DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration

OFCM

OFFICE OF THE FEDERAL COORDINATOR FOR
METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

National Plan For Tropical Cyclone Research

FCM-P25 1990

Washington, DC
December 1990

THE FEDERAL COMMITTEE FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH (FCMSSR)

DR. JOHN A. KNAUSS, CHAIRMAN
Department of Commerce

DR. BRUCE GARDNER
Department of Agriculture

MR. RAYMOND F. SIEWERT
Department of Defense

DR. DAVID B. NELSON
Department of Energy

MR. HARLAN L. WATSON
Department of the Interior

HON. E. V. CURTIS BOHLEN
Department of State

MR. EDWARD T. HARRIS
Department of Transportation

MR. DAVID TORNQUIST
Office of Management and Budget

MR. JOHN MATTICKS
Federal Emergency Management Agency

DR. LENNARD A. FISK
National Aeronautics and Space Administration

DR. ROBERT W. CORELL
National Science Foundation

MR. WILLIAM G. LAYNOR
National Transportation Safety Board

DR. DENWOOD F. ROSS
U.S. Nuclear Regulatory Commission

MR. H. MATTHEW BILLS
Environmental Protection Agency

MR. ROBERT L. CARNAHAN
Federal Coordinator for Meteorology

DR. JAMES A. ALMAZAN, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

THE INTERDEPARTMENTAL COMMITTEE FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH (ICMSSR)

MR. ROBERT L. CARNAHAN, Chairman
Federal Coordinator

DR. NORTON D. STROMMEN
Department of Agriculture

DR. ROBERT C. LANDIS
Department of Commerce

COL GRANT AUFDERHAAR, USAF
Department of Defense

DR. HARRY MOSES
Department of Energy

MR. LEWIS T. MOORE
Department of the Interior

MR. JEFFREY MACLURE
Department of State

MR. RICHARD J. HEUWINKEL
Federal Aviation Administration
Department of Transportation

MR. NEAL THAYER
U.S. Coast Guard
Department of Transportation

MR. FRANCIS SCHIERMEIER
Environmental Protection Agency

MR. ROBERT T. JASKE
Federal Emergency Management Agency

DR. SHELBY TILFORD
National Aeronautics and Space Administration

DR. RICHARD S. GREENFIELD
National Science Foundation

MR. JAMES C. McLEAN, JR.
National Transportation Safety Board

MR. ROBERT A. KORNASIEWICZ
U.S. Nuclear Regulatory Commission

MR. DAVID TORNQUIST
Office of Management and Budget

DR. JAMES A. ALMAZAN, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

FEDERAL COORDINATOR FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

6010 EXECUTIVE BLVD., SUITE 900
ROCKVILLE, MARYLAND 20852

NATIONAL PLAN FOR TROPICAL CYCLONE RESEARCH

FCM-P25-1990

Washington, D.C.
December 1990

CHANGE AND REVIEW LOG

Use this page to record changes and notices of reviews.

Change Number	Page Numbers	Date Posted	Initial
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Changes are indicated by a vertical line in the margin next to the change.

Review Date	Comments	Initial

FOREWORD

In Congressional hearings during the past several years, it has been reiterated that "a vigorous research program in tropical cyclone behavior and forecasting is important if the accuracy of prediction of tropical cyclones is to be significantly improved." Further, Congress has proposed that the Departments of Commerce and Defense establish a joint program to collect operational and reconnaissance data, conduct research, and analyze data on tropical cyclones. The Office of the Federal Coordinator for Meteorology (OFCM) has called upon its interagency working groups to facilitate such a program.

This report was prepared by an Ad Hoc Group for Tropical Cyclone Research (AHG/TCR) under the direction of the OFCM Hurricane and Winter Storms Operations Working Group (WG/HWSO). It addresses many of the issues raised in Congressional hearings, and provides a review of the research requirements of the government agencies concerned with tropical cyclone analyses and warnings. In addition, the plan summarizes current relevant research at government and university laboratories and presents an assessment of additional work required. Although the survey of current research and technology was extensive, some areas are less comprehensive than others; additional information will be published in subsequent reports, as appropriate.

It is my hope that this report will stimulate increased cooperative efforts among the various research groups, both within and without the government; and that the outcome will be long-term improvement in tropical cyclone analysis and warning services. The WG/HWSO expects to provide periodic reports to document progress in these areas.

Robert L. Carnahan
Federal Coordinator for
Meteorological Services
and Supporting Research

CONTENTS

		Page
CHANGE LOG		ii
FOREWORD		iii
LIST OF TABLES		vi
CHAPTER 1	**INTRODUCTION**	1-1
1.1	Ad-Hoc Group for Tropical Cyclone Research	1-1
CHAPTER 2	**PRESSING FORECAST AND WARNING PROBLEMS**	2-1
2.1	Position and Motion	2-1
2.2	Surface Wind Description	2-4
2.3	Synoptic Environment	2-6
2.4	Rainfall	2-9
2.5	Tornadoes	2-9
2.6	Storm Surge	2-9
2.7	Sea State	2-9
2.8	Information and Data Management	2-10
2.9	Nonmeteorological Items	2-11
CHAPTER 3	**REVIEW OF TROPICAL CYCLONE FORECASTING RESEARCH**	3-1
3.1	Air Force Global Weather Center	3-2
3.2	Fleet Numerical Oceanography Center	3-2
3.3	Geophysical Fluid Dynamics Laboratory	3-2
3.4	Geophysics Laboratory (formerly, AFGL)	3-2
3.5	Hurricane Research Division	3-2
3.6	Joint Typhoon Warning Center	3-3
3.7	National Hurricane Center	3-4
3.8	National Meteorological Center	3-5
3.9	NASA/Goddard Space Flight Center (GSFC)	3-5
3.10	National Environmental Satellite, Data, and Information Service (NESDIS)	3-5
3.11	Naval Oceanographic and Atmospheric Research Laboratory (WEST) (formerly NEPRF)	3-6
3.12	Naval Research Laboratory	3-7
3.13	Colorado State University	3-7
3.14	Florida State University	3-7
3.15	Massachusetts Institute of Technology	3-7

		Page
3.16	Naval Postgraduate School	3-8
3.17	Pennsylvania State University	3-9
3.18	State University of New York at Albany	3-9
3.19	U.S. Air Force Academy	3-9
3.20	University of Hawaii	3-9
3.21	University of Wisconsin	3-9
CHAPTER 4	**REQUIREMENTS COMPARED WITH ONGOING RESEARCH**	4-1
4.1	Position and Motion	4-1
4.2	Surface Wind Description	4-2
4.3	Synoptic Environment	4-4
4.4	Rainfall	4-5
4.5	Tornadoes	4-5
4.6	Storm Surge	4-5
4.7	Sea State	4-5
4.8	Information and Data Management	4-6
4.9	Global Model Evaluation	4-6
4.10	Nonmeteorological Items	4-7
CHAPTER 5	**ASSESSMENT OF PROMISING TECHNOLOGY**	5-1
5.1	Improved Models	5-1
5.2	Improved Observations	5-2
5.3	Improved Data Processing	5-3
APPENDIX A	**RESEARCH DATA SETS**	A-1
APPENDIX B	**ABBREVIATIONS**	B-1
APPENDIX C	**REFERENCES**	C-1
APPENDIX D	**DISTRIBUTION**	D-1

LIST OF TABLES

TABLE		Page
2.1	Consolidated Tropical Cyclone (TC) Research Item Priority Rating	2-3
4.1	Research Problems Versus Research Activities	4-2

CHAPTER 1

INTRODUCTION

1.1 **Ad-Hoc Group for Tropical Cyclone Research.** The Ad-Hoc Group for Tropical Cyclone Research (AHG/TCR) is a subgroup of the Working Group for Hurricane and Winter Storms Operations of the Committee for Basic Services, which, in turn, is a subcommittee of the Interdepartmental Committee for Meteorological Services and Supporting Research (ICMSSR). This committee structure is under the Office of the Federal Coordinator for Meteorological Services and Supporting Research (hereafter referred to as the Federal Coordinator). AHG/TCR held its formation meeting in San Diego, California, on May 18, 1989. Primary agency members are listed on the inside back cover. Each of the following organizations contributed to the development of the National Plan for Tropical Cyclone Research:

Air Force Global Weather Central
Central Pacific Hurricane Center
Environmental Group, United States Pacific Command
Fleet Numerical Oceanography Center
Hurricane Research Division, AOML, OAR
Joint Typhoon Warning Center
National Hurricane Center
National Meteorological Center

1.1.1 **Background of AHG/TCR.** The AHG/TCR was formed by or because of four actions:

a. The ICMSSR identified research on tropical cyclones, improvement of information on location and intensity of tropical cyclones, exchange of satellite data, and future of airborne reconnaissance as opportunities for increased interagency coordination at its meeting on November 15, 1988.

b. Mr. Robert L. Carnahan, the Federal Coordinator, charged the Interdepartmental Hurricane Conference Research Committee to explore the forecast and warning problems, identify research that can address those problems, and determine means of obtaining needed data when aerial weather reconnaissance as we now know it is no longer available.

c. Dr. Hal Gerrish, Chairman of the 1989 Research Committee, reported that the committee "strongly endorses appointment of an ad hoc committee of field people to develop a comprehensive plan for research on tropical cyclone meteorology at the earliest possible date." This recommendation was approved by the conference participants.

d. The ICMSSR approved the proposal to establish an Ad Hoc Group for Tropical Cyclone Research under the Working Group for Hurricane and Winter Storms Operations at the March 28, 1989 ICMSSR meeting.

1.1.2 Purpose of AHG/TCR. The Ad Hoc Group, at its first meeting, adopted the following purposes:

a. Obtain rank-ordered lists of the most pressing tropical cyclone forecast problems from the operational forecast centers and disseminate this information to the research community. Prepare for interdepartmental approval and subsequent action a comprehensive listing of these operational forecast and warning problems to guide research in tropical cyclone meteorology for the coming decade.

b. Review recent tropical cyclone research, including manpower and budget figures, for activities at government laboratories, universities and institutes. Identify those activities that are focused to improve the operational forecast and warning process. Recommend plans to facilitate transfer of this research to operational testing.

c. Periodically assess the developing sensors, technologies, and processing and display capabilities that may be adaptable to the tropical cyclone forecast and warning process. Identify promising items and plan interdepartmental cooperation to facilitate transfer of these developments to operations as rapidly as possible.

d. Coordinate the collection, compilation, and analyses of research data sets for improving tropical cyclone prediction. This activity will include blending of existing operational data with new directly or remotely sensed data (either research or operational). All available data sources should be included so that such data will be incorporated into real-time analyses for support of operational tropical cyclone warning and prediction. Determine optimal flow of such data into the operational forecast centers.

e. Publish a national plan containing sections on (1) pressing forecast and warning problems; (2) ongoing tropical cyclone research activities applicable to the forecast and warning problem; (3) developing sensors and technology transferable to operations in the near future; and (4) a compilation of research data sets available for research and analysis. Update the plan periodically.

CHAPTER 2

PRESSING FORECAST AND WARNING PROBLEMS

It was the committee's sense that attempts to improve the tropical cyclone warning system should be based on deficiencies in meeting national warning requirements; that sensors and systems have been applied to, rather than designed for, the problem. Following that reasoning, the first order of business was to identify the most pressing problems. This information was gathered by accepting lists representing the three U.S. tropical cyclone forecast centers: Joint Typhoon Warning Center (JTWC), National Hurricane Center (NHC) and Central Pacific Hurricane Center (CPHC).

Since such lists tend to reflect the thinking of the current authors and invariably omit some items, consolidation of the lists was deemed appropriate. Table 2.1 is the consolidated list categorized into fairly restricted topic areas. Next to each item there is a qualitative assessment of its importance to each of the centers. Because the missions of the three centers vary, their priority assessments also vary. The following paragraphs amplify the items listed in Table 2.1.

2.1 **<u>Position and Motion</u>.** Those items that relate directly and exclusively to track forecasting are included under the heading "position and motion". They involve, at the most elementary level, the improvement of fix capability and, at the most complex level, the improvement of track forecasting models. Positioning and initial motion provide direction and speed of movement. They are the foundation of the track forecast. All other aspects of the tropical cyclone warning depend upon the track forecast. Also, positioning is critical to the improvement of the post-analysis best track, which provides the standard for measuring forecast and aid performance as well as for statistical correlation.

2.1.1 **Positioning.** Because the need to improve the fixes is currently dependent on the availability of aircraft reconnaissance, the assigned priority is high in the Pacific and relatively lower in the Atlantic. This priority dependence reflects the need for refining and improving satellite fix technologies, especially for weak and developing systems. Realistically, if better, more reliable, satellite fixes were available (including intensity and close-in wind field information), the limited aircraft resources could be partially employed to collect synoptic and outer peripheral data. The Special Sensor Microwave/Imager (SSM/I), particularly the 85-GHz channel, may provide the high resolution needed for positioning. The precipitation signatures appearing on the SSM/I imagery require modeling and the results should be studied with Position Code Numbers (PCN) to determine the appropriate confidence values that should be ascribed to each PCN.

Animation of cloud targets can reveal vorticity and, in turn, imply circulation centers in the wind field. Research is needed to determine if methods to discriminate actual animated low-level wind field circulation centers can be developed based primarily on satellite cloud signatures.

2.1.2 Initial Motion. Short-period track forecasting is critically dependent upon accurate initial motion estimates. Since most forecasting guidance is substantially weighted with persistence at the start, the correct determination of the initial motion vector is vital. Where major track changes are taking place and persistence is not a major factor, there is a critical need for a measure of true motion. Improved techniques to eliminate noise inherent in the raw data and analyses are an important component of this problem. This item highlights the dependency of forecasters on the apparent displacement between a sequence of fixes to estimate motion vectors. The noisier the fixes, the more troublesome the dependency.

The use of fixes is another aspect of initial positioning. Fundamentally, the longer the time average, the greater the dampening of fix noise, but the less representative will be the averaged motion of the current (and near future) motion. Statistically, there should be an optimum trade-off, which may be situation-dependent. Research is needed to establish this optimum time-averaging as a function of important variables, such as basin, latitude, intensity, track, and environment.

2.1.3 Track Forecasts. With the implementation of NHC83, a statistical dynamic model developed and implemented over several years beginning in 1983, the track forecasting problem became relatively less urgent in the Atlantic basin. However, it is still considered to be of highest priority in the central and western Pacific. Without doubt, the track is the most important element to be forecast. However, improvements in forecasts of size and intensity would contribute greatly to reduction of the uncertainty in forecasting tropical cyclone impact.

Comparisons between track forecasting errors and customer expectations raise questions. What are the limits of predictability? Can better forecasts be made using conventional methodology, or would chaos theory set fundamental limits to predictability?

Interaction between tropical cyclones in multiple-storm situations complicates track forecasting. Improved understanding of the role played by size, strength, and intensity in this interaction is needed. In addition, the movement of the centroid between these systems in relation to the surrounding synoptic environment begs for understanding. Finally, what are the interactions of tropical cyclones with other synoptic/subsynoptic circulations?

Bao (1981), Fett and Brand (1975) and Lajoie and Nicholas (1974) have developed techniques that address tropical cyclone motion changes keyed to cloud-system orientation evolution. Although none of these methods can consistently demonstrate skill in the operational environment, each has something to offer. Weldon's (1974) and Dvorak's (1984a) work with signatures in the water vapor window might be applied here. Related research results should be reexamined and built upon, with the goal of making the prognostic track information in the imagery available to forecasters.

Table 2.1 Consolidated Tropical Cyclone (TC) Research Items Priority Rating.

Research objectives	JTWC	CPHC	NHC
Improve position and motion (see paragraph 2.1)			
Positioning	med	med	med
Initial motion	med	high	high
Track forecasts	high	high	med
Improve surface wind description (see paragraph 2.2)			
Estimate of intensity (maximum winds or minimum sea level pressure (MSLP)	high	high	med
Intensity prediction	high	med	med
Wind structure	high	high	high
Synoptic environment (see paragraph 2.3)			
Tropical analysis			
Exploit existing data	med	low	med
Improve specification	med	med	high
Improve forecasting	med	high	med
Tropical cyclone genesis	med	low	med
Upgrade other models			
Monsoon	med	low	med
Trop Upper Tropospheric Trough (TUTT)	med	med	med
N. and S. Hemisphere twins	med	low	low
Hybrid or semitropical cyclones	med	low	med
Improve rainfall estimates and forecasts (see paragraph 2.4)			
TC-specific satellite rainfall estimates	low	low	high
TC rainfall forecasting techniques	low	low	high
Improve tornado understanding (see paragraph 2.5)	low	low	high
Improve storm surge prediction (see paragraph 2.6)	low	low	med
Improve sea state models (see paragraph 2.7)			
Estimation	med	med	med
Forecasting	med	high	med
Coastal effects	low	high	low
Information and data management (see paragraph 2.8)			
Data requirements	high	high	high
Damage assessment	low	low	low
Tropical cyclone typing	med	low	med
Objective aid design and performance	high	high	low
Global model evaluation	med	med	med
Non meteorological items (see paragraph 2.9)			
Presentation of information	high	med	high
Action motivation studies	med	low	high
Vertical refuge	low	low	high
Communications	high	low	high
Media interface	med	high	med

Over the past several years, Neumann and collaborators (for example, see Neumann 1979) have published statistical data about mean steering and the amount of variance explained by the flow at various levels and combinations of levels. The Colorado State University group under William Gray arrived at similar conclusions for Pacific tropical cyclones based on analysis of composite data. A missing part of the puzzle is how tropical cyclone response depends on varying parameters (e.g., size, strength, and vertical extent). This knowledge would permit the forecaster to fit the tropical cyclone into the most appropriate steering model. Operational skill must be shown in categorizing tropical cyclones for model fit.

Along-track or speed errors are the largest contributors to overall forecast track errors. The two components of track, direction and speed, are usually considered together in the forecasting process, but this approach is not necessarily optimum. If the two components are decoupled and speed is studied individually, improvements may be possible. For example, a forecast aid may be discounted by the forecaster because the direction is 45° off, when, in fact, its speed is genuine. It may be possible to develop algorithms for speed that address such phenomena as stalling, major track changes, and erratic motion. Speed as a fraction of the flow at the 700- or 500-mb levels is unknown. Likewise, we do not know whether this fraction is influenced by basin, situation, latitude, or season.

Long-wave patterns, no doubt, have an effect on preferred channels, longitudes, or areas for recurvature. For some forecasting purposes, we categorize tropical cyclones as straight runners or recurvers. Yet there is a class of tropical cyclones with tracks that are northward-orientated and that do not fall conveniently into these categories. Rethinking how we might categorize tracks relative to long-wave patterns is a rich area for further study.

2.2 Surface Wind Description. `Surface wind description' includes wind forecasting, specification, measurement, and vertical analysis. It also includes coastal effects, relationships between sea-level pressure and maximum winds, and improvements in the forecast of tropical cyclone development. The terms "intensity," " maximum winds," and "minimum sea level pressure" are used interchangeably in the following discussion, as they are in operational practice.

2.2.1 Intensity (Maximum Winds/MSLP) Diagnosis. Winter tropical cyclones can exhibit higher intensity than that estimated by the Dvorak technique; e.g., Tropical Storm Winona in January 1989. Seasonal and translational adjustments to the Dvorak technique should be the subject of further study.

Colder than normal cloud tops are suspected in the western North Pacific basin, particularly during the off-season months. Colder values result in higher estimates of intensity. Since there is a high correlation between maximum winds on the advisory, peripheral winds, and Enhanced InfraRed (EIR) satellite estimates, attention to the question of basin or seasonal bias in the EIR technique is warranted.

Chan's (1982) hypothesis, that increases in cloud-top vorticity are precursors to "spin up" and subsequent intensification of the tropical cyclone, is an idea that should be examined with the goal of providing operational techniques for intensity forecasting.

Intensity estimation using the Dvorak (1984b) technique, where the current intensity lags the "T" number on weakening systems, is long overdue for evaluation. The question of the appropriateness of the model 0-, 6-, 12-, 18- or 24-hr delay during weakening (or movement overland or over cold water) needs to be resolved. Fluctuations in core convection and their effects on the intensity need to be addressed.

2.2.2 Intensity prediction. Better conceptual models for intensification are needed. The synoptic-statistical technique by Dvorak performs well, but the dynamics of the process are missing. Empiricism is useful, but the answers to the "why's" of the dynamics of growth and decay of the tropical cyclones need to be found. The absence of conceptual model guidance to forecast intensity promotes reliance on persistence, climatological and statistical models, none of which are capable of identifying the unusual and dangerous rapid change situations. On the other hand, a statistical approach based on the environment, synoptic typing, and predictors from the numerical prognosis fields could be designed to provide insight to the important processes.

Satellite cloud signatures, as precursors to rapid or explosive deepening and the peaking day, have not been identified adequately. Research should address these items and their application to intensity forecasts.

While several investigators have developed general relationships between synoptic events and tropical cyclone intensification, none has quantified these relationships. We need to better understand these relationships in terms of pressure/height gradient and relative intensity of events.

2.2.3 Wind Structure. Tropical cyclone winds present a range of problems, from inadequacies in horizontal wind models to deficiencies in models of the vertical distribution of horizontal winds and to orographic influences on the wind field.

2.2.3.1 Better Surface Wind Models. The establishment of better surface wind models and an understanding of surface wind distribution is essential. First, it is important to distinguish remotely sensed data among the types of tropical cyclones, such as partially tropical, semitropical (sometimes referred to as subtropical or hybrid) and extratropical. Given these distinctions, we must understand how the cloud patterns and wind distributions are correlated; e.g., gales near the center or displaced. We need to understand the wind distribution asymmetries with indirect forms of measurement; e.g., remote sensing. Finally, we must know how much intensification can be expected as cold air penetrates to the outside of the eye wall, how long the occasionally large, but apparently short-lived intensification lasts, and how such intensification can be forecast.

2.2.3.2 Relationship of High-level Winds to Surface Winds. Vertical reduction of aircraft flight-level winds is an item that is clearly of interest in the Atlantic and eastern Pacific where aircraft are still available for reconnaissance, but it is also of interest in the western North Pacific where archived aircraft data are used for model development and validation. The general topic is also of importance in reducing winds at elevations such as oil rigs and from wind profilers to the surface. The same technology will be required when we are asked to specify wind loading on upper portions of high rise structures.

2.2.3.3 Nonstandard Wind Averaging Times. Most countries consider a 10-min average wind speed as a sustained wind. There are other wind averaging periods used, e.g., nearly all U.S. measurements are averaged over 1 min. Over the years, other implied averaging periods have been used. Examples are the "fastest mile", and winds measured from moving platforms averaged over a set distance. There is often a need to convert a measurement that is based on one standard to another standard. Algorithms to perform this conversion should be developed and validated.

2.2.3.4 Orographic Effects. Reduction of surface winds due to orography is a topic of importance in all tropical cyclone basins. Even when surface winds over water are known, the actual surface winds inland and along shore can be substantially different. The sustained winds are damaging, but the gust-loading on structures can be even more destructive. Better understanding and modeling of these inland and coastal influences are needed.

2.2.3.5 Surface Wind Description. In recent years, three factors, independently or in combination, have brought new emphasis to the problem of describing tropical cyclone surface winds. These factors are:

1. The loss of aircraft reconnaissance, which has forced greater reliance on satellite data;

2. The critical role of storm surge prediction in emergency planning and the equally important role of prediction of wind forcing; and

3. The extent of gale-force winds, becoming a key element in the timing of emergency actions.

We have great difficulty in measuring the distribution of winds and, with the possible exception of storms transitioning to extratropical where we believe they grow larger, we have little understanding or empirical guidance to aid in the forecast.

2.2.3.6 Maximum Winds. The improvement of maximum wind estimates is another item which has taken on a new importance with the loss of aircraft reconnaissance. The standard error of estimation in Dvorak satellite wind estimates is about one category on the Saffir-Simpson scale. In some major metropolitan areas, this could be a difference of hundreds of thousands of people unnecessarily evacuated, or not evacuated and left vulnerable to storm surge inundation or in unsafe structures.

2.2.3.7 Minimum Sea-level Pressure. The requirement for estimates of MSLP poses a difficult problem for forecasters. Since we usually regard maximum winds to be well-correlated with MSLP, this is almost a restatement of the maximum wind requirement above. The distinction is the requirement for a conservative MSLP for storm surge model computations. MSLP has been recognized as the more conservative of the two correlated measures. A first guess of maximum wind is generally made using a pressure-wind relationship. However, if MSLP is derived from an estimate of maximum winds, we can expect the resulting value to be irregular and noisy.

2.3 Synoptic Environment.

2.3.1 Tropical Analysis. Numerical objective analysis in the tropics leaves much to be desired. Tropical waves, for example, are rarely depicted and tropical cyclone vortices are frequently misplaced. Clearly, a poor analysis cannot lead to a consistently good prognosis. A poor initial analysis is the most frequent cause for poor performance of the statistical-dynamic model NHC83.

2.3.1.1 Existing Data. The challenge is to provide better, more reliable data to support an improved analysis. Because of the drawing down of direct measurement platforms, the capabilities of remote-sensing platforms must be fully exploited. Given that raw fix data can be improved via remote-sensing platforms, limited aircraft reconnaissance assets might be made available to better describe the tropical cyclone and its periphery in the Atlantic and eastern Pacific basins. Real-time SSM/I data are needed for operational use and technique development at the centers. Soundings from remote sensing platforms, e.g., the TIROS-N Operational Vertical Sounder (TOVS) and the Special Sensor Microwave/Temperature (SSM/T), should be evaluated to determine if warming in the upper troposphere, thickness, and other factors can be applied to the tropical cyclone analysis and forecasting problem. There is operational technology in in-situ automated systems, including drifting buoys, moored buoys, and land stations, which report regularly via satellite. These devices are providing measurements that are valuable supplements to satellite data, particularly in data sparse regions, and provide a quantitative anchor to satellite-derived measurements. There is ongoing work both at JTWC (with automatic surface weather observing stations and meteorological buoys) and at an existing network of approximately 100 moored buoys and automated fixed coastal stations operated by the National Data Buoy Center (NDBC).

2.3.1.2 Improve Specification. Many of the synoptically important features of the tropics have horizontal scales that are not resolved by the observation network. Satellite winds are one method of forcing these features into the analysis. However, in the absence of a good three-dimensional conceptual model of these features, winds input at the gradient and cirrus levels are inadequate to resolve the features vertically. We require the development of man-machine technology whereby the conceptual analysis of an experienced tropical analyst can be replicated by numerical analysis for missing features.

2.3.2 Improve Forecasting. The global models seem to be doing a reasonable job in the tropics when they have a good initial analysis. The most important changes may be procedural to insure that analyst bogus information, satellite winds, and reconnaissance data actually impact the analysis.

2.3.3 Tropical Cyclone Genesis. Currently, a preexisting disturbance is observed and then forecast. The "where, when, why, and how" of tropical cyclone genesis is little understood, but remains of vital concern to forecasters. There is a requirement to assess the potential for genesis. Specifically, for most universal application, such assessment should be based on remote sensing. Better understanding is badly needed, especially since centers must now forecast the genesis of tropical depressions.

2.3.4 Upgrade Other Models.

2.3.4.1 Monsoon Models. Monsoon models need to be improved and expanded. Since we cannot explain the workings of the monsoon, we can hardly expect the forecaster to be able to predict changes of this major wind system. There are simplified models of the classic differential heating between land and ocean, but the "real" or "transitional" monsoon may extend along 25° north latitude, eastward from Asia to the dateline. The monsoon may be very intense over the oceanic expanses of the western North Pacific and weak over the Asian land mass. Present numerical models do not correctly predict deep southwesterly flow that may be brought upward through 200 mb by deep persistent convection. This may be partially a resolution problem and a data problem in the analysis mode. Perhaps the momentum field in the monsoon could be better observed by remote sensing. This is one area where basic research is needed to enhance fundamental understanding.

2.3.4.2 TUTT Model. The tropical upper tropospheric trough (TUTT) that is observed during the summer is little understood. Its presence is poorly handled by numerical models. It invalidates tropical cyclone dynamic forecast guidance by influencing the subtropical ridge beneath it and the flow aloft around it. The presence of upper cold lows in the TUTT can have a profound influence on tropical cyclone genesis, motion, and intensity. Sadler has modeled sympathetic tropical cyclone genesis in the trade wind regime from the TUTT lows. There is a basic research requirement for understanding the TUTT and its effect on the surrounding environment and, in particular, on tropical cyclones. The direct or indirect coupling of the TUTT to monsoon surges is also poorly understood.

2.3.4.3 Twin Cyclones. Genesis of twin tropical cyclones in low latitudes and opposite hemispheres is a process that has been little documented in the literature. Also, a surprising number of these twins reach supertyphoon intensity. Better conceptual models and understanding of the role of equatorial westerlies, sympathetic intensification, movement, and teleconnection are subjects for further research.

Mechanisms for the regulation of tropical deep convection are poorly understood. Cross-equatorial interactions between the winter and summer hemispheres can affect tropical cyclone genesis and intensification in low latitudes. Low-level surges across tropical low latitudes from the winter hemisphere can cause major readjustments in the area and strengthen convection in the summer hemisphere. Basic knowledge of interaction between various tropical wave types, is severely limited. For example, what is the role of equatorial waves in twin tropical cyclone formation? What role do the 40- to 50-day surge cycles play? How are large-and small-scale convective areas modulated by these waves and cycles? Are their effects predictable at a temporal scale pertinent to operational forecasting?

2.3.4.4 Hybrid Storm Systems. The recognition and modeling of hybrid or semitropical cyclones is a major concern. Refining satellite analysis techniques to address this area is important. Authors Hebert and Poteat (1975) made a good start, but the understanding of what makes these systems "tick" still eludes us. The transition to and from these systems to tropical cyclones is a major concern to forecasters. Monsoon depressions that may be coded at 25-35 kt with the Dvorak technique, using a shear-type pattern, may have 40-70 kt winds displaced 150 nmi or more from the light and variable wind center. It may be necessary to address these questions by individual basins.

2.4 **Rainfall.** The two items listed under rainfall are recognition that rainfall and flooding are the greatest causes of tropical cyclone deaths in inland areas away from the immediate coast.

2.4.1 Tropical Cyclone-specific Satellite Rainfall Estimates. Remote sensing techniques for rainfall estimation have proven fairly accurate. These techniques, however, do not work well in the tropics. Refinement of these techniques for the tropical problem can, perhaps, reduce the large errors that are frequently present.

2.4.2 Tropical Cyclone Rainfall Forecasting Techniques. The distribution and amount of rainfall associated with tropical cyclones can vary considerably. Only in the most general way is the effect of terrain and forward motion on precipitation understood. Some cyclones produce substantially heavier rainfall than others under apparently identical circumstances. We are obviously lacking in understanding of the fundamental processes involved.

2.5 **Tornadoes.** Most observations of tornado activity associated with tropical cyclones have been with landfall. Some general information is available about where to expect tornadoes relative to the center, but we are unable to anticipate greater or less tornado activity than usual, or to expect tornadoes under a particular satellite cloud signature.

2.6 **Storm Surge.** In the Atlantic and for the coast of the continental United States, storm surge models are far better than the forecast meteorology that can be input to drive them. Therefore, better storm surge forecasts in the Atlantic, can only come from desensitizing the models to meteorology or improving the meteorology. Most of the items discussed in the preceding paragraphs attempt to improve the meteorological input. Comparable models should be selectively developed for storm surge prone areas of U. S. interest in the Pacific basin.

2.7 **Sea State.** Marine advisories for hurricanes and bulletins for typhoons require specification of the radius of 12-ft seas. In addition, wave run-up is, in some cases, an important contributor to water level and is usually measured as storm surge. The centers have little skill in specifying or predicting sea state.

2.7.1 Estimation. In the absence of observations, the centers must estimate the radius of 12-ft seas on the basis of tropical cyclone characteristics. At NHC, this type of estimation usually means accepting the radius of 34-kt winds as the radius of 12-ft seas. The skill in these products is unknown, but is generally conceded to be low. A logical step would be a sea-state postanalysis for several storms to form the basis for parameterization. Remote sensing and better modeling may ultimately lead to a solution to this initialization problem.

2.7.2 Forecasting. At NHC, the time in the forecast cycle is so short that only a fast parametric model would be of practical use. Any model in the forecast mode would be severely limited by the inaccuracies of the track and wind forcing. These areas can be improved; thus, improved sea-state forecast models should be pursued.

2.7.3 Coastal Effects. Surf, shoaling, and wave run-up are often important contributors to water level. This process is not well understood and is ignored in the current storm surge models.

2.8 Information and Data Management.

2.8.1 Data Requirements. Most of the sensors that provide data critical for tropical cyclone tracking and monitoring were developed for other purposes and adapted to the present use. Some systems, such as the Improved Weather Reconnaissance System (IWRS) are highly tailored to this very specialized job. Rather than decide, a priori, that we need a new generation of aircraft and spacecraft for replacement, we need to systematically validate the measurements required to provide an acceptable level of service and develop the optimum mix of remote and in-situ systems which would complement each other to satisfy data requirements. The current reconnaissance aircraft capability will likely need to be replaced within a decade. We may already be late in defining the requirements and initiating procurement of new aircraft. That process should be started as soon as possible.

2.8.2 Damage Assessment. The Saffir-Simpson (Simpson, 1974) Hurricane Scale was developed for the Atlantic basin, but does not address the Pacific Islands. A similar scale which keys on vegetation and structural damage in the data-sparse Pacific Ocean and Caribbean Islands, would be of great value to disaster preparation and postanalysis. In cases where there are few or conflicting reports concerning intensity, damage assessment may be the only tool left to estimate the intensity of a tropical cyclone.

2.8.3 Quantify and Adjust Satellite Data for Diurnal Effects. Because we observe a diurnal cycle in satellite data, it is difficult to establish a development trend for a tropical cyclone. The extent that tropical cyclones follow a diurnal cycle is unclear. Neither the amplitude nor the shape of the diurnal cycle is known. There is no algorithm to normalize satellite data.

2.8.4 Tropical Cyclone Characteristics Typing. There is a requirement to better define the departures of a specific cyclone from the average tropical cyclone. Categories should be defined by classifications based upon the unique differences. Typing might consider depth, areal extent and asymmetries of the outflow and inflow layers, steering levels, environmental influences, teleconnections multiple cyclone interaction, adjacent monsoon flow, TUTT, relative position of upper cold lows, vertical wind shear, vorticity gradients, cloudiness, and sea-surface temperature. These data might be handled in a correlation matrix so anomalous features could be identified more readily and analogs more specifically identified.

2.8.5 Objective Aid Design and Performance. Aids are designed, software is engineered, developed and implemented into the operational forecast system. Unfortunately, the forecaster must make a precise forecast based on guidance provided by an aid that may be inappropriate to the case at hand. The forecaster needs to know the assumptions of the designer and programmer. In addition, he needs to know under what conditions the system performs well or poorly and if specific biases exist.

2.8.6 Global Model Evaluation. Equally as important as the performance of various objective guidance models is the performance of the global models that drive the objective models. Frequently, the objective guidance will be wrong because the supporting global model is wrong. Thus the forecaster needs to be aware of systematic errors in the global models and situations wherein these models perform either abnormally well or abnormally poorly. In the latter case, the forecaster must know the nature of the weakness. It is important to repeat the forecaster must be aware of model characteristics to be able to apply such knowledge. This is a statement of the necessity for wide dissemination of the results of model evaluation.

2.9 Nonmeteorological Items. Improved public awareness and communication have contributed greatly to the reduced loss of life from tropical cyclones in recent years. Some nonmeteorological problems must be resolved or improved upon if we are to continue to hold the line on tropical cyclone-related casualties.

2.9.1 Presentation of Information. The satellite and coming Next Generation Radar (NEXRAD) era threaten to inundate tropical cyclone warning services with data. Only a small fraction of these data will be processed and an even smaller amount presented to the customer. However, much of the mesoscale information could be useful to the public, in general, and to emergency management officials, in particular. Thus, we will need innovative ways to extract and present detailed information in a timely and clear manner.

2.9.2 Action Motivation Studies. The words we use and the graphics we show are intended to motivate people to follow a desired course of action. There is little scientific evidence to indicate the extent to which we are successful. We need systematic studies to guide how best to motivate a nonhomogeneous population at risk to follow various courses of action.

2.9.3 Vertical Refuge. Evacuation of many coastal communities will require more than 24 hours. There will be situations when, because of an unexpected track change or explosive deepening, it will be impossible to give enough advance notice to permit total clearance. This means that we may have people trapped in automobiles or in unsafe shelters. To alleviate this situation, the possibility of emergency vertical refuge in high-rise buildings needs to be evaluated. This would require a study of the limitations of designating both public and private buildings for such purposes. Consideration needs to be given to physical safety and legal liability, as well as other social issues.

2.9.4 Communications. Communications are the life blood of the tropical cyclone warning service. The possibilities are almost limitless as to the combinations of communication resources, message content, and message release times. The present communications systems evolved over many years and there is little assurance that they are near optimum. We need an end-to-end communications study to evaluate how well the system is performing. Such a study would consider the electronic and physical aspects of the current system, the use of languages, the message syntax, the message context and the timing of various releases, on a regional and cultural basis.

2.9.5 Media Interface. Communications are designed to convey information. The mass media (radio, television, newspapers) employ individuals who are experts at disseminating information. The understanding of these individuals can be crucial to the impact of the warning message on the public. Training sessions or seminars have been organized to enhance their understanding of the warning process and hazards of tropical storms. Are there more effective ways to educate and motivate these people?

CHAPTER 3

REVIEW OF TROPICAL CYCLONE FORECASTING RESEARCH

There is considerable tropical cyclone research at various government laboratories and in universities. In this section, the tropical cyclone research that may have operational application is reviewed. Only current research projects and work completed in the past year or two are included. This review is a compilation of summaries prepared by numerous authors. Because of the large amount of information, descriptions of individual research efforts are as brief as possible, although manpower and budget figures have been included when available. The research (technique development) at government agencies is summarized first, followed by university research.

The agencies that provided input for this research summary are:

A. Government Operational Agencies and Laboratories

1. Air Force Global Weather Central (AFGWC) Omaha, NE
2. Fleet Numerical Oceanography Center (FNOC), Monterey, CA
3. Geophysical Fluid Dynamics Laboratory (GFDL), Princeton NJ
4. Geophysics Laboratory (GL), Hanscom AFB, MA
5. Hurricane Research Division (HRD), Miami, FL
6. Joint Typhoon Warning Center (JTWC), Nimitz Hill, Guam
7. National Hurricane Center (NHC), Miami, FL
8. National Meteorological Center (NMC), Washington, DC
9. NASA/Goddard Space Flight Center (NSFC), Greenbelt, MD
10. National Environmental Satellite, Data and Information Service (NESDIS), Washington, DC and Ft. Collins, CO
11. Naval Oceanographic and Atmospheric Research Laboratory (NOARL) WEST (Formerly NEPRF), Monterey, CA
12. Naval Research Laboratory (NRL), Washington, DC

B. Universities

1. Colorado State University (CSU), Ft. Collins, CO
2. Florida State University (FSU), Tallahassee, FL
3. Massachusetts Institute of Technology (MIT), Cambridge, MA
4. Naval Postgraduate School (NPS), Monterey, CA
5. Pennsylvania State University (PSU), University Park, PA
6. State University of New York at Albany (SUNYA)
7. U.S. Air Force Academy (USAFA), Colorado Springs, CO
8. University of Hawaii (UH), Honolulu, HI
9. University of Wisconsin (UWISC), Madison, WI

3.1 Air Force Global Weather Center.

3.1.1 SSM/I Data. SSM/I data from the Defense Meteorological Satellite Program (DMSP) are being used to identify shearing tropical cyclones. This data is also being used to estimate the extent of 30 and 50 kt winds around tropical and extratropical cyclones. This project is led by Lt. Col. Charles Holliday.

3.2 Fleet Numerical Oceanography Center.

3.2.1 Bogussing Technique for a Global Prediction Model. Techniques are being developed to incorporate bogus tropical cyclone circulations into the data assimilation process for the Navy Operational Global Atmospheric Prediction System (NOGAPS). Techniques are also being developed to track tropical cyclone vortices in the NOGAPS forecast output. The personnel involved in this project are Charles Mauck, Gail Brown and Harry Hamilton.

3.3 Geophysical Fluid Dynamics Laboratory.

3.3.1 Numerical Simulation of Tropical Cyclones. Numerical simulations with real data are used to investigate the importance of various physical processes in tropical cyclogenesis. Cases from several ocean basins are considered. The personnel involved in this project are Yoshio Kurihara and Robert Tuleya.

3.4 Geophysics Laboratory (formerly, AFGL).

3.4.1 Hurricane Algorithms for NEXRAD. Composite hurricane wind data are used to develop hurricane monitoring algorithms for NEXRAD. The annual budget for this work is 2.5 staff years. The project manager is Ken Glover.

3.4.2 Satellite Observations of Tropical Cyclones. Techniques for estimating storm position and intensity based on SSM/I and Operational Line Scanner (OLS) IR imagery are being developed. These data are also being used to study the response of the microwave channels to conditions at the center of tropical cyclones. Methods for improving the display of microwave imagery to identify storm features are also being studied. The personnel involved in this project are Morton Glass and Gerald Felde.

3.5 Hurricane Research Division.

3.5.1 Synoptic-flow Experiments. Omega dropwindsonde observations are collected within about 1,000 km from the center of tropical cyclones to investigate the vortex steering flow. Thirteen cases have been obtained since 1982. The personnel involved in this project are Robert Burpee and James Franklin.

3.5.2 Dynamics of the Hurricane Core. Observational and theoretical studies of the evolution of the eyewall circulation are being carried out. Real-time aircraft data are analyzed to determine current intensity and short term intensity changes. Methods for objective track determination using spline-fitting techniques are also being tested in real-time. The personnel involved in this project are Hugh Willoughby, William Barry and Ed Rahn.

3.5.3 Vortex Motion and Dynamics. Two-dimensional (barotropic) and simple three-dimensional models are used to increase the understanding of vortex/environmental interaction. The personnel involved in this project are Lloyd Shapiro and Hugh Willoughby.

3.5.4 Boundary Layer Studies. Stepped-frequency Microwave Radiometer (SFRM) data from the NOAA WP-3D aircraft are being used to estimate the surface wind speed in tropical cyclones. Aircraft and buoy data are also being used to determine the relationships between flight-level and surface winds in hurricane boundary layers. Plans are under way for combining numerous data types using a spline-fitting technique to produce real-time surface wind analyses. The personnel involved in this project are Peter Black and Mark Powell.

3.5.5 Development of a Nested Spectral Hurricane Forecast Model. Aircraft, satellite and conventional synoptic data are analyzed in real-time by fitting cubic B-splines to the observations on nested domains. The analysis is used to initialize a barotropic track forecast model. The use of aircraft data enables the model to be initialized without the use of a bogus vortex to represent the storm circulation. The personnel involved in this project are Mark DeMaria, K. Vic Ooyama and Sim Aberson.

3.5.6 Land-falling Hurricane Structure. The evolution of the precipitation structure of tropical cyclones during landfall is being studied using digitized National Weather Service (NWS) radar data. The personnel involved in this project are Peter Dodge and Michael Black.

3.6 Joint Typhoon Warning Center.

3.6.1 Position Estimation Techniques. Position estimation techniques are being improved by enhancing the resolution of the cold end of the temperature scale of geostationary infrared satellite imagery. This allows for easier identification of the curvature of convective elements which improves the position estimates. Techniques for enhancing the warm end of the temperature scale are also being developed to improve the position estimates of sheared systems where the low-level center is partially or completely exposed. This procedure also helps to identify land areas for gridding purposes. These techniques are especially useful at night. This project is led by 1Lt Robert Hudson.

3.6.2 Storm Motion and Intensity Forecasting Improvements. A new tropical cyclone climatology is being developed to improve storm motion and intensity forecasting. The climatology can be accessed interactively on a desktop computer. The system can be used operationally to display the tracks of storms that are similar to the current storm of interest. This climatology can also be used to determine intensity trends. This project is led by Captain Daniel Shoemaker.

3.6.3 Graphics Workstation for Satellite Data. A system that transfers satellite observations to a graphics workstation is being developed. This system will be used to implement automatic Dvorak intensity estimation and to obtain pixel-count information. The pixel-count information is being used to relate the total convection to the observed surface winds. The object of an objective surface wind estimate is to help account for diurnal variations in Dvorak intensity estimates. The pixel-count information is also being used to identify the potential for rapid intensification. This project is led by Captain Daniel Shoemaker.

3.6.4 Objective Forecast Aid Verification. A study of objective forecast aids is being performed to determine whether the performance of the aids depends on the synoptic conditions. The goal is to build an interactive data base which can be used to provide forecasters with a quantitative estimate of the confidence of the aids in a given situation. This project is led by Mr. Frank Wells.

3.6.5 Wind Estimation. A technique is being developed to estimate the outer wind structure from the Dvorak intensity estimate and a size parameter determined from infrared satellite imagery. Microwave imager and conventional data will also be used. This project is led by Captain Daniel Shoemaker. Enhancement of the low-level temperatures from geostationary infrared satellite data is being used to infer areas of strong subsidence. This information is also used to determine changes in storm motion due to changes in position of pressure ridges.

3.7 National Hurricane Center.

3.7.1 Data Processing. Winds and heights from NMC analyses and forecast models are archived. Software for microcomputers is being developed to display data fields as well as storm tracks, warning areas, strike probabilities, and estimated wind distributions. The personnel involved in this project are Colin McAdie and Edward Rappaport.

3.7.2 Forecast Techniques. The statistical-dynamical track forecast model (NHC83) and the program for predicting the probabilities of a hurricane strike are being improved. The Automated Tropical Cyclone Forecast System (ATCF) developed by NOARL is being adapted for use at NHC. The personnel involved in this project are Jerry Jarrell, Colin McAdie, Edward Rappaport, James Gross, and Charles Neumann. Charles Neumann is supported through a contract with Science Applications International Corporation.

3.7.3 Satellite studies. Software is being developed for real-time display of rainfall and surface wind speed estimates from SSM/I data. Estimates of tropical cyclone intensities from satellites and aircraft are being compared. This project is lead by Ed Rappaport.

3.7.4 Storm Surge. Work is continuing in the preparation of a storm surge atlas for the U.S. coastline. The personnel involved in this project are Brian Jarvinen and Victor Wiggert.

3.8 National Meteorological Center.

3.8.1 Steering Current in a Track Forecast Model. A method is being developed to initialize a numerical model so the initial motion of the model storm matches the observed motion. This project is led by Makut Mathur.

3.8.2 Bogussing Technique for the Medium Range Forecast Model. A method to include the storm circulation in the Medium Range Forecast model is being developed. Commonly, the vortex is missing in the analysis or the vortex center and/or model precipitation fields are displaced from the observed locations. This project is led by Stephen Lord.

3.8.3 Initial Vortex Specification. A method to determine a bogus vortex that is dynamically consistent with the physics and large-scale features of a numerical model is being developed. The personnel involved in this project are Alan Shapiro and Stephen Lord.

3.9 NASA/Goddard Space Flight Center (GSFC).

3.9.1 Remote Sensing of Precipitation in Tropical Cyclones. Techniques are being developed to estimate precipitation in the vicinity of tropical cyclones using passive microwave and infrared sensors. Efforts are being made to combine the infrared approach (which has greater temporal resolution) with the passive microwave technique (which has greater accuracy but is available less often).

3.9.2 Remote Sensing of the Stratospheric Response to Tropical Cyclones. The Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) is being used to map the total ozone in the vicinity of tropical cyclones. The TOMS-observed total ozone can provide information on the interaction of tropical cyclones with synoptic-scale weather systems.

3.10 National Environmental Satellite, Data, and Information Service (NESDIS).

3.10.1 Diurnal Variations of Tropical Cyclones. The diurnal variations of convective clouds in tropical cyclones were studied using infrared cloud-top temperature thresholds. The amplitude and phase of the oscillation depend strongly on the temperature threshold used, with more variation for colder temperatures. There is an early morning (near sunrise) maximum of cold (<65° C) IR cloud area, associated with convectively active tropical cyclones over the open ocean. The project leader is Raymond Zehr.

3.10.2 Objective Techniques to Estimate Tropical Cyclone Intensity. Improvements to the Dvorak technique of estimating tropical cyclone intensity from infrared (IR) imagery are being developed. Emphasis is on very intense storms and early stage systems. Multi-radius computation and time averaging techniques are being developed. Raymond Zehr is the project leader.

3.10.3 Outer Wind Estimates from Objective IR Techniques. Techniques are being developed to estimate the radius of 30-and 50-kt winds from IR imagery. Raymond Zehr leads this project.

3.10.4 Tropical Cyclone Genesis. Research is under way to improve understanding and enhance forecasting of the development of tropical cyclones from weak tropical weather systems. This project is lead by Raymond Zehr.

3.10.5 Cloud-track Wind Data Sets. Cloud-track winds are combined with radiosonde winds to produce tropical wind analyses. These analyses are being used to study the hurricane outflow layer. The project leader is Gary Ellrod, Satellite Applications Laboratory.

3.10.6 Water Vapor Image Techniques. 6.7-micrometer water vapor image techniques are under development to aid in forecasting tropical cyclone recurvature or non-recurvature. The project leader is Mike Mogil, Satellite Applications Laboratory.

3.10.7 New Cooperative Institute for Research in the Atmosphere (CIRA) Workstation Capabilities and New Satellite Data Types. A new Wide Word Workstation has been installed at CIRA, awaiting installation of a high speed data line. Improved capability for tropical cyclone forecast product development is anticipated. Special emphasis will be on techniques which utilize new satellite data types, such as the SSM/I on DMSP, and the Advanced Microwave Sounding Unit (AMSU) on NOAA satellites. The project personnel involved in this project are Raymond Zehr, Jim Purdom, NESDIS, Fort Collins, Co, and Debra Lubich CIRA, Fort Collins, CO.

3.11 Naval Oceanographic and Atmospheric Research Laboratory (WEST) (formerly NEPRF).

3.11.1 Navy Automated Tropical Cyclone Forecasting System (NATCF). The NATCF system is desktop computer application software that automates nearly all JTWC office procedures. The software functions include data base management, graphics, objective analysis, and forecast track plotting. Mr. Ron Miller has the lead on this project.

3.11.2 Tropical Cyclone Forecast Simulation (TCFS). The TCFS is desktop computer application software for instructing new tropical cyclone forecasters through the use of past cases. This project is led by Mr. Ron Miller.

3.11.3 Tropical Cyclone Diagnostic Tool. A simple barotropic model has been developed to help forecasters diagnose the tropical cyclone circulation and its interaction with the environment. The software is being integrated into the NATCF and TCFS. This project is led by Mr. Ron Miller.

3.11.4 Tropical Cyclone Forecasters Handbook. Forecasters' experiences are being compiled in a handbook. This project is led by Mr. Ron Miller.

3.11.5 Tropical Cyclone Artificial Intelligence Project. Tropical cyclone forecasting knowledge is being assembled into a rule-based expert system in parallel with the development of the forecasters handbook. This project is led by Mr. Buck Sampson.

3.12 Naval Research Laboratory.

3.12.1 Numerical Modeling of Tropical Cyclones. A numerical modeling effort is ongoing to understand the behavior of Hurricanes Florence of 1988 and Hugo of 1989. The topics under study include the dynamic and thermodynamic structures, response to changing sea-surface temperature, landfall, midtropospheric dry air intrusion, responses to upper level and low-level momentum and moisture fluxes, and the effects of various observations and assimilation methods. This 2-year project is led by Simon Chang.

3.13 Colorado State University.

3.13.1 Tropical Cyclone Genesis Versus Prominent Tropical Disturbance Non-genesis. The personnel involved in this project are William Gray, Raymond Zehr (NOAA) and one Ph.D. student. This work is supported by the Geophysics Laboratory.

3.13.2 Tropical Cyclone Motion as Related to Steering Flow and Recurvature. The personnel involved in this project are William Gray and two M.S. students. This work is funded by the Office of Naval Research (ONR).

3.13.3 Tropical Cyclone Intensity: Factors That Best Tip Off Rapid Deepening Versus Non-deepening. The personnel involved in this project are William Gray, Raymond Zehr (NOAA) and one M.S. student. This work is supported by the Geophysics Laboratory.

3.13.4 Seasonal Tropical Cyclone Frequency and Intensity Prediction in the Atlantic and Western North Pacific. The leader of this project is William Gray. This work is supported by the National Science Foundation (NSF).

3.14 Florida State University.

3.14.1 Numerical Prediction of Tropical Cyclones. Numerical prediction of tropical cyclones is being studied using two models. One is a high-resolution global spectral model with a triangular truncation of 170 (T170). The other is a mesoscale regional model with a horizontal resolution of about 50 km. The focus of the work is on the recurvature problem with the global model and on the landfall problem with the regional model. The sensitivity to enhanced vertical resolution near the tropopause (outflow) level and the importance of the divergent component of the wind are being studied with the global model. The regional model is being used to develop parameterizations of land surface processes, including ground wetness. Satellite and surface based data sets are used with the regional model to develop the parameterizations. The personnel involved in this project are T.N. Krishnamurti, D. Oosterhof, K.S. Yap and Jack Beven. This work is funded by the NSF and the ONR.

3.15 Massachusetts Institute of Technology.

3.15.1 Finite-amplitude Nature of Tropical Cyclogenesis. A theoretical analysis is being performed to understand why a finite-amplitude "starter" is needed to initiate tropical cyclone intensification. The personnel involved in this project are Mark Handel and Kerry Emanuel. This work is supported by the National Science Foundation.

3.15.2 Interaction of Tropical Cyclones with the Ocean. The negative feedback of sea surface temperature decreases on tropical cyclone intensity is being studied using coupled air-sea models. An observational study is also being performed to relate reduced cyclone intensity to the depth of the oceanic mixed layer and the size and speed of motion of tropical cyclones. The personnel involved in this work are Kerry Emanuel, R. Rotunno, P. Gallacher and Lars Schade. This work is supported by the NSF.

3.15.3 The Role of Upper Troposphere Potential Vorticity Anomalies in Tropical Cyclogenesis. An observational study is being performed to determine the relationship between the transformation of weak disturbances into tropical cyclones and the approach of upper-tropospheric potential vorticity anomalies. The personnel involved in this project are Kerry Emanuel and Daniel Reilly. This work is supported by the NSF.

3.15.4 Large-scale Vertical Wind Shear. The effect of large-scale vertical wind shear on the steering of tropical cyclones (a theoretical study) is being performed to understand the effect of vertical wind shear on the interaction of upper- and lower-tropospheric potential vorticity anomalies associated with tropical cyclones. The personnel involved in this project are Kerry Emanuel and Chun-Chieh Wu. This work is supported by the National Science Foundation.

3.16 Naval Postgraduate School.

3.16.1 Basic Research Studies. The basic research studies are in support of the ONR tropical cyclone motion initiative. Analytical and numerical models are being used to understand the physical processes in tropical cyclone motion, with emphasis on the role of asymmetries. Also completed are some observational studies in support of the basic research and in preparation for the 1990 field experiment in the western North Pacific. The personnel involved in these studies include four faculty members, one foreign consultant, two Ph.D. students and two M.S. students.

3.16.2 Applied Research Studies. The applied research studies are in support of the JTWC. The topics of these studies include (1) development of a statistical technique to predict tropical cyclone intensities using empirical orthogonal function representations of the synoptic influences; (2) evaluation of the time consistency of the objective aids used for track prediction; (3) demonstration of the feasibility of using a lag-averaged technique for improving the track predictions; (4) demonstration of the usefulness of an empirical orthogonal function representation of the vorticity fields in the assessment of the synoptic influences on tropical cyclone motion; and (5) development of a prototype expert system to evaluate the tropical cyclone wind conditions at Cubi Point, Philippines. The personnel involved in the work include two faculty members and three M.S. students. This work is funded by the NPS Direct Research Fund.

3.17 Pennsylvania State University.

3.17.1 Participation in the ONR Tropical Cyclone Motion Experiment. Two wind profilers and a variety of other ground-based remote sensing devices will be taken to the western North Pacific region during July-September 1990 for the ONR experiment. The PSU work will focus on the principal rainbands that pass over the instrumented site and on upper level outflow jets. The personnel involved in this work are William Frank and Dennis Thomson in collaboration with Greg Holland of The Bureau of Meteorology Research Center, Australia.

3.17.2 Numerical Modeling of Tropical Cyclogenesis. Three-dimensional model simulations are used to study mesoscale vortex formation in convective systems. It will be determined whether the vortices that form in the middle levels in convective systems over land will extend downward to the surface and become coupled with the warm oceanic energy source in a maritime environment. The personnel involved in this work are William Frank and Shuyi Chen. This work is funded by the National Science Foundation.

3.18 State University of New York at Albany.

3.18.1 External Influences on Hurricane Intensity. The effect of eddy fluxes of momentum and heat (related to interaction with synoptic-scale systems) on tropical cyclone intensity changes is studied using data analyses and a simplified model. The personnel involved in this work include John Molinari and one research associate. This work is funded by the National Oceanic and Atmospheric Administration (NOAA).

3.19 U.S. Air Force Academy.

3.19.1 Time Series Prediction of Hurricane Movement. A nonlinear time series model is used to predict tropical cyclone tracks from the previous track positions. The leader of this project is Thomas Curry.

3.20 University of Hawaii.

3.20.1 Observational and Theoretical Aspects of Tropical Cyclone Motion. Tropical cyclone motion is being studied using observational studies, numerical modeling of specific cases and idealized cases, and the development of a nonlinear theoretical model. The emphasis of this work is on western North Pacific typhoons. The personnel involved in this work are T.A. Schroeder and B. Wang.

3.20.2 Influence of Multivortex Interactions on Tropical Cyclone Motion. Observations and theoretical studies on the interaction between tropical cyclones are being carried out. The leader of this project is M.A. Lander.

3.20.3 Tropical Cyclone Outflow Layer. Theoretical and numerical studies of the instability of the outflow layer are being carried out. The leader of this project is D.E. Stevens.

3.21 University of Wisconsin.

3.21.1 Evaluation of Visible Infrared Spin-scan Radiometer Atmospheric Sounder (VAS) Data. The quality and utility of VAS data are evaluated in tropical analyses using dropwindsonde data as verification. Water vapor imagery is also used to provide midtropospheric wind information. A method is also being developed to estimate sea-surface temperatures from the VAS data. The budget for this project supports one person per year.

3.21.2 Effect of Satellite-derived Winds on Hurricane Track Forecasts. The effect of high-density satellite-derived winds in the tropical cyclone environment is evaluated with a barotropic hurricane track forecast model. The budget for this project supports one person per year.

3.21.3 Hurricane Intensity Estimation from TIROS Microwave Data. Passive microwave observations from the NOAA polar-orbiting satellites are used to estimate the surface pressure in tropical cyclones. A model has been developed for Atlantic storms and a western North Pacific typhoon study is under way.

3.21.4 Observation of Tropical Cyclones from Microwave Data. The SSM/I is being used to determine very accurate center fixes of tropical cyclones. The Scanning Multichannel Radiometer (SSMR) is used to develop a model for rainfall estimation in tropical cyclones. The budget for this project supports one-half person per year for 2 years.

3.21.5 Australian Monsoon Experiment (AMEX). A barotropic model initialized with AMEX data was used to test the sensitivity of tropical cyclone tracks to various environmental parameters. The personnel involved in this work are Christopher Velden and Greg Holland. The budget for this project supports one-half person per year for 2 years.

3.21.6 Tropical Cyclone Environmental Influences (Proposed). The effect of environmental influences on tropical cyclone intensity changes will be studied. These effects include vertical wind shear and core static stability. The personnel involved in this project are Robert Merrill and Christopher Velden.

3.21.7 Typhoon Motion Experiment participation. Satellite data were collected, archived, postprocessed and disseminated during the 1990 ONR tropical cyclone motion experiment in the western North Pacific. This project was supported with funds from the ONR.

CHAPTER 4

REQUIREMENTS COMPARED WITH ONGOING RESEARCH

In this national plan it was deemed appropriate to compare the ongoing research presented in Chapter 3 with pressing forecast problems described in Chapter 2. The comparison was made by group members (or their representatives) in session. The purpose was to highlight important areas that are not being researched or that are receiving disproportionate research attention. The expectation is that researchers would tend to gravitate toward problems not being addressed by other investigators and that funding agencies would more readily fund projects that are high-ranked on the list of pressing problems and not overworked by other groups. There is a tendency here to stress applied research, because we started with a list of operational requirements from the field; however, we recognize the value of basic research and in many cases will cite ongoing basic research, which may now, or in the future, be applicable to stated problems.

The format of this section follows that of Chapter 2 in that the same topics are considered in the same order; however, the emphasis is on the known research that relates to the topics. Table 4.1 lists the pressing research items, in the same format as Table 2.1, and also shows the organizations that have research activity in those areas. Several of the "research activities" are, in fact, operational centers and in those cases the activity is best described as "techniques development."

4.1 Position and Motion.

4.1.1 Positioning. The Hurricane Research Division of the Atlantic Oceanographic and Marine Laboratory (AOML) is heavily involved in positioning studies through the use of aircraft data. The Geophysics Laboratory (Air Force Systems Command) participates in this topic through its SSM/I related research. The University of Wisconsin (UWISC) is also involved in research in this area as it relates to satellite position estimates in general.

4.1.2 Initial Motion. This area was arbitrarily restricted to obtaining motion estimates independent of indicated fix-to-fix movement. All known, pertinent, research deals with estimation of the future basic motion from deep-layer mean fields and initiation of forecast models. A closely related topic is filtering the vortex (either bogus or natural) from the large-scale steering fields. The filtering problem is being researched and results should constitute an important approach to the initial motion problem. Estimating tropical cyclone motion from satellite data has been attempted by many groups and abandoned because the quantitative satellite data are too inaccurate for tropical regions and the qualitative information is not precise.

Table 4.1 Research Problems Versus Research Activities

Research objectives	Research Activities
Improve position and motion (see paragraph 4.1)	
Positioning	HRD, GL, UWISC
Initial motion	NMC, NOARL, FNOC
Track forecasts	Several
Improve surface wind description (see paragraph 4.2)	
Est. of intensity (max winds or MSLP)	Several
Intensity prediction	NESDIS, CSU, JTWC, JTWC
Wind structure	Several
Synoptic environment (see paragraph 4.3)	
Tropical analysis	HRD, FSU, NMC, UH
Exploit existing data	NOARL, UWISC, NHC
Improve specification	Operational Centers
Improve forecasting	NMC, FNOC, HRD, GFDL
Tropical cyclone genesis	CSU, JTWC, GFDL, FSU
Upgrade other models	
Monsoon	FSU, ST LOU U, NPS
Trop upper tropospheric trough	NASA, UH
N. and S. Hemisphere twins	UH
Hybrid or semitropical cyclones	M [illegible]
Improve rainfall estimates and forecasts (see paragraph 4.4)	
TC-specific remotely sensed rainfall estimate	NASA, GL
TC rainfall forecasting techniques	NASA, HRD, U Mass
Improve tornado understanding (see paragraph 4.5)	NSSL, GL, U Ok
Improve storm surge prediction (see paragraph 4.6)	NHC, TDL, HRD
Improve sea state models (see paragraph 4.7)	
Estimation	Not known
Forecasting	OceanWx, FNOC, NOARL
Coastal effects	Not known
Information and data management (see paragraph 4.8)	
Data requirements	NASA, NMC, ONR
Damage assessment	U Chi
Tropical cyclone typing	Not known
Objective aid design and performance	NOARL, FNOC, JTWC
Evaluation of global models (see paragraph 4.9)	NMC, FNOC, NPS
Nonmeteorological items (see paragraph 4.10)	
Presentation of information	NASA
Action motivation studies	Unknown
Vertical refuge	Unknown
Communication	Unknown
Media interface	NHC, JTWC

4.1.3 Track Forecasts. Virtually all research activities with tropical cyclone programs have some effort in the track forecasting area. Currently, the most prominent is the 1990 western North Pacific ONR field experiment.

4.2 Surface Wind Description. Surface Wind description is widely recognized as the next major tropical cyclone forecast challenge after track forecasting. Here, also, there are many players and the variety can be partially attributed to available sensor data. There is a dearth of good surface truth data. For this reason, work at the University of Massachusetts (U. Mass) on developing remote wind measuring equipment takes on a high level of importance. HRD, with NOAA's Aircraft Operations Center, has been heavily involved in validating that equipment. CSU has a history of using rawinsonde and archived aircraft data to examine various aspects of the tropical cyclone wind field. GSFC has an involvement in trying to exploit current remote sensors and encourage development of advanced sensors. NESDIS has been a leader in acquiring cloud drift winds ever closer to the tropical cyclone and improving pattern recognition techniques, which are in use worldwide to estimate intensities. NEXRAD promises to offer some opportunities for near-coast and overland wind studies.

4.2.1 Intensity (Maximum Winds/MSLP) Diagnosis. HRD is the leader in intensity diagnosis through use of measurements of surface winds. However, since aircraft are only available in the Atlantic and eastern Pacific, satellite-based intensity estimates will continue to be the mainstay. NESDIS and JTWC are the clear leaders in the development and improvement of satellite applications.

4.2.2 Intensity Prediction. Research on better prediction of intensity has been hampered to some extent by the quality of surface truth data. The real problem is that the emphasis simply has not been on intensity forecasting. The JTWC has a serious effort to develop intensity forecast techniques and there is some effort in this direction at NESDIS and CSU. This is an area that is both important <u>and</u> not overloaded with investigators.

4.2.3 Wind Structure. This is an area where there are many players with little or no duplication of effort, because the problem is complex and probably does not have a single solution.

4.2.3.1 Better Surface Wind Models. To our knowledge, no one is working on the problem of categorizing tropical cyclones by type as a preliminary to wind structure studies, except, JTWC with a minor effort and CSU with only an expressed interest in the topic. The U Mass SSM/I study expects to improve the quality of wind field estimates.

4.2.3.2 Vertical Variability of Winds. Vertical reduction of aircraft flight-level winds is clearly an important part of the HRD research effort. Indirectly, these findings can apply to the more general problem of adjustment of winds to a standard reference level.

4.2.3.3 Nonstandard Wind-averaging Times HRD, in dealing with the variety of wind measurements, has had to resolve the issue of nonstandard wind averaging times. The solution to this problem may be a simple stability-dependent application of algorithms developed in the course of research.

4.2.3.4 Orographic Effects. Orographic effects relate to the other wind structure problems in that much of the available data suffer from orographic influence; however, no organization is known to be working on this problem.

4.2.3.5 Surface Wind Depiction. The horizontal description of surface winds is related to the above topic of models of surface winds around tropical cyclones. To some extent, all centers dealing with surface winds are using and improving surface wind models (or perhaps more appropriately, parameterizations). There is no known research effort to improve tropical cyclone surface wind models.

4.2.3.6 Maximum Winds. In areas that have aircraft, the maximum winds problem will benefit directly from the HRD measurement efforts. NESDIS has a continuous project to improve the Dvorak-type pattern recognition scheme. JTWC has a similar project for the Eastern Hemisphere.

4.2.3.7 Minimum Sea-level Pressure. In areas that have aircraft, minimum sea-level pressure (MSLP) is not a problem because current measurements (or even extrapolations) are accurate enough for operational purposes. The reliability of MSLP estimates from satellites leaves much to be desired and, indeed, there is no known effort to develop a capability to directly measure surface pressure. Indirectly, an improvement in the Dvorak-type technique would also improve the estimation of MSLP.

4.3 Synoptic Environment.

4.3.1 Tropical Analysis. The operational numerical centers are constantly striving to improve the numerical objective analyses throughout the globe with generally less emphasis on the tropics. In recent years, this lack of emphasis on the tropics may have changed. NMC, for example, has a strong program in place to cooperate with NHC in improving its tropical analysis. The problems are no longer just data problems. As more data have become available, largely in the form of cloud-drift winds, it has become apparent that the objective analyses are less sensitive to data than desired, and even the most common tropical features are not always depicted. Tropical waves, for example, are rarely depicted and tropical cyclone vortices are frequently misplaced.

4.3.1.1 Existing Data. Much of the ongoing effort at NMC, and at such places as the UWISC, is to exploit the existing data, primarily satellite winds. The former has concentrated on model mechanics that tend to exclude data in areas of large change, while the latter has stressed maximum use of the available data to support a vertically consistent three-dimensional analysis. The UH, FSU, HRD, and NOARL have active programs in this area. The NHC is committed to maintaining a quality analysis as part of its World Meteorological Organization (WMO), Regional Specialized Meteorological Center (RSMC) responsibilities and for its own internal use.

4.3.1.2 Improve Specification. Two NHC objectives are to portray the synoptically important features of the tropics and to create data files that will cause the NMC analysis to do likewise. It is expected that attainment of these goals will require an experienced tropical analyst to interact with the NMC computers. The operational centers are concurrently improving their objective analysis models.

4.3.2 Improve Forecasting. There is ongoing work at NMC, FNOC, HRD, and GFDL to improve aspects of the global models. New, large and fast computers will permit fine resolution models. There should be some improvement as smaller scales are resolved.

4.3.3 Tropical Cyclone Genesis. There is ongoing work in tropical cyclone genesis at CSU, JTWC, GFDL, and FSU.

4.3.4 Upgrade Other models.

4.3.4.1 Monsoon Models. Monsoons are being studied at FSU, St. Louis University (ST LOU U) and the NPS. While details are unknown, this work appears to be aimed at increasing basic understanding of the phenomena.

4.3.4.2 TUTT Model. The TUTT has been, and continues to be, an ongoing project at the UH. GSFC also has an ongoing research project on the TUTT.

4.3.4.3 Twin Cyclones. The UH has an interest in twin cyclones; however, the extent of their research program is unknown.

4.3.4.4 Hybrid Storm Systems. MIT has an interest in hybrid storm systems; however, the extent of their research program is unknown.

4.4 Rainfall. GSFC and GL have ongoing tropical rainfall remote-sensing programs.

4.5 Tornadoes. The National Severe Storms Laboratory (NSSL), GL, and the University of Oklahoma (U Ok) have research programs that include studies of tornadoes around tropical cyclones.

4.6 Storm Surge. The NHC, the NWS Techniques Development Laboratory, and HRD have programs to improve storm surge prediction.

4.7 Sea State. The sea state has been researched primarily at AOML and at NOARL working with FNOC.

4.7.1 Estimation. Historical effort ongoing at AOML is the improvement of tropical-cyclone-related sea-state specification. In the absence of observations, the centers must estimate the radius of 12-ft seas on the basis of tropical cyclone characteristics. A parametric model at AOML (Duncan Ross model) satisfies this requirement; however, it should be tested operationally.

4.7.2 Forecasting. The Navy has progressed considerably in forecasting sea states. A very good model, developed by Cardone (Oceanweather, Inc.), resides at FNOC. It is unclear whether this model would satisfy the operational requirements of the tropical cyclone forecast centers.

4.7.3 Coastal Effects. There is no known program in support of tropical-cyclone-related coastal effects problems (see paragraph 2.7.3).

4.8 Information and Data Management.

4.8.1 Data Requirements. NASA has a program to specify data requirements as related to future satellite design. NMC has an effort to determine the utility of various data types in model initialization. HRD has been in the forefront of applying new airborne measurement techniques. There is no known program to specify data requirements based on reducing uncertainty in tropical cyclone impact forecasts.

4.8.2 Damage Assessment. The University of Chicago (U Chi), under T.T. Fujita, has a program of damage assessment. It is not known to what extent this program could address the damage assessment concerns expressed in paragraph 2.8.2.

4.8.3 Quantify and Adjust Satellite Data for Diurnal Effects. The JTWC and NESDIS (under Zehr,) have projects to quantify and adjust satellite data for diurnal effects.

4.8.4 Tropical Cyclone Characteristics Typing. Tropical cyclone characteristics typing was considered by the ad-hoc group to be a novel and worthwhile project; however, there is no known program using this approach.

4.8.5 Objective Aid Design and Performance. NOARL, FNOC and JTWC have projects in the area of objective aid design and performance. Since there is very little continuity between the aids in different basins, the work that is primarily targeted to the western North Pacific will have little application in other areas.

4.9 Global Model Evaluation. NMC, FNOC, NPS, and other universities and operational centers have programs to evaluate operational global models. NHC and JTWC have supported short-term trouble-shooting projects when erratic or poor performance by a usually reliable model suggests a flaw in an underlying global or regional model.

4.10 <u>Nonmeteorological Items</u>. Research on nonmeteorological items has not been conducted by labs or universities in connection with meteorology research programs. FSU (Geography Department) and the University of Minnesota (U Minn) have had programs in these areas.

4.10.1 Presentation of information. NASA is studying the problem of information dissemination in a general sense; and there probably are many universities and private companies also pursuing this topic.

4.10.2 Action Motivation Studies. The U Minn, FSU, and the Hazards Management Group (a private company) have been involved in action motivation studies.

4.10.3 Vertical Refuge. Vertical refuge is important to several communities along the Atlantic and Gulf coasts, and to several legislatures. Research in this topic is underway at the College of Architecture, Texas A&M University.

4.10.4 Communications. There is no known research program in tropical cyclone communications.

4.10.5 Media Interface. There is no known research program in media interface with forecasting organizations.

Intentionally left blank

CHAPTER 5

ASSESSMENT OF PROMISING TECHNOLOGY

Forecasters and numerical models continue to suffer from the lack of quantitative data over the tropics and sub-tropics. Therefore, analyses require manual interpretation of qualitative information. The next generation Geostationary Operational Environmental Satellite (GOES) series satellites, with the first satellite in the series planned for launch during 1991, is expected to provide more accurate and higher resolution "sounding" data than presently available from geosynchronous satellites. Similar improvements are expected from polar-orbiter satellite systems. However, much of the information available to the analyst will remain qualitative in nature. Therefore, it is expected that the best possible analysis for the tropical and sub-tropical regions will involve a man/computer interactive multiple level analysis scheme with an initial objective analysis modified by the analyst. Although quite difficult, the scheme should contain four-dimensional checks for dynamical consistency. Such a scheme is being pursued at NHC. These new sounding capabilities and this analysis approach should improve initial analyses and forecasts of the large scale flow patterns over the tropical and sub-tropical regions. However, it is likely that the accuracy of these analyses and forecasts will continue to lag those at mid-latitudes where more quantitative data are available.

5.1 Improved Models. Modelers indicate that such improved initial data sets, in the tropical cyclone, its near environment, and over the general tropical and subtropical belt, will result in significant improvements in tropical cyclone track and intensity predictions. Any major improvements in longer range forecasts (36- to 72- hours) will likely only come through improved dynamical models. Global, hemispheric, and regional models have shown considerable promise in recent years for forecasting storm motion. Such models showed some excellent forecasts for Hugo, but they also suffered from a lack of consistency. These models are presently out-performed by statistical/dynamical models through 72-hour forecast periods, but have been closing the gap in recent years. In addition, these dynamic models often provide the best guidance available for difficult forecast situations.

5.1.1 Statistical/Dynamical Models. Statistical/dynamical models will likely continue to be the best performers for tropical cyclone track predictions, for the next several years, through forecast periods up to 36 hours or more. Results from improved versions of NHC83, (called NHC90) indicate that tropical cyclone forecast track errors might be reduced by as much as 10 to 20 percent through the use of these types of models over the next few years, depending upon the performance of the associated dynamical model.

5.1.2 Mesoscale Models. In addition to the models cited above, mesoscale models such as the new ETA coordinate system model, under development and testing at NMC, are showing great promise. Hopefully, these models and perhaps the regional and hemispheric dynamical models mentioned earlier will start to show some skill in the prediction of tropical cyclone formation and intensity. Such skill is sorely lacking at this time.

5.2 Improved Observations. Methods for observations in and around tropical cyclones continue to improve.

5.2.1 Satellite Observations. New satellite technology includes the Air Force SSM/I system aboard a polar orbiting satellite. This system shows promise for improved rainfall estimates and surface wind estimates outside of high rain rate areas where wind speeds are less than 30 to 50 knots . The microwave sensor also provides essentially a "smeared" radar image which can help in center locations of tropical cyclones.

5.2.2 Lightning Detection. Lightning detection systems are also coming into use for monitoring the convective activity in hurricanes well away from land. These systems have a potential for tracking movement of the convective bands and "eyewall" and perhaps to infer intensity changes.

5.2.3 Aircraft Observations. New aircraft capabilities include the Air Force Improved Weather Reconnaissance System (IWRS) capabilities using satellite data links which provide detailed wind fields in real time for operational use in storm surge calculations and damage potential warnings. Also these systems provide capabilities for improved tropical cyclone tracking using the mass field, a methodology that has shown potential for significant improvement in the 12- to 36-hour forecasts.

Present operational reconnaissance aircraft provide valuable data in the core of the hurricane. However, these data are generally limited to measurements taken along the flight path or to dropwindsonde data below it at infrequent intervals. These aircraft are also slow. Doppler radar capabilities are now an integral part of NOAA's research aircraft operations. These systems provide entire data fields within several miles of the path of the aircraft. Even though remote sensing technology continues to advance, the use of satellite-based sensors in the core of the hurricane is rather limited, partially due to the poor resolution provided from orbital altitudes of 400 miles or more. Perhaps these same sensors could be adapted for use on fast, high-altitude jet aircraft. The result could be a comprehensive data set provided by the aircraft flying through the storm and satellite surveillance of the storms environment. Also, single or orthogonal passes through the tropical cyclone could quickly provide entire data fields. This would permit more time for near-environment sampling for model use and assist in "calibration" of the course satellite data. Shorter response times for the faster aircraft would reduce the number of flights scheduled and subsequently canceled after deployments due to more recent data. The combination of all these factors would not only mean that data coverage would be greatly improved, but that perhaps four or five specially equipped aircraft could meet the Atlantic basin operational data needs as compared to maintaining large reconnaissance squadrons with aging aircraft.

5.2.4 Radar Observations. The addition of doppler capabilities for the NWS NEXRAD systems will add a new dimension to hurricane warning capabilities. These systems are scheduled for installation along the Gulf of Mexico and Atlantic coasts of the U.S. during the early and mid 1990's. The doppler capabilities will provide much needed information on tropical cyclone wind fields and their changes as they move inland (Wood and Marks, 1989). These and other capabilities will permit more refined warnings during hurricane events. It is envisioned that there will be warnings within warnings. That is, hurricane warnings will be issued for a broad area of the coast, as they are today, to provide time for evacuations and other preparations, well in advance of the arrival of strong winds and heavy rains on that coast. The NEXRAD system will then be used by local NWS offices to provide short term warnings as rainbands, high winds, and possible tornadoes move toward specific locations. This will permit incomplete emergency preparations to continue in safety until more extreme conditions approach.

In addition to the wind and storm surge problems normally associated with hurricanes as they approach the coast, heavy rains and flooding frequently occur over widespread areas extending well inland. The NEXRAD system should aid in improving rainfall forecasts and permit better warnings for inland river flooding such as that caused by hurricane Agnes in 1972. The remnants of Agnes caused major flooding from North Carolina through Pennsylvania and New York with the loss of 122 lives and $2 billion in damage.

5.3 Improved Data Processing. Improved observing systems and anticipated improvements in analysis, forecasting and warning programs require efficient accessing, processing and analyzing of large quantities of different types of data from numerous sources. These data also provide the opportunity for improved forecasts from numerical models.

5.3.1 National Meteorological Center Computer. The class VII computer scheduled for NMC at Suitland, MD will permit operational implementation of next generation hurricane prediction models.

5.3.2 Advanced Weather Interactive Processing Systems (AWIPS). Products must be provided to users which optimize desired responses. The AWIPS will be the primary tool for accomplishing this task. Critical meteorological information required by local, state and federal officials and private industry, can be displayed graphically and either accessed or transmitted to users. For example, warning areas, predictions of coastal flooding, expected rainfall, maps of probabilities, etc., would be generated and made accessible to users. Providing a uniform product for these users should then minimize chances of confusion and result in a more effective warning and evacuation process.

Intentionally left blank

APPENDIX A

TROPICAL CYCLONE DATA SETS

JTWC (W North Pacific, Indian Ocean) A-3

NOAA/NESDIS (Atlantic, East Pacific) A-4

NOAA/NESDIS (Selected Atlantic Storms) A-5

NOAA/NESDIS (Selected Atlantic Storms) A-6

NOAA/NESDIS (Pacific) A-7

NOAA/AOML (Atlantic) A-8

NOAA/AOML (Atlantic) A-9

NOAA/AOML (Atlantic) A-10

NOAA/NMC (Gilbert, Beryl, Florence, Fabio, Aletta, Gilma, Uleki, Keith) A-11

NOAA/NMC (Keith, Joan, Helene, Cosme, Allison, Dalilia) A-12

NOAA/NMC (Global Archive) A-13

NOARL A-14

USAF/AWS (Weather Recon) A-15

Intentionally left blank

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a. TITLE AND/OR STORM NAME:	JOINT TYPHOON WARNING CENTER TRACK AND FIX DATA FOR TROPICAL CYCLONES
b. DATA SET ID:	Track and FIX
c. START DATE:	1986
d. STOP DATE:	1988
e. PLATFORM AND SENSOR:	
f. GEOGRAPHIC COVERAGE:	Western North Pacific, North Indian, South Indian, and South Pacific Oceans
g. PRINCIPAL INVESTIGATOR:	JTWC

h. REMARKS: For Particulars Concerning Warning and Fix Data Prior 1986, Please contact the Joint Typhoon Warning Center (JTWC).

2. **PARAMETERS IN DATA SET:**

a. FIX	
1) PARAMETER A:	Satellite
2) PARAMETER B:	Aircraft (Dedicated Aircraft Recon Available until August 1987)
3) PARAMETER C:	Radar
4) PARAMETER D:	Synoptic
b. TRACK	
1) PARAMETER E:	Initial Warning (Position and Intensity)
2) PARAMETER F:	Best Track Position (Initial, Minus 12-and Minus 24-hour)
3) PARAMETER G:	Best Track Position (24-, 48- and 72-hour)
4) PARAMETER H:	JTWC Forecast (24-, 48- and 72-hour)
5) REMARKS:	

3. **STORAGE MEDIA:**

a. MEDIUM:	5 1/4" Floppy Diskettes (IBM Compatible) or 3 1/2" (Macintosh Compatible)
b. FILM SIZE:	Contact JTWC
c. FILE TAG:	Track or Fix
d. FORMAT:	Contact JTWC
e. REMARKS:	

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Please send data request to: NOCC/JTWC, COMNAVMAR Box 17, FPO San Francisco 96630-5000. Identify desired specifics, such as, year, area and include the appropriate number of disks.
b. COST:	None
c. PAYABLE TO:	N/A
d. REMARKS:	

5. **POINT OF CONTACT:**

a. NAME:	Frank H. Wells
b. ADDRESS:	NAVOCEANCOMCEN/JTWC COMNAVMAR BOX 17 FPO San Francisco 96630-5000
c. COMMERCIAL TELEPHONE:	(671) 344-5240
d. FTS:	N/A
e. AUTOVON:	344-5240 (GUAM)
f. FACSIMILE TELEPHONE NUMBER:	(671) 477-6186
g. E-MAIL ADDRESS:	N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a. TITLE AND/OR STORM NAME:	All Atlantic and East Pacific tropical cyclones
b. DATA SET ID:	Digital geostationary (GOES) satellite data
c. START DATE:	1981
d. STOP DATE:	Present
e. PLATFORM AND SENSOR:	GOES satellite
f. GEOGRAPHIC COVERAGE:	Western Hemisphere
g. PRINCIPAL INVESTIGATOR:	UW-Space Science and Engineering Center

h. REMARKS: Geographical coverage varies with satellite configuration (whether one or two satellites in operation)

2. **PARAMETERS IN DATA SET:**

a. PARAMETER A:	Infrared imagery
b. PARAMETER B:	Visible imagers
c. PARAMETER C:`	Water vapor imagery
d. PARAMETER D:	Multispectral VAS imagery
e. PARAMETER F:	Navigation
f. PARAMETER G:	

g. REMARKS: Digital data are in the form of brightness temperature
Nominally, IR and VIS, imagery is available at 30 min. intervals
Variable spatial and temporal coverage with water vapor and VAS data

3. **STORAGE MEDIA:**

a. MEDIUM:	Computer compatible 9-track tapes (1600 or 6250 bpi)
b. FILM SIZE:	Variable depending on geographic coverage
c. FILE TAG:	N/A
d. FORMAT:	Provided

e. REMARKS: Documentation on file structure and format is given in the first file of distributed tape. Videotapes (1/2" VAS) of selected satellite imagery from hurricanes Elena and Gloria (1985), Gilbert (1988) and Hugo (1989) are also available from Chris Velden ($20/tape, payable to the University of Wisconsin)

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Andy Horvitz Satellite Data Services Division, NOAA/NESDIS, Room 100, Princeton Executive Center Washington, DC 20233 (301) 763-8400
b. COST:	$66/scene ($100 minimum)
c. PAYABLE TO:	NOAA/NESDIS

d. REMARKS: payment in advance required; allow 4-6 weeks for delivery

5. **POINT OF CONTACT:**

a. NAME:	Chris Velden or Robert Merrill
b. ADDRESS:	University of Wisconsin - SSEC 1225 West Dayton Street Madison, WI 53706
c. COMMERCIAL TELEPHONE:	(608) 262-9168 or 263-6842
d. FTS:	364-5325
e. AUTOVON:	N/A
f. FACSIMILE TELEPHONE NUMBER:	(608) 262-5974
g. E-MAIL ADDRESS:	R.FOX (OMNET) ATTN: C. Velden

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a. TITLE AND/OR STORM NAME:	Selected Atlantic storms
b. DATA SET ID:	GOES satellite derived cloud drift and water vapor motion winds
c. START DATE:	1985
d. STOP DATE:	1989
e. PLATFORM AND SENSOR:	GOES
f. GEOGRAPHIC COVERAGE:	Western Atlantic, Caribbean, Gulf of Mexico
g. PRINCIPAL INVESTIGATOR:	N/A
h. REMARKS: Nominal availability at 00 and 12 UTC Selected cases only	

2. **PARAMETERS IN DATA SET:**

a. PARAMETER A:	Wind speed (m/sec)
b. PARAMETER B:	Wind direction
c. PARAMETER C:	Wind height
d. PARAMETER D:	Wind type (cloud drift or water vapor motion)
e. PARAMETER E.	Station ID
f. PARAMETER F:	Lat/Long
h. PARAMETER G:	N/A
i. REMARKS:	N/A

3. **STORAGE MEDIA:**

a. MEDIUM:	Computer compatible 9-track tape
b. FILM SIZE:	Variable
c. FILE TAG:	N/A
d. FORMAT:	EBCDIC fixed block
e. REMARKS: Documentation will be provided	

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Contact Chris Velden or Robert Merrill
b. COST:	Negotiable
c. PAYABLE TO:	TBD
d. REMARKS: Cost depends on size request	

5. **POINT OF CONTACT:**

a. NAME:	Chris Velden or Robert Merrill
b. ADDRESS:	University of Wisconsin - SSEC 1225 West Dayton Street Madison, WI 53706
c. COMMERCIAL TELEPHONE:	(608) 262-9168 or 263-6842
d. FTS:	364-5325
e. AUTOVON:	(608) 262-5974
f. FACSIMILE TELEPHONE NUMBER:	(608) 262-5974
g. E-MAIL ADDRESS:	R. FOX (OMNET) ATTN: C. Velden

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a. TITLE AND/OR STORM NAME:	Selected Atlantic storms
b. DATA SET ID:	VAS satellite soundings
c. START DATE:	1985
d. STOP DATE:	1988
e. PLATFORM AND SENSOR:	GOES VISSR Atmospheric Sounder
f. GEOGRAPHIC COVERAGE:	Western Atlantic, Gulf of Mexico
g. PRINCIPAL INVESTIGATOR:	N/A

h. REMARKS: Sounding availability is variable
Physical simultaneous retrieval method used

2. **PARAMETERS IN DATA SET:**

a. PARAMETER A:	Temperature
b. PARAMETER B:	Dew point
c. PARAMETER C:	Height
d. PARAMETER D:	Derived gradient winds (variable availability)
e. PARAMETER E:	MSLP
f. PARAMETER F:	Station elevation (m)
g. PARAMETER G:	Station identification
h. PARAMETER H:	Lat/Long

i. REMARKS: MANDATORY LEVEL T, Td, Z, U, V

3. **STORAGE MEDIA:**

a. MEDIUM:	Computer compatible 9-track tape
b. FILM SIZE:	312 bytes per report x # reports (typically 300)
c. FILE TAG:	N/A
d. FORMAT:	Fixed block EBCDIC

e. REMARKS: Documentation will be provided

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Contact Chris Velden or Robert Merrill
b. COST:	Negotiable
c. PAYABLE TO:	TBD

d. REMARKS: Cost depends on size of request

5. **POINT OF CONTACT:**

a. NAME:	Contact Chris Velden or Robert Merrill
b. ADDRESS:	University of Wisconsin - SSEC 1225 West Dayton Street Madison, WI 53706
c. COMMERCIAL TELEPHONE	(608) 262-9168 or 263-6842
d. FTS:	364-5325
e. AUTOVON:	N/A
f. FACSIMILE TELEPHONE NUMBER:	(608) 262-5974
g. E-MAIL ADDRESS:	R. FOX (OMNET) ATTN: C. Velden

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a.	TITLE AND/OR STORM NAME:	Digital Satellite Images
b.	DATA SET ID:	ISCCP B1 GMS
c.	START DATE:	July, 1983
d.	STOP DATE:	Present
e.	PLATFORM AND SENSOR:	GMS series of geostationary satellite
f.	GEOGRAPHIC COVERAGE:	Sub-point: Equator, 140 E
g.	PRINCIPAL INVESTIGATOR:	N/A

h. REMARKS: 3-hourly full disk at 10-km resolution in both visible and IR. A portion of this disk set is available at CIRA/CSU. The entire data set is available at: NOAA/NESDIS/NCDS Satellite Data Services Division, Rm. 100 Princeton Executive Center, Washington, DC 20233
Contact: Andy Horvitz, 301-763-8400 (See Para 4)

2. **PARAMETERS IN DATA SET:**

a.	PARAMETER A:	IR brightness (equivalent blackbody temperature, conventional infrared imagery)
b.	PARAMETER B:	Visible brightness (conventional visible imagery)
c.	PARAMETER C:	Navigation and calibration information
d	PARAMETER D:	N/A
f.	PARAMETER F:	N/A
h.	PARAMETER G:	N/A
i.	REMARKS:	

3. **STORAGE MEDIA:**

a.	MEDIUM:	9-track magnetic tape (6250 PI)
b.	FILM SIZE:	1100 X 1100 X 8-bit
c.	FILE TAG:	N/A
d.	FORMAT:	N/A
e.	REMARKS:	

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a.	INSTRUCTIONS:	Small data requests may be available from CIRA/CSU, for the cost of magnetic tapes and shipping. We have most of the data for the 6-month period, July 1-Dec 31, for 1983 through 1986. Some "hard-copy" images may also be available. Large data requests must be handled by NESDIS Satellite Data Services Division (See Para 1h).
b.	COST:	TBD
c.	PAYABLE TO:	TBD
d.	REMARKS:	

5. **POINT OF CONTACT:**

a.	NAME:	Raymond Zehr, NOAA/NESDIS/Debra Lubich, CIRA
b.	ADDRESS:	CIRA Bldg. Colorado State University Fort Collins, CO 80523
c.	COMMERCIAL TELEPHONE:	303-491-8446
d.	FTS:	323-1124
e.	AUTOVON:	N/A
f.	FACSIMILE TELEPHONE NUMBER:	N/A
g.	E-MAIL ADDRESS:	N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:** NOAA P-3 Flight Level Data

   a. TITLE AND/OR STORM NAME: Numerous Atlantic Tropical Cyclones
   b. DATA SET ID: N/A
   c. START DATE: 1977
   d. STOP DATE: Present
   e. PLATFORM AND SENSOR: NOAA WP-3D Aircraft
   f. GEOGRAPHIC COVERAGE: Typically 0-2 degrees from storm center
   g. PRINCIPAL INVESTIGATOR: Hurricane Research Division
   h. REMARKS: Several Eastern Pacific Storms may also be available

2. **PARAMETERS IN DATA SET:**

   a. PARAMETER A: Horizontal wind
   b. PARAMETER B: Vertical wind
   c. PARAMETER C: Temperature
   d. PARAMETER D: Dew Point Temperature
   e. PARAMETER E: Height
   f. PARAMETER F: Estimated Surface Pressure
   g. PARAMETER G: Pressure
   h. PARAMETER H: Radiometer data
   i. REMARKS: Numerous other aircraft parameters are also available

3. **STORAGE MEDIA:**

   a. MEDIUM: Magnetic Tape
   b. FILM SIZE: N/A
   c. FILE TAG: N/A
   d. FORMAT: See para 3e
   e. REMARKS: Format, etc depend on flight and year.

4. **HOW TO OBTAIN COPIES OF DATA SET:**

   a. INSTRUCTIONS: Depends on size of request, contact 5a for further information
   b. COST: Variable
   c. PAYABLE TO: TBD
   d. REMARKS:

5. **POINT OF CONTACT:**

   a. NAME: Howard A. Friedman
   b. ADDRESS: 4301 Rickenbacker Causeway
   NOAA/AOML/HRD
   Miami, FL 33149
   c. COMMERCIAL TELEPHONE: 305-361-4319
   d. FTS: 350-1319
   e. AUTOVON: N/A
   f. FACSIMILE TELEPHONE NUMBER: N/A
   g. E-MAIL ADDRESS: N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:** NOAA P-3 Omega Dropwindsonde Data

a.	TITLE AND/OR STORM NAME:	Eight Tropical Cyclones since 1982
b.	DATA SET ID:	N/A
c.	START DATE:	1982
d.	STOP DATE:	Present
e.	PLATFORM AND SENSOR:	NOAA WP-3D Aircraft
f.	GEOGRAPHIC COVERAGE:	Typically 0-10 degrees from storm center
g.	PRINCIPAL INVESTIGATOR:	Hurricane Research Division
h.	REMARKS:	

2. **PARAMETERS IN DATA SET:**

a.	PARAMETER A:	Horizontal Wind
b.	PARAMETER B:	Temperature
c.	PARAMETER C:	Dew Point Temperature
d.	PARAMETER D:	Pressure
f.	PARAMETER F:	N/A
h.	PARAMETER G:	N/A

i. REMARKS: Processed data usually at 50 mb intervals from surface to 400mb.

3. **STORAGE MEDIA:**

a.	MEDIUM:	Magnetic Tape
b.	FILM SIZE:	N/A
c.	FILE TAG:	N/A
d.	FORMAT:	See para 3e.

e. REMARKS: Format, etc. depend on flight and year

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a.	INSTRUCTIONS:	Depends on site of request, contact 5a for further information
b.	COST:	Variable
c.	PAYABLE TO:	TBD
d.	REMARKS:	

5. **POINT OF CONTACT:**

a.	NAME:	Howard A. Friedman
b.	ADDRESS:	4301 Rickenbacker Causeway NOAA/AOML/HRD Miami, FL 33149
c.	COMMERCIAL TELEPHONE:	305-361-4319
d.	FTS:	350-1319
e.	AUTOVON:	N/A
f.	FACSIMILE TELEPHONE NUMBER:	N/A
g.	E-MAIL ADDRESS:	N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:** NOAA P-3 Airborne Radar Data

a. TITLE AND/OR STORM NAME:	Numerous Atlantic Tropical Cyclones
b. DATA SET ID:	N/A
c. START DATE:	1977
d. STOP DATE:	Present
e. PLATFORM AND SENSOR:	NOAA WP-3D Aircraft
f. GEOGRAPHIC COVERAGE:	Typically 0-1 degrees from Storm Center
g. PRINCIPAL INVESTIGATOR:	Hurricane Research Division
h. REMARKS:	

2. **PARAMETERS IN DATA SET:**

a. PARAMETER A:	Doppler winds (Since 1982)
b. PARAMETER B:	Reflectivity (Since 1977)
c. PARAMETER C:	N/A
d. PARAMETER D:	N/A
f. PARAMETER F:	N/A
h. PARAMETER G:	N/A
i. REMARKS:	

3. **STORAGE MEDIA:**

a. MEDIUM:	Magnetic Tape
b. FILM SIZE:	N/A
c. FILE TAG:	N/A
d. FORMAT:	See para 3d.

e. REMARKS: Format, etc. depend on flight and year.

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Depends on site of request, contact 5a for further information
b. COST:	Variable
c. PAYABLE TO:	TBD
d. REMARKS:	

5. **POINT OF CONTACT:**

a. NAME:	Howard A. Friedman
b. ADDRESS:	4301 Rickenbacker Causeway NOAA/AOML/HRD Miami, FL 33149
c. COMMERCIAL TELEPHONE:	305-361-4319
d. FTS:	350-1319
e. AUTOVON:	N/A
f. FACSIMILE TELEPHONE NUMBER:	N/A
g. E-MAIL ADDRESS:	N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a. TITLE AND/OR STORM NAMES AND DATES:	
HURRICANE GILBERT	Sept. 10 to Sept. 17, 1988
T. S. BERYL	Aug. 8, 1988 00Z
T. S. FLORENCE	Sept. 7, 1988 12Z
HURRICANE FABIO	Aug. 2, 1988 to Aug. 5, 1988
T. S. ALETTA	June 17, 1988 to June 17, 1988
T. S. GILMA	Aug. 2, 1988
HURRICANE ULEKI	Aug. 29, 1988 to Aug. 30, 1988
T. S. KEITH	Nov. 21, 1988, 00Z
e. PLATFORM AND SENSOR:	N/A
f. GEOGRAPHIC COVERAGE:	Global
g. PRINCIPAL INVESTIGATOR:	John Ward
h. REMARKS:	

2. **PARAMETERS IN DATA SET:**

a. PARAMETER A:	Temperature
b. PARAMETER B:	Vorticity
c. PARAMETER C:	Divergence
d. PARAMETER D:	Specific Humidity
f. PARAMETER F:	N/A
h. PARAMETER G:	N/A

i. REMARKS: T80 spectral coefficients from NMC aviation run 16 levels of information in sequence for forecast hours 0, 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66, & 72.

3. **STORAGE MEDIA:**

a. MEDIUM:	6250 9-Track Tape
b. FILM SIZE:	N/A
c. FILE TAG:	AVNCOF
d. FORMAT:	VS
e. REMARKS:	

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Write to: Dr. William Bonner, Director National Meteorological Center W/NMC, WWB, Rm. 204 Washington, DC 20233
b. COST:	TBD
c. PAYABLE TO:	TBD
d. REMARKS:	

5. **POINT OF CONTACT:**

a. NAME:	Dr. John H. Ward
b. ADDRESS:	NMC W/WMC22, WWB, Rm. 204 Washington, DC 20233
c. COMMERCIAL TELEPHONE:	(301) 763-8056
d. FTS:	763-8056
e. AUTOVON:	N/A
f. FACSIMILE TELEPHONE NUMBER:	N/A
g. E-MAIL ADDRESS:	N/A

TROPICAL CYCLONE RESEARCH DATA SET

1.DESCRIPTION OF DATA SET:

a.	TITLE AND/OR STORM NAMES AND DATES:	
	T. S. KEITH	Nov. 21, 1988, 00Z
	T. S. KEITH	Nov. 22, 1988, 00Z
	HURRICANE JOAN	Oct. 14, 1988, 12Z
	HURRICANE JOAN	Oct. 12, 1988, 12Z
	HURRICANE HELENE	Sept. 22, 1988, 00Z
	HURRICANE HELENE	Sept. 24, 1988, 12Z
	HURRICANE COSME	June 21, 1989, 12Z
	T. S. ALLISON	June 25, 1989, 12Z
	HURRICANE DALILA	July 17, 1989, 12Z
	HURRICANE DALILA	July 18, 1989, 00Z
d.	STOP DATE:	N/A
e.	PLATFORM AND SENSOR:	N/A
f.	GEOGRAPHIC COVERAGE:	Global
g.	PRINCIPAL INVESTIGATOR:	Mukut Mathur
h.	REMARKS:	

2. PARAMETERS IN DATA SET:

a.	PARAMETER A:	Temperature
b.	PARAMETER B:	Vorticity
c.	PARAMETER C:	Divergence
d.	PARAMETER D:	Specific Humidity
f.	PARAMETER F:	N/A
h.	PARAMETER G:	N/A

i. REMARKS: T80 spectral coefficients from NMC aviation run; 18 levels information in sequence for forecast hours 0, 6, 12, 18, 24, 30 36, 42, 48, 54, 60, 66, & 72.

3. STORAGE MEDIA:

a.	MEDIUM:	6250 Magnetic Tape
b.	FILM SIZE:	N/A
c.	File TAG:	AVNCOF
d.	FORMAT:	VS
e.	REMARKS:	

4. HOW TO OBTAIN COPIES OF DATA SET:

a.	INSTRUCTIONS:	Write to: Director National Meteorological Center W/NMC, WWB, Rm. 101 Washington, DC 20233
b.	COST:	TBD
c.	PAYABLE TO:	TBD
d.	REMARKS:	

5. POINT OF CONTACT:

a.	NAME:	Mukut Mathur
b.	ADDRESS:	NMC, W/WMC22, WWB, Rm. 204 Washington, DC 20233
c.	COMMERCIAL TELEPHONE:	(301) 763-8161
d.	FTS:	763-8161
e.	AUTOVON:	N/A
f.	FACSIMILE TELEPHONE NUMBER:	N/A
g.	E-MAIL ADDRESS:	N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**
   - a. TITLE AND/OR STORM NAME: NMC Global Tropical Cyclone Archive
   - b. DATA SET ID: (YYMMDDHH), HH=0., 12, HH=O contains 00, 06 UTC and HH=12 contains 12, 18 UTC files.
   - c. START DATE: Gloria, 20 Sep 1985 00 UTC - 28 Sep 1985 UTC
     Emily, 21 Sep 1987 00 UTC - 27 Sep 1987 12 UTC
     Floyd, 08 Oct 1987 00 UTC - 14 Oct 1987 12 UTC.
     Future cases to be archived include Gilbert and Joan (1988). In 1989 and subsequent years, we will archive most Atlantic hurricane cases, and in 1990 and subsequent years, we will archive selected storms from the East Pacific and the western North Pacific.
   - d. STOP DATE: Same
   - e. PLATFORM AND SENSOR: All operational observations gathered and processed by NMC, including upper air, surface, satellite winds, TIROS thickness aircraft and reconnaissance data.
   - f. GEOGRAPHIC COVERAGE: Global
   - g. PRINCIPAL INVESTIGATOR: Dr. Stephen J. Lord
     NMC, W/NMC2 WWB Rm. 204
     Washington, DC 20233
     (301) 763-8301
   - h. REMARKS: Special requests for data sets not already gathers may be forwarded to the principal investigator above.

2. **PARAMETERS IN DATA SET:** **Several subsets of files exist as follows:**
   - a. PARAMETER A: Operational analyses of wind, geopotential height, moisture on mandatory pressure levels with a special representation of Rhomboidal 40 waves.
   - b. PARAMETER B: Operational analyses on sigma coordinate surfaces represented as Triangular 80 waves.
   - c. PARAMETER C: Operational 6 hour forecasts on sigma coordinate surfaces represented as Triangular 80 waves valid at the analysis time. These forecasts are used as a background field for the model analysis.
   - d. PARAMETER D: Global observations as described in 1e above.
   - f. PARAMETER F: N/A
   - h. PARAMETER G: N/A

3. **STORAGE MEDIA:**
   - a. MEDIUM: Data sets are recovered from optical disk and copied to magnetic tape.
   - b. FILM SIZE: Approximately 7 days of twice daily files will fit on one tape.
   - c. File TAG: N/A
   - d. FORMAT: The data format may be either of two types as listed below.
     1. IBM internal binary (all observations currently available only in this format).
     2. WMO gridded bineary (GRIB) In this case, FORTRAN 77 code is available for unpacking the GRIB records. Precision is the full 32 bit representation for all spectral coefficients.
   - e. REMARKS: Data may be obtained by writing or telephoning the Principal Investigator in 1g above.

4. **HOW TO OBTAIN COPIES OF DATA SET:**
   - a. INSTRUCTIONS: Write to:
     Director, National Meteorological Center
     W/NMC, WWB, Rm. 101
     Washington, DC 20233
   - b. COST: TBD
   - c. PAYABLE TO: TBD
   - d. REMARKS:

5. **POINT OF CONTACT:**
   - a. NAME: Dr. Stephen J. Lord
   - b. ADDRESS: See 1g
   - c. COMMERCIAL TELEPHONE: See 1g
   - d. FTS: 763-8161
   - e. AUTOVON: N/A

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a.	TITLE OR STORM NAME:	Tropical Cyclone Data Base
b.	DATA SET ID:	Best Track, Forecasts and Fixes
c.	BEST TRACK:	6 hourly lat, long, max winds
d.	FORECASTS:	JTWC 24, 48, 72 forecast lat, long Objective aid 24, 48, 72 forecast lat, long
e.	FIXES:	Satellite, Aircraft, Radar, Synoptic fixes

2. **PARAMETERS IN DATA SET:**

Time/Area Coverage

Basin	Latitude	Longitude	Best Track	Forecasts	Fixes
Western North Pacific (WP)	EQ-60N	100E-180E	1945-1989	1966-1977 1978-1989	1966-1977 1979-1989
North Indian Ocean (I0)	EQ-60N	40-E-100E	1945-1989	1978-1989	1972-1989
Eastern North Pacific (EP)	EQ-60N	180W-80W	1945-1989	--------	1989
North Atlantic (AL)	EQ-60N	100W-10E	1945-1989	--------	1989
Southern Hemi-sphere (SH)	EQ-60S	20E-120W	1945-1989	1980-1989	1980-1989

(Note Southern Hemisphere storm years are July 1-June 30. For example, the first tropical cyclone on or after July 1, 1982 would be the first storm of the 1983 storm year).

3. **STORAGE MEDIA:**	Available on 5 1/4" floppy disk or magnetic tape. Data is ASCII and format will be sent with each data request.
4. **HOW TO OBTAIN COPIES:**	See para 5.

5. **POINT OF CONTACT:**

a.	NAME:	Ronald J. Miller
b.	ADDRESS:	Naval Oceanographic Atmospheric Research Laboratory Atmospheric Directorate Monterey, CA 93943-5006
c.	COMMERCIAL TELEPHONE:	(408) 647-4733
d.	FTS:	N/A
e.	AUTOVON:	N/A
f.	FACSIMILE TELEPHONE NO:	N/A
g.	E-MAIL ADDRESS:	OMNET ADDRESS: R.MILLER.NOARL

TROPICAL CYCLONE RESEARCH DATA SET

1. **DESCRIPTION OF DATA SET:**

a. TITLE AND/OR STORM NAME:	Weather Reconnaissance
b. DATA SET ID:	Weather Reconnaissance
c. START DATE:	Varied
d. STOP DATE:	Varied
e. PLATFORM AND SENSOR:	WC-130 Aircraft
f. GEOGRAPHIC COVERAGE:	Varied
g. PRINCIPAL INVESTIGATOR:	N/A
h. REMARKS:	

2. **PARAMETERS IN DATA SET:**

a. PARAMETER A:	N/A
b. PARAMETER B:	N/A
c. PARAMETER C:	N/A
d. PARAMETER D:	N/A
f. PARAMETER F:	N/A
h. PARAMETER G:	N/A
i. REMARKS:	

3. **STORAGE MEDIA:**

a. MEDIUM:	On paper
b. FILM SIZE:	N/A
c. FILE TAG:	N/A
d. FORMAT:	N/A
e. REMARKS: Stored at NCDC, Asheville, NC	

4. **HOW TO OBTAIN COPIES OF DATA SET:**

a. INSTRUCTIONS:	Contact Mr. John Walsh; See 5.a. and b.
b. COST:	TBD
c. PAYABLE TO:	TBD
d. REMARKS:	

5. **POINT OF CONTACT:**

a. NAME:	Mr. John Walsh
b. ADDRESS:	OL-A, USAFETAC Asheville, NC 28801-2723
c. COMMERCIAL TELEPHONE:	(704) 259-0218/0404
d. FTS:	N/A
e. AUTOVON:	697-8358
f. FACSIMILE TELEPHONE NUMBER:	N/A
g. E-MAIL ADDRESS:	N/A

Intentionally left blank

APPENDIX B

ABBREVIATIONS

-A-

AFCRL	Air Force Cambridge Research Laboratory (see AFGL)
AFGL	Air Force Geophysics Laboratory (Formerly AFCRL)
AFGWC	Air Force Global Weather Central
AHG/TCR	Ad-Hoc Group for Tropical Cyclone Research
AMEX	Australian Monsoon Experiment
AMSU	Advanced Microwave Sounding Unit
AOML	Atlantic Oceanographic and Marine Laboratory
ATCF	Automated Tropical Cyclone Forecast System
AWIPS	Advanced Weather Interactive Processing Systems

-C-

CIRA	Cooperative Institute for Research in the Atmosphere
CSU	Colorado State University

-D-

DMSP	Defense Meteorological Satellite Program

-E-

EBCDIC	Extended Binary Coded Decimal Interchange Code
EIR	enhanced infrared
E-mail	Electronic main

-F-

FNOC	Fleet Numerical Oceanography Center
FSU	Florida State University

-G-

GFDL	Geophysical Fluid Dynamics Laboratory
GL	Geophysics Laboratory
GOES	Geostationary Operational Environmental Satellite
GRIB	gridded binary (data)
GSFC	Goddard Space Flight Center

-H-

HRD	Hurricane Research Division

-I-

ICMSSR	Meteorological Services and Supporting Research
IR	infrared
IWRS	Improved Weather Reconnaissance System

-J-

JTWC	Joint Typhoon Warning Center

-K-

kt	knot(s)

-M-

MIT	Massachusetts Institute of Technology
MSLP	minimum sea level pressure

-N-

NASA	National Aeronautics and Space Administration
NATCF	Navy Automated Tropical Cyclone Forecasting System
NCDC	National Climatic Data Center
NDBC	National Dat Buoy Center
NEPRF	Naval Environmental Prediction Research Facility
NESDIS	National Environmental Satellite, Data and Information Service
NEXRAD	Next Generation Weather Radar
NHC	National Hurricane Center
NHC83	an NHC statistical dynamic model for forecasting track of tropical storms
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NOARL	Naval Oceanographic and Atmospheric Research Laboratory
NOGAPS	Navy Operational Global Atmospheric Prediction System
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSFC	NASA/Goddard Space Flight Center
NSSL	National Severe Storms Laboratory
NWS	National Weather Service

-O-

OLS	Operational Line Scanner
ONR	Office of Naval Research

-P-

PCN	Position Code Numbers
PSU	Pennsylvania State University
RSMC	Regional Specialized Meteorological Center
SFRM	stepped-frequency microwave radiometer
SLP	sea level pressure
SSM/I	special sensor microwave imager
SSM/T	special sensor microwave/temperature
SSMR	scanning multichannel radiometer
ST LOU U	St. Louis University
SUNYA	State University of New York at Albany

-T-

TBD	to be determined
TC	tropica cyclone
TCFS	Tropical Cyclone Forecast Simulation
TOVS	TIROS-N Operational Vertical Sounder
TUTT	tropical upper tropospheric trough

-U-

U Chi	University of Chicago
U Mass	University of Massachusetts
U Minn	University of Minnesota
U Ok	University of Oklahoma
U WISC	University of Wisconsin
UH	University of Hawaii
USAFA	U.S. Air Force Academy
UWISC	University of Wisconsin

-V-

VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin-scan Radiometer

-W-

WMO	World Meteorological Organization
WWB	World Weather Building

APPENDIX C

REFERENCES

Bao	Bao, C., 1981: Forecasting typhoon movement based on satellite cloud maps. Report UHMET 81-03, University of Hawaii, 26 pp.
Chan	Chan, J.C.L., 1982. On the physical parameters responsible for T.C. motion. Atm. Sci. Paper 358, Colorado State Univ. Fort Collins, CO 200pp
Dvorak, Vernon, 1984a	Satellite observed upper level moisture patterns associated with tropical cyclone movement. Postprints 15th Conference on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., Boston, 163-168.
Dvorak (84b)	Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 47 pp.
Fett & Brand	Fett, R.W., and S. Brand, 1975: Tropical cyclone movement forecasts based on observations from satellites. J. Appl. Meteor., 452-456.
Hebert, P.J., and K.O. Poteat, 1975:	A satellite classification technique for subtropical cyclones. NOAA Technical Memorandum NWS SR-83, U.S. Department of Commerce, National Weather Service, Fort Worth, TX, 76102, 25 pp.
Lajoie & Nicholas	Lajoie, F.A., and N. Nicholas, 1974: A relationship between the direction of movement of tropical cyclones and the structure of Meteorology, Melbourne, Australia, 22 pp.
Neumann, C.J., 1979:	On the use of deep-layer-mean geopotential height fields in statistical prediction of tropical cyclone motion. 6th Conference on Probability and Statistics in Atmospheric Sciences, Amer. Meteor. Soc., Boston, 32-38.
Sadler	Sadler, J.C., 1978: Mid-season typhoon developments and intensity changes and the tropical upper tropospheric trough. Mon. Wea. Rev., 106, 1137-1152.
Simpson	Simpson, R.H., 1974: The hurricane disaster potential scale. Weatherwise, 27, 169-186.
Weldon	Weldon, R., 1979: Cloud patterns and the upper air wind field. NESS, Applications Division Satellite Training Course Notes, Part IV.

APPENDIX D

DISTRIBUTION

DEPARTMENT OF COMMERCE

Director, AOML Hurricane Research Division 5

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Assistant Administrator for Ocean Services
and Coastal Zone Management 1
Director, Office of Public Affairs, NOAA 2
Assistant Administrator for Weather 1
Director, Office of Meteorology 1
Chief, International Activities Division 1
Chief, Warning and Forecast Branch 1
Chief, Aviation Services Branch 1
Chief, Services Development Branch 1
Director, Office of Hydrology 1
Director, National Climate Program 1
Director, Office of Climate and Atmospheric Research 1
NOAA Library 2
Director, National Meteorological Center 1
Chief, Meteorological Operations Division 1
Chief, Development Division 1
Chief, Satellite Services Division 1
Director, National Hurricane Center 20
Director, NWS Eastern Region 2
Director, NWS Central Region 2
Director, NWS Southern Region 2
Director, NWS Western Region 2
Director, NWS Pacific Region 3
Director, Central Pacific Hurricane Center 1
Geophysical Fluid Dynamics Lab 1
National Environmental Satellite, Data and Information Services 2
Chief, Library Division, MASC 1
Director, Environmental Research Laboratories 1
Chief, Information Services Division, National Climatic
Data Center 2

DEPARTMENT OF DEFENSE

DEPARTMENT OF THE AIR FORCE

HQ USAF/XOOSA	2
HQ USAF/XOOSZ	1
HQ USAF/REO	1
HQ MAC/XPPT/XPQS/DOOS	3
HQ PACAF/DOW	3
HQ AFRES/DOOM	1
HQ 4AF/DOO	1
HQ ARS/DO	1
453 WRS/DO	1
HQ 403 TAW/DO	1
815 TAS/DO	1
815 WOF	1
HQ AWS/CSE	10
AFGWC/CC	2
3350 TCHTG/TTMU	1
AFGL/LY	1
AFGL Library	1
ETAC LIBRARY	2

DEPARTMENT OF THE ARMY

HQ Department of the Army/DAMI-POI	3
HQ TRADOC	1
USAICS	1

DEPARTMENT OF THE NAVY

Commandant of the Marine Corps (DCS/Aviation)	1
Oceanographer of the Navy	1
Commander, Naval Oceanography Command	10
Commanding Officer, NAVEASTOCEANCEN	1
Commanding Officer, NAVWESTOCEANCEN	2
Commanding Officer, NAVOCEANCOMCEN/JTWC	5
Commanding Officer, Fleet Numerical Oceanography Center	1
Commanding Officer, NOARL (West)	1
Prof. Russell L. Elsberry, Department of Meteorology Naval Postgraduate School	2
Office of Naval Research	1

JOINT CHIEFS OF STAFF

OJCS/J3/Environmental Services Division 1
USPACOM/J37 1

FEDERAL AVIATION ADMINISTRATION

Air Traffic Service (AAT-134) 1

U.S. COAST GUARD

Commandant, USCG Headquarters (G-010) 1
Commander, Atlantic Area, USCG 1
Commander, First Coast Guard District 1
Commander, (OPC) Third Coast Guard District 1
Commander, Fifth Coast Guard District 1
Commander, (RE) Seventh Coast Guard District 1
Commander, Eight Coast Guard District 1
Commander, Pacific Area, USCG 1
Commander, Eleventh Coast Guard District 1
Commander, Fourteenth Coast Guard District 1
Commanding Officer, USCG Reserve Training Center 1
  Yorktown, VA

DEPARTMENT OF AGRICULTURE

World Agriculture Outlook Board 1

DEPARTMENT OF INTERIOR

Chief, Science and Technology Staff 1
Bureau of Reclamation, Office of Liaison
  Engineering and Research 1

DEPARTMENT OF STATE

Office of Advanced Technology 1

NATIONAL SCIENCE FOUNDATION

Director, Meteorology Program 1
Director, Division of Atmospheric Science 1

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Goddard Space Flight Center 2
Director, Atmospheric Sciences Division, MSFC 1

OTHER U.S.

Roddenbery Memorial Library, Cairo, Georgia 1
Congressional Research Service, Library of Congress 1
University of Chicago Library, The Joseph Regenstein Library 1
Natural Hazards Research and Applications Information
Center, Institute of Behavioral Science 1
Colorado State University 2
Florida State University 1
Massachusetts Institute of Technology 1
Naval Postgraduate School 1
Pennsylvania State University 1
State University of New York at Albany 1
Texas A&M University 1
U.S. Air Force Academy 1
University of Hawaii 1
University of Wisconsin 1
University of Massachusetts 1
University of Chicago 1
University of Minnesota 1
American Meteorological Society 1

☆ U.S. GOVERNMENT PRINTING OFFICE: 1991 — 281-559/40405

WORKING GROUP FOR HURRICANE AND WINTER STORMS OPERATIONS (WG/HWSO)

MR. JOHN SOKICH, Chairman
Department of Commerce

MR. GLENN HAMILTON
Department of Commerce

MR. DANE CLARK
Department of Commerce

MR. EUGENE D. LEGG, JR.
Department of Commerce

LTCOL THOMAS J. WITHERELL, USAF
Department of Defense

CDR LARRY WARRENFELTZ, USN
Department of Defense

MR. KONSTANTINE NEZER
Department of Transportation

MR. JEFFERY MACLURE
Department of State

COL FLOYD F. HAUTH, USAF, Secretary
Office of the Federal Coordinator for Meteorology
Department of Commerce

AD HOC GROUP FOR TROPICAL CYCLONE RESEARCH (AHG/TCR)

MR. JERRY JARRELL, Chairman
Department of Commerce

MR. RAYMOND ZEHR
Department of Commerce

DR. MARK DeMARIA
Department of Commerce

DR. STEPHEN J. LORD
Department of Commerce

CAPT MARK RAFFENSBERGER, USAF
Department of Defense

MR. MORTON GLASS
Department of Defense

DR. ROBERT ABBEY, JR.
Department of Defense

COL FLOYD F. HAUTH, USAF, Secretary
Office of the Federal Coordinator for Meteorology
Department of Commerce