, NOAA.

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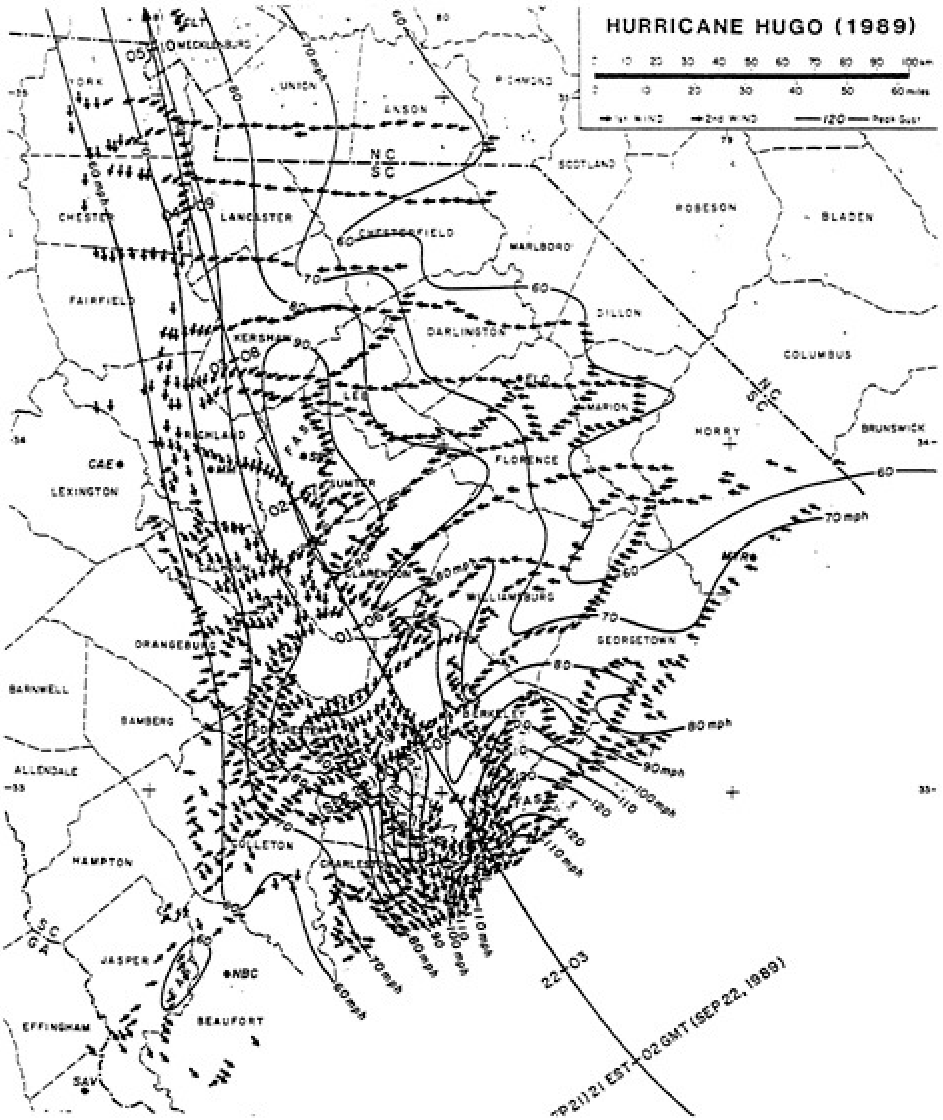

FIGURE 2-17 Estimated distribution of peak gust speed along the track of Hurricane Hugo as this rapidly moving storm came inland. Contours in miles per hour. The track of the center of the storm is shown by the broad solid line. Note that the highest peak gusts, probably in excess of 130 mph (38 m/s), occurred to the right of the track at the sea coast. It is in this location where storm motion and circulation combine and surface frictional effects are minimized. Source: T. T. Fujita, University of Chicago.

1988). It is unclear whether the next decade will see a continuation of this quiet period or a return to the more vigorous activity of the 1950s and 1960s (Gray, 1990). The panel notes that the last two years of the "quiet" 1980s featured two very intense storms: Hurricanes Gilbert (1988) and Hugo (1989). It has been speculated that the projected global warming may result in an increase in the overall intensity of hurricanes (Emanuel, 1987).

IMPROVING THE WIND CLIMATOLOGY OF THE UNITED STATES

Surface wind has traditionally been measured by instruments mounted on masts and towers extending upward from the surface of the earth. Measurements of surface wind direction using wind vanes were first made by the ancient Greeks and are among the oldest meteorological measurements. The effects of the wind on surface features have been the basis of qualitative estimates of wind speed from antiquity; quantitative observations of wind speed using anemometers began in the middle of the fifteenth century. Use of such instruments, albeit greatly improved by several centuries of experience, continues as part of the routine collection of weather data. Currently, near-surface wind data are measured at approximately 750 stations across the United States. Approximately 225 of these are NOAA National Weather Service facilities; others are operated by the Federal Aviation Administration, the military services, and other cooperating organizations, both public and private. The standard measurement height is 33 ft or 10 m. However, in practice a wide range of heights are in use.

Upper-air data are obtained at fewer stations. The main observing system for winds from the surface to around 100,000 ft (30 km) consists of balloon-borne rawinsondes (short for "radio wind sounding") launched from 70 National Weather Service facilities scattered across the 48 states. The primary purpose of these observations is to provide the data necessary to initialize numerical weather forecast models. Upper winds are also estimated by tracking clouds observed from satellites; these data are used to supplement those obtained from rawinsondes, particularly over the oceans. Supplemental reports from commercial aircraft provide information on turbulence in the upper air. Special U.S. Air Force and NOAA aircraft are also used to observe upper-level winds and are particularly valuable for observing winds within hurricanes. However, such special aircraft observations are used primarily for atmospheric research.

These traditional techniques suffer from a number of shortcomings. For example, observations from many observing stations are available only hourly and from some stations for only selected hours of the day. Rawinsondes are launched only twice daily (7 a.m. and 7 p.m. EST). Many surface observations rely on human observers visually estimating a sustained speed and a prevailing direction. Where continuous data are available, they are often in analog or strip chart form and therefore labor intensive to reduce. Few data are available from many remote sites. As a consequence of these and other problems, the current, best-available wind climatology of the United States is known to contain many biases.

The ongoing modernization of the operational observation program of the National Weather Service and the concurrent development of new research instrumentation present opportunities to greatly improve the wind climatology data base (Golden, 1989). The three, key, wind-measuring systems being deployed in the 1990s by the National Weather Service are the Next-Generation Radar (NEXRAD), the Automated Surface Observing System (ASOS), and the profiler. These will be supplemented and complemented by similar systems being deployed by the Federal Aviation Administration, other federal agencies, and the military services.

NEXRAD is a Doppler radar capable of measuring winds (with respect to the radar location) up to 112 mph (50 m/s). The National Weather Service will deploy 114 NEXRAD systems throughout the United States, probably by 1996. The Federal Aviation Administration will deploy a complementary system of shorter-range Terminal Doppler Weather Radars to watch for the occurrence of downbursts and wind shears near airports.

The ASOS will record both 10-m mean wind speed and direction, and peak gust speed at 1-minute intervals. Approximately 1500 of these units will be installed throughout the United States, mainly at airports.

Thirty tropospheric profiler systems have been installed in the central one-half of the United States in demonstration network. These are vertically pointing Doppler radars that provide high-resolution profiles of the horizontal winds from about 1500 ft (500 m) to 48,000 ft (16,000 m) above the ground. A wind profile is available every 5 minutes. At present, these are being used only for atmospheric research.

It must be stressed that these systems are being deployed to support the current operational requirements of the deploying agencies. In the case of the National Weather Service, these are weather forecasting and severe weather warning. Current plans call for very small, selected sets of data to be archived. There is no plan to archive data routinely for national climatological purposes. Yet archiving is critical to issues of levels of acceptable risk and corresponding structural design requirements.

The distinct difference between these state-of-the-art systems and the traditional instrumentation that they are scheduled to replace is that they will provide nearly continuous digital data streams of wind information. Many features of these data streams are complementary; if used together, they could provide a much improved picture of winds from near surface to the tropopause in both stormy and clear weather. However, they still do not provide the kind and quantity of wind-speed data needed by wind engineers.

EXPANDING THE WIND-ENGINEERING DATA BASE

The prediction of wind speed and its micrometeorology are critical in the application of research to practice. The micrometerology of wind includes its gustiness, its variation with time and space, and gust sizes.

The American Society of Civil Engineers (ASCE) standard ANSI/ASCE 7-88 (formerly American National Standards Institute standard ANSI A58.1) gives wind-load requirements for design of buildings and structures in the United States. The standard is developed by using a consensus process wherein it is balloted by committee members with backgrounds in consulting engineering, research, the construction industry, education, government, design, and private practice. The load requirements provided in the standard are intended for use by architects, structural engineers, and those engaged in preparing and administering local building codes.

Prediction of wind speeds for design given in the current ANSI/ASCE 7-88 standard are based on data collected at 129 National Weather Service stations around the country. These stations number less than three per state on the average. Some states contain only one station that provides data usable for the prediction of wind speed.

To predict wind speeds for the lifespan of a building or longer, it is necessary to have long-term, wind-speed records at a closely spaced network of stations. With the development of the ASOS, there is the potential to gather data at many more stations because the instrument package can be deployed in large numbers and its data can be retrieved by a centralized location. However, standardization in data recording, continuation of historical records, and organized archiving are critical to ensure that the data are usable to the wind-engineering profession.

There are very few wind-recording stations located in coastal areas that are in the path of hurricanes. Moreover, wind-recording instruments are often damaged or without power during the passage of severe hurricanes. As a result, recorded data of hurricane winds are sparse. Design wind speeds in coastal areas given in the ANSI/ASCE 7-88 standard are based on the Monte Carlo numerical simulation of hurricanes. Closely spaced stations along the coastline are needed to obtain better definition of hurricane winds. Another option is to develop a deployable wind-recording station that can be placed in the path of an approaching hurricane. It is extremely important to improve current methods for collecting hurricane wind-speed data if reliable predictions of wind speeds are to be obtained.

Wind speeds are also affected by wind climate and by topography. Mountains and valleys significantly affect the wind speed at various locations. Deployment of ASOS packages in a closely spaced grid network can provide data in topographically difficult terrain. Good examples of this type of terrain are Puerto Rico and the islands of Hawaii. Data gathered at many stations can help regional zonation of design wind speeds.

Calibration of the anemometer sites is critical for improving wind-speed assessments for design and other purposes. It is recommended that a systematic calibration of the wind-speed variation due to roughness characteristics and nearby obstructions be undertaken for all existing anemometer sites.

Standardization of wind data collection and archiving is critical. Wind data are used for a variety of applications including assessing wind forces on buildings, predicting atmospheric diffusion, extracting wind energy, and improving agricultural efficiency, and in the aviation industry. To meet these applications, a set of recommendations was set forth at the Workshop on Wind Climate held in Asheville, North Carolina, in 1979. These recommendations can provide a starting point in standardization of wind data collection and archiving (see Table 2-4).

In general, then, the wind data base can be expanded by establishing a closely spaced network of data-collecting stations, by developing rapidly deployable instrument packages in hurricane-prone areas, and by standardizing collection and archiving of wind data.

RECOMMENDATIONS

Measurements of Extreme Wind Speeds

There is a need to confirm the maximum wind speeds that can occur in tornadoes, downbursts, hurricanes, and other high-speed winds. Technology in the form of portable Doppler radar (Bluestein and Unruh, 1989) and Laser-Infrared Doppler Atmospheric Radar is now available to directly measure speeds in tornadoes and downbursts. Small, easily transported balloon sounding systems (e.g., the Cross-Chain Loran Atmospheric Sounding System (CLASS) developed by the National Center for Atmospheric Research; also see Bluestein et al., 1988, 1989) are also available to explore the thermodynamics of the parent storm. Further, the research community has demonstrated the feasibility of intercepting such phenomena with both ground vehicles and light aircraft (Colgate, 1982). Thus, in principle, it is now possible to obtain actual measurements of dangerous winds and related, in-cloud conditions and so refine the current, maximum-speed estimates.

Research on the development of instruments for probing tornadoes, downbursts, and their parent storms should be continued, and field programs to apply these instruments should be encouraged. It should be recognized that to collect data from several events will require a multiyear effort.

There is also an urgent need to establish the characteristics of the nearshore surface winds produced by hurricanes. Valuable data can be obtained by equipping existing installations, such as those operated by the Federal Aviation Administration and the U.S. Coast Guard, with recording systems for use in extreme events. Rapidly deployable, storm-resistant surface instruments are needed to establish detailed pressure and near-surface wind fields beneath these storms as they make landfall. Many of the research tools developed for exploring tornadoes and downbursts could be adapted to investigating hurricane winds, particularly during the critical landfall period. Similarly, the storm chase operations pioneered by the NOAA National Severe Storms Laboratory and researchers at the University of Oklahoma serve as models for the development of techniques for deploying such instruments in the path of advancing hurricanes. Further, to increase the probability of obtaining data from hurricanes, cooperative international projects could be initiated with nations having high frequencies of tropical cyclone occurrences: the eastern coast of India, the southern coast of China, the eastern coast of Taiwan, the northern portion of the Philippines, and certain South Pacific islands.

TABLE 2.4 Meteorological Variables Required for Wind Engineering Applications

*Surface wind data (10 m above ground)**

Variable	**Averaging time**	**Primary uses**
1. Wind speed and direction (derived from components)	20 min	Wind energy, pollutant dispersion, forces on structures, agriculture**, aviation
2. Peak wind speed/direction	2 s	Forces on structures
3. Fastest one-minute speed/ direction	1 min	Wind turbine, forces on structures
4. Fastest-mile wind speed/ direction	--	Continuity with previous data
5. Standard deviation of wind fluctuations	20 min	Pollutant dispersion

Low-level wind data
*(at levels of approximately 100, 300, and 500 m above ground)****

Variable	**Averaging time**	**Primary uses**
1. Wind speed and direction and their fluctuations	20 min	Wind energy, pollutant dispersion, forces on structures, aviation, numerical and physical modeling

Associated meteorological variables

Variable	**At levels above ground**	**Averaging time**	**Frequency**	**Uses**
1. Air Temperature	3 m 100, 300, and 500 m	20 min 1 min	3/h 8/day	Wind energy, pollutant dispersion, agriculture, forces on structures
2. Barometric pressure	3 m	20 min	3/h	Wind energy, pollutant dispersion, agriculture
3. Relative humidity	3 m 100, 300, and 500 m	20 min 1 min	3/h 8/day	Wind turbine icing, agriculture, forces on structures

* These data should be obtained three times per hour (20 min module) for every hour of the day and every day of the year.

** Wind speed and direction data at 3 m above ground are also desired for agriculture.

*** These data should be obtained at three-hour intervals every day.

Source: K.C. Mehta, Proceedings of the Workshop on Wind Climate, Asheville, North Carolina, November 12-13, 1979.

There is a pressing need to deploy in the Caribbean a network of reliable, upper-air stations based on the CLASS balloon system and the profiler technology. These would replace the currently degraded balloon network and provide the data needed to develop improved models for prediction of hurricane movement and intensity changes. There is also a need to install Doppler radars in the Caribbean (presently there are only three conventional radars to cover this region: one each at the National Weather Service offices in Key West, Florida, and San Juan, Puerto Rico, and the third in the Bahamas).

Extreme Wind Climatology

There is a need to better establish the distribution of the occurrence of extreme wind speeds in the United States. Not only are there requirements for more data, but there are urgent needs for programs to ensure the quality of these data and to archive them in ways that facilitate analysis.

Grazulis (1990) has made several recommendations for revising the national data base on tornadoes (maintained by the National Severe Storms Forecast Center, Kansas City, Kansas). These include documenting the basis for assigning an intensity value, standardizing assessment of damage (particularly to mobile homes), and providing training on damage assessment to National Weather Service personnel and others contributing material to the data base.

Violent tornadoes and tornado outbreaks merit special efforts since these pose great threats to life in the central half of the United States and are the most difficult wind hazards to forecast. Violent tornado winds present the greatest challenges in building design and construction. For such cases, damage surveys should be made both to verify forecasts and warnings and to obtain data on building performance. These surveys, conducted by a multidisciplinary team, should be systematically carried out using both low-flying aircraft and ground inspections during postdisaster investigations; the survey team should be on call for immediate response.

Grazulis has also recommended the development of tornado climatology on a state (Schmidlin, 1988) or regional basis (Anthony, 1988) to allow for the strong influence exerted by local effects. Historical research should be undertaken to extend the data base to include all events that have been documented only in local newspapers and insurance records, with due recognition being given to biases in such data.

With the deployment of the complementary NEXRAD and Terminal Doppler Weather Radar systems, there will be the opportunity to develop a data base on the frequency of occurrence of mesocyclones (the precursor circulation of many tornadoes and other strong, thunderstorm-related winds), to monitor the strong winds accompanying extratropical cyclones, and to observe the low-level (but not near-surface) winds in hurricanes. Routine measurements with these systems should provide additional data on the likelihood of damaging winds in remote areas. A program for establishing a climatology of strong winds using data derived from these Doppler radars should be developed and implemented in parallel with the deployment of the NEXRAD and Terminal Doppler systems.

One of the problems frequently encountered in obtaining wind data during extreme events is that many facilities rely on commercial electricity service with limited, if any, provision for backup power. During an extreme wind event, commercial service often fails before the extreme wind speeds occur, with consequent loss of data. Particularly in hurricane-prone coastal regions, NEXRAD and Terminal Doppler Weather Radar systems should be provided with full backup power capability to ensure that full sets of data become available.

3

Wind-Engineering Research Needs

INTRODUCTION

Wind-related problems cover a wide range of topics including damage to both low-rise structures (housing and small commercial and industrial buildings) and mid-and high-rise buildings (residential and office), bridges, towers, stacks, and power lines. In addition, a number of non-wind-load-related issues deserve research attention. Reentrainment of exhaust gases from laboratory building fume hood exhausts into building ventilation systems and local dispersion of toxic gas releases or of toxic fumes from accidental spills represent health and safety issues to which wind engineering can make major contributions to eliminate or reduce the hazard. These are areas that do not have adequate design methodologies at present. Other issues that affect the economic success of a project include pedestrian acceptability of wind and blowing dust or snow near building entrances and in plaza areas.

Wind-engineering research can also result in the reduction of soil erosion caused by wind and the proper modeling of iceberg movement and oil spills, both of which are important issues related to offshore oil operations. Moreover, wind energy potentially represents approximately 10 percent of electric system installations in the United States.

The United States currently sustains several billion dollars per year in property and economic losses due to windstorms, along with significant loss of life. In September 1989, Hurricane Hugo caused $4 billion to $5 billion in insured losses, yielding a total loss value of $7 billion to $8 billion to the U.S. mainland alone. Yet even with this large actual loss record and tremendous potential loss waiting to occur, the United States spends no more than about $4 million per year on wind mitigation, most of which is allocated to storm warning capability. *Less than $1 million is spent each year in wind-engineering mitigation research* (National Research Council, 1989).

Indeed, even the annual loss figures presented above suffer from a high degree of uncertainty due to lack of funding for research into windstorm effects. The United States has not commissioned a study of wind damage loss assessments since the mid-1970s.

In spite of the lack of funding, engineers have explored the reasons for the heavy financial losses in the United States. A task committee of the American Society of Civil Engineers (ASCE) published a series of nine, coordinated papers in 1989, which detailed many of the reasons for large losses and outlined a number of solutions (American Society of Civil Engineers, 1989). The insurance industry also published a document in 1989 demonstrating that strengthening housing units during construction to resist hurricane winds would result in a minimal additional cost in the range of 1.5 to 4.0 percent (All-Industry Research Advisory Council, 1989).

Although much is known about how to mitigate wind damage, much is yet to be learned. Sustained research is needed in the areas of defining wind loads, determining more economical ways to resist these wind loads in both new and existing structures, and finding ways to implement solutions in the construction environment, where training of construction workers is limited and inspection is a cost that local communities would prefer not to incur.

In this chapter, various areas of wind engineering are identified and the issues related to research are presented.

RESEARCH METHODOLOGY

Various methodologies have been developed to advance our knowledge base in wind-engineering research and practices. These methodologies include physical modeling using atmospheric, boundary-layer wind tunnels; numerical modeling taking advantage of powerful computing capability; and full-scale field measurements to verify predictions made by physical and/or numerical modeling. In addition, innovative experimental approaches, such as tornado simulation, are required to address particular problems (Lund and Snow, 1991). Recent developments in the area of probabilistic methods and statistical inference provide powerful tools to facilitate implementation of uncertainties arising from the complex nature of wind problems. Post-windstorm disaster investigations also provide the best and most direct way to assess the current state of wind-hazard mitigation practices and can contribute significantly to our efforts to reduce the threat of hazards.

Physical Modeling

That portion of the atmosphere within the first 1000 to 2000 ft of the earth's surface comprises the *atmospheric boundary layer (ABL)* . Physical modeling in wind tunnels of atmospheric winds within the ABL has matured over the past 30 years. This modeling capability permits engineers to address the effects of winds on the built environment on a routine, engineering-design basis. Windflow about buildings and over complex terrain, wind loads on structures, dispersion of pollutants, wind effects on pedestrians, snow or sand deposition and drift, and heat transfer from structures are some of the problems that can be addressed through wind tunnel modeling.

Boundary-layer wind tunnels are designed specifically to model the variation in mean wind speed with height above ground and the vertical distribution of turbulence, or gustiness, in the ABL. Figure 3-1 shows how the wind speed varies with height and how that variation changes with the character of roughness on the ground surface. Boundary-layer wind tunnels differ from aeronautical wind tunnels in that they contain long test sections to allow the development of appropriate velocity and turbulence profiles.

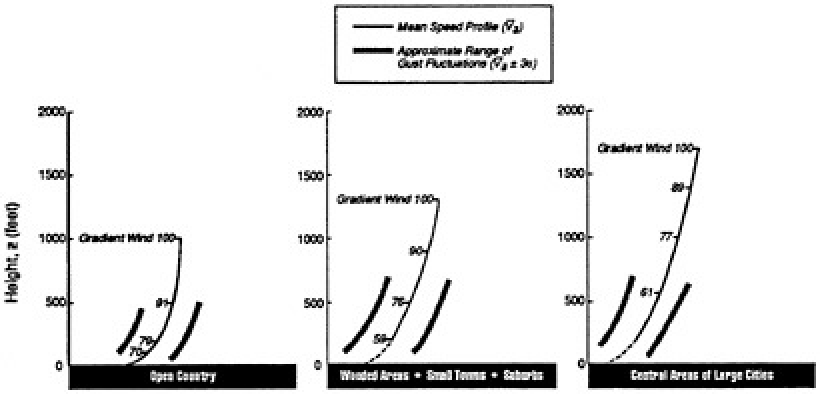

FIGURE 3-1 Mean wind velocity over level terrains of differing roughness. Source: Davenport, A. G. 1967. Gust Loading Factors. Journal of Structural Division. Reproduced by permission of American Society of Civil Engineers.

Figure 3-2 shows the first major boundary-layer wind tunnel built at Colorado State University in 1961. Scale models of terrain, buildings, bridges, power plants, or other features of interest can be installed in the wind tunnel for study. Figure 3-3 shows a typical wind tunnel study for wind loads on a structure, in which a model under study, along with a model of the surrounding city, has been installed in a boundary-layer wind tunnel.

The thermal structure of the atmosphere is important in many applications, such as dispersion of pollutants. Boundary-layer wind tunnels can be constructed to include the temperature variation of the atmosphere in the model wind simulation. Stably stratified winds (when the ground is colder than the air above, such as night conditions or winds over water or snow) or unstably stratified winds (when the ground is warmer than the air above, such as winds on a hot, summer day) can be modeled by appropriate cooling and heating of the model ground surface or air.

Modeling technology is sufficiently developed that several consulting engineering firms are now routinely testing for wind loads on buildings, dispersion of pollutants, pedestrian comfort in wind, and snow deposition and drifting. These studies are inexpensive for major development projects, often accounting for less than 0.1 percent of the total project cost. In some cases, cost savings of 5 to 10 percent or more may be obtained as a result of these tests.

A wide variety of wind tunnel tests are available on a commercial or research basis to define wind effects on structures. A plastic model of a

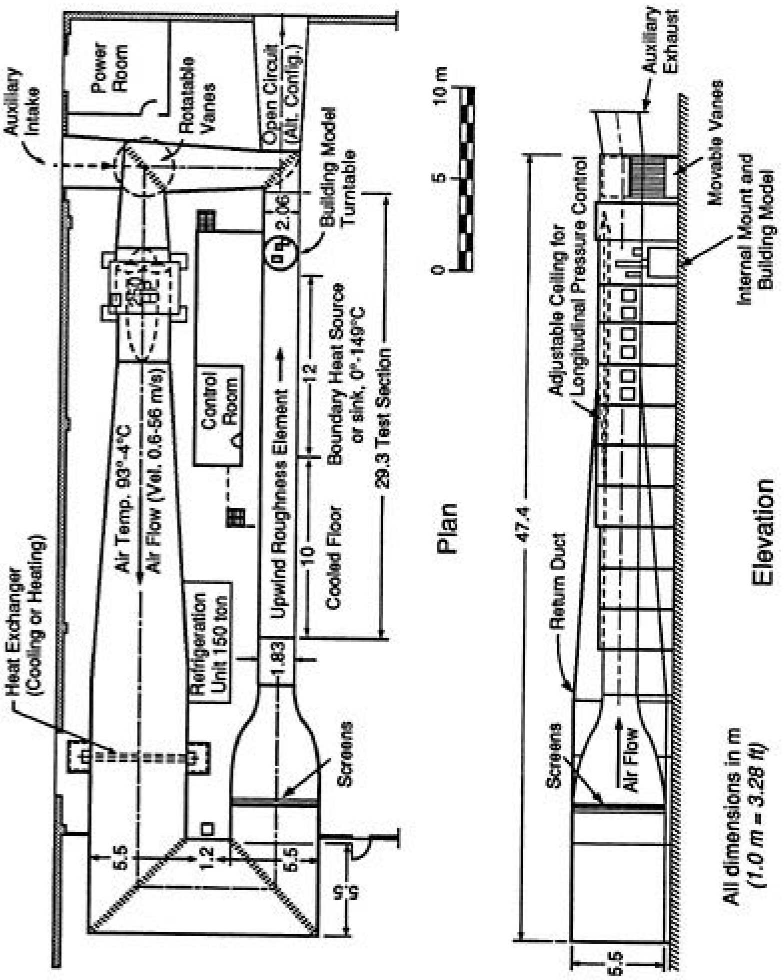

FIGURE 3-2 Meteorological wind tunnel, fluid dynamics and diffusion laboratory, Colorado State University. Source: Jack Cermak.

structure under study can be instrumented at hundreds of locations to measure locally fluctuating pressures for use in design of the structure's cladding. For wind loads acting on a larger panel, groups of pressure sensors can be combined to give area-averaged pressure forces. Alternatively, a model of the structure can be mounted on a balance to measure the instantaneous, fluctuating wind loads applying to the entire structure. A similar balance can also measure the combined, externally applied wind load and internal inertial response loads of the structure.

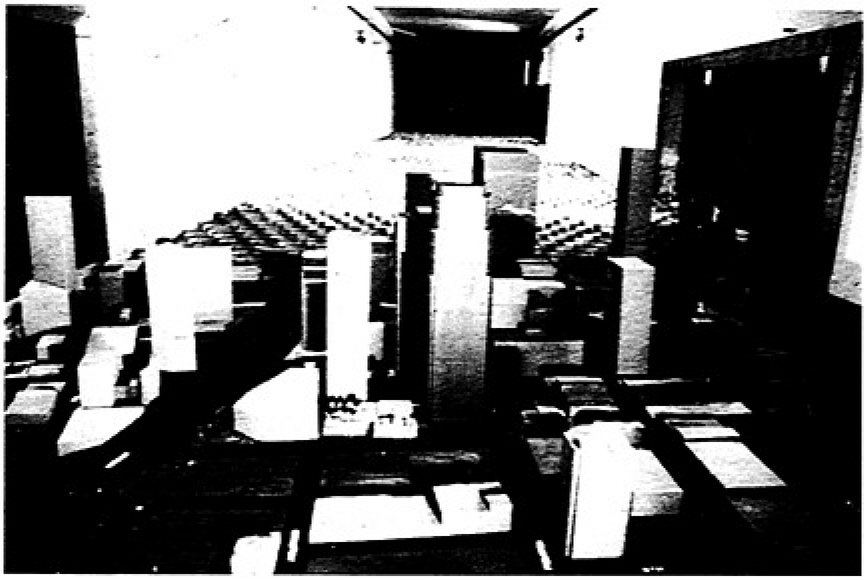

FIGURE 3-3 Model under study in a boundary layer wind tunnel. Source: Cermak Peterka Peterson, Inc.

For other applications, tracer gases, such as low-concentration hydrocarbons or carbon dioxide, can be released from points of pollution release in the wind tunnel model to measure their mean and peak concentrations at downwind points of interest with a gas chromatograph. In this way, for example, the fraction of a toxic gas released at a fume hood exhaust on a building roof that is reentrained into a building intake can be measured and modified during the design phase of a building. Figure 3-4 shows downwash from a roof vent caused by wind flow around the building. If this plume contained toxic gases, reentrainment into nearby building-air intakes could pose health concerns. Correction of this type of problem after the building is placed into service can be very expensive and personnel may be subjected to dangerous levels of toxic materials. The same measurement approach can be used in emergency response planning for accidental spills or gas releases or to design devices to limit, contain, or delay these releases.

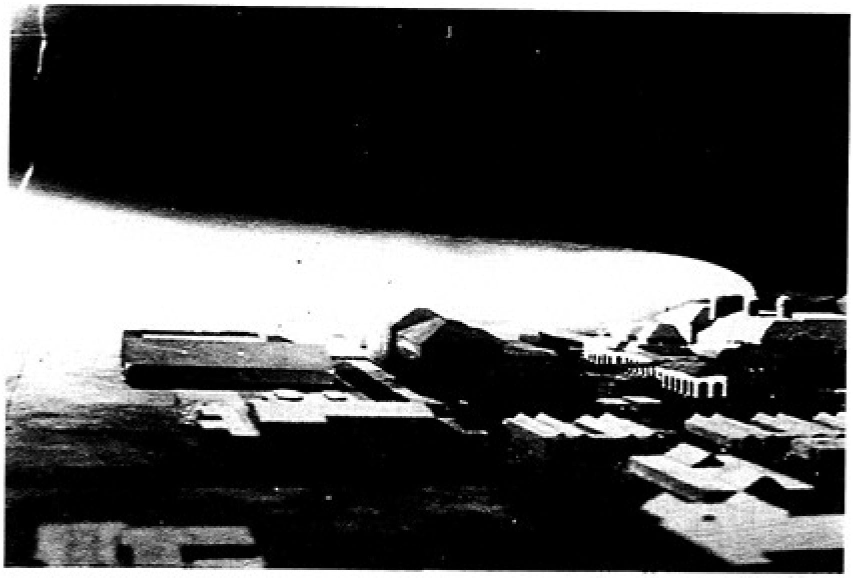

FIGURE 3-4 Building exhaust downwash model under test in wind tunnel.
Source: Cermak Peterka Peterson, Inc.

Wind tunnel tests can also be used to measure wind fluctuations in pedestrian areas near structures so that pedestrian wind exposure—and consequent comfort levels—can be gauged. In addition, winds in approach areas to helicopter pads can be measured to identify high turbulence or wind shear that could endanger helicopter operations on windy days. Wind-speed measurements in wind tunnels can also be used to locate anemometers to prevent shielding from upwind obstacles or to find correction factors for data from shielded anemometers.

Transport of particulate material is a highly complex process that, in many cases, can be modeled satisfactorily in a wind tunnel. Snow deposition and drift in the presence of wind or snow drifting are important for designing building entrances, highway geometries, parking lots, or pedestrian walkways to avoid drift buildup, and accompanying maintenance costs. Depths of snow drifts on roofs can be estimated to aid in design of roof structures for snow load.

For small projects such as single-or multiple-family dwellings, small commercial structures, or industrial buildings, wind tunnel tests are often too costly relative to the overall project cost. For these structures, which make up the overwhelming bulk of construction in the United States, reliance must be placed on building codes to define wind loads. Because of the high cost of full-scale tests, wind tunnel data, obtained on a research basis, have been used to develop the wind-loading provisions of these codes.

Unfortunately, funds have been insufficient to develop, through research and testing, the level of understanding of wind loads that would provide maximum economy of construction. Currently, no private organizations possess the resources or mission to fund the appropriate level of research needed for code development. Neither has the National Science Foundation nor any other federal agency found sufficient funds to support such an effort. Thus, research funds are vitally needed for better definition of wind loads in a codified form.

Numerical Modeling

Numerical modeling of turbulent flows around complex boundaries is difficult and demands the use of very large computers. Consequently, the calculation of wind flow around structures, of the dispersion of pollutants over buildings or complex terrain, and of wind loads on structures using numerical solutions of the governing differential equations is still in its infancy. These calculations have the potential to predict wind flow, pollution dispersion, and wind loads with great accuracy.

To date, the mean concentrations of pollutants far downwind of buildings and over some complex terrain features and the mean pressures on simple cubical buildings have been predicted with some skill. Fluctuating concentrations or pressures are still not within the range of calculation capability, nor can mean values be calculated for other than very simple geometries. The availability of inexpensive but powerful computers will make possible significant progress in numerical calculation capability in the near future. Still needed are improved numerical algorithms, protocols for easy implementation of parallel processing, and improved graphical display software.

For many years, empirical mathematical models have been used for the prediction of pollutant dispersion by winds. However, in many instances, these empirical models are subject to large errors. Numerical solutions to the governing equations could significantly increase the accuracy of such predictions. Two major areas in which research is needed are fast algorithms and turbulence modeling for winds in which temperature gradients are important.

The development of numerical modeling warrants special attention. Initially, the requirements will be for groups with special expertise working in cooperation with others interested in computational fluid dynamics and with access to powerful computers. Further development should then lead to the broader usage of these techniques.

Field Measurements

Field measurements of wind and its effects are necessary to validate predictions made by physical or numerical modeling. Complexities in field measurements arise from the surrounding topography, the wind climate, the unpredictable nature of wind, the complicated structural system of buildings, and the unavailability of off-the-shelf instrumentation. In addition, perhaps the most basic, intrinsic difficulty of field measurements is their nonrepeatability. The natural wind has too many large variations in intensity, direction, and turbulence levels, as well as in meteorological aspects, to expect it to repeat itself precisely. These complexities make field measurements expensive and time consuming.

New technologies in instrumentation and data acquisition systems provide opportunities in field measurements that were not available previously. Solid-state electronics, remote sensing devices, and computerized data acquisition systems permit reliable and detailed measurements. Data on the response of high-rise buildings, window glass, and other structures or elements can be obtained using these technologies.

To reduce the cost of field measurements as well as to gain meaningful results, field measurements should be targeted for specific objectives. A few, carefully planned, long-term experiments should be conducted in the field to provide baseline data. These experiments should be supplemented by well-targeted, short-term experiments using mobile equipment, perhaps in the region of hurricane landfalls.

The site for an experiment should be topographically clean with frequent high winds. Complex topography should be avoided. A fairly extensive array of meteorological instruments must be deployed to assess gust sizes and directions, air densities, and storm characteristics. It is necessary to have at least one tall meteorological tower and a few short ones at each site. The structures for which responses are measured should be structurally simple: transmission lines, long-span bridges, or free-standing towers are good candidates for measuring responses. International, cooperative projects with other windstorm-prone countries can help to reduce manpower costs and speed up data collection.

Field measurements have the potential of providing significant benefits in the future. It is recommended that a few, long-term field experiments be established to provide baseline data. Along with these experiments, physical modeling in the wind tunnel and numerical modeling should be planned to develop improved modeling technologies.

Innovative Experimental Approaches

Although boundary-layer wind tunnels provide a major tool for exploring wind loads on structures, they cannot provide all necessary experimental capability. These facilities do not, for example, directly simulate tornadoes, thunderstorm outflows, or hurricane eyewall winds. The extent to which these phenomena are different in wind-loading characteristics from the straight-line winds associated with extratropical windstorms or frontal passages, which boundary-layer wind tunnels simulate well, is unknown. Investigation into unique physical facilities that could model these phenomena should be undertaken. The ability of numerical models to perform this type of modeling should also be investigated.

Some laboratory simulators have been used to model tornadoes on small scales. These facilities provide great insight into the structure of tornadoes, but they are not funded at a level sufficient to exploit their full potential. A combination of laboratory measurements, numerical simulations, and full-scale testing is the most likely route to fuller understanding of tornado flows. Larger laboratory facilities than currently exist would benefit this investigation. Improvements in Doppler radar might provide field measurements of tornado velocity fields for comparison to laboratory and numerical simulations. Additional improvements in radars or other instruments capable of measuring tornado velocity fields are also needed.

The resistance of small structures, such as wood frame buildings, small office or business buildings, and masonry buildings to wind loads is currently difficult to predict. Model versions of these structures cannot duplicate their complicated failure modes. Physical modeling facilities are needed in which simulated wind loads can be applied to full scale models of such smaller structures. Otherwise, a very large wind tunnel can impose the wind loads by winds occurring in nature. Research is needed to determine the most effective method for testing these structures and to design and build such facilities. A numerical component should accompany this research effort so that the results from numerical studies can be used to reduce the extent of the needed physical studies. Facilities to model wind-wave action on structures are also needed to better analyze and quantify the complex, fluid-structure interactions experienced by offshore platforms.

Structural Safety and Reliability

Traditionally, structural safety in the design process is ensured by including appropriate safety factors to account for shortcomings stemming from a lack of full knowledge, from insufficient data, or from inherent variability in the problem's parameters. Unfortunately, the factor of safety concept does not provide a quantitative measure of structural safety or reliability. Probabilistic assessment of structural safety is receiving increased attention and acceptance with the emergence of probability-based design formats such as the load and resistance factor design.

Recent developments in the area of probabilistic methods and statistical inference offer a convenient mathematical framework to cope with uncertainties arising from a variety of sources. Research is needed to quantify the uncertainties associated with various problem parameters, to examine propagation of these uncertainties, and to assess the influence of uncertainties on the design process.

Damage Investigations

Post-wind-storm disaster investigations offer the best opportunity to assess how successfully current knowledge and technology are being applied to reduce the impacts of extreme wind hazards. The examination of damaged structures and lifeline systems allows wind engineers to identify future needs in wind-engineering research and practices, and to develop better ways to effectively implement these technologies once they are developed.

SEVERE WIND FORCES

Windflow over bluff bodies, such as buildings or bridges, is different in many respects from flow over streamlined bodies such as wings or airfoils. Such bodies are immersed in the atmospheric, boundary-layer flow in which the mean velocity varies rapidly with height above ground and the turbulence in the approaching wind is much higher than that which typically impinges on an airfoil in flight. The turbulent nature of the wind has been illustrated in Figure 2-16, which shows that wind is composed of a mean with turbulent fluctuations (gusts). The gustiness in the wind and its variation with height above ground (Figure 3-1) are the main features that distinguish it from aeronautical flows characterized by smooth flow.

Bluff body aerodynamics control wind loads on such diverse structures as buildings, bridges, tall solid towers, trussed towers, stacks, cooling towers, and cables. The basic wind-load mechanisms are buffeting caused by turbulence (gustiness) in the approaching wind, wake excitation caused by turbulence generated in the region immediately downwind of the structure, wake excitation caused by vortex shedding from the structure (periodic shedding from alternate sides of the body of packets of fluid that have rolled up into a rotating mass), aeroelastic effects in which the wind loads are altered by the motion of the body, and galloping excitation caused when aerodynamic damping (resistance to motion in a fluid caused by fluid viscosity) and mechanical damping (resistance to motion caused by internal friction within the structure itself) are overcome by aeroelastic effects.

Local cladding loads on the surface of buildings are a significant design issue because water leakage through unintentional wall and roof cracks is a major cause of building damage. The largest fluctuating pressures usually act outward from the building surface and can cause cladding to fall during a storm. Although wind-load codes specify local wind pressures, wind tunnel tests often find significant variations from that loading. One of the largest local pressures on a building is frequently found near a corner of the roof. The flow mechanism responsible for this phenomenon is called roof vortex, shown in Figure 3-5. Additional research into local pressure fluctuations has the potential to improve empirical predictions of cladding pressures for use in building codes.

Wind loads on structures fluctuate randomly in time in response to random changes in wind speed and direction and to random pressure fluctuations generated by the wind flow about the structure. Wind-loading mechanisms have not been satisfactorily described mathematically because of the extreme complexity of the turbulent flows responsible for wind-loading variability. As a result, wind loads are now largely expressed empirically. New developments in chaos theory provide possible avenues for understanding the nature of turbulence and wind loading in the presence of turbulence. An analytical component of wind-load research emphasizing chaos theory might provide advances in understanding these complex wind-load mechanisms.

FIGURE 3-5 Roof vortex in wind tunnel model leading to high roof wind loads. Source: Fluid Mechanics and Wind Engineering Program at Colorado State University.

Low Buildings

A few research projects have been funded by the metal buildings industry to study design loads appropriate for small buildings. As a result, a revised wind-load code has been produced for use in the design of preengineered metal buildings. The U.S. wind-load standard, ASCE 7-88, also used these data for prediction of wind loads on low buildings.

The data set for low buildings is small and does not cover many building shapes. In addition, the formulation for wind loads, as currently stated in the codes, is sufficiently complicated that misinterpretation of load application is a strong possibility. Information on code description of wind loading for low buildings needs to be expanded to cover more representative building shapes, and code provisions need to be made easier for designers to apply.

Wood frame structures in particular do not have clearly defined paths for transfer of wind loads from point of application to the ground. This lack of clear load path results in complicated engineering analysis of this type of structure. For this reason, current building codes include "deemed-to-comply" provisions that, while not strictly for that purpose, imply that a frame structure constructed according to specified rules (for example, wood studs placed 16 inches on center in walls) is presumed to satisfy the wind load requirements of the code. The large amount of damage to frame structures by less than design-level winds, as observed during many postdisaster studies, clearly highlights the limitations of this approach.

Much of the damage to frame structures originates in connections, such as roof-to-sidewall connections, which are frequently toenailed instead of fastened with a metal bracket. Research is needed to produce realistic analysis procedures for frame structures, including connections. Such research would strive to eliminate excess material and strengthen deficient areas. Deemed-to-comply provisions could then be reformulated, potentially reducing the cost of construction while ensuring less wind damage.

Similar research is needed for masonry structures, which are often vulnerable to wind damage if not properly reinforced. Damage investigations show that unreinforced masonry walls are a common structural failure point even when they are subjected to winds well below the design level. Properly reinforcing masonry structures also strengthens their resistance to earthquake loadings.

Life safety is a critical issue during tornadoes that clearly exceed the design wind speed. Tornado damage evaluation (National Research Council, 1981) shows that structures that have received a structural engineer's attention during design usually sustain little damage even in winds estimated at 150 mph (65 m/s) or higher (more than 90 percent of all tornadoes have maximum wind speeds less than 150 mph). This is because most structures contain redundancies that are difficult to account for during engineering design. Further, safety factors are used to account for variations in materials strength, workmanship, and uncertainty of the actual load and its distribution over the structure for a given wind speed.

There is no reason why all structures could not have the same level of structural strength and resulting life safety benefits as engineered structures. Sufficient understanding of small structure response to loads is needed to permit the analysis and codification of small structure response at the same level of sophistication as is currently available for the larger, engineered structures.

Research has been performed to show how to strengthen a small room of a house, such as a closet, to allow it and its occupants to survive a tornado (McDonald, 1991). The cost of such a room for a typical house is only a few hundred dollars. It is likely that research into frame construction could sufficiently lower the cost of the basic structure to more than pay for protective rooms of this sort.

Flexible Structures

A flexible structure is one whose wind-induced motion is relatively large. Flexible structures are susceptible to the dynamic loading and response effects discussed earlier under bluff body aerodynamics. There is no universal definition of a flexible structure to set it apart for separate attention by a designer, so not all flexible structures are recognized as such by designers. This failure to treat adequately the dynamic character of the structure can lead to premature failure, often from fatigue. The Tacoma Narrows bridge near Seattle is a well-known example of failure to anticipate the dynamic action of a structure in the wind. The bridge failed in 1940, shortly after construction. The failure occurred in only a moderate wind due to an aerodynamic instability that caused the motion of the bridge in the wind to amplify the loading, in turn further increasing the motion until failure occurred.

The experience with large, wind-turbine blades built during the late 1970s and early 1980s is another good example of the consequences of failing to anticipate the magnitude of dynamic loads. These blades were designed with much the same technology used for aircraft propellers. However, the increased turbulence and vertical velocity gradients of the atmospheric boundary layer caused higher fluctuating loads than expected and led to early fatigue failure of these blades.

Deflections of a flexible structure cause the loads that the structure must resist to increase above those induced by the wind alone and may lend to fatigue. The motion acts as a magnifier of applied wind loads through the phenomenon of resonance. Additional complexity is introduced by structures that exhibit geometric, nonlinear behavior, such as towers supported with guy wires and large-span, flexible-roof systems. Inclusion of the effects of structure flexibility into the design of a structure is not a straightforward process. Adequate models do not exist to predict the response loads of flexible structures except in very limited cases. A major research effort will be required to improve knowledge of dynamic loading effects so that relatively simple procedures can be employed by a designer to account for these effects. The dynamics of structures that exhibit inelastic behavior also warrants attention. One way to obtain answers at present is to perform a wind tunnel or other special study.

Damping and Structure Control

To decrease the effects of fatigue, structure deflections can be reduced by increasing the structure stiffness or by increasing its damping ability. Prediction of damping in many structures, including buildings, is relatively primitive. The uncertainty in wind loading on a building can easily be 50 to 100 percent due to uncertainty about damping behavior. Increasing the damping in structures could significantly decrease the cost of construction of buildings, bridges, towers, and other flexible structures. Recent research and practice indicate that design for control of damping in structures is within reach if adequate resources can be applied to research into damping methods.

Current damping practice includes the use of tuned mass dampers (massive weights near a building top that are attached to the building frame through springs), viscoelastic dampers (thousands of small devices placed throughout a building to dissipate kinetic energy in the structure), or aerodynamic farings (changes in the structure shape to reduce the wind loads causing the motion—a technique used on bridges but not practical for buildings). These approaches to limiting motion are relatively expensive.

Active control of structure motion is a promising research area for reducing the cost of many structures. It involves the sensing of structure motion with a control system that activates motion reduction devices (such as a tuned mass damper). Once activated, the system tends to reduce the structure motion. Active control devices are common on aircraft and have the potential to significantly reduce the cost of engineered structures susceptible to wind-induced motion. Considerable research is required before these devices could be considered to control wind-induced motion of buildings, bridges, or towers. Similar active systems, properly designed and installed, can also provide potential benefits to the structure's resistance to earthquake loads.

Sloshing of fluid in a tank is another method for dissipating energy in a structure. Limited applications have been used in the United States to restrict motion in water towers. Recent research demonstrates potential application for damping of buildings and bridges by using fluid sloshing. Research in the United States is needed to develop fluid-sloshing damping technology to a practical design level.

Bridges

Conventional bridges are not very sensitive to the dynamic effects of wind because of their relatively high stiffness. On the contrary, suspended-span bridges, which include suspension and cable-stayed bridges, are very sensitive to wind effects. In addition to buffeting effects of wind, they are susceptible to aeroelastic effects, which to a great extent caused the Tacoma Narrows disaster. These suspended-span bridges are often even more sensitive to wind during various construction phases than they are after completion.

The aerodynamic stability of a bridge is governed by the bridge geometry, its spectrum of natural frequencies, and its damping. Information on the aerodynamic behavior of bridges is determined through physical modeling in wind tunnels. A wide range of model tests are available, such as section models, taut strip models, and full-bridge models.

Section model tests, which are currently the primary investigative tool, help to determine aerodynamic characteristics of the bridge section that are then utilized in an analytical model to determine the bridge's overall dynamic behavior. However, an analysis based only on section model test results conducted in smooth flow often fails to describe the three-dimensional bridge behavior in natural wind conditions. Improvements have been suggested in this regard, such as appropriate modeling of turbulence in the approach flow. Full-bridge models, if they are both structurally and aerodynamically accurate, can provide information on the overall dynamic behavior of the bridge and offer the convenience of modeling the surrounding terrain to accurately simulate the approach flow conditions.

Motion reduction devices can help to improve the aeroelastic stability of a bridge. These can be considered during the design phase or can be incorporated once the bridge is built. The behavior of freestanding bridge towers during construction deserves special attention and, often, motion reduction devices are needed to control their motion.

Motion Perception

Many structures move sufficiently in the wind that occupants can sense the motion and may object to its magnitude. These structures include office buildings, residential buildings, offshore platforms, airport control towers, bridges, and other flexible structures. Very little research has been performed on the levels of motion that are acceptable for various uses. The design of many buildings is governed by the acceptability of motion to its occupants; the current level is based on only a few, uncontrolled studies. However, the construction costs of some structures might be significantly reduced if these levels were relaxed on the basis of more solid research into acceptable levels of motion.

Offshore Winds and Their Effects

Wind-related issues concerning offshore drilling activities may be divided into two general areas: the design and analysis of offshore structures, and offshore exploration and operation.

Wind speeds at various return intervals are the essential input for the design of conventional fixed structures. For these relatively stiff structures, only the steady wind effects are of interest and they typically contribute less than 10 percent of the total environmental loads. However, for exploration in deep water, where conventional platforms may not be appropriate due to their sensitivity to the dynamic wave load effects, attention has been focused on the development of innovative structural systems to explore the frontiers of offshore reserves. The most promising of these systems are the so-called complaint structures, such as the tension leg platform.

Recent, preliminary studies have suggested that, under certain conditions, wind loads are comparable to wave loading at low frequencies, which emphasizes the need to improve our understanding of the wind-loading mechanisms and to quantify their effects. A limited amount of data from wind measurements taken over the ocean exhibit considerable variability. The problem is essentially due to the difficulty of taking measurements, and it is compounded by the variable nature of the sea surface, which continuously translates and deforms. If the wind flow field and its characteristics are not much influenced by the exact form of the surface, but rather by the energy loss and rate of momentum transfer due to surface friction, then the relationship established for the wind characteristics over land may be applicable over the sea surface.

The steady wind loads are expressed in terms of wind velocity and aerodynamic force coefficients. The overall-platform aerodynamic force coefficient is determined by synthesizing force coefficients of the several components and substructures of the platform, based on a projected area approach utilizing code recommended values. Generally, these values are conservative due to complex structural configurations and the influence of interference and shielding. There is a need for better quantification of the interference and shielding effects to develop a procedure for more accurate assessment of steady, aerodynamic load effects on platforms.

Wind intensity significantly affects offshore exploration activities, especially the operation of floating rigs and drilling ships. Windstorm information is vital for the planning of drilling operations. The operation of platform cranes, the transfer of personnel, and offshore helicopter flight operation are also affected by wind conditions. Wind forecasts and real-time data are crucial for the smooth operation and safety of these activities.

Fatigue Problems

Fatigue occurs when a structure fails after a large number of cycles of oscillation or vibration at a stress level well below that which will cause failure after only a small number of cycles. Fatigue is a major problem for bridges and for many other structures or portions of structures.

The fluctuating nature of wind causes cyclic loadings on roof and wall panels of buildings. In a slow-moving hurricane, such cyclic loadings can cause fatigue failures of these panels, resulting in their removal and consequent wind and water damage to the building interior. For example, widespread damage to residential units in Darwin, Australia, during Cyclone Tracy in December 1974 was attributed to fatigue failure in roof panels. In addition, damage in the Caribbean during Hurricanes Gilbert (September 1988) and

Hugo (September 1989) suggests that metal roof panels in these areas failed due to the fatigue of materials.

In the design and field operation of a wind turbine, fatigue failure of the rotor has been the dominant concern. The rotor can be subjected to as many as 1×10^8 cycles of ultrahigh stress level during its life span.

Fatigue failure of many engineering materials has been studied through cyclic load testing in which the load changes from positive to negative within each cycle, or from zero to positive within each cycle. Wind loading, however, involves cyclic loading in the presence of a significant mean load that can change sign from storm to storm. It is not clear that the fatigue load models developed without the presence of a mean load can satisfactorily predict fatigue loading due to wind.

Further research in load history and cyclic loading should be pursued to improve understanding of fatigue problem in windstorms. Future use of higher-strength materials, entailing lighter components, is likely to increase fatigue-related problems, thus making such research even more critical.

CODES AND STANDARDS

Building codes in each locality control design and construction of buildings and structures in that locality. Most communities in the United States adopt, in large part, one of three model building codes, namely, the National Building Code of the Building Officials and Code Administrators International, the Standard Building Code, or the Uniform Building Code. Wind-load provisions in these model building codes are patterned after the ASCE Standard on Minimum Design Loads for Buildings and Other Structures, ANSI/ASCE 7-88.

ANSI/ASCE 7-88 is the only consensus wind-load standard currently available in the United States. All three model codes utilize the basic wind-speed map of the ANSI/ASCE 7-88. However, the similarity in wind-load provisions between model building codes and the ANSI/ASCE 7-88 stops with the wind-speed map.

The factors that influence the magnitude of wind loads on a building, in addition to wind speed, are the terrain surrounding the building, the shape of the building, and the desired safety of the building frame and components. The model building codes use some of these factors from the ANSI/ASCE 7-88, modify some factors based on experience, or ignore some of the factors as a part of tradition. In addition, some factors in model building codes are adopted from industry manuals.

The use, adoption, and modification of wind-load factors by the model building codes result from an attempt to simplify the wind-load provisions, but also represent the lobbying efforts of industries and special interest groups. Even with these modifications, final wind loads for most buildings are fairly consistent in all model building codes, though anomalies exist and, in some cases, the wind loads between model building codes differ by 50 percent or more. All three model building codes provide the use of ANSI/ASCE 7-88 as an alternative to be applied at the discretion of the designer. The nation would benefit immensely if the wind-load provisions in the model building codes were the same as those found in the ANSI/ASCE 7-88 standard.

The current version of the ANSI/ASCE standard, which was crafted by a volunteer group, represents an outstanding effort but does not represent the best that could be produced by a funded development effort. Needed improvements to the ANSI/ASCE 7-88 include better wind-speed definition; improved wind directionality; improved gust factor models; inclusion of torsional wind loads (twisting about the vertical axis of buildings); improved local pressure prediction and overall frame loads through a family of loading coefficients for various building shapes; improved along wind dynamic loading prediction model; inclusion of a workable across-wind model of wind loading; wind-load prediction for structures during construction; fatigue-loading prediction; inclusion of a risk-based design procedure; and improved standard construction details.

Improvements in code provisions could save billions of dollars each year in reduced construction costs and windstorm damage. This benefit can be realized only through an extensive research program directed specifically at the various needed improvements.

RETROFIT REROOFING

Retrofit, as used in this report, refers to the covering of an existing roof with new roof materials and/or structure to provide increased weathertightness or to improve drainage. In 1988, approximately 250,000,000 sq ft of metal retrofit roofing systems were installed in the United States. This market is growing at the rate of about 15 to 20 percent per year.

In its simplest form, retrofit reroofing is the adding of another roof over an existing roof, in the same shape and form as the existing one. In most instances, however, retrofit reroofing systems consist of building a structure with a new roof elevated above an existing roof. Retrofit substructures are designed for both function and economy. The normal function is to provide slope and direction to the new roof for proper drainage. The economical challenge is to design lightweight members while minimizing the number of pieces and the impact of additional wind loads on the existing structure.

In the northern part of the United States, the primary loading for reroofing systems is snow load. In the southern part, the lightweight reroofing systems are extremely sensitive to wind. The new geometric configuration of the roofing system may affect the wind load that is imposed on the system. For instance, if the original system was flat and the new system had a ridge line, additional loads would be imposed in the area of the ridge. The existing structure must accommodate these increased wind loads. The accurate assessment of wind loads is a critical factor to be considered in most reroofing systems. At present, however, the installation of new reroofs receives little engineering attention.

ADDITIONAL RESEARCH TOPICS

In addition to the research needs described above relating to the impact of severe wind forces on the built environment, a number of other research topics deserve the attention of the wind-engineering community. Some of these have been noticed only recently by the public because of the demonstrated adverse impacts on the human environment of occurrences such as oil spills and soil erosion. Some of them, such as wind flow issues in the urban environment, pollutant dispersion, and ventilation, are highlighted because of the demand for more comfortable and healthier living. The development of new technology and the use of new materials also offer the opportunity to reexamine the use of wind as an alternative energy source, the research needs of which are described briefly in this section.

Wind Flow in the Urban Environment

Acceptability for human comfort of any development includes both the aesthetic values of the space and the physical environment designed for project occupants. A plaza intended for relaxation will not be used if the space is noisy, dirty, chilly, windy, or dangerous in some way. One of the major factors influencing the intended use of pedestrian areas is the physical comfort of the area, including wind forces on, and thermal comfort of, the individual. Wind in a pedestrian area can cause the space to be underutilized, especially if the temperature is low. A pedestrian's thermal balance is influenced by air temperature, humidity, wind speed, the presence of sunlight or shade, and the amount of clothing worn. To date, little research has been performed to guide the development of better models for pedestrian acceptability in the presence of wind, temperature, humidity, etc.

Several cities, including Boston, San Francisco, and Pittsburgh, require that wind tunnel tests be performed for all projects in which the wind speeds are likely to cause pedestrian comfort problems. However, even where cities have wind-speed requirements, no attempts have been made to account for thermal comfort. Most cities have no requirements at all for wind comfort and leave decisions on pedestrian acceptability to developers. Since developers have an uneven interest in the ultimate quality of the developed space, quite different acceptability criteria are frequently applied to similar projects in the same city. Implementation of accurate and economical prediction methods for pedestrian environments could lead to improved productivity of new and existing projects. Research is thus needed to provide realistic guidelines for human comfort.

Pollutant Dispersion

Wind engineering has made major contributions to the understanding and treatment of air pollution problems. However, many challenges remain.

Atmospheric dispersion problems have historically been addressed with empirical equations based on a Gaussian dispersion model. These equations work reasonably well in situations that do not involve terrain or large, nearby structures. In instances where complicated geometries come into play, the models may be in error by factors of 10, 100, or more.

Dispersion problems can be divided into two categories: extraordinary events that occur rarely, and regular or daily events. An example of the former would be industrial spills occurring infrequently but with immediate threat to human life. Reingestion of fume hood or laboratory exhausts that could induce long-term health effects through low-level repeated exposure would be an example of the latter.

Emergency response to toxic spills is now often based on little or no advance planning. In industrial settings, likely spill locations and magnitudes can often be anticipated and planned for. Wind tunnel studies can be performed ahead of time and the results stored on a computer for quick reference. The computer can then be connected to meteorological instrumentation to develop a real-time prediction of toxic cloud extent. Although some simple systems of this type do exist, additional research is needed to optimize the design.

Laboratory or fume hood exhausts from buildings are frequently reingested into the air intake system, thereby exposing occupants to dangerous levels of chemicals on a regular basis. Wind tunnel modeling of these cases can readily identify solutions. However, research is needed in both numerical and wind tunnel modeling to develop methods of prediction that are more economical than current wind tunnel testing methods.

New pollution sources are required to show that national, ambient air quality standards are being met using modeling procedures approved by the Environmental Protection Agency. New air quality regulations will require a demonstration that health and safety thresholds are not exceeded or that the cancer risk is insignificant. However, present Gaussian-type or other empirical models are inadequate to describe pollution dispersion in a number of situations, and wind tunnel or numerical modeling is required to adequately address these situations, which include dispersion in winds about buildings, complex terrain, nonuniform roughness (urban or industrial settings), blowing dust or particulates, area or volume sources, mobile sources, mountain valley wind systems (thermally driven flows), and land or sea breezes.

Although wind tunnel modeling of pollution dispersal is relatively well developed and numerical modeling is developing, there are a number of research areas in which work will enhance our ability to quantitatively evaluate pollution levels. These include Reynolds number effects, dense gas effects, plume buoyancy effects, dispersion in stable or unstable atmospheric stratification, and hybrid modeling in which physical and numerical modeling are combined.

Ventilation

Increasing energy efficiency has become a major goal in the United States. Concern about the increase of carbon dioxide production and acid rain effects from the burning of fossil fuels has led to the consensus that the nation's per capita energy usage must drop.

Wind engineering is one of the bases of ventilation technology, since wind is the driving force for infiltration of air through building skins and also causes direct heat transfer from the building exterior surface. Improved models of infiltration and heat transfer can thus improve energy efficiency in buildings. Use of wind speeds to control natural ventilation could have significant energy benefits.

Wind Energy

Nationwide, more than 10,000 wind turbines generating about 700 MW of electrical capacity were in operation by the end of 1984. According to the Office of Technology Assessment (1985), wind energy as an alternative energy source could provide 21,000-MW capacity, representing about 10 percent of electric system installations.

The trend in research and development has been toward larger rotors to achieve economies of scale. A wind turbine with a capacity of 4 MW requires a rotor diameter approaching 400 ft. In wind energy systems of all size ranges, the rotor is the part most vulnerable to structural failure. The rotor is stressed by a variety of forces: gravity-induced stress reversals, centrifugal forces, wind-induced thrusts, and wind turbulence. Of these forces, the last two are directly related to the properties of wind.

As mentioned above, fluctuating wind gusts can cause fatigue problems. Research in time and spatial variations of wind gusts and their dynamic effect on turbine rotors should be pursued vigorously to understand cyclic loading on the rotor structure and to mitigate fatigue failures.

Soil Erosion

Soil erosion by wind is a global problem that induces both on-site and off-site damage. The on-site damage includes sandblasting of plants, exposure of plant roots, loss of plant nutrients, and loss of agricultural productivity. The off-site damage can be in varied forms: air and water pollution, sand deposition on highways, dust damage to households, automobile damage, and landscape damage. Off-site wind erosion costs in the western United States are estimated at between $3.8 billion and $12 billion per year (Piper, 1988). These costs are much higher than the on-site costs. For example, in New Mexico, on-site costs of wind erosion are estimated to be $10 million annually (Davis and Condra, 1989), whereas off-site costs are about $466 million per year (Huszar and Piper, 1986).

Reducing damage due to wind erosion will require improvements in the technology of wind erosion prediction as well as erosion control. Near-ground wind characteristics, dust transport models, the erodibility of soil, and instrumentation of a soil sampler are all fruitful topics for research in mitigating wind erosion.

Modeling of Iceberg Movement and Oil Spills

Wind plays an important role in iceberg drift. The potential threat of an iceberg impact with an offshore installation is of great concern in some northern, offshore oil fields. The overall ice management task involves projecting iceberg position in view of the environmental conditions determined from weather forecasts.

Winds and surface currents are also important driving forces for the movement of oil spills. Forecasts of actual trajectories of oil slicks provide essential input to spill monitoring and control activities. Research to refine models for both iceberg and oil slick movement would thus directly aid in addressing the environmental and safety risks associated with the production and transport of oil.

RECOMMENDATIONS

A number of observations, conclusions, and recommendations can be drawn from the discussion presented in this chapter:

1. A strong research effort is needed to better define wind loads in a codified form for small projects, such as housing for single or multiple families, small commercial structures, or industrial buildings, which comprise the overwhelming bulk of construction in the United States. For these types of structures, wind tunnel tests are often too costly to consider; thus reliance must be placed on building codes to define wind loads. Because of the high cost of full-scale tests, wind tunnel data obtained on a research basis have been used to develop the wind-loading provisions of current codes. Unfortunately, funds have been insufficient to attain the level of understanding of wind loads that would provide maximum economy of construction. No private organizations have the resources or mission to fund the level of research needed for better code development. Neither the National Science Foundation nor any other federal agency has found sufficient funds for this task.
2. The availability of inexpensive but powerful computers will make possible significant progress in numerical calculation capabilities in the near future. Still needed are improved numerical algorithms, development of turbulence modeling (especially considering the temperature gradients and protocols for easy implementation of parallel processing), and improved graphical display software.

3. It is recognized that full-scale field experiments are costly. Nevertheless, field measurements can provide significant, future benefits. It is recommended that a few, long-term field experiments be conducted to yield baseline data, provided that a National Wind Science and Engineering Program can be established to secure sustained funding for the experiments. In tandem with these experiments, physical modeling in the wind tunnel and numerical modeling should be planned to develop improved modeling technologies.
4. A combination of laboratory measurements, numerical simulation, and full-scale testing represents the quickest path to a more complete understanding of tornado flows. Larger laboratory facilities than currently exist would benefit this investigation. Additional improvements in radar or other instruments capable of measuring tornado velocity fields are also needed.
5. Closely spaced wind-observing stations along the coastline are needed to obtain better definition of hurricane winds. One option is to develop a deployable wind-recording station that can be placed in the path of an approaching hurricane.
6. Additional research into the phenomenon of windflow around buildings should be conducted to improve the empirical prediction of cladding pressures.
7. New developments in chaos theory provide possible avenues for understanding the nature of turbulence and wind loading in the presence of turbulence. An analytical component of wind-load research emphasizing the chaos theory might provide advances in understanding the complex wind-load mechanisms.
8. A major research effort is required to improve knowledge of dynamic loading effects on flexible structures, so that relatively simple procedures can be employed by a designer to account for dynamic load effects.
9. Active control devices may be effective in controlling wind-induced motions of structures. However, considerable research on these devices is required to ensure that they perform as designed after construction.
10. Sloshing of fluid in a tank could be used for damping the motion of buildings and bridges, but its effective use will have to be demonstrated through further research.
11. Additional research is needed to better define the levels of motion that are acceptable for various uses in flexible structures. Findings from this research might substantially reduce the construction costs of some structures.
12. Aerodynamic force coefficients used for offshore platform design are conservative in general due to complex, structural configurations and the influence of interference and shielding. Better quantification of the interference and shielding effects to develop a procedure for more accurate assessment of steady, aerodynamic load effects on these platforms is strongly needed. The motion of compliant, offshore structures subject to strong winds needs to be investigated by both computational and experimental methods to better understand and quantify the dynamic effect of wind.

13. Further research in load history and cyclic loading should be pursued to improve understanding of the fatigue problem in windstorms. Use of higher-strength materials, entailing lighter components, is likely to increase fatigue-related problems, thus making such research even more critical.
14. Most cities have no requirements for wind comfort and leave decisions on pedestrian acceptability to developers. As a result, quite different acceptability criteria are frequently applied to similar projects in the same city. Research in this area is needed to provide realistic and uniform guidelines for human comfort.
15. Research is needed to develop better numerical models and more economical wind tunnel testing methods for prediction of fume hood exhausts to ensure that the public is not endangered by the reingestion of exhausts into air intake systems.
16. Fluctuating wind gusts can cause fatigue problems on rotors of wind turbines. Research in time and spatial variations of wind gusts and their dynamic effect on turbine rotors should be pursued vigorously to understand cyclic loading on the rotor structure and to mitigate fatigue failures.
17. To improve the technology of wind erosion prediction and control, research is needed on near-ground wind characteristics, instrumentation of a soil sampler, dust transport models, and erodibility of soil.

4

Mitigation, Preparedness, Response, and Recovery

The analysis of any natural hazard, including wind hazards, must consider the interrelated phases of mitigation, preparedness planning, emergency response, and recovery. Although the focus of this chapter is on wind-induced disasters, these problems will be addressed with an all-hazards approach, because many of the basic issues cut across different types of hazards.

MITIGATION MEASURES

A variety of measures can be undertaken to mitigate the effects of damaging winds (National Research Council, 1989; Beatley and Berke, 1989). Some of these techniques are structural in nature, such as the construction of barriers and seawalls. Others are of a nonstructural nature, such as those regarding land use. The direct effect of these actions is to lessen property destruction, increase occupant safety, and lower the level of disruption to the community. Although a number of different activities may be undertaken, discussion will be limited to an examination of building code provisions and land-use management.

Codes and Code Enforcement

The significance of codes and code enforcement is manifested by a recent survey (Manning, 1991) conducted by the Southern Building Code Congress International under the auspices of the State Farm Insurance and Casualty Company. In this survey, questionnaires and examinations were administered to the building departments of 12 jurisdictions along the Atlantic and Gulf coasts. Ratings of these jurisdictions were based on the following nine factors:

1. construction compliance survey,
2. number of inspectors,
3. inspectors passing examinations,
4. number of plan reviewers,
5. plan reviewers passing examinations,
6. plan review of residential plans,
7. related building department training and certifications,
8. public awareness and prescriptive provisions, and
9. code editions and certificate of occupancy.

Results of the survey showed an overall rating of 10.4 out of a full score of 20. The survey also suggested that jurisdictions rating less than 14 are probably not in compliance with the wind-load provisions of the codes. Only 2 of the 12 jurisdictions scored higher than 14.

Even more alarming is the finding that only about 30 percent of those taking the building inspector and plan review examinations scored a passing grade. These results prompted the survey author to recommend that education for inspectors, plan reviewers, and builders is an area in need of immediate attention.

These results notwithstanding, the public generally assumes that if a building subject to a building code is issued a permit, is inspected during the various phases of construction, and is finally issued a certificate of occupancy upon completion, the building must then comply in every respect with the code, including the ability to sustain wind loads. This may not necessarily be true, as evidenced by the survey cited above. Several of the reasons for this discrepancy are elaborated below.

Quality of Code Enforcement. The quality of code enforcement varies greatly among jurisdictions. Some of the factors determining the quality of a jurisdiction's code enforcement program include the commitment of elected officials, political considerations, the salary level offered to personnel, and the number and qualifications of authorized personnel.

There is increasing awareness of the importance of building code enforcement, as evidenced by the increasing number of states that have adopted statewide codes. Increased emphasis is also being placed on the qualifications of personnel employed to enforce these codes. It is becoming standard practice, particularly where statewide codes are adopted, to require that all building inspectors be certified, which usually entails attending a specified number of hours of continuing education classes each year.

Empirical (Prescriptive) Code Requirements. Over the years, local and model codes have developed empirical provisions to regulate common types of construction (such as wood-framed or masonry buildings not exceeding two or three stories in height). These empirical provisions contain minimal requirements for lateral loading, give no consideration of resistance to high winds, and are based on construction practices that have "withstood the test of time" without any type of verification. Technically, adherence to the empirical requirements does not set aside the need to verify compliance with the additional provisions for wind loads, earthquake loads, etc. However, it is common practice for building permits to be issued for buildings "designed" to comply with code empirical requirements that have not been subjected to an engineering analysis to determine if the structure can resist the required wind loads.

Empirical provisions generally specify minimum wall thickness or minimum member sizes and spacing, along with some rudimentary bracing requirements. Generally, these requirements are not a function of the design wind pressure, which is, for instance, more than double for a 110-mph (47-m/s) wind than for a 70-mph (31-m/s) wind. On the other hand, engineering analyses and investigations of wind damage show that properly tying the various structural elements together, so as to provide a continuous load path to the foundation, is also needed if the structure is to survive the effects of high winds. Usually, these latter requirements are missing from empirical provisions.

Over the last two decades, the increasing desirability of coastal parcels has led to the construction of a large number of structures that are extremely vulnerable to high winds. Due to extensive hurricane damage in coastal areas during this period and the continuing development of these vulnerable zones, code-making bodies are now focusing more attention on building code requirements for coastal areas. These efforts have raised many questions about the validity of some empirical provisions, because when subjected to a rigorous, rational, engineering analysis, they simply do not work.

Several years ago, North Carolina revised its state building code to require more stringent empirical provisions for nonengineered structures built along the Atlantic coast. Many areas of Florida, Texas, and other Gulf states subject to high winds have enforced prescriptive requirements for small buildings that are based on engineering evaluation, but the requirements have not been applied consistently in all areas of concern. Both the Southern Building Code Congress International and the International Conference of Building Officials have efforts under way to resolve the apparent conflicts between their empirical provisions and the results of analytical studies. These efforts will probably result in major modifications of the empirical provisions, rather than doing away with them, and will require an engineering analysis in all cases. The revised provisions will be structured so that the requirements are a function of the basic wind speed.

Architect and Engineer Registration Laws. A code enforcement program can be aided by state laws regulating the licensing of architects and engineers. However, these laws do not apply to most buildings, since it is common practice to exempt small buildings—especially dwellings—from the requirement that the design be done by a licensed person. In addition, the most stringent laws are of little value of they are not enforced, and in many instances, enforcement is haphazard.

In conclusion, the quality of code enforcement greatly influences the quality of the built environment. Signs point to continued improvement in both the quality and the quantity of code enforcement personnel. Empirical provisions of building codes, which heretofore have proved inadequate in high-wind areas, are being reviewed and revised. This should further enhance the ability of many small buildings to sustain high wind loads. Although it may be unrealistic to require that all buildings be designed by a licensed architect or engineer, this may not be necessary if more strict code enforcement is provided and if codes contain empirical provisions that are based on realistic wind loads and are the result of structural testing and analysis.

Land Use Management

In addition to altering the design or construction of buildings and structures through codes, another nonstructural mitigation measure involves managing the use of land in areas that are susceptible to wind-induced disasters. The primary goal of this strategy is to prevent or limit the location of vulnerable populations and commercial, residential, and industrial development in hazardous areas so as to avoid or reduce exposure to the hazard. With regard to wind-induced hazards, most of the effort in land-use management has focused upon hurricane mitigation (Brower et al., 1987). Little attention has been given to using these measures to mitigate tornado damage, since tornado vulnerability extends over such broad regions, with an irregular frequency of return.

The general strategy of land-use management is to influence the location, density, timing, and type of development in hazardous areas (Brower et al., 1987). A variety of specific land-use management tactics may be employed to implement this strategy. For example, fee-simple *land acquisition* in hazardous areas by public authorities can control development and allow for public use of the property, often as recreation areas. The primary obstacles to implementing this tactic are the financial costs involved. It is most feasible when the land is undeveloped. As a second tactic, the *control of development rights* may be attempted either through purchase or transfer. The former involves the actual purchase by the government of development rights, whereas the latter is a procedure whereby development rights are transferred from a high-hazard zone to a less hazardous area in the jurisdiction. Large-scale application of the transfer of development rights has yet to occur for a variety of legal, political, and other reasons.

Probably the most common land-use management tactic employed to mitigate wind-induced hazards involves *zoning* or land-use controls. Some of these measures involve such conventional zoning practices as controlling the density and type of development. Provisions may include such features as coastal setbacks, special-use permits, and incentive zoning. In addition, *subdivision regulation* can be utilized as can taxation and fiscal incentives. Also, policies to prevent the location of public facilities in hazardous areas can be developed and are easily within the purview of governmental units.

Spurred by federal efforts such as the Coastal Zone Management Act and state and local initiatives, mitigation efforts have increased significantly since 1970. However, the adoption and implementation of these measures are still quite uneven. Some states, such as North Carolina, Florida, and South Carolina, have implemented statewide coastal or beachfront development acts that provide necessary empowerment for local land-use management. Other states have been less active. Even in those states with strong legislation, however, prior development and a lack of enforcement have resulted in an increasingly vulnerable condition.

EMERGENCY PLANNING AND RESPONSE FOR DISASTERS

In addition to mitigation, the effective management of wind-induced disasters requires the development of emergency preparedness and response planning. The levels of destruction and casualties are not dependent simply upon proper mitigation activities. They are also influenced by the effectiveness of local warning systems; the quality of evacuation planning; and the adequacy of postimpact response activities, such as search and rescue, the provision of emergency medical care, and the restoration of lifelines.

Structure of U.S. Emergency Planning and Disaster Management

In order to understand the status of emergency preparedness and response planning in the United States, it is useful to provide a brief background on the historical development of the field and the characteristics of its current structure. The Federal Civil Defense Act of 1950 established the Federal Civil Defense Administration as a part of the Executive Office of the President. Most significantly, the act specified that the primary responsibility for responding to nuclear attacks and other forms of attack resided with the states and their political subdivisions (i.e., local governments). This designation became a precedent that exists to this day with regard to all types of disasters. Throughout the past 40 years the structure has changed many times. Further, the priority placed upon nuclear attack planning as opposed to natural and technological disaster preparedness has fluctuated. However, the mandated authority of the local communities as having primary responsibility for planning and response for disasters still continues.

Emergency planning and disaster management activities vary significantly throughout the nation. While larger metropolitan areas and counties may have full-time, professional staffs and adequate resources to undertake these activities, many political jurisdictions do not (Hoetmer, 1983). Also, the local governmental entity charged with emergency and disaster planning differs from jurisdiction to jurisdiction. In some city and county jurisdictions, the emergency management agency is an independent or autonomous unit. In others, it is a subdivision of a larger agency (Wenger et al., 1987). Therefore, there is a lack of standardization among local units in a number of different respects, including their domains and responsibilities, the manner in which they undertake planning and response activities, and the adequacy of their local resources (Drabek, 1985).

This lack of standardization has two significant consequences for emergency preparedness and response to wind-induced hazards. First, it means that planning must be placed within the local community context, including its hazard vulnerability, past disaster experience, governmental structure, power structure, and resource availability. There is no one, ideal model of local community planning arrangements that will be appropriate for all communities (Wenger et al., 1987). Second, it indicates that it is very difficult for federal and state agencies to develop planning programs that can be applied uniformly to all communities.

The Extensiveness of Local Community Emergency Preparedness

To assess the level of emergency preparedness and response planning in the United States, it is necessary to take an "all-hazards approach" to the problem. That is, as opposed to only focusing upon planning specifically for wind-induced disasters, the evaluation should be in terms of general disaster planning for all types of hazards. This approach is justified and perhaps more cost effective and politically attractive because most of the major problems and functions of planning and response cut across different types of hazards. It recognizes that the problems of preparedness and response for wind-induced disasters are not unique, and that planning for general disaster response can have effective and efficient payoff for any specific hazard, including those precipitated by winds. For the past decade, FEMA (the Federal Emergency Management Agency) has supported an all-hazards approach to emergency management planning.

Significant Improvement

Preparedness and response planning has significantly improved since 1977. Facilities and resources have been upgraded; emergency operating centers are now much more common; and computer-aided systems for decision making and inventory are increasingly being used. There has been an increase in integrated, community-wide planning that takes an all-hazards approach (Quarantelli, 1985), and the level of professionalism among the emergency management community has risen significantly, although there are still no national, professional standards for the field.

There has also been an attempt to standardize emergency management principles and models of control through the application of the Incident Command System (ICS) to all types of disasters. Although ICS was originally developed to coordinate the activities of a large number of fire departments that were responding to the same incident, it is now advocated as a general model to coordinate all disaster response.

Given the decentralized and nonstandardized nature of emergency preparedness and response planning, it must be noted that these improvements do not characterize all local areas or jurisdictions (Wenger et al., 1987). Further, most of the improvement in planning appears to be concentrated on resource procurement, the installation of computer and communication equipment, and the construction of physical structures.

However, the acquisition of material resources obviously does not solve many of the problems that occur during disaster response, such as those involving interorganizational authority relationships, coordination, communication, and conflicts over domain. ICS is an attempt to solve these management problems, but its suitability for being adopted in a great variety of local communities and utilized in all types of disasters has yet to be empirically established through systematic research (Wenger and Quarantelli, 1988).

Some Continuing Weaknesses in Community Preparedness Planning

A number of researchers have observed that local planning is fragmented among several independent clusters (Caplow et al., 1984; Dynes, 1983; Leik et al., 1981; Mader, 1985; Quarantelli, 1985). Disaster planning is often undertaken by the "social control sector" of the community, which includes such local units as government, police, fire, emergency management, and public works. Further, independent planning is often done by the "medical and social service sector." Hospitals, emergency medical services, and social service agencies develop rather elaborate plans for victim assistance. Also, public utilities and lifeline organizations frequently engage in extensive, independent training. Finally, emergency planning is increasingly being undertaken by organizations from the "private sector." This trend is evident among those businesses and corporations involved in the production, use, and transportation of hazardous materials, but it is not limited to them. Business organizations, schools, and voluntary associations are also becoming more oriented toward emergency planning.

Unfortunately, these sectors tend to engage in planning in isolation from one another, although their disaster response activities are inherently interrelated. If local response to wind-induced hazards is to be effective, it must involve the integration of various sectors of the community. A fragmented approach produces inefficient plans and can generate an ineffective, uncoordinated response.

In addition, some plans continue to be developed as if earthquakes, floods, hurricanes, tornadoes, and toxic spills had no common managerial requirements. Although the utilization of an all-hazards approach has become more widespread in recent years, there is still a tendency toward agent-specific planning.

Finally, emergency planning in the United States has tended to focus, to a considerable degree, upon the immediate pre-impact and postimpact periods. Planning for recovery and long-range mitigation is not well integrated into the planning that is designed to guide emergency activities. Although the phases of mitigation, preparedness, response, and recovery are viewed as an interrelated system, planning for the activities tends to be fragmented and focused on short-term needs.

In sum, with regard to general emergency planning, these three weaknesses indicate the fragmented nature of the planning process. Such fragmentation impedes the achievement of a system-wide, coordinated, and comprehensive response to disasters.

Specific Emergency Preparedness and Response Planning for Wind Hazards

Although most of the general planning components of an all-hazards approach have application for wind-induced disasters, certain elements are more directly applicable than others. In assessing the state of planning and preparedness activities, the distinction can be made between pre-impact and postimpact periods.

Pre-Impact Activities

The preparedness activities having the most direct applicability for wind-induced hazards are warning, evacuation, sheltering, and public awareness or information distribution. There have been significant improvements in the entire process of warning the public of severe wind-induced disasters. As discussed in Chapter 2, the ability to detect severe winds and issue warnings has evolved over the years and will continue to improve with the installation of the Next-Generation Radar (NEXRAD) system. Hurricane predictions have also improved with technological developments and the use of satellite monitoring.

Equally important, the National Weather Service has been increasingly concerned with the dissemination of information to the public. A variety of communication linkages, including weather radio, a National Warning System, and the Emergency Broadcasting System, connect the weather service to mass media outlets and emergency response organizations. Furthermore, an understanding of the social and psychological dimensions of warning is steadily improving the warning process. Researchers have established how warnings should be issued, who should issue them, how they should be written, and how they should be disseminated (Drabek, 1986). Increasingly, this information is being implemented in the warning process, as officials realize that a warning that is issued is not necessarily a warning that is received and acted upon.

Within localities, the status of warning systems varies significantly by type of hazard and community. Local hurricane warning systems in coastal areas are relatively good. Although they rely most heavily upon mass media distribution, they utilize a variety of dissemination devices. The situation with regard to other types of wind-induced hazards is quite mixed and there is considerable variation in the adequacy of local systems. Some communities have rather elaborate warning systems. They rely upon the mass media but also utilize such devices as tone alert and call-down systems. Other communities still have outmoded siren systems that convey limited information and suffer from considerable dead spots.

Planning and preparedness for coastal evacuation has improved dramatically over the past two decades. Assisted by such technological innovations as the Sea, Lake and Overland Surge Heights (SLOSH) model and other computerized decision aids, evacuation planning has improved for the Atlantic and Gulf coasts. Massive evacuations have been successfully accomplished for a number of hurricanes, including Alicia, Elena, Gloria, Gilbert, and Hugo.

Despite these successes, two problems remain concerning the use of technical information in emergency response decision making, particularly during hurricane threats. The first problem stems from a failure to access available data. For example, the National Hurricane Center issues specific forecasts about hurricane positions and intensities, but many coastal communities do not subscribe to the NWS information network.

The second problem involves the difficulty in making effective use of technical data. Federally funded and coordinated studies have mapped the areas that need evacuation in various hurricane scenarios and calculated the lead times necessary to effect successful evacuations. That information, in conjunction with hurricane forecasts, should make the timing of evacuation decisions straightforward. However, the uncertainty (error) of forecasts complicates decision making, and few communities have developed an adequate means of incorporating forecast uncertainties into response systems. Emergency management officials need training and decision-making aids to help them devise more informed decision strategies.

Evacuation issues illustrate the importance of the linkage between mitigation, preparedness, and response. With increasing coastal development there is a corresponding increase in the size of the vulnerable population that must be evacuated during a hurricane, which in turn can increase the evacuation time. As a result, the lead time for determining the appropriateness of evacuation is shortened, and timely forecasts and predictions are even more important.

States and communities are now attempting to prevent the development of intractable evacuation situations through the application of land-use management tools. Planners are required to take actions to mitigate the impact of proposed developments on shelter demand, roadway capacities, or evacuation lead times. However, these planners often have insufficient expertise in projecting the impacts of such developments and would benefit from more research in this area.

With regard to emergency sheltering, the provision of adequate, safe shelter for hurricane evacuees is an increasingly challenging problem. Public schools are often used as shelters because they are public, possess kitchen and bathroom facilities, have large amounts of floor space, and are usually numerous and dispersed enough to be accessible to many evacuees. However, they are not selected as shelters because of any special safety features with respect to strong winds. As detailed in Chapter 1, it is common for schools to experience significant damage during storms. Although someone with construction expertise normally inspects buildings and approves their suitability as shelters in hurricanes, it is rare for such individuals to possess any special training in wind engineering.

Evacuation is normally recommended or mandated only for buildings subject to storm surge inundation and, outside the surge zone, for mobile homes or substandard housing. Emergency preparedness officials also question whether housing units several stories above ground level near the coast will be safe during a strong hurricane. If not, occupants of such units would have to evacuate them, thereby increasing shelter demand and roadway congestion, or they would have to take refuge in bathrooms or hallways. There has been limited research on vertical refuge or shelter (Ruch et al., 1990). Little is known about how residents would conduct themselves if advised to leave such structures or if told to stay in only the most secure parts of the buildings. Although decades of research on human response to disaster indicate that people respond in a rational and altruistic fashion, there are some unknowns regarding how people might behave inside buildings during the storm itself, particularly if utilities, communications, and elevators were not functioning. These same issues are magnified when considering vertical refuge in which the buildings are subject to storm surge and in which nonresidents seek shelter in the upper floors of high-rise structures.

With regard to tornado sheltering, structural improvements can be made to existing buildings to offer greater safety. For example, any building whose floor or roof can be uplifted presents greater chances for injury or death. Buildings with nonlifting floors, such as those constructed of concrete, have a higher safety margin. For residences, retrofitting for in-residence shelter can be constructed. Public buildings, such as schools and nursing homes, can be hardened and outside walls can be reinforced to prevent collapse. In addition, external shelters may be required as part of state or local zoning measures for hazardous structures, such as residences with high wind vulnerability.

The adequacy of public information and hazard awareness programs varies considerably. Certain locales along the Gulf and Atlantic coasts and some communities within "tornado alley" have extensive programs for public education about disasters. These "disaster subcultures" have elaborate provisions and relatively high levels of public awareness and knowledge concerning appropriate disaster response. However, in other communities, such programs and the corresponding level of public information are basically nonexistent.

Postimpact Response Activities

In general, research indicates that, as with planning activities, there has been an improvement in disaster response activities. These include search and rescue; the provision of emergency medical services; the provision of food, shelter, and clothing to victims; and the restoration of lifelines and essential services. However, the improvement in response is not commensurate with the level of improvement in disaster planning. For example, although increased attention to search and rescue over the past two decades has resulted in specialized rescue units, more highly trained professionals, and more sophisticated rescue strategies and techniques (Krimgold and Lopez-Ramirez, 1989), most search and rescue activity is emergent, unplanned, and undertaken by volunteers and victims, not by these trained professional units (Wenger, 1989). (Further, there is little systematic evidence on how damage patterns to buildings and structures correlate with injuries and deaths among victims and how such information influences rescue efforts.)

Similar to the search and rescue issue is the situation of emergency medical services (EMS). The provision of EMS has improved throughout the United States, particularly for handling day-to-day emergencies. There is a tendency for communities to rely upon their daily EMS systems during disasters, even though it has been demonstrated that these normal systems are not adequate for handling the increased demands and the qualitatively different context posed by a disaster (Quarantelli, 1983).

Research has also shown that for both individuals and organizations the postimpact emergency period is epitomized by behavior and activities that run counter to popular thought. It is now recognized that the common images of antisocial behavior, looting, panic, disaster shock, and helpless victims are mythical (Wenger et al., 1975, 1980).

Similarly, there are a number of mythical concerns about organizational response to disaster. For example, often there are concerns about a shortage of personnel and material resources. Neither of these has been found to be empirically valid. In fact, a surplus—not a shortage—of personnel and resources is the general pattern in disaster response as these elements converge upon the disaster site.

What are the actual problems related to disaster response? In addition to the previously noted convergence problem, other concerns are manifest in such issues as the gathering and distribution of information on the scope of the disaster, intraorganizational and interorganizational communication, interorganizational coordination, authority relationships, task allocation, and resource allocation. Disaster planning is often oriented toward solving such immediate and evident problems as search and rescue, restoration of lifelines, and sheltering. Little attention is paid to difficulties associated not with the disaster agent per se, but with the response of the local organizations to that disaster. To a significant degree, these problems are related to the fragmentation of the planning effort within local communities.

PLANNING FOR RECOVERY AND FUTURE MITIGATION

Most of the planning for recovery from disasters has been undertaken at the federal level and is linked to the federal provision of disaster assistance under the Disaster Relief and Emergency Assistance Act of 1988, which FEMA has the primary responsibility for administrating. Following a presidential declaration of a disaster, a number of assistance programs are implemented, two of which are particularly relevant to future mitigation efforts. Section 409 of the 1988 act includes a requirement that calls for those state and local governments receiving aid to submit a hazard mitigation plan that includes safe land-use and construction practices for the disaster areas in order to receive further federal funds. Section 1362 of the National Flood Insurance Program allows for the purchase of damaged property and relocation; however, this program is underfunded when compared with the estimated number of eligible structures (Brower et al., 1987).

Local community planning for recovery and the linking of recovery efforts to future mitigation continue to be very weak in the United States. As noted previously, most communities focus their disaster planning efforts upon the immediate pre-impact and postimpact emergency phases. Very little attention is paid to long-term recovery, which is often viewed as being a "federal problem." Furthermore, after receiving a presidential declaration, many communities are unfamiliar with the available federal programs and must engage in mitigation planning under the Section 405 requirements in an ad hoc manner.

RECOMMENDATIONS

General Issues Regarding Future Research

There has been a general improvement in emergency management in the United States for wind-induced and other types of disasters, but research is needed in a number of areas. Regardless of the specific research questions investigated, future research should be governed increasingly by the following two principles.

First, the study of emergency preparedness and response must be approached in a multidisciplinary fashion. The problems cut across a number of different disciplines, including meteorology, civil engineering, architecture, landscape architecture, economics, sociology, urban and regional planning, geography, political science and policy analysis, and medicine. Of course, the role of meteorologists and civil engineers is critical, particularly with regard to pre-impact planning and mitigation, but in discussing emergency preparedness and response, their input must be integrated with that of other disciplines.

For example, consider research into the impact of tornadoes upon the loss of life, injuries, and property destruction within communities. Such a study must not be limited to an examination of traditional engineering concerns. It must also consider such variables as the nature and effectiveness of warnings, the timing of the impact (people are more likely to be injured or to die in automobiles than in structures during tornadoes; normal traffic and work patterns influence the number of people who become victims), the nature and implementation of building codes, the nature of the housing stock within the community, the extent and quality of local emergency preparedness planning for disasters, and the effectiveness of local emergency medical provisions.

As another example, important research should be undertaken on the epidemiology of death and injury in relationship to wind effects and destruction to the built and natural environments. Examining the relationship between structural or nonstructural damage and occupant behavior requires the input of civil engineers, architects, sociologists, epidemiologists, and emergency medical specialists.

Second, future research must increasingly utilize and refine quick-response field methodologies. Disasters can serve as natural laboratories from which to learn and improve our capabilities to reduce impacts of future events. In this regard, postdisaster reconnaissance studies are important for evaluation of the extent to which state-of-the-art knowledge and techniques have been implemented. If these techniques have not been implemented, problems can be defined and solutions proposed to eliminate the obstacles in the future.

To ensure a postdisaster study's effectiveness, different phases of disaster response and recovery should be considered, including the phase immediately following the disaster during which highly perishable information can be documented. Postdisaster studies should also include revisits of disaster sites at various periods after the disaster to monitor its ongoing or long-term impacts and to assess progress. Some important questions that should be posed include the following: Have better public policies been developed and adopted for better land-use management? Have the local building codes and regulations been updated or improved? Have emergency planning and response programs been developed or improved? Has any recovery and reconstruction planning been proposed or developed? Valuable information collected and analyzed during the hours, days, months, and years following a disaster can enhance the effectiveness of hazard and risk assessment, awareness and education, preparedness, prediction and warnings, and mitigation.

The Disaster Research Center at the University of Delaware has utilized this approach for 26 years. The Natural Hazards Center at the University of Colorado funds small projects with the assistance of the National Science Foundation. The Committee on Natural Disasters of the National Research Council also supports limited quick-response studies of a primarily engineering nature, but the opportunities to engage in this type of research are currently limited. Increased support is urgently needed.

Specific Research Needs

Future research should focus upon local adoption and implementation of building code and land-use mitigation measures. As indicated earlier, the problem with mitigation of wind-induced disasters does not lie with the techniques. The current review and revision of empirical provisions in the codes promise to increase mitigation in the future, and the techniques of land-use management are effective tools for lowering the vulnerability of areas to wind hazards.

Instead, the problem rests with the adoption and implementation of these measures. The quality of enforcement of building codes in local communities can be improved. Review and revision of empirical provisions in the codes must be undertaken in order to increase the ability of small buildings to withstand high wind loads. With regard to land-use management activities, the major difficulty is in gaining adoption, implementation, and enforcement at the local level. Therefore, the major impediments to mitigation appear to be embedded in social and political factors at the state and local levels.

For example, the organizations that promulgate the predominant building codes have memberships strongly influenced by the codes. Therefore, the codes developed and offered by the organizations are not derived purely on the basis of engineering, but have been modified by perceived acceptability and practicality.

Even though existing building codes contain imperfections and could be improved through further research, the fact remains that much of the nation's wind damage every year could be prevented if more structures were built in compliance with existing codes. In some instances, failure to meet these standards is the result of state and local governments' deliberate decisions to not adopt them in the belief that the expected benefits of higher construction standards do not justify the increased costs.

Even in communities that do adopt the standards, many structures are built without conforming to the codes. In many cases, communities provide inadequate staffing or will to enforce the codes. In other instances, builders possess insufficient familiarity with the codes or with sound wind construction techniques. Performance codes, which specify loads that surfaces and components must withstand, are more difficult to implement or to comply with than prescriptive codes, which specify construction techniques such as component dimensions and connection spacings.

Therefore, a priority area for future research is to examine those factors that influence local adoption of mitigation measures for wind-induced disasters. Research in the area of seismic hazards has recently focused upon this important issue (Beatley and Berke, 1989; Mader, 1980; Wyner and Mann, 1983). This research indicates that a combination of economic, social, and political factors serves to both facilitate and hinder local adoption. Similar research should be undertaken with regard to wind effects. Factors that facilitate building code adoption and enforcement within local communities should be studied. Similar research on the social, political, and economic impediments to, and incentives for, land-use measures must also be undertaken. Furthermore, research should focus on the feasibility of using such nonstructural mitigation measures for hazards other than hurricanes.

Research into the factors associated with state and local recovery planning is urgently needed. In particular, this research effort should focus upon linking recovery efforts to mitigation. Such mitigation measures include retrofitting; land-use management; and effective building code adoption, implementation, and enforcement. The question of which policies and institutions discourage states and communities from adopting and enforcing more stringent codes and land-use measures should be addressed. The insurance and financial industries have exerted little pressure to bring about more wind-resistant construction. The federal government makes disaster assistance available in communities experiencing wind disasters without regard to their prior mitigation efforts, and there appear to be few sanctions for failing to follow the postdisaster mitigation plans required by FEMA.

Research into the continued development and utilization of new technology with regard to wind-induced disaster forecasts and prediction should be supported. However, the development of new technologies must be integrated with efforts to improve local community warning systems. Although the planned improvements in the National Weather Service detection and forecast capabilities, such as NEXRAD, are important, they must not be viewed as constituting a "technological fix." Research should continue to focus upon improving the linkage between forecasters, the mass media, and the public.

Epidemiological studies of the nature of death and injuries in disasters in relationship to damage to the built and natural environment should receive high priority. As previously noted, the topic is of extreme importance and requires a multidisciplinary research effort. Civil engineers, architects, emergency response experts, sociologists, epidemiologists, emergency medical specialists, and emergency planners all have important roles to play in this type of study. Simply put, we need to know definitively how people are killed and injured in wind-induced disasters, how structural and nonstructural damage interact with human behavior to lessen or increase the risk to life, and how search and rescue and emergency medical action can reduce the number of casualties.

Research into hurricane evacuation planning is needed in light of increased coastal development. This research should be multifaceted and should examine such issues as the utilization of computer-based decision aids, survey research on evacuation behavior, and transportation modeling.

Studies of disaster response should focus upon improving organizational and interorganizational coordination, damage assessment, integrating volunteer with organizational efforts in search and rescue, and improving the restoration of lifeline services. Although disaster planning has improved within the United States, disaster response continues to be hindered by a number of problems. Central to them are the difficulties in coordinating response activities across a variety of public and private response agencies. In particular, damage assessment is often not well planned or coordinated. There is also a serious need to examine how the massive search and rescue activities of volunteers can be integrated with those of professional rescue units. Finally, research on the restoration of lifelines is urgently needed. Some of the important research questions posed in this area include the following: What are the central problems faced by lifeline organizations in the aftermath of disaster and how can they be solved? What are the critical lifeline services that should receive priority attention? What components of emergency response are most dependent upon which types of lifelines?

Research should be focused upon lessening the fragmentation inherent in emergency planning and response for wind-induced disasters. Research should be undertaken to examine alternative strategies for integrating emergency and disaster preparedness and response efforts within local communities. A number of issues are ripe for study. For example, research into integrating emergency preparedness planning with the normal, ongoing professional planning efforts within communities should be encouraged as a step toward eliminating the fragmentation of planning within communities. With regard to response, systematic and objective research on the effectiveness and applicability of the Incident Command System to all settings should be undertaken given its rapid dissemination and adoption.

5

Education and Technology Transfer

This chapter addresses the issues concerning wind-engineering education for university students and practicing professionals. Education and training issues are discussed first, followed by recommendations for improving technology transfer.

EDUCATION AND TRAINING

It is important that future generations of wind engineers be developed for the growth and expansion of wind engineering. As the awareness of the nation's wind vulnerability inevitably increases and the importance of wind engineering is more widely recognized, the need to ensure a sufficiently large pool of engineers with wind-related training will become more apparent. Indeed, education is one of the cornerstones of any National Wind Science and Engineering Program proposal.

The nurturing of future wind engineers can occur at both graduate and undergraduate levels, through advanced courses in wind engineering by engineering schools and introductory wind-engineering courses designed for related fields, such as meteorology and social sciences. A concerted effort is needed to attract talented individuals to the wind-engineering field and improve the personnel infrastructure in this area. One specific strategy to accomplish this would be to establish a number of undergraduate fellowships–perhaps 20 or so–to encourage students early in their academic careers to pursue the wind-engineering profession. The National Science Foundation might provide an appropriate funding source for such fellowships.

At present, only a handful of universities offer a graduate-level course in wind engineering, while a few other schools offer wind engineering as a part of other courses dealing with, for example, waves and earthquakes. The pressing need in wind-engineering education is for an expansion of course offerings, as well as for new, exciting, adequately funded research projects to attract graduate students. Computers and laboratory (including wind tunnel) facilities are both critical elements in this invigoration of wind-engineering educational opportunities.

At the undergraduate level, an introductory interdisciplinary course that synthesizes fundamentals of meteorology, aerodynamics, turbulence, structural mechanics and design, structural vibrations, and probability and statistics is desirable. Wind-engineering-based design concepts should be incorporated to help students to experience the actual practice of wind-engineering knowledge and skills. In the technical courses, time should be allotted for the study and use of building codes and specifications and how they affect the design implementation of a professional work product.

Graduate programs with concentration in wind engineering should

Graduate programs with concentration in wind engineering should emphasize structural analysis and design or fluid dynamics. An effort to enhance and better advertise the existence of job opportunities in wind-related fields in academia, government laboratories, or the private sector is also important. Better career opportunities will make the wind-engineering specialty a more attractive option among graduate students.

For individuals already in the design profession, there is a need to hone those skills specifically related to wind design and analysis. This can be accomplished by circulating research abstracts widely and by creating seminar series, short courses, television courses for industry, video-based continuing education, interactive courseware, intelligent computer-aided instruction, and university internships.

Seminar series and short courses can help design professionals learn of recent advances as well as the theoretical background of the practical aspects of wind engineering.

Continuing education also can be effectively pursued through audio and video interactive courseware. Hypermedia presentations embedded with artificial intelligence can be powerful tools for teachers and students. In this approach, an expert's thinking process can be encapsulated in a computer knowledge base, allowing both the knowledge and the reasoning behind the knowledge to be tapped.

Enhancing the interaction between universities and research institutes and industry will also benefit the wind-engineering field. Universities and research institutes should provide opportunities for practicing engineers to serve as research residents or interns with emphasis on wind engineering. Similarly, faculty or researchers should be offered opportunities at design firms to gain experience in practical engineering problems.

TECHNOLOGY TRANSFER

A coordinated effort is needed to focus on the transfer of the existing knowledge base in wind engineering through traditional and innovative means. This objective is especially critical in a multidisciplinary area such as wind engineering.

Educators must train personnel as well as conduct basic research in wind engineering. The knowledge derived from this research is needed by practicing architects and engineers responsible for designing buildings and structures; scientists and engineers for manufacturing materials and building components; individuals for developing testing standards; and associations for representing building products manufacturers. Perhaps the most important targets of all for wind-engineering technology transfer are the personnel who adopt, publish, and promulgate the use of building codes, such as Building Officials and Code Administrators International, International Conference of Building Officials, Southern Building Code Congress International, and the National Fire Protection Association's Life Safety Code. Development of a user-friendly knowledge base, effective communication with codes and standards organizations, establishment of a wind-engineering information center, distribution of technical literature and monographs, and the adoption of advances in related fields are important vehicles to facilitate effective dissemination of wind-engineering research and development activities into actual practice.

It is the knowledge base that helps design and construct economical and reliable structures. An essential prerequisite for such a knowledge-oriented field is to package information for immediate dissemination to the users in a conveniently codified form. Computer software packages and networked computer bulletin boards can be instrumental in this task. With personal computers becoming increasingly powerful and versatile, software can be made available to expedite the transfer of the state of the art in wind engineering and to provide quick feedback for improvements.

Effective communication with the organizations responsible for promulgating building codes and standards can accelerate the implementation of a good knowledge base into these codes. To ensure the transfer of proper, uniform technology from model-construction-code organizations to professional designers, contractors, and construction code enforcement personnel, the existing educational programs administered by the three model-code organizations must be expanded and coordinated. Plans to automate the wind-related sections of codes and standards in a computer data base should be instituted. When completed, this process will lead to the broader application of a more consistent and technologically advanced set of codes and standards.

A wind-engineering library is vital for gathering and archiving pertinent texts dealing with all aspects of wind engineering and its subdisciplines, as well as journals, conference proceedings, reports, and theses. The library should also focus on data gathering for both full-scale and laboratory experiments, damage assessment information, and available software related to different aspects of wind engineering. Such a library could perhaps be modeled on the successful example of the Earthquake Engineering Library and the National Information Service on Earthquake Engineering computer applications of the Earthquake Engineering Research Center at the University of California, Berkeley.

In addition, there should be a periodic review describing all wind-engineering research activities, such as that published in the *Wind Engineering Research Digest* (WERD) in the late 1970s (only three volumes of WERD were published before funds ran out). This publication served as an effective medium to quickly disseminate information on ongoing research rather than waiting several years for this information to appear in technical journals. It thus encouraged researchers working on similar topics to communicate and interact.

Today, the Wind Engineering Research Council's publication, *The Wind Engineer*, is a potentially effective means for transferring technical information, provided it is received by those who need the information. A useful abstract program could consist of news releases to industry, including results of recent research and development activities within wind-engineering circles. Circulation of such abstracts will keep practicing engineers up to date and may motivate them to participate in future short courses addressing recent topics in wind engineering.

A discussion of technology transfer remains incomplete without addressing the transfer of existing technologies in related fields. For example, the use of technologies in electronics could enhance wind-engineering practice, and the use of remote sensing and Doppler radar boundary-layer profiles would advance wind-speed measurement. Utilization of recent developments in sensor technology (e.g., piezopolymers) and advances in computer architecture, intelligent digital signal interpretation and processing, and information storage and retrieval capabilities promise to improve our measurement capabilities and assessment of the performance of the built environment. The potential for advancing the state of the art in wind engineering utilizing knowledge-based systems is addressed below.

POTENTIAL IMPACT OF COMPUTERS

In the decade ahead, there is a potential for significantly advancing the state of the art in wind engineering as personal computers and software become more powerful and flexible. Personal computers are available at reasonable cost, and there has been an impressive growth in the field of artificial intelligence and expert systems during the past decade. The so-called knowledge-based system can offer intelligent assistance to designers and planners in accomplishing a wide spectrum of tasks, including risk assessment.

Knowledge-Based Expert Systems

A knowledge-based expert system (KBES) is a computer program designed to mimic human thought processes by utilizing a specific domain of knowledge, facts, and procedures to solve complex problems at an expert level of performance for such generic tasks as design, diagnosis, interpretation, monitoring, and planning. One main feature distinguishing a KBES from a conventional algorithmic—and typically numerical—program is that the knowledge pertaining to a specific problem is explicitly encapsulated in a knowledge base rather than being part of sequentially executable statements. Recent exploitation of expert systems has been facilitated by the development of software "shell" and production systems for mainframe and personal computers. These enable engineers to develop their own expert systems without extensive prior computer-programming experience and have facilitated the availability of numerous methods for achieving expert system design and implementation at various levels of sophistication.

Though they are not without their limitations, the potential applications of KBESs in wind engineering are many. They may include analysis and prediction of extreme winds, risk and damage assessment, design and synthesis, monitoring and control, and decision making for hurricane response, among others. A few examples of these applications are given below.

Extreme Winds: Analysis and Prediction

It is expected that more comprehensive field measurements of the wind distributions in tornadoes and hurricanes will be obtained during the 1990s. By using such data, a KBES could be designed to produce physically consistent distributions of wind speed or pressure in convective vortices. Another KBES could then be developed for wind-hazard analysis.

Expert systems could also be developed using wind profiler and Next-Generation Radar (NEXRAD) data to identify those severe thunderstorms (out of an ensemble) most likely to spawn tornadoes within one to two hours. In addition, a predictive system could be applied in wind engineering to forecast expected extreme events on the basis of current information. This forecasting system would rely on a combination of experience, models, and procedures.

Wind-Loading Assistant

Many of the wind-loading provisions of building codes and specifications can be automated. A KBES "wind-loading assistant" based on these computerized data could offer advice to design professionals who must use the provisions of building codes and specifications. An expert system called WINDLOADER, which is under development, incorporates the Australian Wind Loading code. Similar efforts to incorporate U.S. codes and design specifications into a KBES system should be pursued.

Risk and Damage Assessment

The determination of hazard, vulnerability, and significance of the facilities, and the analysis of damage potential constitute the essential prerequisites for risk assessment. A synthesis of these attributes leads to the development of a hazard-vulnerability-damage model for risk assessment. The assessment of vulnerability and damage potential of a built environment involves the use of qualitative knowledge that is often vague, uncertain, and imprecise.

The integration of information on wind hazards and facilities at risk is an analytical task based heavily on experience. Therefore, a knowledge-based expert system offers an ideal solution. Based on observations from past storms, inductive and inexact inference mechanisms can be utilized to encapsulate the body of information concerning damage patterns, often expressed in the form of causal relations or rules in the knowledge base.

Design

Artificial intelligence tools can significantly improve the design process by better and more explicit knowledge representation and definition of the design goals and constraints. A typical design cycle is one of design-evaluate-redesign. Although this iterative design cycle has proved itself in structural engineering, the incorporation of wind criteria as part of this analysis has not yet been accomplished. An expert system may help to configure a structural system and its components to resist wind loads for both the serviceability and survivability limit states on the basis of a set of alternative possibilities.

Monitoring and Control

In the field study of full-scale structures, surface pressures, accelerations, and strains at various locations are monitored. The primary objective of such measurements is to validate or compare laboratory, computational, or analytical predictions of structural behavior in winds. Data monitoring and control expert systems can help to automate wind tunnel and full-scale experiments by the process of continuous or intermittent interpretation of signals. Such a system could observe the experimental progress and alert the user if there is a departure from the expected. At the same time, the system may help to define appropriate actions in response to the monitoring. For example, unusual readings from a pressure transducer may be detected and remedial action suggested for the continuation of the experiments. These systems would minimize downtime and the need for repetition of experiments in which faulty data are discovered during the analysis.

Urban Planning

The planning of a new urban development can be facilitated and improved by means of an expert system. For example, the knowledge needed to ensure human comfort with regard to the windflow around buildings at plaza level is generally not available to urban planners. This knowledge, once coded into an expert system, could be more easily accessible to architects and urban planners in the early stages of development. Another potential application may involve the building layout of coastal communities to provide optimal shelter configurations to enhance structure performance in hurricanes.

Decision Making for Hurricane Response

Many local government agencies, private businesses, and military installations use personal-computer-based software to incorporate hurricane forecast uncertainty into the decision-making process, using official watch/warning information from the National Hurricane Center. For example, a bar chart can be generated indicating that there is a 10 percent chance of a storm's sustained winds exceeding 120 mph in the next 24 hours. This graphical approach to forecast uncertainties helps users to comprehend the concept of forecast error and to deal with uncertainties in a quantitative fashion.

Decision makers often need assistance in integrating forecast information with other factors to arrive at an overall assessment of risk and an evaluation of response alternatives. Some software is accompanied by a questionnaire posing a set of specially constructed hurricane threats. Based on the users' response to the hypothetical threats, a regression model is derived to reflect their decision process, which is then integrated into the software to generate possible responses to real threats. Additional incorporation of knowledge gleaned from a host of past hurricane experiences spanning a wide range of scenarios will result in transforming the current algorithmic approach to a knowledge-based approach within the context of an expert system.

RECOMMENDATIONS

The following recommendations are developed from the discussion presented in this chapter.

1. Enhance continuing education for design and construction professionals by creating seminar series, short courses, television courses, video-based classes, interactive courseware, intelligent computer-aided instruction, and university/industry internships and by circulating research abstracts.
2. Revitalize undergraduate and graduate education in wind engineering by widening the availability and breadth of coursework and by providing competitive undergraduate fellowships for pursuing wind-engineering programs.
3. Educate decision makers at the national, state, and local levels through briefings, workshops, and personal contact on the imminent risks of wind hazards and the benefits of research and development.
4. Promote media programs, in nontechnical language, to educate the public on the likelihood and consequences of wind hazards and on effective mitigation measures.
5. Encourage active participation by design professionals in the formulation of codes pertaining to wind-load provisions, and develop automated wind-related codes and standards in a computer data base.
6. Establish a wind-engineering information center for archiving pertinent materials dealing with all aspects of wind engineering, including laboratory and full-scale data, damage assessment information, and software. Develop, using the latest technology, knowledge-based systems for real-time problem solving related to meteorological predictions of extreme winds, risk and damage assessment, and decision making for hurricane evaluation.

6

Cooperative Efforts

INTRODUCTION

The mitigation of wind hazard is a universal quest that requires a multidisciplinary approach to find solutions. It is not the sole domain of meteorologists, engineers, architects, planners, or any of the other design professionals. Input must also be obtained from related disciplines, such as psychology, sociology, and economics, and from building manufacturers and materials suppliers. Additionally, public officials and the populace must continually be apprised of the consequences of wind hazards because their cooperation in adopting strategies for mitigating wind hazard is essential. A concerted effort must be made to encourage industry-academia interaction in wind-engineering research.

The International Decade for Natural Disaster Reduction (IDNDR) and especially the U.S. Decade for Natural Disaster Reduction provide excellent opportunities for evaluating the U.S. program on wind-hazard mitigation and for revitalizing research efforts in this area. Given the limited funds available for research worldwide, it is an opportune time to embark on cooperative, international efforts to develop new measures to mitigate wind hazards.

To minimize duplicate efforts, it is important to disseminate information about ongoing research as rapidly as possible through such methods as resuming publication of the *Wind Engineering Research Digest* (WERD). As mentioned in Chapter 5, the establishment of a central location for all wind-engineering-related publications–a Wind Engineering Research Library–will facilitate and encourage information exchange.

INDUSTRY-ACADEMIA COOPERATION

Wind-engineering research within the academic community is relatively young. As detailed earlier, it lacks the adequate financial resources essential for a vigorous, concerted program to address the engineering challenges that extreme winds pose. Cooperative research efforts by industry and academia in seeking answers for improved design of wind-resistant systems will greatly speed progress in this area and will provide more visibility for the resultant research findings. A generous financial commitment toward research and development by the building industry and materials manufacturers could help provide much-needed resources to augment the limited funding currently available from the National Science Foundation and other federal agencies. The size of this commitment could, for example, be determined as a percentage of total construction costs. In addition to supporting research, industry must participate more actively in the development of codes and industry must participate more actively in the development of codes and standards (see Chapter 3).

Over the years, industry has lent its support to various research efforts. For instance, it has supported a few research projects on determining fluctuating wind pressures on roofs and low-rise metal buildings. The variation of wind pressures over a structure is important for the proper design of roofing, cladding, glazing, components, fastenings, and main frames capable of withstanding extreme wind loads. In addition, the members of the Primary Glass Manufacturers Council have supported recent work by the American Society for Testing and Materials in developing glass strength standards that take into account the imposed wind-load conditions.

However, much research of direct benefit to industry remains unfunded and could benefit from cooperative efforts. For example, the roofing industry realizes that failures of roofing and connectors constitute a large portion of the total damage cost attributable to extreme winds. By pooling available information on reasons for these failures and by helping to fund a cooperative research program with academia, industry could help promote a major step forward in this area. A key finding of a recent workshop on roof wind uplift testing (Courville, 1989) was that industry recognized the need for such research but refrained from funding it on its own because of the expense. The federal government thus has a role to play in co-funding such research and providing incentives to industry to share the burden. Overall, federal coordination and encouragement of wind research will ensure that a broader scope of research topics is addressed than the narrowly focused agenda industry would likely pursue on its own.

DISSEMINATION OF RESEARCH FINDINGS

The National Science Foundation provided the funding for initiating and publishing three volumes of the WERD. However, publication was suspended after the third volume, more than 13 years ago, because funding was not available to continue this activity (the third volume of the WERD was published in 1978). Of the 97 U.S. wind-engineering projects listed in this volume (see Table 6-1), 13 were supported by NSF, 30 by private industry, 8 by universities, and the other 44 by federal and state agencies. The report (Chiu, 1978) grouped the then-ongoing research activities into 17 different categories. Most of the projects were in the category of wind loading on structures, followed closely by the categories of structure of wind and model testing. The research emphasis, thus, was clearly related to the needs of structural engineers and architects. An updated report, followed by periodic subsequent reports, is necessary to ascertain current research activities and to identify areas that should be pursued more vigorously.

TABLE 6.1 U.S. Projects Listed in the WERD.

Multiple sponsors	1
National Institute of Standards and Technology	5
National Science Foundation	13
Nuclear Regulatory Commission	2
U.S. Department of Commerce (National Oceanic and Atmospheric Administration)	5
U.S. Department of Energy	12
Other federal agencies	10
Others	1
Private industry	30
State government	10
Universities	8
Total	97

Source: Chiu (1978).

INTERNATIONAL COOPERATIVE EFFORTS

The need for rapid dissemination of knowledge gained from postdisaster studies of damage caused by extreme winds cannot be emphasized enough. In the United States, the Committee on Natural Disasters of the National Research Council has been dispatching teams consisting of engineers, meteorologists, and social scientists to survey and report on the damage caused by hurricanes and tornadoes as well as other natural disasters for many years. This activity should be extended to the international scene with concurrence, cooperation, and support from affected countries. Such an activity will further enhance the program of the IDNDR.

Hurricanes Gilbert in 1988 and Hugo in 1989 drew much attention to the severe damage that can be caused by extreme winds. Likewise, the 1990 winter windstorms in England, France, and northern Europe further emphasized the need for mitigation strategies. The wind-engineering program in the United States can gain much from cooperative projects by participating in more international postdisaster windstorm damage surveys to learn of failure mechanisms and by encouraging more mutual exchange of the latest technology for improving the design of structures to withstand the effects of strong winds. In addition, the International Standards Organization has been promoting common guidelines in Europe for designing for wind effects. Input and participation by the United States in this effort should be pursued.

It would also be advantageous to the United States to pursue a more vigorous, concerted, and coordinated program of cooperative international wind-engineering research. For example, the principal test method used by curtain wall and window manufacturers for evaluating structural performance follows the ASTM E330 procedures in which the wall or window unit is mounted in a test chamber and subjected to both positive and negative static air pressures equivalent to the maximum wind loads specified for the project. However, some of the materials used in curtain wall construction are time sensitive to loads and to the rate of change of loads. Yet in the United States, these products are not tested with the types of loads simulating actual high-wind conditions, such as high gust velocities and relatively rapid fluctuations. Test methods that can better simulate actual severe wind conditions are required, and such tests must be accomplished at a reasonable cost. The United Kingdom and some other European countries do have testing methods and facilities that can simulate a rapid change in wind pressure (Beckett and Godfrey, 1974). Similarly, the Japanese have a computer-controlled apparatus that can closely imitate the pressure changes during a typical gale.

In fact, other countries such as Australia, Canada, China, Germany, Japan, and the United Kingdom are putting more effort into conducting experimental wind-engineering research than the United States is. Several of the major construction companies in Japan (Kumagai Gumi, Shimizu, and Kajima) have in-house research staffs engaged in wind-engineering research using boundary-layer wind tunnels. However, many of the projects are proprietary. In the Tsukuba Science City alone, there are more than 35 wind tunnels for research purposes (Marshall, 1984). The boundary-layer wind tunnels at the Public Works Research Institute and the Building Research Institute are extremely well equipped for physical model studies of buildings and structures, and several universities also have wind tunnels available for studying wind effects on structures. Cooperative U.S.-Japan research efforts will therefore greatly benefit the U.S. wind research program.

The way was paved for initiating U.S.-Japan contacts by holding two U.S.-Japan Research Seminars, the first in 1970 and the second in 1974 (Chiu, 1970; Ishizaki and Chiu, 1974), which were jointly sponsored by the National Science Foundation and the Japan Society for the Promotion of Science. These seminars should be reinstated as soon as possible as regular, biennial events and should include selected participants from industry. The annual Panel Conferences of the U.S.-Japan Program in Natural Resources have been limited primarily to representatives from governmental agencies. Discussions at these panel conferences have also been concentrated, to a large degree, on seismic rather than wind issues.

The eastern coast of India (especially the state of Andhra Pradesh) is exposed to the frequent, violent tropical cyclones spawned in the Bay of Bengal. The Philippines (Luzon particularly); Taiwan; Hong Kong; the southeastern coast of China; the Ryukyu Islands; and various islands in the South Pacific, such as Guam and Saipan, are also exposed to strong tropical cyclones. Typhoons make landfalls more frequently in the aforementioned places than on the eastern coast of the United States; they can provide fertile field laboratory sites for full-scale studies of extreme wind effects on structures.

Typhoon landfalls on Taiwan, for example, are more frequent than on the Atlantic coast of the United States. It would be advantageous, through a bilateral cooperative research project, to have in readiness a mobile wind-speed measuring system that can be deployed quickly to the predicted landfall area to obtain actual wind speeds near the ground. In addition to the immediate benefit of obtaining valuable wind-speed data, the project would provide an opportunity for the development of remote sensing systems and rugged sensors that could withstand the expected higher wind speeds. As stated in Chapter 2, the difficulty in obtaining reliably recorded wind speeds near the ground has been a hindrance to the development of a good data base for deriving reliable design wind speeds.

In addition to the above, it should be noted that recent events in Eastern Europe and the former Soviet Union may lead to additional opportunities for sharing wind data and conducting cooperative research with these countries. Furthermore, the growing interest in global climate change research could provide yet another avenue to pursue potential international cooperation in wind engineering. The IDNDR would be a particularly good vehicle to promote these and all such international research efforts.

Increased cooperation and integration must exist not only with other nations, but also with related disciplines. The Research Committee on Disasters of the International Sociological Association has hundreds of members throughout the world. These social scientists study issues important to the mitigation of, response to, and recovery from wind-induced disasters. Integration of the technical engineering aspects of wind disasters with the social sciences aspects is necessary because the problem of wind-induced disasters is inherently multidisciplinary.

Over the years, a number of national, regional, and international conferences, symposia, and workshops have been held to promote mutual exchange of wind-engineering research findings and to encourage cooperative research projects. A list of selected meetings is presented in Appendix A. The number of such meetings has increased over time, attesting to the apparent interest in finding solutions for wind-hazard mitigation. It is encouraging to note that attendance by design professionals as well as industry representatives at these conferences is also increasing. Such forums should be actively promoted as part of the effort to catalyze and share the results of cooperative international research.

RECOMMENDATIONS

The following recommendations to encourage cooperative efforts in mitigating damage from wind hazard are drawn from the above text:

1. Encourage the building industry and industrial manufacturers to financially support nonproprietary wind research and development projects within both academic and industrial laboratories.
2. Pursue joint international wind research efforts (e.g., wind characterization and structural response) under the rubric of the IDNDR with a special emphasis on developing a mutual research program with Japan, whose state-of-the-art research facilities provide important opportunities for study not available in the United States.
3. Actively solicit industry involvement in developing building codes and standards, and encourage U.S. input to the development of the International Standards Organization's code on wind loads.
4. Encourage the organization of and participation in national, regional, and international seminars, conferences, symposia, and workshops to disseminate research findings.
5. Fund active participation in post-wind-disaster studies for mutual sharing of postdisaster survey findings and lessons learned.

7

Conclusions and Recommendations

This chapter summarizes the issues, conclusions, and recommendations developed from the discussions in the previous chapters. The Panel on the Assessment of Wind Engineering Issues in the United States concludes that the key to implementing these recommendations is the immediate establishment of a National Wind Science and Engineering Program. This national program, enacted by the U.S. Congress and backed by a sustained budgetary commitment, would revitalize wind-hazard research. *To minimize human suffering and property losses in the future, it is important to encourage the professional community to proceed with research, to develop effective technology transfer methodologies, and to implement existing technologies*. This program must be established now to reach the goals set forth herewith with a minimum funding level of $20 million per year for the first five years.

The following focus areas—listed as key needs—and recommendations are derived from the previous chapters:

WIND HAZARDS AND RELATED ISSUES

Key Needs

1. To provoke a national awareness of the imminent hazard of wind-related disasters, especially upon vulnerable coastlines.
2. To address the nation's wind vulnerability through a federally coordinated plan to pursue necessary wind research and to apply this expanded knowledge base at the local level.

Recommendations

1. Establish a National Wind Science and Engineering Program (NAWSEP) to fund and coordinate research in wind science and to transfer this knowledge to local communities, code bodies, the design professions, the construction industry, and other user groups.
2. Through the NAWSEP, encourage the development and continuous refinement of research-based design standards and building codes, which together are the most powerful and direct tools to reduce the impact of wind hazards.
3. Promote the adoption and enforcement of such standards by a vigorous program of informing local governments of their vulnerability to wind hazards

4. Address the problem of cost-effective retrofit of existing structures to make them wind safe through technical research, as well as through communication to property owners about the soundness of such investments in terms of avoided losses.
5. Encourage innovative community land-use planning to locate structures away from areas most vulnerable to wind, acknowledging that this is often a costly and controversial mitigation strategy.

NATURE OF WIND

Key Needs

1. To improve the verification of, and the data base for, extreme wind events, including interdisciplinary quick-response assessments of damage from ground and aerial surveys, and to maintain a quality publication on storm data, including reasons for F-scale assignment to a given event.
2. To quantify, through actual data analysis and model simulations, the relative roles of wind, pressure drop, and flying debris in overall damage production by extreme wind events.
3. To improve models and techniques for warnings and forecasts (0–48 hours) of extreme wind events (such as tornadoes, downbursts, and hurricanes).
4. To provide for the archiving of digital data from new observing systems such as Next-Generation Radar (NEXRAD), Automated Surface Observing System (ASOS), and profilers, especially for near-surface wind.

Recommendations

1. Augment the climatology of the United States through improved observations and instrumentation, digital archival programs for current and new observing systems, and new quality control and analysis techniques.
2. Establish an extreme winds data base through improved and expanded instrumentation, using field programs (e.g., STORM) to augment the existing national observing network.
3. Improve wind-hazard forecasting through the development of better numerical prediction models coupled with hazard-specific technique development. University and private sector collaboration could be sought at Experimental Forecast Facilities at National Weather Service offices. These facilities should include an evaluation program for all models and techniques developed.
4. Maintain and expand postdisaster quick-response surveys for forecast validation, impact assessment of wind hazard, and wind measurement retrieval and intercomparisons with damage assessment. The effort should

also include follow-up research on data from damage surveys to refine estimates of the distribution and probabilities of peak wind speeds.

WIND ENGINEERING

Significant advances have taken place over the past three decades in the field of wind engineering. Much of this research effort has been directed toward tall buildings, long-span bridges, and other major developments funded directly by end users, and such research should continue. However, it is time to focus attention on those problems that have a greater impact on society.

Key Needs

1. To implement existing methods to improve the performance of nonengineered buildings, such as single-family dwellings, light industrial buildings, and small commercial structures. Specifically, to refine wind-load requirements as put forth in codes and standards so that design practice and construction of nonengineered structures are put on a more scientific basis.
2. To enhance the ability to conduct state-of-the-art wind research and computer modeling by upgrading experimental facilities and making use of the increasing computational abilities of computers.
3. To address the economic and societal impact associated with the dispersion of pollutants, the urban wind environment, the tapping of wind energy, and soil erosion.

Recommendations

1. Pursue research to quantify the benefit/cost ratios for various strategies to mitigate wind damage.
2. Use the results of quick-response postdisaster studies to assess the performance of structures and lifeline facilities during severe winds and to validate or improve design methodologies.
3. Enhance risk analysis procedures for structures subjected to extreme winds.
4. Improve codes and standards by researching wind effects through wind tunnel testing and full-scale measurements.
5. Conduct research on building structures to develop efficient frame and cladding systems to resist wind loads while decreasing constructed cost.
6. Develop improved physical simulation facilities with more quantitative measurement capabilities for downbursts, tornadoes, and hurricane winds.
7. Develop numerical modeling capabilities using supercomputers to simulate windstorms, windflow around structures, and associated wind-load effects. Improve measurement capabilities and assessment of the performance

of the built environment using recent developments in sensor technology (e.g., piezopolymers and advances in computer architecture, intelligent signal interpretation, and processing and information storage and retrieval capabilities).

8. Develop experimental facilities for wind-load measurements of full-scale structures and assemblages.
9. Develop more innovative and quantitative procedures for studying dispersion of pollutants (including oil spills and dispersion in air).
10. Study problems associated with offshore wind environments and wind energy.

MITIGATION, PREPAREDNESS, RESPONSE, AND RECOVERY

Key Needs

1. To mitigate life and property losses by improving building codes and especially by encouraging their wider adoption and enforcement; to develop economically feasible land-use management practices.
2. To improve emergency preparedness, response, and recovery, especially lifeline systems protection and restoration through special attention to hazard warnings, evacuation, sheltering, and public education.
3. To reduce the current fragmentation and diversity of disaster planning and emergency response.
4. To more closely link disaster recovery to postdisaster mitigation measures such as retrofitting, land-use planning, and building code enforcement.

Recommendations

1. Encourage research to be multidisciplinary and to study the linkages among mitigation, preparedness, response, and recovery.
2. Use quick-response field studies to assess public/official response and preparedness.
3. Adopt and implement applicable mitigation measures (codes and standards and land-use planning) at the local level, including effective enforcement of these measures through insurance incentives or other methods; conduct research into government and business recovery planning to identify policies and institutions that discourage future mitigation efforts such as retrofitting, land-use planning, and building code enforcement.
4. Develop and utilize new technology for improving local warning systems.
5. Study the epidemiology of death and injury due to wind hazards with a focus on determining the relationship of structural and nonstructural damage to occupant behavior and casualty levels.

6. Increase research into hurricane evacuation and refine the criteria for the selection of safe public shelters.

EDUCATION AND TECHNOLOGY TRANSFER

Key Needs

1. To institute a major thrust in wind-engineering education and training, including other closely related disciplines such as meteorology and sociology.
2. To begin a coordinated effort to transfer the developing knowledge base in wind engineering through traditional and innovative means. In this regard, the most important needs are

- improved education and knowledge transfer to both developers and users of codes and standards;
- a clearing house for wind-engineering literature and data; and
- the periodic compilation of recent wind-engineering research activities.

Recommendations

1. Enhance continuing education for design and construction professionals to improve wind analysis, design, construction, and inspection by creating seminar series, short courses, television courses, video-based classes, interactive courseware, intelligent computer-aided instruction, and university/industry internships and by circulating research abstracts.
2. Revitalize undergraduate and graduate education in wind engineering by widening the availability and breadth of coursework and by providing 20 competitive undergraduate fellowships for pursuing wind-engineering programs.
3. Educate decision makers at the national, state, and local levels through briefings, workshops, and personal contact on the imminent risks of wind hazards and the benefits of research and development.
4. Promote media programs, in nontechnical language, to educate the public on the likelihood and consequences of wind hazards and on effective mitigation measures.
5. Encourage active participation by design professionals in the formulation of codes pertaining to wind-load provisions, and develop automated wind-related codes and standards in a computer data base.
6. Establish a wind-engineering information center for archiving pertinent materials dealing with all aspects of wind engineering, including laboratory-and full-scale data, damage assessment information, and software; develop, using the latest technology, knowledge-based systems for real-time problem solving related to meteorological predictions of extreme winds, risk, and damage assessment and decision making for hurricane evaluation.

COOPERATIVE EFFORTS

Key Needs

1. To maximize research efforts by sharing findings and conducting cooperative work. This cooperation should involve interaction among academia, industry, international associations, and the news media. Such cooperative work should be approached on a multidisciplinary and multihazard basis.
2. To increase support from the private sector for wind-engineering research.

Recommendations

1. Encourage the building industry and industrial manufacturers to financially support nonproprietary wind research and development projects within both academic and industrial laboratories.
2. Pursue joint international wind research efforts (e.g., wind characterization and structural response) under the rubric of the International Decade for Natural Disaster Reduction with a special emphasis on developing a mutual research program with Japan, whose state-of-the-art research facilities provide important opportunities for study not available in the United States.
3. Actively solicit industry involvement in developing building codes and standards and encourage U.S. input to the development of the International Standards Organization's code on wind loads.
4. Encourage the organization of and participation in national, regional, and international seminars, conferences, symposia, and workshops to disseminate research findings.
5. Fund active participation in post-wind-disaster studies for mutual sharing of postdisaster survey findings and lessons learned.

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Appendix

U.S. CONFERENCES/SYMPOSIA/WORKSHOPS

Conference on Wind Loads on Structures (First U.S. National Conference on Wind Engineering), December 18–19, 1970, California Institute of Technology, Pasadena, California.

Fifth U.S. National Conference on Wind Engineering, November 6–8, 1985, Texas Tech University, Lubbock, Texas.

Fourth U.S. National Conference on Wind Engineering Research, July 27–29, 1981, University of Washington, Seattle, Washington.

Second U.S. National Conference on Wind Engineering Research, June 22–25, 1975, Colorado State University, Fort Collins, Colorado.

Seminar/Workshop on Wind Engineering, June 3–6, 1987, Colorado State University, Fort Collins, Colorado.

Sixth U.S. National Conference on Wind Engineering, March 8–10, 1989, University of Houston, Texas.

Symposium on Tornadoes, Assessment of Knowledge and Implications for Man, June 22–24, 1976, Texas Tech University, Lubbock, Texas.

Third U.S. National Conference on Wind Engineering Research, February 26–March 1, 1978, University of Florida, Gainesville, Florida.

Wind Engineering Research Council/National Science Foundation Wind Engineering Symposium, November 2–4, 1987, Kansas City, Missouri.

JOINT SEMINARS/SYMPOSIA/WORKSHOPS

CCNAA-AIT Joint Seminar on Research for Multiple Hazards Mitigation, January 16–19, 1984, National Cheng-Kung University, Tainan, Taiwan.

CCNAA-AIT Joint Seminar on Research and Application for Multiple Hazards Mitigation, April 11–15, 1988, Taipei, Taiwan.

Indo-U.S. Workshop on Wind Disaster Mitigation, December 17–20, 1985, Structural Engineering Research Centre, Madras, India.

Peoples Republic of China-United States-Japan Trilateral Symposium/Workshop on Engineering for Multiple Natural Hazard Mitigation, January 7–12, 1985, Beijing, China.

U.S.-Asia Conference on Engineering for Mitigating Natural Hazards Damage, December 14–18, 1987, Bangkok, Thailand.

U.S.-Japan Research Seminar on Wind Loads on Structures, October 19–24, 1970, University of Hawaii, Honolulu.

U.S.-Japan Seminar on Wind Effects on Structures, September 9–13, 1974, Kyoto, Japan.

U.S.-Southeast Asia Symposium on Natural Hazards Protection, September 26–30, 1977, Manila, Philippines.

INTERNATIONAL CONFERENCES ON WIND ENGINEERING

Conference on Wind Effects on Buildings and Structures (First International Conference on Wind Effects on Buildings and Structures), National Physical Laboratory, June 26–28, 1963, Teddington, England.

Eighth International Conference on Wind Engineering, July 8–12, 1992, West Ontario, Canada.

Fifth International Conference on Wind Engineering, July 8–14, 1979, Colorado State University, Fort Collins, Colorado.

Fourth International Conference on Wind Effects on Buildings and Structures, September 8–12, 1975, Heathrow, England.

International Research Seminar on Wind Effects on Buildings and Structures (Second International Conference on Wind Effects on Buildings and Structures), September 11–15, 1967, Ottawa, Canada.

Seventh International Conference on Wind Engineering, July 6–10, 1987, Aachen, West Germany.

Sixth International Conference on Wind Engineering, March 21–25, 1983, Gold Coast, Australia, April 6–7, 1983, Auckland, New Zealand.

Third International Conference on Wind Effects on Buildings and Structures, September 6–11, 1971, Tokyo, Japan.