APPENDIX A
SUMMARY OF SATELLITE DATA USED IN NCEP'S OPERATIONAL DATA ASSIMILATION SYSTEMS

- **HIRS sounder radiances**
- **AMSU-A sounder radiances**
- **AMSU-B sounder radiances**
- **GOES sounder radiances**
- **GOES, Meteosat, GMS winds**
- **GOES precipitation rate**
- **SSM/I precipitation rates**
- **TMI precipitation rates**
- **SSM/I ocean surface wind speeds**
- **ERS-2 WS ocean surface wind vectors**
- **SeaWinds ocean surface wind vectors**
- **AVHRR SST**
- **AVHRR vegetation fraction**
- **AVHRR surface type**
- **Multi-satellite snow cover**
- **Multi-satellite sea ice**
- **SBUV/2 ozone profile and total ozone**
- **AIRS**
- **MODIS winds**
- **Altimeter sea level observations (ocean data assimilation and wave data assimilation system)**

Note: Refer to Appendix Q for the acronyms used in this appendix.

Polar orbiting platforms used in NCEP's operational data assimilation systems include high-quality data from functioning instruments on the following platforms:

- **NOAA polar orbiting satellites** (e.g., HIRS, AMSU-A, AMSU-B, AVHRR)
- **Defense Meteorological Satellite Program (DMSP);** for example: SSM/I
- **NASA;** for example:
  - **TRMM** (e.g., TMI)
  - **QuikSCAT** (e.g., SeaWinds)
  - **Aqua** (e.g., AMSU-A, AIRS, MODIS)
  - **Terra** (e.g., MODIS)
- **European Remote Sensing Satellite (ERS)**—for example:
  - **ERS-2 (**e.g., WS [Wind Scatterometer])

<u>NOTES</u>

- Atmospheric observations (all instruments in the above table except altimeter observations) are used by:
  - NCEP Global Data Assimilation System (GDAS)
  - NCEP Regional Data Assimilation System (RDAS)

  (Provided they meet the data cutoff times of 1:15 for the RDAS and 2:45 for the GDAS)
- Sea Surface Temperature (SST) retrievals are used by all atmospheric weather models for a daily lower boundary condition.
- Ocean observations (altimeter observations in table above) are used in NCEP's:
  - Global Ocean Data Assimilation System (GODAS) for climate forecasting
  - Real-Time Ocean Forecast System (RTOFS) for daily ocean forecasting
  - Global Wave Forecast System

APPENDIX B
IMPORTANT UPGRADES TO GLOBAL MODELS AND OPERATIONAL USE OF HIGH-RESOLUTION REGIONAL MODELS

Improvement in hurricane track forecasts has been well documented over the past three decades. Figure B-1 shows the reduction of the 72 hour official track error of the TPC/NHC over this period from 400 nm to less than 200 nm. The improved skill closely follows the continuous advancement of operational numerical models and their enhanced forecast capabilities.

The documentation of model track skill originated with CLIPER in the 1970s, a statistical model based on climatology and persistence, which became the benchmark for track skill for all future model track forecasts (Neuman 1972). An improvement of track skill continued in the 1980s with the use of a hybrid model that combined statistical techniques with background fields from NOAA's global model (e.g., the NHC-83, NHC-90 [Neuman and McAdie 1991]), the development of a barotropic model (VICBAR) for operations, a one level advection model (BAMS), and a quasi-lagrangian dynamical model (QLM) that ran at NCEP in the late 1980s and early 1990s. These early models all helped define the downward linear trend into the early-mid 1990s to reduce the forecast errors at all forecast times. The description and performance characteristics of these early track models are described in DeMaria (1997); McAdie and Lawrence (2000).

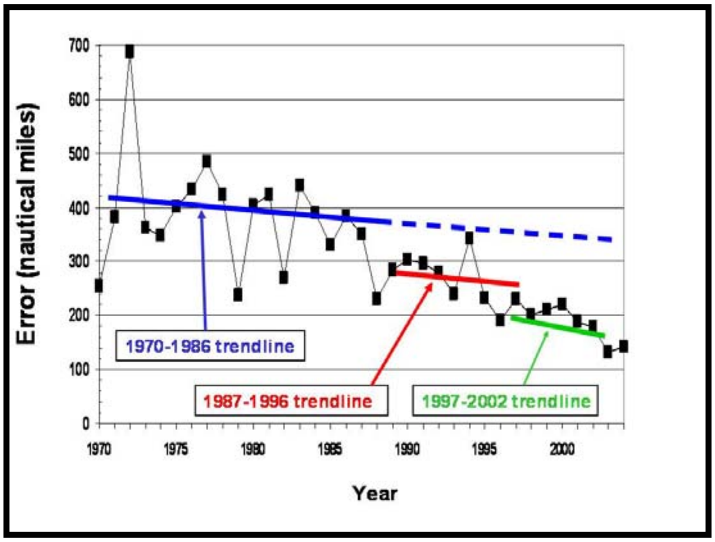


Figure B-1. TPC/NHC 72-Hour Track Forecast Errors, Atlantic Basin

As shown in Figure B-1, a pronounced acceleration in track forecast skill occurred in the mid-1990s with increased use of global models (e.g., the Global Forecast System (GFS; formerly the MRF/AVN) run at the National Centers for Environmental Prediction (NCEP); the Navy Operational Global Atmospheric Prediction System (NOGAPS) run at Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the United Kingdom Meteorological Office global model (UKMO)). The increase in forecast skill is tied to the availability of global observations (e.g., satellites), an advancement of global modeling numerical techniques that could maximize the usefulness of these data, and increased sophistication in representing model physics to provide routine high quality global analyses.

Since the early 1990s, the horizontal resolution of the NOGAPS global spectral model has tripled while its vertical resolution has nearly doubled. For example, from 1989 to1994, the NOGAPS model resolution was T79L18 (~165 km horizontal resolution, 18 vertical levels), using the Arakawa-Schubert convective parameterization scheme (Arakawa-Schubert 1974) ; from 1994 to 2000, the NOGAPS model resolution was either T159L18 or T159L24 (by 1998), using the Arakawa-Schubert convective parameterization scheme. From 2000 to 2002, the NOGAPS model resolution was T159L24, using the Emanuel convective parameterization scheme (Emanuel 1991, Emanuel and Zivkovic-Rothman 1999). Finally, from 2002 to the present, the resolution of the NOGAPS model has been T239L30, using the Emanuel convective parameterization scheme. Similar upgrades to other global models also occurred.

There were other important upgrades to the global models, and a few examples follow. To represent the hurricane scale, a bogus vortex was developed by Lord (1993) and incorporated in the NCEP global model. The direct use of satellite radiances replaced the use of retrievals in the GFS data assimilation system at NCEP in 1995 (Derber and Wu 1998). The assimilation of high density multispectral GOES-8 winds (Velden et al. 1997) into NOGAPS was initiated at FNMOC in 1996 (Goerss et al. 1998).

Although global model forecasts were advancing to provide better track forecasts, after the devastation of Hurricane Andrew in 1992 in South Florida and a clear inability of the global models to forecast the catastrophic landfall winds, a resurgence in developing high-resolution dynamical hurricane models became a focus not only for improving track forecasts but also offered promise for providing the higher resolution forecast models needed to address hurricane intensity forecasts. Research for more than two decades since the late 1970s, led by the pioneering effort of Yoshio Kurihara at NOAA’s Geophysical a Dynamics Laboratory (GFDL), led to the development of a movable nested grid hurricane model (Kurihara and Bender 1980). The TPC/NHC requested that the high resolution, nested, movable GFDL model be evaluated to assess its performance in a semi-operational mode at the TPC/NHC in 1993. The seminal GFDL forecasts of Hurricane Emily and the recurvature of this storm off the outer banks of North Carolina in 1993 led to a pioneering collaboration between NOAA research and NOAA operations.

For the 1994 hurricane season, the GFDL model was monitored for operational performance. Due to its promising performance in providing higher track skill for the Atlantic and East Pacific basins than all other operational models, the GFDL model was transitioned into NCEP operations for the 1995 hurricane season. A version of the GFDL that is run at FNMOC, the GFDN, became operational in May 1996 (Rennick 1999). Although many transitional modeling and code obstacles existed at the time to transition a research model into operations, the joint efforts of the NCEP Environmental Modeling Center (EMC) and GFDL became a defining collaboration that has endured to the present.

With continuous yearly upgrades to the GFDL model, which were aligned with the upgrades to the NCEP global model, the GFDL model became the top track performance model and the mainstay for hurricane forecast guidance at TPC/NHC (Kurihara et al, 1998). In carrying out the joint vision for operational performance standards, the close collaboration between EMC and

GFDL is considered one the most successful collaborations within NOAA and perhaps within the U.S. modeling community between research and operations.

As skillful track forecasts became more consistently deliverable to TPC/NHC, CPHC, and JTWC forecasters during the 1990s, particularly with the operational implementation of the GFDL and GFDN models, more attention became focused on improving intensity forecasts from dynamical models within the hurricane community. An aspect of addressing the intensity issue required the coupling of the atmosphere with the ocean. To meet this requirement, the University of Rhode Island (URI) offered an ocean model that could be readily coupled to the GFDL model (Bender et al. 2001). The coupled GFDL model was run on 163 forecasts during the 1995–98 seasons (Bender and Ginnis 2000). The coupling of the atmosphere with the ocean improved intensity forecasts, with the mean absolute error in the forecast of central pressure reduced by about 26 percent compared to the operational (non-coupled) GFDL model.

The coupled GFDL model became operational in 2001. It provided an upgrade to the GFDL system for hurricane scenarios where changes in sea surface temperatures (SSTs) were important to intensity changes. This effort formed unique three-way collaborations between operational hurricane modeling at EMC, NOAA research, and academia. With support through the USWRP, this close working collaboration has continued to the present.

To date, the coupled GFDL model has become the benchmark for performance against which the future operational NCEP hurricane model—the Hurricane Weather and Research Forecast system (HWRF)—will be measured for track forecast skill and forecast consistency.

APPENDIX C
RESEARCH MODELS

The NASA GEOS-5 Atmospheric Model and Data Assimilation System

The Global Modeling and Assimilation Office (GMAO) at the NASA Goddard Space Flight Center is developing a new atmospheric data assimilation system (DAS) to synthesize the large volume of observations from Earth Observing System (EOS) satellites and other satellites. This system will be used for a global atmospheric reanalysis of the satellite era as well as to generate products in support of NASA instrument teams. The reanalysis, referred to as the Modern Era Retrospective-analysis for Research and Applications (MERRA),[1] supports NASA's Earth science interests by placing the current suite of research satellite observations in a climate context and by providing the science and applications communities with state-of-the-art global analyses.

The DAS consists of the Goddard Earth Observing System version 5 (GEOS-5) atmospheric model coupled to the Gridpoint Statistical Interpolation (GSI) analysis scheme being developed by NCEP/EMC and GMAO.

The GEOS-5 atmospheric model is a weather-and-climate-capable model using the finite-volume dynamical core (Lin, 2004). In developing GEOS-5, attention has focused on the representation of moist processes (see http://gmao.gsfc.nasa.gov/systems/geos5/). The moist physics package uses a single phase prognostic condensate and a prognostic cloud fraction. Two separate cloud types are distinguished by their source: *"anvil" cloud* originates from detraining convection, and *large-scale cloud* originates from a PDF-based condensation calculation. Ice and liquid phases for each cloud type are considered. Once created, condensate and fraction from the anvil and statistical cloud types experience the same loss processes: evaporation of condensate and fraction, auto-conversion of liquid or mixed phase condensate, sedimentation of frozen condensate, and accretion of condensate by falling precipitation. Development of GEOS-5 was guided by a realistic representation of tracer transports and stratospheric dynamics. The ozone analysis of the DAS is input to the radiation package along with an aerosol climatology. GEOS-5 is coupled to a catchment-based hydrologic model (Koster et al. 2000) and a sophisticated multi-layer snow model (Stieglitz et al. 2001).

The GSI analysis solver was developed at NCEP to support inhomogeneous and anisotropic 3D background error covariances (e.g., Wu et al., 2002; Derber et al. 2003; Purser et al. 2003). The data streams currently assimilated by the DAS are listed in table C-1. The DAS is currently being used to test the impact of data selection strategies for AIRS radiance data and the impact of MODIS derived motion vector winds on weather prediction skill. A clear advantage of NASA's use of the GSI solver is the relative ease of transition of new techniques to operational models.

For MERRA and for regular products, the system will use a 0.5° resolution model and analysis, with 72 levels to 0.01 hPa. The GEOS-5 model is being run globally at 0.25° horizontal resolution to generate 5-day forecasts of tropical cyclone activity as a contribution to the MAP06

[1] MERRA website is http://gmao.gsfc.nasa.gov/merra/.

project (http://map06.gsfc.nasa.gov). The model is being initialized with the 0.5° DAS. This project will provide a critical test of the weather capabilities of the model and DAS.

Table C-1. Observation Data Sources and Parameters Used as Input to the NCEP DAS

Conventional Data	Surface ship and buoy observations
Radiosondes	SSM/I rain rate and wind speed
Pibal winds	TMI rain rate
Wind profiles	QuikSCAT wind speed and direction
Conventional aircraft reports, ASDAR, MDCARS	
NEXRAD radar winds	**Satellite Data**
Dropsondes	TOVS 1b radiances
GMS, METEOSAT, cloud drift IR and visible winds	DMSP SSM/I radiances
MODIS clear sky and water vapor winds	GOES sounder T_B
GOES cloud drift IR winds	Aqua/AIRS radiances (150 channels)
GOES water vapor cloud top winds	Aqua/AMSU-A radiances
Surface land observation	SBUV2 ozone (Version 8 retrievals)

The Florida State University Global Model and Multimodel Superensemble

The Florida State University (FSU) global model (Krishnamurti et al. 1991) uses a spectral transform method with semi-implicit time differencing to solve the dynamic equations. The model has a horizontal grid resolution of T126 (~80 km) and uses 14 layers in the vertical between roughly 50 and 1000 hPa. An array of physical parameterization schemes is employed for shallow and deep convection, dry convective adjustment, surface fluxes, planetary boundary layer mixing, short and longwave radiation, interaction of clouds with radiation, and surface energy balance. The model is initialized from large-scale analyses from the European Center for Medium Range Weather Forecasting (ECMWF) with 0.5 ° horizontal resolution and 28 vertical levels. Precipitation estimates from NASA's Tropical Rainfall Measuring Mission (TRMM) and Defense Meteorological Satellites Program Special Sensor Microwave Imager (SSMI) satellites are used as input for physical initialization to improve the initial representation of precipitation processes in the model. The FSU model has shown good success in predicting hurricane tracks (Williford et al. 1998).

A significant advance in hurricane prediction research came with the development of the FSU multimodel superensemble forecast system (Krishnamurti et al. 1999; 2000a, 2000b; 2001). This system utilizes track and intensity forecasts from several global and regional forecast models including NCEP's GFS global model, the U.S. Navy's NOGAPS, the ECMWF global model, the FSU global model, and the GFDL hurricane forecast model, in addition to several simpler dynamical and statistical models used by NHC. A key part of the multimodel superensemble is the training phase, in which prior forecasts and observations are used to derive linear regression–based statistical coefficients. During the forecast period, the superensemble forecasts are constructed using these statistical coefficients and current multimodel forecasts. Williford et al. (2003) showed that the superensemble method performed well in 1999.

MM5

The Pennsylvania State University—National Center for Atmospheric Research mesoscale model is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulations. It was developed as a community mesoscale model and the Fifth-Generation model (MM5) is the latest in a series developed from a mesoscale model used by Richard Anthes at Pennsylvania State University in the early 1970's, later documented by Anthes and Warner (1978). Since that time, it has undergone many changes designed to broaden its use. These include (i) a multiple-nest capability; (ii) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale; (iii) multitasking capability on shared- and distributed-memory machines; (iv) four-dimensional data-assimilation capability; and (v) expanded physics options. This model has been used extensively by the research community to conduct both idealized and real-case simulations in order to study the dynamics and physics of hurricanes, often at very high horizontal grid resolution (~1-6 km), as well as to examine the impacts of various observations on hurricane simulations via data assimilation. Such studies have examined (a) the genesis of hurricanes; (b) the influence of shear on storm intensity and precipitation distribution; (c) the organization of upward motion in the hurricane eyewall and the role of buoyancy; (d) the sensitivity of hurricane intensity and precipitation to boundary layer, cumulus, and microphysical parameterizations; (e) vortex Rossby wave dynamics; (f) the impact of atmosphere-ocean coupling; (f) techniques for inserting bogus vortices for model initialization; (g) and satellite data assimilation. While use of this model has led to significant advances in our understanding of hurricanes, its relevance to operational forecasting has been limited because of the large differences between the MM5 model and operational models and the lack of a pathway for transition of research results to operations. With the advent of the WRF model, use of the MM5 model is expected to significantly decline.

WRF

The Weather Research and Forecasting (WRF) Model is the next-generation mesocale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), NOAA/NCEP, the NOAA Global Systems Division of the Earth System Research Laboratory (ESRL) (formerly the Forecast Systems Laboratory), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration.

WRF features two dynamic cores, the Advanced Research WRF (ARW) core developed at NCAR and the Nonhydrostatic Mesoscale Model (NMM) core developed by NCEP. The NMM is being implemented operationally as the core of the HWRF and is described in section 4.4.2. The ARW core is based upon equations that are fully compressible and nonhydrostatic. The horizontal grid has Arakawa C-grid staggering with a vertical coordinate based on terrain-following hydrostatic pressure. Time integration uses a 3^{rd} order Runge-Kutta scheme with smaller time steps for acoustic and gravity-wave modes. Current data assimilation capabilities are experimental and are based upon a 3-dimensional variational (3D-VAR) data assimilation system (Barker et al. 2004). Four-dimensional variational data assimilation (4D-VAR) is also under development.

Application of the ARW model generally follows that of MM5: It is used to study the dynamical and physical processes related to hurricane genesis, intensification, rainfall, landfall, and extratropical transition. In addition to basic research, NCAR has implemented the ARW model as an experimental hurricane prediction system run in real time in 2004 and 2005. Forecasts in 2004 and 2005 used the same grid spacing and physics options. A 2-way nested configuration was used that features a 12 km outer fixed domain with an inner 4 km mesh. During 2004, the 4 km nest was fixed in space and contained 450x500 points in the north-south and east-west directions, respectively. The location of the 4 km domain was chosen to contain the storm throughout the 48 h forecast period. In 2005, a feature-following capability was added that positions the nest at the location of the minimum 500 hPa geopotential height within a radius of the last position of the vortex center (or within a radius of the first guess, when first starting). The repositioning occurs every 15 simulation minutes, and the width of the search radius is based on the maximum distance the vortex can move at 40 m s^{-1}.

On the 12 km domain, the Kain-Fritsch cumulus parameterization was used, while the inner domain used no parameterization. Both domains used an explicit microphysics scheme that predicts only one cloud variable (water for temperatures greater than 0ºC and ice for temperatures less than 0ºC) and one precipitation variable, either rain or snow (again thresholded on 0ºC). Both domains use the Yonsei University (YSU) scheme for the planetary boundary layer (Noh et al. 2001). This is a first-order closure scheme that is similar in concept to the scheme of Hong and Pan (1996), but in comparison tests it appears less biased toward excessive vertical mixing.

The forecasts were integrated from 00 UTC and occasionally at 12 UTC during the time when a hurricane threatened landfall within either 48 h (2004) or 72 h (2005). During 2004, both domains were initialized directly from the NCEP Global Forecast System (GFS) model with no additional data assimilation or balancing. In 2005, forecasts were initialized using the GFDL model, with the GFS used only when the GFDL was unavailable.

Evaluation of the skill of the forecast system is ongoing, but several seasons of forecasts with a stable model configuration and initialization technique will likely be required to assess forecast skill effectively. An advantage of the ARW over MM5 is that, because both the ARW and NMM WRF use a similar modeling framework, transitioning research results to operations is easier. However, any techniques or model physics developed for the ARW must be implemented within and fully tested with the NMM core.

APPENDIX D

2005 FORECASTS AND MODELS USED AT THE TPC/NHC AND CPHC

ID	Name/Description[1]	Type	Timeliness (Early/Late)	Parameters Forecast
OFCL	Official NHC or CPHC forecast			Trk, Int
CLP5	CLIPER5 (Climatology and Persistence model)	Statistical baseline	E	Trk
SHF5	SHIFOR5 (Climatology and Persistence model)	Statistical baseline	E	Int
A98E	NHC98 (Atlantic)[2]	Statistical-dynamical	E	Trk
P91E	NHC91 (Pacific)	Statistical-dynamical	E	Trk
BAMS	Beta and advection model (shallow layer)	Single-layer trajectory	E	Trk
BAMM	Beta and advection model (medium layer)	Single-layer trajectory	E	Trk
BAMD	Beta and advection model (deep layer)	Single-layer trajectory	E	Trk
LBAR	Limited area barotropic model	Single-layer regional dynamical	E	Trk
GFDL	NWS/Geophysical Fluid Dynamics Laboratory model	Multi-layer regional dynamical	L	Trk, Int
GFSO	NWS/Global Forecast System (formerly Aviation)	Multi-layer global dynamical	L	Trk, Int
UKM	United Kingdom Met Service model	Multi-layer global dynamical	L	Trk, Int
NGPS	Navy Operational Global Prediction System	Multi-layer global dynamical	L	Trk, Int
GFDN	Navy version of GFDL	Multi-layer regional dynamical	L	Trk, Int
CMC	Environment Canada global model	Multi-level global dynamical	L	Trk, Int
ETA	NWS/Eta	Multi-level regional dynamical	L	Trk, Int
AFW1	Air Force MM5[2]	Multi-layer regional dynamical	L	Trk, Int
OFCI	Previous cycle OFCL, adjusted	Interpolated	E	Trk, Int
GFDI	Previous cycle GFDL, adjusted	Interpolated-dynamical	E	Trk, Int
GFSI	Previous cycle GFS, adjusted	Interpolated-dynamical	E	Trk, Int
UKMI	Previous cycle UKM, adjusted	Interpolated-dynamical	E	Trk, Int
NGPI	Previous cycle NGPS, adjusted	Interpolated-dynamical	E	Trk, Int
GFNI	Previous cycle GFDN, adjusted	Interpolated-dynamical	E	Trk, Int
AEMI	Previous cycle AEMN, adjusted	Consensus	E	Trk, Int
SHIP	Statistical Hurricane Intensity Prediction Scheme (SHIPS)	Statistical-dynamical	E	Int
DSHP	SHIPS with inland decay	Statistical-dynamical	E	Int
AEMN	GFS ensemble mean	Consensus	L	Trk, Int
GUNA	Average of GFDI, UKMI, NGPI, and GFSI	Consensus	E	Trk
CONU	Average of at least 2 of GFDI, UKMI, NGPI, GFSI, and GFNI	Consensus	E	Trk
ICON	Average of GFDI and DSHP	Consensus	E	Int
FSSE	FSU Super-ensemble[2]	Weighted consensus	E	Trk, Int
GUNS	Average of GFDI, UKMI, NGPI	Consensus	E	Trk

1. Items were used in 2005 by both TPC/NHC and CPHC unless otherwise footnoted (and highlighted in blue).
2. Item was used only at TPC/NHC in 2005.

APPENDIX E

2005 FORECASTS AND MODELS USED AT THE JTWC

ID	Name/Description	Type	Timeliness (Early/Late)	Parameters Forecast
JTWC	Official JTWC forecast			Trk, Int
GFSO	NWS/Global Forecast System (formerly Aviation)	Multi-layer global dynamical	L	Trk, Int
GFSI	Previous cycle GFS, adjusted	Interpolated-dynamical	E	Trk, Int
JAVN	CDR Mike Fiorino (NHC) vortex tracker applied to GFSO *	Multi-layer global dynamical	E	Trk, Int
JAVI	Previous cycle JAVN, adjusted *	Interpolated-dynamical	E	Trk, Int
UKM	United Kingdom Met Service model	Multi-layer global dynamical	L	Trk, Int
UKMI	Previous cycle UKM, adjusted	Interpolated-dynamical	E	Trk, Int
JUKM	CDR Mike Fiorino (NHC) vortex tracker applied to UKM *	Multi-layer global dynamical	E	Trk, Int
JUKI	Previous cycle JUKM, adjusted *	Interpolated-dynamical	E	Trk, Int
NGPS	Navy Operational Global Prediction System	Multi-layer global dynamical	L	Trk, Int
NGPI	Previous cycle NGPS, adjusted	Interpolated-dynamical	E	Trk, Int
JNGP	CDR Mike Fiorino (NHC) vortex tracker applied to NGPS *	Multi-layer global dynamical	E	Trk, Int
JNGI	Previous cycle JNGP, adjusted *	Interpolated-dynamical	E	Trk, Int
GFDN	Navy version of GFDL	Multi-layer regional dynamical	L	Trk, Int
GFNI	Previous cycle GFDN, adjusted	Interpolated-dynamical	E	Trk, Int
AFW1	Air Force MM5	Multi-layer regional dynamical	L	Trk, Int
AFWI	Previous cycle AFW1, adjusted *	Interpolated-dynamical	E	Trk, Int
COWP	Coupled Ocean Atmosphere Prediction System *	Multi-layer regional dynamical	E	Trk, Int
COWI	Previous cycle COWP, adjusted *	Interpolated-dynamical	E	Trk, Int
EGRR	United Kingdom Met Service model *	Multi-layer global dynamical	E	Trk, Int
EGRI	Previous cycle EGRR, adjusted *	Interpolated-dynamical	E	Trk, Int
JGSM	Japan Meteorological Agency Global Spectral Model *	Multi-layer global dynamical	E	Trk, Int
JGSI	Previous cycle JGSM, adjusted *	Interpolated-dynamical	E	Trk, Int
JJGS	CDR Mike Fiorino (NHC) vortex tracker applied to JGSM *	Multi-layer global dynamical	E	Trk, Int
JJGI	Previous cycle JJGS *	Interpolated-dynamical	E	Trk, Int
JTYM	Japan Meteorological Agency Typhoon Model *	Multi-layer regional dynamical	E	Trk, Int
JTYI	Previous cycle JTYM, adjusted *	Interpolated-dynamical	E	Trk, Int

ID	Name/Description	Type	Timeliness (Early/Late)	Parameters Forecast
TCLP	Australia Bureau of Met Tropical Cyclone Limited Area Prediction System *	Multi-layer regional dynamical	E	Trk, Int
TCLI	Previous cycle TCLP, adjusted *	Interpolated-dynamical	E	Trk, Int
WBAR	University of Munich (Harry Weber) Barotropic Model *	Single-layer global dynamical	E	Trk
WBAI	Previous cycle WBAR, adjusted *	Interpolated-dynamical	E	Trk
CONW	Average of at least 2 of AFWI, AVNI, COWI, EGRI, GFNI, JGSI, JTYI, NGPI, TCLI, WBAI *	Consensus	E	Trk, Int
SBAM	Beta and advection model (shallow layer) initialized from NOGAPS *	Single-layer trajectory	E	Trk
MBAM	Beta and advection model (medium layer) initialized from NOGAPS *	Single-layer trajectory	E	Trk
FBAM	Beta and advection model (deep layer) * initialized from NOGAPS	Single-layer trajectory	E	Trk
STIP	CIRA/NESDIS Statistical Typhoon Intensity Prediction System *	Statistical-dynamical	E	Int
STID	CIRA/NESDIS Statistical Typhoon Intensity Prediction System (Decay Model) *	Statistical-dynamical	E	Int
ST5D	5 Day Statistical Intensity Forecast (STIFOR) *	Statistical-dynamical	E	Int
ST10	CONW Statistical Intensity Prediction Scheme *	Statistical-dynamical	E	Int
PTRO	Météo France Model *	Multi-layer regional dynamical	E	Trk
KBAR	Korea Meteorological Agency Barotropic Model *	Single-layer global dynamical	E	Trk
KBAI	Previous cycle KBAR, adjusted *	Interpolated-dynamical	E	Trk
KREG	Korea Meteorological Agency Regional Model *	Single-layer regional dynamical	E	Trk
KREI	Previous cycle KREG, adjusted *	Interpolated-dynamical	E	Trk
K426	Korea Meteorological Agency Global Model (low resolution) *	Multi-layer global dynamical	E	Trk
K42I	Previous cycle K426, adjusted *	Interpolated-dynamical	E	Trk
K213	Korea Meteorological Agency Global Model (high resolution) *	Multi-layer global dynamical	E	Trk
K21I	Previous cycle K213, adjusted *	Interpolated-dynamical	E	Trk

* Denotes models used exclusively at JTWC in 2005.

APPENDIX F
TRACK GUIDANCE MODEL ERRORS FOR 2005

The number of cases ("# Cases" at bottom of each table) indicates the number of TPC/NHC, CPHC, or JTWC forecasts represented in the error computation.

Table F-1. Homogeneous Comparison of Selected Subset of **Atlantic Basin** Early Track Guidance Model Errors (n mi) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	31.0	54.2	77.3	100.2	146.1	195.6	248.4
CLP5	46.9	100.3	162.3	211.9	271.4	341.9	457.9
GFSI	35.6	60.2	85.3	116.3	198.3	275.7	359.6
GFDI	33.9	57.7	78.9	103.9	163.3	253.6	337.4
GFNI	37.1	66.1	96.8	129.6	207.9	299.4	405.4
UKMI	38.1	65.9	93.9	118.5	169.5	216.2	263.1
NGPI	34.7	61.6	90.3	118.8	178.0	236.3	324.5
GUNA	29.1	50.1	72.5	96.1	148.0	194.7	249.9
CONU	29.4	50.6	74.0	97.7	150.2	197.3	257.1
FSSE	29.3	49.5	72.1	96.1	156.6	219.8	261.9
AEMI	35.7	60.7	85.9	113.4	181.8	240.6	264.0
# Cases	398	358	319	268	183	110	71

Table F-2. Homogeneous Comparison of Selected Subset of **Eastern Pacific Ocean Basin** Early Track Guidance Model Errors (n mi) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	28.0	48.0	65.9	79.4	103.6	119.0	132.8
CLP5	34.6	71.0	109.8	146.9	215.0	262.4	319.9
GFSI	34.2	60.4	87.4	113.6	176.0	238.2	256.8
GFDI	32.0	57.1	78.4	97.6	153.1	218.0	288.9
GFNI	41.5	74.9	104.5	125.5	161.2	206.4	244.0
UKMI	36.9	63.3	89.8	113.0	173.2	221.6	297.6
NGPI	38.4	71.2	97.9	123.3	174.6	220.6	267.1
GUNA	27.5	45.9	63.6	77.6	108.3	128.1	147.5
CONU	28.7	48.9	67.3	80.6	108.9	131.7	152.1
AEMI	34.0	61.2	88.8	117.8	176.8	236.0	265.8
BAMS	35.6	63.5	94.9	125.7	182.4	235.8	293.4
BAMM	34.4	58.0	82.2	107.5	148.8	181.5	227.7
BAMD	36.9	65.3	94.1	120.8	169.0	225.2	256.0
LBAR	32.6	69.3	116.2	164.4	255.7	337.9	437.1
P91E	34.6	66.6	100.1	136.3	227.5	318.8	456.4
# Cases	172	149	135	119	93	73	53

Table F-3. Heterogeneous Comparison of Selected Subset of **Northwest Pacific Ocean** Basin Early Track Guidance Model Errors (n mi) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	40	61	81	102	156	231	284
CONW	36	55	73	94	142	207	272
AFWI	45	78	115	156	279	--	--
AVNI	37	61	85	115	191	296	393
COWI	44	78	118	161	255	--	--
EGRI	46	76	108	139	211	252	306
GFNI	44	74	103	130	204	287	381
JGSI	38	61	80	99	141	234	--
JTYI	38	61	84	113	171	--	--
NGPI	43	70	96	119	182	278	360
TCLI	45	78	117	158	246	253	275
WBAI	49	83	117	154	228	--	--
# Cases	543	503	452	403	312	176	119

Table F-4. Heterogeneous Comparison of Selected Subset of **North Indian Ocean** Early Track Guidance Model Errors (n mi) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	42	62	84	116	118	133	134
CONW	41	65	91	116	123	154	185
AFWI	46	77	107	138	112	--	--
AVNI	44	60	77	94	91	84	69
COWI	40	57	66	83	112	--	--
EGRI	45	70	98	122	229	272	79
GFNI	51	67	88	114	166	279	405
JGSI	34	52	77	113	213	--	--
JTYI	45	76	121	187	317	--	--
NGPI	46	71	93	121	78	95	107
TCLI	57	96	141	179	203	--	--
WBAI	58	113	174	237	197	--	--
# Cases	77	67	56	49	18	10	8

Table F-5. Heterogeneous Comparison of Selected Subset of **Southern Hemisphere** Early Track Guidance Model Errors (n mi) against Official (JTWC) Forecast **for 2005**
(Comparison at 96 and 120 h are against CONW.)

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	41	69	91	114	199	--	--
CONW	40	67	94	117	207	248	292
AFWI	58	103	136	176	274	--	--
AVNI	44	75	111	146	223	310	394
EGRI	45	74	95	137	259	325	366
GFNI	51	89	122	147	210	282	373
NGPI	45	80	118	148	242	333	409
TCLI	52	91	134	149	338	--	--
WBAI	55	108	165	211	321	--	--
# Cases	239	213	192	169	41	--	--

APPENDIX G
INTENSITY GUIDANCE MODEL ERRORS FOR 2005

Although not computed operationally, included for reference in tables G-1 and G-2 is a simple intensity consensus model (ICON) that is an average of GFDI and DSHP. In each table, The number of cases ("# Cases" at bottom of each table) indicates the number of TPC/NHC, CPHC, or JTWC forecasts represented in the error computation.

Table G-1. Homogeneous Comparison of Selected Subset of **Atlantic Basin** Early Intensity Guidance Model Errors (kt) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	7.8	11.9	14.4	16.1	19.3	17.8	20.1
SHF5	10.8	17.2	20.6	21.9	24.9	26.4	23.8
GFDI	9.7	14.1	16.8	18.0	21.1	23.6	24.1
SHIP	10.2	15.9	19.0	19.8	21.6	22.3	23.6
DSHP	9.0	12.9	15.5	17.7	20.8	20.2	23.8
FSSE	8.6	12.7	15.4	17.4	21.2	23.1	23.0
ICON	8.8	12.4	14.7	16.3	19.5	20.2	21.9
# Cases	430	401	356	312	231	161	112

Table G-2. Homogeneous Comparison of Selected Subset of E**ast Pacific Ocean Basin** Early Intensity Guidance Model Errors (kt) **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
OFCL	6.0	10.2	13.9	16.5	18.5	19.0	19.9
SHF5	7.0	11.7	15.4	18.5	20.1	20.1	19.0
GFDI	7.4	11.5	14.7	17.0	20.4	20.0	17.2
SHIP	6.6	10.6	13.9	16.6	19.4	20.5	22.1
DSHP	6.3	10.1	13.4	16.0	19.3	20.5	22.1
ICON	6.3	9.8	12.5	14.5	17.7	17.3	16.5
# Cases	247	220	190	165	129	102	85

Table G-3. Heterogeneous Comparison of **Western North Pacific Ocean** Early Intensity Guidance Models (kts) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	7.2	11.6	14.8	17.6	23.4	25.7	26.6
CONW	9.4	16.4	22.1	25.8	29.7	30.8	28.2
AFWI	11.2	19.0	24.4	27.3	30.0	--	--
AVNI	10.6	18.5	24.8	29.5	35.9	39.5	38.3
GFNI	9.3	15.1	20.4	23.5	24.5	24.3	23.8
JGSI	10.6	18.3	23.8	27.3	33.2	47.0	--
JTYI	9.2	15.2	20.0	23.6	27.0	--	--
NGPI	11.3	18.6	24.1	28.4	33.8	34.4	32.8
TCLI	9.6	16.6	21.6	24.6	27.3	44.5	59.0
ST5D	7.8	13.1	17.8	20.7	25.5	26.3	24.9
STIP	8.2	14.0	17.8	20.8	25.5	28.4	26.6
# Cases	543	503	452	403	312	176	119

Table G-4. Heterogeneous Comparison of **North Indian Ocean** Early Intensity Guidance Models (kts) against Official (JTWC) Forecast **for 2005**

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	4.8	8.1	11.4	13.0	21.4	11.0	11.3
CONW	7.1	11.6	12.9	13.5	14.5	15.3	5.7
AFWI	7.7	14.5	18.5	21.1	25.6	--	--
AVNI	7.0	11.5	14.5	16.7	14.9	12.4	9.0
GFNI	8.2	13.3	16.0	16.3	13.2	16.2	14.0
JGSI	8.9	12.9	17.5	19.7	26.0	--	--
JTYI	8.0	15.3	19.5	22.8	23.5	--	--
NGPI	7.9	12.7	13.6	15.3	15.6	17.4	7.8
TCLI	9.0	13.8	16.6	19.0	18.5	--	--
ST5D	6.8	11.6	12.2	14.5	13.2	16.6	9.5
STIP	9.6	17.8	25.1	28.2	28.6	--	--
# Cases	77	67	56	49	18	10	8

Table G-5. Heterogeneous Comparison of **Southern Hemisphere** Early Intensity Guidance Models (kts) against Official (JTWC) Forecast **for 2005**
(Comparison at 96 and 120 h are against CONW)

Model ID	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
JTWC	9.4	15.7	21.7	25.5	32.9	--	--
CONW	10.5	19.0	25.4	29.5	34.7	32.2	35.7
AFWI	11.1	20.1	28.0	32.8	16.8	--	--
AVNI	11.8	20.7	27.3	32.7	44.8	36.4	40.3
GFNI	10.0	17.7	23.5	26.8	25.3	27.7	38.6
NGPI	12.4	21.6	28.5	32.4	39.5	38.2	41.3
TCLI	13.7	19.5	22.2	23.7	23.0	--	--
ST5D	10.3	17.5	22.4	24.6	29.6	25.9	24.5
# Cases	239	213	192	169	41	140	106

APPENDIX H
ARTICLE FROM *NOAA MAGAZINE*

NOAA IS ENCOURAGING EVERYONE TO PREPARE FOR HURRICANE SEASON

July 30, 2006 — NOAA is ready as we enter the peak of the North Atlantic Hurricane Season and we want to make sure you are as well. While NOAA will again provide the best possible forecasts, it is vital that everyone living in hurricane prone areas be prepared. Max Mayfield, director of the NOAA National Hurricane Center says, "The message for everyone is the same, whether we have an active season or a below-normal season, you've got to have a plan in place and you've got to be ready to implement that plan. Remember one hurricane hitting where you live is enough to make it a bad season."

How is NOAA Prepared for Hurricane Season

This year, NOAA committed more than $300 million dollars to track and forecast hurricanes. In FY 2007, NOAA requested an additional $109 million dollars for hurricane-related investments. Currently, NOAA is focusing on further improving hurricane track and intensity forecasting through better observations, enhancing its modeling efforts (including those related to storm surge and inland flooding) and the continuation of Joint Hurricane Testbed to advance the transfer of new research and technology into operational hurricane prediction.

Improving NOAA equipment is also critical. NOAA aircraft, the W-P3 Orions and the Gulf Stream IV, provide essential observations and data critical to the NOAA National Hurricane Center forecasters and supplement the U.S. Air Force Reserve reconnaissance flights. The $14.2 million dollars NOAA received in FY 2006 supplemental appropriations to improve future aircraft service will add an additional W-P3 in 2007, and upgrade the radar and instrumentation on all of NOAA's aircraft.

NOAA also works year-round with federal, state and local emergency managers; educating them about weather effects from hurricanes, while they educate NOAA about response issues and their challenges. It is a constant learning process and the key is working together to ensure that the public takes appropriate action this hurricane season.

Most preparedness activity and outreach takes place outside hurricane season. In May of 2006, as part of NOAA's ongoing mission to enhance economic security and national safety, the NOAA National Weather Service again led its annual Hurricane Awareness Tour — this year focusing on Gulf Coast states. The tour helped raise awareness about the potential effects from a hurricane landfall with FEMA, local governments, emergency managers, schools, the public and the media working as a team to increase hurricane awareness and encourage preparedness in this vulnerable area of the nation.

APPENDIX I
NPOESS SATELLITE DATA PERTINENT TO TROPICAL CYCLONE ANALYSIS AND FORECASTING

This appendix reviews the NPOESS sensors and data that are pertinent to tropical cyclone analysis and forecasting. The expectations of use are derived from extrapolations of current practices for both analysis and NWP models. As noted in the footnotes associated with the discussions regarding the Conical Microwave Imager/Sounder and Radar Altimeter, the exact specifications and future acquisition of both of these sensors are in doubt/jeopardy.

Visible/Infrared Imager/Radiometer Suite (VIIRS)

- Polar-Orbiting VIS/IR Imagery
  - Not currently used directly in NWP systems except for sea surface temperature (SST) estimates (see next bullet). In the future, it may provide some useful information after substantial development effort.
- IR SSTs
  - VIIRS provides retrievals (currently) and radiances (in the future) for SST estimates. Technology will evolve rapidly over next 5 years so that in the NPOESS era, direct use of radiances will provide the best SST information.

Crosstrack Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS)

- Temperature and moisture retrievals
  - Temperature and moisture retrievals are not used either in analysis or in NWP models.
- Radiances
  - IR (CrIS) and microwave (ATMS) radiances are used in data assimilation to provide essential temperature and moisture information for initializing hurricane forecast models.

Conical Microwave Imager/Sounder (CMIS)[2]

- For analysis, a microwave imager/sounder can view tropical cyclone inner-core structure often obscured by upper-level clouds and thus masked in visible and infrared imagery.
- For analysis, a microwave imager/sounder can derive column integrated atmospheric water vapor over the oceans, also known as total precipitable water (TPW). TPW measurements are useful for the analysis of tropical cyclone intensity trends. TPW can also be derived using IR and microwave radiances through data assimilation.
- A microwave imager/sounder can provide surface wind information as well as integrated moisture information for analysis in non-precipitating regions. For analysis, surface wind and rain rate information are the only quantities currently used from microwave imager. Rain contamination is an important quality control issue for both analysis and NWP.

[2] CMIS has been terminated; a new Microwave Imager/Sounder will be competed—not available until C2 (i.e., 2016 at the earliest).

  - The radius of 50 kt winds is a critical parameter for ship routing and the radius of 34 kt winds are important for coastal evacuations because these storm-response activities must be completed before the arrival of gale force winds.
    - Microwave estimates of surface winds suffer in measuring high winds and are contaminated by heavy rain
    - Microwave radiances may contribute to statistical intensity prediction models.
    - For NWP, current practice is to derive wind speeds from imagery. However, in the future, microwave radiance information will be used directly to provide a cleaner signal for data assimilation.
  - Integrated moisture estimates are useful for the analysis of tropical cyclone intensity trends.
    - Integrated moisture can also be derived using IR and microwave sounder radiances through data assimilation.
- A microwave imager/sounder can provide intermittent analysis of rainfall rate and some cloud properties such as liquid water.
  - However, it does not provide time-continuous information in general. Impact on analysis depends critically on time continuity of coverage (i.e., number of satellites, time between overpasses).
  - This information may be useful in future for NWP models.
  - Similar information can be provided by ATMS.
- A microwave imager/sounder may provide intermittent analysis of tropospheric warm core structure, rain rate, some cloud properties, and approximate wind structure (using a diagnostic model) due to direct overpasses.
    - It does not provide time-continuous information in general. Impact on analysis depends critically on time continuity of coverage (i.e., number of satellites, time between overpasses).
  - Rain rate and cloud properties may be useful in future for NWP models.

Radar Altimeter (ALT)[3]

- Radar altimetry measures sea surface height and wave heights.
- Many studies have shown that the ocean's subsurface thermal structure plays an important role in tropical cyclone intensification. The subsurface structure can often be deduced from satellite altimetry data.
  - The modeling of the oceanic heat content (OHC) shows that the ocean energy available to the storm can vary considerably, depending on the subsurface ocean structure. The OHC can be estimated using a combination of sea surface temperature and ocean altimeter measurements.
- For NWP, altimeter measurements are critical to providing information (through the ocean and wave data assimilation process) to coupled atmosphere-ocean-wave hurricane NWP models.

[3] The NPOESS ALT, a previously baselined sensor, has been placed into a Deferred/Government Furnished Equipment category. The ALT sensor will not be on NPOESS unless an external government agency agrees to sponsor the acquisition of the sensor and provides it to the NPOESS IPO.

APPENDIX J
METOP SATELLITE DATA PERTINENT TO TROPICAL CYCLONE ANALYSIS AND FORECASTING

This appendix reviews the MetOp sensors and data that are potentially pertinent to tropical cyclone analysis and forecasting. The expectations of use are derived from extrapolations of current practices for both analysis and NWP models.

Infrared Atmospheric Sounding Interferometer (IASI)

IASI is one of the most advanced onboard instruments measuring infrared (IR) radiation emitted from the surface of the Earth to derive data of unprecedented accuracy and resolution on humidity and atmospheric temperature profiles in the troposphere and lower stratosphere. It also can measure some of the chemical components playing a key role in climate monitoring, global change, and atmospheric chemistry.

The Microwave Humidity Sounder (MHS)

MHS acquires measurements at various altitudes of atmospheric humidity, including rain, snow, hail and sleet, and temperature by measuring microwave radiation emitted from the surface of the Earth.

Advanced Scatterometer (ASCAT)

ASCAT, an enhanced follow-on instrument to the highly successful scatterometers flown on ESA's ERS-1 and ERS-2 satellites, measures wind speed and direction over the ocean. Its six antennas allow for simultaneous coverage of two swaths on either side of the satellite ground track, providing twice the information of the earlier instruments. ASCAT also contributes to activities in areas as diverse as land and sea ice monitoring, soil moisture, snow properties, and soil thawing.

Advanced Microwave Sounding Units (AMSU-A1 and AMSU-A2)

The AMSU instruments measure scene radiance in the microwave spectrum. The data from these instruments are used in conjunction with the High-resolution Infrared Sounder (HIRS) instrument to calculate the global atmospheric temperature and humidity profiles from the Earth's surface to the upper stratosphere. The data are also used to provide precipitation and surface measurements including snow cover, sea ice concentration, and soil moisture.

High-resolution Infrared Radiation Sounder (HIRS/4)

HIRS/4 is a 20-channel radiometric sounder measuring radiance in the IR spectrum. Data from HIRS/4 are used in conjunction with data from the AMSU instruments to calculate the atmosphere's vertical temperature profile and pressure from the Earth's surface to about 40 km altitude. HIRS/4 data are also used to determine ocean surface temperatures, total atmospheric ozone levels, precipitable water, cloud height and coverage, and surface radiance.

APPENDIX K
NCEP DATA ASSIMILATION DEVELOPMENT

1. Advanced Data Assimilation Techniques

Recently, new techniques have been developed to improve data assimilation. Broadly speaking, these techniques may be classified in three categories: 4D-VAR, Ensemble Data Assimilation (EDA), and Situation-Dependent Background Errors (SDBE). A short description of these three techniques follows.

4D-VAR

The 4D-VAR technique has the following advantages:

- All observation increments over the data window are considered at their observing time.
- The impacts of all observations on the model solution are realized at the observing time in the model.
- 4D-VAR allows for some time and space variability of the background error, although efforts to implement this degree of freedom have been rudimentary so far, even at ECMWF.
- In principle, the resulting analysis is a model solution so that it is a balanced, model-adjusted state. In practice, this ideal balance is not achieved because of inconsistencies introduced by simplifications and approximations.

The disadvantages of 4D-VAR are the following:

- In addition to needing a 3D-VAR framework, 4D-VAR requires approximately three times more software, including a tangent linear and adjoint versions of the forecast model. Every change to the model (e.g., physics, dynamics) will impact the 4D-VAR system directly. Any inconsistencies in the entire 4D-VAR system will cause it to perform suboptimally. These interrelationships may slow development of the entire forecast system.
- Operational maintenance and change-management of a 4D-VAR system is much more difficult, due to its complexity and larger volume of code (see above). Code management costs will increase as will coordination time between scientists working on different parts of the system.
- A full (no approximations) 4D-VAR system is 10-30 times more expensive computationally than 3D-VAR. 4D-VAR systems with approximations or simplifications are generally 2–5 times more expensive than 3D-VAR. Examples of simplifying approximations currently used at operational NWP centers include performing the analysis at lower horizontal resolution and using a simplified assimilating model (e.g., no physics or simplified physics).

In addition to the examples noted above, there are many ways of simplifying a 4D-VAR system. One possible simplification involves the "model" used in the 4D-VAR. It has been customary to use the same forecast model as in the free forecast. Therefore, simplifications have been made in the model physics or in horizontal/vertical resolution relative to the forecast model. However, a fresh look at the 4D-VAR problem may be in order. It may be feasible to construct a simple model for observation increments that can become part of the 4D-VAR technique. This model would remove the need for using the full free forecast model and its accompanying tangent linear and adjoint models.

Ensemble Data Assimilation

In EDA, the most likely atmospheric state is produced by finding the linear combination of ensemble forecast realizations that best matches the available observations. With EDA, background errors can be estimated directly from the ensemble at every analysis time and throughout the forecast domain. In a fully interactive EDA system, the ensemble perturbations are derived from the analysis error covariance. In this way, information from both the analysis and ensemble are used in a consistent manner. Although EDA is a relatively new technology, it is being vigorously pursued by about half a dozen groups in the research community, including a one-person effort at NCEP/EMC. The consistent use of information by the analysis and ensemble generation techniques is the major goal of an EDA-based system. However, it is yet to be demonstrated that this can be done reliably in an operational setting. A comparison of various EDA schemes is currently being sponsored by the THORPEX program.

EDA has the following advantages:

- No ancillary model components such as tangent linear and adjoint models are required; therefore, the code infrastructure is reduced considerably.
- The analysis code can be simpler, although in practice this may not necessarily be the case.
- There is a natural information feedback between the ensemble and data assimilation systems, which has not been fully explored in the 4D-VAR context. Unfortunately, some preliminary investigations by ECMWF in this area have been disappointing, so a lot more work needs to be done.
- Ensemble forecasts scale very well on massively parallel computers and, therefore, are very efficient to run operationally.

EDA has the following disadvantages:

- It is much less mature in practical applications than 3D-VAR. There are still many unknowns regarding ensemble construction, stability of background error formulation, and the impact of model error—particularly, any model bias. Many of the studies showing extremely optimistic results have been done with simulated data or without any large data source (e.g., satellite data).
- The technique appears to be very sensitive to the characteristics of the background (model) error, even more than 3D-VAR and 4D-VAR.

- Costs are proportional to the ensemble size and resolution. An ensemble run at full horizontal and vertical resolution would be highly desirable, although some cost reduction can be achieved by running the ensembles at lower resolution.
- The ensemble generation technique is critical; short term (3–6 hour) ensemble characteristics have not been well characterized.
- It is critical that the ensembles span the entire possible range of analysis states. If observations lie outside the ensemble envelope, extrapolation errors will be potentially fatal (i.e., could cause a major bust).

Situation-Dependent Background Errors

It is widely recognized that the major outstanding analysis problem is improved formulation of the background error part of the analysis equation. Many improvements over the past 10 years have been in this area, including a major upgrade to the ECMWF system. Nonetheless, 3D-VAR systems have background error formulations that are constant in time and geographically varying in a very limited way (e.g., latitudinal and vertically varying only, derived empirically from the model forecast climatology). The SDBE approach attacks the fundamental analysis problem directly and is particularly relevant to the hurricane problem. Some early work on this was done at ECMWF, the Met Office (METO), but was abandoned in favor of a simplified 4D-VAR.

One of the most significant modeling challenges to improve numerical forecasts of hurricane structure and intensity in high-resolution models is the initialization of the hurricane vortex. To advance this effort, a local 3D-VAR using SDBE covariances is being developed at EMC to initialize the hurricane core circulation in the HWRF using real-time airborne Doppler radar from NOAA's WP-3D aircraft and the newly funded instrument upgrade package on the NOAA Gulfstream IV aircraft (see section 3.1.1)**.** For storms approaching landfall, the data assimilation will also make use of the coastal WSR-88D high-resolution radar data. The NCEP Gridpoint Statistical Interpolation (GSI) now contains coding structures intended for admission of SDBE and will be exploited in the HWRF to initialize the hurricane core through development of flow-dependent algorithms. Developing SDBE using extensions to the GSI has the following advantages:

- It addresses directly the most fundamental part of the analysis problem.
- There would be direct continuity with previous work, including diagnostics, performance statistics, and other infrastructure software, and ease of comparison and diagnosis that comes with incremental change.
- The methodology is affordable now in a development and testing mode, while resources can be garnered for final testing and operational implementation in 1–3 years.
- The methodology is innovative and has a good chance of succeeding.
- It can be applied most advantageously in a 4D-VAR context.
- It can incorporate information from ensemble forecast runs.

The preferred development strategy for an NCEP Global and Regional Advanced Data Assimilation System (GRADAS) is, first and foremost, to develop SDBE within the GSI. 4D-

VAR extensions to the GSI, using a simple model for observation increments, will also be developed for improved use of high time-resolution observations such as surface and radar data and satellite imagery. This approach will result in systematic and incremental augmentations of the current NCEP global and regional analysis code and produce a simplified 4D-VAR that can also use ensemble-based information.

2. EMC's Data Assimilation Priorities

The following data assimilation priorities at EMC are associated with development of the above strategy:

- Improving the background error covariances and their evolution for the atmosphere, ocean, and land
- Assessing the impact of atmosphere, ocean, and land model errors and biases
- Identifying the key variables to be measured for NWP, including the requirements of accuracy and resolution in time and space and the tradeoffs between resolution and areal coverage
- Development of strategies to extract maximum meteorological information from the data (e.g., adaptive thinning, "super-obbing," recursive filters, etc.)
- Specifying the observation errors, especially in sensitive regions such as the inner core, and for surface observations in steep topography
- Development of techniques for optimal use of spatially dense correlated observations
- Development of adaptive quality-control techniques
- Development of assimilation techniques for available quantities (e.g., Doppler line-of-sight winds, air-sea fluxes, trace gases, aerosols)
- Modeling of radiative interactions with microphysics and aerosols

3. Data Assimilation Challenges for the Tropics and Hurricanes

Data assimilation for the tropics and hurricanes includes the following specific challenges:

- **Balance equations**: In the tropics (and for mesoscale in general), balance is dominated by moist processes and is much more complex than for the larger scales. Failure to properly treat the balance issues will result in a rapid loss of useful information at the beginning of the forecast. The increase in nonlinearity due to moist processes makes the tropical/hurricane problem more difficult to solve.
- **Analysis variables:** To accurately analyze variables in the tropics such as cloud liquid water and cloud ice, a balance has to be achieved and all the fields involved need to be initialized. This means that the surface and ocean fields must be correctly specified. The ability to achieve a realistic balance is not as straightforward as for the larger scales.
- **Background error covariance:** For the tropics, it is essential to have circulation-dependent error covariances, but they are difficult to determine. For example, the structure of the background error covariances for cloud and surface fields are almost

certainly dependent on small-scale dynamics that are not well known. Furthermore, it is critical to include in the background error covariances the relationships between the variables (e.g., water vapor and clouds).

4. Focused Data Assimilation Efforts Dealing with the Coupled Ocean Model

The coupled ocean model data assimilation efforts will focus on these items:

- Upper ocean and mixed layer as being of primary importance
- Skin temperature, which is a primary measurement from satellites
- Bulk water temperatures obtained from ship observations (the satellite retrievals are calibrated to the bulk temperature)
- Profiles of the thermal (and salinity) structure and mixed layer depth that are provided by floats and expendable conductivity temperature and depth probes

APPENDIX L
NCEP GLOBAL MODEL DEVELOPMENT

1. NCEP Global Model Development

This appendix describes an evolutionary plan for the NCEP global model. A number of external considerations are described, since they must be included in any long-range planning. These considerations include the emerging Earth System Modeling Framework (ESMF), the separate evolution of the model adiabatic dynamics and physics components, a short review on the basics of forecast model techniques, the concept of primary and secondary models, forecast system diversity, and interaction with other NOAA modeling groups for both the weather and climate applications.

The Global Forecast System (GFS) has many critical applications and functions in the NCEP operational job suite and is the cornerstone of NCEP's suite. Some of these forecast applications are noted below, with explicit relevance to hurricanes highlighted in bold type:

1. Global weather (1–16 days) with many applications such as Aviation, medium-range (3–8 days) precipitation and severe weather, **hurricane tracks**
2. **Initial and boundary conditions for hurricane regional model (i.e., HWRF)**
3. Boundary conditions for North American run
4. Boundary and initial conditions and background field for the Regional Spectral Model
5. Driver for ocean wave models and, in the future, other ocean models
6. Ozone distribution and transport and, in the future, other atmospheric constituents
7. **Background field for global data assimilation system**
8. **Ensemble system model (to include hurricane tracks)**
9. Coupled Climate Forecast System (CFS) model

The predecessor to the current NCEP GFS was developed in the late 1970's and was first implemented in August 1980. This model was based on the spectral representation for all forecast variables. In response to increased computing resources and changing computer architecture at NCEP, the GFS has evolved to higher resolution, both horizontally and vertically, and a more modular code structure. The current horizontal resolution is T382, or approximately 35 km; vertically there are 64 layers in a domain from the surface to 0.2 hPa (approximately 55 km). The GFS adiabatic dynamics and physics require application of Fourier and Legendre transforms to convert between spectral and gridpoint spaces. Advective processes are computed on the transform grid from spectral coefficients. A sigma (normalized pressure) vertical coordinate in current used (September 2004). A hybrid sigma-pressure coordinate option is included in the operational code and will be fully tested for operations in FY2005. The time integration scheme is a three-time-level leap-frog scheme with semi-implicit integration. Physical parameterizations and nonlinear dynamics computations are applied on a reduced Gaussian grid for computational economy. Changes to the physical parameterizations occur on the average of twice per year, with changes to the adiabatic dynamics much less frequently.

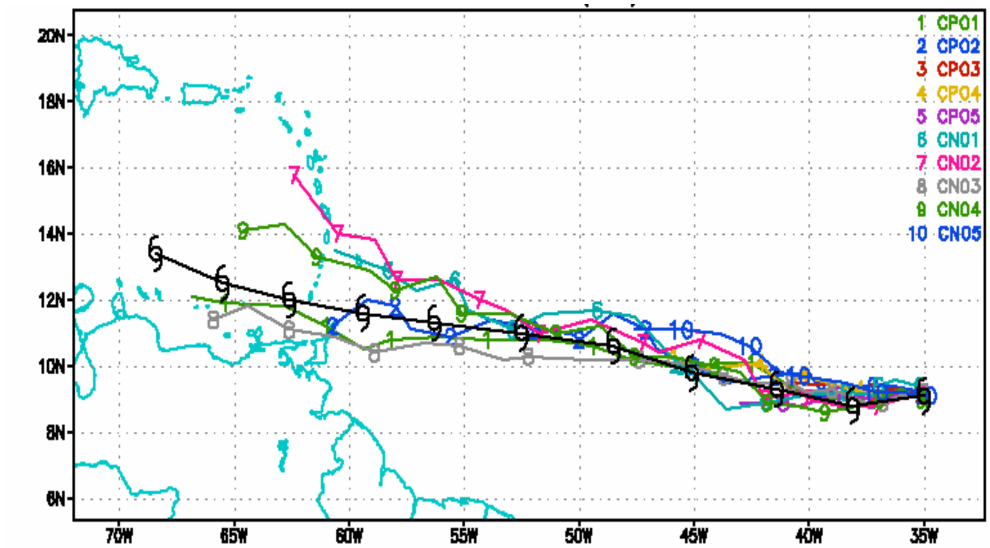
Ensembles and Forecast System Diversity

When initial and model related errors are well captured, ensemble forecasts can convey case-dependent variations in forecast uncertainty. Currently no other methods can provide such information. Variations in forecast uncertainty can have a significant impact on users. Small expected errors in the track of a hurricane (figure L-1a), for example, call for a different emergency response from a case when the possible tracks cover a larger area of the coast (figure L-1b). Therefore, all uncertain forecast information must be presented in a probabilistic or other format that conveys the associated forecast uncertainty.

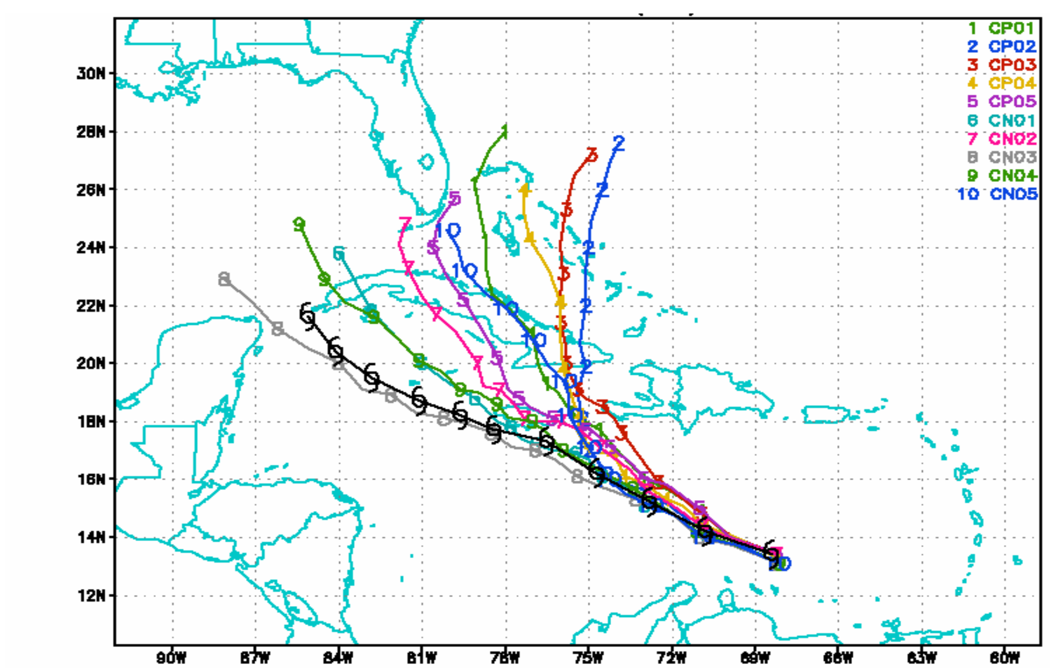
Ensembles can be formed in a number of ways. One can collect single forecasts generated by different NWP centers. Methods have also been devised to simulate initial and model-related errors. Today, in addition to a single higher resolution forecast, most NWP centers, including NCEP, also generate their own set of global ensemble forecasts. The NCEP Global Ensemble Forecast System (GEFS) recently underwent two major changes that are significant for hurricane forecasting. First, with an implementation in 2005, the initial perturbations related to tropical storms were revised. With the use of the hurricane relocation algorithm, the position of the tropical storms is no longer perturbed, and the perturbations in the magnitude and shape of the storms are better controlled (figure L-1). These changes further improved the track prediction performance of the GEFS system. As figure L-2 shows, there was a significant reduction in the error of the ensemble mean track. Importantly, the spread in the ensemble also was reduced to a level that now closely matches that of the error. This is an indication of a well-calibrated track forecasting system that is statistically reliable and can generate probabilistic forecasts that are consistent with observations. With these changes, the performance of the ensemble mean track exceeds that of the higher resolution Global Forecast System (GFS) averaged over the 2005 Atlantic hurricane season (figure L-3, courtesy of Jim Goerss, U. S. Navy) for all lead times, beginning with 12 hours (not shown in figure L-2). However, the ensemble mean forecast errors were still higher than the multi-model consensus CONU for all forecast periods.

The second change is related to the implementation of a multi-center ensemble approach that is aimed at optimally combining ensembles generated first in North America (North American Ensemble Forecast System, NAEFS, currently NCEP and Meteorological Service of Canada ensembles are available, FNMOC and possibly UK MetOffice ensembles to be added later). The NAEFS effort includes the exchange of all ensemble members generated by the participating centers for a large number of variables; the optimal combination of information from the different ensembles; the statistical bias correction of many of the variables; and the expression of the forecasts in terms of climatological percentiles, based on the NCAR-NCEP reanalysis data, allowing for a simple downscaling of the forecasts.

NCEP is interested in working with the hurricane user community in developing new and improved products based on the NAEFS and other ensemble data. Bias-corrected and downscaled probabilistic high wind, precipitation and other products are examples of the opportunities for providing more diverse and informative products generated automatically for the user community. Plans are also being considered for using the ensemble approach in limited area (WRF) hurricane ensemble forecasting.



(a)



(b)

Figure L-1. Two forecast examples for Hurricane Ivan generated with the 2005 version of the NCEP Global Ensemble Forecast System. The ensemble in figure L-1a indicates a case with relatively small track uncertainty while that in figure L-1b shows a case with large uncertainty. Such information can be critical in emergency management applications.

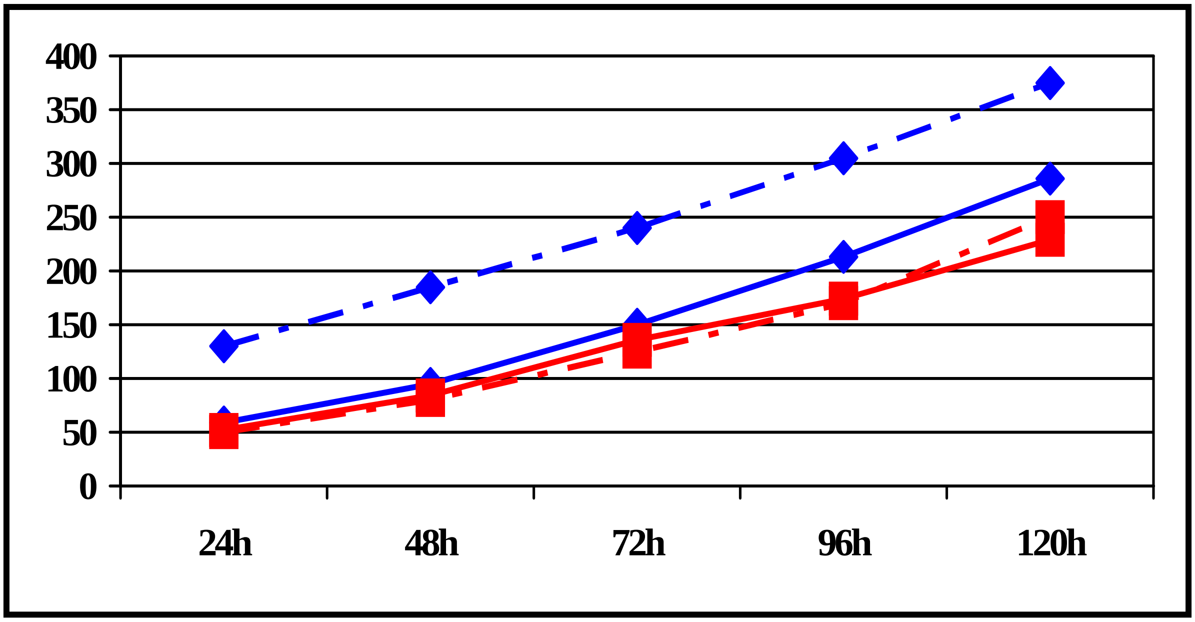


Figure L-2. Track error of (solid lines) and spread around the ensemble mean forecast (dashed lines) for 8/23-10/1 2004 Atlantic storms with the then operational (blue) and since implemented (red) versions of the NCEP Global Ensemble Forecast System. The closely matching error and spread curves indicate an ensemble forecast system that is statistically reliable for tropical storm prediction applications.

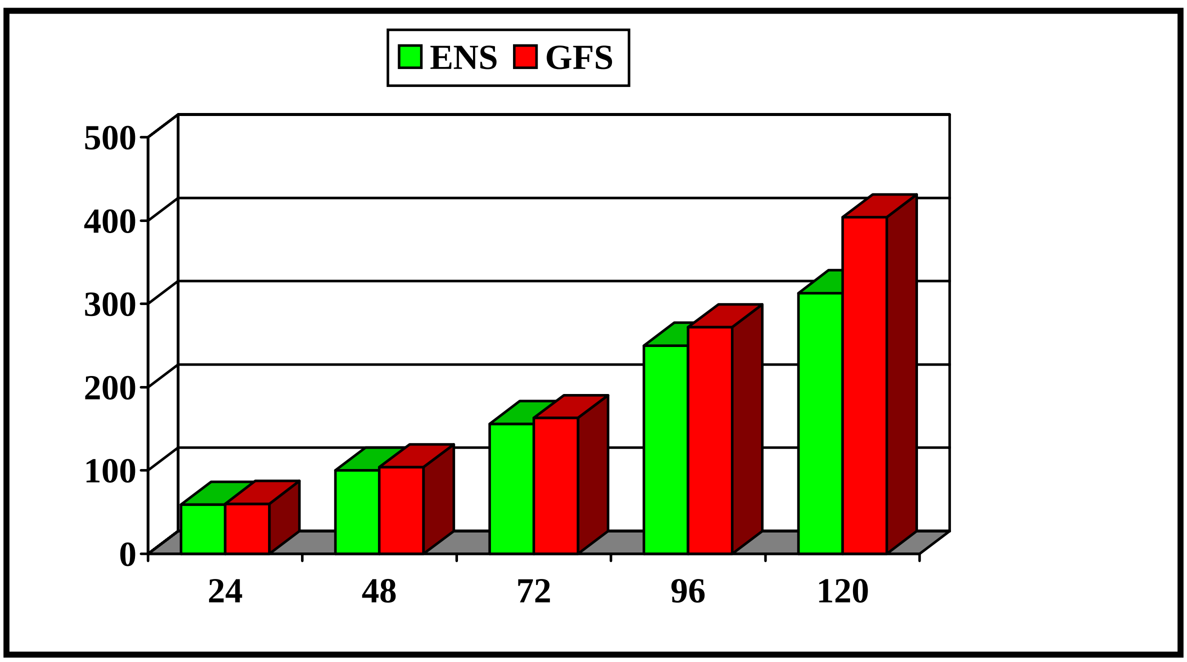


Figure L-3. NCEP global ensemble mean (green) and Global Forecast System (GFS, red) tropical storm track forecast errors (nm) averaged over the 2005 Atlantic Hurricane season. The error in the ensemble mean track is lower than that in the high-resolution single forecast at all lead times. Of interest, the computational cost of generating either the lower resolution ensemble or the higher resolution single forecast is similar. (Courtesy of Dr. James Goerss, U. S. Navy.)

ESMF and the Common Modeling Structure

The ESMF is a multi-agency project to develop both a model superstructure and infrastructure. The superstructure is defined as a set of standards that allow new components to be coupled together with minimal impact on remaining components. Components may be defined as complete models (e.g. ocean model) or parts of a complete model (e.g. dynamics, physics, or parts of each). The infrastructure is a set of portable, reusable utility routines that can be used across different models.

Both superstructure and infrastructure must be flexible enough to allow evolution of NCEP's models and general enough to accommodate both global and regional models and data assimilation modules for each application. It must also accommodate both primary and secondary models, some of which could originate from other parts of NOAA or from outside NOAA. ESMF-compatible code should be easily transferable to NCEP operations, given the high degree of modularity and portability standards inherent with ESMF.

2. Model Requirements

The next-generation NCEP global model must provide skillful guidance for all applications listed in the introduction to Appendix L, demonstrate at least the computational efficiency of NCEP's current global model and provide the flexibility to meet future demands. The following set of highly desirable global numerical model properties should be considered in developing NCEP's next-generation model.

Requirements for Dynamics

The next-generation NCEP model will evolve to one with the following properties:

"Same" Model for Global and Regional Applications

The model dynamics should be capable of representing both the global and mesoscale circulations in the atmosphere. The current resolution of the global model is ~35 km, which is very similar to the resolution of NCEP's regional model in September 2000. Other international NWP centers, such as the UK Met Office and the Canadian Meteorological Center (CMC), use the same dynamics for both global and regional models. This strategy facilitates the data assimilation applications since the model background properties are more consistent across various applications. It reduces code maintenance for complex communications strategies and dynamics algorithms, and it facilitates the inevitable march to improved forecasts through higher horizontal and vertical resolution.

Non-hydrostatic Option through a "Switch"

If a single dynamics is required for both global and mesoscale applications, then the ability to switch efficiently between hydrostatic and nonhydrostatic dynamics is critical. Although non-hydrostatic dynamics for global applications appears necessary at horizontal resolutions of below 10-12 km, this resolution will not be feasible operationally for many years to come. However, the experience gained at regional forecasting, where full non-hydrostatic dynamics is now operational, can be useful provided the same dynamics structure is used. Moreover, some improvements to the vertical velocity calculation may provide an improved dynamical response to convective heating, even at coarser resolution. This is an area of active research.

ESMF standards

As stated above, ESMF standards will enhance portability and reuse of software, provide a common modeling structure, and thereby decrease the time needed to bring in model components from outside NCEP (provided they are ESMF-compatible). This common modeling structure can be used to provide a more unified system for running NCEP's operational global and regional forecast systems.

Two-Way Nesting

A well-designed, two-way nesting capability is required if a single model structure is going to be used for both global and regional models. One-way nesting is used to drive NCEP's North American run. However, at this time, the global and regional models are separate modules with very different dynamics and physics. An earlier forecast from the global model supplies the boundary conditions for the regional model, which is run before the global model. In the future, when NPOESS satellite data is available with shorter latency than current data, it may be possible to drive the North American model (and others) with concurrent boundary conditions from NCEP's global model. At an even further stage of development, a two-way nesting capability may be possible if the global and regional models have a common dynamics and physics. The full, two-way nested configuration for global forecasting is an area of active research at this time.

Conservative Scheme for Adiabatic Dynamics

The dynamics should be formulated to conserve, in a domain-integrated sense, as many of the quantities in the continuous formulation of the equations as possible. First order quantities, such as mass, should be conserved as demonstrated by the continuous forecast equations. Moreover, the continuous equations can also be combined to demonstrate the conservations of quadratic quantities such as potential vorticity, total energy, and enstrophy under well-defined conditions (e.g., adiabatic, nondivergent flow). It appears desirable to have a discretization of the continuous equations that preserves these relationships, although there is not unanimous agreement on this issue. A scheme that does not formally conserve these quantities should still be tested and evaluated for its conservation properties. Such conservation may become increasingly important with the length of the forecast application.

Hybrid Vertical Coordinate and Vertical Discretization

A hybrid coordinate, with a terrain-following coordinate near the lower boundary but approaching an isentropic coordinate in the upper troposphere and stratosphere, may provide a better discretization of the dynamics, due to reduced vertical discretization errors. In addition, careful vertical discretization may be helpful in providing improved conservative properties for the dynamics. These are leading edge research problems, however, and considerable work is needed in this area.

Formal Accuracy

The formal accuracy of a particular numerical scheme is an important factor, although less formally accurate schemes with good conservation properties have been shown to be excellent schemes. In addition, as horizontal resolution increases, the influence of formal accuracy becomes less. One area of research concerns the discretization of physical processes, which can contribute positively to a more accurate solution.

Consistent Treatment of All Forms of Water Substance

The heat content and density of air and all forms of moisture needs to be accounted for in a consistent manner. Also, the impacts of water vapor and other gases on the gas constant and specific heat must be addressed consistently.

Conservation of Tracers, Including Moisture

The total quantities of tracers should be conserved in the absence of sources and sinks. The numerical schemes should not produce unrealistic quantities such as negative values.

Requirements for Physics

The GFS physics has been applied to daily, global weather forecasting, to Seasonal to Interannual (S/I) forecasting with the coupled Climate Forecast System (CFS), to regional mesoscale forecasting with the Regional Spectral Model (RSM), and to hurricane forecasting in the GFDL model. In the case of the CFS, the GFS physics produced coupled atmosphere-ocean simulations with very small (< 0.5 K) climate drift in the tropic. Furthermore, the GFS physics appears to have considerable skill in forecasting seasonal tropical wind shear, which is a major predictor of tropical cyclogenesis and convective activity in general.

The application of physical parameterizations for high horizontal and vertical resolution is an area of active research. Use of ultra-high resolution (1-2 km) nested models to capture the cloud-scale physics for a global model (also called “superparameterization”) may prove fruitful for directing new development in the future. Assumptions common to current physical parameterizations, e.g., hydrostatic and isobaric processes, may prove limiting at resolutions below 10 km, in much the same way as the hydrostatic assumption is unsatisfactory for the adiabatic dynamics. The general application of physical parameterizations with general (“non-sigma”) vertical coordinates also needs to be explored.

To facilitate and encourage more advanced research on global modeling, the NCEP GFS can be transformed into a more general system, while maintaining a strong heritage and connection to operations. In this way, incremental and controlled evolution can be achieved with reduced risk.

Requirements for Computational Efficiency

NCEP’s job suite is defined by a time window for data assimilation, model integration and product generation; by the number of available computing processors; and by the speed of the computing interconnect fabric. The object is to produce the most accurate forecast within the allowable time window, provided the forecast system code is maintainable and upgradeable within resources available to EMC and its partners.

3. Model Development Strategies

At present, there are five principal strategic options for development of NCEP's next-generation dynamics:

1. Upgrade the current operational spectral model (sigma-pressure hybrid version)
2. Upscale the Non-hydrostatic Mesoscale Model (NMM) to global domain
3. Apply Semi-Implicit (SI) and Fully-Implicit (FI) Semi-Lagrangian (SL) formulation (Kar dynamics)
4. Adopt the Finite-Volume (FV) dynamics
5. Adopt the University of Wisconsin sigma-theta dynamics

To minimize future code rewriting and reorganization, these development efforts should take place within an ESMF-compatible structure. Preliminary work on such a structure has begun and is still evolving. Although it is currently unclear to what degree an ESMF-compatible structure can be suitable for operations, it should be able to house each of the above strategies, which are discussed in more detail below. To give a common beginning to all development efforts, the codes need to be placed into this structure as a first step. This step will make it easier for all participants to share code as soon as possible, will allow results to be compared more readily, and will save development time because the ESMF infrastructure codes will provide standard techniques for implementing message passing, other communications chores, standardized gridding, etc.

Evolve the current operational spectral model (sigma-pressure hybrid).

After placing the current operational, sigma-pressure hybrid spectral model into an ESMF-compatible structure, the model could be developed further by taking the following steps:

- Improve the accuracy of the vertical discretization
- Generalize the vertical coordinate, which can allow a sigma-theta option
- Add FISL and/or SISL capabilities
- Improve mass and thermodynamic consistency for all forms of water
- Continue to experiment with high-resolution downscaling using the RSM

This development strategy has the following advantages:

- Strong continuity with operations will allow evolutionary progress.
- An ESMF-compatible structure is being constructed and tested.
- Spectral method potentially has the most accurate horizontal dynamics formulation.
- Tracers are already included, although they are not in the most economical or even the most desirable form.

- A regional model (the RSM) has already been constructed and tested; it is part of the Short-Range Ensemble Forecast (SREF) system.

This strategy has the following disadvantages:

- The computational efficiency on higher resolution, limited area domains may decrease for spectral models, due to the overhead in converting from grid to spectral space with a smaller number of grid points.
- A nesting technique will require additional code support since different spectral functions must be used for the global and regional applications.
- Adding fully implicit time differencing and SL advection to increase the time step will involve major changes to code structure and require considerable resources.
- In all likelihood, introduction of FISL and/or SISL techniques will reduce conservation properties.

Upscale NMM to Global Domain

The NMM became the primary regional model at NCEP on June 13, 2006, when the Gridpoint Statistical Interpolation (GSI) system was coupled with the NMM in the Weather Research and Forecasting (WRF) system structure. The NMM can be converted into a global model on a latitude-longitude grid by filtering the smallest waves near the poles to ensure computational stability (as in many Eulerian gridpoint models on a sphere). A second strategy is to integrate the model on two separate domains using mercator grids, with a coupling mechanism between the domains for information transfer. Using the ESMF-compatible structure, coupling may be facilitated. For participation in this global model development project, the following steps must be taken:

- Place the NMM into the ESMF-compatible structure
- Either (a) add low pass filters in the polar regions to allow longer time steps or (b) couple domain components on two mercator grids (bi-mercator [BM] technique)
- Consider the possibility of a stretched grid (as already done by CMC) for global and regional applications
- Continue to develop dynamics in response to requirements stated in Section II

This development strategy has the following advantages:

- The NMM dynamics is very scalable and has been shown to run efficiently and to give good quality forecasts on a regional domain.
- The NMM uses a hybrid sigma-pressure vertical coordinate already.
- The NMM currently allows a non-hydrostatic option via a switch.
- Global upscaling through low pass filtering in polar regions is a known technology, but may not be without risk.

This strategy has the following disadvantages:

- Upscaling the NMM dynamics from regional to global introduces some risk, but this may be mitigated by introducing global model physics into the NMM. Nevertheless, thorough testing will be required because of the large number of new weather regimes that must be forecast skillfully, such as the tropics and the Arctic.
- Resources will need to be expended to move the NMM into the NCEP ESMF-compatible modeling structure.
- The BM strategy is innovative, but it is also high risk because of the possible inconsistencies of the evolving model solutions on separate grids and the problem of extracting regional boundary conditions where the grids are stitched together.

Apply Semi-Implicit (SI) and Fully-Implicit (FI) Semi-Lagrangian (SL) Formulation (Kar)

This formulation uses a FI or SI formulation of the non-advective, nonlinear terms in the full dynamics equations. In addition, SL advection can be used consistently with the SI or FI formulation. Using both of these techniques together can allow increased efficiency through longer time steps, but not without additional of significant computational overhead. Initial results using a shallow water model have been very encouraging, and development of a 3D hydrostatic FISL model is well underway. Application of these techniques to operational-grade models, such as the GFS and the NMM, can be done more efficiently by using these models in an ESMF-compatible framework which other members of the group are using. For participation in this global model development project, the following strategic options could be taken:

1. Formulate, apply and restructure the NMM and/or GFS to use SI, FI and SL techniques
2. Continue to develop the FISL and SISL shallow water formulations into a full, 3D, operational grade model

Option 1 is preferred since the work required to develop, test, and implement a new, operational grade model is estimated to be less. Application of FISL or SISL techniques could be directed at either the NMM or GFS. The result of this application will be a totally different type of model, which may have a good combination of accuracy and computational efficiency. SL techniques have, however, no formal conservation guarantee of mass or dynamical quantities, although the impact of exact conservation alone may not be of critical importance. Considerable research, using isentropic diagnostics, needs to be done. It should be noted that ECMWF uses a spectral-SL scheme for forecasts in daily and seasonal time domains.

This development strategy has the following advantages:

- The code and scripting surrounding the GFS or NMM models can be used to house the FISL and SISL dynamics so that it need not be developed for a new model.
- The new techniques can be compared cleanly within the operational GFS or NMM frameworks.

- If successful, the new techniques will result in an evolved model with increased efficiency and most, if not all, of the same good characteristics of NCEP's current operational model.

This strategy has the following disadvantages:

- The work necessary to restructure the GFS and/or NMM for efficient operation on parallel computing architectures, is large. It will involve new strategies and code for defining haloes in the GFS.
- The formal non-conservation of mass may be troublesome for NCEP's Seasonal-to-Interannual climate forecast mission.

Adopt the Finite-Volume (FV) Dynamics

The FV dynamics has been tested at NASA/GSFC, GFDL, and NCAR for climate applications and, more recently, for data assimilation using NCEP's GSI code. The FV dynamics may have better conservative properties than other SL formulations. While NASA/GSFC has had some experience using the FV model in a cycled data assimilation system, this system has not yet achieved the same maturity in testing as NCEP's system.

This development strategy has the following advantages:

- Substantial community testing has been done for climate applications.
- Community support should be available from GMAO and possibly GFDL.
- Conservation properties may be improved over traditional SL schemes.

This strategy has the following disadvantages:

- The FV model has not yet been fully demonstrated for NWP and data assimilations.
- The work to downscale this model to a regional application is underway but not complete.
- A non-hydrostatic formulation of this model is under development but not currently available.
- A generalized coordinate version is not yet available.

Adopt the University of Wisconsin Dynamics

The University of Wisconsin (UW) dynamics is a specific implementation of a sigma-theta hybrid coordinate, which has potentially very nice conservation properties. Detailed score comparisons with NCEP's GFS, which have been made for the past two years, show that the UW model has comparable 500 hPa height scores and improved moisture verification scores when NCEP's physics are used. More detailed comparisons, including tropical forecast skill, will be useful to demonstrate the potential advantages of the hybrid coordinate. Thus, the UW model will be run by UW personnel on NCEP's computer for comparisons using NCEP's verification suite. This activity should produce improved understanding of the impacts of dynamics formulations on global forecasts at different time and space scales.

This development strategy has the following advantages:

- The model has some potentially nice conservation properties.
- Side-by-side testing can be useful in understanding the behavior of NCEP's model.

This strategy has the following disadvantages:

- This model is not supported.
- The model's computational efficiency and program structure are unknown.
- The model has not been fully tested for the broad variety of NCEP's applications.
- The formal accuracy of this model may be less than second order.

4. The Chosen Strategy

It is currently unclear whether either the spectral or gridpoint discretizations will be ultimately superior or whether neither will demonstrate a clear advantage. Among international weather centers, both spectral (ECMWF, Japan Meteorological Agency) and gridpoint (Met Office, Canada) methods are used. However, a spectral method has only been used at the Japan Meteorological Agency for both global and regional applications, where both methods are required. It appears that the most popular choice is a gridpoint method, either through direct nesting or a stretched grid technique. It should be recalled that spectral models still evaluate advective processes on a grid, so that the choice of discretizing the advection boils down to representing horizontal gradients from spectral coefficients, from horizontal interpolations in a SL technique, or from finite difference approximations from grid values.

The chosen strategy is to consolidate EMC model development efforts into three projects as follows:

1. Develop an ESMF-compatible Prototype Framework (PF), which will run the latest version of the NCEP Global Forecast System (GFS)
2. Upscale the NMM to a global domain and incorporate SISL and FISL techniques
3. Generalize the PF to incorporate the NMM as both a global and regional model

The outcome of the above strategy will determine the longer term work (2007–2011). If preliminary projects for producing operational, ESMF-compatible systems are successful, this will enable efficient testing of "multi-model" strategies as well as expanding the suite of operational products to include ocean prediction, environmental monitoring (e.g., CO_2, aerosols), marine ecosystem monitoring and prediction, hydrological prediction, water and air quality monitoring and prediction, and space weather forecasting.

APPENDIX M
SOME FUTURE WORK PLANNED FOR THE HWRF AIR-SEA-LAND-HURRICANE PREDICTION SYSTEM

1. The following additional tasks are associated with WAVEWATCH III:
   - Include new stress and flux parameterizations in the wave model for use in coupling with the HWRF model as necessary and feasible.
   - Include shallow water (surf zone) physics parameterizations in the WAVEWATCH III model, utilizing established parameterizations from models such as Simulating WAves Nearshore (SWAN) and STeady State spectral WAVE (STWAVE). Note that the multi-grid version of WAVEWATCH III that is presently under development at NCEP already includes the capability of drying (movement over land) and wetting (back over water) of grid points.
   - Expand WAVEWATCH III to include irregular and/or unstructured grid approaches for the use in coastal areas. This approach will provide wave forcing for inundation models at the local resolution of such models. In the first approach, a full time-resolving model will be considered. Such a model may be excessively expensive for operational use and is intended mainly to demonstrate the physical feasibility of coupled modeling of waves and surges
   - Economical modeling of waves on irregular and/or unstructured grids may require implicit propagation schemes and/or the use of a quasi-steady approach. Implementation of such approaches in WAVEWATCH III can build upon established techniques for coastal wave models.

2. The work underway on HYCOM modeling with interaction with the ADCIRC team at NOS includes the following activities:
   - Body tides and the complicated problem of including tidal boundary conditions at the open boundaries of the domain have been implemented in HYCOM. Calibration of the tides is underway.
   - Simulations during hurricane events from HYCOM alone. These simulations show adequate skill in storm surge predictions while using operational GDAS winds. The surge estimates from the Real Time Ocean Forecast System (RTOFS) can be used as a first guess of the surge and serve to guide the deployment of the ADCIRC model in areas for which detailed advance knowledge of inundation is useful.
   - In December 2005, the HYCOM-based RTOFS for the Atlantic became operational. The work done on the tides in HYCOM was essential to this development. For hurricane events, the model has a resolution of 4-7 km. Daily fields of nowcast and forecasts of sea surface elevations and transports are now available to provide open boundary conditions to ADCIRC. Air-sea fluxes and wave fields from real-time and historical storms generated by this system are used for testing and validation of the new hurricane system components.

- Strategies for coupling of HYCOM fields to the high-resolution NOS coastal models and the representation of coast line configuration and coastal bathymetry are currently underway. They include NOS requirements for wave-related fluxes in their coastal models.
- Work continues on including turbulent boundary layer effects in HYCOM due to the waves. A series of simulations will be carried out jointly with NOS to deal with problems related to open boundary nesting of HYCOM and ADCIRC for selected cases. In addition, work on improving the representation of tides in HYCOM will continue.

3. The additional planned work dealing with the HWRF, the Noah LSM, the prediction of the distribution of low level surface winds and rainfall amounts, and forecasting of stream and river flow and flood levels includes the following activities:

    - Couple the LSM with the movable, nested grid of the HWRF; investigate the impact of the Noah LSM on the prediction of the distribution of low level surface winds and rainfall amounts and the overall decay rate upon landfall. This will be contrasted with the simple one-layer slab model currently in the HWRF and the GFDL operational hurricane models.
    - Compare the predicted wind and rainfall amounts from HWRF with observations, including the proposed meso-network in Alabama by the U.S. Army. This will include present hurricanes as well as significant landfalling cases that have occurred over the past few years. Standard verification techniques for rainfall verification will be used, as well as new techniques designed especially for landfalling hurricanes (see section 3.4.5).
    - Initiate a project that will use the runoff output of the Noah LSM as input to various objective techniques to forecast river flow and flooding. Successful precipitation prediction by itself may be attractive, but the true importance of precipitation lies as an input to provide accurate forecasting of stream and river flow and flood levels. Traditionally, river and flood forecasts have not used hurricane model predictions of precipitation as input to predict river and flood forecasts. Evaluation of model-predicted wind and precipitation fields will continue.
    - Upgrade and change (as required) the HWRF model physics packages to improve skill of precipitation and wind fields, especially the distribution of low-level surface winds and precipitation. The upgrades and changes will be based on the aforementioned verification and evaluation of predicted precipitation and wind fields and their deviations from the observed fields determined from historical observations and the proposed meso-net data in Alabama. The predictability of intense destructive features will be evaluated through the use of ensemble and high-resolution forecasts.
    - Continue the evaluation of the effect of utilizing HWRF-determined runoff in the forecast of river flow and flooding. The evaluation will be contrasted with more basic forecasts utilizing precipitation without regard to moisture conditions of the underlying soil. The basic forecasts may include coarse resolution rainfall forecasts from simple models of climatological hurricane rainfall and forecaster-subjective methods of supplying QPF. In addition, further refinements will be made to other physics packages of HWRF to improve predictive skill.

APPENDIX N
QUESTIONS FROM THE
AIR-SEA INTERACTIONS IN TROPICAL CYCLONES WORKSHOP

(Shay et al. 2005)

Focused questions arose from the *Air-Sea Interactions in Tropical Cyclones Workshop* involving the collaboration of the hurricane air-sea community in addressing fundamental issues needed to advance the HWRF and other air-sea coupled hurricane models.

1. Where is the air-sea community on observing and modeling the oceanic and coupled response to tropical cyclones? What is the state-of-the-art in areas of air-sea interaction/boundary layer processes and upper ocean physics? What promising technologies are on the horizon? Will they be available over the next 2 to 5 years?
2. How can we maximize recently acquired data sets such as ONR-CBLAST, NSF/ NOAA Isidore/Lili, HFP, and MMS Georges data sets?
3. What are the relevant time/space scales at which models need to be resolved relative to intensity change?
4. What is the impact of oceanic coupling on forecasting the atmospheric structure and intensity?
5. How do we improve initialization schemes? How important are positive feedback regimes such as the Gulf Stream and the Loop Current on storm intensity and structure?
6. Can we use some of the work from GODAE for assimilation of satellite, drifter, and float data?
7. What observations are needed to improve mixing parameterizations? What about wave coupling to the OML and ABL?
8. What is the appropriate mix of observations needed to improve the ocean and air-sea boundary layer processes in oceanic or coupled models?
9. What metric(s) need to be implemented for consistent assessment of model(s) performance? For example, is showing intensity changes from models enough for a validation? How do we implement data and metrics in near-real time for forecasting needs?
10. What new real-time experimental plans need to be developed to support model forecasts? For example, sampling scenarios may differ over the Loop Current than the subtropical front in the North Atlantic.
11. Do we follow the life cycle of one storm, or observe two storms under differing oceanic conditions each year? Will this approach provide enough statistics to really improve the models?

12. How do we maximize use of GOOS float and ship-of-opportunity data? Will NDBC upgrades be useful? What about Coastal Ocean Observing Systems?
13. Do we rely on moored instrumentation or do we integrate time series from floats/drifters with snapshots from expendable sensors from aircraft?
14. Where do we see satellite remote sensing support going? What type of data will be useful in supporting experimental plans and data assimilation in models?

APPENDIX P
SOCIAL SCIENCE RESEARCH

Representative Research Questions
1. Warning Process
How does information flow from forecasters to various types of decision makers?
How should probabilistic forecasts be structured to promote public understanding?
Do people respond better to consistent forecasts with lower probabilities of accuracy, or should forecasters sacrifice consistency for reasonable accuracy?
Are terms like watch, warning, and surge well understood or should new terminologies be developed and tested?
Are current watch/warning lead times the most useful to responders?
What graphics and visualization techniques promote appropriate reactions?
Is the Saffir-Simpson scale adequate, or would a different or additional scale be more useful?
How can the level of danger from surge, rainfall, and inland flooding be conveyed effectively?
How do risk perceptions vary in heterogeneous populations?
How can warning messages target high-risk groups?
What are the consequences of broadcast media consolidation to the warning process?
Can local WFOs be used more effectively in the warning process?
2. Decision Making
What are the processes by which various user groups receive, interpret, and use forecasts and warnings?
How do end users handle conflicting messages?
How can NWS products and processes be improved to promote more effective decisions and responses?
How do forecast and warning messages influence timing in decision making?
What products and timing best meet the needs of various categories of businesses and organizations?
How do social vulnerability issues (gender, race, class) play out in risk perception and response?
How do formal and informal social networks affect response to warning messages?
What are the best methods for educating various user groups in the effective use of forecasts and warnings in their decision-making processes?
How do the cultures of various organizations involved in responding to forecasts and warnings encourage or impede change?
How can the forecast community understand and navigate the political processes involved in hurricane-related decisions?

Representative Research Questions
3. Behavioral Response
How can response and evacuation behavior best be modeled?
How do context and resources affect the timing of hurricane response among various user groups?
What are the lags between various warning messages and protective actions?
What changes in the warning process are likely to promote evacuation among those who should leave, while deterring unnecessary evacuation?
What are the effects of "false alarms" on future hurricane response among different user groups?
What are the effects of various warning methods and processes on traffic patterns?
How do media accounts of a hurricane event affect future behavior?
How can behavioral studies from various events be structured to allow for comparative research?
How can behavioral data bases be made available to researchers while protecting the identify of respondents?
4. Social Impacts and Valuation
How can relevant social costs be included in the economic analyses of hurricane impacts?
How can the methods and tools of social science be used to document long-term social and economic costs?
What are the costs and benefits of either shrinking the warning area or increasing lead times?
Can meaningful metrics be developed to measure the economic value of hurricane forecasts and warnings that take into account the quality of the forecast, the value of communication process variables, and the value of responsiveness?
Is it even relevant to put a value on improved forecasts separate from the entire communication and response process?
How can spatial data analysis most effectively result in a clearer understanding of hurricane impacts?
How can impact measurements take into account the relative value of losses to various segments of the affected population?

APPENDIX Q
LIST OF ACRONYMS

3D	three-dimensional
3D-VAR	Three-Dimensional Variational Data Assimilation
4DDA	Four-Dimensional Data Assimilation
4D-VAR	Four-Dimensional Variational Data Assimilation
ADCIRC	Advanced Circulation [Model]
ADOS	Autonomous Drifting Ocean Station
ADT	Advanced Dvorak Technique
AFB	Air Force Base
AFFO	Announcement of Federal Funding Opportunity
AFRC	U.S. Air Force Reserve Command
AFWA	Air Force Weather Agency
AGCM	atmospheric general circulation model
ALT	Radar Altimeter
AMOP	Administrative Model Oversight Panel
AMPR	Advanced Microwave Precipitation Radiometer
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer—Enhanced
AMSU	Advanced Microwave Sounding Unit
AOML	Atlantic Oceanographic and Meteorological Laboratory (of NOAA/OAR)
AOR	area of responsibility
APP	American Meteorological Society Policy Program
APR	Airborne Precipitation Radar
ARMR	Airborne Rain Mapping Radar
ARW	Advanced Research WRF
ASCAT	Advanced Scatterometer [MetOp-A satellite instrument]
ASOS	Automated Surface Observing Systems
ATCF	Automated Tropical Cyclone Forecasting System
ATMS	Advanced Technology Microwave Sounder
AVAPS	Airborne Vertical Atmospheric Profiling System
AVN	Aviation Model [NOAA/NCEP predecessor to GFS]
AXBT	Airborne Expendable Bathythermographs
AXCP	Airborne Expendable Current Profilers
AXCTD	Airborne Expendable Conductivity Temperature and Depth [probe]
BASC	Board on Atmospheric Sciences and Climate (of NAS/NRC)
BAT	Best Available Turbulence
BEI	Battlespace Environments Institute
BFRL	Building and Fire Research Laboratory (of NIST)

BIO	Biological Science Directorate [of NSF]
BOM	Australia Bureau of Meteorology
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection and Moisture Experiment
CARCAH	Chief, Aerial Reconnaissance Coordination, All Hurricanes
CBLAST-DRI	Coupled Boundary Layers Air-Sea Transfer Departmental Research Initiative
CD	compact disk
CENR	Committee on Environment and Natural Resources (of NSTC)
CFS	Coupled Climate Forecast System
CHAT	Caribbean Hurricane Awareness Tour
CHL	Coastal and Hydraulics Laboratory (of USACE/ERDC)
CICS	Cooperative Institute for Climate Studies [University of Maryland]
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIOSS	Cooperative Institute for Oceanographic Satellite Studies [Oregon State University]
CIRA	Cooperative Institute for Research in the Atmosphere
CLIPER	Climatology and Persistence [Model]
C-MAN	Coastal Marine Automated Network
CMA	Chinese Meteorological Administration
CMC	Canadian Meteorological Center
CMIS	Conical Microwave Imager/Sounder
CNES	Centre National d'Etudes Spatiales
CNMOC	Commander, Naval Oceanographic and Meteorological Command
COAMPS®	Coupled Ocean/Atmosphere Mesoscale Prediction System
CONDUIT	Cooperative Opportunity for NCEP Data Using IDD Technology
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CPHC	Central Pacific Hurricane Center
CrIS	Cross-track Infrared Sounder
CSU	Colorado State University
CWB	Taiwan Central Weather Bureau
DAC	Drifter Data Assembly Center [of GDP]
DMSP	Defense Meteorological Satellite Program
DOC	U.S. Department of Commerce; Drifter Operations Center [of GDP]
DOD	U.S. Department of Defense
DPR	Dual-frequency Precipitation Radar
DR	[NAS/NRC] Disasters Roundtable
DTC	Developmental Testbed Center
DVD	digital video disk
EAS	Emergency Alert System
ECMWF	European Center for Medium-Range Weather Forecasting
EDA	ensemble data assimilation
EDOP	ER-2 Doppler Radar

EIR	enhanced infrared
EMC	[NOAA/NCEP] Environmental Modeling Center
ENG	Directorate for Engineering [of NSF]
ENSO	El Nino–Southern Oscillation
EOS	Earth Observing System
ERDC	U.S. Army Engineer Research and Development Center
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESMF	Earth System Modeling Framework
ESRL	Earth System Research Laboratory
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FASTEX	Fronts and Atlantic Storm-Track Experiment
FCMSSR	Federal Committee for Meteorological Services and Supporting Research
FEMA	Federal Emergency Management Agency
FISL	fully implicit semi-Langrangian
FNMOC	Navy Fleet Numerical Meteorology and Oceanography Center
FSU	Florida State University
GDAS	[NOAA/NCEP] Global Data Assimilation System
GDP	Global Drifter Program
GEO	Geosciences Directorate [of NSF]
GEOS	Goddard Earth Observing System
GEOSS	Global Earth Observation System of Systems
GFDL	Geophysical Fluid Dynamics Laboratory [NOAA/OAR]
GFDN	Geophysical Fluid Dynamics Laboratory Hurricane Prediction System—Navy version
GFO	[NOAA] Geosat Follow-On [mission]
GFS	[NCEP] Global Forecast System
GIS	geographical information system
GMAO	Global Modeling and Assimilation Office (of NASA/GSFC)
GMI	GPM Microwave Imager
GODAE	Global Ocean Data Assimilation Experiment
GODAS	Global Ocean Data Assimilation System
GOES	Geostationary Operational Environmental Satellite
GOOS	[NOAA] Global Ocean Observing System
GOOS	[NOAA] Global Ocean Observing System
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRADAS	Global and Regional Advanced Data Assimilation System
GSFC	NASA Goddard Space Flight Center
GSI	[NCEP] Gridpoint Statistical Interpolation [System]
HAMSR	High Altitude MMIC Sounding Radiometer

HAT	Hurricane Awareness Tour
HFSEWG	Hurricane Forecast Social and Economic Working Group
HHS	U.S. Department of Health and Human Services
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
HIRS	High Resolution Infrared Radiation Sounder
HIRWG	Hurricane Intensity Research Working Group [of NOAA/SAB]
HLT	Hurricane Liaison Team
HPC	Hydrological Prediction Center (of NOAA/NCEP); High Performance Computing [DOD]
HPCMP	High Performance Computing Modernization Program [DOD]
HRD	Hurricane Research Division (of NOAA/OAR/AOML)
HSAI	HPC [High Performance Computing] Software Applications Institute [institutes are sponsored by HPCMP]
HSE	[NSF] Task Force on Hurricane Science and Engineering
HUD	U.S. Department of Housing and Urban Development
HWRF	Hurricane Weather Research and Forecast [model] (see WRF)
HYCOM	Hybrid-Coordinate Ocean Model [NCEP]
IASI	Infrared Atmospheric Sounding Interferometer
ICMSSR	Interdepartmental Committee for Meteorological Services and Supporting Research
ICON	intensity consensus model
IDEA	Integrated Dynamics through Earth's Atmosphere (joint NASA-NOAA initiative)
IEOS	Integrated Earth Observation System
IFEX	Intensity Forecasting Experiment
IHC	Interdepartmental Hurricane Conference
IPO	Integrated Program Office
IR	infrared
ISRO	Indian Space Research Organization
IT	information technology
IWGEO	Interagency Working Group on Earth Observations [replaced by US GEO]
IWRAP	Imaging Wind and Rain Profiling System
JAAWIN	Joint Air Force and Army Weather Information Network
JAG/TCR	Joint Action Group for Tropical Cyclone Research
JAXA	Japanese Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JHT	Joint Hurricane Testbed
JMA	Japan Meteorological Agency
JPL	Jet Propulsion Laboratory
JTWC	Joint Typhoon Warning Center
KMA	Korean Meteorological Administration
kt	knot(s)
LSM	land surface model

MAP	Modeling, Analysis, and Prediction [Program]
MERRA	Modern Era Retrospective analysis for Research and Applications
MHS	Microwave Humidity Sounder
MJO	Madden-Julian Oscillation
MM5	Fifth-Generation Mesoscale Model
MMIC	monolithic microwave integrated circuit
MODIS	Moderate Resolution Imaging Spectroradiometer
MPAR	multifunction phased array radar
MRF	Medium Range Forecast model [NOAA/NCEP predecessor to GFS]
MTSAT	Multifunctional Transport Satellite (Japanese geostationary satellite)
MURI	Multidisciplinary Research Program of the University Research Initiative
MVOI	multivariate optimum interpolation
MWW3	Multi-grid WAVEWATCH III [ocean wave model]
NAE	National Academy of Engineering
NAMMA	NASA African Monsoon Multidisciplinary Activities
NARAC	National Atmospheric Release Advisory Center
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NAVDAS	NRL Atmospheric Variational Data Assimilation System
NAVDAS-AR	NAVDAS Accelerated Representer
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NCOM	NRL Coastal Ocean Model
NDBC	National Data Buoy Center
NESDIS	[NOAA} National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Center
NHOP	National Hurricane Operations Plan
NHP	National Hurricane Program (of FEMA)
NIST	National Institute of Standards and Technology
NLDAS	North American Land Data Assimilation System
NLETS	National Law Enforcement Telecommunications System
nmi	nautical mile(s)
NMM	Nonhydrostatic Mesoscale Model
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NOPP	National Ocean Partnership Program
NOS	[NOAA] National Ocean Service
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NRL	Naval Research Laboratory
NRL-Monterey	Marine Meteorology Division [of NRL Ocean and Atmospheric Science and Technology Directorate]

NSB	National Science Board (of NSF)
NSF	National Science Foundation
NSSL	[NOAA] National Severe Storm Laboratory
NSTC	National Science and Technology Council
NWP	Numeric Weather Prediction
NWR	NOAA Weather Radio
NWS	National Weather Service
OAR	[NOAA] Office of Oceanic and Atmospheric Research
OBS	Ocean Battlespace Sensing S&T [ONR department]
ODAS	ocean data assimilation system
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
OHC	ocean heat content
OML	oceanic mixed layer
OMPS	Ozone Mapping and Profiler Suite
ONR	Office of Naval Research
OPC	Ocean Prediction Center [of NOAA/NCEP]
OSSE	observing system simulation experiment
OSTP	Office of Science and Technology Policy
OSU	Oregon State University
OSVW	ocean surface vector winds
PBL	planetary boundary layer
PDA	personal digital assistant
PDT	Prospectus Development Team [for USWRP]
POM	Princeton Ocean Model
QPF	quantitative precipitation forecasting
QuikSCAT	Quick Scatterometer
R&D	research and development
RAINEX	Rainband and Intensity Change Experiment
R-CLIPER	Rainfall Climatology and Persistence model
recco	reconnaissance code
RSM	Regional Spectral Model
RSMC	Regional Specialized Meteorological Center
RTOFS	Real Time Ocean Forecast System
RTP	Rapid Transition Project [in U.S. Navy/ONR R&D process]
S&T	Science and Technology
SAB	[NOAA] Science Advisory Board
SATCOM	satellite communications
SATCON	satellite consensus
SBIR	Small Business Innovative Research

SDBE	situation-dependent background errors
SDR	Subcommittee on Disaster Reduction [of NSTC/CENR]
SFMR	Stepped-Frequency Microwave Radiometer
SHIFOR	Statistical Hurricane Intensity Forecast [Model]
SHIPS	Statistical Hurricane Intensity Prediction Scheme
S/I	seasonal to interannual
SISL	semi-implicit semi-Lagrangian
SLOSH	Sea, Lake, and Overland Surge [Model]
SPC	Storm Prediction Center (of NOAA/NCEP)
SRA	Scanning Radar Altimeter
SREF	Short-Range Ensemble Forecast
SSI	spectral statistical interpolation
SSM/I	Special Sensor Microwave Imager
SSMI/S	Special Sensor Microwave Imager/Sounder
SST	sea surface temperature
STAR	Center for Satellite Applications and Research (of NOAA/NESDIS)
STI	Shanghai Typhoon Institute
STIP	Science and Technology Infusion Plan (NOAA)
STIPS	Statistical Typhoon Intensity Prediction Scheme
STTR	Small Business Technology Transfer
STWAVE	Steady State Spectral Wave
SWAN	Simulating Waves Nearshore
SWMF	Space Weather Modeling Framework
TAFB	Tropical Analysis and Forecast Branch (of NOAA/NCEP/TPC)
TCHP	tropical cyclone heat potential
TCSP	Tropical Cloud Systems and Processes
THORPEX	a component program of the WMO World Weather Research Programme
TMI	Tropical Microwave Imager
TPC	Tropical Prediction Center (of NOAA/NCEP)
TRaP	Tropical Rainfall Potential [method for estimating rainfall]
TRMM	Tropical Rainfall Measuring Mission
TSB	Tropical Support Branch (of NOAA/NCEP/TPC)
TUTT	Tropical Upper Tropospheric Trough
UAS	unmanned aircraft system
UCAR	University Corporation for Atmospheric Research
UKMO	United Kingdom Meteorological Office; also the UKMO global model
US GEO	United States Group on Earth Observations [of CENR, replaces IWGEO]
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USWRP	U.S. Weather Research Program
UW	University of Wisconsin
UW-CIMSS	Unversity of Wisconsin Cooperative Institute for Meteorological Satellite Studies

VIIRS	Visible/Infrared Imager Radiometer Suite
VOS	Voluntary Observing Ship [program]
WCR	warm core ring
WFO	National Weather Service Forecast Office
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting [modeling initiative]
WRF-ARW	Advanced Research WRF
WSUAV	Weather Scout Unmanned Aerial Vehicle
XBT	Expendable Bathythermograph
YIP	Young Investigator Program
YSU	Yonsei University