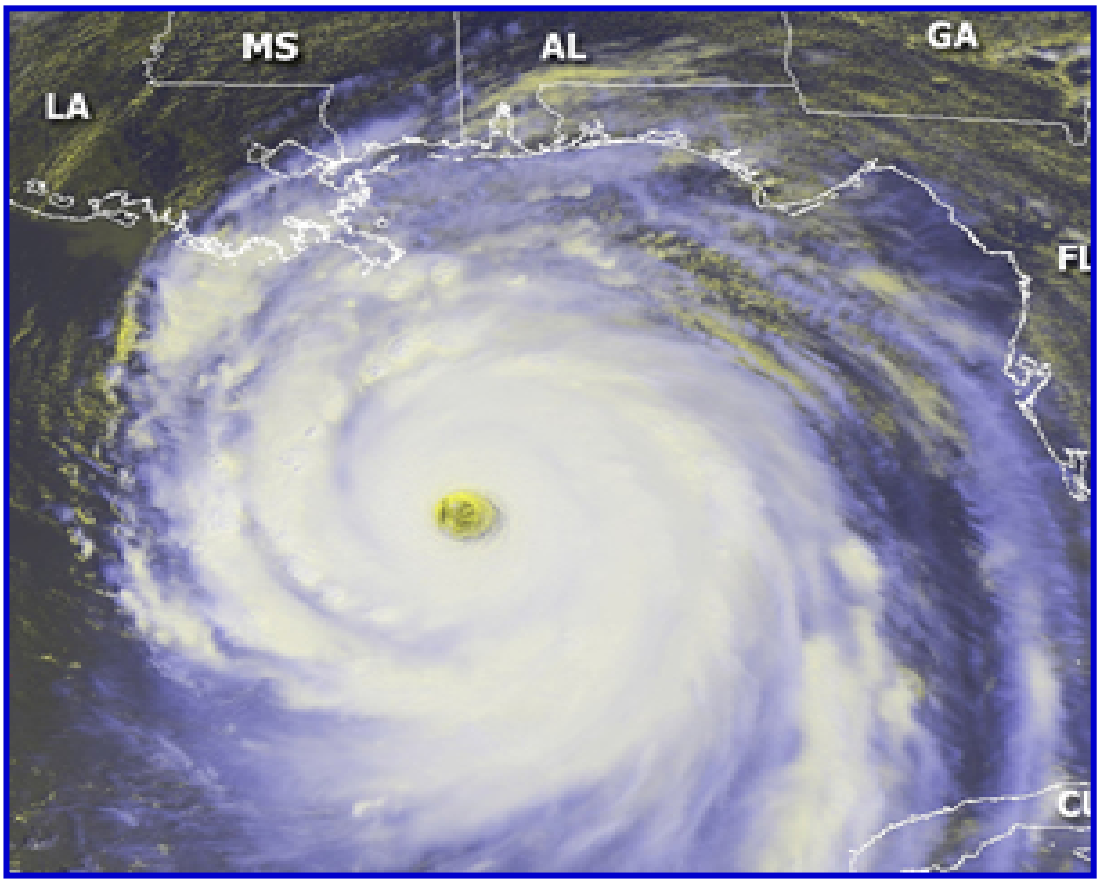
INTERAGENCY STRATEGIC RESEARCH PLAN FOR TROPICAL CYCLONES

THE WAY AHEAD

FCM-P36-2007



February 2007

Office of the Federal Coordinator for Meteorological Services
and Supporting Research

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

VADM CONRAD C. LAUTENBACHER, JR., USN (RET.)
Chairman, Department of Commerce

DR. SHARON L. HAYS
Office of Science and Technology Policy

DR. RAYMOND MOTHA
Department of Agriculture

BRIG GEN DAVID L. JOHNSON, USAF (RET.)
Department of Commerce

MR. ALAN SHAFFER
Department of Defense

DR. JERRY ELWOOD
Department of Energy

MR. KEVIN "SPANKY" KIRSCH
Science and Technology Directorate
Department of Homeland Security

DR. MICHAEL SOUKUP
Department of the Interior

MR. RALPH BRAIBANTI
Department of State

MR. RANDOLPH LYON
Office of Management and Budget

MS. VICTORIA COX
Department of Transportation

MR. DAVID MAURSTAD
Federal Emergency Management Agency
Department of Homeland Security

DR. MARY L. CLEAVE
National Aeronautics and Space Administration

DR. MARGARET S. LEINEN
National Science Foundation

MR. PAUL MISENCIK
National Transportation Safety Board

MR. JAMES WIGGINS
U.S. Nuclear Regulatory Commission

DR. LAWRENCE REITER
Environmental Protection Agency

MR. SAMUEL P. WILLIAMSON
Federal Coordinator

MR. JAMES B. HARRISON, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

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

MR. SAMUEL P. WILLIAMSON, Chairman
Federal Coordinator

MR. THOMAS PUTERBAUGH
Department of Agriculture

MR. JOHN E. JONES, JR.
Department of Commerce

RADM FRED BYUS, USN
United States Navy
Department of Defense

BRIG GEN LAWRENCE A. STUTZRIEM, USAF
United States Air Force
Department of Defense

MR. RICKEY PETTY
Department of Energy

MR. KEVIN "SPANKY" KIRSCH
Science and Technology Directorate
Department of Homeland Security

MR. JOHN VIMONT
Department of the Interior

MR. ANTHONY FURST (Acting)
Federal Highway Administration
Department of Transportation

MR. JAMES H. WILLIAMS
Federal Aviation Administration
Department of Transportation

DR. JONATHAN M. BERKSON
United States Coast Guard
Department of Homeland Security

MR. JEFFREY MACLURE
Department of State

DR. S. T. RAO
Environmental Protection Agency

MR. JOHN GAMBEL
Federal Emergency Management Agency
Department of Homeland Security

DR. RAMESH KAKAR
National Aeronautics and Space Administration

DR. JARVIS MOYERS
National Science Foundation

MR. DONALD E. EICK
National Transportation Safety Board

MS. LETA A. BROWN
U.S. Nuclear Regulatory Commission

MS. EMILY WOGLOM
Office of Management and Budget

MR. JAMES B. HARRISON, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

Front Cover Photo Credit
Hurricane Katrina, August 28, 2005: As of 1800 UTC, located 180 mi SSE of the mouth of the Mississippi River and moving NW at 13 MPH. Maximum sustained winds were 175 MPH, making Katrina a category 5 storm on the Saffir-Simpson scale. (Courtesy of NOAA, http://www.osei.noaa.gov)

Federal Committee for Meteorological Services
and Supporting Research (FCMSSR)

Interdepartmental Committee for Meteorological Services
and Supporting Research (ICMSSR)

Committee for Cooperative Research (CCR)

Joint Action Group for Tropical Cyclone Research (JAG/TCR)

INTERAGENCY STRATEGIC RESEARCH PLAN FOR TROPICAL CYCLONES

THE WAY AHEAD

Office of the Federal Coordinator for
Meteorological Services and Supporting Research

8455 Colesville Road, Suite 1500
Silver Spring, Maryland 20910
301-427-2002
www.ofcm.gov

FCM-P36-2007
Washington, DC
February 2007

FOREWORD

The 2004 and 2005 Atlantic hurricane seasons demonstrated the vulnerability of the U.S. mainland to landfalling tropical cyclones. Given the continued economic development and population growth along the Atlantic and Gulf coasts, we know that the relatively benign 2006 season was a welcome respite but not an enduring end to the danger these storms present to persons, property, and coastal ecosystems. Economic losses to landfalling hurricanes on the U.S. mainland have roughly doubled each decade from 1900 to 2005. If a reminder were needed, there were dangerous typhoons in the western Pacific and tropical cyclones in the Indian Ocean—the same kind of meteorological event as Atlantic hurricanes, merely blowing under a different local name—to show that the tropical cyclone threat to populations and the environment, economic well-being, military operations, and U.S. interests abroad is still with us and global in extent.

In the spring of 2004, the 58th Interdepartmental Hurricane Conference recommended that a comprehensive strategy be developed to guide interagency tropical cyclone research and development (R&D) over the next decade. That recommendation was subsequently supported by both of my key coordinating committees: the Interdepartmental Committee for Meteorological Services and Supporting Research and the Federal Committee for Meteorological Services and Supporting Research (FCMSSR). This R&D plan presents a comprehensive strategy, developed over the past two years by members of my staff and the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM)-sponsored interagency Joint Action Group for Tropical Cyclone Research (JAG/TCR).

Highly accurate meteorological forecasts that can be used to ensure that credible hurricane warnings are issued in a timely manner are an essential factor in avoiding injury or loss of life and reducing property loss and economic disruption. The strategy presented here focuses on R&D and the transition of research to operations to meet the current and future operational needs of the forecast and warning centers. Equally important, all civilian and military operations in harm's way must have confidence in these forecasts and warnings; they must understand them and take appropriate actions to protect people and property and, when necessary, evacuate to safer locations. We need to continue and expand efforts to ensure that timely information from our operational centers reaches decisionmakers and that they are prepared to act on that information. For this reason, this plan emphasizes research in the social sciences, aimed at improving the efficacy of the education and dissemination factors in the end-to-end system by which the ultimate users of forecasts and warnings, those in the path of a dangerous storm, can be better prepared to respond.

Another vital element in this plan is its recognition of the diverse community already deeply involved in tropical cyclone operations and R&D. Working partnerships already exist among the operational forecast and warning centers, the operational modeling centers that support them, a number of R&D-oriented Federal entities, the academic community, and an increasing number of partners in the private sector. Capitalizing on these partnerships, the plan has taken a grass-roots approach, working from the operational priorities and current programs and plans of the FCMSSR partner agencies. It highlights future capabilities and research priorities that are required to meet the operational needs of the Nation's tropical cyclone forecast and warning

centers. The plan also incorporates the strengths of existing partnerships and presents cogent recommendations for expanding and enhancing them, to achieve the effective transition of successful research results into operations.

This plan is complemented by and consistent in many aspects with two other concurrent reports—the National Science Board's Task Force on Hurricane Science and Engineering (HSE) report entitled, *Hurricane Warning: The Critical Need for a National Hurricane Research Initiative*, and a report issued by the National Oceanic and Atmospheric Administration's Science Advisory Board (SAB) Hurricane Intensity Research Working Group (HIRWG).

I want to express my deepest gratitude for the hard work and long hours expended by my staff and the members of the JAG/TCR. As shown in the membership list on pages v–vii, you can see that the plan before you is a product of collaboration extending across multiple agencies. It provides a strategy for ensuring that collaboration and coordination remain the watchword for the next decade of work in confronting the extreme threats posed by tropical cyclones.

/S/

Samuel P. Williamson
Federal Coordinator for Meteorological Services
and Supporting Research

MEMORANDUM FOR: Mr. Samuel P. Williamson
Federal Coordinator for Meteorology

FROM: Cochairpersons, Joint Action Group for Tropical Cyclone Research (JAG/TCR)

SUBJECT: Plan on Interagency Strategic Research Plan for Tropical Cyclones

The JAG/TCR has completed its assigned task to develop a comprehensive strategy for tropical cyclone research and development to guide interagency efforts over the next decade. We are pleased to provide the subject plan, titled*: Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead.*

/S/

Dr. Frank Marks, Cochairperson
Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division
NOAA, Office of Oceanic and Atmospheric Research
U.S. Department of Commerce

/S/

Ms. Robbie Hood, Cochairperson
Marshall Space Flight Center
National Aeronautics and Space Administration

CONCURRENCES:

The undersigned concur that the plan, *Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead*, meets the tasks assigned to the JAG/TCR.

/S/

Dr. Naomi Surgi
NOAA, National Weather Service
U.S. Department of Commerce

/S/

Dr. James Goerss
Naval Research Laboratory
U.S. Department of Defense

/S/

Col Michael Babcock
U.S. Air Force Directorate of Weather
U.S. Department of Defense

/S/

Dr. Ramesh Kakar
Science Mission Directorate
National Aeronautics and Space Administration

CONCURRENCES—continued

/S/

Mr. John Gambel
Mitigation Division, Emergency
Preparedness and Response
U.S. Department of Homeland Security

/S/

Dr. Stephan Nelson
Physical and Dynamic Meteorology
National Science Foundation

/S/

Dr. Jack Davis
U.S. Army Engineer R&D Center
U.S. Department of Defense

/S/

Dr. Christopher Landsea
NOAA, National Weather Service
U.S. Department of Commerce

/S/

Mr. Jeffrey Hawkins
Naval Research Laboratory
U.S. Department of Defense

/S/

Dr. Mark DeMaria
NOAA, National Environmental Satellite,
Data and Information Services
U.S. Department of Commerce

/S/

Dr. Ronald Ferek
Office of Naval Research
U.S Department of Defense

/S/

Lt Col Robert Falvey
Joint Typhoon Warning Center
U.S. Department of Defense

/S/

Dr. James McFadden
NOAA, Office of Marine and Aviation Operation/Aircraft Operations Center
U.S Department of Commerce

/S/

Dr. Scott Braun
Goddard Space Flight Center
National Aeronautics and Space Administration

/S/

Dr. Daniel Melendez
NOAA, National Weather Service
U.S. Department of Commerce

/S/

Mr. Scott Kiser
NOAA, National Weather Service
U.S. Department of Commerce

/S/

Mr. Mark Welshinger
Senior Staff Meteorologist, OFCM
Executive Secretary, JAG/TCR

Contents

Foreword

Memorandum from the JAG/TCR

Executive Summary

1 Introduction 1-1

1.1 Why is More Hurricane R&D Needed? 1-1
1.2 Tropical Cyclone Forecasts and Warnings: Recent Cases 1-3
1.2.1 Hurricane Floyd, September 1999 1-4
1.2.2 Super Typhoon 04W (Typhoon Ewiniar), July 2006 1-5
1.2.3 Hurricane Dennis, July 2005 1-6
1.2.4 Hurricane Rita, September 2005 1-7
1.3 The Need for Hurricane R&D Priorities and Coordination 1-8
1.4 Operational Tropical Cyclone Forecast and Warning Centers 1-9
1.4.1 Tropical Prediction Center/National Hurricane Center 1-9
1.4.2 Joint Typhoon Warning Center 1-11
1.4.3 Central Pacific Hurricane Center 1-11
1.4.4 Supporting Role of Other NOAA/NCEP Operational Centers 1-11
1.5 Introduction to the Tropical Cyclone R&D Community 1-12
1.5.1 Federal R&D Organizations 1-12
1.5.2 Academic Partners in Tropical Cyclone R&D 1-14
1.5.3 Coordination Roles in the Tropical Cyclone Community of Practice 1-15
1.5.4 Other Participants in the R&D Community 1-16
1.6 Formation of the JAG/TCR 1-16
1.7 Structure of the R&D Plan 1-17

2 The Tropical Cyclone R&D community 2-1

2.1 Tropical Cyclone Research as a Community Effort 2-1
2.2 Federal Entities Conducting or Managing Tropical Cyclone R&D in the Physical Sciences 2-2
2.2.1 NOAA 2-2
2.2.2 National Science Foundation 2-4
2.2.3 Department of Defense 2-4
2.2.4 National Aeronautics and Space Administration 2-6
2.2.5 U.S. Geological Survey, Department of the Interior 2-7
2.3 Federal Entities Conducting or Managing Other R&D Activities Relevant to Tropical Cyclone Operations 2-8
2.3.1 Federal Emergency Management Agency, Department of Homeland Security 2-8
2.3.2 Department of Health & Human Services 2-8
2.3.3 Department of Housing and Urban Development 2-9
2.3.4 National Institute of Standards and Technology, Department of Commerce 2-9

2.4 Federal Policy and Coordination Roles for Tropical Cyclone R&D 2-9
2.4.1 OFCM 2-10
2.4.2 Office of Science and Technology Policy 2-10
2.4.3 National Science and Technology Council 2-11
2.4.4 NSF National Science Board 2-11
2.4.5 Joint Hurricane Testbed 2-12
2.4.6 Joint Center for Satellite Data Assimilation 2-12
2.5 Role of Academia in Tropical Cyclone Research 2-13
2.6 International Contributions to Tropical Cyclone Research 2-14
2.6.1 Principal Tropical Cyclone R&D Centers around the World 2-14
2.6.2 GEOSS and the Nation's Hurricane Forecast and Warning Program 2-16
2.7 External Advisory and Advocacy Groups 2-16
2.7.1 National Academy of Sciences and National Research Council 2-16
2.7.2 American Meteorological Society Policy Program 2-17
2.8 Prior Documentation of Tropical Cyclone Operational and Research Needs 2-17
2.8.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers 2-18
2.8.2 Interdepartmental Hurricane Conferences 2-18
2.8.3 USWRP Implementation Plan for Hurricane Landfall 2-20
2.8.4 HWRF Model Workshop 2-21
2.8.5 NOAA/OAR Science and Technology Infusion Plan 2-22
2.8.6 Workshop on Air-Sea Interactions in Tropical Cyclones 2-23
2.8.7 Previous Efforts in Social Sciences 2-24
2.8.8 Concurrent Hurricane Projects/Studies 2-26
2.8.9 Results of the 60th IHC 2-26
2.8.10 Summary on Prior Documentation of Operational and Research Needs 2-28

3. Current Capabilities and Limitations 3-1

3.1 Data Collection and Observations for Tropical Cyclone Fixing and Analysis 3-1
3.1.1 Operational and Research Aircraft for Observing Tropical Cyclones 3-1
3.1.2 Satellite Platforms, Instruments, and Data Streams 3-7
3.1.3 Ocean Observatons 3-12
3.1.4 Land-Based Surface Systems 3-17
3.1.5 Adaptive (Targeted) Observation Strategies 3-18
3.1.6 Observations of the Tropical Cyclone Inner Core 3-19
3.2 Statistical Analysis and Prediction Techniques 3-20
3.3 Numerical Models 3-21
3.3.1 Global Models 3-23
3.3.2 High-Resolution Regional Models 3-27
3.3.3 Ocean and Wave Models 3-31
3.3.4 Data Assimilation Capability 3-33
3.3.5 Use of Research Models 3-35
3.4 Forecasting and Warning 3-35
3.4.1 Track 3-36
3.4.2 Consensus Forecasting 3-38
3.4.3 Intensity and Structure 3-38
3.4.4 Sea State and Storm Surge 3-40

3.4.5 Precipitation and Fresh Water Flooding 3-42
3.4.6 Severe Weather Activity 3-47
3.5 Tropical Cyclone Field Experiments 3-47
3.5.1 NASA-Sponsored Experiments 3-47
3.5.2 NSF-Sponsored Rainband and Intensity Change Experiment 3-48
3.5.3 NOAA-Sponsored Experiments 3-48
3.5.4 ONR-Sponsored Experiments 3-48
3.5.5 Tropical Cyclone Experiments—Summary 3-49
3.6 Current Procedures for Transitioning Tropical Cyclone Research into Forecast and Warning Operations 3-49
3.6.1 The Challenge of Efficient and Productive Transition to Meet Operational Needs 3-49
3.6.2 The Joint Hurricane Testbed 3-51
3.6.3 Transitioning ONR Research to Operations 3-53
3.6.4 The Transition Process at NCEP/EMC 3-54
3.6.5 JCSDA: Transitioning New Data Assimilation Systems into Operations 3-54
3.7 Education, Training, and Outreach 3-56
3.7.1 Education, Training, and Outreach Efforts of NOAA/NWS, FEMA, and Other Civilian Agencies 3-56
3.7.2 Education, Training, and Outreach Efforts of ONR, NRL, and the JTWC 3-61
3.7.3 Education, Training, and Outreach: Continued Efforts Needed 3-63
3.8 Summary 3-65

4. Future Capabilities to Meet Operational Needs 4-1

4.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers 4-2
4.2 Data Collection: Plans for Observation Platforms and Instruments 4-4
4.2.1 The GOES-N and GOES-R Series of Geostationary Satellites 4-5
4.2.2 NPOESS and NPP 4-5
4.2.3 MetOp Satellites 4-6
4.2.4 Jason-2 and Oceansat 3 Satellites 4-7
4.2.5 Global Precipitation Measurement Mission 4-7
4.2.6 CloudSat Mission 4-8
4.2.7 Constellation Observing System for Meteorology, Ionosphere, and Climate 4-8
4.2.8 Unmanned Aircraft Systems 4-10
4.2.9 Multifunction Phased Array Radar 4-11
4.2.10 Airborne Scanning Radar Altimeter 4-11
4.2.11 Improvements to IWRAP 4-12
4.2.12 Tropospheric Winds 4-12
4.2.13 Summary 4-15
4.3 Statistical Analysis and Prediction Techniques 4-15
4.4 Advanced NWP Modeling Systems 4-15
4.4.1 The Earth System Modeling Framework 4-17
4.4.2 NOAA's Plans for Hurricane Prediction Ssytems 4-18
4.4.3 DOD Plans for Hurricane Prediction Systems 4-29
4.5 Transitioning Research Results to Operational Capability 4-31
4.5.1 Plans for Major Transition Programs at JCSDA 4-31

4.5.2 Developmental Testbed Center 4-31
4.5.3 Essential Elements of an Efficient Transition Process in a Community Context 4-32
4.6 Summary 4-32

5. Research Priorities 5-1
5.1 Research Priorities in Atmospheric and Ocean Science 5-1
5.1.1 General Research and NWP Modeling Topics 5-3
5.1.2 NWP Model Development Topics 5-6
5.1.3 Observaions and Observing Strategies 5-7
5.2 Climate Research Priorities—Intraseasonal, Interannual, and Longer-Term Variability of Tropical Cyclones 5-9
5.3 Research Needs in the Social Sciences 5-10
5.3.1 Warning Process 5-11
5.3.2 Decisionmaking 5-11
5.3.3 Behavioral Response 5-11
5.3.4 Social Impacts and Valuations 5-12
5.3.5 Social Sciences Summary 5-12
5.4 Oversight of the R&D Program for Tropical Cyclones 5-12
5.5 Summary 5-13

6. Key Findings and Recommendations: The Way Ahead 6-1
6.1 Introduction 6-1
6.2 Summary of Key Findings 6-3
6.2.1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers 6-3
6.2.2 Data Collection/Observations 6-3
6.2.3 NWP Modeling and Data Assimilation 6-4
6.2.4 Forecasting and Warning 6-6
6.2.5 Tropical Cyclone Research and Research Coordination 6-6
6.2.6 Education, Outreach, and Workforce Development 6-7
6.3 Recommendations 6-7
6.4 Resource Estimates Associated with Recommendations 6-11
6.5 Summary 6-13

References REF-1

Appendices

A. Summary of Satellite Data Used in NCEP's Operational Data Assimilation Systems
B. Important Upgrades to Global Models and Operational Use of High-Resolution Regional Models
C. Research Models
D. 2005 Forecasts and Models Used at the TPC/NHC and CPHC
E. 2005 Forecasts and Models Used at the JTWC
F. Track Guidance Model Errors for 2005
G. Intensity Guidance Model Errors for 2005

Appendices—continued

H. Article from *NOAA Magazine*: "NOAA is Encouraging Everyone to Prepare for Hurricane Season"
I. NPOESS Satellite Data Pertinent to Tropical Cyclone Analysis and Forecasting
J. MetOp Satellite Data Pertinent to Tropical Cyclone Analysis and Forecasting
K. NCEP Data Assimilation Development
L. NCEP Global Model Development
M. Some Future Work Planned for the HWRF Air-Sea-Land-Hurricane Prediction System
N. Questions from the *Air-Sea Interactions in Tropical Cyclones* Workshop (Shay et al. 2005)
P. Social Science Research
Q. List of Acronyms

Figures

ES-1 Areas of responsibility assigned to the operational tropical cyclone forecast and warning centers. xvii

1-1 This image is made from data received from the NASA Tropical Rainfall Measurement Mission (TRMM) satellite showing Typhoon Maria closing in on Japan (August 7, 2006). 1-1

1-2 GOES-12 1 km visible imagery of Hurricane Katrina; August 29, 2005; 09:57:10. Credit: NOAA. 1-2

1-3 Best track position of Hurricane Floyd. 1-4

1-4 July 5, 1200 UTC, JTWC forecast indicating tropical cyclone passage over Sasebo in 96 hours..... 1-6

1-5 Overall track, Super Typhoon 04W (Ewiniar). 1-6

1-6 Destruction in Sabine Pass, Texas, left in the wake of Hurricane Rita. 1-7

1-7 Best track position of Hurricane Rita. 1-8

1-8 TPC/NHC Advisory #10 for Rita. 1-8

1-9 Areas of responsibility (AORs) assigned to the operational tropical cyclone forecast and warning centers. 1-10

1-10 The Joint Typhoon Warning Center. 1-11

1-11 The NOAA/NWS Weather Service Forecast Office, Honolulu, Hawaii. 1-12

2-1 Representation of the flow of requirements (black arrows) and the transfer of knowledge and information (blue arrows) within the tropical cyclone community of practice 2-1

2-2 This image was captured by the MODIS instrument on the Aqua Spacecraft on October 24, 2005..... 2-7

3-1 Geostationary satellite position and intensity fixes by JTWC during 2005..... 3-9

3-2 Microwave position fixes by JTWC during 2005.....3-10

3-3 Comparison of altimeter-derived estimates of ocean heat content (left) and satellite-derived sea surface temperature (right) 3-14

3-4 The Argo array 3-16

3-5 Percentage improvement in NOGAPS tropical cyclone track forecast error for August 14–September 30, 2004 3-25

3-6 Two examples of erratically moving storms 3-26

3-7 GFDL intensity skill (Atlantic basin) relative to SHIFOR since 2000.....3-29

3-8 Comparison of intensity skill (Atlantic basin) between the 2005 operational GFDL model, the GFDL model made operational in 2006, and the statistical intensity models (SHIPS and DECAY SHIPS), run for select cases from the 2003-2005 hurricane seasons.....3-29

3-9 Positive impact of improved Loop Current initialization in the 2006 GFDL compared with the operational 2005 GFDL for Hurricane Katrina 3-32

3-10 Negative impact of removing AMSU, HIRS, QuikSCAT surface wind data from the hurricane track forecast guidance in the Atlantic basin in 2003 (34 cases).....3-34

3-11 Percent improvement in NOGAPS tropical cyclone track forecast error for August 14–September 30, 2004 3-35

3-12 Annual average official track errors, with trend lines superimposed, for tropical storms and hurricanes in the Atlantic basin, 1970–2005 3-37

3-13 Mean track forecast error (nm) and 5-year running mean for 24, 48, and 72 hours for tropical cyclones in the western North Pacific Ocean, 1978–2005 3-37

3-14 Atlantic basin track guidance model errors in nautical miles for 2005 of the GUNA model, a consensus model, and the individual models that are used to construct it.....3-38

3-15 Annual average official intensity errors for the Atlantic Basin tropical cyclones for the period 1990-2005, with trend lines superimposed.....3-39

Figures—continued

3-16 Plot of 72-h accumulated rain (shaded), 12 UTC 17 September to 12 UTC 20 September, 2003 for (a) Stage IV observations; (b) GFS; (c) GFDL; (d) Eta; (e) R-CLIPER....3-45

3-17 Comparisons of tropical cyclone QPF from different models showing how well they perform at (a) matching QPF patterns in the observed data; (b)matching extreme rainfall amounts, (c) matching the volume of observed rainfall, and (d) sensitivity of model QPF error to its storm track forecast error....3-46

3-18 The hurricane component of CBLAST-DRI aimed to measure, analyze, understand, and parameterize air-sea fluxes in the hurricane environment....3-49

3-19 The U.S. Navy/ONR process used to transition research to operations....3-54

3-20 NCEP's role in transitioning research in models to operations through EMC processes....3-55

4-1 First GOES-13 full-disk visible image, June 22, 2006, 1730-1800 UTC.... 4-5

4-2 The constellation of six COSMIC satellites surrounded by satellites from the Global Positioning System, whose signals COSMIC will use.... 4-8

4-3 Launch of the COSMIC constellation of six satellites.... 4-8

4-4 A comparison of the current global coverage of instruments launched via radiosondes each day (in red) with the expected coverage from the COSMIC satellite network in a 24-hour period (in green) .. 4-9

4-5 ESMF application example using NASA's GEOS-5 AGCM....4-18

4-6 HWRF Air-Sea-Land Hurricane Prediction System....4-23

4-7 The Noah Land-Surface Model....4-27

5-1 Distinction between basic and applied research.... 5-1

5-2 Best-track estimate of Hurricane Frances intensity as determined in the post-analysis of all available data (e.g., satellite, aircraft, GPS dropwindsondes).... 5-8

6-1 Illustration of recommendations 1 and 2....6-10

Tables

ES-1 JAG/TCR Recommendations....xx

1-1 Saffir-Simpson Hurricane Scale.... 1-3

2-1 Tropical Cyclone Gaps, Solutions, and Impacts (from NOAA STIP)....2-23

3-1 Physical Specifications and Operational Capabilities of Hurricane Aircraft.... 3-2

3-2 Comparison of Observing Systems aboard Hurricane Aircraft.... 3-4

3-3 Additional Information on Some of the Specialized Instrumentation aboard WP-3D Aircraft.... 3-5

3-4 Upgrades to the GFS Model and its Predecessor AVN and MRF Models....3-24

3-5 Upgrades to the NOGAPS Model....3-25

3-6 Mean 2005 GFS Track Errors (in nautical miles) for a Sample of Cases from 2004....3-26

3-7 Upgrades to the GFDL Forecast System since 1998....3-28

3-8 Snapshot of Hurricane-Related Internet Sites....3-59

4-1 Operational Needs of the Tropical Cyclone Forecast and Warning Centers (TPC/NHC, JTWC, and CPHC).... 4-3

4-2 Essential Observations to be Assimilated into HWRF....4-21

5-1 Research Priorities in Atmospheric and Ocean Science.... 5-2

6-1 Illustration of the Tropical Cyclone Community of Practice.... 6-2

6-2 JAG/TCR Recommendations.... 6-8

6-3 Additional Resource Estimates ($ millions above Current Plan) Associated with the JAG/TCR Recommendations....6-12