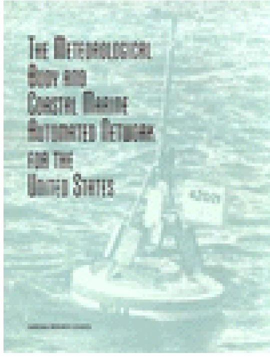

The Meteorological Buoy and Coastal Marine Automated Network for the United States

Lance F. Bosart, Principal Investigator; William A. Sprigg, Study Director; Board on Atmospheric Sciences and Climate, National Research Council

ISBN: 0-309-52398-2, 110 pages, 8.5 x 11, (1998)

This free PDF was downloaded from:
http://www.nap.edu/catalog/6108.html

Visit the National Academies Press online, the authoritative source for all books from the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council:

- Download hundreds of free books in PDF
- Read thousands of books online for free
- Purchase printed books and PDF files
- Explore our innovative research tools – try the Research Dashboard now
- Sign up to be notified when new books are published

Thank you for downloading this free PDF. If you have comments, questions or want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, visit us online, or send an email to comments@nap.edu.

This book plus thousands more are available at www.nap.edu.

Copyright © National Academy of Sciences. All rights reserved.
Unless otherwise indicated, all materials in this PDF file are copyrighted by the National Academy of Sciences. Distribution or copying is strictly prohibited without permission of the National Academies Press <http://www.nap.edu/permissions/>. Permission is granted for this material to be posted on a secure password-protected Web site. The content may not be posted on a public Web site.

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

THE METEOROLOGICAL BUOY AND COASTAL MARINE AUTOMATED NETWORK FOR THE UNITED STATES

LANCE F. BOSART, *Principal Investigator*

WILLIAM A. SPRIGG, *Study Director*

Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.   1998

NATIONAL ACADEMY PRESS • 2101 Constitution Avenue, N.W. • Washington, DC 20418

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice-chairman, respectively, of the National Research Council.

This study was supported by Contract no.50–DKNA–6–90040 between the National Academy of Sciences and the National Oceanic and Atmospheric Administration. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for this project.

Library of Congress Catalog Card Number 98–85592
International Standard Book Number 0–309–06088–5

Additional copies of this report are available from:
National Academy Press
2101 Constitution Ave., NW
Box 285
Washington, DC 20055
800–624–6242
202–334–3313 (in the Washington metropolitan area)
http://www.nap.edu

Printed in the United States of America.

THE METEOROLOGICAL BUOY AND COASTAL MARINE AUTOMATED NETWORK FOR THE UNITED STATES

Principal Investigator
LANCE F. BOSART, State University of New York, Albany

Study Director
WILLIAM A. SPRIGG

Research Assistant
TENECIA A. BROWN

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

ERIC J. BARRON (*Co–Chair*), Pennsylvania State University, University Park
JAMES R. MAHONEY (*Co–Chair*), International Technology Corporation, Washington, D.C.
SUSAN K. AVERY, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder
LANCE F. BOSART, State University of New York, Albany
MARVIN A. GELLER, State University of New York, Stony Brook
DONALD M. HUNTEN, University of Arizona, Tucson
JOHN IMBRIE, Brown University, Providence, Rhode Island
CHARLES E. KOLB, Aerodyne Research, Inc., Billerica, Massachusetts
THOMAS J. LENNON, Sonalysts, Inc., Alexandria, Virginia
MARK R. SCHOEBERL, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
JOANNE SIMPSON, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
NIEN DAK SZE, Atmospheric and Environmental Research, Inc., Cambridge, Massachusetts

Staff

ELBET W. (JOE) FRIDAY, JR., Executive Director
GREGORY H. SYMMES,* Acting Director
WILLIAM A. SPRIGG, Director
H. FRANK EDEN, Senior Program Officer
LOWELL SMITH,* Senior Program Officer
DAVID H. SLADE, Senior Program Officer
LAURIE S. GELLER, Staff Officer
PETER SCHULTZ, Staff Officer
ELLEN F. RICE, Reports Officer
DORIS BOUADJEMI,* Administrative Assistant
KELLY NORSINGLE, Senior Project Assistant
TENECIA A. BROWN, Senior Program Assistant
DIANE F. GUSTAFSON, Administrative Assistant
ANDREW E. EVANS,* Program Summer Intern

---

*Denotes past staff members who were active during the preparation of this report.

COMMISSION ON GEOSCIENCES, ENVIRONMENT, AND RESOURCES

GEORGE M. HORNBERGER (Chair), University of Virginia, Charlottesville
PATRICK R. ATKINS, Aluminum Company of America, Pittsburgh, Pennsylvania
JERRY F. FRANKLIN, University of Washington, Seattle
B. JOHN GARRICK, PLG, Inc., Newport Beach, California
THOMAS E. GRAEDEL, Yale University, New Haven, Connecticut
DEBRA KNOPMAN, Progressive Foundation, Washington, D.C.
KAI N. LEE, Williams College, Williamstown, Massachusetts
JUDITH E. MCDOWELL, Woods Hole Oceanographic Institution, Massachusetts
RICHARD A. MESERVE, Covington & Burling, Washington, D.C.
HUGH C. MORRIS, Canadian Global Change Program, Delta, British Columbia
RAYMOND A. PRICE, Queen's University at Kingston, Ontario
H. RONALD PULLIAM, University of Georgia, Athens, Georgia
THOMAS C. SCHELLING, University of Maryland, College Park
VICTORIA J. TSCHINKEL, Landers and Parsons, Tallahassee, Florida
E–AN ZEN, University of Maryland, College Park
MARY LOU ZOBACK, U.S. Geological Survey, Menlo Park, California

Staff

ROBERT M. HAMILTON, Executive Director
GREGORY H. SYMMES, Assistant Executive Director
JEANETTE A. SPOON, Administrative & Financial Officer
SANDI S. FITZPATRICK, Administrative Associate
MARQUITA S. SMITH, Administrative Assistant/Technology Analyst

Copyright © National Academy of Sciences. All rights reserved.

Preface

In late April 1997, the National Oceanic and Atmospheric Administration (NOAA) asked the National Research Council's (NRC's) Board on Atmospheric Sciences and Climate (BASC) to examine its meteorological data buoy program and the Coastal Marine Automated Network (C-MAN) for, primarily, their value in analyzing current weather conditions and in providing weather forecasts and warnings. As 1997 began, 33 of the 118 buoy/C-MAN stations managed by NOAA no longer had the funds required to remain in operation. NOAA asked the NRC to recommend a distribution of observing platforms that would maintain essential weather and forecast capabilities.

Professor Lance F. Bosart, from the Department of Earth and Atmospheric Sciences, State University of New York at Albany, and a member of BASC, is the principal investigator and author of this report. Dr. Bosart was assisted quite serendipitously by the scheduling of four meetings during the course of the study: the American Meteorological Society Colloquium on Coastal Environmental Information Services, May 29, 1997; the 1997 Gordon Research Conference on Coastal Ocean Circulation held June 15-17, 1997, at Colby-Sawyer College in New London, New Hampshire; the U.S. Weather Research Program (USWRP) Scientific Coordinating Committee workshop held in Washington, D.C. in September 1997; and the National Association of State Universities and Land Grant Colleges Action Committee discussion with the NOAA Undersecretary on Oceans and Atmosphere in Washington, D.C. on May 13, 1997. Discussions at these meetings provided opportunities to assess applications of the meteorological buoy/C-MAN system with representatives of commercial shipping, the insurance industry, the United States Navy and Coast Guard, the National Oceanic and Atmospheric Administration, and academic research groups. Many of the people who participated in these gatherings provided invaluable information for this study.

The BASC staff met several times with NOAA headquarters and National Weather Service personnel to assemble information. On November

5 and 6, 1997, a public workshop was held with the principal investigator and NRC staff. The workshop provided an opportunity for interested parties to submit comments or information relevant to the study and an opportunity for open discussion of issues. Many comments were received from coast to coast, and from various interests including scientists, private industry, fishermen, weather forecasters, and news reporters. It is hoped that this report will prove useful not only to NOAA, but also to other federal and state agencies with responsibilities in the coastal zone, as well as to those whose livelihoods depend on the safe and sustainable use of our coasts.

The counsel and written contributions on marine and coastal observations and forecasting of Professor Leonard J. Pietrafesa of North Carolina State University have proven to be invaluable for this study. The NOAA Offices of the Chief Scientist and the National Weather Service's Data Buoy Center, Office of Meteorology, and National Centers for Environmental Prediction were very helpful in providing essential data and information. Others deserving special thanks for their contribution are Robert A. Adriance, Jr. from BOAT/U.S., Dr. Peter G. Black from NOAA's Atlantic Oceanographic and Marine Laboratories Hurricane Research Division, Dr. Wendell A. Nuss from the Naval Postgraduate School, Dr. Franklin B. Schwing from NOAA Pacific Fisheries Environmental Groups, Dr. P. Ted Strub from Oregon State University, and Dr. Floyd Hauth of the NRC's Committee on the National Weather Service Modernization. There were many more who responded to our call for information and ideas, and many more who, upon hearing that this study was being conducted, wrote of their concerns and provided further useful information. A list of individuals who contributed by mail, telephone, fax, and e-mail is provided in Appendix A. Tenecia A. Brown, the study's research assistant and point of contact for many contributors, and Celeste A. Iovinella, the study's point of contact in Albany, New York, also are acknowledged for adeptly managing a flood of information while assembling data and preparing manuscripts.

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRCs Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Eric J. Barron, Pennsylvania State University
Robert C. Beardsley, Woods Hole Oceanographic Institution
Carl A. Friehe, University of California-Irvine
James R. Holton, University of Washington
George M. Hornberger, University of Virginia
Christopher N. K. Mooers, University of Miami
Wendell A. Nuss, Naval Postgraduate School
James J. O'Brien, Florida State University
John M. Wallace, University of Washington
James A. Westphal, California Institute of Technology
Robert M. White, University Corporation for Atmospheric Research

While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authors and the NRC.

WILLIAM A. SPRIGG
Study Director

Contents

APPENDIXES

Executive Summary

The meteorological buoy and Coastal Marine Automated Network (C-MAN) systems along U.S. coasts are designed to detect hazardous weather before it strikes the shore. Although the suite of observations from individual platforms may vary, these systems generally report information on air and water temperature, air pressure, and wind and wave conditions. Weather forecasters and researchers interested in coastal weather and ocean processes rely extensively on the data provided by the National Oceanic and Atmospheric Administration (NOAA) operated buoy/C-MAN network. Real-time observations from these stations are used by public and private weather forecasters to provide information on possible hazardous wind, sea-state, and water-level conditions to public safety officials, public and private marine interests, shipping companies, fishing and recreational interests, and the general public. These systems collect information under conditions of weather too severe for human observers, and thus provide vital information, not only for public warnings and forecasts but for research that will lead to better understanding of storm characteristics and improved forecasts.

This study responds to a request from the Administrator of NOAA to examine the meteorological buoy/C-MAN system for, primarily, its value in analyzing current weather conditions and in providing weather forecasts and warnings, and to recommend a distribution of observing platforms that would maintain essential weather forecast capabilities. Prompting this request was a shortfall in funding that places 33 of the 118 buoy/C-MAN stations in jeopardy. In further discussion with the Administrator and NOAA's chief scientist and staff, it was recognized that identification of specific platform placements would have to be done taking factors into account that were beyond the scope of this study, such as identification of populations most at risk to coastal weather-related hazards. The study nonetheless identifies such factors and defines a strategy, based on scientific principles, for ultimately determining these platform locations.

It is important to note that quantitative studies of the value of specific components of the surface (land and marine) observational network (including the buoy/C-MAN system) do not exist. There is no rigorous study that has evaluated the impact of forecast quality for a specific surface station. Ongoing studies in conjunction with the North American Observing Strategy (NAOS) are trying to evaluate this issue quantitatively, but no definitive results have yet been established. While some experimental results do demonstrate that marine observations have a positive impact on numerical initialized analyses and forecasts, the research necessary to prove their value remains to be done. Without more extensive numerical analyses, recommendations to expand the network of observing sites are admittedly, largely judgmental, but are based on many years of forecaster experience. Therefore, the recommendations that follow are based on the value of the buoy/C-MAN system to the preparation of storm watches and warnings, the demonstrated value to public safety and recreational and commercial uses, the needs of the research community, and the importance of surface observations to calibrate (or "ground truth") observations made remotely from space-based instruments.

PROPOSED CORE BUOY/C-MAN NETWORK

The rapidly increasing U.S. coastal population is particularly vulnerable to the disruptive effects of coastal flooding, storm surges, intense extratropical storms, and tropical cyclones (TCs); therefore, it depends on accurate and timely warnings of severe weather. Coastal weather forecasters at the National Weather Service (NWS) rely extensively on the data provided by the NOAA operated buoy/C-MAN network. Researchers also depend on the buoy/C-MAN network for data that will lead to better understanding of storm characteristics and improved forecasts.

This study recommends that a core buoy/C-MAN network be established and maintained.

Such a core network could be based on NOAA's 1995 Marine Observation (MAROB) plan. The MAROB plan is founded on the concept that the observational data density coverage from buoy/C-MAN locations has to be increased in recognition of the growing marine (coastal and offshore) responsibilities of the modernized and restructured NWS. The MAROB plan calls for the present number of observing platforms to be increased by approximately 200 stations (above the current base-funded total of 69 C-MAN and moored buoy stations) to provide adequate support for weather forecasting operations. In essence, the study herein agrees with that assessment. However, while the MAROB plan appears reasonable, the exact number and placement of observing platforms should be determined through more objective assessment and numerical analyses.

The fine tuning required to update the MAROB plan should consider the increased warning responsibilities of the NWS, the inextricable linkage between the operational and research communities, and the strategy outlined below. The proposed modifications to the core MAROB plan include:

- addition of moored buoys around Hawaii, the eastern Pacific, Gulf of California, Gulf of Mexico, the Atlantic coast, and the Caribbean with locations to be determined based upon operational and research requirements;
- increased use of adaptive data gathering strategies to allow deployment of additional drifting buoys in the central tropical Atlantic during the hurricane season and over the open ocean waters when the potential exists for severe extratropical cyclones (ETCs) to threaten coastal regions; and
- replacement of some C-MAN systems by moored and drifting buoys in areas where the C-MAN sites are situated near land-based coastal surface observation sites.

Implementation of this recommendation will require a long-term commitment from federal agencies to support the buoy/C-MAN network. Management and funding responsibility for the existing buoy/C-MAN network is spread across multiple federal agencies that often have different interests, funding commitments, and data requirements. Recent funding cuts that threaten the continued operation of 33 of the 118 existing buoy/C-MAN stations are an indication that the existing management approach is a barrier to the long-term stability of the system. Stability of operations requires that a single federal agency, NOAA, be given the responsibility and means to install, operate, and maintain the core, base-funded network. Firm agreements among collaborating agencies are needed, as is a continuing mechanism to oversee and review the implementation and operation of the system. A biennial report on the status of the network by a team of experts drawn from the NOAA operations community, other agency and private sector user groups, and the academic research community could serve as that continuous mechanism.

REVIEW OF COMPLEMENTARY OBSERVING SYSTEMS

A comprehensive plan for integrating disparate observational systems that are crucial to weather forecasting and climate monitoring does not exist. If the data obtained from the core buoy/C-MAN network are to be used most effectively in forecasting and research applications, they need to be integrated with data from land-based and remote-sensing observational platforms to create a comprehensive global data set.

> **This study recommends that a comprehensive review be conducted of all atmospheric and surface complementary observing systems, ranging from radars, lidars, satellites, aircraft, and balloons to drifting and moored buoys and the C-MAN system, and that this review lead into a study of how to design and implement a coupled atmospheric and oceanic observing system for weather and climate prediction using surface and space-based platforms.**

Both review and study are essential if the United States is to meet its international commitments in the weather and climate arena and provide its citizens with more timely and accurate warnings of hazardous weather, particularly in the increasingly populated coastal regions. Throughout this report there are many reminders that operational responsibilities and research are inextricably linked. Although this study concentrates on the weather and climate applications of the buoy/C-MAN network, there are many other applications for ocean, ecosystem, and environmental sciences.

PROPOSED BUOY/C-MAN DEPLOYMENT STRATEGY

The decision as to where and how fast changes should be made in the existing network is difficult and beyond the scope of this study. For example, although costs were considered in order to demonstrate that the network is realistically attainable, what the U.S. government can actually afford at this time is left to the agencies responsible for deployment of the system.

However, this report does outline a strategy for assessing costs and expected benefits. The analysis will further help identify priorities for platform and instrument installation and strengthen community support for the program. Such an analysis is part of a recommended strategy for guiding decisions on buoy/C-MAN placement. The strategy should consider the following points.

- It is necessary to identify those coastal areas most prone to storms and assess the magnitude of danger from them, including assessment of where populations are most dense and where those at risk are without the means of either protecting themselves or retreating from an advancing storm.

- It is important to consider which coastal regions are most prone to locally hazardous conditions, such as fog related and coastal upwelling.
- The strategy should consider the coastal population density and the magnitude of the seasonally varying coastal storm threat in any buoy/C-MAN deployment, repair, replacement, and abandonment decisions.
- It is necessary to consider the scale of storms, so that the network is not so thin as to miss important characteristics of storm intensity and direction of movement.
- The strategy should consider that new and important ways to apply buoy and C-MAN data will continue to emerge as more people learn that they can obtain and use the data.

An overall approach for making decisions about how, where, and when to implement the recommended buoy/C-MAN system should be based on the above five criteria, as well as the two technical recommendations discussed above.

Observations in and of themselves are of limited value unless they are coupled with an operational data assimilation system and forecast model. Consideration of observation priorities also must take into account the maintenance and upgrades of the forecast and warning system that uses the observations.

CHAPTER ONE

Introduction

The network of coastal marine (C-MAN) and offshore moored buoys provides a critical source of continuous meteorological and oceanographic data. Platforms and the suite of instruments they hold vary according to need. Typically wind, air and water temperature, air pressure, and waves are measured. In addition to support from the NWS, funding for the network is provided from several sources, including the Department of Interior (Western Pacific and Mineral Management Service), NASA, National Ocean Service, St. Lawrence Seaway Development Corporation, U.S. Coast Guard, U.S. Army Corps of Engineers, and the U.S. Navy. Real-time observations from these buoys are used by public and private weather forecasters to provide information on possible hazardous wind, sea-state, and water-level conditions to public safety officials, public and private marine interests, shipping companies, fishing and recreational interests, and the general public. For example, fishing interests make use of sea-surface temperature (SST) and wind and wave observations from these buoys for protection, safety, and to reduce the costs of recreational and commercial fishing expeditions. Real-time buoy observations are used frequently in search and rescue missions by the Coast Guard and by various agencies responsible for ameliorating the effects of marine accidents, such as toxic oil spills, which can threaten local and regional ecosystems. And research leading to improved forecasts and greater understanding of ocean/atmosphere effects on coastal currents and ecosystem structure, for example, often depend on the long time series of observations from these platforms.

The meteorological and oceanographic observations collected from the C-MAN and moored buoys also are used by scientists in a variety of basic and applied research (discussed more fully in Chapter 4). For example, wind, wave, SST, mean sea-level pressure, and air temperature observations can be used in case studies of important local and regional weather phenomena (Figure 1). Similarly, the buoy/C-MAN observations can be stratified on weekly, monthly, seasonal, annual, and interannual time scales to help document important local and regional climate features, including their intraseasonal and interannual variability. These analyses can be effective in isolating important climate signals associated with the El Niño-Southern Oscillation (ENSO) or other persistent flow anomalies and teleconnections, such as the North Atlantic Oscillation (NAO) and the Pacific-North American pattern.

It is important to appreciate the critical link that exists between operational and research communities, and how this linkage assures that buoy/ C-MAN observations are used to the fullest extent. In support of their marine warning and public safety responsibilities, weather forecasters are constantly monitoring the meteorological and oceanographic observations routinely transmitted from the buoys/C-MANs. As part of this regular monitoring process the forecasters gain a keen sense of understanding of the operational problems associated with coastal and marine meteorology. They also gain understanding of scientific issues and challenges that they face in their efforts to produce better forecast models. Knowledge of operational constraints in forecast procedures can be communicated to researchers at workshops and conferences or through individual local contacts. This communication can lead to more rapid and effective transfer of technology from

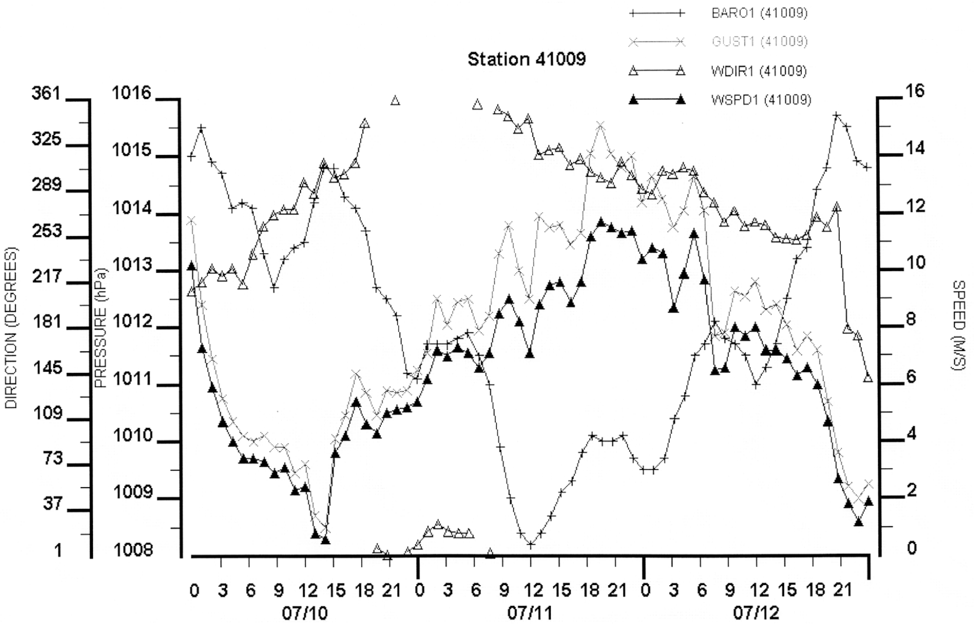

FIGURE 1 Time series of hourly meteorological observations at buoy 41001 (near Cape Hatteras, North Carolina, at 34.68 N and 72.64 W) for the period 0000 UTC 8-12 July 1996. This period corresponds to the time Hurricane Bertha passed to the south of the moored buoy location. Observations reported for sea-level pressure (hPa), wind direction (degrees), wind speed (m/s), and peak gusts (m/s). (Source: National Data Buoy Center Station Information Internet Site)

research to operations and to improved services. A few forecasters at individual NWS offices are also working with university scientists on operationally oriented research of local and regional interest (e.g., marine air surges along the west coast of the United States) through the Cooperative Meteorological Education and Training program sponsored by the NWS and the University Corporation for Atmospheric Research.

At the National Centers for Environmental Prediction (NCEP), the increasing use of coupled atmospheric and oceanic models in support of research and operational climate prediction on seasonal to interannual time scales requires the continuous monitoring of oceanic conditions (and the atmospheric conditions above the ocean) on a global basis. The buoy/C-MAN observations, as well as observations obtained from a growing use of drifting buoys, are crucial to the overall success of the NCEP mission. Likewise, this ocean-based monitoring capability is crucial if scientists are to observe and document trends in SST, sea-level pressure, wind, and temperature regimes. The quality of these analyses will determine how well we understand the relationships between the variability of these quantities and that of large-scale intraseasonal and interannual climate.

Persistent and highly anomalous weather regimes are frequently associated with extended periods of temperature or precipitation extremes that impose enormous stress on humankind. Both the research and operational communities have vested interests in learning more about the causes of weather and climate variability. They understand that complex weather and climate issues must be addressed from a global perspective, and that knowledge gained will lead to improvements in public safety. Both communities have grown to depend routinely on the regular and timely collection of meteorological and oceanographic observations from an array of marine locations. In this context, research and operations are inextricably linked. And this linkage can only grow stronger thanks to ongoing activities at universities, in private industry, at various NWS offices, and at federal research laboratories and entities such as NCEP.

This study originates from a request by the Undersecretary of Commerce for Oceans and Atmosphere to recommend a distribution of observing platforms that would maintain essential weather forecast capabilities. Prompting this request was a shortfall in funding that makes it improbable that 33 of the 118 buoy/C-MAN stations can continue under NOAA operations. In further discussion with the undersecretary and NOAA's chief scientist and staff, it was recognized that identification of specific platform placements would have to be done taking factors into account that were beyond the scope of this study, such as identification of populations most at risk to coastal weather and related hazards. The study nonetheless identifies such factors and defines a strategy, based on scientific principles, for ultimately determining these platform locations. Both appear in Chapter 5 along with a possible distribution of buoy/C-MAN stations. One point is worth highlighting. The first question likely to be asked when beginning a study of this nature is, "What do numerical experiments tell us about the impact on the weather forecast of removing a number of surface observations?" In the course of this study, no successful assessment of specific components of a surface observational network could be found. There appears to be no firm evidence that can point to either a positive or a negative impact for a specific surface station on forecast accuracy. One recent study (Huo et al., 1998) shows that surface marine observations have a positive effect on numerical model initialized analyses and the resulting forecasts. There is hard evidence on the spatial scale of storms, which helps define the ideal spacing of observing sites. However, the recommendations of this report are somewhat judgemental, but are based on long years of experience by many professional weather forecasters, those who insure against property loss, and Coast Guard staff, who search for and rescue those whose lives may be in jeopardy offshore. The NWS, in ongoing studies related to the NAOS, is evaluating this issue with respect to the nation's radiosonde network. But quantitative, definitive results are not yet available. The need to reduce this ambiguity is among the major justifications for a review of all complementary observing systems (see Recommendation #2 in Chapter 5).

THE NETWORK INFRASTRUCTURE

The National Data Buoy Center (NDBC) began operations in the late 1960s when buoy development and operation was conducted by the U.S. Coast Guard (USCG). NOAA took over the operation of NDBC in 1970, at which time the program was relocated to the Stennis Space Center in Mississippi. NDBC is staffed by NOAA, the Coast Guard, and contract employees. In fiscal year (FY) 1997 the NDBC budget was approximately $12 million. Additional funds were garnered from other federal and state agencies in support of non base-funded buoys and C-MANs. Given the remoteness and wide geographical locations of NDBC buoys, the timely deployment and maintenance of these stations require careful planning and execution to minimize critical data loss that must be balanced against very real constraints related to budgets, weather, and resource availability.

NDBC's fleet of moored buoys includes six types: 3-meter, 10-meter, and 12-meter discus hulls, 6-meter boat-shaped (NOMAD) hulls, and the newest, the Coastal Buoy, and the Coastal Oceanographic Line-of-Sight (COLOS) buoy (Figure 2). Hull types depend upon buoy location,

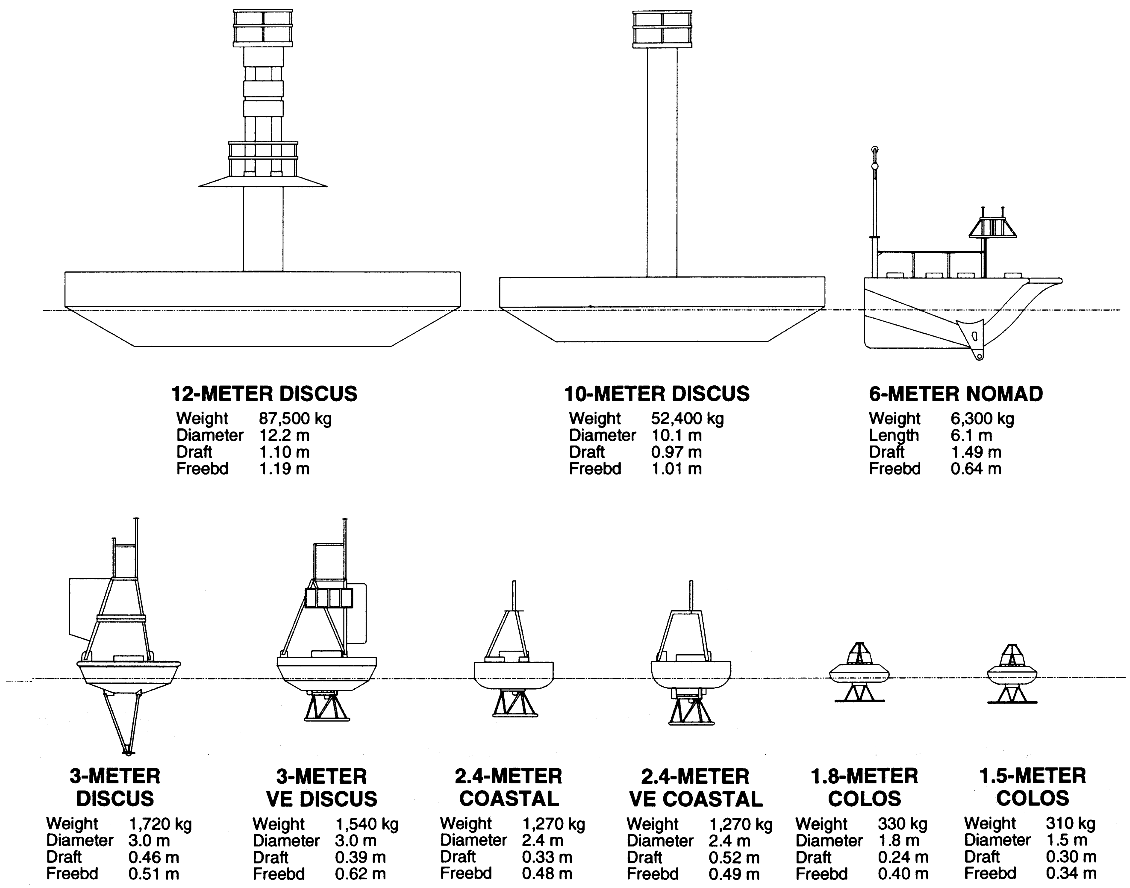

FIGURE 2 Schematic drawings of the six standard moored buoy hull types used by NOAA-NDBC including 3-meter, 10-meter, and 12-meter discus hulls, a 6-meter boat-shaped (NOMAD) hull, and the newer design 2.4-meter coastal buoy and 1.5-meter Coastal Oceanographic Line-of-Sight (COLUS) buoy. (Source: National Data Buoy Center)

sustainability, and intended measurement purposes. For example, moored deep-ocean buoys usually require large discus hulls and sophisticated anchoring systems.

Typically, buoy and C-MAN systems include observation of water temperature, wind and wave characteristics, and air pressure. Buoy platforms offer many opportunities to measure atmosphere and ocean characteristics, including, for example, sampling of atmospheric aerosols (Sholkovitz et al., 1998). Other sensors may prove useful on these platforms, including those capable of measuring solar radiation, fluxes of material across the air-sea interface, and upward looking sounders for inversion height, cloud droplets, and profiles of wind and temperature. Recent advances in sensor, buoy, and communications technologies will lead to lower costs and improve measurements capabilites. NDBC is evaluating acoustic anemometers that will be less prone to mechanical failure than the present propeller anenometers, and therefore reduce life-cycle costs. Nevertheless, these sensors will extend the upper limit of operational wind-speed measurements. Prototype directional wave measurement systems based on simpler sensors and advanced digital signal processing have the potential to greatly reduce sensor costs. New ionomer foam 3-meter buoys are being introduced to increase reserve buoyancy and reduce vulnerability to vandalism. Compared to existing metal hulls, repair and refurbishment costs of the foam hulls will be lower. Higher transmission rates through the Geostationary Observational Environment Satellite (GOES) system will lead to faster data dissemination and increase the amount of data transmitted. If additional capability is desired, low earth orbit satellites can be used, though at increased costs. Regardless of the satellite, the buoys will transmit event-driven "special" observations to alert forecasters of rapidly changing conditions; this will significantly benefit the NWS marine warning and advisory mission. Finally, mariners will be able to hear the latest observations over the telephone because of computer voice generation technology tied into the Internet.

Data obtained from moored buoys, subsequent to automated processing on site, are routinely transmitted to a NOAA GOES. From there the data are distributed widely to public and private user groups in addition to the NWS. Moored buoy data are further quality checked at NDBC and then sent to the National Climatic Data Center (NCDC) and the National Oceanographic Data Center (NODC) for archiving purposes where they are made available to the research and operational communities. C-MAN data are processed similarly by NDBC and made available through NCDC and NODC. Drifting buoy data collected by NDBC are transmitted to Polar Orbiting Environmental Satellites (POES) and then relayed to ground stations. Data transmission from drifting buoys to POES and from POES to ground stations is restricted to when the satellites are within line of sight of the buoys.

NDBC estimates buoy costs in 10-buoy sets to take advantage of the economies of scale. NDBC cost estimates further assume a fully funded existing infrastructure. The numbers that follow represent a range of costs (FY98 dollars) with the lower numbers representative of nearshore or coastal stations and the higher numbers for deep-water moored buoys (in lots of 10):

- manufacture: $1,185,000 to $2,615,000
- deployment: $240,000 (the difference is not significant for the different buoy types)
- maintenance: $474,000 to $547,000 per year; and
- operation: $81,000 per year (the difference is not significant for different buoy types).

CHAPTER TWO

NOAA's Present and Proposed Coastal Ocean Buoy and C-MAN Network

We know satellites can provide SST and estimates of surface wind, sea state, and sea level where near- or on-shore features do not interfere, and radars, ship-based systems, aircraft, and other serendipitous sources of environmental observations are sometimes available, weather forecasters nonetheless rely heavily on the existing NOAA buoy/C-MAN network. The weather forecasters of the NWS hope to improve real-time observations through an expansion and redesign of that network. This chapter describes the present network and the network proposed by NOAA.

PRESENT COASTAL OCEAN BUOY AND C-MAN NETWORK

The main purpose of the NOAA buoy/C-MAN network is to provide reliable, accurate, and cost-effective atmospheric and oceanic observations in support of weather forecasting, especially including the issuance of marine warnings to the general public as well as all public and private coastal interests. This network also supports international agreements on climate monitoring. NDBC oversees buoy development, deployment, and management. Beginning in the mid 1970s the first NOMAD-type buoys were deployed in the Atlantic Ocean and the Gulf of Mexico, and by 1979 a network of 26 moored-buoy stations was in existence (the C-MAN program began in 1983). Over the next decade additional moored buoys continued to be deployed by NDBC such that by 1990 the operational network of moored buoys totaled 75 stations. By 1996, this network number had declined to 69 moored buoys owing to funding problems within NOAA and other agencies that had provided earlier support for the deployment of additional buoys and C-MAN stations.

The existing distribution of approximately 1,000 land-based automated surface-observing stations supported by the NWS, the Federal Aviation Administration, and the military is shown in Figure 3. On average, over the conterminous United States there is a surface weather reporting station roughly every 50–100 km. The known spatial scale of storms suggests that,

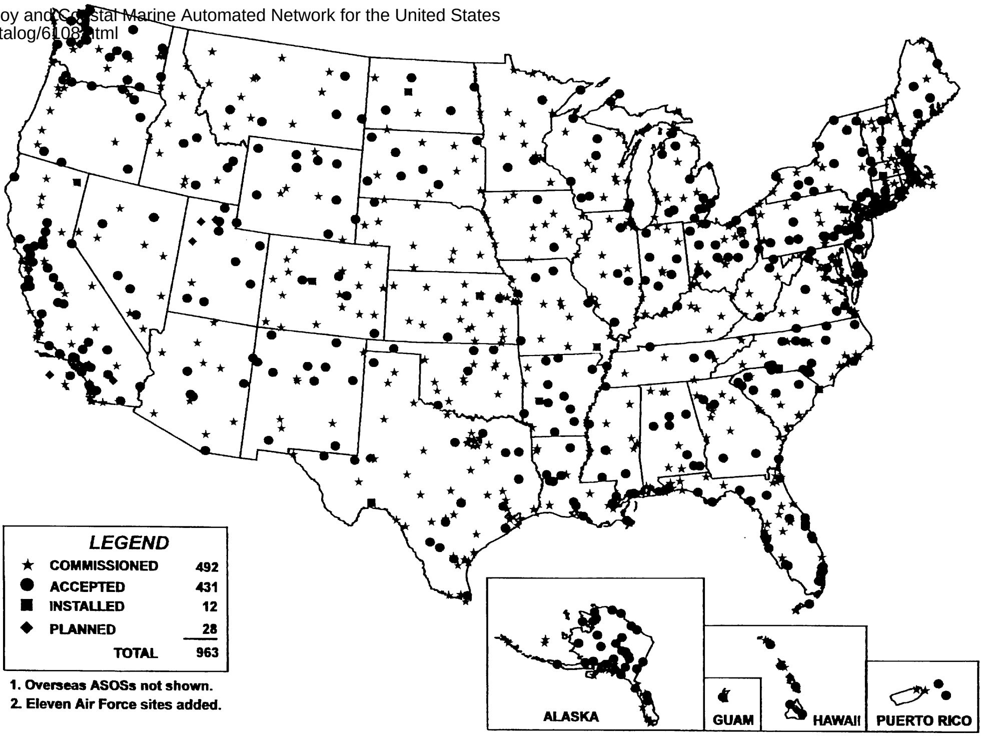

FIGURE 3 Distribution of the approximately 1,000 Tri-Agency (National Oceanic and Atmospheric Administration [NOAA], National Weather Service [NWS], Federal Aviation Administration [FAA], and military) Automated Surface Observing Stations (ASOS) for the conterminous United States as of 30 September 1997 including commissioned, accepted, installed, and planned ASOS stations. (Courtesy of Wendell Nuss, Department of Meteorology, Naval Postgraduate School)

in order to ensure capturing a storm's intensity and other important characteristics, observations should be made approximately every 30–50 km. While this is realistically unattainable with in situ sensors, particularly over water, it is nonetheless a standard against which surface-based observation networks should be compared. The greatest density of observations is clustered around major metropolitan areas and in coastal regions. The NWS receives data from approximately 11,000 cooperative observer (coop) stations. Figure 4 shows the locations of 7,294 of the nearly 11,000 COOP stations for which data are published by NOAA (T. Ross, personal communication, 1998). They provide information on daily precipitation and temperatures, and on the approximately 1,000 (and steadily increasing) automated mesonet stations (not shown) that report weather conditions every 5 minutes on the scale of counties (e.g., the Oklahoma mesonet).

In contrast, the current NOAA core-funded buoy/C-MAN network is mapped in Figure 5. While station density is considerably less in the coastal waters as is readily apparent from a comparison of Figures 3 and 5, the cost of attempting to make the in situ network over water as dense as that over land is prohibitive. The existing national buoy/C-MAN network is displayed in Figure 6. In contrast to Figure 5, Figure 6 includes both the NOAA core-funded stations Figure 5 and the stations that, until recently, were funded by other federal and state agencies and private sector interests. The latter group are referred to as "unfunded" in Figure 6. Because the recently unfunded stations make up approximately one-third of the total existing network, present funding levels for the core NOAA program cannot be expected to maintain the buoy/C-MAN network in anywhere near its present configuration. In recognition of the importance of maintaining an enhanced high-caliber buoy/C-MAN network consistent with the ongoing NWS modernization and restructuring and the increased NWS responsibilities for coastal marine warnings and public safety issues, NOAA's Office of Meteorology prepared a MAROB network initiative in 1994.

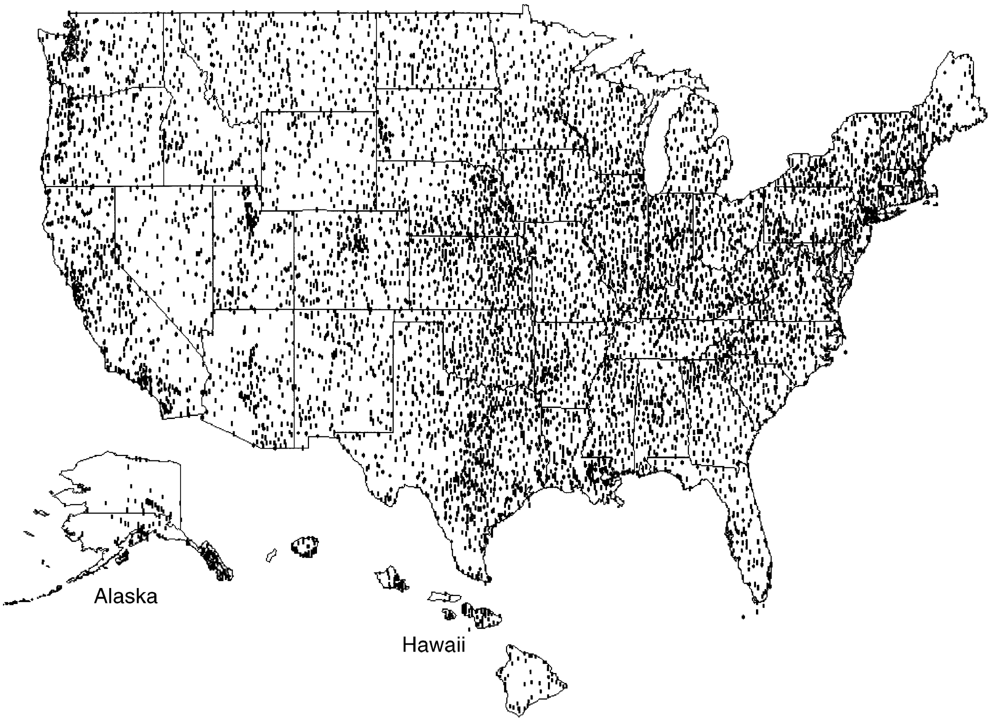

FIGURE 4 Distribution of approximately 7,300 of the nearly 11,000 National Weather Service (NWS) cooperative weather and climate stations that record daily maximum and minimum temperature and 24-hour precipitation amount (map current as of 30 June 1997). (Source: National Climate Data Center)

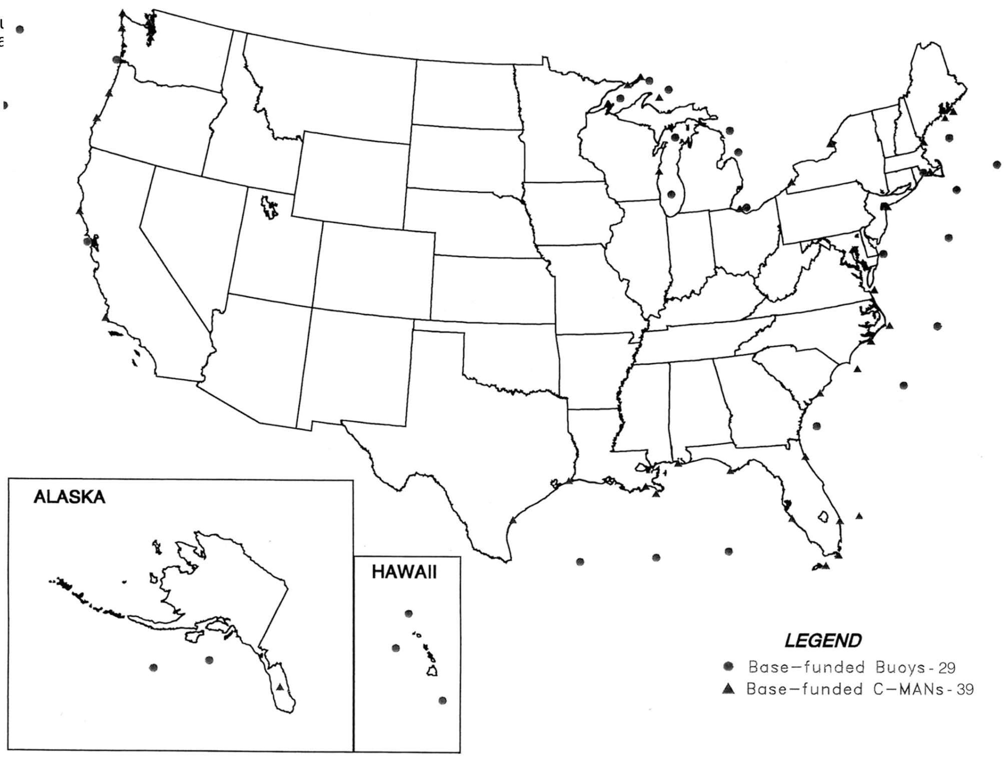

FIGURE 5 Current distribution of NOAA base-funded moored buoys and Coastal-Marine Automated Network (C-MAN) stations across the conterminous United States. (Source: U.S. Department of Commerce, National Oceanic and Atmospheric Administration-Marine Weather Services)

NOAA PROPOSAL FOR AN IMPROVED MARINE OBSERVATION (MAROB) NETWORK

The NWS modernization and restructuring (NRC,1991; Department of Commerce,1997) has increased the number of field offices responsible for coastal and offshore weather services. These NWS field offices are responsible for issuing weather watches and warnings for hazardous (severe) weather to the general public and coastal marine interests. An important component of the modernized NWS coastal warning system is the network of recently deployed Doppler radars (WSR-88D) shown in Figure 7. These radars provide information on three-dimensional storm structure and movement. However, they cannot observe the offshore wind structure in the lowest part of the atmosphere below 1–2 km near the coast, and below 2–4 km more than 100 km offshore due to the effect of the Earth's curvature and the spreading of the radar beam with distance from the radar location. Because of these natural geometric effects, Doppler radars cannot observe

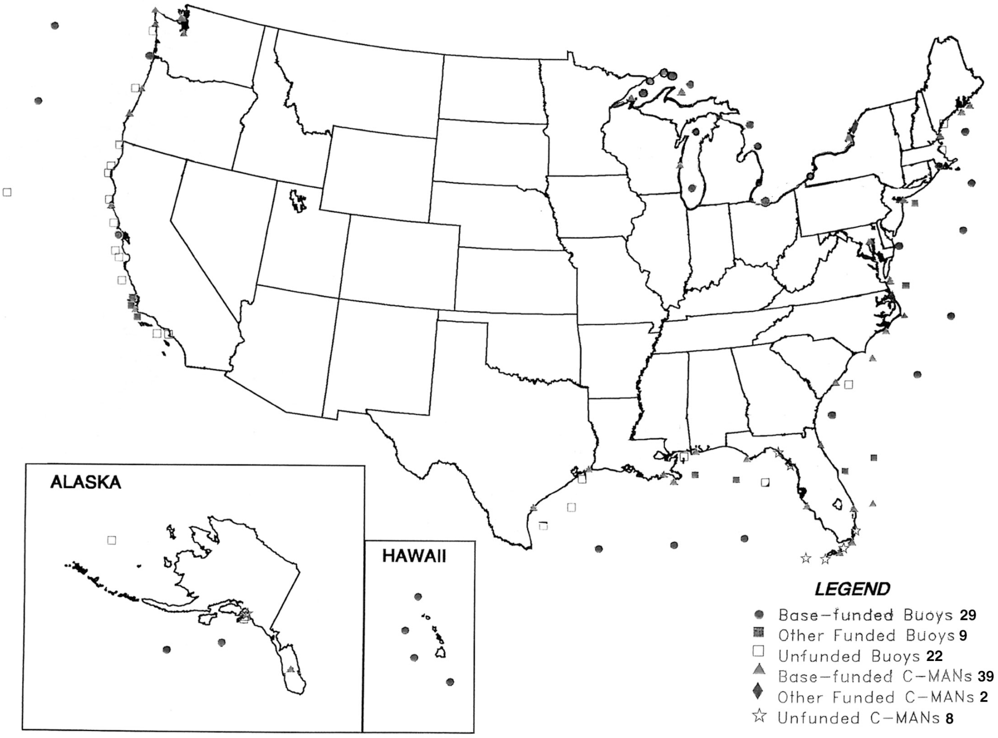

FIGURE 6 Distribution of existing NOAA base-funded moored buoys and C-MAN stations shown in Fig. 5 plus the additional NOAA unfunded stations that together make up the current moored buoy and C-MAN station network. (Source: U.S. Department of Commerce, National Oceanic and Atmospheric Administration-Marine Weather Services)

ocean surface winds and waves of crucial interest to operational forecasters responsible for preparation and issuance of coastal marine watches and warnings. Although it is possible to develop indirect (statistical) techniques to estimate surface winds based upon Doppler wind observations several kilometers above the ground, these statistical techniques depend upon the availability of surface observations within the radar surveillance area for development, validation, and refinement. However, the NOAA core, base-funded buoy/C-MAN station network shown in Figure 5 and the current existing station network mapped in Figure 6 are unable to provide the critical offshore weather observations needed by NWS forecasters to meet their required coastal marine warning responsibilities. Shore-based over-the-horizon radar measurement systems are being explored for use in determining wind, wave, and ocean currents (Georges and Thome, 1990; Georges et al., 1993). The few systems available are relatively costly, but they can extend the range of observation to thousands of kilometers offshore by

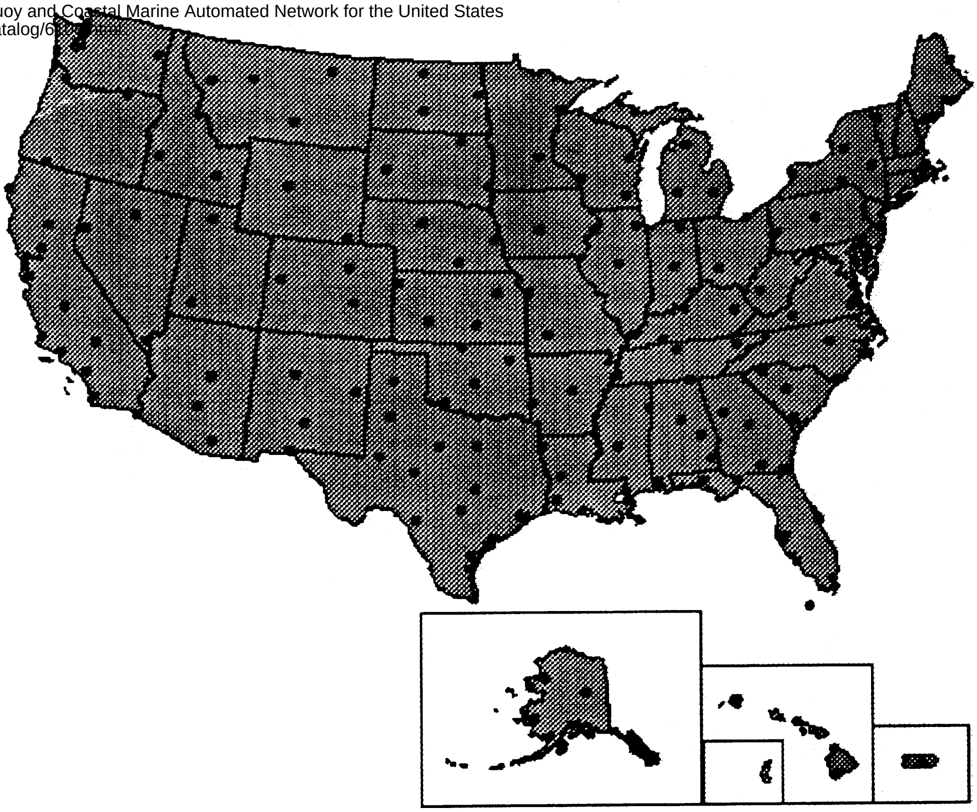

FIGURE 7 Operational WSR-88D Doppler radar network (NWS and military) for the conterminous United States. (Source: U.S. Department of Commerce, National Oceanic and Atmospheric Administration)

bouncing radio waves off the ionosphere. Where available, they may be able to add to the arrangement of the observing platforms.

As is readily evident from Figures 5 and 6, the existing buoy/C-MAN station network is relatively coarse. Although the existing operational network is adequate for describing weather and sea conditions on relatively large scales, it is highly inadequate for observations on smaller space and time scales (mesoscale). Important mesoscale wind and rain-bearing weather systems on spatial scales of less than 200 km and with time scales of less than 2–4 hours may develop rapidly in coastal waters and move onshore. The difficulty of monitoring offshore mesoscale weather systems is exacerbated by the relative coarseness of the present buoy/C-MAN network. Significant small-scale weather variations can be expected in coastal waters. Weather disturbances interact with coastal topography and the associated heating and cooling contrasts between land and ocean that change with the time of day and the time of year. Important mesoscale weather variations also can occur because of smaller scale differences in SST, water depth, current structure, and the configuration of the coastline. Although it is possible to infer some information on the structure of mesoscale weather systems from satellite imagery, this information tends to be qualitative. Likewise, in many cases of hazardous weather, thick high clouds often obscure near-surface wind and sea-state signatures.

These observed mesoscale weather variations, so important to operational forecasters charged with coastal marine warning responsibilities, are inherent features of coastal storm systems. The important issue for public safety is that these features may be unresolved by the sparse existing (unfunded) network Figure 6. This point is reinforced in Figure 8, which shows the distribution of multiple agency (federal and state) weather and climate stations in central California along with the locations of NOAA moored buoys. Although the data density gradient across the central California coastline shown in Figure 8 is very large, NWS forecasters have the

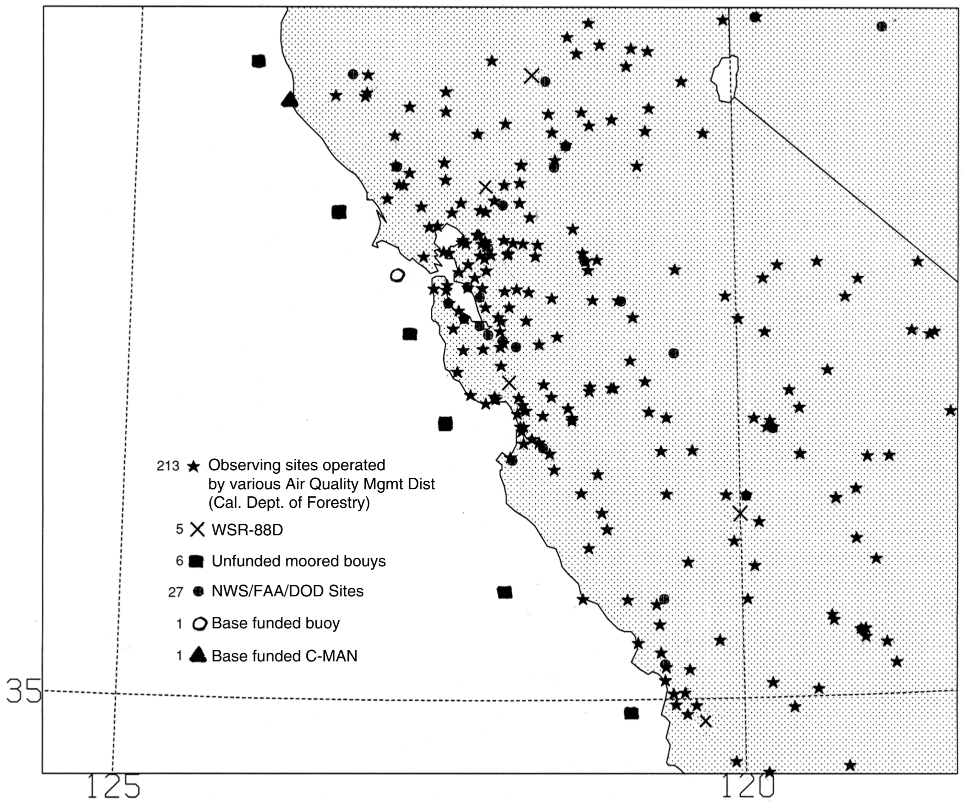

FIGURE 8 Distribution of multiple agency (federal and state) weather and climate stations in central California along with the locations of NOAA moored buoys and C-MAN stations over the adjacent Pacific Ocean. (Courtesy of Wendell Nuss, Department of Meteorology, Naval Postgraduate School)

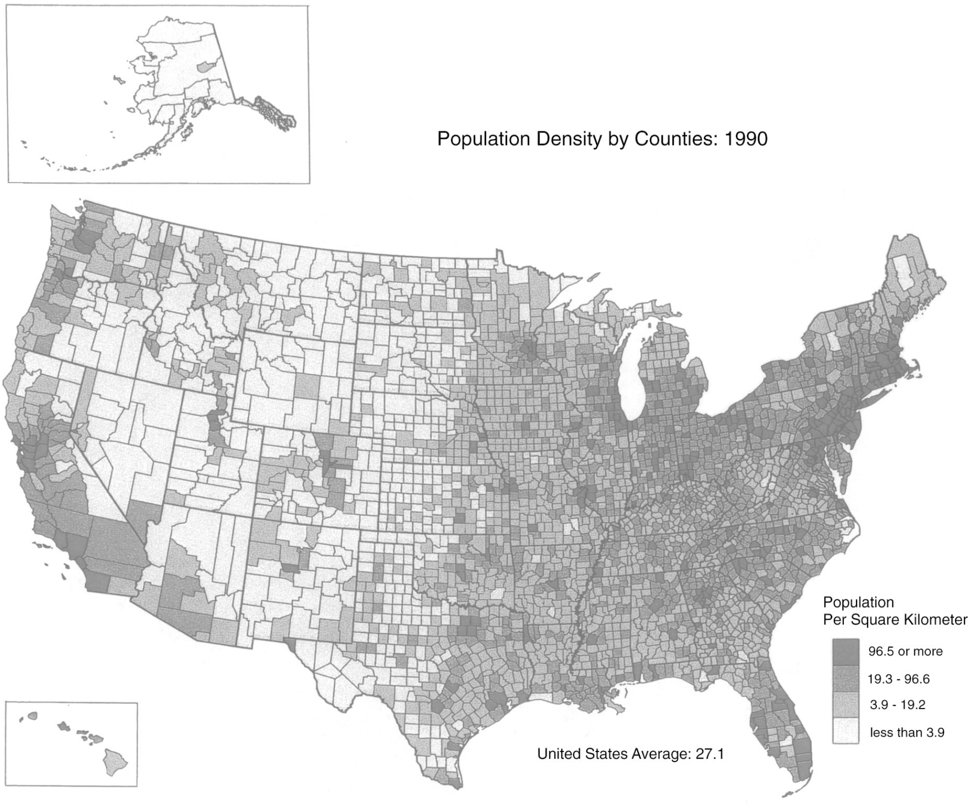

FIGURE 9 Conterminous U.S. population density expressed as population per square kilometer by county as of 1990. (Source: U.S. Department of Commerce, Economics and Statistics Administration - Bureau of Census)

same responsibilities for issuing watches and warnings for hazardous weather both offshore and onshore. The need for coastal observations is reinforced by examination of the conterminous U.S. population density shown in Figure 9. This map reveals that the majority of the most densely populated counties are located near the Pacific and Atlantic coasts, the Gulf of Mexico, and the Great Lakes. Based on statistics from the 1990 census it is estimated that more than 50 percent of all Americans live within 100 km of a coastline.

The skewness of the observed population toward coastal regions and the need to provide timely and comprehensive coastal marine warnings for this population is the principal motivating force behind the NOAA MAROB initiative. The purpose of the MAROB network is to improve marine environmental monitoring and prediction by increasing the availability of automated marine observations along the Atlantic and Pacific coasts, the Gulf of Mexico, the Great Lakes, Alaska, near Hawaii, and near Puerto Rico and the U.S. Virgin Islands.

MAROB OBJECTIVES

NOAA has established the following core objectives for MAROB:

- *Environmental Monitoring*—integrate with Doppler radar and satellite technology to improve detection and tracking of hazardous weather conditions over-water ranging from localized severe weather to major oceanic storms to hurricanes in order to provide more timely and precise warnings of these events;
- *Modeling and Numerical Forecast Guidance*—to provide a denser network of surface observations for improving forecast models of storm development and prediction of winds, waves, and storm surges;
- *Warning and Forecast Verification*—to provide an objective measure of the accuracy of operational warnings and forecasts and numerical forecast guidance as a means of assessing performance and identifying areas needing improvements;
- *Climatology*—to improve knowledge of long-term, over-water weather patterns and their local and regional variability and to establish baseline trends for climate studies;
- *New Technology*—to provide critical sea-truth data required for the development and validation of existing and planned new remote-sensing technology for winds, waves, and sea surface temperatures;
- *Support Other NOAA Programs*—to provide measurements of sea-level and shoreline change, in support of hazardous chemical spill responses, basic research in ocean dynamics and air-sea interaction, the NOAA Coastal Ocean Program, the Global Ocean Observing System, the Climate Change Program, and the modernization of NOAA's infrastructure support of all ocean programs (Marine 2000);
- *Other Agency and Private Sector Applications*—to provide data to other federal agencies involved in ocean-related programs and to the private sector for improved value-added information and products for client users; and
- *Ocean Sentinels*—to enable the NWS to disseminate critical observations and weather updates on present and expected weather and ocean conditions that, together with forecasts and warnings, will allow a wide spectrum of users to make more informed operational decisions for safeguarding life and property.

The MAROB network as proposed by NOAA is illustrated in a series of maps for the conterminous United States (Figure 10), Alaska (Figure 11), Hawaii (Figure 12), and the Caribbean and tropical western Atlantic Ocean (Figure 13). The MAROB plan adds just under 200 moored buoys and C-MAN stations to the network (above the current base-funded total of 69 C-MAN and moored buoy stations)

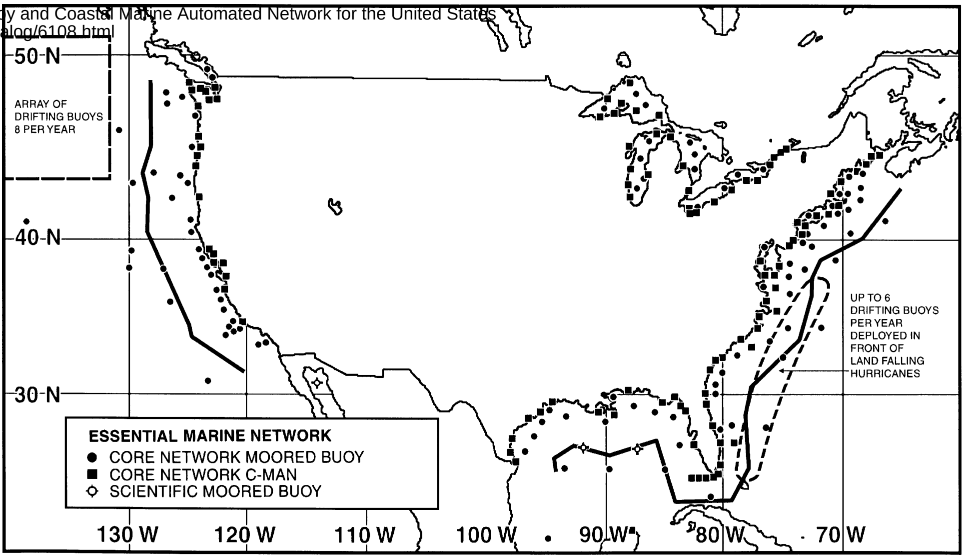

FIGURE 10 Marine Observation (MAROB) network as originally proposed by NOAA in the MAROB plan and as further modified in this report for the waters surrounding the conterminous United States. (Courtesy of Douglas R. Scally, National Data Buoy Center)

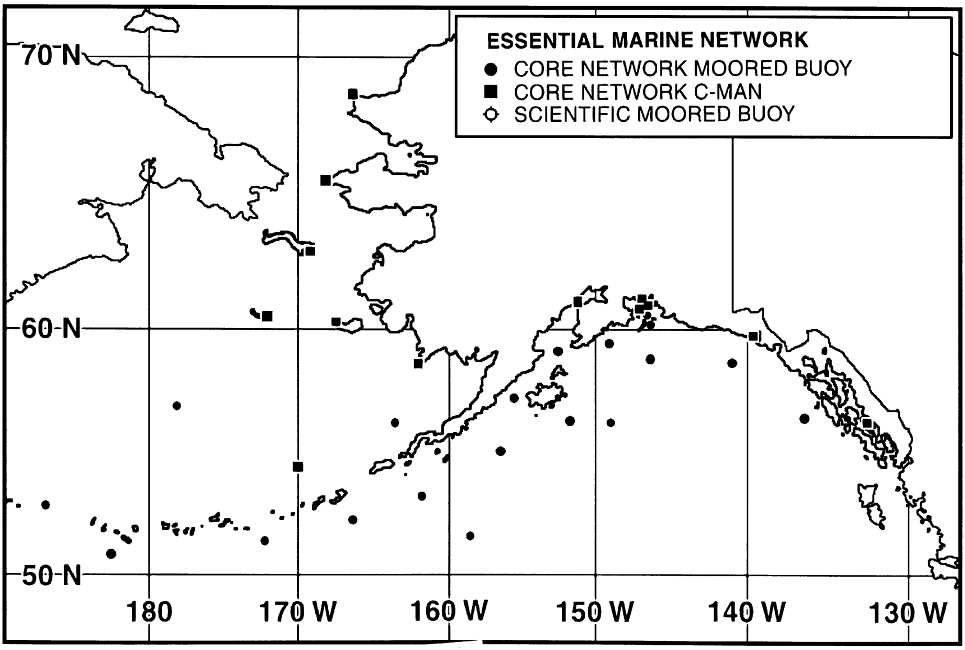

FIGURE 11 As in Fig. 10 except for the waters in the Alaska region. (Courtesy of Douglas R. Scally, National Data Buoy Center)

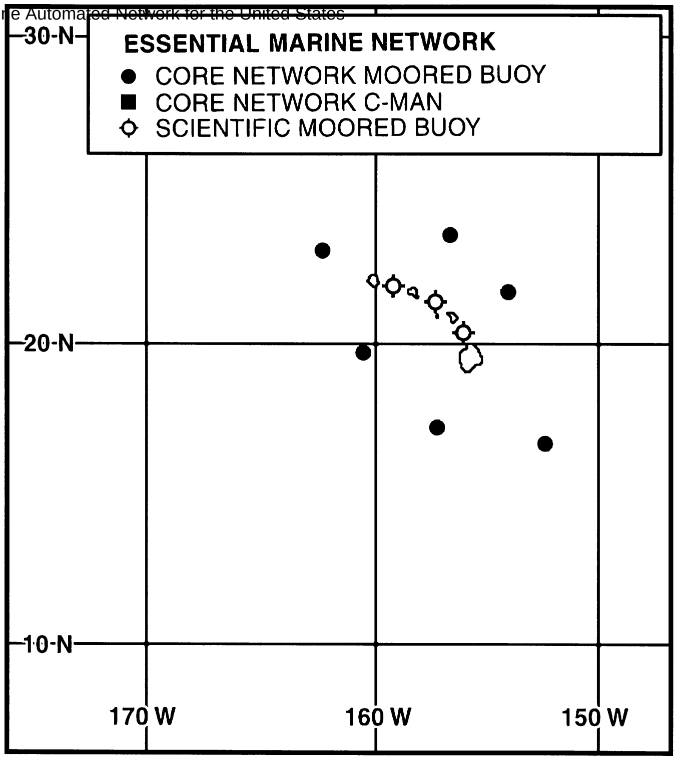

FIGURE 12 As in Fig. 10 except for the waters in the Hawaii region. (Courtesy of Douglas R. Scally, National Data Buoy Center)

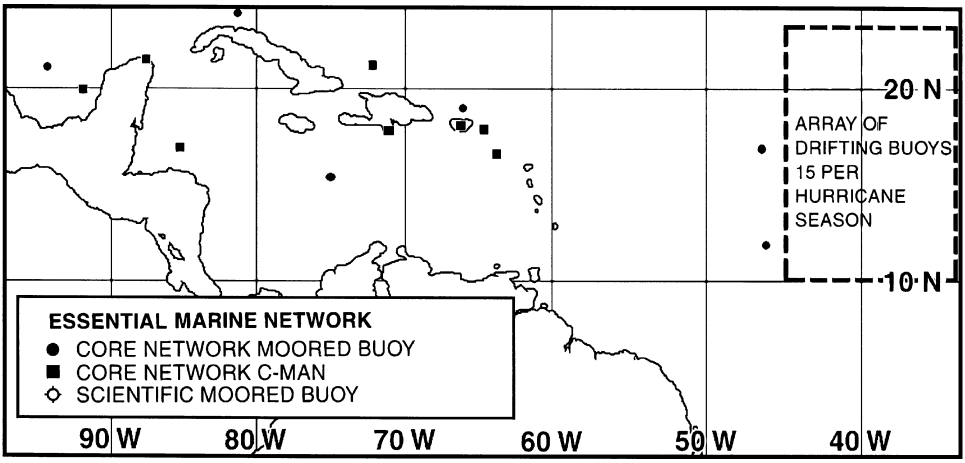

FIGURE 13 As in Fig. 10 except for the waters of the Caribbean and the western tropical Atlantic Ocean. (Courtesy of Douglas R. Scally, National Data Buoy Center)

A comparison of Figures 6 and 10 shows that the proposed MAROB network represents a significant upgrade in station density relative to the existing buoy/C-MAN network. The proposed station configuration is consistent with the large coastal population density illustrated in Figure 9. Note, however, that the proposed MAROB network still would leave significant discontinuities in station density between water and land areas (see also Figure 8). Although the warning responsibilities of NWS forecasters remain unchanged across the coastlines, there are fewer data available offshore to meet warning responsibilities in an admittedly more hazardous region.

Rough calculations show that approximately $40-$50 million may be needed to manufacture the 200 new observing platforms called for under the MAROB plan. Another $4.8 million would be needed to deploy them. To maintain and operate the new platforms would require perhaps another $1.2 million each year. In addition to fixed costs, there are further costs associated with applied, technical, and engineering development. NDBC estimates that these developmental costs can range from $500,000 to $750,000 per year for the entire buoy/C-MAN network. As noted by the NDBC, developmental costs must be considered within the context of the entire network. The higher cost number of $750,000 per year is the NDBC estimate of annual development costs associated with the proposed MAROB program.

CHAPTER THREE

Applications of Buoy/C-MAN Data Network

MARINE FORECAST PROBLEMS

The transition from a marine to a continental environment across a coastline involves changes in the air-flow pattern induced by terrain and land use characteristics and differences in temperature and atmospheric stability (NRC, 1992). The C-MAN stations help forecasters monitor unique localized conditions known to occur near coastal promontories and extending 5–10 km offshore. As discussed by Rotunno and Pietrafesa (1996), major coastline irregularities such as capes, inlets, and coastal mountains will have localized winds that can differ significantly from the general wind flow well offshore. Depending upon the prevailing wind direction, these irregularities block and deflect the flow, causing highly local circulations and channeling of the flow that can result in highly erratic local wind regimes. These erratic winds at times can act on the local sea surface to produce hazardous wave conditions that can differ significantly from the surrounding sea (Bond et al., 1997). C-MAN reporting stations also provide the first indication of the severe effects of ocean storms and hurricanes as they approach the coast based on changes in the reported wind direction and speed, temperature, and sea-level pressure. Forecasters must have knowledge of these often rapidly changing coastal weather conditions in order to provide timely and accurate warnings of high winds, storm surges, and coastal flooding associated with tropical and extratropical storms (Meadows et al., 1997; Xie et al., 1997). The winter of 1997-98 has provided ample evidence of the effect of coastal storms on island erosion and flooding and on massive beach erosion.

Coastal harbors and inlets can experience severe localized wind and wave conditions at considerable variance from reported conditions over the open ocean or inland. Contributing factors to these differences include the steepness of the coastal terrain, the shape and orientation of the coastline, sea floor topography, and underwater features such as sandbars, which can trigger eddy circulations (Bond et al., 1997; Winant and Dorman, 1997).

C-MAN buoys provide essential measurements of winds and waves within the areas of NWS marine forecast responsibility. Given that nearshore ocean currents, underwater topography, cross-shore thermal gradients, and coastline irregularity can combine to produce winds and waves that can vary on scales of tens of kilometers, forecasters must be continually alert to rapidly changing weather conditions in the coastal environment (NRC, 1992). For example, mariners often report wind speeds and wave heights that are twice those being forecast or that vary substantially over a few kilometers, even well offshore. The planned NOAA MAROB network (Figures 10 through 13) is designed to address some of these problems and to provide the forecaster a more effective and reliable coastal database on which to base the issuance of timely and accurate marine warnings. Small-scale wind and wave patterns and the timing of the onset of wind and wave conditions that reach advisory and warning thresholds are of critical importance to mariners and coastal residents. In cases of hazardous spills along the coastline, it is especially urgent that buoy/C-MAN observations be available with sufficient horizontal resolution to permit the numerical simulation of oceanic currents and surface water trajectories as guidance for spill response and clean-up teams.

Weather systems that affect western North America most often originate over the data-sparse Pacific Ocean. Buoys moored more than 250 km offshore can provide valuable early warning information on atmospheric and oceanic conditions associated with storms headed toward the coast. A combination of coastal Doppler radar precipitation, wind, and wave information; C-MAN observations near shore; moored buoy observations located well offshore; and satellite imagery provide information for NWS forecasters to improve warning lead times associated with major storms approaching the coast. Moored buoys also furnish data on large ocean swells that can originate from western Pacific typhoons or from intense extra tropical cyclones (ETCs) near Antarctica. Large ocean swells from distant storms can be especially troublesome when they mix with local wind-generated waves at the time of high tide and elevated coastal Ekman water levels to produce dangerous coastal surf conditions (Davis and Dolan, 1992). These hazardous wave conditions can result in treacherous coastal navigation conditions as well as cause coastal flooding and shoreline erosion. Hawaii is particularly at risk from dangerous wave conditions associated with distant Pacific storms. Alaska can also be subject to sea ice riding atop the elevated water levels and high waves.

During the early (late May through mid-July) and late (late September through November) parts of the Atlantic hurricane season, tropical storms frequently originate over the southwestern Gulf of Mexico (Bay of Campeche) and the western Caribbean Sea. Although this region is mostly devoid of moored buoys, a critical need exists to monitor atmospheric conditions in these regions on a regular basis. During the middle of the hurricane season (mid-July to mid-September) tropical storms are more likely to originate from African disturbances embedded in the trade wind easterlies (10–20°N) that reach the eastern Atlantic Ocean. Drifting buoys have been used effectively to provide pressure and wind information in the trade wind easterlies (10–20°N) across the eastern Atlantic Ocean in these critical tropical storm-spawning latitudes. A coastal observation program would be shortsighted without an adaptive observation provision to deploy more drifting buoys to monitor environmental conditions in the various tropical storm regions of the Atlantic Ocean and Gulf of Mexico and to increase the number of moored buoys in the Caribbean and Gulf of Mexico. In addition to enhancing warnings for the United States, Puerto Rico, and the Virgin Islands, the buoy data (moored and drifters) would help to support hurricane warnings for the Caribbean and Central American countries as well as Mexico in fulfillment of the international responsibilities of NOAA's Tropical Prediction Center (TPC) in this area.

The buoys also contribute to a greater understanding of air-sea interaction processes under a wide variety of weather conditions, including tropical and extratropical storms and major oceanic convective outbreaks. These data can be used in the development of finer-scale regional models that can predict wind, wave, sea, and ocean thermal conditions unique to a particular coastal region. Ocean model forecast skill is dependent upon the availability of observations on sufficiently fine enough scales to reveal the complex interactions between wind-generated waves and ocean currents. Forecasters use this model guidance to get an idea of likely wind, wave, and current scenarios associated with a spectrum of tropical and extratropical storms that approach the coast. It is critical that forecasters have a chance to monitor model simulations of the atmospheric and oceanic circulations in their areas of local responsibility on a real-time basis and with the benefit of buoy observations for model verification purposes. This strategy is one important way to validate the model forecasts and to give forecasters a basis for assessing what aspects of the model forecasts are useful guidance for the issuance of coastal marine warnings, what areas require forecast improvements, and recognition of the unsolved forecast problems.

IMPROVING WEATHER FORECAST MODELS

Prospects for markedly improved prediction of disruptive weather are particularly good at this point in the history of meteorological research. Through modernization of the NWS, the nation now has access to the advanced tools necessary for observation as well as modeling of atmospheric conditions. Meteorological buoy and C-MAN station technology extend the area over which reliable model forecast boundary and initial conditions may be determined.

Research observing capabilities are maturing to the point of operational readiness. Moreover, with recent improvements in forecast skill come increasing opportunities for adaptive observing strategies. Rapidly advancing massively parallel computing architectures already permit the computational speed necessary to adequately represent atmospheric processes in numerical models including, as necessary, the explicit representation of convection. Mathematical techniques for four-dimensional data assimilation and ensemble forecasting are increasingly practicable. Communications now afford the opportunity for instantaneous distribution of data and forecast information through broadcasts and computer-interrogated systems, such as the World Wide Web. Scientific understanding of storms and weather-related processes is now at a relatively advanced stage, and the prospects for improved understanding are excellent.

The success of numerical modeling depends on the quality of the initial and boundary data and the assimilation system, the representation of processes that occur below the level of the discretization, and the accuracy of discrete approximations to the continuous equations. Different simulation problems place different requirements on each category.

For the open ocean, and in the coastal ocean and large lakes, the surface mixed layer can respond slowly or quickly, and thus atmospheric and oceanic time and space scales can be disparate or similar over the entire spectrum of important problems. Examples abound, such as the formation of atmospheric and oceanic fronts, modification of the surface wind field, sea-state generation, hurricane track and intensity, ocean response to intense atmospheric forcing, radiation fog, mid latitude extra tropical cyclones (ETCs) genesis and coastal and estuarine storm surge, to name a few. Hence, finer-resolution data than are presently available are required. The landfall of hurricanes pose the single largest threat to the destruction of property and the associated risk of fatalities, injuries, and illness. Additionally, hurricanes at sea globally pose a major operational impediment for the U.S. Navy and other Department of Defense operations.

At present, the prediction of hurricane movement (storm track) has improved by approximately 1 percent per annum over the past 25 years (Marks and Shay, 1998). Recent research reports suggest that a significant breakthrough of up to 15 percent improvement over the last 2-3 years may have been achieved, principally through the addition of observations targeted on the hurricane environment when storms are 96–48 hours offshore

(Marks and Shay, 1998). This fact alone speaks to the value of offshore in situ observations that can be ingested into the models in real time. Typically, upwards of 300 km of coastline must be warned and evacuated 48 hours in advance of hurricane landfall because the prediction of hurricane movement, while improved, remains uncertain. Furthermore, little skill has been demonstrated in the operational forecasts of hurricane intensity (Marks and Shay, 1998). This crucial aspect of hurricane prediction often spells the difference between the arrival of powerful winds and enormous storm surges and associated flooding with devastating property destruction or simply the arrival of a breezy rainstorm with localized high water and superficial damages (Xie et al., 1997). Evacuation to protect tens to hundreds of thousands of lives is mandatory in the first instance and entirely unnecessary in the other.

Studies related to hurricane forecasts near landfall include quantification of mechanisms associated with rapid intensity change and initialization of dynamical hurricane models with coastal radar, satellite, and at sea in situ data. Studies also include efforts to provide current analysis of storm intensity and track from satellite and radar data, to explore adaptive observing strategies for forecasts within and beyond two days, to understand the effects of coastlines and coastal mountains, and to determine the mechanisms that underlie the occurrence of localized extreme winds, rainfall, tornadoes, storm surge, and fresh water flooding.

Looking to the future, focused research may unlock secrets about hurricane dynamics and the predictability of the attendant hazards at sea and near landfall. There are early indications from preliminary research that numerical representations of the hurricane vortex in dynamical forecast models can be greatly improved, that increasingly realistic upper-ocean models can be coupled to these atmosphere models, and that the coupled model system can be used as the primary forecast tool when such models are properly initialized by a combination of continuously monitored marine buoys and targeted storm-specific observations in the atmospheric and upper ocean environments. The likely impact of such techniques, when used in combination with a denser marine observational network, observations from space, airborne observations in and near hurricanes, and of increasingly sophisticated forecast models, offer the hope of reducing the uncertainty in forecasts of hurricane track and changes in hurricane intensity. Assuming such gains are achieved, highly useful forecast information will become available with longer lead times from the Tropical Prediction Center (TPC) and NWS. Owing to the improved accuracy and reliability of these forecasts, much smaller stretches of coastline need to be evacuated and fortified in the event of an approaching storm. Less affected areas, while alerted and able to take measured precautions, will be free to engage in commerce and business with only mild disruption. These expected forecast improvements may increase the use and value of hurricane forecasts, mainly due to greater advance notice of the need to evacuate and the reduction of coastline subjected to such extreme evacuation and fortification.

Accurate predictions of winter storm tracks and intensities have been difficult for operational meteorologists. Much of this inaccuracy arises because many of these storms traverse or originate from the particularly data sparse regions of the western North Atlantic, the western and central North Pacific oceans, and the Gulf of Mexico. This forecasting difficulty is compounded further, since the wintertime environment in which many of these systems develop along the U.S. eastern seaboard is highly baroclinic due to the proximity of the omnipresent Gulf Stream which acts to enhance the low level horizontal baroclinicity dramatically within the mid-Atlantic coastal zone (Cione, et al., 1993). This situation is especially true off the coastline of the Carolinas where, on average, the Gulf Stream is closest to land between 34–36°N. During periods of offshore flow and cold advection, low-level horizontal thermal contrasts between air temperatures at coastal stations and those immediately above the Gulf Stream can result in the rapid and intense destabilization of the marine atmospheric boundary layer within the Gulf Stream locale. This airmass conditioning or modification period often precedes wintertime coastal cyclogenesis or redevelopment.

Recently significant boundary layer improvements to operational weather forecast models have been implemented. For example, the NCEP Eta model now incorporates a complex boundary layer physics package that utilizes several vertical layers below 1 km. Nevertheless, it is difficult for any current operational numerical model to fully capture all the important fine-scale details of the mid-Atlantic coastal baroclinic zone, which during winter months is often typified by SST and air temperature gradients on the order of 10–15°C over 5–10 km within the vicinity of the Gulf Stream SST frontal zone. It is this understandable yet still problematic distinction between the averaged and highly smoothed surface data used in today's operational weather forecast models and the actual mid-Atlantic coastal zone surface conditions that most likely gives the impression that coastal cyclone intensification is not usually well represented in numerical weather prediction models.

Moreover, in the offing is a national domain full-physics mesoscale model with appropriate treatment of coastal and oceanic influences. When combined with targeted observations that are assimilated from the North Atlantic, Gulf and North Pacific, Gulf and North Atlantic regions, it will represent a major step toward improved specificity and reliability of 1–6 day winter storm forecasts. Furthermore, better utilization of the modernized continental observing system, including WSR-88D radars and satellite derived SSTs, should improve numerical forecast deficiencies on the 1–12 hour timescale, especially over urbanized coastal zones where surface and air traffic disruptions dominate. The prediction of localized precipitation patterns, amount, type, and timing should improve, resulting in more reliable and credible forecasts of heavy rain, snow, or ice. Furthermore, it is likely that winds and large temperature swings will be indicated more precisely and with higher specificity within sub-sections of forecast zones, especially in the nation's coastal regions. The objective forecast guidance should improve enough so that many industries, governments, and individuals will alter more demonstrably their behavior with respect to specific forecasts of winter storms after they learn from experience to trust their reliability and specificity.

Presently, various forms of deep convection, many of which are organized in mesoscale convective systems are capable of giving rise to flash floods, hail, tornadoes, lightning, and microbursts. Forecasters and researchers can neither reliably predict the initiation of convection, the dissipation of mature convective systems (Emanuel and Kalnay, 1997), nor the specific regions in which severe weather will occur.

However, as more and better data become available and as numerical models improve, the primary mechanisms responsible for the initiation and dissipation of convection will be better understood. Forecast models will be better able to represent convection explicitly and to parameterize convection in ways that better represent the bulk effects of sustained, organized convection. Models will be more capable of assimilating relevant information related to a convectively disturbed initial state. Model forecasts of convection will be more reliable in a deterministic sense for periods in excess of 2 hours. In comparison to today's convective forecasts at 2 hours, detailed statistical forecast products will likely have more useful skill, perhaps for periods out to 6–10 hours. Flash floods will likely be statistically anticipated in specific watersheds for longer periods than they are now, perhaps up to 6 hours. Hailfall will be more routinely discriminated from heavy rain as a matter of course in polarimetric radar observations and perhaps be statistically predicted one day in advance in an area-wide susceptibility sense. Coastal severe weather (including possible tornado occurrences) perhaps will be forecast statistically with moderate probability over very limited areas for periods up to a few hours, as will other convectively driven strong wind events. Lightning, a serious problem in many coastal inland and offshore areas and a by-product of convection, will be more favorably bounded by forecasts of convection initiation and dissipation.

The prediction of cloud ceiling and visibility at ground level, the intensity of coastal storms, and orographic precipitation and winds are among the remaining major forecast challenges (Rotunno and Pietrafesa, 1996). For example, restricted coastal and marine ceiling and visibility routinely impede commercial and military aviation. Poor visibility also impedes transportation, most notably coastal vehicular traffic during the morning rush hour in some of our largest cities. Some of the conditions associated with impaired visibility are poorly predicted. Such conditions are often weakly forced dynamically, and are heavily influenced by microphysical and radiative processes that are not well represented in forecast models (Hirschberg, 1998).

Forecasting the intensity of precipitation, winds, and beach erosion associated with coastal cyclones is a primary objective in the United States. The forecast deficiencies are similar to that of winter storms. An important distinction for coastal storms is that the principal hazards are often rain and wind related, as in the "nor'easters" of the east coast or the "pineapple express" storms of the west coast. Both flash flooding and generalized flooding can result, and windswept surf can erode community beaches. Coastal ocean temperature and salinity structure, marine boundary layer stability, and coastal topography influence the landfalling storm intensity (Marks and Shay, 1998). Such influences are not well observed (especially the oceanic aspects), are relatively less-well understood, and are poorly initialized in limited-area forecast models.

Ceiling and visibility forecasts can be improved through explicit representation and improved parameterization of cloud processes and localized advective and radiative effects (Emanual and Kalnay, 1997). Coastal storm forecasts of precipitation and winds will improve markedly as a direct consequence of superior oceanic analyses of the initial state (Rotunno and Pietrafesa, 1996). These analysis improvements will be achieved because of observations over the upstream ocean that are targeted, as determined from baroclinic wave sensitivity criteria, and from improved knowledge of forcing conditions within the nearby coastal waters. The overall observational strategy should be both practicably necessary and realistically sufficient and will be known as the "essential program" that embodies the determination of the "best practicable mix" of observations, data assimilation schemes, and forecast models for operations extending into the next millennium. This focus is consistent with the objectives of the (NOAA-led) multi-agency thrust to develop and implement the NAOS for weather and climate monitoring. The activities required to achieve this program focus include fundamental studies to improve understanding and to develop improved parameterizations of physical processes. In addition, one must explore observational strategies, prototype instrumentation development, data assimilation techniques, and the development and refinement of numerical models. Finally, forecast demonstration projects, in a research mode, are needed to provide "proof of concept" for improved prediction capabilities and to demonstrate societal benefits.

COASTAL IMPACTS OF SEVERE WINTER STORMS AND HURRICANES

The prediction of explosive oceanic cyclogenesis, close encounters with hurricanes, and hurricane landfall are examples of critical problems of great concern to marine interests and forecasters. Explosively deepening oceanic cyclones are marked by rapidly falling pressures, widespread areas of gale, storm or even hurricane force winds, large wind waves and swells, confused seas, and coastal storm surges. These storms represent a significant hazard to mariners and coastal residents alike. The sparsity of surface pressure, wind, temperature, and moisture information over the open ocean and the Great Lakes impacts both the forecast and warning process, especially during the storm development stage. The result is that warnings often underestimate the eventual storm severity and are often not issued with sufficient timeliness to enable mariners and coastal residents to take protective action for life and property. Similar problems exist with landfalling hurricanes. Although less frequent, landfalling hurricanes carry much greater potential for causing loss of life and property in coastal regions. This problem has been fully recognized by NOAA in a series of Natural Disaster Survey Reports for winter storms and landfalling tropical storms. These NOAA reports have consistently recommended that the coastal and offshore data network over the Gulf of Mexico and the Atlantic and Pacific Oceans be expanded to allow for improved prediction and warning of explosive cyclogenesis and landfalling hurricanes. A synopsis of the relevant findings and recommendations on coastal and marine observations from recent NOAA Natural Disaster Survey Reports is found in Appendix E.

Finally, we have abundant evidence that NOAA/NWS information is accessed frequently. Gilhousen (1997) noted that the posting of buoy/C-MAN observations on the Internet (http://www.ndbc.noaa.gov) by NDBC revolutionized the way these observations could be made available to public and private maritime interests. According to Gilhousen (1997), NDBC experienced almost 160,000 hits (visits, pages or files transmitted) during February 1997. Gilhousen (1997) also indicated that the NWS Forecast Office in Tallahassee, Florida (http://www.nws.fsu.edu), which has been posting NDBC observations for 2 years, has experienced between

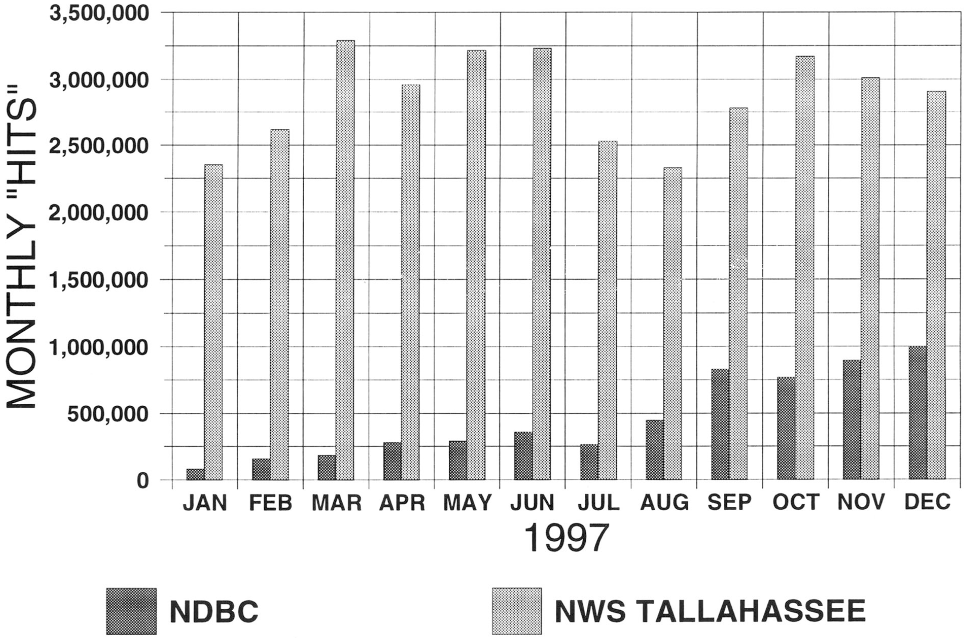

FIGURE 14 Monthly number of Internet visits ("hits") for 1997 to the official web sites of the National Data Buoy Center (NDBC) and NWS Forecast Office in Tallahassee, Florida. (Courtesy of Douglas R. Scally, National Data Buoy Center)

2 and 3 million hits per month. These numbers indicate great interest in marine observations and provide additional evidence that many user communities would support efforts to improve marine observations through the enhancement of the buoy/C-MAN system. Gilhousen (personal communication, 1998) has summarized the Internet hit numbers for 1997 and his statistics are given in Figure 14.

COASTAL WEATHER OBSERVATIONS, FORECASTS, AND WARNINGS

Weather forecasts and warnings in the United States are produced through a process that begins with the assimilation and error checking of a variety of surface (land and marine) and upper-air observations from around the globe. Complementary observing systems are used to build an integrated global database that is essential to describing the global wind, temperature, and moisture patterns. In addition to the buoy/C-MAN surface observations of air and water temperature, wind, waves, pressure, humidity, and other variables as needed, the global database includes surface observations with a similar suite of variables from: (1) commercial ships of opportunity and military vessels; (2) lightships; (3) drifting buoys; (4) oil and gas platforms; (5) National Ocean Survey (NOS) installations; (6) base reflectivity and base velocity observations from the Doppler radar network; (7) automated commercial aircraft temperature, moisture, and wind reports; (8) reconnaissance aircraft reports; (9) satellite-derived radiances that can be converted to vertical atmosphere temperature profiles; (10) satellite-derived precipitable water, rainfall rates, and cloud liquid water content; (11) satellite-derived cloud-drift winds at various levels in the atmosphere; and (12) satellite-derived sea-surface temperatures and scatterometer-determined surface wind estimates over the oceans. These voluminous and disparate data sources, representative of several different scales (space and time) of atmospheric and oceanic motion and thermal structure, must be assimilated into a global analysis mosaic. This data assimilation is accomplished by means of an analysis and initialization system suitable for global and regional weather prediction models of the type that are run routinely at NCEP.

VOLUNTEER OBSERVING SHIPS

Two platforms that are particularly useful in obtaining observations over much of the world's oceans are satellites in space and commercial and other volunteer ships of opportunity at sea. Ship reports are concentrated along the major global trade routes and are provided at internationally agreed upon synoptic times, typically four or eight times per day (and sometimes more frequently near major oceanic cyclones and hurricanes). It is implausible to assume that volunteer ship reports will be obtained from locations where crucial data are needed on storm structure, movement, and intensity. Ironically, as NCEP model performance on predicting cyclones continues to improve, the likelihood of obtaining valuable ship observations near storms will decrease because the ships will deviate from their predetermined courses to avoid the worst of the storms. The reliability of warnings and forecasts suffers from this irregular availability of ship data. Similarly, the reliability of ship-reported wind, wave, and swell observations are subject to wide variation, especially at night, because these observations are made visually by observers with vastly different training.

The real value of observations from commercial and other volunteer ships of opportunity lies in their ability to sample vast stretches of ocean on synoptic scales (approximately 1,000 km) where the cost of operating and maintaining fixed observational platforms, such as deep-water moored buoys, would be prohibitive. As storms approach within a few hundred kilometers of the coast, a higher data quality, consistency, and spatial resolution are required in order to provide accurate forecast information and sufficient warning lead times to the general public and coastal marine interests. Hence, mobile ship weather reports are no substitute for a fixed array of C-MANs and moored buoys providing consistent and continuous measurements of the basic state atmospheric (i.e., pressure, temperature, winds, and moisture) and oceanic (i.e., SSTs, significant wave heights, periods, and directions) variables.

Model forecasts of wind, temperature, significant wave heights, relative humidity, and precipitation, among other variables, along with derived statistical-dynamical guidance products from these models, are examined by operational meteorologists at various NWS offices across the United States several times daily. Forecasters charged with the responsibility for preparing forecasts and issuing warnings to the general public, interested federal, state and local agencies, and public safety officials scrutinize and interpret the model forecasts. They compare them against all available observations (e.g., local and regional surface and radar observations and satellite imagery) to fine tune the model forecasts based on local and regional influences not specifically included in the models (e.g., complex coastal terrain effects that can affect the distribution of flooding, such as along the California coast and behind east coast barrier islands). This "end-to-end" forecast process, whether applied to aviation, public, fire, weather, or marine forecasts, depends critically upon the first step in the process: the acquisition of observations from a functional and representative database. For the marine community, this database is heavily dependent upon the availability of fixed observations taken at buoy/C-MAN sites and observations routinely reported by ships of opportunity and military vessels.

SPACE-BASED SATELLITE PLATFORMS

In the past three decades remarkable progress has been made in remote sensing and in the capabilities of space technology to aid in the study and understanding of Earth processes in general and the weather in particular. Emanuel and Kalnay (1997) provide an excellent overview of remote sensing capabilities, applications, and limitations.

While the extensive suite of satellite measurements and instruments is of great value for weather forecasting, there are serious caveats related to remote sensing. First, it is known that measurements made by satellite sensors are usually only indirectly related to the geophysical parameter of interest. Temporal and spatial variability in atmospheric aerosols and water vapor and variability in sea-surface roughness not related to wind, for example, introduce errors and uncertainties into the satellite estimates of such oceanic parameters as SST, wind stress, and sea-surface elevation. Improvements to the algorithms that relate the satellite measurements to the parameters of interest must be pursued and the accuracy of the satellite measurements must be demonstrated before conventional observations are reduced or retired in favor of spaceborne observations.

Most satellite estimates will always require coincident direct-surface and upper-air measurements to perform the ongoing task of calibration, and surface platforms will be needed to make measurements not possible by remote sensing. The best determinations of the geophysical fields of interest will be obtained by combining satellite and direct measurements, blending the unmatched spatial coverage of satellite sensors with direct observations of greater accuracy or more direct connection to the geophysical parameters of concern. Therefore, a well-chosen network of direct observations will become more, not less, important as satellite techniques advance.

A network of reliable, accurate surface observations is required to reduce such errors in the Volunteer Observing Ships (VOS) network and satellite data sets to acceptable levels and will be required for the foreseeable future. Here, oceanic drifters have a role to play as well. Next, spatial fields of sea level are very useful for validation of ocean models and for an integral constraint on initialization. Presumably the cadre of space-based altimeters could provide this information. However, the frequency of transits (e.g., for polar orbiting satellites) is such that the coverage is not necessarily synoptic in the temporal weather sense. In addition, altimeter data in the regions of ocean margins are suspect because of deficiencies in uncertainties of the geoid. Accurate measurements of sea level are best provided by a combination of long-term altimeters where time differencing techniques can be used in combination with in situ data from the coastal tide gauge network. In the atmosphere, there is little information about boundary layer structure, especially in the divergent trade cumulus regions, which tend to lie in oceanic regions without upper air observations. Since the ability of models to simulate and assimilate near surface data depend on boundary layer processes, this is a serious gap which again is best addressed by both satellite, coastal radar, drifter and marine buoy and C-MAN data.

Space-based observations of the surface wind field have only recently become available from a number of sources. Since mid-1987, surface wind-speed information has been available from the passive microwave sensors of the Defense Meteorological Satellite Program's Special Sensor Microwave Imager (SSM/I) satellite. Global coverage at 35-km resolution is achieved approximately every 3 days. A second similar satellite, thereby providing twice the sampling, was launched in late 1991. NCEP is presently considering the inclusion of SSM/I wind speeds into its analysis and forecast system). Since July 1991, wind velocity observations have been available from the Earth Remote Sensing (ERS-1) satellite's active microwave scatterometer. These vector wind data are now being evaluated for implementation at the European Centre for Medium Range Weather Forecasts (ECMWF). The National Aeronautics and Space Administration (NASA) scatterometer, launched in 1996, permitted the construction of gridded 12-hourly-fields of wind velocity with 50-km resolution (the satellite failed in 1997). However, both the active and passive microwave instruments suffer from a degraded signal below wind speeds of 3 m s^{-1}. For the purpose of constructing a wind stress forcing function, conversion of the wind velocity observations still requires measurement of humidity, SST, and surface air temperature in order to calculate the stability-dependent drag coefficient. While satellites measure SST several times daily at most locations under cloudfree conditions and wind speeds, buoys measure SST, air temperature, wind speeds, and direction continuously. These buoy data and ship reports are more suitable for estimating wind stress, with satellite data used to fill in spatial voids.

In general, advanced satellite remote wind sensors such as radar scatterometers, radar altimeters, and passive microwave sensors, lack the sensitivity to resolve winds above about 20 m s^{-1}, which means that remote sensors are able to resolve the intensity of extra tropical cyclones (ETCs) and tropical cyclones (TCs) only up to Category 1 on the Saffir-Simpson scale. In situ sensors are needed to correctly resolve the intensity of storms of greater intensity. Satellite spatial resolution is an overall problem, where gradients are often missed and land-sea boundaries are sharply defined and averaged are radiances subsequently meaningless. Space-based sensors also cannot measure surface air pressure.

In general, the VOS SST retrievals are accurate only to about 1.0°C. This accuracy may be improved by using more expendable bathythermographs (XBT), but may also require changes in equipment and methods. The most accurate real-time SST data sets are from drifting and moored buoys. NCEP now relies heavily on buoy data, not only where VOS data are lacking but also to affect quality control of VOS data from well-traveled shipping lanes. The best-resolved SST products in space and time now use techniques that combine Advanced Very High Resolution Radar (AVHRR) data with other data. For example, the joint use of AVHRR and drifter data has been shown to be accurate within ± 0.3°C. The NCEP SST field is now produced by using the buoy data to remove large-scale biases and trends in the AVHRR fields and to screen the VOS observations. Then, the smaller-scale curvatures of the field are established by the AVHRR data, and all data are objectively blended to yield an SST map.

There remain some significant and fundamental physical questions about the meaning of SST, since boundary processes, diurnal variations, and skin effects can lead to differences on the order of several tenths of a degree in the top meter or so of the ocean. It is not obvious that model parameterizations or measurements should be cast in terms of a single SST variable or, if a single variable is used, how it should be defined and observed. From the standpoint of direct observations, the SST is a central independent variable in bulk formula methods for determining air-sea heat flux, while from a large-scale modeling standpoint the SST (really the heat content in a thick near-surface layer in most models) is the key variable with which to gauge the evolution of the coupled atmosphere-ocean system. From both standpoints it is important to understand the relationship(s) of the SST (really the near-surface temperature profile) to the derived quantities-fluxes and time evolution of a model layer. This problem and many of the other SST issues noted above are discussed in a recent report (Joint Oceanographic Institute, 1992).

Together with surface wind stress and SST, the field of upper-ocean thermal structure is central to the successful initialization of coupled atmosphere-ocean models. The XBTs, taken in large part from ships of the VOS network are the primary source of global upper-ocean thermal data. However, only a small fraction of the VOS fleet operates XBTs and the data in fact are inadequate to generate monthly maps of upper-ocean thermal structure, and only bimonthly maps can be constructed.

In the context of seasonal to interannual prediction, sea-level observations are useful as an integral constraint on model initialization fields and as a model validation data set. Space-based techniques (e.g., GEOSAT and, more recently, the ERS-1 and the Ocean Surface Topography Experiment [TOPEX]/Poseidon altimeters) will yield routine global sea-level maps, but surface observations should be maintained until the need for them has been demonstrably superseded. The ERS-1 and TOPEX/Poseidon missions will afford a good opportunity over the next several years to demonstrate the utility of altimetry. Beyond the demonstration of utility lies the question of future continuity of a series of altimetric missions with instruments of known accuracy.

This discussion also raises the issues of data management, user access, quality control, and data continuity. Observations do little good unless the resulting data are accessible and the user is confident that the accuracy, influencing factors such as type of instrument and exposure, and quality control over the period of record are known. Furthermore, for an ever increasing number of applications, these data are needed over decades and longer periods with due consideration given to "comparability of record" over the duration of such records.

CHAPTER FOUR

Importance of Buoy/C-MAN Observations to Research and Operational Services

Coastal marine observations in general, and buoy/C-MAN observations in particular, have been essential to warning and forecast operations and to a variety of basic and applied research over the past few decades. In this section, and in this analysis of the buoy/C-MAN network, a scientific perspective has been applied. The separation of weather operations from research is no longer clear. Advances in science and technology are, if not in practice at least in intent, rapidly being transferred to warning and forecast operations. This section presents an overview of some of the significant contributions of buoy/C-MAN data in supporting research and in extending the range of warning and forecast services.

The United States arguably faces the world's greatest weather challenges with the most formidable array of weather extremes and the highest economic stakes. Property losses from severe weather continue to rise significantly in inflation-adjusted dollars. The growth in these losses, allowing for inflation, is rapid, doubling or tripling in constant dollars every decade. One category 5 hurricane could conceivably result in $50 billion in damage (Pielke et al., 1997). The U.S. National Mitigation Strategy (Federal Emergency Management Agency, 1995) points out that from 1980 to 1993, the value of insurable property on the Atlantic and Gulf Coasts increased 179 percent. Three hurricanes, Hugo in 1989 and Andrew and Iniki in 1992, resulted in a total of 70 deaths and $41 billion in damages. This damage was over 40 percent of the total reported damage caused by natural disasters in the United States between 1980 and 1993.

Significant variations in wind, waves, and weather in the region between 5 km and 50–100 km of the coast can occur. Likewise, equally significant variations can occur in the immediate coastal waters due to coastal land features. Such variations, often undocumented because of sparse offshore observations, may be critical to marine safety.

While weather has never posed greater or more urgent threats to the Nation's public safety, property, economic growth, and national security, reliable, accurate knowledge of the weather has enormous potential for benefit to agricultural productivity, construction, energy efficiency, national defense, transportation, water resource management, and the economy in general. This potential has never been so close at hand, given the advance in measurement technology, modeling, and understanding. Considering that much of the U.S. population lives in or near coastal zones, including the Great Lakes (Figure 9), more data leading to improved forecasts will result in improved economic efficiency. The following example from a report of the USWRP sixth prospectus development team (Pielke et al., 1997) concerning oil and gas exploration illustrates the point.

Improved forecasts of tropical weather conditions (wind, waves, and rain) can reduce delays in drilling operations at a cost of up to $250,000 per rig per day. There are several thousand rigs in the Gulf of Mexico. Improved hurricane track predictions could reduce days of production shutdown, each day of which costs the industry and the U.S. treasury a combined $15 M. The biggest and potentially avoidable, impact on oil and gas production operations comes from the threat of tropical cyclones (TCs). Shut-downs impact operating companies severely: they incur the costs associated with deferral of production, transportation of crews to safety and back, downtime for protecting equipment and structures and, later, for damage assessment, and the costs of facility repairs prior to resumption of safe operations. While fixed structures usually come back on-line within 48 to 72 hours of evacuation, floating production systems, like those now operating in deep waters, may take up to a week to resume production. Most companies allow for 5 to 7 days of weather-related production losses each year in their business plans. While costs of extreme events grab the headlines, simple forecast errors in more benign circumstances can also lead to economic losses and transfer of wealth among economic sectors. Improved storm track and landfall forecasts can save lives, save days of production shutdown, and avoid false alarms and unnecessary shutdowns for oil and gas companies operating offshore.

One of the most valuable operational uses of buoy/C-MAN observations is that they permit forecasters to monitor pressure, wind, wave, and temperature conditions continuously in the coastal and immediate offshore waters. These reports allow forecasters to fine tune model-generated forecast storm tracks and to evaluate critical derived information (such as the strength of the coastal baroclinic zone) necessary to issue watches and warnings promptly for marine and coastal interests. These same buoy/C-MAN reports have been used by a variety of researchers, often in cooperation with NWS operational meteorologists, to study coastal meteorological events of major interest to forecasters. The importance of the buoy/C-MAN network for research and operational purposes has been noted by Rotunno and Pietrafesa (1996) who conclude that "an expansion and enhancement of current NDBC C-MAN and buoy systems is essential."

The proposed expansion and enhancement of the buoy/C-MAN network by Rotunno and Pietrafesa (1996) and the NOAA MAROB plan detailed earlier are consistent with the stated objectives of the U.S. Weather Research Program (USWRP). The USWRP has three top research priorities that are linked to operations: (1) quantitative precipitation forecasting; (2) TC forecasting; and (3) adaptive measurement strategies. These three USWRP research priorities are driven by an operational need to provide forecasters better guidance on hazardous weather threats so that warnings can be improved and by the desire to advance basic scientific knowledge in these areas, out of which will come improved forecasting capability. Research and operations are inextricably linked in the modernized and restructured NWS, and this linkage is fully recognized in the USWRP. The three research priorities of the USWRP will require a robust buoy/C-MAN network as noted by Rotunno and Pietrafesa (1996).

In August 1997, a Pacific Coast workshop was held that dealt with the problems of coastal forecasting and the associated operational requirements. (A workshop synopsis can be found in Hirschberg, 1998.) Four categories of forecast problems were identified on various time scales: (1) short-term and long-term quantitative precipitation forecasting, (2) mesoscale wind forecasting from a few hours to a few days, (3) marine layer forecasts of ceiling and visibility, and (4) sea surface conditions as measured by wind waves, swell, and currents. These types of issues are common to all of the coastal areas of the United States, including the Great Lakes and other sizable inland water bodies. Along the Gulf and Atlantic coasts there are additional forecast complexities related to the occasional landfalling tropical storm. Explosive extra tropical cyclones (ETCs) cause additional forecast problems along parts of most coastal regions and over the Great Lakes. A denser buoy/C-MAN observational network in the coastal and offshore waters is central to progress in scientific understanding of coastal weather and marine processes and in improved operational prediction capabilities.

COASTAL ISSUES AND APPLICATIONS

Coastal baroclinic zones, often called coastal fronts, have been documented by Bosart et al. (1972) and Bosart (1975). Coastal fronts possess operational significance because the frontal position often coincides with the rain/snow line and the axis of heaviest precipitation in advance of a coastal cyclone. Coastal marine observations (including buoy and C-MAN reports) have been critical to the success of various scientific investigations of coastal front life cycles and behavior. These critical observations have enabled researchers and operational meteorologists to show that coastal fronts are marked by the confluence of marine and continental air masses and are associated with strong low-level temperature contrasts across a 10 km wide frontal zone that can exceed 10°C. Coastal fronts are most commonly found in winter along portions of the Atlantic and Gulf coasts (e.g., New England, the Carolinas, the lower Texas coast). They tend to form in regions of differential heating between the land and ocean, adjacent to regions of differential heating between the Gulf Stream and the cooler continental shelf waters, and in some instances, by differential surface roughness (e.g., Bosart, 1981; Keshishian and Bosart, 1987; Nielsen 1989; Roebber, 1989; Nielsen and Neilley, 1990; Riordan et al., 1985, 1995; Riordan, 1990; Gyakum, 1991; Holt and Raman, 1992). Coastal fronts may also form inland in response to the formation of extended thermal gradients produced by differential heating associated with precipitation and evaporation or the blocking and lifting of moist air by the Appalachian Mountains (e.g., Branick et al.,1988; Bell and Bosart, 1988; Bosart and Dean, 1991; Nielsen and Dole, 1992; Fritsch et al., 1992).

The buoy/C-MAN observations have been especially helpful in studies of the marine environment in which coastal fronts form in situ offshore. The availability of NWS NWS88D Doppler radar observations in conjunction with buoy/C-MAN reports and other conventional data sources has enabled researchers to better understand how differential diabatic heating across near-shore and offshore oceanic thermal gradients has contributed to in situ coastal frontogenesis and cyclogenesis (e.g., Davis and Dolan, 1992; Cione et al., 1993; Davis et al., 1993). The results from research on coastal storms and related phenomena have been used in turn by operational meteorologists to make improved weather forecasts (e.g., Gurka et al., 1995; Keeter et al., 1995). Similarly, research on oceanic coastal cyclone frequencies and cyclogenesis processes has also benefited from the availability of a regular network of coastal and offshore marine observations with regard to defining cyclone warm sector conditions, offshore deepening rates, and coastal wind and wave conditions (e.g., Bosart and Sanders, 1991). Modeling studies of coastal frontogenesis and coastal cyclogenesis (e.g., Ballentine, 1980; Stauffer and Warner, 1987; Lapenta and Seaman, 1990, 1992; Doyle and Warner, 1993a, b, c, d; Chien et al., 1997) have helped to uncover important mesoscale aspects of coastal front life cycles for which confirmatory evidence has been obtained from coastal marine observations.

In a recent study, Khandekar and Lalheharry (1996) used data from American and Canadian moored buoys to help evaluate Environment

Canada's ocean wave prediction model. The buoy data indicate that the wave model underpredicts the highest wave heights. Verification of model forecasts is a critical use of moored buoy data. In a related study, Bouws et al. (1996) investigated the recent trend for observed wave heights to increase over the North Atlantic Ocean. The scientific issue was whether wave height trends were related to increases in swell size as opposed to changes in the heights of wind-driven waves. Hurrell (1995) showed that the positive phase of the North Atlantic Oscillation (NAO) has increased, favoring an increase in the strength of the westerlies across the North Atlantic Ocean basin since 1960. Bouws et al. (1996) used the information on the positive time tendency of the NAO to conclude that the wave height increase could be attributed to increased swell, a conclusion confirmed by Kushnir et al. (1997). Clearly, wave spectra information obtained from moored buoys are of critical importance to research studies of this nature, and which have important weather and climate ramifications. Note that Nowlin et al. (1996) have concluded that measurements of SST, wind, and wind stress measurements are of the highest priority in the construction of an ocean observing system for climate studies.

The Gulf of Mexico is also a very important cyclogenesis region for North America. An important recent example occurred in March 1993 when the Gulf of Mexico spawned a vicious extratropical storm, eventually known as Superstorm 1993 (e.g., NOAA, 1994). Severe weather in the form of heavy snow, heavy rains, high winds, tornadoes, and coastal storm surges associated with Superstorm 1993 killed many people, injured many more, caused hundreds of millions of dollars in property damage, and generally disrupted human activity across much of eastern North America from Cuba to eastern Canada (e.g., Caplan 1995; Uccellini et al., 1995; Alfonso and Naranjo, 1996; Bosart et al., 1996; Dickinson et al., 1997; Schultz et al., 1997). Although Superstorm 1993 was well forecasted several days in advance over the northeastern United States (e.g., Caplan, 1995; Kocin et al., 1995; Uccellini et al., 1995), the initial cyclogenesis over the northwestern Gulf of Mexico was poorly forecasted (e.g., Dickinson et al. 1997). Gilhousen (1994) showed that the buoy/C-MAN observations over the northwest Gulf of Mexico were crucial for establishing the initial (and unforecasted) intensity of Superstorm 1993.

Dickinson et al. (1997), besides showing that Superstorm 1993 was the deepest ETC to occur over the Gulf of Mexico in the 40-year period 1957-1996, also established that the NCEP and to a lesser extent operational prediction models performed poorly in predicting the intensity of the initial cyclogenesis over the Gulf of Mexico. They showed that the initial poor model forecasts of Superstorm 1993 could probably be attributed to a combination of: (1) a significant underestimation of the initial strength of the surface baroclinity over the northwest Gulf of Mexico that was apparent in the buoy/C-MAN observations reported by Gilhousen (1994), (2) a misrepresentation of the strength of the warm oceanic ring situated over the northwestern Gulf of Mexico (Gilhousen, 1994), (3) a failure of the NCEP models to represent properly the bulk effects of cumulus convection associated with the massive convective outbreak over the Gulf of Mexico during the incipient and rapidly intensifying phase of the storm, and (4) an underestimation of the intensity of a dynamical tropopause disturbance embedded in the subtropical jet stream that helped to trigger the massive convection and initial cyclogenesis over the Gulf of Mexico. It is quite likely that a better representation of the marine environment over the Gulf of Mexico at the time of the incipient cyclogenesis would have resulted in better model forecasts of the initial storm development.

The Gulf of Mexico has also been the target of many warm season research investigations that are also critically dependent upon availability and reliability of marine observations. Weiss (1992), Thompson et al. (1994), and Breaker et al. (1997) have investigated the return flow of moisture from the Gulf of Mexico to the continent as winds turn poleward behind retreating anticyclones. Given the importance of the timing of the return flow of moisture to episodic storm and precipitation events, sometimes severe, over the Plains and lower Mississippi Valley, it is crucial that offshore marine observations be readily available to forecasters charged with multiple public safety responsibilities (e.g., the evacuation of personnel from offshore oil platforms before hazardous weather arrives) and to researchers trying to document and understand the life cycles of the often complex convective systems that form in this region (e.g., Fritsch et al., 1986; Johns and Doswell, 1992; Hagemeyer, 1997; Laing and Fritsch, 1997). Coastal frontogenesis along the lower Texas coast can often be associated with exceptionally heavy rains and, occasionally, the spin up of tropical cyclones (e.g., Bosart, 1984; Bosart et al., 1992). Without the availability of buoy/C-MAN observations, these research case study investigations, with results that may also have potential operational utility, would not be possible.

TC research has also benefited significantly from the availability of coastal marine observations. Powell and Black (1990), Breaker et al. (1994), Houston and Powell (1994), Dobos et al. (1995), Powell (1996), and Powell and Houston (1996) have used these observations along with base reflectivity data from the NWS operational coastal Doppler radar network (WSD88D) and wind observations derived from low-level passes by NOAA research aircraft to construct detailed offshore wind analyses accompanying landfalling tropical storms. The buoy/C-MAN observations are of critical importance for calibration purposes in the construction of these wind analyses. The derived wind analyses are also of critical importance to forecasters at NOAA's TPC in the fine-tuning of hurricane landfall positions and for coordinating with federal, state, and local emergency management officials on evacuation plans. In a related study, Mettlach et al. (1994) have used moored buoy measurements to compute significant wave heights (3–8 m) and dominant wave periods (20–25 s) along the west coast of North America (Alaska to California) associated with supertyphoon Flo in the central North Pacific Ocean in September 1990. Most recently, Cione and Black (1998) have used historical buoy/C-MAN observations taken in the vicinity of tropical storms to construct profiles of thermodynamic variables as a function of radial distance from the storm center.

In recent years there has also been a renewed interest in the problems of winter weather forecasting over the Great Lakes, particularly for the forecasting of lake-effect snow (e.g., Niziol et al., 1995). Passarelli and Braham (1981) showed that low-level convergence over Lake Michigan associated with a winter land breeze off snow-covered terrain helped to drive a thermally direct snow-band circulation over the lake. More recently, Reinking et al. (1993) and Byrd et al. (1991) have reported on new lake-effect snow studies over Lake Ontario. With the advent of NWS Doppler radar (88D) observations, forecasters can now monitor lake-effect snow bands much more carefully than previously. They have also been able to take advantage of research that has established the importance of vertical wind shear profiles to the type, intensity, location, and duration of lake-effect snow bands (e.g., Niziol et al., 1995). However, critical measurements of temperature, pressure, wind, and maritime air profiles over the Great Lakes during lake snow events are lacking. These measurements are required to help assess quantitatively the convergence into the lake bands and the strength of the thermally direct frontogenetical circulations that help to drive the bands. Meadows et al. (1997) remark that "the buoys are providing high-quality, long-term wave measurements for the Great Lakes. Unfortunately, the buoys are usually removed during the heavy icing season of November to March...." Given the importance of weather information over the lakes, it is hoped that future enhancements to the buoy program will include construction and deployment of moored buoys capable of withstanding the severe winter conditions on the Great Lakes.

There is also a long history of research that has taken advantage of buoy/C-MAN observations along the west coast of North America for a variety of synoptic and mesoscale studies, a number of which have had operational utility. The Catalina Eddy, a mesoscale circulation that occurs in the coastal waters of southern California in response to airflow over and around prominent topographic barriers, is of local significance because the marine layer deepens with the onset of the offshore cyclonic circulation (e.g., Bosart, 1983; Mass, 1989; Wakimoto, 1987; Thompson et al., 1997). The deepening of the marine layer is associated with a lessening of the concentration of pollutants in the coastal atmosphere of the Los Angeles basin, but may be associated with the longer range transport of pollutants northwestward along the coast toward Santa Barbara and inland through the mountain passes to the lower deserts of California, Nevada, and Arizona. Buoy/C-MAN observations are of critical importance to forecasters and air pollution officials who monitor the life cycle of the Catalina Eddy circulation.

Severe storm and heavy precipitation studies over coastal and interior North America would also benefit from the maintenance and enhancement of a critical buoy/C-MAN network. The timing, frequency, and intensity of low-level moisture surges into the southwestern United States are of crucial importance to the onset and severity of the summer monsoon precipitation in this region. Studies by Douglas (1993, 1995), Douglas et al. (1993), Douglas and Li (1996), and Stensrud et al. (1997) have shown that the Gulf of California is an important low-level moisture source for the summer monsoon. These same studies, however, have shown that low-level time-mean flow is not properly simulated in the NCEP/ECMWF prediction models, because surface observations are lacking. Given the potential devastation and loss of life associated with flash floods in this region, it is important that the buoy/C-MAN network be enhanced to provide more reliable low-level wind information in the Gulf of California and in the Pacific south and west of San Diego. Finally, the occasional episodic severe weather outbreak (usually in the cooler half of the year) across coastal and interior California (e.g., Monteverdi and Johnson, 1996) might be easier to forecast if more information were available on wind, temperature, and moisture conditions from moored buoys on air masses approaching coastal California.

Mass and Albright (1987), Dorman et al. (1995), Mass and Bond (1996), and Bond et al. (1996), among others, have investigated the mesoscale aspects of coastal cool surges along the West Coast that are associated with southerly wind reversals and coastal mesoscale pressure ridges. These authors have demonstrated that the mesoscale circulation aspects of the onshore marine "pushes," which often end coastal interior valley heat waves, would be very difficult to deduce without the additional meteorological information provided by the buoy/C-MAN network. Bond et al. (1997) have presented an overview of the Coastal Observation and Simulation with Topography Experiment (COAST) conducted recently in the Pacific

Northwest. They make the point that the success of research investigations like COAST depend very much upon the synthesis of disparate data sources and types of which buoy/C-MAN observations are one important component. Finally, we note that recent studies of the synoptic and mesoscale structures of frontal systems approaching and crossing the Washington and Oregon coast (e.g., Steenburgh and Mass, 1996; Colle and Mass, 1996; Chien and Mass 1997; Chien et al., 1997) have validated the importance of the research philosophy governing the COAST experiment.

RESEARCH RELATED TO TROPICAL WEATHER APPLICATIONS

NOAA and its predecessor agencies, through the offshore moored buoy platforms and C-MAN sites have provided invaluable data on numerous tropical storms and hurricanes. Forecasters at NOAA's National Hurricane Center (NHC), now the TPC, and researchers at AOMLHRD, formerly the National Hurricane Research Laboratory, make extensive use of these data. Initially the buoy platforms were intended simply to replace the ocean weather ship program, and to provide a "Maginot" line of defense along coastal regions to aid in the warning of approaching storms and to supplement the network of satellite observations with in situ measurements. Over the years, users have come to rely on the augmented network of open ocean and coastal automatic weather stations for day-to-day operations and for in-depth research.

Tropical Cyclone Winds

Data acquired by the prototype experimental data buoys deployed by NDBC in the Gulf of Mexico and off the east coast, beginning in the 1970s, provided the first accurate marine surface measurements in the core of intense tropical cycloones (TCs) (e.g., Gulf of Mexico Hurricane Eloise, 1975 at Environmental Buoy #71; EB71; East Coast Hurricane Belle, 1976 at EB04). These data sets and the many additional data from hurricanes that followed have greatly improved our understanding of the structure of the marine surface wind fields in intense TC wind fields and have had a significant impact on TC forecasts and warnings, TC boundary layer research, diagnostic studies, three-dimensional dynamic models, ocean response modeling, and specification of design criteria for offshore and coastal structure.

First, the surface wind measurements provided the first direct evidence that Monin/Obukov planetary boundary layer (PBL) similarity theory could be applied to describe the vertical shear of the horizontal wind in the mative boundary layer of tropical cyclones (e.g., Ross and Cardone, 1978; Cardone and Ross, 1979; Powell, 1980; Powell and Black, 1990; Liu et al., 1997). This finding has had a major impact on diagnostic studies and modeling of tropical cyclones with full three-dimensional dynamical models. These studies also have provided a basis for identifying the relationship of the flight-level wind observations (acquired by reconnaissance aircraft at flight levels typically of 850 mb and 700 mb) to winds near the surface, which impact life and property.

Second, the buoy data have provided the first reliable data sets against which models of the TC PBL wind field may be evaluated and refined. Before the deployment of the buoy array, virtually no such data were available. For example, the first practical dynamically based numerical model of the wind field in the TC marine PBL (Cardone et al., 1976) could be compared only to winds from an oil platform (rig 50) in Hurricane Camille 1969, manually scaled off a strip chart whose time tics were uncertain because of a sticking clock drive, that was recording the output of an anemometer of uncertain calibration mounted on the top of the drilling rig. The measured wind data sets obtained from the NDBC buoys in the Gulf of Mexico and off the U.S. east coast have allowed validation and refinement of that first model and of alternative parametric models (e.g., Holland, 1980; Georgiou, 1985). Typically, during the 1970s and 1980s, only one of the available NDBC buoys would encounter a given TC, so that only one or at most two quadrants of the storm circulation could be investigated. The expansion of the buoy array and the addition of the C-MAN array in the late 1980s and 1990s has made possible, especially near landfall, an accurate synoptic analysis of the entire wind field (Powell, 1982; Powell et al., 1991), thereby allowing resolution of secondary wind maxima and storm asymmetries. Such analyses are now produced routinely in real time at HRD for the NHC/TPC (Powell and Houston, 1997; Houston, et al., 1997).

It is important to note that, in general, advanced satellite remote wind sensors such as radar scatterometers, radar altimeters, and passive microwave sensors, lack the sensitivity to resolve winds above about 20 m s^{-1}, which means that remote sensors are able to resolve the intensity of TCs only up to category 1 on the Saffir-Simpson scale. In situ sensors are needed to correctly resolve the intensity of storms of greater intensity.

Ocean Response Modeling

The enhanced ability enabled by the NDBC buoy measurements to specify surface wind and stress fields in TCs through synoptic analysis and modeling has had, and continues to have, a large impact on ocean response modeling. Numerous modeling studies have reported on storm surge, mixed-layer, and three-dimensional current response to hurricanes (e.g., Forristall et al., 1980). The buoys have made an even greater impact on understanding ocean wave generation under extreme wind forcing and on ocean wave modeling, because the buoys also provide accurate measurements of wave height, period, and the frequency spectrum. For example, Ochi (1994) used buoy wind and wave measurements acquired in hurricanes Eloise, Frederic, Anita, Belle, Kate, and Gloria to establish useful new functional relationships between the wind and wave parameters. First and second generation wave models developed in the 1970s and early 1980s were often validated against wave data acquired by NDBC buoys (e.g., Ross and Cardone, 1978). The advanced community third-generation spectral wave prediction model (WAM), which now is used at most operational numerical weather prediction centers around the world for global and regional wave forecasting, was not released and published until it was thoroughly validated against measured NDBC wave data acquired in Gulf of Mexico hurricanes Anita in 1977 and Frederic in 1979 (Wave Advanced Dynamics Model 1; WAMD1 Group, 1988).

Many new studies are underway utilizing data sets acquired in intense U.S. east coast storms during the active 1995 (notably Felix and Luis) and 1996 (Fran and Bertha) seasons. The availability of directional wave sensors on many NDBC buoys during these years are allowing further refinement of source terms representing physical mechanisms of wave growth and dissipation. The NDBC buoys and their Canadian cousins moored on the Scotian Shelf and Grand Banks have measured record high sea states (significant wave heights up to 17 m and maximum wave heights up to 30 m) in recent severe hurricanes, as well as in severe extratropical storms such as the Storm of the Century (1993) and Halloween Storm (1991) (Cardone et al., 1996). These data sets have revealed a tendency for even the most advanced wave models to under-specify extreme sea states, a finding that has stimulated further research in ocean wave dynamics. In fact, an important field experiment and modeling program Surface Wave Advanced Dynamics Experiment (SWADE) in 1990/1991, was based on the existing U.S. East coast NDBC buoy array (Cardone et al., 1995).

Another reliable use of buoys may be in research and forecasting of coastal upwelling. Upwelling regions are key to much of the ocean's biological productivity, and buoy measurements provide critical data for coupling meteorological, oceanographic, and biological models in developing the means to manage coastal food sources.

COASTAL OCEANOGRAPHIC RESEARCH AND COASTAL WEATHER

The coastal buoy network is an important source of continuous weather and wave information to fishing, shipping, and recreational interests. In addition, the real-time data from these buoys and the climatologies and time series subsequently generated from them are essential to ongoing oceanograpic and marine research. For example, from available buoy data scientists have determined the typical annual signal of wind and SST along the U.S. west coast. Three distinct geographical regions have been identified (Dorman and Winant, 1995; Schwing et al., 1997a, b). Each region has a unique biological signature (with respect to primary production), zooplankton, and fish communities (Parrish et al., 1981, 1983; U.S. GLOBEC, 1994). Buoy data can also define seasonal changes such as the "spring transition" into upwelling favorable conditions along the coast (Strub et al., 1987a).

The Coastal Ocean Forecast System, jointly developed by NWS, National Ocean Service, and Princeton University researchers shows the value of in situ observations. In areas where high-quality, relatively dense observational networks are available, forecasts of surface and subsurface ocean temperature are more accurate (e.g., Kelley et al., 1997).

Schwing et al. (1997a) show regional differences in annual alongshore wind and SST at selected buoys off the west coast. Winds within the Southern California Bight are weak and variable throughout the year, particularly in summer, relative to those north of Point Conception. South of Cape Mendocino, winds are equatorward throughout the year. Minimum SSTs off much of California occur in late spring, due to the cooling effect of coastal upwelling. Winds are typically highly variable on shorter synoptic (3-14 day) time scales in all months, creating brief periods of downwelling (southerly winds along the California coast) and warmer SSTs. Buoy winds and SSTs also display significant interannual differences.

Based on this well-defined seasonality, conditions vary on synoptic as well as interannual scales in ways that are not possible to forecast. Local wind stress is an important factor in driving coastal currents and determining their variability on synoptic scales (Strub et al., 1987b; Winant et al., 1987; Chelton et al., 1988; Rosenfeld et al., 1994; Paduan and Rosenfeld, 1996). This ocean response to wind-forcing also influences the position of water mass features, such as coastal jets and eddies, and the distribution of heat, salt, nutrients, carbon, and marine organisms (Huyer, 1983; Kosro et al., 1991). All these studies used data collected by coastal buoys. More recent studies have shown the spatial patterns of wind stress and air-sea heat flux from buoy and ship data to be much more complex than previously thought (Winant and Dorman, 1997). Buoy winds are useful in separating the effects of regional winds and the remote ocean connection to tropical ENSO activity (Ramp et al., 1997). They also are incorporated in larger data sets, for example, the Comprehensive Ocean Atmosphere Data System (Woodruff et al., 1987) which have been used to identify decadal-scale fluctuations in wind forcing and SST (Schwing et al., 1997b). Because these variations are unpredictable, information from coastal buoys is essential for monitoring changing conditions for synoptic and climate forecast models. Wind stress and heat flux information from buoys are critical elements for diagnostic and prognostic atmosphere, ocean circulation, mixed layer, and wave modeling (Blumberg and Mellor, 1987; WAMD1 Group, 1988; Clancy, 1997). Some of these data are included in the model forcing fields, incorporated into assimilation schemes in prediction models, and used to verify model output. Other models that rely on input from buoys include those used to predict the evolution of hazardous coastal events, such as oil spills and harmful algal blooms.

Bosart (1981) showed that the failure of the NCEP (then NMC) models to predict the Presidents' Day snowstorm on February 19, 1979, could be attributued in part to the failure of the NMC analyses to accurately depict the strength of the temperature contrast from the coast eastward to the Gulf Stream. In addition, the NMC surface analyses were systematically too cold in the offshore waters, a situation that precluded the models from representing the existence of unstable air offshore.

Bosart and Sanders (1991) examined the NMC model failures in a case of a surprise snowstorm across part of New York and New England on October 4, 1987. Again, Bosart and Sanders (1991) were able to show that, if offshore marine observations had been used, they would have helped place the surface cyclone correctly and define the strong surface temperature gradient. And in the case of the March Superstorm, Gilhousen (1994) and Dickinson et al. (1997) showed that NCEP initial analyses misplaced the location of the region of strong thermal contrast over the Gulf of Mexico and underrepresented its intensity, which may have contributed to the poor model forecasts of the initial cyclogenesis.

Huo, et al. (1998) ran a numerical experiment with the Canadian Regional Element (RFE) Model in which the original RFE surface temperature analysis was replaced by a new objective analysis in which all available temperature observations from buoys and ships of opportunity over the Gulf of Mexico were included. A comparison of the RFE runs using the original and modified objective analyses suggested that forecasts of the incipient cyclogenesis were significantly improved with the better surface temperature analysis. The authors conclude that although the results of their limited study cannot be taken as definitive, they do suggest that attempts to improve the lower tropospheric thermal field in model initial analyses in data sparse regions might lead to improved forecasts.

Coastal buoy data are needed for "ground-truthing" satellite data (e.g., scatterometer, SST) and refining algorithms. Very few alternative permanent sites in the ocean are available for this purpose. These ground measurements will become even more critical as we advance technologically toward greater use of remote sensing and as new space, air-borne, and shore-based observational systems are developed. Buoy data can also be integrated with satellite data to create a more complete and accurate picture of the coastal environment.

In addition to direct studies of the coastal ocean, buoy data have been applied to studies of coastal meteorological processes, such as the structure of the marine boundary layer (Beardsley et al., 1987) and coastal gravity currents (Dorman, 1987). These observations in real time are important in tracking the development and movement of storms before landfall.

Meteorological and surface ocean variables are important for identifying conditions within critical reproductive periods for living marine resources. U.S. GLOBEC (1994) lists a number of studies showing correlation between coastal environmental conditions, typically wind and temperature, and recruitment in fishery stocks, as well as many of their prey species. Measurements from buoys provide data to quantify this relationship and to characterize individual years by their effect on reproductive and recruitment success. Wind reversals, or relaxations in upwelling, are linked to recruitment in nearshore marine species (Farrell et al., 1991).

Winter storms in California and Oregon, with the possibility of increased rainfall that some may link to El Niño, are being studied by government and university scientists hoping to improve forecasts of heavy rain, snow, and wind along the west coast. The study, called CALJET (California Land-Falling Jets Experiment), begun on December 1, 1997, includes researchers and forecasters from NOAA, the U.S. Navy, and various universities. The study will run through March 1998, which is the wet season in that area. This field experiment is aimed at scientifically examining the required observations to improve one type of coastal forecast problem. Studies of this type are needed for many other phenomena as well.

The CALJET study illustrates two points particularly relevant to the analysis of the buoy/C-MAN system herein. First, experiments of opportunity may be tapped for additional data that could augment the core buoy/C-MAN operational network. Second, CALJET uses a great variety of instruments and platforms that should be considered when looking for alternative or complementary observing methods to the moored buoy or C-MAN station network. Rapidly intensifying coastal storms occur over the mid-Atlantic during the winter season (Sanders and Gyakum, 1980; Sanders, 1986; Rogers and Bosart, 1986). These storms produce heavy snow, gale force winds, and crippling ice, and have been known to batter the eastern seaboard of North America from the Carolinas to Newfoundland. On average, there are 13-15 substantial storms per year, which annually cost over a billion dollars in property damage (Dirks et al., 1988). The toll on human life has also been great, for example, 50 lives were lost in the April 6-7, 1982, snowstorm and 70 deaths were attributed to the February 11-12, 1983, "Megalopolitan" snowstorm (e.g., Sanders and Bosart, 1985a, b; Bosart and Sanders, 1986; Chang et al., 1989). The Presidents' Day Storm on February 18-19, 1979, (e.g., Bosart, 1981; Uccellini et al. 1984, 1985, 1987) and the March 12-14, 1993, superstorm (e.g., Kocin et al., 1995; Uccellini et al., 1995; Bosart et al., 1996; Dickinson et al., 1997) produced copious amounts of snowfall and effectively paralyzed much of the eastern United States. There is also a long history of these storms disrupting naval operations, commercial shipping, and fishing, occasionally resulting in extreme damage to marine vessels, including sinking.

During the late fall through early spring, strong horizontal temperature contrasts often arise due to the offshore presence of the Gulf Stream and cold dry air over the adjacent land. Many times, the average distance to the Gulf Stream from Cape Hatteras, North Carolina is less than 60 km, with typical air temperature above the Gulf Stream front ranging between 22°C and 24°C, while nearby land based air temperatures range between –20°C and 10°C. As a result, large gradients in low-level air temperature are often observed. In fact, during periods of strong offshore cold advection, where average land surface temperatures can remain at or below 0°C for extended periods of time, horizontal gradients of air temperature can exceed 30°C 50 km^{-1} or 0.6°C km^{-1}. These large horizontal gradients of air temperature translate into large horizontal gradients of surface latent and sensible heat fluxes. Under strong cold air outbreak (CAO) conditions, total surface turbulent heat flux values have been observed to exceed 1500 W m^{-2} (Wayland and Raman, 1989; Riordan, 1990; Vukovich, 1991). Even under moderate CAO conditions, the degree of vertical heat and moisture transport that occurs within the lower troposphere is enough to quickly destabilize the low-level offshore Gulf Stream environment. Fantini (1990) has shown that this pre-storm destabilization may act to significantly increase the likelihood for subsequent rapid cyclogenesis or reintensification.

The apparent importance of pre-storm periods on future cyclonic intensification prompted an investigation to look at the effects of pre-storm baroclinicity on wintertime coastal cyclogenesis. The climatological study conducted by Cione et al. (1993) incorporated cold season (November-April) cyclonic episodes from the period 1982 through 1990 along the Carolina and Virginia coasts. Storms entering or spawned in this area are subjected to the highly variable baroclinic zone associated with the lateral, onshore-offshore meanders of the Gulf Stream (Pietrafesa and Janowitz, 1980), and buoy data are essential to the study strategy.

Cione et al. (1993) show that the pre-storm baroclinicity was strongly associated with the intensification of coastal cyclones. This is potentially very useful for operational winter storm forecasting. The findings of this study and their potential value to forecasting depend greatly on the availability of satellite-derived SST observations. But when clouds or aerosols interfere, buoy data are the only reliable source of data to drive the promising new forecast tools.

Another example of the utility of marine buoy data is in the prediction of flooding along the North Carolina coast and in coastal sounds during the passage of severe TCs and ETCs (Xie et al., 1997). Collaborating researchers from North Carolina State University and the NWS operational forecasters in Raleigh use a 1 km resolution version of the Princeton Coastal Ocean Model. Predicted storm tracks with marine buoy and C-MAN winds are used to direct inputs in both forecasting and, following storm passage, post-analysis assessment. This flooding model, while in a developmental mode, was cited as a success story and the Raleigh Forecast Office was given a NOAA Unit Citation Award in 1997.

In addition to the above, use of the buoy and C-MAN data becomes important, particularly during storm conditions; they initialize and verify ocean circulation and mixed-layer wave models, predict the path and spread of toxic spills, ground-truth satellite measurements, and in studying marine biology. The buoy/C-MAN data are useful also in studies of the marine boundary layer, distant locations to monitor ENSO signatures, coastal climatology studies, wind stress and air-sea heat flux, coastal flooding, and beach erosion, to name several applications. Also, the personal views of one experienced forecaster was solicited (Ainsworth, personal communication, 1998) in Appendix G.

CHAPTER FIVE

Proposed Core Network and Recommendations

The existing buoy/C-MAN systems provide critical observations to forecasters in a variety of hazardous weather conditions. When NWS forecast offices in the western region issue coastal marine warnings, the primary reason for the issuance of these warnings are observations received from the buoy/C-MAN network. This warning strategy remained true even after the operational deployment of Doppler radars (WSR-88D) along the coast in the early years of this decade. Because of the curvature of the earth, the preferred siting of the radars in the coastal mountains and operational requirements that limit the lowest elevation angle of the center of the radar beam to 0.5 degrees above the horizon, coastal radars may not fully detect offshore weather systems of critical interest to mariners and coastal interests. The only reliable way for forecasters to monitor rapidly changing offshore and coastal weather conditions in order to issue timely and accurate warnings of hazardous weather is through data received from the buoy/C-MAN network.

There has been a very rapid growth in the number of individuals and groups in the marine community who regularly use real-time data from the existing buoy/C-MAN stations. This user growth has been especially rapid since the NWS and NDBC started making real-time observations from the buoy/C-MAN stations available over the Internet. The marine forecasting service needs of these users could not have been readily anticipated, even as recently as 2 years ago. Internet users, ranging from fishermen to recreational boat owners, to public safety officials increasingly require access to the basic bouy/C-MAN observations (e.g., wind direction and speed, temperature, wave height and direction, swell period) for making independent decisions in pursuit of their daily livelihoods and public duties and responsibilities. People from all walks of life have become increasingly sophisticated users. They have learned how to work with the basic data for their own purposes. In doing so, they have become dependent upon the availability of reliable real-time marine observations. The failure or withdrawal of existing buoys has raised concern in the marine data user community as attested to by the avalanche of unsolicited letters that have been received by the principal investigator and NRC staff preparing this report, pleading for the repair, restoration, or addition of buoy/C-MAN stations.

This report concludes that a core (platform and attached suite of instrumentation) buoy/C-MAN network is required to support essential operational nowcasts, forecasts, and warnings by the modernized and restructured NWS.

PROPOSED CORE BUOY/C-MAN NETWORK

The rapidly increasing U.S. coastal population is particularly vulnerable to the disruptive effects of coastal flooding, storm surges, intense extratropical storms, and TCs, and it therefore depends on accurate and timely warnings of severe weather. Coastal weather forecasters at NWS rely extensively on the data provided by the NOAA operated buoy/C-MAN network. Researchers also depend on the buoy/C-MAN network for data that will lead to better understanding of storm characteristics and improved forecasts.

In 1995 NWS issued a MAROB plan for the enhancement of a core network of buoy/C-MAN installations that would be commensurate with the modernized and restructured NWS. The MAROB plan was based on the concept that the observational data density coverage from buoy/C-MAN locations had to be increased in recognition of the growing marine (coastal and offshore) responsibilities of the modernized and restructured NWS and the explosive population growth within 100–200 km of the coasts over the past two decades. This report accepts the general elements of the MAROB plan. Modifications are suggested to ensure a fully functional buoy/C-MAN network that is consistent with operational needs and requirements of NWS, but also addresses the legitimate data needs of the scientific community. The philosophy underlying the modernized and restructured NWS is that operations and research are inextricably linked. This philosophy also governs the USWRP. Improvements in weather forecasting and warning capabilities arise because of increased scientific understanding that comes from the analysis and diagnosis of weather and climate events using operational data sets and from modeling studies using these same data sets.

Recommendation #1:

A core, base-funded buoy/C-MAN network should be established and maintained.

Such a core network could be based on the 1995 MAROB plan. Any plan for the buoy/C-MAN network should take into account the following three specific characteristics:

- the addition of moored buoys around Hawaii, the eastern Pacific, Gulf of California, Gulf of Mexico, the Atlantic coast, and the Caribbean with locations to be determined on the basis of operational and research requirements;
- an increase in the use of adaptive data gathering strategies that will allow for the deployment of additional drifting buoys in the central tropical Atlantic during the hurricane season and over the open ocean waters when the potential exists for severe ETCs to threaten coastal regions; and
- the replacement of some C-MAN systems by moored and drifting buoys in areas where the C-MAN sites are situated close to nearby land-based coastal surface observation sites.

The NOAA MAROB plan is a possible candidate for a base-funded core network. If the MAROB plan is adopted, it should be revised in the following three ways: (1) additional moored buoys should be added over the open ocean, (2) several C-MAN stations should be removed in favor of additional moored buoys, and (3) more drifting buoys should be added as part of an adaptive observations strategy. The increase in the number of drifting buoys should help the TPC better meet its national and international responsibilities for hurricane monitoring and warning and should prove useful in forecasting severe oceanic ETCs that threaten coastal regions.

The purpose of the proposed moored buoy addition in the Gulf of California is to permit forecasters to monitor poleward moisture surges associated with the summer monsoon of the southwestern United States. These moisture surges can be associated with widespread heavy convective rain episodes and flash flooding over the southwestern United States. The additional moored buoy that is proposed to be situated to the west of Baja California can be used by forecasters to provide an earlier warning of moisture surges from the equatorial tropical Pacific toward California in winter (the so-called Pineapple Express). It will also provide forecasters with valuable data on eastern Pacific hurricanes that may threaten California and Mexico during El Niño periods, as well as inform forecasters of moisture surges into the southwestern United States during the warm season. Illustrations and specifications of the moored-buoys proposed for the Hawaiian and other regions are shown in Figures 15 and 16.

The proposed moored buoy additions around the Hawaiian Islands are designed to give forecasters information on winds, waves, and swells in the gaps between the main islands. Forecasters know that the easterly trade winds tend to be channeled and accelerated in the gaps between the islands. What they lack are specific measurements on which to base the timing (onset and duration) of high wind and dangerous surf advisories and warnings.

As noted in Chapter 3, the Gulf of Mexico is occasionally ravaged by dangerous tropical storms that enter the region from the Caribbean. Furthermore, the southwestern Gulf of Mexico (Bay of Campeche area) is a favorable region for the genesis of tropical storms, especially early and late in the hurricane season. The proposed moored buoy additions in the Gulf of Mexico are designed to allow forecasters at TPC to monitor the details of tropical storm development and movement in anticipation of refining tropical storm watches and warnings; this helps fulfill the international responsibilities of TPC. For similar reasons, a moored buoy has been proposed to be situated in the western Caribbean equatorward of Jamaica. Hurricanes that track through this region frequently reach the Gulf of Mexico and have been some of the most intense storms on record in the Atlantic basin. Another critical need area lies near Puerto Rico, the U.S. Virgin Islands, and the Mona and Anegada Passages. Farther east, it is proposed that additional drifting buoys be deployed as needed between 10–20°N and 35–55°E to help TPC forecasters in preparing 5-day outlooks and monitoring environmental pressure, wind, and SST conditions in a region critical to the passage of African disturbances that often grow into tropical depressions and TCs. Note that the data provided from the proposed moored and drifting buoy additions will also be used by NCEP to initialize their operational global weather and climate prediction models.

The future buoy network should be redesigned with specific warning and forecast objectives paramount. Based on previous uses of the buoy network for hurricane forecast needs, a mix of moored and drifting platforms would be optimal. For example, an offshore "Maginot" first line of defense is required to provide real-time surface truth for aircraft reconnaissance observations while potentially dangerous storms are still offshore, and to provide input for final landfall surface wind distribution forecasts. In addition, a second line of buoys is required in the coastal zone for the purpose of immediate warnings, forecast verification, and post-storm critical wind analysis for comparison with storm surge damage and coastal wind damage. Although the network of coastal C-MAN sites assists in this effort, it is not possible for these sites to be totally representative of offshore exposures.

Central to implementing this concept is a totally new redesign effort currently underway at NDBC. The concept is to design a new, low-cost plug-and-play platform in which sensor suites would be modular and the latest in communications, computer, and sensor technology would be employed to reduce costs significantly. Future platforms would be smaller than previous ones, only 3 m in diameter with a 3 m mast for winds. The 10 m platform design currently in use was driven by wave requirements and the need for a stable observing platform. However, new methods for directional wave spectra have been developed from industry and university research laboratories that can be deployed for smaller platforms. In addition, matching the instrument capability with the observation requirement should reduce costs while increasing efficiency. Pressure sensors, for example, are an order of magnitude cheaper for forecast requirements of, for example, ± 1-2 hPa rather than ± 0.1 hPa. Reliable new and critically needed sensors for humidity/dew point have been developed in industry and university laboratories and can now be deployed. The lack of a moisture sensor has been a critical deficiency in the existing network for the past 20 years. Likewise, new optical technology for rain measurement can now be deployed on buoys as demonstrated in the Tropical Ocean-Global Atmosphere Coupled Atmosphere-Ocean Experiment (TOGA/COARE) and new acoustic technology for wind speed and direction is now maturing and can be used in conjunction with in situ conventional and sonic anemometers for wind speed. The new modular design concept can produce a buoy platform for 25 percent of the cost of previous platforms, thus allowing for the deployment of additional platforms at current funding levels.

In concert with the moored buoy array, selective air-deployments of drifting buoys should be planned and conducted to obtain critical surface observations ahead of and within specific storm systems, especially hurricanes. For this task, a reserve stockpile of new, low-cost drifters should be assembled prior to each hurricane season ready for use in critical landfall forecast situations. Four buoys per deployment could reduce data-void regions between existing moored observational platforms. The technology for doing this has been successfully demonstrated during the 1995-96 hurricane season. A second drifter array should also be deployed over the central and eastern Atlantic for monitoring African wave disturbances that often breed tropical storms. Such an array concept was successfully demonstrated during the 1996-97 hurricane season. It was shown that significant observations concerning storm development could be obtained without having to deploy aircraft reconnaissance assets at an early time period when potentially dangerous storms are far from landfall. Also, this drifter array provided valuable SST observations that showed water temperatures of 0.5-2.0°C warmer than values estimated remotely from satellite retrievals over the Atlantic. The SST discrepancy arose because the presence of widespread Saharan dust layers over the Atlantic produced a thick aerosol layer in the lower to middle troposphere that artificially lowered satellite-sensed SSTs. The dust-influenced satellite cool SST bias led to the conclusion that storm development potential was lower than was really the case and is another example of why surface-based observations are necessary to complement remotely sensed observations.

REVIEW OF COMPLEMENTARY OBSERVING SYSTEMS

Presently no comprehensive plan exists within NOAA for integrating disparate observational systems that are crucial to weather forecasting and climate monitoring. For its data to be most effective in forecasting and research, the core base-funded buoy/C-MAN network needs to be integrated with other land-based and remote sensing observational platforms into a comprehensive global observation system that can generate data sets that can be used to construct global, regional, and local analyses. One example: Integrate the Next Generation Water Level Monitoring System with the buoy/C-MAN system. These analyses will be used to initialize atmospheric and oceanic prediction models for multiple purposes, such as: (1) preparing routine weather forecasts, (2) anticipating where warnings for hazardous weather are likely to be needed several days in advance, (3) making forecasts of intraseasonal and interannual climate variability, (4) issuing wind, wave, swell, and current forecasts to facilitate toxic spill cleanups, and (5) conducting scientific research.

The need for an integrated data approach for weather and climate data was recently articulated by Thomas R. Karl, chair, Climate Research Committee, in a letter dated October 17, 1997 to the Honorable Timothy E. Wirth, Undersecretary for Global Affairs (Appendix B). The existence of a comprehensive data acquisition and management plan, supported by a commitment to base funding of the critical components, is essential if the United States is to meet its international commitments in the weather and climate arena and provide its citizens more timely and accurate warnings of hazardous weather, particularly in the increasingly populated coastal regions, within the context of the modernized and restructured NWS. Undersecretary Wirth then presented these collective ideas that embraced the above position, as the principal speaker in a special session entitled “Mitigating Against the Effects of Natural Disasters” (of which 80 percent are weather related) at the November 17, 1997, meeting of the National Association of State Universities and Land Grant Colleges in Washington, D.C.

Recommendation #2:

> **A comprehensive review of all complementary observing systems that are essential for providing crucial global weather and climate data for operational and research purposes, including the buoy/C-MAN systems, should be conducted, and this review should lead into a study of how to design and implement a coupled atmospheric and oceanic observing system for weather and climatic prediction using surface and space-based platforms.**

Given that research and operations are inextricably linked, this assessment should be done within the context of the ongoing NAOS evaluation by NOAA, and with the recognition of the programmatic goals of the USWRP and U.S. Global Change Research Program.

A PROPOSED BUOY/C-MAN DEPLOYMENT STRATEGY

Much of this study looks at the needs and capabilities of a national buoy/C-MAN network from a technical perspective. The two technical recommendations of this report must be considered and the following aspects incorporated when deciding how, where, and at what pace to implement the required system and in any buoy/C-MAN deployment, repair, replacement, and abandonment decisions (note the letters from the U.S. Coast Guard and Boat/USA in Appendixes C and D).

A comprehensive and rigorous quantitative analysis demonstrating the benefits of maintaining a coastal observing system is needed. The analysis will help identify priorities for platform and instrument installation, increase community use of data and forecasts, increase public awareness of the infrastructure needed to provide weather warnings and forecasts, and strengthen overall community support for the program. This analysis is part of a recommended strategy for modifying the existing MAROB plan.

First, it will be necessary to examine which coastal areas are climatologically most prone to storms and to assess the magnitude of the danger from these storms. In addition, more study will be required to determine where observations may yield key clues as to development and movement of storms that will have greater impact further inland, as in the monsoon rains of the southwest or winter snows in the Rocky Mountains and Great Plains.

Second, as part of the climatological assessment, it must be determined which coastal regions are also prone to local weather changes. These changes may involve, for example, nearby upwelling regions that may increase fog or coastal topography that may alter winds. These create hazardous conditions, often sudden and unpredictable, that can be detected by a well-positioned sentinel buoy.

Third, the number of people at risk will vary in proportion to the population density. A further breakdown in the assessment of those at risk would consider populations without the means to protect themselves or retreat from advancing storms and the need to protect particularly vulnerable or valuable investments, say for reasons of national and economic security or public safety. The coastal population density and the magnitude of the seasonally varying coastal storm threat must be considered in any buoy/C-MAN deployment, repair, replacement, and abandonment decisions.

Fourth, the scale of storms that impact our coasts suggests that to be fairly certain of determining the intensity and other important characteristics of the storm, points of observation should be appropriately spaced 30 to 50 km apart in the alongshore direction. While this may seem extreme and too expensive to contemplate, this nonetheless should be considered, particularly when matched against the aforementioned criteria and the importance of mesoscale nowcasting and forecasting to the NWS.

Fifth, as citizens begin to understand that they can access data derived directly from the buoy/C-MAN sites in near real-time via the Internet, the number of users will continue to grow. Evidence to support this assertion has been demonstrated in Figure 14. This knowledge will increase awareness of hazardous environmental conditions and reduce the risk of mishap. Thus, in areas where fishermen and recreational users of the coastal zone are particularly active, they should be encouraged to access and use this information resource for their safety.

CHAPTER SIX

Concluding Perspective

Congress, in appropriating funds for the modernization and restructuring of the NWS, specified that a benchmark for the modernization would be no degradation of existing services. However, the demand for increased services by the marine community and coastal recreational interests shows that this benchmark concept should be revised to better reflect the rapidly increasing use of the Nation's coastal zones for commercial and recreational purposes. The need exists for NWS to provide more comprehensive offshore weather information and forecasts in recognition of increased coastal zone use. This need in turn requires that NWS increase the spatial coverage and density of marine observation platforms in support of weather and climate services aimed at the protection of life and property. Public safety officials can act on their increased responsibilities to support the rapidly expanding marine community. As part of this process, the modernized and restructured NWS must increasingly deal with forecasting problems and related public safety issues associated with smaller-scale (mesoscale) weather systems, including, severe weather outbreaks (e.g., the occurrence of squall lines and tornadoes), heavy precipitation bands (rain or snow) that can lead to flooding, near-shore high-wind zones associated with landfalling hurricanes or wind channeling by coastal orographic barriers, and coastal storm surges associated with winter storms and landfalling hurricanes.

The detection of mesoscale weather systems, typically occurring on horizontal scales of 50–100 km over a period of a few hours, is predicated on the ability of forecasters to monitor the weather on finer time and space scales than they have ever done. This requirement places an increasing demand for weather services that must be recognized and appreciated within the context of the aforementioned congressional benchmark. Accordingly, the concept of no degradation of services must be similarly modernized and restructured to reflect the increased (and very real) needs of the rapidly expanding marine user community. Recommendation #1 addresses this issue and is the basis for the design of the essential network proposed herein.

Management and funding responsibility for the existing buoy/C-MAN network is spread across multiple federal agencies that often have different interests, funding commitments, and data requirements. When the sponsoring agency decides it no longer needs the platform, funding and data stop, and along with them, the added value to weather forecasts and warnings. To maintain stability of operations, it is important that a single federal agency, NOAA, be given the responsibility and means to install, operate, and maintain the core base-funded moored buoys and C-MAN stations. This will enable Recommendation #1 to be implemented more expeditiously. Other federal agencies and private interests would still have the opportunity to deploy additional buoys above and beyond the core base-funded network. If NOAA is granted sole authority to fund and maintain the core buoy/ C-MAN network, then it is incumbent upon the agency to vigorously pursue new opportunities for technological advances, in conjunction with the private sector, in the design and deployment of more cost-effective buoy platforms.

The NDBC has developed a workable approach and strategy for designing, fabricating, testing, deploying, operating, and maintaining the marine buoy/C-MAN network over the years. However, there are opportunities with new industry- and university laboratory-developed technology, including instrument packages, buoys, and data delivery systems that could cut costs, improve observational capacity and quality, and thus further NOAA's ability to make improved weather forecasts. The extent to which NDBC can take advantage of these new opportunities would improve the tractability and viability of the modified MAROB plan that is proposed for adoption. Similar opportunities for cost-effective technological advances exist in the design and construction of the suite of instruments that are mounted on the buoy/C-MAN platforms. Considering the broad responsibilities of NOAA in maintaining other weather and climate observing systems and in data management, the buoy/C-MAN network can be integrated in strategic ways to assure the most cost-efficient monitoring system is in place.

It is beyond the scope of this study to address specific buoy/C-MAN deployment, maintenance, and repair issues. Any attempt to do so without a specific strategy supported by hard evidence would be divisive and likely would pit various public and private groups against one another. More generally, however, NOAA should conduct a much more comprehensive analysis of the impact of buoy data on the national weather and climate data system as indicated in Recommendations #2. This task would blend well with the ongoing study of NAOS and would help to position NOAA to formulate a cost-effective "big picture" data strategy for the atmosphere and oceans.

Finally, a continuing mechanism for overseeing and reviewing the implementation and operation of the buoy/C-MAN network is needed. Such a mechanism might include a panel of experts drawn from NOAA operational units, other agency and private sector user groups, and the academic research community. An annual or biennial status report on the network could be published by the panel for general dissemination.

References

Alfonso, A. P., and L. R. Naranjo. 1996. Genesis and evolution of a severe squall over western Cuba. A case study of 13 March 1993. Wea. and Forecasting 11:89–102.

Baker, D. J. 1995. "When the Rains Came." The Washington Post. 25 Jan. 1995, A25.

Ballentine, R. J., 1980: A numerical investigation of New England coastal frontogenesis. Mon. Wea. Rev. 108:1479–1497.

Beardsley, R. C., C. E. Dorman, C. A Friehe, L. K. Rosenfeld, and C. D. Winant. 1987. Local atmospheric forcing during the Coastal Ocean Dynamics Experiment, 1. A description of the marine boundary layer and atmospheric conditions over a northern California upwelling region. J. Geophys. Res. 92:1467–1488.

Bell, G. D., and L. F. Bosart. 1988. Appalachian cold–air damming. Mon. Wea. Rev. 166:137–161.

Blumberg, A. F., and G. L. Mellor. 1987. A description of a three–dimensional coastal circulation model. in Three–dimensional Coastal Circulation Models, N. Heaps, ed. Amer. Geophys. Union. Washington, D.C. 208 p.

Bond, N. A., C. F. Mass, and J. E. Overland. 1996. Coastally trapped wind reversals along the United States West Coast during the warm season. Part I. Climatology and temporal evolution. Mon. Wea. Rev. 124:430–445.

Bond, N. A., C. F. Mass, B. F. Smull, R. A. Houze, M. J. Yang, B. A. Colle, S. A. Braun, M. A. Shapiro, B. R. Colman, P. J. Neiman, J. E. Overland, W. D. Neff, and J. D. Doyle. 1997. The coastal observation and simulation with topography (COAST) experiment. Bull. Amer. Meteor. Soc. 78:1941–1955.

Bosart, L. F. 1975. New England coastal frontogenesis. Quart. J. Roy. Met. Soc. 101:957–978.

Bosart, L. F. 1981. The Presidents' Day snowstorm of February 1979: A sub-synoptic scale event. Mon. Wea. Rev. 109:1542–1566.

Bosart, L. F. 1983. Analysis of a California Catalina Eddy event. Mon. Wea. Rev. 111:8, 1619–1633.

Bosart, L. F. 1984. The Texas coastal rainstorm of 17-21 September 1979: An example of synoptic-mesoscale interaction. Mon. Wea. Rev. 112:1108–1133.

Bosart, L. F. and D. B. Dean. 1991. The Agnes rainstorm of June 1972: Surface feature evolution culminating in inland storm redevelopment. Wea. and Forecasting 6:515–537.

Bosart, L. F., G. J. Hakim, K. R. Tyle, M. A. Bedrick, W. E. Bracken, M. J. Dickinson, and D. M. Schultz. 1996. Large-scale antecedent conditions associated with the 12-14 March 1993 cyclone ("Superstorm '93") over eastern North America. Mon. Wea. Rev. 124:1865–1891.

Bosart, L. F., C. C. Lai, and R. A. Weisman. 1992. A case study of heavy rainfall associated with weak cyclogenesis in the northwest Gulf of Mexico. Mon. Wea. Rev. 120:2469–2500.

Bosart, L. F., C. J. Vaudo, and J. H. Helsdon, Jr. 1972. Coastal frontogenesis. J. Appl. Meteor. 11:1236–1258.

Bosart, L. F. and F. Sanders. 1986. Mesoscale structure in the megalopolitan snowstorm of 11–12 February 1983. Part III. A large amplitude gravity wave and coastal frontogenesis. J. Atmos. Sci. 43:924–939.

Bosart, L. F., and F. Sanders. 1991. An early-season coastal storm: Conceptual success and model failure. Mon. Wea. Rev. 19:2832–2851.

Bouws, E., D. Jannink, and G. J. Komen. 1996. The increasing wave height in the north Atlantic ocean. Bull. Amer. Meteor. Soc. 77:2275–2277.

Branick, M. L., F. Vitale, C.C. Lai, and L. F. Bosart. 1988. The synoptic and subsynoptic structure of a long-lived severe convective system. Mon. Wea. Rev. 116:1335–1370.

Breaker, L. C., L. D. Burroughs, Y. Y. Chao, J. F. Culp, N. L. Guinasso Jr., R. L. Teboulle, and C. R. Wong. 1994. The impact of Hurricane Andrew on the near-surface marine environment in the Bahamas and the Gulf of Mexico. Wea. and Forecasting 9:542–556.

Breaker, L. C., D. B. Gilhousen, and L. D. Burroughs. 1997. Preliminary result from long-term measurements of atmospheric moisture in the marine boundary layer in the Gulf of Mexico. J. Atmos. Ocean Tech. 15(3):661–676.

Byrd, G. P., R. A. Anstett, J. E. Heim, and D. M. Usinski. 1991. Mobile sounding observations of lake-effect snowbands in western and central New York. Mon. Wea. Rev. 119:2323–2332.

Caplan, P. M. 1995. The 12-14 March 1993 superstorm: Performance of the NMC global medium-range model. Bull. Amer. Meteor. Soc. 76:201–212.

Cardone, V. J., W. J. Pierson, and E. G. Ward. 1976. Hindcasting the directional spectra of hurricane generated waves. J. of Petrol. Technology 28:385–394.

Cardone, V. J., and D. B. Ross. 1979. State-of-the-art wave prediction methods and data requirements. In Ocean Wave Climate, M. D. Earle, and A. Malahoff eds., Plenum Publishing Corp. New York. 61–91.

Cardone, V. J., H. C. Graber, R. E. Jensen, S. Hasselmann, and M. J. Caruso. 1995. In search of the true surface wind field in SWADE IOP-1: Ocean wave modelling perspective. The Global Atmosphere and Ocean System. 3(2-3):107–150.

Cardone, V. J., R. E. Jensen, D. T. Resio, V. R. Swail, and A. T. Cox. 1996. Evaluation of contemporary ocean wave models in rare extreme events: The Halloween Storm of October, 1991 and the storm of the century of March 1993. J. of Atmos. and Oceanic Tech. 13(1):198–230.

Chelton, D. B., A. W. Bratkovich, R. L. Bernstein, and P. M. Kosro. 1988. Poleward flow off central California during spring and summer of 1981 and 1984. J. Geophys. Res. 93:10, 604–610, 620.

Chang, S., K. Brehme, R. Madala, and K. Sashegyi. 1989. A numerical study of the east coast snowstorm of 10-12 February 1983. Mon. Wea. Rev. 117:1768–1778.

Chien, F.C., and C. F. Mass. 1997. Interaction of a warm-season frontal system with the coastal mountains of the western United States. Part II: Evolution of a Puget Sound convergence zone. Mon. Wea. Rev. 125:1730–1752.

Chien, F. C., C. F. Mass, and Y. H. Kuo. 1997. Interaction of a warm-season frontal system with the coastal mountains of the western United States. Part I. Prefrontal onshore push, coastal ridging, and along shore southerlies. Mon. Wea. Rev. 125:1705–1729.

Cione, J. J., and P. G. Black. 1998. Surface thermodynamic observations within the tropical cyclone inner core. Preprints, Special Sessions on Tropical Cyclone Intensity Changes, American Meteorological Society. January 11-16, 1998. Phoenix, Arizona pp. 21-25

Cione, J. J., S. Raman, and L. J. Pietrafesa. 1993. The effect of Gulf Stream-induced baroclinicity on U.S. East Coast winter cyclones. Mon. Wea. Rev. 121:421–430.

Clancy, M. 1997. An Overview of Meteorological and Oceanographic Modeling at Fleet Numerical Meteorology and Oceanography Center. pp. 59–63. Changing Oceans and Changing Fisheries: Environmental Data for Fisheries Research and Management, Boehlert, G.W., and J.D. Schumacher, eds. NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-239, 146 p.

Colle, B. A., and C. F. Mass. 1996. An observational and modeling study of the interaction of low-level southwesterly flow with the Olympic Mountains during COAST IOP 4. Mon. Wea. Rev. 124:2152–2175.

Davis, R. E., and R. Dolan. 1992. The All Hallow's Eve coastal storm—October 1991. J. Coastal Res. 8:978–983.

Davis, R. E., R. Dolan, and G. Demme. 1993. Synoptic climatology of Atlantic coast north-easters. Int. J. Climatol. 13:171–189.

Department of Commerce. 1997. National Implementation Plan for Modernization of the National Weather Service; for Fiscal Year 1998. National Weather Service, NOAA, Silver Spring, Md. 190pp.

Dickinson, M. J., M. A. Bedrick, L. F. Bosart, W. E. Bracken, G. J. Hakim, D. M. Schultz, and K. R. Tyle. 1997. The March 1993 superstorm cyclogenesis: Incipient phase synoptic- and convective-scale flow interaction and model performance. Mon. Wea. Rev. 125:3041–3072.

Dirks, R. A., J. P. Kuettner, and J. A. Moore. 1988. Genesis of Atlantic lows experiment (GALE): An overview. Bull. Amer. Meteor. Sco. 69:148–160.

Dobos, P. H., R. J. Lind, and R. L. Elsberry. 1995. Surface wind comparisons with radar wind profiler observations near tropical cyclones. Wea. and Forecasting 10:564–575.

Dorman, C. E. 1987. Possible role of gravity currents in northern California's coastal summer wind reversals. J. Geophys. Res. 92:1497–1506.

Dorman, C. E., A. J. Enriques, and C. A. Friehe. 1995. Structure of the lower atmosphere over the northern California coast during winter. Mon. Wea. Rev. 123:2384–2404.

Dorman, C. E., and C. D. Winant. 1995. Buoy observations of the atmosphere along the west coast of the United States, 1981–1990. J. Geophys. Res. 100:16029–16044.

Douglas, M. W. 1993. Current research into the monsoon. Sonorensis, Arizona Sonora Desert Museum Newsletter 13(3):10–11.

Douglas, M. W. 1995. The summertime low-level jet over the Gulf of California. Mon. Wea. Rev. 123:2334–2347.

Douglas, M. W., and S. Li. 1996. Diurnal variation of the lower-tropospheric flow over the Arizona low desert from SWAMP-1993 observations. Mon. Wea. Rev. 124:1211–1224.

Douglas, M. W., R. W. Maddox, K. W. Howard, and S. Reyes. 1993. The Mexican monsoon. J. Climate 6:1665–1677.

Doyle, J. D., and T. T. Warner. 1993a. The impact of the sea surface temperature resolution on mesoscale coastal processes during GLE IOP 2. Mon. Wea. Rev. 121:313–334.

Doyle, J. D., and T. T. Warner. 1993b. A Three-dimensional numerical investigation of a Carolina coastal low-level jet during GALE IOP 2. Mon. Wea. Rev. 121:1030–1047.

Doyle, J. D., and T. T. Warner. 1993c. A numerical investigation of coastal frontogenesis and mesoscale cyclogenesis during GALE IOP 2. Mon. Wea. Rev. 121:1048–1077.

Doyle, J. D., and T. T. Warner. 1993d. Nonhydrostatic simulations of coastal mesobeta-scale vortices and frontogenesis. Mon. Wea. Rev. 121:3371–3392.

Emanuel, K., and E. Kalnay. 1997. Observations in aid of weather prediction of North America: Report of prospectus development team seven. Bull. Amer. Meteor. Soc. 78:2859–2868.

Fantini, M. 1990. The influence of heat and moisture fluxes from the ocean on the development of baroclinic waves. J. atmos. Sci. 47:840–855.

Farrell, T. M., D. Bracher, and J. Roughgarden. 1991. Cross-shelf transport causes recruitment to intertidal populations in central California. Limnol Oceanogr. 36:279–288.

Federal Emergency Management Agency. 1995. National Mitigation Strategy - Partnerships for Building Safer Communities. FEMA. Washington, D.C.: 26pp

Forristall, G. Z., E. G. Ward, and V. J. Cardone. 1980. Directional spectra and wave kinematics in hurricanes Carmen and Eloise. 17th International Conference on Coastal Engineering. Sydney, Australia, 23-28 March 1980.

Fritsch, J. M., R. J. Kane, and C. R. Chelius. 1986. The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. J. Climate Appl. Meteor. 25:1333–1345.

Fritsch, J. M., J. Kapolka, and P. A. Hirschberg. 1992. The effects of subcloud-layer diabatic processes on cold air damming. J. Atmos. Sci. 49:49–70.

Georges, T. M., J. A. Harlan, L. R. Meyer and R. G. Peer. 1993. Tracking hurricane Claudette with the Air Force over-the-horizon radar. J. Atmos. Ocean Tech. 10(4):441–451.

Georges, T. M. and G. D. Thome. 1990. An opportunity for long-distance oceanographic and meteorological monitoring using over-the-horizon defense radars. Bull. Amer. Metero. Soc. 71(12):1739–1745.

Georgiou, P. N. 1985. Design wind speeds in tropical cyclone-prone regions. Rep. BLTW-2, Univ. of Western Ontario. London, Ontario.

Gilhousen, D. B. 1994. The value of NDBC observations during March 1993's "Storm of the Century." Wea. and Forecasting 9:255–264.

Gilhousen, D. B. 1997. Real-time buoy and C-MAN reports on the Internet. Mariners Weather Log 41:27–28.

Gurka, J. J., E. P. Auciello, A. F. Gigi, J. S. Waldstreicher, K. K. Keeter, S. Businger, and L. G. Lee. 1995. Winter weather forecasting throughout the eastern United States. Part II. An operational perspective of cyclogenesis. Wea. and Forecasting 10:21–41.

Gyakum, J. R. 1991. Meteorological precursors to the explosive intensification of the QE II storm. Mon. Wea. Rev. 119:1105–1131.

Hagemeyer, B. C. 1997. Peninsular Florida tornado outbreaks. Wea. and Forecasting 12:399–427.

Hirschberg, P. A. 1998. Report on the workshop on Pacific coastal forecasting system operational requirements. Preprints, Second Conference on Coastal Atmospheric and Ocean Prediction and Processes, American Meteorological Society. January 11-16, 1998. Phoenix, Arizona.

Holland, G. J. 1980. An analytic model of the wind and pressure profiles in hurricanes. Mon. Wea. Rev. 108:12121–1218.

Holt, T. R., and S. Raman. 1992. Three-dimensional mean and turbulence structure of a coastal front influenced by the Gulf Stream. Mon. Wea. Rev. 120:17–39.

Huo, Z., D. L. Zhang, and J. R. Gyakum. 1998. An application of potential vorticity inversion to improving the numerical prediction of the March 1993 superstorm. Mon. Wea. Rev. 126:424–436.

Houston, S. H., and M. D. Powell. 1994. Observed and modeled wind and water-level response from tropical storm Marco (1990). Wea. and Forecasting 9:427–439.

Houston, S. H., M. D. Powell, and P. P. Dodge. 1997. Surface wind fields in 1996 hurricanes Bertha and Fran at landfall. Preprints, 22nd Conference on Hurricanes and Tropical Meteorology American Meteorological Society 19-23 May 1997. Fort Collins, Colorado. Pp. 92–93.

Hurrell, J. W. 1995. Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. Science 269:676–679.

Huyer, A. 1983. Coastal upwelling in the California Current. Prog. Oceanogr. 12:259–284.

Johns, R. H., and C. A. Doswell III. 1992. Severe local storms forecasting. Wea. and Forecasting 6:515–537.

Joint Oceanographic Institutes Inc. (JOI). 1992. Ad Hoc Working Group Report: Sea surface temperature. Clancy, R. M., and R. A. Weller, eds. Washington, D.C.: Joint Oceanographic Institute, Inc.

Khandekar, M. L., and R. Lalheharry. 1996. An evaluation of Environment Canada's operational ocean wave model based on moored buoy data. Wea. and Forecasting 11:137–152.

Keeter, K. K., S. Businger, L. G. Lee, and J. S. Waldstreicher. 1995. Winter weather forecasting throughout the Eastern United States. Part IV: Lake effect snow. Wea. and Forecasting 10:42–609.

Kelley, J. G. W., F. Aikman, L. Breaker, W. G. Mellor. 1997. Coastal Ocean Forecasts: Realtime Forecasts of the Physical State of Water Level, 3-D Currents, Temperature and Salinity for the U.S. Coast Guard. Sea Technology 38(5):10–17.

Keshishian, L. G., and L. F. Bosart. 1987. A case study of extended East Coast frontogenesis. Mon. Wea. Rev. 115:100–117.

Kocin, P. J., P. N. Schumacher, R. F. Morales, Jr., and L. W. Uccellini, 1995. Overview of the 12-14 March 1993 superstorm. Bull. Amer. Meteor. Soc. 76:165–182.

Kosro, P. M., A. Huyer, S. R. Ramp, R. L. Smith, F. P. Chavez, T. J. Cowles, M. P. Abbott, P. T. Strub, R. T. Barber, P. Jessen, and L. F. Small. 1991. The structure of the transition zone between coastal waters and the open ocean off northern California, winter and summer 1987. J. Geophys. Res. 96:14707–14730.

Kushnir, Y., V. J. Cardone, J. G. Greenwood, and M. A. Cane. 1997. The recent increase in North Atlantic wave heights. J. Climate 10:2107–2113.

Laing, A. G., and J. M. Fritsch. 1997. The global population of mesoscale convective complexes. Quart. J. Roy. Meteor. Soc. 123:389–405.

Lapenta, W. M., and N. L. Seaman. 1990. A numerical investigation of East Coast cyclogenesis during the cold-air damming event of 27-28 February 1982. Part I. Dynamic and thermodynamic structure. Mon. Wea. Rev. 118:2668–2695.

Lapenta, W. M., and N. L. Seaman. 1992. A numerical investigation of East Coast cyclogenesis during the cold-air damming event of 27-28 February 1982. Part II: Importance of physical mechanisms. Mon. Wea. Rev. 120:52–76.

Liu, Y., S. L. Zhang, and M. K. Yau. 1997. A multiscale numerical study of Hurricane Andrew (1992). Part I. Explicit simulation and verification. Mon. Wea. Rev. 125:3073–3093.

Marks, F. D., and L. K. Shay. 1998. Landfalling tropical cyclones: Forecast problems and associated research opportunities. Bull. Amer. Meteor. Soc. 79:867–876

Mass, C. F. 1989. The origin of the Catalina eddy. Mon. Wea. Rev. 117:2406–2436.

Mass, C. F., and M. D. Albright. l987. Coastal southerlies and alongshore surges of the West Coast of North America. Evidence of mesoscale topographically trapped response to synoptic forcing. Mon. Wea. Rev. 115:1707–1738.

Mass, C. F., and N. A. Bond. 1996. Coastally trapped wind reversals along the United States West Coast during the warm season. Part II. Synoptic evolution. Mon. Wea. Rev. 124:446–461.

Meadows, G. A., L. A. Meadows, W. L. Wood, J. M. Hubertz, and M. Perlin. 1997. The relationship between Great Lakes water levels, wave energies, and shoreline damage. Bull. Amer. Meteor. Soc. 78:675–683.

Mettlach, T., D. Wang, and P. Wittmann. 1994. Analysis and prediction of ocean swell using instrumented buoys. J. Atmos. Ocean Tech. 11:506–524.

Monteverdi, J. P., and S. Johnson. 1996. A supercell thunderstorm with hook echo in the San Joaquin Valley, California. Wea. and Forecasting 11:246–261.

NASA Space Applications Advisory Committee. 1987. Linking Remote Sensing Technology and Global Needs. A Strategic Vision. Washington, D.C.

NRC (National Research Council). 1991. Toward a New National Weather Service - A First Report. National Academy Press, Washington, D.C.

NRC (National Research Council). 1992. Coastal Meteorology: A review of the state of the science. National Academy Press, Washington, D.C.

Nielsen, J. W. 1989. The formation of New England coastal fronts. Mon. Wea. Rev. 117:1380–1401.

Nielsen, J. W., and R. M. Dole. 1992. A survey of extratropical cyclone characteristics during GALE. Mon. Wea. Rev. 120:1156–1167.

Nielsen, J. W., and P. P. Neilley. 1990. The vertical structure of New England coastal fronts. Mon. Wea. Rev. 118:1793–1807.

Niziol, T. A., W. R. Snyder, and J. S. Waldstreicher. 1995. Winter weather forecasting throughout the eastern United States. Part IV. Lake-effect snow. Wea. and Forecasting 10:61–77.

NOAA, United States Department of Commerce. 1989. Hurricane Gilbert, 3-16 September 1988. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1990. Hurricane Hugo, 10-22 September 1989. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1992. The Halloween Nor'easter of 1991, East Coast of the United States....Maine to Florida and Puerto Rico. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1993a. Hurricane Andrew, 23-26 August 1992. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1993b. Hurricane Iniki, 6-13 September 1992. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1994. Superstorm of March 1993. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1997a. Hurricane Bertha, 5-14 July 1996. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

NOAA, United States Department of Commerce. 1997b. Hurricane Fran, 28 August-8 September 1996. Natural Disaster Survey Report. National Weather Service, Silver Spring, Maryland.

Nowlin, W. D., Jr., N. Smith, G. Needler, P. K. Taylor, R. Weller, R. Schmitt, L. Merlivat, A. Vezina, A. Alexiou, M. McPhaden, and M. Wakatsuchi. 1996. An ocean observing system for climate. Bull. Amer. Meteor. Soc. 2243–2273.

Ochi, M. A. 1994. On hurricane-generated seas: Ocean Wave Measurement and Analysis Proceedings, Second International Symposium, New Orleans, Louisiana, ASCE, pp. 374–387.

Paduan, J. D., and L. K. Rosenfeld. 1996. Remotely sensed surface currents in Monterey Bay from shore-based HF radar (Coastal Ocean Dynamics Application Radar). J. Geophys. Res. 101:20669–20686.

Parrish, R. H., A. Bakun, D. M. Husby, and C. S. Nelson. 1983. Comparative climatology of selected environmental processes in relation to eastern boundary current fish production. FAO Fish Rep. 291:731–778.

Parrish, R. H., C. S. Nelson, and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California Current. Biol. Oceanogr. 1:175–203.

Passarelli, R. E. Jr., and R. R. Braham Jr. 1981. The role of the winter land breeze in the formation of Great Lake snow storms. Bull. Amer. Meteor. Soc. 62:482–491.

Pielke, R. A., Jr., J. Kimple, and the Sixth Prospectus Development Team. 1997. Societal aspects of weather: Report of the sixth prospectus development team of the U.S. Weather Research Program to NOAA and NSF. Bull. Amer. Meteor. Soc. 78:867–876.

Pietrafesa, L. J., and G. S. Janowitz. 1980. On the dynamics of the Gulf Stream front in the Carolina capes. Proceedings of the Second International Symposium on Stratified Flows, Trondheim, Norway, June 24-27, 1980, Tapin Publishing Company, pp. 184–197.

Powell, M. D. 1980. Evaluations of diagnostic boundary layer models applied to hurricanes. Mon. Wea. Rev. 108:757–766.

Powell, M. D. 1982. The transition of the hurricane Frederic boundary layer wind field from the open Gulf of Mexico to landfall. Mon. Wea. Rev. 110:1912–1932.

Powell, M. D., and P. G. Black. 1990. The relationship of hurricane reconnaissance flight-level measurements to winds measured by NOAA's oceanic platforms. J. Wind Eng. Ind. Aerodyn. 36:381–349.

Powell, M. D., and S. H. Houston. 1996. Hurricane Andrew's wind field at landfall in south Florida. Part II. Applications to real-time analysis and preliminary damage assessment. Wea. and Forecasting 11:329–349.

Powell, M. D., P. P. Dodge, and M. L. Black. 1991. The landfall of hurricane Hugo in the Carolinas: Surface wind distribution. Wea. and Forecasting 6:379–399.

Powell, M. D., and S. H. Houston. 1997. Surface wind fields of 1995 hurricanes Erin, Opal, Luis, Marilyn, and Roxanne at landfall. Preprints, 22nd Conference on Hurricanes and Tropical Meteorology, American Meteorological Society. May 19-23, 1997, Fort Collins, Colorado. Pp. 90–91.

Powell, M. D., S. H. Houston, and T. A. Reinhold. 1996. Hurricane Andrew's landfall in South Florida. Part I. Standardizing measurements for documentation of surface wind fields. Wea. and Forecasting 11:304–328.

Ramp, S. R., J. L. McClean, C. A. Collins, A. J. Semtner, and K. A. S. Hays. 1997. Observations and modeling of the 1991-1992 El Niño signal off central California. J. Geophy. Res. 102:5553–5582.

Reinking, R. F., R. Caiazza, R. A. Kropfli, B. W. Orr, B. E. Martner, T. A. Niziol, G. P. Byrd, R. S. Penc, R. J. Zamora, J. B. Snider, R. J. Ballentine, A. J. Stamm, C. D. Bedford, P. Joe, and A. J. Koscielny. 1993. The Lake Ontario winter storms (LOWS) project. Bull. Amer. Meteor. Soc. 74:1828–1849.

Riordan, A. J. 1990. Examination of the mesoscale features of the GALE coastal front of 24-25 January 1986. Mon. Wea. Rev. 118:258–282.

Riordan, A. J., T. H. Anderson, and S. Chiswell. 1995. Small-scale structure of a coastal front as revealed by dual-doppler radar. Mon. Wea. Rev. 123:622–640.

Riordan, A. J., S. Raman, J. M. Davis, and S. Viessman. 1985. Measurements in the marine boundary layer near a coastal front. Geophys. Res. Lett. 12:681–684.

Roebber, P. J. 1989. The role of heat and moisture fluxes associated with large-scale ocean current meanders in maritime cyclogenesis. Mon. Wea. Rev. 117:1676–1694.

Rogers, E., and L. F. Bosart. 1986. An investigation of explosively deepening oceanic cyclones. Mon. Wea. Rev. 114:702–718.

Rosenfeld, L. R., F. B. Schwing, N. Garfield, and D. E. Tracy. 1994. Bifurcated flow from an upwelling center: A cold water source for Monterey Bay. Cont. Shelf. Res. 14:931–964.

Ross, D. B., and V. J. Cardone. 1978. A comparison of parametric and spectral hurricane wave prediction products. Pp. 647-665 in Turbulent Fluxes through the Sea Surface, Wave Dynamics, and Prediction, A. Favre and K. Hasselmann, eds. New York: Plenum Press

Rotunno, R., L., and J. Pietrafesa. 1996. Coastal meteorology and oceanography: Report of the third prospectus development team of the U.S. Weather Research Program to NOAA and NSF. Bull. Amer. Meteor. Soc. 77:1578–1585.

Sanders, F. 1986. Explosive cyclogenesis in the west central North Atlantic Ocean, 1981-1984. Part I: Composite structure and mean behavior. Mon. Wea. Rev. 114:1781–1811.

Sanders, F. J., and L. F. Bosart. 1985a. Mesoscale structure in the megalopolitan snowstorm of 11-12 February 1983. Part I. Frontogenetical forcing and symmetric instability. J. Atmos. Sci. 42:1050–1061.

Sanders, F., and L. F. Bosart. 1985b. Mesoscale structure in the megalopolitan snowstorm, 11–12 February 1983. Part II. Doppler radar study of the New England snowband. J. Atmos. Sci. 42:1398–1407.

Sanders, F. J. and J. R. Gyakum. 1980. Synoptic-dynamic climatology of the 'bomb'. Mon. Wea. Rev. 108:1589–1606.

Schultz, D. M., W. E. Bracken, L. F. Bosart, G. J. Hakim, M. A. Bedrick, M. J. Dickinson, and K. R. Tyle. 1997. The 1993 superstorm cold surge: Frontal structure, gap flow, and tropical impact. Mon. Wea. Rev. 125:5–39.

Schwing, F. B., T. L. Hayward, T. Murphree, K. M. Sakuma, A. S. Mascarenas, Jr., A. W. Mantyla, S. I. Larios Castillo, S. L. Cummings, K. Baltz, D. G. Ainley, and F. Chavez. 1997b. The state of the California Current, 1996-1997: Mixed signals from the tropics. CalCOF1 Rep. 38, in press.

Schwing, F. B., R. H. Parrish, and R. Mendelssohn. 1997a. Recent trends in the spatial variability of the SST and wind fields of the California Current system. In the Global Versus Local Changes in Upwelling Systems: Proceedings of the First International CEOS Workshop, (M. H. Durand, R. Mendelssohn, P. Cury, C. Roy, and D. Pauly, eds.) ORSTOM, Paris, France, in press.

Sholkovitz, E., G. Allsup, R. Arthur, and D. Hosom. 1998. Aerosol Sampling from Ocean Buoys Shows Promise. EOS, Transactions, Amer. Geophys. Union 79(3):29–37.

Stauffer, D. R., and T. T. Warner. 1987. A numerical study of Appalachian cold-air damming and coastal frontogenesis. Mon. Wea. Rev. 115:799–821.

Steenburgh, W. J., and C. F. Mass. 1996. Interaction of an intense extratropical cyclone with coastal orography. Mon. Wea. Rev. 124:1329–1352.

Stensrud, D. M, R. L. Gall, and M. K. Nordquist. 1997. Surges over the Gulf of California during the Mexican monsoon. Mon. Wea. Rev. 125:417–437.

Strub, P. T., J. S. Allen, A. Huyer, and R. L. Smith. 1987a. Large-scale structure of the spring transition in the coastal ocean off western North America. J. Geophys. Res. 92:1527–1544.

Strub, P. T., J. S. Allen, A. Huyer, R. L. Smith, and R. C. Beardsley. 1987b. Seasonal cycles of currents, temperatures, winds, and sea level over the northeast Pacific continental shelf: 35'N to 48'N. J. Geophys. Res. 92:1507–1526.

Thompson, R. L., J. M. Lewis, and R. A. Maddox. 1994. Autumnal return of tropical air to the Gulf of Mexico's coastal plain. Wea. and Forecasting 9:348–360.

Thompson, W. T., S. D. Burk, and J. Rosenthal. 1997. An investigation of the Catalina Eddy. Mon. Wea. Rev. 1135–1146.

Uccellini, L. W., D. Keyser, K. F. Brill, and D. H. Wash. 1985. The Presidents' Day cyclone of February 1979: Influence of upstream trough amplification and associated tropopause folding on rapid cyclogenesis. Mon. Wea. Rev. 113:962–988.

Uccellini, L. W., P. J. Kocin, R. A. Petersen, C. H. Wash, and K. F. Brill. 1984. The Presidents' Day cyclone of 18-19 February 1979: Synoptic overview and analysis of the subtropical jet streak influencing the precyclogenetic period. Mon. Wea. Rev. 112:31–55.

Uccellini, L. W., P. J. Kocin, R. S. Schneider, P. M. Stokols, and R. A. Dorr. 1995. Forecasting the 12-14 March 1993 superstorm. Bull. Amer. Meteor. Soc. 76:183–199.

Uccellini, L. W., R. A. Petersen, K. F. Brill, P. J. Kocin, and J. J. Tuccillo. 1987. Synergistic interactions between an upper-level jet streak and diabatic processes that influence the development of a low-level jet and a secondary coastal cyclone. Mon. Wea. Rev. 115:2227–2261.

U.S. GLOBEC. 1994. Eastern Boundary Current Program. A Science Plan for the California Current. U.S. GLOBEC Report No. I University of California at Berkely, Berkeley, California. 99 pp.

Vukovich, F. M., J. W. Dunn, and B. W. Crissman. 1991. Aspects of the evolution of the marine boundary-layer during cold air outbreaks off the southeast coast of the United States. Mon. Wea. Rev. 119:2252–2278.

Wakimoto, R. M. 1987. The Catalina Eddy and its effect on pollution over southern California. Mon. Wea. Rev. 115:837–855.

WAMD1 Group. 1988. The WAM model-a third generation ocean wave prediction model. J. Phys. Oceanog. 18:1275–1810.

Wayland, R., and S. Raman. 1989. Mean and turbulent structure of a baroclinic marine boundary-layer during the 28 January 1986 cold air outbreak (GALE 86). Boundary-Layer Meteor. 48:227–254.

Weiss, S. J. 1992. Some aspects of forecasting severe thunderstorms during cool-season return flow episodes. J. Appl. Meteor. 31:964–982.

Winant, C. D., R. C. Beardsley, and R. E. Davis. 1987. Moored wind, temperature, and current observations made during Coastal Ocean Dynamics Experiments I and 2 over the northern California continental shelf and upper slope. J. Geophys. Res. 92:1569–1604.

Winant, C. D., and C. E. Dorman. 1997. Seasonal patterns of surface windstress and heat flux over the Southern California Bight. J. Geophys. Res. 102:5641–5653.

Woodruff, S. D., R. J. Slutz, R. L. Jenne, and P. M. Steurer. 1987. A comprehensive ocean-atmosphere data set. Bull. Amer. Meteor. Soc. 68:1239–1250.

Xie, L., L. F. Pietrafesa, E. Böhm, and X. Li. 1997. Gulf stream-hurricane interactions off North Carolina coast. Preprints, 22nd Conference on Hurricanes and Tropical Meteorology. American Meteorological Society, May 19-23, 1997. Fort Collins, Colorado. Pp. 429–430.

APPENDIXES

APPENDIX A

List of Contributors

Robert Adriance, BOAT/U.S., Alexandria, Virginia

Alfred Beeton, Chief Scientist Emeritus, National Oceanic and Atmospheric Administration, Washington, D.C.

Peter Black, Hurricane Research Division, National Oceanic and Atmospheic Administration, Miami, Florida

Louis Botsford, Wildlife, Fish and Conservation Biology, University of California, Davis

Larry Breaker, National Weather Service, National Oceanic and Atmospheric Admininstration, Washington, D.C.

William Busch, University of Maryland, Baltimore

Brad Butman, Woods Hole Field Center, Woods Hole, Massachusetts

David Checkley, Scripps Institution of Oceanography, LaJolla, California

Joseph Cione, Hurricane Research Division, National Oceanic and Atmospheric Administration, Miami, Florida

Brad Colman, National Weather Service, Seattle, Washington

Laura Cook, Marine Weather Services, National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland

Edward Essick, Public Constituent, San Rafael, California

A. L. Hamilton, Esq., Public Constituent, Cameron Park, California

Andrew Horowitz, Office of Meteorology, National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland

Jerry Galt, National Oceanic and Atmospheric Administration, Seattle, Washington

David Gilhousen, National Data Buoy Center, Stennis Space Center, Mississippi

Bob Guza, Scripps Institution of Oceanography, LaJolla, California

Robert Leffler, Office of Meteorology, National Weather Service, National Oceanic and Atmospheric Administration, Silver Spring, Maryland

Jerry McCall, National Data Buoy Center, Stennis Space Center, Mississippi

Hugh Milburn, Pacific Marine Environmental Laboratory, Seattle, Washington

Christopher N. K. Mooers, University of Miami, Miami, Florida

Tom Murray, National Oceanic and Atmospheric Administration, Washington, D.C.

Wendell Nuss, The Naval Postgraduate School, San Rafael, California

Leonard Pietrafesa, North Carolina State University, Raleigh

Greg Purvis, United States Coast Guard, Washington, D.C.

Dave Reynolds, National Weather Service, Monterey, California

G. Curtis Roegner, University of Oregon, Charleston

Tom Ross, National Climatic Data Center, Raleigh, North Carolina

Douglas Scally, National Data Buoy Center, Stennis Space Center, Mississippi

Franklin Schwing, Pacific Fisheries Environmental Group, Pacific Grove, California

Scott Stripling, Forecast Office, San Juan, Puerto Rico

Louis Uccellini, National Weather Service, National Oceanic and Atmospheric Administration, Washington, D.C.

Thomas Weingartner, University of Alaska, Fairbanks

Joe Wiggins, United States Coast Guard, Washington, D.C.

Clint Winant, Scripps Institution of Oceanography, LaJolla, California

Bruce Wright, Office of Oil Spill Damage Assessment and Restoration, National Oceanic and Atmospheric Administration, Juneau, Alaska

APPENDIX B

Letter from the Climate Research Committee to the Department of State

October 17, 1997

The Honorable John H. Gibbons
Assistant to the President for Science and Technology
Executive Office of the President
Office of Science and Technology Policy
Washington, D.C. 20502

Dear Dr. Gibbons:

The United Nations Framework Convention on Climate Change has as one of its ultimate objectives the stabilization of greenhouse-gas concentrations to prevent dangerous anthropogenic interference with the climate system. Important to this objective is a continuous quantitative record of climate. Without this record, *we cannot credibly assess natural climate variability, estimate anthropogenic effects on climate, judge the efficacy of negotiated mitigation efforts, or consider appropriate mid-course policy options.*

Unfortunately, a number of evaluations of the state of pertinent observation systems, by the National Research Council and others, have concluded that our ability to establish and maintain these records is deteriorating. These evaluations include Report No. 855 (1997) of the World Meteorological Organization, and the reports listed in Attachment 1. We also draw your attention to the World Climate Research Programme's message to the Conference of the Parties to the UN Framework Convention on Climate Change. It states that without action to reverse the decline in observation networks, we will be less able to characterize climate change in the next 25 years than we have been during the past 25 years.

Article 5(b) of the UN Framework states that the parties shall "...support international and intergovernmental efforts to strengthen systematic observation...." Our ability to assess changes in our planet's climate will be at risk without action to reverse the deterioration of our climate observing systems. On behalf of the Climate Research Committee, I urge you to use your good offices to ensure that the United States implements Article 5(b) and that other parties to the convention do so as well.

Sincerely,

Thomas R. Karl

Thomas R. Karl
Chairman, Climate Research Committee

Attachments

- *TOGA: A Review of Progress and Future Opportunities. National Academy Press. 66 pp. 1990*

"It is ironic and unfortunate that the new TOGA initiatives for long-term observations of the global atmosphere are being implemented in the face of an overall deterioration in some of the key elements of the World Weather Watch, whose long-term stability was taken for granted in the TOGA strategy document...some of the weather services are being forced to cut back on their contributions to the conventional observing system." (p. 55)

"To maintain a viable atmospheric observing system...continuous daily operation of upper-air stations in the equatorial Pacific and elsewhere in the tropics [is necessary]." (p. 55)

- *Opportunities in the Hydrologic Sciences. National Academy Press. 348 pp. 1991*

"It is therefore difficult for agencies and individuals to be doggedly persistent about the continuity of high-quality hydrologic data sets...We must reemphasize the value and importance of observational and experimental skills." (p. 6)

"Improvements in the use of operational data require that special attention be given to the maintenance of continuous long-term data sets of established quality and reliability. Experience has shown that exciting scientific and social issues often lead to an erosion in the data collection programs that provide a basis for much of our understanding of hydrologic systems and the documented changes in regional and global environments." (p. 11)

- *A Decade of International Climate Research: The First Ten Years of the World Climate Research Programme. National Academy Press. 55 pp. 1992*

"The WCRP has not been successful in convincing [others] ...to halt the decay of conventional observing systems in the tropics." (p. 49)

"Despite their importance, present capabilities for monitoring the climate system are...deteriorating....Substantial effort by the WCRP...is required to...ensure baseline institutional and governmental commitment to the system." (p. 54)

- *Ocean-Atmosphere Observations Supporting Short-Term Climate Predictions. National Academy Press. 51 pp. 1994*

“When...a set of observations begun under research funding is suggested for ‘transition’ to an operational agency, both the research and operational sponsors must be clear that the receiving agency has a commitment to sustain the observations, the technical capability to do so successfully, and avenues for the ongoing involvement of scientists...” (p. 2)

“Most satellite estimates will always require coincident direct-surface and upper-air measurements to perform the ongoing task of calibration, and surface platforms will be needed to make measurements not possible by remote sensing. The best determinations of the geophysical fields of interest will be obtained by combining satellite and direct measurements, blending the unmatched spatial coverage of satellite sensors with the direct observations of greater accuracy or more direct connections to the geophysical parameters of concern. Therefore, a well-chosen network of direct observations will become more, not less important as satellite techniques advance.” (p. 3)

- *Preserving Scientific Data on Our Physical Universe: A New Strategy for Archiving the Nations Scientific Information Resources. National Academy Press. 67 pp. 1995*

“Observed data provide a baseline for determining rates of change and for computing the frequency of occurrence of unusual events. They specify the observed envelope of variability. The longer the record, the greater our confidence in the conclusions we draw from it.” (p. 1)

“NOAA, as well as every other federal science agency, should ensure that:

- all its data are shared and readily available,
- It fulfills its responsibility for quality control, metadata structure, documentation, and creation of its data products,
- It participates in electronic networks that enable access, sharing, and transfer of data; and
- It expressly incorporates the long-term view in planning and carrying out its data management responsibilities.” (p. 9)

- *Learning to Predict Climate Variations Associated with El Niño and the Southern Oscillation. National Academy Press. 171 pp. 1996*

“For future progress in the study of climate variations, it is essential to maintain what we already have, including the upper-air observing network, satellite altimetry, and the upper-ocean and surface-meteorological measurements made routinely in and over the ocean.” (p. 137)

APPENDIX C

Letter from the U.S. Coast Guard

9494
11/19/97

National Academy of Sciences
2101 Constitution Avenue N.W.
Washington D.C. 20418-0001
Att: Dr. William A. Sprigg

Dr. Sprigg:

Thank you for inviting the Coast Guard to participate in the Essential Meteorological Buoy and CMAN Systems Data and Information Gathering Session.

As discussed at the session the C-MAN and Meteorological Data Buoys system is a very important tool used by the Coast Guard for search and rescue planning and response. The Coast Guard receives approximately 50, 000 requests for assistance a year, 95% of these occurring between shore and 50 NM offshore, with a total of 4,992 lives saved and $ 2213.8 million property loss prevented in FY 96. Weather data from the C-MAN and meteorological Data Buoys are very important in determining the correct Coast Guard resources to dispatch, particularly our surface vessels. The data is critical in forecasting on scene weather, which is used to formulate search plans, optimizing search effectiveness through complex leeway and drift calculations. Increasing the number of C-MAN and Meteorological Data Buoys would help the Coast Guard meet its goal of 90% lives and 70% property saved at sea.

Sincerely,

J E Wiggins

J. E. WIGGINS
Commander, U. S. Coast Guard
Chief of Policy Division, Office of Search and Rescue

APPENDIX D

Letter from BOAT/U.S.

December 16, 1997

National Research Council
Board of Atmospheric Sciences and Climate
2101 Constitution Ave, NW   20418

Dear Sirs;

This is to express the support of Boat Owners Association of the United States (BOAT/U.S.) for the National Weather Service's C-MANN Weather Buoy System. BOAT/U.S. represents over a half million members from all 50 states. Of these Members, almost 150,000 insure their boats through a unique "Loss Prevention Program" that seeks not just to insure boats but also to learn why losses occured and to educate members on how they could have been avoided.

It is almost axiomatic that to avoid trouble on the water a boat's skipper must constantly be aware of the weather conditions. As a source of real-time weather and sea-state information, the C-MANN system has proven to be invaluable. No other source of information—radio, television, or VHF radio broadcasts—do as much to help boaters avoid dangerous weather conditions.

For the past few seasons, BOAT/U.S. has promoted use of the C-MANN system in both the *BOAT/U.S. Magazine* and in *Seaworthy*, a Loss-Prevention publication of the Marine Insurance Division. The result is that the BOAT/U.S. membership has come to rely on the C-MANN buoys to insure their safety on the water.

Sincerely,

Robert Adriance, Jr.

Robert Adriance, Jr.
Assistant Vice President, Technical Services

APPENDIX E

Findings from NOAA Natural Disaster Survey Reports

HURRICANE GILBERT[1]
3–16 SEPTEMBER 1988

Finding 1.4 (Need for Higher Resolution in NWS Products)

“New technologies exist that can provide the opportunity for better understanding and study of hurricane situations. It was apparent from this survey and others that a need for heavy rain and wind speed information on a higher spatial resolution along the coast and over open water exists. Currently, there is a paucity of observations from today’s infrastructure. Such information along and near the coast is crucial during hurricane situations.........”

HURRICANE HUGO
10–22 SEPTEMBER 1989

Finding 3.1

“The density of surface observations in the Caribbean and the Carolinas is extremely low. This posed a significant problem to forecasters trying to obtain information during the storm.”

---

[1] References for each disaster survey are found in the reference section at the end of this report under “NOAA, United States Department of Commerce,” listed by the name of the storm under specific study.

THE HALLOWEEN NOR'EASTER OF 1991
EAST COAST OF THE UNITED STATES...
MAINE TO FLORIDA AND PUERTO RICO
28 OCTOBER–1 NOVEMBER 1991

Finding 2

"The availability and continuity of an adequate, reliable, and timely data base (consisting of meteorological observations, sea state conditions, and water level measurements) is vital if NWS offices are to provide accurate and timely coastal flood watches and warnings. This includes those areas behind barrier islands, particularly where large rivers or embayments are involved (e.g., Pamlico Sound) so that adequate warning for seiches and coastal flooding can be given."

Recommendation 2-3

"The NWS should install an adequate marine observational network that would fill the gaps in the current arrangement and would provide the minimum coverage necessary for the reconfigured forecast areas in the modernized NWS. This network should include shoreline/shallow water wave height measurements."

HURRICANE ANDREW
23–26 AUGUST 1992

Finding I.I.1

"Satellite imagery is the only source of information over data-sparse oceans, except for ships which generally avoid rough weather."

Finding II.I.1

"The U.S. Coast Guard (USCG) has decided to remove all large navigational buoys and replace them with other, smaller types of buoys. The replacement buoys are too small to be fitted with meteorological instruments. Loss of the current buoys, in the near future, will mean the loss of hourly data from stations along the Atlantic and Gulf of Mexico coasts."

Recommendation II.I.1

"The NWS, through its National Data Buoy Center, should ensure that sufficient capabilities are present to maintain hourly observations along the Atlantic and Gulf of Mexico coastal waters."

HURRICANE INIKI
6–13 SEPTEMBER 1992

Finding 3.4

"Although Iniki passed between the existing data buoy network south and west of Hawaii, the sea height information provided by this network was the only real-time data available and allowed CPHC forecasters to make reasonable coastal sea height forecasts."

THE GREAT NOR'EASTER OF DECEMBER 1992
10–14 DECEMBER 1992

Finding II-2

"Coastal and offshore data (e.g., wind, seas) are especially important to forecasters during coastal flood events for the determination of storm surge and wave battery. Limited observational data were available from a large area of the ocean off the northeast U.S. coast at the time the storm occurred. This lack of data coverage was also addressed in the Halloween Nor'easter of '91 and the Northeast Blizzard of '78 reports. The loss of the Coast Guard's Large Navigational Buoys just off the Delaware coast barely a month prior to the Great Nor'easter of December 1992 proved to be a particularly great handicap to forecasters."

Recommendation II-2

"The NWS should supplement the present marine observational network in order to fill the gaps which presently exist and to provide the minimum coverage necessary for the reconfigured forecast areas in the modernized NWS. This network should include shoreline/shallow water wave height measurements. Towards this mandate, the national Marine Observation Network (MAROB) initiative must continue to be pressed forward."

SUPERSTORM OF MARCH 1993
12–14 MARCH 1993

Finding 1.1

"NWS could have made improvements to the Coastal Flood Watches and Warnings for the Florida Gulf Coast. A significant contributing factor to this problem was the insufficient number of Gulf of Mexico marine and coastal observations, water level measurements, and a lack of storm surge guidance products to assist in forecasting these events. NWS has never had sufficient marine observations nor enough real-time water level information. The need for these data were also noted as deficiencies in the Disaster Survey Team report on the Halloween Nor'easter of 1991. Chapter 4 and Finding and Recommendation 4.1 further address these problems."

Finding 4.1

"High availability of buoy and coastal station observation data are vital to support the NWS marine forecast and warning program. The scarcity of marine weather observations greatly impacted the quality of NWS marine forecast and warning services during the Superstorm. A similar finding was noted in previous DST Reports."

Recommendation 4.1

"NOAA should pursue additional marine observation sources including collaborative efforts with state and private organizations."

Finding 4.3

"The NGWLMS [Next Generation Water Level Measurement System] can support up to 11 ancillary measurements such as air temperature, atmospheric pressure, and wind speed and direction. Optimization of this additional capability could partially compensate for the scarcity of marine observations."

Recommendation 4.3

"NWS should take action to include the addition of environmental sensors at NGWLMS stations to measure additional parameters for relay in real-time to NMC (now NCEP) for processing and dissemination on the Automated Field Observation System (AFOS)."

HURRICANE BERTHA
5–14 JULY 1996

Finding 9:

"Rip currents associated with Bertha resulted in 3 deaths and over 100 rescues along the Florida and southeast Georgia coasts. Heavy surf advisories were cancelled before two of the deaths occurred. Lack of data off the southeast Florida coast forced forecasters to estimate wave heights from local wind forecasts."

Recommendation 9:

"NWSFO Miami must redouble its efforts at seeking partnerships with Beach Patrol units and other organizations to secure critical wave height and surf reports."

HURRICANE FRAN
28 AUGUST–8 SEPTEMBER 1996

Finding 6:

"Coastal flood warnings and forecasts could be improved with access to better ocean level data. There is a lack of real-time observations along the most critical east-facing beaches. For example, NWFSO Wilmington, North Carolina, has access to only four automated coastal observing sites along its 125-mile (approximately 200 km) coastal area of responsibility."

Recommendation 6:

"Efforts to properly equip coastal areas with real-time ocean level observations, for both land and marine areas, should be intensified. The NWS and the National Ocean Service (NOS) should collaborate to provide NWS operational access to NOS data and real-time graphing of data. The Chesapeake Bay and other Sea, Lake, and Overland Surge from Hurricanes (SLOSH) basins should be updated on a scheduled basis to maximize the model's output and subsequent NWS surge forecasts."

APPENDIX F

Sample Weekly Status Report, National Data Buoy Center

February 27, 1998

NDBC DATA PLATFORM STATUS REPORT
February 19, 1998 - February 26, 1998

MOORED BUOYS

			PERCENT OF DATA DISSEMINATED IN REAL TIME				
STATION ID	HULL NO./CONFIG. AND LOCATION	LOCATION LAT / LONG	SEA LEVEL PRESS	WIND SPEED & DIR	AIR TEMP	SEA SFC TEMP	SIG WAVE HT.
41001*	6N13 /D E HATTERAS	34.68N/ 72.64W	100	S	100	100	S
41002*	6N35 /D S HATTERAS	32.27N/ 75.19W	99	99	99	99	99
41004	3D18 /D EDISTO	32.51N/ 79.10W	99	99	99	S	99
41008*	3D52 /V GRAYS REEF	31.40N/ 80.87W	98	98	98	98	98
41009	6N19 /D CANAVERAL	28.50N/ 80.18W	100	100	100	100	100
41010	6N36 /D CANAVERAL EAST	28.89N/ 78.55W	100	100	100	100	100
42001*	10D08/V MID GULF	25.93N/ 89.65W	96	96	96	96	95
42002*	10D07/V W GULF	25.89N/ 93.57W	99	99	99	99	99
42003*	10D09/V E GULF	25.94N/ 85.91W	100	100	S	100	100
42007	3D23 /D OTP	30.09N/ 88.77W	98	61	42	98	98
42019	3D48 /D FREEPORT	27.92N/ 95.35W	100	100	100	100	100
42020	3D45 /D CORPUS CHRISTI	26.92N/ 96.70W	100	100	100	100	100
42035	3D36 /V GALVESTON	29.25N/ 94.41W	99	99	99	99	99
42036	3D32 /D W. TAMPA	28.51N/ 84.51W	99	99	99	99	99
42039	3D20 /D PENSACOLA S.	28.78N/ 86.04W	S	S	S	S	S
42040	3D30 /D MOBILE SOUTH	29.20N/ 88.25W	99	99	99	99	99
44004*	6N37 /D HOTEL	38.46N/ 70.69W	45	49	48	43	32
44005*	6N03 /D GULF OF ME	42.90N/ 68.94W	R	R	R	R	R
44007	3D19 /V PORTLAND	43.53N/ 70.14W	99	99	99	99	99
44008*	3D17 /V NANTUCKET	40.50N/ 69.43W	S	S	S	S	S
44009*	3D43 /D DELAWARE BAY	38.46N/ 74.70W	95	95	S	95	95
44011*	6N23 /D GEORGES BANK	41.08N/ 66.58W	100	100	100	100	100
44013	3D06 /D BOSTON	42.35N/ 70.69W	99	99	99	99	99
44014	3D26 /D VIRGINIA BEACH	36.58N/ 74.83W	S	S	S	S	S
44025	3D05 /D LONG ISLAND	40.25N/ 73.17W	80	82	81	79	75
45001*	3D27 /V MID SUPERIOR	48.06N/ 87.78W	R	R	R	R	R
45002*	3D37 /V N MICHIGAN	45.30N/ 86.42W	R	R	R	R	R
45003*	3D14 /V N HURON	45.32N/ 82.77W	R	R	R	R	R
45004*	3D38 /V E SUPERIOR	47.56N/ 86.55W	R	R	R	R	R
45005*	3D33 /D W ERIE	41.68N/ 82.40W	R	R	R	R	R
45006*	6N10 /D W SUPERIOR	47.32N/ 89.87W	R	R	R	R	R
45007*	3D35 /D S MICHIGAN	42.68N/ 87.03W	R	R	R	R	R
45008*	2DV1 /D S HURON	44.28N/ 82.42W	R	R	R	R	R
46001*	6N29 /D GULF OF AK	56.30N/148.17W	98	98	98	98	98
46002*	6N04 /D OREGON	42.53N/130.26W	99	99	99	99	99
46003*	6N21 /D S ALEUTIANS	51.85N/155.92W	11	11	11	11	10
46005*	6N33 /D WASHINGTON	46.08N/131.00W	99	99	S	99	99

46006*	6N28 /D SE PAPA	40.84N/137.49W	89	89	89	89	89
46011	3D15 /D SANTA MARIA	34.88N/120.87W	100	100	100	100	100

MOORED BUOYS			PERCENT OF DATA DISSEMINATED IN REAL TIME				
STATION ID	HULL NO./CONFIG. AND LOCATION	LOCATION LAT / LONG	SEA LEVEL PRESS	WIND SPEED & DIR	AIR TEMP	SEA SFC TEMP	SIG WAVE HT.
46012	3DV06/D HALF MOON BAY	37.39N/122.73W	S	S	S	S	S
46013	3D09 /V BODEGA	38.23N/123.30W	R	R	R	R	R
46014	3D08 /D PT ARENA	39.22N/123.97W	99	99	99	99	99
46022	3D49 /V EEL RIVER	40.74N/124.51W	79	79	79	79	79
46023	10D04/D PT ARGUELLO	34.71N/120.97W	99	99	99	99	99
46025	3D13 /V CATALINA RDG	33.75N/119.08W	93	93	93	93	92
46026*	3D16 /D SAN FRANCISCO	37.75N/122.82W	99	99	99	S	99
46027	3D53 /V ST GEORGES	41.85N/124.39W	R	R	R	R	R
46028	3D12 /D C SAN MARTIN	35.74N/121.88W	R	R	R	R	R
46029*	3DV01/V COL RIVER BAR	46.18N/124.19W	S	S	S	S	S
46030	3DV07/V BLUNTS REEF	40.42N/124.53W	S	S	S	S	S
46035	12D02/D BERING SEA	56.91N/177.81W	79	79	79	77	72
46041	3DV05/D C ELIZABETH	47.42N/124.52W	S	S	S	S	S
46042	3D42 /D MONTEREY	36.75N/122.41W	R	R	R	R	R
46045	3DV08/D REDONDO BEACH	33.84N/118.45W	100	100	100	100	S
46050	3D40 /D YAQUINA BAY	44.62N/124.53W	S	S	S	S	S
46054	10D12/D SANTA BARB W	34.27N/120.45W	95	95	95	95	95
46059	6N32 /D CALIFORNIA	37.98N/130.00W	S	100	S	100	100
46060	3DV04/V N. P.WM. SOUND	60.58N/146.83W	100	100	100	100	100
46061	6N34 /V S. P.WM. SOUND	60.22N/146.83W	100	100	100	100	100
46062	10D06/D POINT SAN LUIS	35.10N/121.01W	99	99	99	99	99
51001*	6N24 /G NW HAWAII	23.40N/162.27W	99	99	99	99	99
51002*	6N26 /G SW HAWAII	17.19N/157.83W	100	100	100	100	100
51003*	6N18 /G W HAWAII	19.14N/160.81W	100	100	100	100	100
51004*	6N20 /G SE HAWAII	17.44N/152.51W	D	D	D	D	D
51028	3D44 /D CHRISTMAS ISL	.00N/153.88W	95	95	95	95	95

```
Total Base Funded Buoys: 30
Total Other Buoys      : 35
--------------------------
Total Moored Buoys     : 65
```

*Base funded station of National Weather Service (NWS);
however, all stations report data to NWS.

REMARKS:

41001 - Wind data failed 9/2/97,wave data failed 11/03/97.
41004 - Water temp data failed 2/2/97.
42003 - Air temp data failed 9/6/97.
42007 - Wind and air temp data failed 2/22/98.
42039 - Station failed 2/6/98.
44004 - Parity errors in data.
44005 - Buoy adrift 12/2/97, recovered to port 12/4/97.
44008 - Water temp data failed 12/10/97, station failed 1/3/98.
44009 - Air temp data failed 2/6/98.
44014 - Station failed 10/20/97, service scheduled week of 3/2/98.
44025 - Parity errors in data.
45001 - Buoy recovered for winter 10/30/97.
45002 - Redeployment scheduled week of 3/2/98.
45003 - Redeployment scheduled week of 3/2/98.
45004 - Buoy recovered for winter 10/30/97.

45005 - Redeployment scheduled week of 3/2/98.
45006 - Buoy recovered for winter 10/30/97.
45007 - Redeployment scheduled week of 3/2/98.
45008 - Buoy recovered for winter 11/10/97.
46003 - Parity errors in data.
46005 - Air temp data failed 11/19/97.
46006 - Parity errors in data.
46012 - Water temp failed 10/23/96, station failed 7/12/97, service scheduled week of 3/9/98.
46013 - Buoy recovered to port 11/4/97, redeployment scheduled week of 3/9/98.
46022 - Station failed 2/24/98, restored 2/25/98.
46026 - Water temp data failed 11/24/97.
46027 - Buoy adrift and beached 10/4/97, recovered to port 10/9/97.
46028 - Buoy adrift 7/17/97, recovered to port 7/22/97, redeployment scheduled week of 3/16/98.
46029 - Air temp data failed 6/26/97, water temp data failed 11/17/97, pressure data failed 12/27/97, remaining data failed 1/25/98.
46030 - Station failed 10/22/97.
46035 - Parity errors in data.
46041 - Air temp data failed 6/2/96, station failed 6/14/97, replacement scheduled 4/27/98.
46042 - Buoy adrift 10/25/97, recovered to port 10/28/97, redeployment scheduled week of 3/16/98.
46045 - Wave data failed 1/20/98.
46050 - Station failed 1/15/98.
46059 - Air temp and pressure data failed 12/10/97.
51004 - Buoy confirmed adrift 1/15/98, replacement scheduled 3/30/98.

NDBC MOORED BUOY STATION LEGEND:

HULL NO./CONFIGURATION

Hull Type	Anemometer Ht	Payload Types
12D - 12-meter discus		
10D - 10-meter discus	10 m	D - DACT
6N - 6-meter NOMAD	5 m	V - VEEP
3D, 3DV - 3-meter discus	5 m	G - GSBP
2D - 2.4-meter discus	3 m	

Example: 6N29/G means 6-meter NOMAD buoy, hull number 29, with GSBP payload.

DATA STATUS

S - Sensor/system failure
R - Buoy Retrieved
N - No sensor installed

D - Buoy off station or adrift
E - Data under evaluation, not reported

C-MAN STATIONS			PERCENT OF DATA DISSEMINATED IN REAL TIME					
STATION ID	LOCATION/CONFIG.	LOCATION LAT / LONG	SEA LEVEL PRESS	WIND SPEED &DIR	AIR TEMP	SEA SFC TEMP	SIG WAVE HT.	TID

APPENDIX G

Data Buoy Impacts on Warning and Forecast Operations

Thomas Ainsworth, National Weather Service, Western Region

Data buoys provide reliable real-time (hourly) meteorological and oceanographic data to NWS forecasters and the general public. Moored data buoys in the eastern Pacific have repeatedly provided crucial upstream intelligence in support of all Western Region warning and forecast programs, in both coastal and inland areas. At least half of all NWS marine warnings are based principally on buoy (and C-MAN) data. Sea pressure, pressure tendency, and wind observations from buoys are also used for synoptic warnings for inland areas of the Western Region. Buoy data accurately assesses storm strength, wind speeds, and sea conditions before storms make landfall and permit forecasters to compare NCEP model prognoses to ground truth.

Consider:

1) November 15, 1994. Buoy 46002 observed the central pressure of a deepening cyclone to be 995 mb, much less than model forecasts. The forecaster at NWSFO Portland wrote in the State Forecast Discussion (SFD) product, "...WITH DEEPR LOW THAN PROGS INDICATED WILL ISSUE HIGH WIND WARNING FOR COASTAL ZONES." The Seattle forecaster wrote, "...(observation from buoy 46002 indicate) LOW WAS POORLY INITIALIZED BY FORECAST MODELS...WILL HOLD ONTO (high wind) WATCH." Wind gusts from this storm were in excess of 60 mph on the Oregon coast and 40 to 50 mph winds affected Western Washington.

2) January 6, 1995. The Seattle forecaster justified the Gale Warning for the Washington coast by citing buoy data in his State Forecast Discussion. "...CLASSIC...RAPIDLY DVLPG SFC LOW BOMB...BUOY 46059 HAS DROPPED 8MB IN LAST 4 HOURS..."

3) Dec. 12, 1995. Offshore buoys were first to indicate the storm approaching had all-time EPAC low SLP (ships were vacating the storm area). Forecasters confidently issued wind warnings with remarkable 24h lead time. So much lead time in Seattle, for example, the warnings were

published in the next morning's edition of newspapers (with graphical explanations), still 9-12 hrs before the height of the storm which produced 100+ mph winds on the coast and verified high wind warnings east of the Cascade Mountains.

Marine customers have repeatedly explained to WR NWS offices their primary requirement for buoy data is for ensuring the safety of their crew and passengers onboard. Several examples of customer input received over the years include:

1) A personal call from a customer in the Western Region reported he did not take his boat out to buoy 46025 ("Santa Monica Basin" buoy) on February 7, 1995, because of the hourly buoy reports. The buoy was observing continuous swell at 8-10 feet. Forecasts of decreasing swell were adjusted because of the buoy observations.

2) After the start of crabbing season near San Francisco was delayed 20 days, commercial fishermen were very anxious to start on November 27, 1994. Observations from Buoy 46012 ("Half Moon Bay" buoy) included 12 foot seas and 25 kt winds. Fortunately, many boats postponed their trips to sea. Two boats that went out, never returned. There were four fatalities.

3) According to responses from sailors and fishermen in California, the most desired information from the NOAA Weather Radio broadcast is the hourly buoy observations.

4) NWS participation in annual Western Region boat shows allows interaction with over one million people in marine related industries. Service evaluation forms filled out by show patrons consistently emphasize the importance of buoy data to their operations and safety.

West coast radars are ineffective in assessing meteorological and oceanographic conditions in the coastal zone because of their base elevation (as high as 7500 ft in southern Oregon) and beam blockage by mountainous terrain. Coverage patterns by the Portland and Medford, Oregon, radars exclude the central Oregon coastal waters completely. Without buoy data, ground truth information of offshore conditions would be very difficult to assess. Denying forecasters the benefits of buoy data would directly affect the way NWS offices support news media, citizens with commercial and recreational marine interests, coastal residents, harbor masters, and other government agencies.

All NDBC-operated data buoys measure wind speed, direction, and gust; barometric pressure; air temperature; sea surface temperature; wave height; and wave period. No other instrument provides forecasters with spectral wave information. Along with the spectral energies, measurements such as significant wave height, wave steepness, average wave period, and dominant period are also derived from buoy observations. NDBC recently began posting on its home page an experimental, automated sea-swell separation method based on the energy spectra. In addition to their use in operational weather forecasting, warnings, and atmospheric models, moored buoy data are used for scientific and research programs, during emergency response to chemical spills, in legal proceedings, and in engineering design. Sea truth observations from buoys help calibrate remotely sensed measurements from spacecraft. Fisherman and sailors on ocean-going vessels, both commercial and recreational, depend on NOAA Weather Radio broadcasts of buoy observations for purposes of crew and passenger safety, and use buoy observations in deciding whether to leave port.

The loss of NOAA data buoys does not leave NWS forecasters, and the numerous other consumers of buoy data, completely without data. There are other instruments available that provide some data from the marine environment in much different fashions than moored buoys and are not intended to supplant the information currently reported by buoys.

Drifting buoys are not yet equipped to measure wind velocity or sea state off the west coast yet. There have been documented cases where sea-level pressure data from drifting buoys have improved surface analyses; however, problems persist in communicating even limited drifting buoy data to forecast offices in a timely fashion.

Ships participating in the volunteer observing ships program provide helpful surface meteorological reports from the large data sparse areas between buoys. However, ship reports differ considerably from fixed buoy reports. Winds are measured as high as 30 meters off the surface. Because of the ships' movement, reports come from a different location each time, which may affect pressure tendency reports. Sea state conditions reported by ships are estimated by the crew, not measured. Ocean vessels (smartly) divert around storms and thus vacate areas from which forecasters are most interested in receiving observations. Satellite imagery and their derived products complement surface weather observations. In fact, satellite and surface observations are both considered indispensable tools in meteorology and oceanography. Satellites provide basic cloud imagery and low-level cloud and fog imagery 24 hours per day, which greatly assists forecasters determining storm motion and intensity trends (deepening and weakening). Not only do they provide imagery, but they also compute wind velocity from cloud motions at several levels, and provide worldwide operational sea ice analyses, and SST analyses. Satellites do not measure wave conditions, and satellite-derived wind data are not used by numerical wave prediction models. Generally speaking, satellite estimates of surface conditions (e.g., wind, ice, SST) are limited to cloud-free regions (or nearly cloud free). Where there is significant weather, storm clouds prevent satellites from "seeing" and reporting surface weather observations.

Operational meteorology in recent years has come to rely more and more on products from numerical weather prediction models. NWS generates ocean wind and wave model forecasts with a number of sea surface weather observations available in near real ground truth of actual conditions. This sort of blind acceptance would likely lead to more "surprise" developments. In summary, documented cases in which ground truth buoy data improved NWS warnings and forecasts over numerical model guidance are available. The lead time for hurricane wind force warnings over inland portions of the Western Region as long as 24 hours are due, in large part, to data supplied by offshore buoys.

Years of interactive outreach efforts by NWS field offices with mariners and coastal residents are highlighted by a common conclusion: the safety and livelihood of these customers depend on reliable buoy reports. Lives have been saved by citizens heeding NWS warnings and data buoy reports of hazardous weather conditions. Customer reaction to potential buoy losses is always negative. The value of data buoys must not be weighed solely on their contribution to numerical atmospheric prediction models. They are deemed extremely important to NWS forecasters and citizens alike.

FIGURE 15 Pictures of representative moored buoy types deployed in the Alaska/Bering Sea (12-meter discus), mid-Gulf of Mexico (10-meter discus), Hawaii (6-meter NOMAD), and Great Lakes (3-meter discus) regions. (Source: U. S. Department of Commerce, National Oceanic and Atmospheric Administration)

FIGURE 16 Pictures of representative C-MAN stations at Thomas Point, Maryland, and Stannard Rock, Michigan. (Source: U. S. Department of Commerce, National Oceanic and Atmospheric Administration)

FIGURE 15 Pictures of representative moored buoy types deployed in the Alaska/Bering Sea (12-meter discus), mid-Gulf of Mexico (10-meter discus), Hawaii (6-meter NOMAD), and Great Lakes (3-meter discus) regions. (Source: U. S. Department of Commerce, National Oceanic and Atmospheric Administration)

FIGURE 16 Pictures of representative C-MAN stations at Thomas Point, Maryland, and Stannard Rock, Michigan. (Source: U. S. Department of Commerce, National Oceanic and Atmospheric Administration)