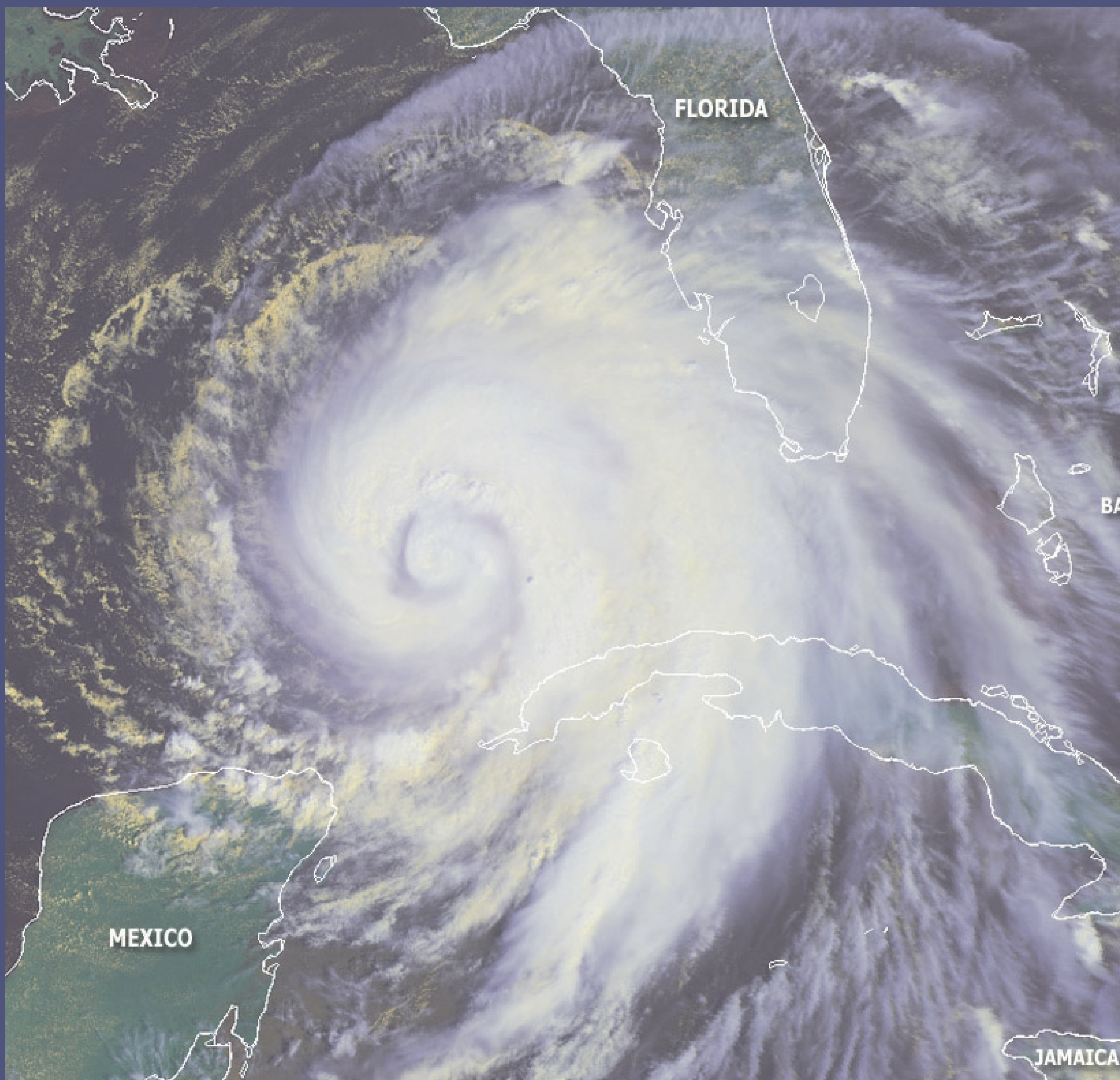
63rd Interdepartmental Hurricane Conference



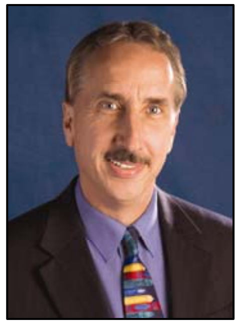
Tropical Cyclone Research: Identifying Gaps and Focusing Research on Operational Needs

Ultimate Goal: Improved Services to Prevent Loss of Life and Injuries and to Reduce the Nation's Vulnerability to these Devastating Storms

March 2-5, 2009
St. Petersburg, FL

CITY OF ST. PETERSBURG
Office of the Mayor

Rick Baker, Mayor



Welcome to the 63rd Interdepartmental Hurricane Conference!

I would like to welcome each of you attending the 63rd Interdepartmental Hurricane Conference in our great city of St. Petersburg. We are pleased that you have come to our community to hold these important meetings!

While you are here, please take time to enjoy our downtown area and The Pier, Baywalk, the Salvador Dali museum and the wide variety of restaurants and nightlife all within walking distance of your hotel. We invite you to stroll around downtown and admire some of Florida's best Mediterranean-Revival style architecture and two dozen properties recorded in the National Historic Register. From our white sandy beaches, to our parks, to the smiling faces greeting you across our city, we hope you relish your days on the bay this week.

The citizens of St. Petersburg recognize the important work you do for our city and the country and we appreciate the unique contributions you make to our safety, security and preparedness. Thank you for coming to St. Petersburg and we send our best wishes for a successful conference. Please visit us again soon.

Sincerely,

Rick Baker
Mayor

CITY OF ST. PETERSBURG, P.O. BOX 2842, ST. PETERSBURG, FLORIDA 33731, PHONE (727) 893-7201

UNITED STATES DEPARTMENT OF COMMERCE
The Deputy Under Secretary for
Oceans and Atmosphere
Washington, D.C. 20230

March 2, 2009

Dear Colleagues:

Welcome to the 63rd Interdepartmental Hurricane Conference (IHC) and to the great city of St. Petersburg, Florida! Thank you for your efforts to improve our Nation's hurricane forecasting and warning program—the ultimate goal of the IHC. This goal is only reached through the collaborative and collective input from our interagency partners in the meteorology and oceanography operations and research community and the emergency management community.

I wish you a highly productive and rewarding conference and I appreciate your efforts and support.

Sincerely,

Mary M. Glackin

OFCM

OFFICE OF THE FEDERAL COORDINATOR
FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

SUITE 1500, 8455 COLESVILLE ROAD
SILVER SPRING, MARYLAND 20910

March 2, 2009

Dear Colleagues,

Welcome to the 63rd Interdepartmental Hurricane Conference! We are looking forward to a very informative and productive conference.

Last year's conference focused on developing a baseline of research activities to track against the research needs outlined in the OFCM plan, "Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead," and to begin building an implementation strategy. The conference also explored processes to build strong local partnerships for a more effective warning system. This year's conference focuses on strategic partnership alliances and linking research to operational needs, with the aim of accelerating improvements in hurricane forecasts, warnings, and services. Our ultimate goal is to improve services to prevent loss of life and injuries and to reduce the nation's vulnerability to these devastating storms.

In addition to our focus on partnership alliances, other topics at this year's conference include:

- The 2008 Tropical Cyclone Season in Review
- Identifying Tropical Cyclone Research Needs, Progress, and Gaps
- Observations and Observing Strategies for Tropical Cyclones and their Environment
- Tropical Cyclone Model Development and Technology Transfer
- Research to Improve Prediction of Intensity, Structure, Track, Precipitation, and Coastal and Inland Inundation
- The Joint Hurricane Testbed: Project Updates and Plans for the Future
- Products, Services, and Lessons Learned from the 2008 Season

Thank you for joining us this week in St. Petersburg to prepare for the coming hurricane season, to exchange ideas and plans, and to renew our commitment to improving the hurricane forecasting and warning system. I hope you enjoy the conference and our great host city!

Sincere regards,

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

Session 1
The 2008 Tropical Cyclone Season in Review

SESSION 1

A Year of Destructive Landfalls:
Overview of the 2008 Atlantic Hurricane Season

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NOAA/NWS Tropical Prediction Center/National Hurricane Center

The 2008 Atlantic hurricane season continued the period of above normal activity that started in 1995. Sixteen tropical storms and one tropical depression formed. Eight of the storms became hurricanes and five became major hurricanes (category 3 or higher on the Saffir-Simpson hurricane scale). Four hurricanes (Gustav, Ike, Omar, and Paloma) reached category 4 strength.

Six named storms made landfall in the United States, including three hurricanes. These storms resulted in an estimated $24 billion in property damages. Elsewhere, the Caribbean islands of Hispaniola and Cuba were affected by a series of cyclones that caused widespread devastation and loss of life. The overall death toll from the 2008 Atlantic tropical cyclones is over 700.

Overview of the 2008 Eastern North Pacific Hurricane Season

Richard J. Pasch and Eric S. Blake
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NOAA/NWS Tropical Prediction Center/National Hurricane Center

Tropical cyclone activity during the 2008 eastern North Pacific season was below average. There were sixteen tropical storms of which seven became hurricanes. Two of the hurricanes became major hurricanes. Although the number of tropical storms was near average, the numbers of hurricanes and major hurricanes were below average. There were several weak and short-lived storms, and the Accumulated Cyclone Energy index for 2008 was about 75% of the long-term median value. Among the highlights of the year were Hurricane Norbert, the strongest storm on record to strike the western Baja California peninsula, and Tropical Storm Alma, which was the only tropical storm of record to make landfall along the Pacific coast of Nicaragua.

2008 Atlantic and Eastern North Pacific Forecast Verification

James L. Franklin
NOAA/NWS/National Hurricane Center

Some highlights from a preliminary verification of official track and intensity forecasts from the National Hurricane Center during the 2008 season are given below. The performance of the guidance models is also discussed. As of this writing final numbers are not yet available, but will be presented at the conference.

For the Atlantic basin, official track errors set records for accuracy at all time periods. Forecast errors continue their downward trends, while skill was also up in 2008. The official track forecast skill was very close to that of the consensus models, but was beaten by EMXI. EMXI and GFDI provided best dynamical track guidance. The UKMET, which performed well in 2007, did not do so in 2008. The performance of NOGAPS lagged again. The HWRF has not quite attained the skill of the GFDL, but is competitive, and a combination of the two is better than either alone. The best consensus model was TVCN (a variable consensus that includes EMXI). It was not a good year for the corrected consensus models.

Official intensity errors for the Atlantic basin in 2008 were below the previous 5-yr means, but the 2008 Decay-SHIFOR errors were also lower than its 5-yr mean, so there was no real change in skill. Official intensity errors have remained essentially unchanged over the last 20 years, while skill has been relatively flat over the past 5-6 years. The best model at nearly every time period was statistical, although GHMI did well at 4 and 5 days. ICON, a simple four-model consensus (DSHP/LGEM/HWRF/GHMI) beat everything else, including the corrected consensus model FSSE.

In the eastern North Pacific, the official track forecast errors set records at 24-72 h. The official forecast beat the individual dynamical models, and also beat the consensus at 4 and 5 days. Among the guidance models, the GFDL, HWRF, and ECMWF were strong performers, although the ECMWF had trouble holding on to systems through 5 days. The benefit of a dynamical model consensus is larger in the eastern North Pacific than it is in the Atlantic; this is suggestive of different error mechanisms in the two basins.

For intensity, the official forecast mostly beat the individual models and even the consensus at 12 and 36 h. Official wind biases turned sharply negative at 96-120 h, which was also true in 2007. The best model at most time periods was statistical, and DSHP provided the most skillful guidance overall. The HWRF continued to have trouble in this basin, while the four-model intensity consensus ICON performed very well.

Central Pacific 2008 Hurricane Season Summary

James Weyman
Director, Central Pacific Hurricane Center

There was little tropical cyclone activity in the Central Pacific during the 2008 tropical cyclone season. The first and only tropical cyclone in Central Pacific Basin for 2008 was Kika which peaked at minimal tropical storm strength. There were no impacts to Hawaiian Islands or other Pacific Islands from Kika. The presentation will show possible reasons for this low activity and will also list some of the changes at CPHC which have occurred in 2008 or scheduled for 2009.

A Review of the Joint Typhoon Warning Center
2008 Tropical Cyclone Season

Mr. Robert J. Falvey
(robert.falvey@navy.mil)

Joint Typhoon Warning Center

A review of the 2008 tropical cyclone activity with discussion of significant events for the JTWC Pacific and Indian Ocean forecast areas of responsibility will be presented.

53d Weather Reconnaissance Review of the 2008 Hurricane Season

LTC Richard M. Harter
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53d Weather Reconnaissance Squadron

The 2008 hurricane season was an above average year for the 53d Weather Reconnaissance Squadron with 1150 flying hours (compared to 1062 average flying hours per season over the last 10 years). Overall, the Stepped Frequency Microwave Radiometer performed reasonably well on ten WC-130J aircraft, providing critical surface wind speed and rainfall rate data to the customer. The squadron returned to Guam for the first time since 2003 to participate in the Tropical Cyclone Structure Experiment. The squadron flew 31 missions (263 operational flying hours) and launched 750 dropsondes, 250 AXBTs, and 24 buoys in support of the project.

NOAA Aircraft Operations Center (AOC)
2008 Seasonal Summary and Future Plans

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NOAA Aircraft Operations Center

After a relatively slow season in 2007 and with the seasonal forecast calling for above average storm activity in 2008, AOC was ready with its two WP-3Ds and G-IVSP aircraft to perform often and long during the summer months. In 2007, the NOAA aircraft flew a combined total of only 45 flights for 272.7 hours – slightly more than were flown in 2006.

The 2008 season turned out to be much busier but still below the 2005 mark. The G-IV flew 24 flights related to its surveillance missions and two research flights in support of the HRD rapid intensification experiment on Hurricane Paloma. Total time for this aircraft in the 2008 season was 192.1 hrs.

The two NOAA P-3s had a little better time of it flying 64 flights for 422.1 hours in support of the 3-Dimensional Tail Doppler Radar effort organized and directed jointly by HRD and NOAA's Environmental Modeling Center, rapid intensification research into Hurricane Paloma for HRD, the NESDIS Ocean Winds experiment and Ocean Heat Content studies in the Gulf of Mexico flown under the direction of scientists from the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences. These missions were flown out of MacDill AFB in Florida as well as Barbados into Dolly, AL92, Fay, Gustav, Hanna, Ike, Kyle and Paloma

The NOAA Citation jet and Gulfstream jet prop aircraft also participated in the 2008 hurricane season effort flying 25 damage assessment digital photography flights for 75.2 hours following the landfall of Hurricane Ike in Texas.

The total for all NOAA aircraft for the 2008 season was 115 flights and 689.4 hrs.

AOC continues to upgrade its aircraft and instrumentation, and in 2009 expects to accomplish the following:

- Complete Depot Level Maintenance on one of our WP-3Ds, N42RF
- Complete the installation of the tail Doppler radar on the NOAA G-IV
- Begin testing the new G-IV TDR in storm environment
- Accept delivery of and begin instrument installations on N44RF, NOAA's 3rd P-3
- Complete Hi-Speed Satellite communications aboard the two current P-3s
- Installation of RVP-8 radar digital signal processor on at least one P-3
- Begin operation of 2nd generation AVAPS dropsonde system
- Begin integration of new aircraft data system (AAMPS)

Session 3
Observations and Observing Strategies for Tropical Cyclones and their Environment, Part 1

SESSION 3

Examination of the Tropical Cyclone Environment through Comparison of COSMIC with Other Satellite Data

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Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS

Recent work has identified casual relationships between tropical cyclone activity and the influence of Saharan Air Layers (SALs). Dunion and Velden (2004) devised a method for detecting SALs through geostationary satellite imagery and discussed the negative influence of SAL interaction on individual and seasonal cyclone activity. Evan et al. (2006) constructed a long-term climatology of dust prevalence over the tropical Atlantic Ocean from AVHRR imagery and showed a correspondence of more dust advected from the Saharan Desert with diminished Atlantic tropical cyclone activity.

This study explores the utility of data from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) in detecting anomalies of moisture near tropical cyclones. An indirect, yet highly accurate measure of moisture is obtained through a measure of the refractivity of Earth-occulting GPS signals traversing the atmosphere and intercepted by the COSMIC satellites (Anthes et al. 2008). This technique is effective for detecting vertical layers of anomalous moisture, as are found with SALs. COSMIC refractivity data can be analyzed in conjunction with aerosol subtype data from NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite to identify the dry air and desert dust components, respectively, of SAL regions. Atlantic tropical cyclones observed in 2006, 2007, and 2008 are analyzed with COSMIC and CALIPSO.

Since COSMIC profiles can sample the atmosphere both in the vertical and horizontal directions, the data can be used to observe the internal thermodynamic structure of a hurricane or typhoon. A COSMIC profile was found to transect the inner core of Supertyphoon Sepat 2007. Microwave imagery from AMSU-B, SSM/I, and TMI sensors, transmitted between 2 and 4 hours after the COSMIC profile, revealed the development of two concentric eyewalls. When compared against a baseline COSMIC profile located approximately 800 km east of the storm's center, the transecting COSMIC profile reveals the high moisture regions of the eyewalls with a significant positive difference of measured refractivity, and similarly reveals the relatively dry outer eye region with a near-zero difference of refractivity. This analytical method is applied to other tropical cyclones at various intensity stages. Other examples of additional cyclone-transecting COSMIC profiles, and identifiable cyclone features, will be presented and analyzed.
This study also adopts the methodologies of Dunion and Velden (2004) and Evan et al. (2006) in constructing a summertime climatology of SAL prevalence over the tropical Atlantic Ocean using the SAL-detecting bands of the GOES-8 and the METEOSAT-8 satellites. The influence of SAL regions, as detected through the geostationary imagery, is investigated for recent cyclones and on a seasonal basis. COSMIC, CALIPSO, and geostationary satellite data depictions of SAL are cross-validated where possible.

Ken Knapp of the NOAA National Climatic Data Center is acknowledged for providing the GOES and METEOSAT imagery. Funding for this study has been provided by NOAA.

The Hurricane Satellite (HURSAT) Dataset

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NOAA/NCDC

Historical satellite data of hurricanes are a valuable asset for understanding hurricane structure. However, few resources provide satellite observations for tropical cyclones. For example, the Navy Research Laboratory (http://www.nrlmry.navy.mil/tc_pages/tc_home.html) maintains a thorough catalog of tropical cyclone imagery since 1998. However, this data cannot be used for quantitative analysis given it is stored simply as image files. The Hurricane Satellite (HURSAT) dataset developed at NCDC provides satellite observations from a variety of satellites remapped and reformatted for portability: http://www.ncdc.noaa.gov/oa/rsad/hursat/

Remapping – Brightness temperatures are remapped from the original satellite swath projection to an equal-angle projection based on the resolution of the satellite data. A grid is selected centered on the tropical cyclone position at the time of the satellite scan (interpolated from 6-hourly best track position) generally with a size of 21º latitude and 21º longitude (approximately 1100 km from the center of the storm).

Satellites – HURSAT data presently use data from the AVHRR, SSMI and geostationary data worldwide (GOES, GMS, Meteosat, etc.). Future NOAA satellites may be included.

Format – All HURSAT data are provided in CF-compliant netCDF format. This maximizes portability between operating systems and viewing software. Furthermore, other formats are available if desired. HURSAT-B1 data are used to produce movie loops (MPEG) of the lifetime of all tropical cyclones in the period of record: 1978-2007. HURSAT-MW was processed to create imagery of tropical cyclones using SSMI derived parameters: column water vapor, cloud liquid water, rain rate and surface wind speed. HURSAT AVHRR has been processed to provide Objective Dvorak imagery. Plans for HURSAT also include processing all data into Google Earth-compatible imagery using the KML standard.

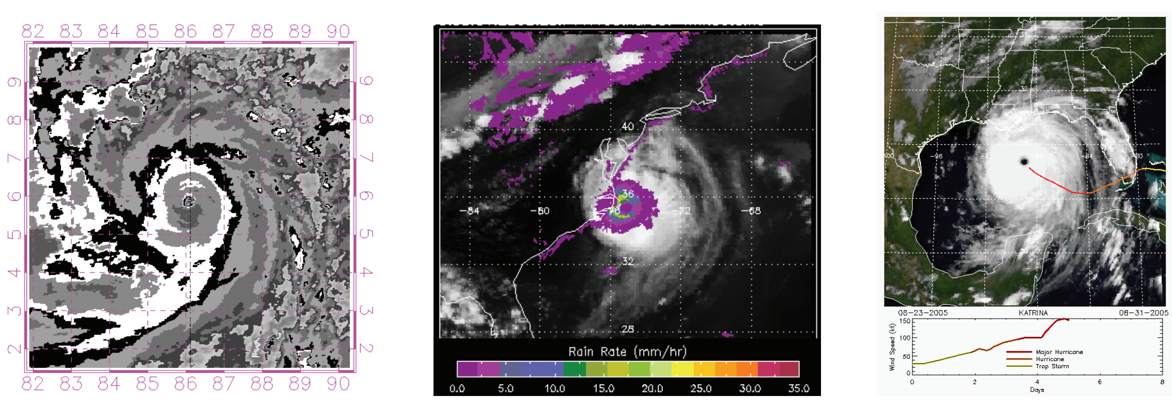

Figure – Samples of HURSAT imagery: left) AVHRR BD image of an Indian Ocean tropical cyclone in 1979, middle) SSMI-derived rain rate from 1993 Hurricane Emily, right) Excerpt image from an MPEG of 2005 Hurricane Katrina derived from HURSAT-B1.

Using Remotely-Sensed Observations to Describe and Predict Tropical Cyclone Formation

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The interpretation of a tropical cyclone's structure from satellite imagery has been a key element for structure and intensity estimation. One of the most important examples is the Dvorak technique, which was developed in the 1970s, and is still used in many tropical cyclone forecasting centers. This technique provides a source of tropical cyclone intensity estimates over the tropical oceans. The longevity of the Dvorak technique clearly speaks to the utility of satellite-based observations for tropical cyclone analysis. An aspect of tropical cyclone development that can clearly benefit from use of satellite-based observations is the genesis process. Tropical cyclones, for the most part, develop over oceans where traditional observation platforms such as rawinsonde stations cannot be located. Therefore, the best opportunity for locating and discriminating those cloud clusters that will develop into tropical cyclones from those that will not is from analysis of satellite-based observations.

This document introduces an objective technique, based on brightness temperature observations, which aims to discriminate those tropical cloud systems, which will develop into tropical cyclones from those that will not. The basis of the technique is that the convective structures embedded in cloud clusters become more axisymmetric as the wind field of the disturbance organizes and intensifies. To quantify this evolution, two tasks are required: 1) the center of the system needs to be located in an objective manner, and 2) the departure from axisymmetry of the weather system needs to be quantified. Time series of the combined results of these two tasks are used to examine the evolution of tropical disturbances.

In this presentation results from storms that developed in the Atlantic will be shown. Time series of the departure from axisymmetry are shown to discriminate between developing and non-developing cloud clusters with a high rate of success and low false alarm rate. The technique has utility as a stand-alone system to choose the cloud clusters that will go on to develop, but also has great potential to be used as the early-detection part of a larger intensity algorithm.

Moving Toward an Operational Satellite Ocean Surface Vector Winds Capability with a Dual Frequency Scatterometer

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Remotely sensed ocean surface vector wind (OSVW) measurements continue to be an important source of data for operational tropical cyclone (TC) analysis and forecasting at the National Hurricane Center (NHC) and the Central Pacific Hurricane Center (CPHC). These data are also used heavily for marine analysis and forecasting applications elsewhere within in the National Weather Service (NWS) at NCEP centers (NHC, OPC) and coastal weather forecast offices (WFOs).

Currently, OSVW data available in NWS operations are from the NASA QuikSCAT scatterometer and the Advanced Scatterometer (ASCAT) onboard EUMETSAT's METOP-A satellite. Despite the documented shortcomings of the retrievals associated with these instruments, they have had a positive impact on NWS tropical cyclone and very positive impact on marine forecast and warning operations. However, QuikSCAT is well beyond its planned mission life, and ASCAT wind retrievals are inferior to those from QuikSCAT in terms of coverage and performance at high wind speeds. To move toward an operational satellite OSVW capability that will meet NOAA's operational needs, NOAA and NASA JPL are exploring a partnership with the Japanese Space Agency (JAXA) to fly a Dual Frequency Scatterometer (DFS) onboard the second mission in the JAXA GCOM-Water cycle (GCOM-W) series, currently scheduled to launch in 2016. With this launch date, funding must begin in FY2011 to meet JAXA-imposed deadlines for instrument delivery.

This partnership offers the opportunity for international collaboration to significantly limit mission while substantially improving the quality of satellite OSVW retrievals available for NWS tropical cyclone and marine operational warning and forecast applications. While DFS would not achieve all of the proposed capabilities of the Extended Ocean Vector Winds Mission (XOWVM), DFS would utilize C-band and Ku-band retrievals to mitigate rain contamination, which would greatly improve the quality of wind retrievals in the TC environment. DFS would also offer increased spatial resolution compared to QuikSCAT and provide similar spatial coverage.

The design of DFS will be discussed, along with the potential benefits of partnership with JAXA. Simulated retrievals from DFS in the TC environment will be presented. The quality of the DFS retrievals will be compared and contrasted with simulated retrievals from QuikSCAT and XOVWM for TC center fixing/identification, intensity (maximum wind) analysis, and the analysis of the outer TC wind field (wind radii). Preliminary results suggest that DFS retrievals in the TC environment provide a much more accurate representation of the wind field relative to QuikSCAT. Finally, a path forward will be outlined to work toward establishing an operational satellite OSVW capability for NWS operations.

Developing GOES-R Tropical Cyclone Products via Proxies

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The next generation GOES satellites (beginning with GOES-R) will include the Advanced Baseline Imager (ABI) with vastly improved spectral, spatial and temporal resolution relative to the current GOES I-M series satellites. It will also include the Geostationary Lightning Mapper (GLM) which, together with the ABI, offers the potential to significantly improve the analysis and forecasts of tropical weather phenomenon. One of the distinct advantages of GOES-R is the high temporal resolution that is possible from geostationary orbit. Such capabilities are ideal for studying/analyzing tropical weather phenomenon, which often evolve quickly and are poorly sampled by both conventional observations and low-earth orbiting satellites.

This presentation will provide a brief summary of the GOES-R capabilities and describe CIRA research to develop tropical cyclone analysis and forecast applications using proxy data. Imagery from the SEVERI instrument on the Meteosat Second Generation (MSG) satellite series is used as proxy for the ABI and data from the ground-based World Wide Lightning Locator Network (WWLLN) is a proxy for the GLM. Algorithms have been developed to simulate many of the ABI channels from combinations of SEVERI imagery. The simulated ABI data will be used to demonstrate a number of new products for analysis of the storm structure and storm environment.

Although the WWLLN data only detects the very high current cloud to ground lightning strikes, it can still capture the basic lightning patterns in tropical cyclones and their environments. The lightning density (strikes per unit area and time) was calculated for all Atlantic tropical cyclones from 2005-2008 in a storm-relative cylindrical coordinate system. The WWLLN lightning density is calibrated by comparison with the annual climatology from the OTD/LIS instruments on low-earth orbit satellites. This calibration helps to correct for variations of WWLLN network between 2005 and 2008, and accounts for its low detection rate. Results show that the lightning density has potential to improve statistical tropical cyclone intensity prediction, and is a good discriminator of rapid intensity change, provided that the vertical wind shear is accounted for. The relationship between lightning density and intensity change and rapid intensification are much stronger in low wind shear regimes.

Measuring the Three-Dimensional Structure of Hurricanes with a Microwave Sounder

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Jet Propulsion Laboratory, California Institute of Technology

Analysis of data from hurricane aircraft experiments has shown that there is a very high correlation between microwave sounder observations and radar observations of convective systems. The correlation is so strong that it is possible to develop a model function that can be used to transform the radiometric brightness temperatures into vertical profiles of equivalent radar reflectivity. This new method makes it possible to use current and future satellite sounders to generate proxy precipitation and cloud radar data. This in turn will enable a wide range of analyses of convective systems and processes using algorithms and methodologies developed for the radar systems.

We show some preliminary results from the joint NASA-NOAA Tropical Cloud Systems and Processes (TCSP) field campaign in 2005. In that experiment NASA deployed a suite of remote sensing instruments on the high-altitude ER-2 aircraft that included a precipitation radar system and a microwave sounder. The sounder, the High Altitude MMIC Sounding Radiometer (HAMSR), was developed at the Jet Propulsion Laboratory under the NASA Instrument Incubator Program with new technology and is functionally similar to the Advanced Microwave Sounding Unit (AMSU) that is now operating on several NOAA weather satellites. Comparisons of HAMSR observations with those from the ER-2 Doppler Radar (EDOP) shows that height resolved EDOP-equivalent radar reflectivity can be derived from the HAMSR brightness temperatures with good accuracy, although at lower vertical resolution than is possible with the radar. In addition, since HAMSR is a cross-track scanning sensor (like AMSU), reflectivity can be estimated for the entire 3D volume of the atmosphere observed by HAMSR – unlike EDOP, which is a nadir-only sensor. With this new method HAMSR can be used to map out the convective structure of tropical convection from the surface to 15 km with a vertical resolution of roughly 1-2 km.

Efforts to extend this method to the AMSU satellite instruments are under way, and preliminary results are very promising. This will open up a new avenue for hurricane analysis. In particular, it will be possible to get a picture of the internal structure of hurricanes as the sensors pass overhead. Even though the spatial resolution of the satellite sensors is relatively poor, 15-50 km, the additional information – which is otherwise only available from a very few radar systems – is expected to be of high value for nowcasting and forecasting as well as retrospective analysis. This approach will be of particular interest when applied to a geostationary microwave sounder, with its ability to monitor hurricanes continuously throughout their life cycles. Such a system is now under development in response to the National Academy of Sciences' recommendation, in its recent "decadal survey" of earth satellite missions, to develop the Precipitation and All-weather Temperature and Humidity (PATH) mission. Key technology required for such a sensor has been developed at the Jet Propulsion Laboratory, and the "Geostationary Synthetic Thinned Aperture Radiometer" (GeoSTAR) is ready for implementation. A possible joint NASA-NOAA mission, perhaps flying GeoSTAR as a demonstration payload on one of the new GOES-R/S/T satellites, is being explored.

Arc Clouds in the Tropical Cyclone Environment

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Arc clouds are common features in mid-latitude thunderstorms and MCSs. They denote the presence of a density current that forms when dry middle level (~600-800 hPa) air has interacted with precipitation. The convectively-driven downdrafts that result reach the surface/near-surface and spread out from the convective core of the thunderstorm. We hypothesize that the mid-level moisture found in the *moist tropical* North Atlantic sounding described by Dunion (2009) is insufficiently dry to generate extensive arc clouds around an African easterly wave (AEW) or tropical cyclone (TC). However, substantial (100s of km in length and lasting for several hours) arc clouds consistently form in the tropics in the periphery of these tropical disturbances. Dunion (2008) did described two addition types of air masses that are frequently found in the tropical North Atlantic and Caribbean that could effectively initiate the formation of large arc clouds: the *Saharan Air Layer* and *mid-latitude dry air intrusions*. Both of these air masses were found to contain substantially dry air (~50% less moisture than the *moist tropical* sounding) in the middle levels of the atmosphere and can affect the tropical North Atlantic and Caribbean throughout the summer months. We hypothesize that these arc cloud features can significantly impact an AEW or TC (particularly smaller, less developed systems) via two mechanisms: 1) as the arc clouds race away from the convective core region, they create low-level outflow in the quadrant/semicircle of the AEW or TC in which they form. This outflow pattern counters the typical low-level inflow that is vital for TC formation and maintenance and 2) arc clouds are formed when cool, dry air generated by convectively-driven downdrafts rapidly sinks to the surface/near-surface and races away from the AEW/TC's convective region. This combination of downdrafts and cool, dry air help stabilize the middle to lower troposphere and may even act to stabilize the boundary layer. Examples of arc cloud events around several tropical cyclones will be discussed and GPS dropsonde observations from a few of these events will be shown.

Session 4
Observations and Observing Strategies for Tropical Cyclones and their Environment, Part 2

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A New Approach for Continuous Mapping of Tropical Cyclone ABL Winds to the Surface from Research and Reconnaissance Aircraft

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Accurate knowledge of the lower atmospheric boundary layer (ABL) winds is a crucial component in providing accurate intensity forecasts of tropical cyclones and improving our understanding of these severe weather systems. Airborne Doppler radars have been used to measure the ABL winds by obtaining multi-look Doppler profile observations of precipitation within these storms. Using precipitation as a tracer of the winds, and applying velocity-azimuth-display (VAD) retrieval techniques to the mean Doppler measurements, the vertical profile of the horizontal ABL winds can be retrieved. However, as the radar views the volume backscatter in the marine layer and lower atmospheric boundary layer, the Doppler measurements are contaminated by ocean surface backscatter because of the finite antenna beamwidth. Depending on the radar's measurement geometry and aircraft altitude, this contamination can begin to occur at altitudes from 200 m to 1000 m and continue all the way down to the surface. The net result is that the mean Doppler estimates have a significant bias which voids the ABL wind retrievals at these lower altitudes.

Remote Sensing Solutions (RSS), NOAA / NESDIS / STAR and the University of Massachusetts (UMass) have obtained an extensive set of multi-look, dual wavelength Doppler measurements of the atmospheric boundary layer (ABL) within the precipitation bands of tropical cyclones. RSS has developed a new retrieval process that separates the volume and surface backscatter contributions and allows the ABL winds to be fully profiled to the surface. Further, it overcomes limitations associated with ocean vector wind scatterometry, permitting the ocean vector winds to be accurately mapped in the presence of precipitation. This new technique has been applied to measurements obtained by the Imaging Wind and Rain Airborne Profiler (IWRAP). This instrument has been renamed to the Advanced Wind and Rain Airborne Profiler (AWRAP) as a result. Note its sensitivity has also been improved by approximately 15 dB. The measurements demonstrating contamination free ABL wind profiles collected to the surface will be presented along with a discussion of the steps we are taking to realize this approach operationally. In the future, this new technique will enable the NOAA WP-3D aircraft, and potentially the Air Force aircraft, to provide continuous high resolution (30 m vertical and less than 500 m along / cross track) mapping of the ABL wind field to the surface as these aircraft transect tropical storms and cyclones.

Status of the HIWRAP and URAD Conical Scan Radars for Wind Measurements

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Wind measurements are crucial for understanding and forecasting tropical storms since they are closely tied to the overall dynamics of the storm. The High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is a dual-frequency (Ka- and Ku-band), dual-beam (30^0 and 40^0 incidence angle), conical scan, solid-state transmitter-based system, designed for operation on the high-altitude (20 km) Global Hawk UAV. With the inclusion of Ka-band, HIWRAP will be able to image the winds through volume backscattering from clouds and precipitation, enabling it to measure the tropospheric winds above heavy rain at high levels. It will also measure ocean surface winds through scatterometry, similar to QuikScat. These measurements from higher altitudes above storms, will be useful for providing higher spatial and temporal resolution than obtained by current satellites and lower-altitude instrumented aircraft. HIWRAP is currently in the final stages of development and first flights are planned later in the year on the NASA WB-57 manned aircraft (60-65kft ceiling). The UAV Radar (URAD) is an X-band conical scan radar based on a more conventional TWT (tube) design. It is single beam with 2-axis scan so the incidence angle is adjustable with a maximum value of about 40^0. It's current target is a replacement for the EDOP radar on the NASA ER-2 high-altitude aircraft, but it was designed to go in the NASA Global Hawk. The presentation will discuss the status of HIWRAP and URAD and their potential use in hurricanes research, and plans for test flights of HIWRAP on the WB-57 and Global Hawk.

Results of First Flight Tests of the Wide Swath Radar Altimeter (WSRA) During the 2008 Hurricane Season

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Through a NOAA Phase II SBIR Contract, ProSensing Inc. has developed a Wide Swath Radar Altimeter (SRA) intended for airborne measurement of directional ocean wave spectra. The WSRA is a novel solid-state digital beamforming radar, designed to replace the aging prototype Scanning Radar Altimeter (SRA) recently retired by NOAA. The new design includes a flat panel digital beamforming antenna, which allows the radar to achieve the same beamwidth as the NASA prototype 36 GHz SRA while operate at less than half the frequency. The ability to operate at 16 GHz is an important feature of the WSRA, since attenuation due to rain increases rapidly with increasing frequency. This allows the system to operate through heavy rain at higher altitudes than the retired SRA.

During August and September of 2008, the WSRA collected data on six hurricane missions aboard the NOAA AOC P-3. Table 1 shows the flight parameters for each of these missions and the data volume collected by WSRA.

Table 1 WSRA data collection record during the 2008 hurricane season

Storm Name	Takeoff Date/Time UTC	Duration (hrs)	Data Collected
Test Flight (Calm Ocean)	05AUG08 / 14:00	3	250GB
Tropical Storm Fay	18AUG08 / 00:00	8	325GB
Hurricane Gustav CAT 1	01SEP08 / 08:00	8	350GB
Hurricane Ike CAT2 and CAT3	10SEP08 / 08:00	8	425GB
	11SEP08 / 08:00	8	420GB
	12SEP08 / 08:00	8	470GB

WSRA data was collected over a wide range of ocean surface conditions, from calm seas to category 3 hurricanes. Data gathered on the first mission over a clam ocean were used to calculated antenna phase calibration coefficients. These coefficients are used to correctly focus the synthesized antenna beams when performing the digital beamforming algorithm. Preliminary results show that the WSRA has expanded the operational range of the measurement conditions over the retired SRA system. WSRA obtained usable signal from a significantly higher altitudes (12,500 feet vs 5,000 feet). Also, the WSRA signal was not significantly attenuated even under high rain rate conditions often found in hurricanes. Qualitative assessment of ocean wave spectra computed from WSRA data showed reasonable values for significant wave height and wave direction.

Operational Use of Near-Real-Time Sea Surface Directional Wave Spectra from NOAA Wide Swath Radar Altimeter (WSRA) Range Measurements

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The Wide Swath Radar Altimeter (WSRA) was built by ProSensing under the NOAA SBIR program to be an operational replacement for the NASA Scanning Radar Altimeter (SRA). It had its initial test flight on N43RF on August 5, 2008, and subsequently collected data in T.S. Fay on August 18, Hurricane Gustav on September 1, and Hurricane Ike on September 10, 11 and 12. The WSRA is two orders of magnitude more complex than the SRA. It transmits a long, chirped pulse whose range extent at 3 km height would be 2900 m whereas the SRA pulse range extent was only 0.9 m. This allows the WSRA to have better signal level with 10 W peak power than the SRA had with 1.5 KW peak power. The SRA used a dielectric lens to form a narrow beam which was scanned mechanically by a rotating mirror. The WSRA sequentially transmits its chirped pulse on each of 62 slotted wave guide elements which produce narrow beams in the along-track direction, but fan beams in the cross-track direction. Those 62 return pulses are dechirped to provide range resolution and then combined coherently with various phase shifts to produce 80 narrow beams in the cross-track direction. Because of the WSRA complexity, ProSensing made the prudent decision to record all the raw data during the 2008 season to be able to identify and correct any unanticipated problems in the hardware. At 2,400 m altitude the WSRA recorded 1 Giga Byte of raw data every 30 s, limiting data acquisition to about 3.5 hours per flight. A hardware problem was discovered which caused either the radar range measurements or the beam angles to deviate from their nominal values and produce a mean curvature in the cross-track variation of the sea surface. When ad hoc corrections were made to the WSRA nominal range quantization, excellent sea surface topography was produced whose wave height and directional wave spectrum were in good agreement with Buoy 42001. The hardware problem should be resolved soon so that all data from the 2008 season can be processed in a routine fashion to confirm the system performance and eliminate the need to record raw data during the 2009 season, enabling wave topography and directional wave spectra to be produced during the flights.

Transmission of Airborne Doppler Data and Analyses to the Ground from the NOAA WP-3D Aircraft During the 2008 Hurricane Season: Quality Control, Analysis and Superobs.

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For the high-resolution three-dimensional wind observations collected by the NOAA WP-3D aircraft (and soon the NOAA Gulfstream IV aircraft) to be useful for operations, they must be quality controlled and transmitted to the ground as quickly as possible during flight. Analyses of the observations may also be sent to the ground. Since the 2004 Hurricane Season, quality control and analyses of airborne Doppler have been performed on the aircraft and in 2005 the first analysis was sent to the National Hurricane Center. Since 2005 these analyses have been made available (usually in real-time) on an AOML ftp site that is polled by computers at NHC. Since that season efforts have been made to improve quality control, and to make the software more accessible to a number of scientists that fly aboard the NOAA P3s, so that the analyses and QC processing are done in real time. Possibly in 2009, airborne Doppler data will be used to initialize a real-time parallel run of HWRF, leading, eventually to the assimilation in the real-time official run of HWRF.

In 2008, a further step was made in the progress toward including data immediately into numerical simulations, as a research, high-resolution, non-operational run of WRF-ARW was run using airborne Doppler observations transmitted during the flight to the ground. The observations were first quality controlled, and then "superobbed" using software developed by Yonghui Weng and Fuqing Zhang. The observations were then transmitted via ftp AOML, where they were polled and then assimilated using Ensemble Kalman Filtering techniques, into the WRF-ARW model. Examples of the influence of the superobs in changing the initial and early structure of model runs will be shown.

We will also discuss major challenges that face us in 2009. These include the modification of the software to read new output from the Sigmet RVP-8 processor, that should be running on one P3 during the 2009 hurricane season, and the transmission of data in real time to NCEP Central Operations.

First Results from a High Altitude Stepped Frequency Microwave Radiometer

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The Stepped Frequency Microwave Radiometer (SFMR) is an instrument used to measure wind speed at the ocean surface. While installed and used operationally for several years on NOAA and Air Force 'Hurricane Hunter' reconnaissance aircraft, a high-altitude version of the SFMR was first installed on NOAA's G-IV jet aircraft in the summer of 2008. This presentation discusses that instrument, including verification of operation, calibration, and data comparison with in-situ surface measurements in a variety of wind conditions.

The SFMR derives surface wind speed by measuring the emissivity of the ocean over a range of C-Band frequencies (4.7-7.2 GHz). A special version of this unit was developed with a larger antenna so that the areal coverage from high altitude (40,000+ ft) is similar to a normal unit at half of that height. The high altitude unit was installed on the NOAA G-IV high-altitude jet aircraft in the summer of 2008 and data was collected during surveillance missions, starting with Hurricane Ike. In addition, a dedicated calibration mission was flown, using a similar methodology to NOAA P-3 SFMR calibration flights.

The presentation will briefly review basic SFMR theory and describe the G-IV installation. It will then discuss the calibration accomplished and verification of the unit's performance in comparison to dropwindsonde data and other surface wind measurements. Finally, it will highlight any remaining concerns in the instrument's performance and provide a plan for the next steps in transitioning this instrument to operational status.

Simulation of the Impact of New Aircraft- and Satellite-Based Ocean Surface Wind Measurements on Estimates of Hurricane Intensity

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The Hurricane Imaging Radiometer (HIRAD) is a new airborne microwave remote sensor currently under development to enhance real-time hurricane ocean surface wind observations. HIRAD builds on the capabilities of the Stepped Frequency Microwave Radiometer (SFMR), which now operates on NOAA WP-3D, G-IV, and AFRC WC-130J aircraft. Unlike the SFMR, which measures wind speed and rain rate along the ground track directly beneath the aircraft, HIRAD will provide images of the surface wind and rain field over a wide swath (~3 times the aircraft altitude). To demonstrate potential improvement in the measurement of peak hurricane winds, we present a set of Observing System Simulation Experiments (OSSEs) in which measurements from the new instrument as well as those from existing platforms (air, surface, and space-based) are simulated from the output of MM5 high-resolution (~1.7 km) numerical model. Simulated retrieval errors due to both instrument noise as well as model function accuracy are considered over the expected range of incidence angles, wind speeds and rain rates. Based on numerous simulated flight patterns and data source combinations, statistics are developed to describe relationships between the observed and true (from the model's perspective) peak wind speed. These results have implications for improving the estimation of hurricane intensity (as defined by the peak sustained wind anywhere in the storm), which may sometimes go un-observed due to sampling limitations from observations along aircraft flight lines.

Session 5
Observations and Observing Strategies for Tropical Cyclones and their Environment, Part 3

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Evolving Oceanic and Atmospheric Boundary Layer Measurements During Hurricanes Gustav and Ike

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During the 2008 hurricane season, hurricanes Gustav and Ike moved over the Gulf of Mexico and interacted with the Loop Current (LC) and the mesoscale eddy field. As part of the National Center for Environmental Prediction (NCEP)-directed tail Doppler Radar Missions, concurrent oceanic and atmospheric measurements were acquired from sixteen NOAA WP-3D research flights for pre, during and post-storm conditions. Such coupled measurements are absolutely necessary to improve models at the National Centers.

Briefly, over two-hundred global positioning system (GPS) sondes were deployed during the in-storm flights across the Gulf of Mexico to document the evolving atmospheric structure over warm and cool ocean features. Each research flight deployed airborne expendable bathythermographs (AXBT) to document the evolving upper ocean thermal structure across the entire Gulf of Mexico for the first time. In support of operational modeling efforts at NCEP, more than four-hundred AXBTs were deployed on these research flights to document the coupled boundary layer responses. To complement these data, twenty-one drifters (10 with 150-m thermistor chains) and floats were deployed by the Air Force WC-130J northwest of the LC. Over this array, forty-five GPS sondes were deployed and surface winds were mapped from Stepped Frequency Microwave Radiometer (SFMR). These data are being processed to assess data quality and the levels of the observed ocean thermal response in the LC and Gulf Common Water, and to relate upper ocean changes to the evolving boundary layer structure.

This prototype experimental approach will be conducted during the 2009 hurricane season from research aircraft as part of the NOAA Hurricane Forecasting Intensity Program Experiment and Minerals Management Service (MMS) sponsored Dynamics of the Loop Current Study. Several MMS-sponsored moorings will be deployed for about 30 months this summer in the LC-eddy shedding area. This region is where both hurricanes Katrina and Rita rapidly deepened to category-5 status in 2005. In addition to GPS sondes and SFMR measurements, ocean measurements this summer will involve the deployment of aircraft expendable current, temperature and salinity profilers (AXCPs, AXCTDs) prior, during and subsequent to hurricane passage over the eddy shedding area and possibly drifters and floats in the warm eddy and the Gulf Common Water. These measurements will provide signals to examine the oceanic response and assess its' feedback to the hurricane boundary layer aimed at improving coupled forecast models.

Flight Test Results of a Differential Absorption Microwave Radar for Remote Sensing of Atmospheric Pressure

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The accuracy of numerical weather model predictions of the intensity and track of tropical storms may be improved by large spatial coverage and frequent sampling of sea surface barometry. Over oceans, barometric pressure measurements are usually provided by a limited number of in-situ observations conducted by buoy stations and oil platforms. Surface pressure data is also available via manned aircraft deploying dropsondes and provides useful spatial sampling with limited coverage. To improve predictions and forecasts of the intensity and track of tropical storms, large spatial coverage and frequent sampling of sea surface barometry are critically needed for use in numerical weather models.

Work underway at NASA Langley Research Center (LaRC) will assess the feasibility of an active microwave radar working at moderate to strong O_2 absorption bands in the frequency range of 50~56 GHz for surface barometric pressure remote sensing. At these radar wavelengths, the reflection of radar echoes from water surfaces is strongly attenuated by atmospheric column O_2. Because of the uniform mixture of O_2 gases within the atmosphere, the total atmospheric column O_2 is proportional to atmospheric path lengths and the total atmospheric column air, and thus, to surface barometric pressures. Recent research has developed a technique based on the use a dual-frequency, O_2-band radar to overcome many of the difficulties associated with techniques requiring larger frequency separation. The technique uses dual wavelength channels with similar water vapor and liquid water absorption characteristics, as well as similar footprints and sea surface reflectivities, because of the closely-spaced spectra. The microwave absorption effects due to liquid water, water vapor in the atmosphere and the influences of sea surface reflection should be effectively removed by use of the ratio of reflected radar signals of the two channels.

LaRC has developed a prototype Radar based on this measurement technique to estimate barometric pressure and has recently completed several flight tests of the radar.. This paper will present an overview of the differential absorption measurement concept and the radar instrument concept. Further, results of instrument functional testing and initial flight-testing over the Chesapeake Bay will be presented. Finally, technology issues with respect to developing higher altitude or spacecraft instruments based on this technique will be discussed.

WISDOM System Description and Initial Test Results

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NOAA Oceanic and Atmospheric Research

NOAA with support from DHS Science and Technology and a consortium of industrial, academic and other government partners are developing and testing a new system to improve upper air data in areas that are poorly observed. The Weather In Situ Deployment Optimization Method (WISDOM) system is designed around the availability of small (about 1-2 meter) super-pressure balloons, and the availability of small (100 gram) electronics which include over the horizon Global Positioning System and satellite radio capabilities. The concept is that large numbers of WISDOM balloons with the GPS payload could be released to optimize weather prediction at a future time for phenomena of interest. Advanced techniques of assimilation and modeling are used to determine the release locations of the balloons to optimize their trajectories to improve future numerical weather prediction. An initial test of the WISDOM system that was conducted in fall 2008 aimed at late-season tropical cyclone prediction in the Atlantic basin will be discussed.

Coordinated use of Targeted Observations to Improve Tropical Cyclone Track Forecasts

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The Field Phase of the ONR Tropical Cyclone Structure 08 (TCS-08) and THORPEX Pacific Asian Regional Campaign (T-PARC) took place in the Northwest Pacific basin in August-September 2008. One of the primary goals of the multi-national, multi-agency campaign was to collect “targeted” observations within areas deemed important for improving tropical cyclone track forecasts, such as the periphery of a subtropical ridge or a confluence zone near the cyclone. The supplementary observations collected during intensive observing periods included dropwindsondes released from coordinated aircraft missions and driftsonde balloons, airborne Doppler Wind Lidar, off-time rawinsondes, and high-density atmospheric motion vectors produced when the rapid-scanning mode was activated on Japan’s MTSAT2 satellite. The decision of whether to deploy targeted observations was based on the potential threat of the tropical cyclone to land, and the uncertainty in multi-model ensemble forecasts of the track. The decision of where to deploy the targeted observations was based on guidance from up to 10 different targeting products derived from adjoint- and ensemble-based methods, several of which were uploaded onto ECMWF’s PREVIEW Data Targeting System. The coordination of the deployments was achieved via daily virtual conferences spanning 3 continents. The overall procedure, lessons learned, and preliminary results of the influence of targeted observations on tropical cyclone track forecasts will be presented, in addition to recommendations for the design of an adaptive observational network and coordinated targeting procedures in the Atlantic Basin.

A New Strategy for Tropical Cyclone (TC) Reconnaissance Based on Western Pacific TCS08 Proof of Concept

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A new strategy for tropical cyclone reconnaissance was implemented during the Office of Naval Research-sponsored Tropical Cyclone Structure 2008 (TCS08) experiment in the Western Pacific this past summer. This new strategy was to fly WC-130J at maximum altitude near 300 mb and deploy on average 26 GPS dropsondes and 13 AXBTs per flight with a grid resolution of one-half to one degree centered on the cloud cluster or incipient circulation center associated with early stage TC development. AXBTs were deployed at every other grid point and SFMR was used to map the surface winds, a feat made possible at relatively low winds by the larger footprint at the high altitude. The grid varied from 3 to 5 degrees and was either square or rectangular depending on the cloud morphology. This was the first time that AXBTs have been successfully deployed, and data transmitted in real time, from 30,000 ft and the first time reliable SFMR measurements have been made from this high altitude, a feat made possible in relatively low wind environments by the 3-times larger footprint than from nominal 10,000 ft reconnaissance altitude. Radar images were also recorded on USB 'Thumb Drives' and compared with a constellation of coincident satellite microwave images, revealing evolution of TC rainband morphology and providing input for satellite intensity and structure validation. Flights were designed to be coincident with Quikscat and Windsat satellite scatterometer overpasses for augmentation of surface wind field observations.

This strategy proved to be very successful in achieving TCS08 science objectives for TC genesis, structure, intensity change and extra-tropical transition goals. We now suggest that this same strategy may prove effective in meeting emerging observational requirements for model initialization and validation in the Atlantic Basin as the use of coupled TC prediction models grows. We feel that this strategy of flying high in weak systems rather than flying low looking for closed circulations is an idea whose time has come with the advent of the WC-130J capability to routinely fly at 300 mb altitude and its consequent ability to simultaneously map vertical atmospheric structure searching for signatures of mid-level and well as low-level spin-up at the earliest possible time while also mapping the surface wind field with SFMR. Furthermore, simultaneous ocean vertical structure profiles will reveal signatures of ocean eddies that may impact TC development and subsequent intensification. This type of strategy, especially in concert with G-IV and WC-130J surveillance flights in the storm environment would bring a powerful new set of observations into play that would be ideal not only for coupled model initialization and validation but for forecaster diagnostics regarding presence of initial vortex and potential for subsequent spin-up. The additional cost to the reconnaissance program of such a strategy would be relatively modest in the form of support for roughly 20 extra expendables per flight, a cost that is less than half that for flight-hour support for a typical flight.

Poster Session

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Mapping Surface Winds Using Ocean Acoustic Interferometers

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We discuss the feasibility of using an acoustic interferometer consisting of a pair of acoustic hydrophones separated horizontally by a few tens of kilometers to diagnose the location and intensity of the noise generated by tropical cyclones. Since the intensity of noise is strongly dependent on wind, noise mapping is essentially equivalent to wind mapping. The method is based on coherent processing of a broadband ambient noise within a frequency band of tens of Hertz. We demonstrate that resolution of the order of a few kilometers, at distances of the order of a thousand kilometers, is achievable in principle. An estimate of the signal to noise ratio is also provided.

Surface Wind Vector and Rain Rate Observation Capability of the Future Hurricane Imaging Radiometer (HIRAD)

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The Hurricane Imaging Radiometer (HIRAD) is the next-generation Stepped Frequency Microwave Radiometer (SFMR), and it will offer the capability of simultaneous wide-swath observations of both extreme ocean surface wind vector and strong precipitation from either aircraft (including UAS) or satellite platforms. HIRAD will be a compact, lightweight, low-power instrument with no moving parts that will produce valid wind observations under hurricane conditions when existing microwave sensors (radiometers or scatterometers) are hindered by precipitation. The SFMR is a proven aircraft remote sensing system for simultaneously observing extreme ocean surface wind speeds and rain rates, including those of major hurricane intensity. The proposed HIRAD instrument advances beyond the current nadir viewing SFMR to an equivalent wide-swath SFMR imager using passive microwave synthetic thinned aperture radiometer technology. The first version of the instrument will be a single polarization system for wind speed and rain rate, with a dual-polarization system to follow for wind vector capability. This sensor will operate over 4-7 GHz (C-band frequencies) where the required tropical cyclone remote sensing physics has been validated by both SFMR and WindSat radiometers. HIRAD incorporates a unique, technologically advanced array antenna and several other technologies successfully demonstrated by NASA's Instrument Incubator Program. A brassboard (laboratory) version of the instrument has been completed and successfully tested in a test chamber. Development of the aircraft instrument is underway, with flight testing planned for the fall of 2009. Preliminary Observing System Simulation Experiments (OSSEs) show that HIRAD will have a significant positive impact on surface wind analyses as either a new aircraft or satellite sensor. New off-nadir data collected in 2008 by SFMR that affirms the ability of this measurement technique to obtain wind speed data at non-zero incidence angle will be presented, as well as data from the brassboard instrument chamber tests.

Methodology for the Determination of 12-Foot Sea Radii for Tropical Cyclones

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The advent of satellite altimetry and ocean surface vector wind observations has significantly increased the amount of observational data available to marine meteorologists. The Tropical Analysis and Forecast Branch (TAFB) at the National Hurricane Center (NHC) actively incorporates these cutting edge data sets into their ocean analyses, providing the most accurate assessment of the current sea state in their tropical North Atlantic and Northeast Pacific areas of responsibility. This poster will detail the use of the recently-enhanced observational dataset available to TAFB for the determination of the 12-ft sea radii associated with a tropical cyclone (TC).

The Jason-1 polar-orbiting satellite observes global significant wave height data at 3-n mi horizontal resolution with a precision of 0.1 ft. Observations from the Jason altimeter provide wave height information in data-sparse regions of the tropical Atlantic and East Pacific oceans. To "fill in" the sea state analysis in other locations, gridded wave heights from a short-term forecast (most often a six-hour forecast) of a numerical wave model are used as a first-guess field and adjusted accordingly for any reliable observations. One such model used is the Geophysical Fluid Dynamics Laboratory (GFDL) version of the Wave Watch model, which incorporates a more detailed initial wind field for a TC than other numerical wave models. Over data-sparse regions such as the open waters of the tropical East Pacific or Atlantic oceans, ship data are the only in-situ observations available to assist in analyzing the 12-ft sea radii for a TC. Once a TC moves into the Gulf of Mexico, the southwest North Atlantic, or the Caribbean Sea, the observational networks are denser with NOAA Buoys in the offshore waters and Coastal Monitoring Automated Network (CMAN) sites in the near shore waters, primarily along the Gulf Coast. These dense observational networks provide enough data to ensure a much more accurate analysis of the 12-ft sea radii for the TC as compared to instances when a TC is located in the open ocean. Additionally, the dense observations in the western portion of the Atlantic basin allow for a better assessment of the performance of the various numerical models. In the future, TAFB should be able to perform a real-time evaluation of aircraft-based wave height information from the Joint Hurricane Test Bed Scanning Radar Altimeter Project, which could further improve the estimation of the 12-foot sea radii.

The active utilization of remotely-sensed ocean observations allows for a more exact analysis of the initial sea state in regions of little or no in-situ data and provides an "accuracy check" for ship and buoy observations that may contain errors. In turn, more reliable sea state analyses permit a better appraisal of the quality of numerical wave model output. While long-term verification is difficult due to a lack of historic data, we believe all of these advances have significantly improved the estimation of the 12-ft sea radii for TCs over previous methods.

Sea Surface Roughness Measurements Using GPS Reflectometry in Hurricane Ike (2008)

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A number of airborne experiments have been performed during the last decade that studied a sensitivity of GPS reflected signals to ocean surface roughness both for steady, uniform wind conditions, and for hurricane conditions (see, e.g., [1, 2]). A theoretical model [3] is available that relates the characteristics of reflected signals to the slope statistics, and from there, to a near-surface wind speed, if the local wind is the only source of sea roughness at the footprint location. Still a lot of work needs to be done to make this technique more reliable, robust and accurate for operational needs.

Recently, a compact system, able to record raw GPS intermediate frequency (IF) samples, has been designed and tested by the GNSS group at the CU/Aerospace Science Engineering. Such an approach provides the most fundamental measurement, enabling the most advanced and complete post-processing, with data volumes on the order of 1GB/minute. On September 10 and 11, 2008 this GPS bistatic system was flying on board of the NOAA WP-3D research aircraft which collected research-mission data on Hurricane Ike in Gulf of Mexico. The aircraft flew through the hurricane at about 2500 meters performing a characteristic flight track comprising of several radial lags that transverse the hurricane eye at different azimuthal angles. The GPS bistatic radar was recording raw data practically over the entire two flights collecting about 800 GB of data. After the flights the hard drives with data have been sent to the lab for post-processing, and the correlation waveforms for both direct and reflected signals were retrieved from the raw data for all available satellites.

As it is follows from the theoretical model [3], the shape of the correlation waveform, and the slope of its trailing edge depends on rms of L-band limited ocean surface slopes. Empirical spectral models for well-developed seas relate the slope rms to the local wind speed. However, wave fields generated by hurricanes do not follow such a simple rule. System of swells generated by various parts of the hurricane complicates the picture and makes the problem of wind retrieval non-trivial. Presence on board of the aircraft of the Step Frequency Microwave Radiometer (SFMR) allowed making comparisons between wind retrievals obtained with the SFMR and the GPS bistatic radar.

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Development of Miniature SFMR Receiver Modules and the Compact-SFMR

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This paper describes the development of a miniaturized Stepped Frequency Microwave Radiometer (SFMR) receiver module and the next generation compact-SFMR instrument. Funded through the NOAA SBIR program, these receiver modules are intended for use in multi-channel imaging radiometers as well as in compact versions of the standard SFMR. ProSensing is currently testing a prototype compact C-band radiometer receiver (CCR) module, which employs inexpensive surface mount components to implement the standard SFMR electronics in a small, lightweight package. The CCR modules will be used in the Hurricane Imaging Radiometer (HIRad), currently under development by a team of government, university and industrial partners.

As part of SBIR Phase II effort, ProSensing will develop and deliver:

- Ten single sideband copies of the CCR receiver module suitable for imaging correlation radiometers such as the HIRad system. The modules include an integral COLFET load, as well as digitally controlled phase shifters and attenuators to correct for temperature drift.
- A compact-SFMR system with a total instrument weight of 3 kg, including the CCR receiver and horn antenna. Two complete compact-SFMR instruments will be delivered to NOAA, one for deployment on a small UAV, and a second for measuring down welling atmospheric brightness temperature on the NOAA P-3 for improved SFMR low wind speed and rain rate measurements.

The first two prototypes of the CCR are currently being tested at ProSensing and are due to be delivered to NASA MSFC in February, 2009.

The HFIP High Resolution Hurricane Test

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Tropical cyclones are a serious concern for the nation, causing significant risk to life, property and economic vitality. The NOAA National Weather Service has a mission of issuing tropical cyclone forecasts and warnings, aimed at protecting life and property and enhancing the national economy. In the last 10 years, the errors in hurricane track forecasts have been reduced by about 50% through improved model guidance, enhanced observations, and forecaster expertise. However, little progress has been made during this period toward reducing forecasted intensity errors.

To address this shortcoming, NOAA established the Hurricane Forecast Improvement Project (HFIP) in 2007. HFIP is a 10-year plan to improve one to five day tropical cyclone forecasts, with a focus on rapid intensity change. Recent research suggests that prediction models with grid spacing less than 1 km in the inner core of the hurricane may provide a substantial improvement in intensity forecasts. The 2008-09 staging of the high resolution test aims at quantifying the impact of increased horizontal resolution in numerical models on hurricane intensity forecasts. The primary goal of this test is an evaluation of the effect of increasing horizontal resolution within a given model across a variety of storms with different intensity, location and structure. A secondary goal is to provide a data set that can be used to explore the potential value of a multi-model ensemble for improving hurricane forecasts.

The Developmental Testbed Center (DTC) and the HFIP Team hosted a workshop at the National Hurricane Center in Miami, FL, 11-12 March 2008. Experts on hurricanes, numerical modeling and model evaluation met for two days to discuss the strategy for this test. The test plan that was put together following this workshop reflects the consensus reached on the framework for this testing effort. Seven modeling groups expressed interest in participating in the testing effort at the time of the workshop. This presentation will describe the basic elements of the test plan and summarize the current status of the test. Only limited examples of the results will be shown since the bulk of the retrospective hurricane forecasts will not be completed by the time of the Conference.

Coupling a High Resolution Hurricane Storm Surge Model to Operational Weather and Ocean Prediction Systems

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The Coast Survey Development Laboratory of the National Ocean Service (NOS) and the National Centers for Environmental Prediction (NCEP) of the National Weather Service (NWS) are cooperating to evaluate strategies for a next-generation storm surge modeling system. The model used to develop a high resolution Coastal Flooding Model (CFM) is the ADvance CIRCulation (ADCIRC) finite element model. ADCIRC utilizes an unstructured mesh which provides high resolution in areas of complex shoreline and geometry to perform storm surge flood inundation prediction.

The approach is to simulate storm surge for the coastal region using the high resolution unstructured mesh CFM. We examine the impact of boundary and meteorological forcing from a suite of NWS operational weather and ocean prediction models. Open ocean boundary conditions are provided to the CFM by the NCEP Real-Time Ocean Forecast System (RTOFS), which is based on the HYbrid COordinate Model (HYCOM) basin-scale ocean circulation model. The meteorological forcing fields (e.g. the hurricane wind and pressure fields) being tested include the Hurricane Wind analysis system (H*Wind), the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model, and the Hurricane Weather Research and Forecasting (HWRF) model, all of which are currently operational models for forecasting or analyzing hurricane track and intensity.

The coupled system predicts inundation via the inclusion of the high resolution ADCIRC coastal model (the CFM). Furthermore, the outcomes of the coupled system could form decision-support tools that the coastal community can use. Using the expertise in several parts of NOAA as well as having partners in other federal and state agencies will ensure that outcomes are based on an integrated approach that makes the best use of data, modeling approaches, displaying results, and outreach.

An Integrated Tropical Cyclone Information System for Research

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In spite of recent improvements in hurricane track forecast accuracy, currently there are still many unanswered questions about the physical processes that determine hurricane genesis, intensity, track and impact on large-scale environment. Furthermore, a significant amount of work remains to be done in validating hurricane forecast models, understanding their sensitivities and improving their parameterizations. None of this can be accomplished without a comprehensive set of multiparameter observations that are relevant to both the large-scale and the storm-scale processes in the atmosphere and in the ocean.

To address this need, we and our colleagues from Marshall Space Flight Center have developed the framework for a comprehensive Integrated Tropical Cyclone Information System (iTCIS) of high-resolution satellite, airborne and in-situ observations and model outputs pertaining to: i) the thermodynamic and microphysical structure of the storms; ii) the air-sea interaction processes; iii) the larger-scale environment as depicted by the SST, ocean heat content and the aerosol loading of the environment. Our goal was to create a one-stop place to provide the researchers with an extensive set of observed hurricane data, and their graphical representation, together with convection-resolving model output, all organized in an easy way to determine when coincident observations from multiple instruments are available.

Currently the iTCIS is populated with satellite observations of all tropical cyclones observed globally during 2005. Our future plans are to extend the database both forward in time till present as well as backward to 1998. Furthermore, NASA field campaign data will be included and displayed using Goggle Earth field-campaign-specific approach that allows the creation of overlays on-demand. This innovative approach, known as the Real Time Mission Monitor (RTMM) has been developed at the Marshall Space Flight Center. It has proven very valuable during past field campaigns, both during the campaign as well as in the post-campaign analysis. The RTMM is described in a separate presentation.

We began the development of analysis tools that will communicate with the database and will allow for online investigations without the need to download large data volumes. The analysis tools will be used to compute single and multiparameter statistics and to determine spatial, temporal and multiparameter covariances that are needed to evaluate model performance, provide information for data assimilation and characterize and compare observations from different platforms.

We envision that the developed hurricane information system will help in the validation of the hurricane models, in the systematic understanding of their sensitivities and in the improvement of the parameterizations employed by the models. Furthermore, it will help in studying the physical processes that affect hurricane development and impact on large-scale environment.

This talk will describe the structure of the satellite-based component of the iTCIS, the analysis system and the future plans. A poster will accompany the talk. It will illustrate how the iTCIS can be used to discriminate between high resolution WRF model simulations that employ different parameterizations with the goal to determine the model setup that produces most realistic simulations.

The work described here was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Using NASA's Real Time Mission Monitor to Manage and Conduct Airborne Science Missions

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The Real Time Mission Monitor (RTMM) is a visualization and information system that fuses multiple Earth science data sources, to enable real time decision-making for airborne and ground validation experiments. Developed at the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center, RTMM is a situational awareness, decision-support system that integrates satellite imagery, radar, surface and airborne instrument data sets, model output parameters, lightning location observations, aircraft navigation data, soundings, and other applicable Earth science data sets. The integration and delivery of this information is made possible using data acquisition systems, network communication links, network server resources, and visualizations through the Google Earth virtual globe application.

RTMM has proven extremely valuable for optimizing individual Earth science airborne field experiments. Flight planners, mission scientists, instrument scientists and program managers alike appreciate the contributions that RTMM makes to their flight projects. We have received positive feedback from a broad spectrum of scientists who used RTMM during field campaigns including the hurricane-focused 2006 NASA African Monsoon Multidisciplinary Analyses (NAMMA), 2007 NOAA-NASA Aerosonde Hurricane flight, 2007 Tropical Composition, Cloud, and Climate Coupling (TC4), 2008 Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) missions, and the 2008 Soil Moisture Active-Passive Validation Experiment (SMAP-VEX).

Improving and evolving RTMM is a continuous process. RTMM recently integrated the Waypoint Planning Tool, a Java-based application that enables aircraft mission scientists to easily develop a pre-mission flight plan through an interactive point-and-click interface. Individual flight legs are automatically calculated for altitude, latitude, longitude, flight leg distance, cumulative distance, flight leg time, cumulative time, and satellite overpass intersections. The resultant flight plan is then generated in KML and immediately posted to the Google Earth-based RTMM for interested scientists to view the planned flight track and subsequently compare it to the actual real time flight progress.

We are planning additional capabilities to RTMM including collaborations with the Jet Propulsion Laboratory in the joint development of a Tropical Cyclone Information System which will serve as a web portal for access to tropical cyclone data, visualizations and model output.

A description of the system architecture, components, and applications along with reviews and animations of RTMM during the field campaigns, plus planned enhancements and future opportunities will be presented. A poster will complement the talk.

Use of Total Precipitable Water to Aid Hurricane Rainfall Prediction

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The Tropical Rain Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA, or TRMM 3B42) has provided 3-hourly continuous rainfall estimates for tropical cyclones over the global oceans since 1998. Previous work by the authors has established that a positive relationship exists between the hurricane rainfall and environmental moisture parameters such as total precipitable water and horizontal moisture convergence for the Atlantic basin using a 7-yr TRMM 3B42 Atlantic landfalling tropical cyclone database. It suggested that total precipitable water could be used as an additional predictor for tropical cyclone rainfall.

In this study, we extend this work to other basins, including east+central Pacific, northwest Pacific, north Indian Ocean, south Indian Ocean, and south Pacific. We further examine the relationship between total precipitable water and tropical cyclone rainfall as a function of storm intensity, SST, shear magnitude, and geographical locations including over-land vs over-ocean using 10 years of TRMM 3B42 data. Then we construct a statistical regression model by combining maximum wind speed with total precipitable water as an independent variable for forecasting Atlantic hurricane rainfall. Environmental parameters are derived from NOGAPS analysis. The azimuthal mean rain rate is examined as a function of total precipitable water averaged within 500-km radius from the storm center for different tropical cyclone intensities, different basins, high/low SST, high/low shear, and over-land or over-ocean conditions. The correlations among total precipitable water, maximum wind speed, and 12, 24, 36, 48-h future storm volumetric rain are also derived.

Strong Surface Wind Gusts Associated With Heavy Squalls within Hurricane Danny's (1997) Eyewall.

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Some landfalling hurricanes contain massive collapsing cores (CCs) of heavy precipitation within their eyewalls. Several papers indicate the likely linkage between downbursts-like features and strong wind gusts in hurricane eyewalls; however, very few surface-based measurements of winds associated with these features actually exist.

Hurricane Danny (1997) produced one of the greatest precipitation events on record in the United States during its landfall along the Alabama coast. Radar observations indicate that Danny was likely one of the most prolific CC producers during this time of any landfalling U.S. hurricane between 1994 and 2007. Slow-moving Danny stayed within 100 km of the KMOB WSR-88D Doppler radar for many hours while in the vicinity of Dauphin Island, Alabama.

Shortly after Danny drifted into Mobile Bay, the increasingly convective southwest eyewall of the storm buffeted the Coastal Marine Automated Network (C-MAN) site on the east end of Dauphin Island (DPIA1). Wind gusts up to 88 knots were recorded there during this time. While in the eyewall, nearly all the strongest wind gusts each hour occurred during the passage of very heavy squalls often displaying a low-level collapse of their heaviest precipitation cores.

Base velocities from the nearby KMOB WSR-88D indicate the presence of low-level wind maxima in the vicinity of DPIA1 near the 500 m altitude as these squalls passed. Momentum from these slightly-elevated wind maxima was likely diverted toward the surface during the passage of these very heavy precipitation cores, thus providing a favorable situation for strong near-surface wind gusts.

As Danny moved further into Mobile Bay, the low-level wind maxima in the hurricane's southwest eyewall intensified within a nearly continuous collapse of extremely heavy precipitation on the downwind side of an intense and persistent eyewall convective complex. Thus, even stronger near-surface wind gusts likely occurred repeatedly over a multi-hour period over the open waters of Mobile Bay, but were occurring in an area lacking surface observing equipment.

Hurricanes at Landfall: Rain-Field Sizes and Their Relationship to Environmental Conditions

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Predicting the size of a hurricane's rain field can help to determine the overall area that may receive rainfall from the storm as well as the time that rainfall may begin and the duration of the rainfall event. This study examines 28 hurricanes that made landfall along the U.S. coast during 1995-2007. Radar reflectivity data are entered into a GIS and the distance from the center of circulation to the edge of the rain field is measured in each quadrant. To associate the extent of the rain field with the physical forcing mechanisms helping to shape the storm's structure, variables derived from the Statistical Hurricane Intensity Prediction Scheme database, storm intensity, position, and motion, and coastline geometry are examined. Multiple linear regression models utilize these variables to predict the distance from the circulation center to the edge of the rain field for each quadrant. Results confirm that it is important to consider that the physical forcing mechanisms affect the storm differently in each quadrant. The most asymmetrically-shaped rain fields are present within hurricanes that are experiencing trough interaction, as the northeast/right-front quadrant typically extends the farthest from the circulation center, while the southwest/ left rear quadrant exhibits the shortest extent. More than 80% of the variability in rain field extent in the northeast quadrant, which tends to be in the downshear direction, can be explained by the north component of the deep-layer vertical wind shear. In the northwest quadrant, storm motion and intensity are most closely associated to the extent of the rain field, and intensity as well as the shallow-layer vertical wind shear are highly correlated to the rain field extent in the southwest quadrant. The extent of the rain field in the southeast quadrant is the most difficult to predict; vorticity, latitude, and divergence at 200mb combine to account for less than half of the variance in rain field extent in this quadrant of the storm. Overall, investigating the extent of the rain field in each quadrant improves the ability to quantify the overall storm shape.

Challenges in the Prediction of the Life Cycle of Typhoon Sinlaku (2008)

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One of the most scientifically interesting and societally important tropical cyclones during the ONR Tropical Cyclone Structure (TCS-08) and THORPEX Pacific Asian Regional Campaign (T-PARC) field phase was Typhoon Sinlaku in September 2008. This poster will illustrate several challenges in the prediction of Sinlaku from genesis through recurvature.

The genesis of Typhoon Sinlaku was poorly predicted by the operational global models. Only ECMWF predicted Sinlaku's development 1 day in advance of its formation. The ECMWF, GFS, UKMET, and NOGAPS all indicated development during the 4 days prior to formation, but with no run-to-run consistency. New simulations with a 2-km version of the Advanced Research Weather Research and Forecasting (WRF-ARW) model will be presented.

There was also day-to-day and model-to-model inconsistency in the timing and location of the track, particularly when Sinlaku approached Taiwan. Beta-drift may have dominated, given the weak steering flow. Sinlaku's recurvature was most likely due to the influence of a short-wave trough to its north, as is evident via removal of the short-wave using vorticity inversion in the WRF model. The importance of inserting a realistic bogus vortex within WRF to produce accurate predictions of structure and intensity is also emphasized in this study.

In order to diagnose the error sources in Sinlaku's genesis and track forecasts, initial perturbations derived from the THORPEX Interactive Grand Global Ensemble (TIGGE) are used. The vertical structure of the perturbations was found to differ significantly between the ECMWF, UKMO, NCEP, CMC and JMA ensembles. For an ensemble based on a single model, differences between the tracks are evidently owed to differences in the steering flow, and not the cyclone size. On the other hand, for multi-model ensembles, the differences in tracks are due to changes in both the cyclone size and steering flow.

Future plans include the use of adjoint- and ensemble-based diagnostics to elucidate the influence of assimilating high-density satellite wind and dropsonde data in "sensitive" areas.

The Impact of the Saharan Air Layer on the Development of Hurricanes Irene (2005) and Helene (2006)

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The existence of the Saharan air layer (SAL), a layer of warm, dry, dusty air frequently present over the tropical Atlantic Ocean, has long been appreciated. The nature of its impact on hurricanes remains unclear, with some researchers arguing that the SAL amplifies hurricane development and with others arguing that it inhibits it. The potential negative impacts of the SAL include 1) low-level vertical wind shear associated with the African easterly jet; 2) warm air aloft, which increases thermodynamic stability; and 3) dry air, which produces cold downdrafts. Some investigators have assumed the validity of these proposed negative influences and have frequently used them to explain the failure of individual storms to intensify or to explain the relative inactivity of recent hurricane seasons. Multiple NASA satellite data sets and National Centers for Environmental Prediction global analyses are used to characterize the SAL's properties and evolution in relation to hurricanes Irene and Helene. The results will show that neither jet-induced vertical wind shear nor warm SAL air (high stability) were likely to have produced significant negative impacts on these storms. Dry air appears to be a key mechanism for SAL influence. Idealized simulations will be used to evaluate the role of dry air.

Evaluating Ensemble Track Forecasts of Tropical Cyclones

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While tropical cyclone track forecasts in deterministic models continue to undergo evaluation and thereby improve, the verification of *probabilistic* track forecast products derived from ensembles is less routine. This study evaluates the skill of the ECMWF and UKMO ensemble prediction systems for the 2008 Atlantic and West Pacific seasons. First, a "cone of uncertainty" derived from the ensemble forecast is verified, based on the principle that the best track should fall within the cone in 67% of all cases. As is done at NHC, the cone is constructed using a series of circles centered on some "best forecast" at successive forecast times. In this study, the circle at each time is centered on the ensemble mean forecast position, with its radius defined as that enclosing 67% of the ensemble forecast members at that time. In the evaluation, the number of times for which the best track lies within this radius is then counted over the season, for all 1-10 day UKMO ensemble forecasts and 1-5 day ECMWF ensemble forecasts. Preliminary results indicate that for the Atlantic basin, the UKMO ensemble is superior to ECMWF at predicting an appropriate spread of tracks for forecasts up to 2 days, but UKMO then becomes too under-dispersive for longer-range forecasts with the best track falling outside the cone too often. In contrast, the ECMWF shows virtually ideal ensemble spread for all forecast times between 2-5 days. Other products to be evaluated include cones of uncertainty constructed around NHC's consensus model and official forecast tracks, cones of uncertainty of different sizes (percentage spread), and ensemble means as compared against deterministic forecasts.

The Communication of Tropical Cyclone Emergency Information through Use of Geographic Information System (GIS) Products

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The communication of tropical cyclone analysis and forecast information has always been a key method in providing emergency management and decision makers with the necessary tools to make informed decisions. Although there are many methods of delivering such information, the use of GIS provides powerful ways to manipulate, interrogate, visualize and ultimately understand the data. GIS enables the users to quickly and efficiently customize the information to meet their specific mission requirements. The interoperability of GIS data facilitates a wide variety of functions that include merging with other data types, expanded report capabilities and detailed map production. Unlike static content, GIS allows the end user to quickly process the information directly into applications; consequently, they can easily interpret large volumes of information.

The National Hurricane Center (NHC) working with other agencies has expanded its capabilities to produce and distribute experimental tropical cyclone GIS content. During the 2008 hurricane season, NHC delivered breakpoints, watch and warning, storm surge, forecast track and forecast uncertainty cone GIS information in near real-time. Future expectations are to deliver best track and probability information in order to expand the availability of data layers to the user. This experimental line up of products is expected to fill the GIS gap in regards to communication of the real-time forecast and post storm analysis. Furthermore, detailed Meta information describing the products and their limitations accompany these GIS data and the format of choice utilized is the popular and highly utilized ESRI Shapefile format specification. These particular products are targeted for emergency management and decision makers; however, the interoperability of these products has also benefited a wide variety of other users because the data can be used quickly and efficiently with off the shelf GIS applications. The progress made in the area of delivering useful tropical cyclone GIS content in near real-time is closing an identified gap in products and services offered by NHC.

The Near Real-Time and Science Study Satellite Product Suite for the Tropical Cyclone Structure (TCS-08) Field Project

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A wealth of satellite imagery and derived products were provided in near real-time during the Tropical Cyclone Structure (TCS-08) field program (summer 2008) to address multiple objectives: 1) provide mesoscale and synoptic scale weather nowcasting information used to coordinate multiple research aircraft, 2) address topics ranging from tropical cyclone genesis, storm structure, extratropical transition and satellite TC intensity validation, and 3) supplement major data voids due to limited in-situ observations. In response, comprehensive suite of geostationary and polar orbiter digital data sets were acquired and processed, resulting in near real-time products distributed automatically to field program personnel and archived for numerous TCS-08 scientific studies.

The Naval Research Laboratory in Monterey, CA and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) in Madison, WI combined to create a suite of satellite products; 1) visible, infrared (IR), and water vapor imagery over synoptic, mesoscale and storm-specific domains, 2) geostationary-derived cloud and water vapor-tracked winds, 3) microwave enhanced imagery and products highlighting atmospheric moisture over large domains as well as storm-focused rainband and eyewall feature structure, 4) wind shear, convergence and divergence fields, 5) ocean surface winds from scatterometer and polarimetric radiometers, and 6) TC intensity estimates via microwave and IR algorithms. Products were made available to field program scientists via dedicated web pages, ftp and automated email alerts, including for the first time Google Earth dedicated products permitting enhanced geographical orientation, display and visualization. Digital data was also routinely available via a central catalog at the Earth Observation Laboratory (EOL) and the National Center for Atmospheric Research (NCAR) for both real-time utilization and archive purposes.

The satellite suite includes the MTSAT geostationary sensor, the operational and research constellation of microwave polar orbiters (SSM/I, SSMIS, AMSR-E, TMI, and WindSat), microwave sounders (AMSU-A/B, SSMIS, and MHS), scatterometers (QuikSCAT and ASCAT), as well as multiple radars (TRMM precipitation radar and CloudSat). Data latencies ranging from minutes to 1-4 hours enabled the TCS-08 personnel to gather a full range of environmental information in order to address the extensive near real-time and longer term research initiatives as funded by the Office of Naval Research (ONR) and the National Science Foundation (NSF).

Improved GOES Utilization for Tropical Cyclone Forecasting

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Data from the Geostationary Operational Environmental Satellite (GOES) suite has been used monitoring, diagnosing and forecasting tropical cyclones for over thirty years, but their information content is far from exhausted. Several efforts are underway to make even better use of the GOES products for tropical cyclone intensity diagnosis, intensity and formation forecasting. These are described below.

Two of these efforts involve the expansion of the tropical cyclone IR imagery database and its improved used for intensity forecasting. NHC's operational statistical intensity model (SHIPS) is run in a two-step process. The first step creates a forecast based on TC current conditions and the Global Forecast System (GFS) analyses and forecasts. The second step, or correction step, then adjusts the existing forecast to account for satellite information from (IR imagery) and Oceanic Heat Content. The satellite-based predictors have recently been extended back in time so that this two step procedure may no be longer needed. In a related project, direction relative IR imagery is being decomposed into complex empirical orthogonal functions, which can account for propagating features as possible new predictors in SHIPS and the related Rapid Intensification Index (RII). Both of these efforts will be described.

The Dvorak technique is the one of the cornerstones of operational intensity diagnosis, but the method has some known and suspected biases. Using the historical records of both Dvorak and aircraft fixes along with the best track intensity estimate, a calibration that accounts for tropical cyclone intensity, latitude, size (via radius of outer closed isobar), translation speed and intensity trend is created. Preliminary results of this ongoing study are presented.

In addition to the SHIPS, RII, and Dvorak work, the water vapor (WV) imagery from several geostationary satellites is being inter-calibrated to form a global tropical water vapor dataset. Past studies have shown that propagating features, e.g., equatorial waves, can be detected in satellite-based Outgoing Longwave Radiation (OLR) and used for prediction. Unlike OLR, WV imagery provides information about both convective persistence and atmospheric moisture trends. The current study exploits the predictive nature of tropical wave forms as well as the information content of the water vapor imagery to examine the possible predictive information available in the tropical water vapor strip for better diagnosing TC formation. Progress thus far on this project will be described.

The International Best Track Archive for Climate Stewardship (IBTrACS)

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There are currently six Regional Specialized Meteorological Centers (RSMC) and five Tropical Cyclone Warning Centers (TCWC) around the world that forecast and monitor storms in each of the tropical-cyclone-prone basins and annually archive best track data: information on a storm's position, intensity, as well as other related parameters. Despite the widespread interest in global best track data, no central repository of such data was maintained. The International Best Track Archive for Climate Stewardship (IBTrACS) is a project at NOAA's National Climatic Data Center under the auspices of the World Data Center for Meteorology – Asheville to collect and disseminate the historical tropical cyclone best track data from all available centers, merging the disparate data sets into one comprehensive product for the user community. One of the goals of the project is to maintain open data processing methods, so that desired user feedback on data quality is more easily collected. In addition, data provenance is completely recorded so all observations and corrections, either through rigorous quality control or user feedback, may be attributed to their source. Data are available in various formats to accommodate the diverse needs of the tropical cyclone data user community. The presentation will summarize the purpose and vision of the project, the methods used to merge the data, and a discussion of results of global and basin-wide tropical cyclone statistics. More information on IBTrACS is available at http://www.ncdc.noaa.gov/oa/ibtracs/

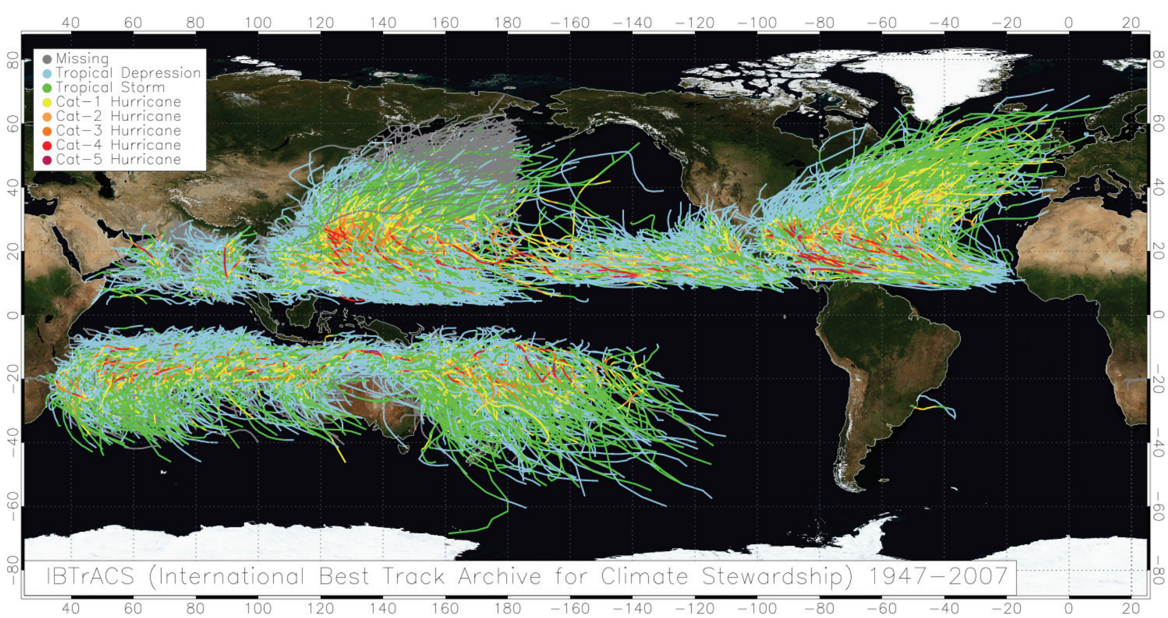

Figure – Tracks of tropical cyclones from IBTrACS during 1947-2007.

Mapping Hurricane Inland Storm Tides

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Historically, hurricane-induced storm-tides were documented through analysis of structural or vegetative damage and high-water marks. However, these sources rarely provided quantitative information about the timing of the flooding, the sequencing of multiple paths by which the storm-surge waters arrived, or the magnitude of waves and wave run-up comprising floodwaters. Nor could highwater marks be used to evaluate storm-surge model performance along the dynamic track of a hurricane with its accompanying changes in wind strength and direction.
In response to these deficiencies, the U.S. Geological Survey (USGS) developed and deployed an experimental mobile storm-tide network to provide detailed time-series data for selected hurricane landfalls (URL: http://water.usgs.gov/waterwatch/hsss/). As part of this program, water-level and barometric pressure monitors are deployed to areas of hurricane landfall resulting in a concentrated network of as many as 80 temporary, tide gages placed along water channels and nearby overland features such as beaches, wetlands, and constructed environments. USGS storm-surge networks have been successful deployed for Hurricanes Rita (2005, 32 water-level monitoring sites); Wilma (2005, 30), Gustav (2008, 80); and Ike (2008, 65); and Tropical Storm Ernesto (2006, 40 sites for which the data were not published.) Data were collected as frequently as every 30 seconds for 1-2 days prior to landfall and for as much as 2 weeks afterwards. Data at some sites in southwest Louisiana were collected for multiple storms. The data are available at (URL: http://water.usgs.gov/osw/programs/storm_surge.html).

The USGS first deployed the mobile storm-tide network for Hurricane Rita. As Hurricane Rita approached the Texas and Louisiana coasts in September 2005, the USGS deployed 32 water-level and 14 barometric pressure sensors at selected locations from Sabine Pass to Abbeville, Louisiana, at distances ranging from a few feet of beaches to 30 miles inland. Sensors were programmed to record data every 30 seconds, placed in 1.25 inch diameter pipes and strapped to permanent objects such as power poles and piers. Temporary benchmarks were driven into or chiseled on to the same or near by objects to serve as elevation controls for the sensors and highwater marks that were expected to result from the flooding.

Sensors were recovered following passage of the storm. Tape-downs from the temporary benchmarks to the surface of the water and to available high-water marks were made to confirm sensor accuracy. Traditional line of sight leveling was employed to tie the sensors, the water marks, and the benchmarks to a common datum and that datum was tied to the NGVD 1988 through use of GPS surveying.

Session 6
Tropical Cyclone Model Development and Technology Transfer, Part 1

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Advancement of the HWRF for Next Generation Hurricane Prediction at NCEP's Environmental Model Center

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Following the initial operational implementation at NCEP of the Hurricane Weather and Research Forecast system (HWRF) in 2007, upgrades were made to the system for the 2008 hurricane season. These upgrades addressed a known weak bias in HWRF intensity forecasts. Forecasts from the 2008 season will be highlighted showing the impact of these upgrades. Further improvements for the 2009 implementation will be highlighted to include advancements to the GSI and HWRF physics to include a gravity wave drag parameterization. The latter has helped improve the synoptic flow impacting both track and in some cases intensity with particularly positive results in EPAC.

Future advancements of the HWRF will also be discussed in terms of advanced coupling to ocean-wave-land models, data assimilation strategies for both atmosphere and ocean, formulation of physics for advanced high resolution and prototype high resolution hurricane ensembles to enhance NHC's hurricane intensity prediction capabilities.

Plans for bringing the HWRF into the DTC repository for community use will also be discussed along with a joint hurricane tutorial with NCAR scheduled for January 2010.

Hurricane Model Transitions to Operations at NCEP/EMC
A Joint Hurricane Testbed (JHT) Program

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The emphasis for this 2005-2007 JHT project has concentrated on HWRF development, its operational implementation, and current and future upgrades. HWRF has been accepted into operations and has been run successfully for the 2007 and 2008 seasons. This development was designed to take into account the strengths of the WRF software system, the use of the well tested NMM dynamic core, and the physics packages of the GFDL highly successful forecast system. The HWRF system continued to make advancements as shown by the results of the busy 2008 tropical Atlantic season. HWRF was quite competitive with its 2008 track forecasts being among the best dynamical models for this active Atlantic season. HWRF was comparable to both the GFDL and GFS forecasts systems with 5 day forecast errors of ~250nm. Furthermore HWRF performed better in intensity forecasts than the GFDL dynamical model up to 84h and had nearly the same skill as the baseline Decay SHIPS statistical model throughout the 120h forecast time period. The SAIC JHT project was an integral contributor to this progress.

Once the model was made operational, this project moved in the direction of solving production model problems and model improvement. One nagging problem noticed in the 2008 season was the unrealistic land surface temperatures predicted during the 2008 tropical season in HWRF. It was discovered that this was a sporadic problem involving spurious radiative surface fluxes. This was resolved by calling radiation for the nest domain at frequent constant intervals. It is anticipated that this upgrade will lead to better forecasts of intensity and track during landfall. Some examples will be shown.

As mentioned, the physics packages have been brought in line with the GFDL model. The HWRF group is now in position to make improvements and upgrades over and above the capabilities of the GFDL model. One such example is the implementation of the NOAH LSM (land surface model) into the HWRF forecast system in test mode. As an additional benefit, the runoff from the LSM can be used to drive a basic stream flow model. Preliminary results indicate better rainfall forecasts with less bias. Another example is the inclusion of gravity wave drag into the operational HWRF for the 2009 season. Preliminary results of these upgrades will be shown.

Besides improving physics, the HWRF group has made advances in developing a high resolution version of the production version of HWRF. Other work continues on the development of a more complete diagnostic package so more objective evaluations can be made over and above the standard evaluations of absolute errors of track and intensity.

Developing Coupled Tropical Cyclone-Wave-Ocean Models for Transition to Operations

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We will discuss the progress in developing coupled tropical cyclone-wave-ocean models for operational implementations at NOAA and Navy. The key element of our coupled modeling approach is the air-sea interface model (ASIM) developed by our research group at URI that consists of the wave boundary layer model and the air-sea heat and momentum flux budget model. The ASIM is imbedded into the TC-wave-ocean coupled model and calculates all the flux boundary conditions for the atmospheric, wave and ocean models.

We will evaluate the performance of the NOAA's operational WAVEWATCH III under a very strong tropical cyclone wind forcing. We will compare the model results with field observations of the surface wave spectra from a scanning radar altimeter, NDBC time series and satellite altimeter measurements in Hurricane Ivan (2004). The results suggest that the operational model tends to overestimate the significant wave height and the dominant wave length, and produces a wave spectrum that is higher in wave energy and narrower in directional spreading. When an improved drag parameterization is introduced and the wave-current interaction is included, the model yields improved forecast of significant wave height and wave spectral energy, but underestimates the dominant wave length.

We will also present the results of numerical simulations of the hurricane induced sea surface temperature cooling in the vicinity of a warm core eddy. When considering hurricane intensity, one often neglected aspect of warm core ocean eddies is the preexisting anticyclonic circulation around the eddy. Depending on the translation speed of the hurricane and the location of the eddy relative to the storm track, this anticyclonic circulation may impact the location and magnitude of the hurricane-induced sea surface cooling. One significant result from these model simulations indicates that when a warm ocean eddy is located to the right of the storm track, the interaction of the preexisting eddy circulation with the hurricane-induced cold wake can cause, in some cases, increased sea surface cooling under the core of the storm relative to the case where no ocean eddy is present at all. Therefore, the presence of a warm core eddy in advance of a hurricane may in some cases create a *less favorable* condition for hurricane intensification; similarly, the presence of a cold core eddy may in some cases create a *more favorable* condition for hurricane intensification.

Coupled Hurricane Atmosphere – Ocean Modeling System (HWRF-HYCOM) and Hurricane Forecast Performance

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Real-time hurricane forecast, using a coupled Hurricane Weather Research and Forecast model and HYbrid Coordinate Ocean Model (HWRF-HYCOM) system, has been successfully conducted in parallel to the NCEP Central Operational (NCO) model. The primary difference between the HWRF-HYCOM and NCO system is the ocean dynamic model (POM for the NCO system), and the method for ocean initialization. The ocean horizontal resolution is *O*(10km) and *O*(20km), and the vertical resolution is hybrid 26 layers vs. 23 levels, for HYCOM and POM respectively. Significant differences between these two systems include 1) the step for the correction of forecast storm location and intensity in the HWRF-HYCOM; 2) the approach in the preparation of the ocean initialization: We derive ocean initial and boundary conditions from the Atlantic-Basin scale, RTOFS (Real-Time Ocean Forecast System) that is currently running once a day in NCEP with data assimilation. Whereas, the ocean model in the operational utilizes remotely sensed sea surface temperature to provide meso-scale features imbedded in a GDEM climatology with their current locations and intensities.

The HWRF-HYCOM hurricane forecast is comparable to that of the NCO system. Forecast errors computed against a best track are generally less than 200-km for track and $\pm 20\%$ for intensity after five days. Improvements for the HWRF-HYCOM systems are expected, particularly on the hurricane intensity estimates, by employing better initial conditions and tuning mixing and bulk parameterizations of air-sea fluxes.

Evaluation and Improvement of Ocean Model Parameterizations for NCEP Operations: Ivan (2004)

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The ocean response to hurricane Ivan (Sept 2004) was simulated within the Gulf of Mexico using the Hybrid Coordinate Ocean Model (HYCOM). In this study, the ocean model response to hurricane Ivan is evaluated against satellite SST measurements and moored ocean current observations. Hurricane Ivan passed directly over 14 Acoustic Doppler Current Profiler (ADCP) moorings that were deployed as part of the Navy Research Laboratory *Slope to Shelf Energetics and Exchange Dynamics (SEED)* project (Teague et al., JPO, 2007). The model was initialized by oceanic fields provided by the latest generation of the U. S. Navy ocean nowcast-forecast system developed at the Naval Research Laboratory. The modeling effort builds upon a previous NOAA JHT grant that eliminated two mixing schemes from contention leaving Mellor Yamada (MY), K- Profile Parameterization (KPP) and Goddard Institute of Space Sciences (GISS) schemes. A baseline experiment is performed that is forced by atmospheric fields from the 27 km resolution COAMPS model, but with high-resolution wind speed and stress fields obtained from the HRD HWIND analysis patched in for the storm region. HWIND vector wind fields are first patched into COAMPS fields, and then wind stress is calculated using bulk formula with the Donelan et al. (GRL, 2003) drag coefficient prior to model runs. The model is nested within a GOM data-assimilative hindcast that uses the U. S. Navy NCODA system. It is run with 26 vertical layers and KPP vertical mixing is used. Surface turbulent fluxes are calculated during the model run using the COARE 2.6 algorithm bulk formula.

Thirteen alternate experiments are run, each differing from this control experiments <u>in a single aspect</u> to isolate sensitivity to spatial resolutions, vertical mixing schemes, surface drag and enthalpy coefficients, surface forcing fields, model initializations, and three-dimensional ocean dynamics, the latter achieved by altering the model code to solve independent one-dimensional momentum and thermodynamical balances at each grid point. Model sensitivities are evaluated by calculating the changes in SST forced by Ivan by calculating turbulent heat flux from ocean to atmosphere following the storm track, and by comparing upper-ocean velocity profiles to SEED mooring measurements. RMS differences between those produced by the baseline experiment and each of the other experiments quantify the sensitivity to the individual model property and parameterization from the baseline experiment. Accurate initialization of ocean features is the most important single factor for improving the accuracy of the ocean response. The impact of three-dimensional ocean dynamics on the SST response pattern and on heat flux from ocean to atmosphere is nearly as large as the initialization of ocean features. Four factors are of intermediate importance: (1) parameterization of surface momentum flux through the drag coefficient; (2) choice of vertical mixing scheme; (3) horizontal resolution; and (4) accurate representation of storm structure in the surface forcing. The least important factor is vertical resolution. The parameterization of surface heat flux through the sensible and latent heat drag coefficients has little influence on SST and current response but has a large impact on heat flux from ocean to atmosphere.

Upgrades to the GFDN Model for 2009 and Beyond

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Major physics and resolution upgrades to the Navy's version of the GFDL Hurricane Prediction System (GFDN) were made operational at the Fleet Numerical Meteorology and Oceanography Center in October, 2008. These changes included doubling of the finest resolution from 1/6 to 1/12 degree, coupling with the Princeton Ocean Model (POM) in all ocean basins (three-dimensional coupling in the Atlantic and one-dimensional coupling elsewhere), and incorporation of dissipative heating and NCEP's Ferrier microphysics package. In all ocean basins except the Atlantic, the ocean model in this new GFDN coupled system is now initialized from the real-time NCODA (Navy Coupled Ocean Data Assimilation) global analysis. NCODA provides more detailed and accurate representation of the 3-dimensional temperature and salinity fields. These improvements were made in close collaboration between scientists at GFDL and URI (University of Rhode Island). Since the new model became operational toward the end of the hurricane and typhoon seasons, their were not enough cases to evaluate the impact of these changes. However, preliminary testing prior to operational implementation suggested that these changes should lead to significant reduction in model errors for both track and intensity.

While this new version of the GFDN forecast system was being tested for operational implementation, work began on extending the coupling in the western Pacific from one-dimensional to a full three-dimensional coupled system. With the NCODA global analysis already operational in GFDN, this important upgrade should enable the model to properly resolve the effect of oceanic mesoscale features such as warm and cold core rings and the Kuroshio current. Recent studies have suggested this can lead to rapid intensity changes in typhoons that pass over these features. This new 3-D coupled system will be delivered to FLEET by March, with implementation planned for the summer. Several examples will be shown of the impact of this upgrade as well as a summary of the overall improvements in the model forecasts. Developmental work is also continuing to extend the three-dimensional coupling to the eastern Pacific as well, with possible implementation by later in the summer.

Future planned improvements of the GFDN model will also be discussed. These include replacing the GDEM climatology currently used in the Atlantic, with the NCODA 3-D temperature and salinity analysis already operational in the other ocean basis in GFDN. As increased computer power becomes available, the finest horizontal grid spacing will be increased from 1/12 to 1/18 of a degree. Major upgrades to the physics of the air-sea momentum and heat fluxes are also planned for the GFDN model in 2011, with implementation of the URI air-sea interface model (AISM) that has been under development at URI for the past several years. Since the air-sea fluxes depend on surface wave related processes near the air-sea interface and are highly variable in space and time, a fully-coupled ocean-wave-atmospheric model is being developed, which uses the current coupled system and NCEP's WWIII model, together with new strategies for wind-wave-current interactions. These will be discussed in more detail. Finally, in collaboration with GFDL scientists, the radiation package in the GFDN model will be upgraded to include interaction with micro-physics species.

Application of COAMPS-TC to TCS-08

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A new version of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is being developed for the prediction of tropical cyclone track, structure, and intensity (COAMPS-TC). COAMPS-TC will include new analysis methodologies for the initialization of the TC structure, and improved air-sea flux and microphysics parameterizations to improve structure and intensity forecasts. The Tropical Cyclone Structure-2008 (TCS-08) field experiment offered an excellent opportunity to exercise a prototype of COAMPS-TC in a real-time environment for a number of tropical cyclones. This enabled us to test the robustness, efficiency, and accuracy of the analysis and prediction capabilities of COAMPS-TC, and to use the results to guide the next phase of development of COAMPS-TC.

A real-time automated system was set up to enable COAMPS-TC to be run for every tropical cyclone in the TCS-08 area (e.g., western Pacific) every 12 hours. COAMPS-TC was run using nested grids. The TCS-08 configuration of COAMPS-TC used a coarse mesh (45 km) that was fixed in time and large enough in areal coverage so that the same coarse grid was used for all TCS-08 applications. The two inner grids (15 and 5 km) were centered on each TC at the start of each forecast, and moved automatically with each storm so that they always remained centered on the TC. The COAMPS-TC forecast model automatically tracked the position of the TC in each forecast. All forecasts were run to 72 h.

A total of 96 forecast were generated over 13 different tropical cyclones. Results show that the prototype of COAMPS-TC produced track forecasts that were competitive with other currently-used TC numerical forecast aids. In terms of the intensity prediction of TCs, COAMPS-TC was generally too weak at the analysis time, and tended to intensify the TCs too much during the 72 forecast, with a bias toward too intense at 72 hours.

These findings have dictated what further research and development needs to be done with COAMPS-TC. We are now testing improvements to our analysis of the TC circulation to better define the initial strength and structure, and studying further improvements to the air-sea interaction and moist physics parameterizations to better model TC intensity changes. In addition, we are working on the integration of an ocean data assimilation system with the atmospheric components of COAMPS-TC. We were able to run this two-way coupled COAMPS-TC for a small number TCs during TCS-08 (and for a number of TCs in other basins, as well) and have integrated this version of COAMPS-TC in our post-TCS-08 research. The set-up and results of COAMPS-TC for TCS-08, and current research on this system will be discussed.

Session 7
Tropical Cyclone Model Development and Technology Transfer, Part 2

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Ensemble, Corrected Consensus, and Weighted Consensus TC Track Forecasts

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The interpolated versions of seven high-quality TC track forecast models are routinely available to the forecasters at NHC. The seven models are: GFS, GFDL, and the Hurricane WRF (AVNI, GFDI, and HWFI; NCEP); NOGAPS and GFDN (NGPI and GFNI; FNMOC); the UKMO global model (EGRI); and the ECMWF global model (EMXI). The operational consensus forecast aid, TVCN, is formed by giving equal weight to the available forecasts from AVNI, GFDI, HWFI, NGPI, GFNI, EGRI, and EMXI. Based on the exceptional TC track forecast performance in the Atlantic of the ECMWF global model for all forecast lengths and of the NCEP GFS ensemble mean (AEMI) for 96 h and 120 h, two experimental consensus forecast aids were constructed and tested for both the Atlantic and eastern North Pacific basins. A weighted consensus aid (CNW6) was constructed by giving the EMXI forecasts six times the weight given to the forecasts from the other models used by TVCN. A second consensus aid (CON3) was constructed by taking the average of the TVCN, EMXI, and AEMI forecasts.

For the Atlantic in 2008, the TC track forecast errors for EMXI were 46 nm, 80 nm, 126 nm, 167 nm, and 209 nm for 24 h, 48 h, 72 h, 96 h, and 120 h, respectively. The respective errors for GFDI, the second best model, were 56 nm, 96 nm, 139 nm, 200 nm, and 259 nm while those for TVCN were 48 nm, 86 nm, 126 nm, 169 nm, and 210 nm. The EMXI errors were comparable to those for TVCN and about 10-20 percent smaller than those for GFDI. While the TC track forecast errors for AEMI were considerably larger than those for GFDI and TVCN for forecast lengths less than 96 h, the respective AEMI errors at 96 h and 120 h were 164 nm and 183 nm. The respective forecast errors for corrected consensus, TVCC, were 47 nm, 86 nm, 127 nm, 172 nm, and 203 nm, comparable to those for TVCN. The respective forecast errors for CNW6 were 45 nm, 78 nm, 117 nm, 158 nm, and 198 nm, a 6-9 percent improvement over those for TVCN. For CON3, the respective errors were 49 nm, 84 nm, 122 nm, 146 nm, and 177 nm, comparable to those for TVCN out to 72 h but 14-16 percent smaller at 96 h and 120 h. In summary, the forecast errors for CNW6 were the smallest for forecast lengths out to 72 h while those for CON3 were the smallest at 96 h and 120 h.

Unlike the Atlantic, the EMXI TC track forecast errors for the eastern North Pacific in 2008 were considerably larger than those for TVCN, especially at the longer forecast lengths, and the AEMI forecast errors were considerably larger than those for EMXI. As a result, it was not surprising to see that the performance of CNW6 and CON3 for this basin was nothing like that for the Atlantic. The TC track forecast errors for TVCN were 45 nm, 76 nm, 104 nm, 151 nm, and 192 nm for 24 h, 48 h, 72 h, 96 h, and 120 h, respectively. The respective errors for TVCC were 45 nm, 79 nm, 94 nm, 149 nm, and 205 nm, about 10 percent better than TVCN at 72 h but 7 percent worse at 120 h. For CNW6, the respective errors were 45 nm, 75 nm, 106 nm, 159 nm, and 216 nm, comparable to those for TVCN out to 72 h but 5-12 percent larger at 96 h and 120 h. The respective errors for CON3 were 48 nm, 87 nm, 131 nm, 176 nm, and 229 nm, 14-26 percent larger than those for TVCN for forecast lengths greater than 24 h.

The Atlantic results indicate that weighted consensus TC track forecast aids are capable of producing improved track forecasts if one or more of the models perform considerably better than the others. However, whether such improved model performance is consistent from season to season is yet to be determined. The eastern North Pacific results suggest that such performance and the utility of weighted consensus TC track forecast aids is likely to be basin dependent.

TC Dressing: A Probabilistic Approach to Providing State-Dependent, Non-Isotropic Forecast Track Error Guidance

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The Goerss Predicted Consensus Error (GPCE) approach has been extended to independently predicting expected across-track and along-track error. In addition, a new product called the Probability of Left/Right/Fast/Slow (P-LRFS) has been produced to provide guidance on 3rd order forecast moments. GPCE-AX and P-LRFS were originally developed using GUNA over 2002-2005 (dependent) and 2006 (independent). GPCE-AX and P-LRFS have been extended to CONU and to CONW. The CONU results (training over 2002-2007, testing over 2008) indicate that GPCE-AX generally outperforms GPCE in terms of reliability (the fraction of time verification is bound by the 70% uncertainty isopleths) and sharpness (the area bound by the 70% isopleths). The CONW results (training over 2004-2006, testing over 2007) are less conclusive; the sharpness and reliability results for GPCE and GPCE-AX are very similar to one another.

Using Partnerships to Meet NOAA's Needs for its Next Generation Storm Surge System

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Storm surge inundation is a main contributor to the damage and loss of life caused by tropical cyclones, as seen in recent hurricane storm surge events (e.g., 2008's Ike, 2005's Katrina, 2004's Ivan). Minimizing the impacts of inundation is an important mission that spans many offices. A NOAA-wide team has been assembled to guide development of its next generation storm surge system. Planning and research accomplishments in support of this effort will be highlighted.

Customers have demonstrated a need for clear and timely communication of inundation risk; meeting this mission requires a multi-faceted approach. Fundamental is prediction of the total water level of inundation at relevant local scales, regardless of source; factors such as surge, waves, and hydrologic flooding all need to be considered. However, a wide range of users exist in a broad community that includes forecasters, emergency managers, coastal planners, and first responders. Requirements for timeliness and accuracy depend on why they are making decisions:

1) coastal land-use & resiliency planning (years to decades before event),
2) emergency management planning (months to years before event),
3) evacuations (days before event),
4) real time response (duration of event), and
5) post-storm recovery (hours to years after event).

Furthermore, clear and effective communication techniques are required to translate technical products to decision-making activities. Continued development of tools such as maps and visualizations of depth of water above land are needed to achieve these goals. Additionally, effective education efforts are needed to ensure proper use and interpretation of products.

To meet this mission the next generation system needs to be flexible and able to consider the need for growth in areas such as observations, ensemble modeling, probabilistic prediction, and mapping/visualization. The system will need to link to federal operational observational and prediction systems. Furthermore, developments need to be systematically vetted within an operational environment (e.g., using standardized procedures and a modeling test bed). Advancement will not be possible without partnerships across the community. By leveraging resources and technologies across regional associations, government agencies, and academic institutions, advancements can be shared and research can be quickly transferred to operations. Finally, effective partnering requires a strong foundation in the development and use of industry-wide standards, models, tools, and benchmarks, a strategy proposed by the NOAA team.

Sensitivity of the HWRF model prediction for Hurricane Ophelia (2005) to the choice of the cloud and precipitation scheme

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To demonstrate how the model cloud and precipitation physics may affect the hurricane track, structure, and intensity prediction by the HWRF model, we conducted several sensitivity numerical experiments designed to show how the simulation would be different if the cumulus convective parameterization was used or omitted from the inner nested mesh and how such a difference is sensitive to the choice of convective parameterization. The model resolution is the same as that used in the operational HWRF model, namely, about 9 km for the nested domain and 27 km for the outer domain. But we used a relatively larger domain for the inner nest than that used in the operational forecast model. Two parameterizations for cumulus convection tested are the Kain-Fritsch (KF) scheme and the Betts-Miller-Janjic (BM) scheme. Other model physics include the GFDL shortwave and longwave radiation schemes, the Mellor-Yamada-Janjic TKE scheme for the planetary boundary layer (PBL), and the LOAH land surface model. These are identical in all experiments. The case of Hurricane Ophelia (2005) was chosen for a demonstration. The model was initialized at 00 UTC 09 September 2005 and integrated for 96 hours. The initial and the lateral boundary conditions were defined using the NCEP GFS global final analysis (FNL).

In this talk, we will demonstrate how the model cloud and precipitation physics may affect the hurricane track, structure, and intensity prediction by the HWRF model. We will show that the simulated storm track, intensity, and structure were largely affected by the choosing of the convective parameterization scheme either used for the inner mesh or just the outer mesh or both meshes. It was not our attempt to determine which combination is the best since no single simulation has performed the best in all aspects of the observed hurricane. Although we only show the simulations for Hurricane Ophelia (2005), the results strongly suggest a need for a detailed evaluation of the cloud and precipitation physics used in the operational HWF model and to understand how the discrepancies affect the storm motion, intensity, and structure. Since some systematic biases have been reported in the operational HWRF model, improvements of the representation of the cloud and precipitation physics would lead to improved prediction skill of hurricane track, structure, and intensity by the HWRF model at NCEP/EMC.

Experiments of Hurricane Initialization with Airborne Doppler Radar Data for the Advanced-research Hurricane WRF (AHW) Model

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Initialization of the hurricane vortex in weather prediction models is vital to intensity forecasts out to at least 48 h. Airborne Doppler radar (ADR) data has sufficiently high horizontal and vertical resolution to resolve the hurricane vortex and its imbedded structures, but has not been extensively used in hurricane initialization. Using the Weather Research and Forecasting (WRF) three-dimensional variational (3D-Var) data assimilation system, the ADR data are assimilated to recover the hurricane vortex dynamic and thermodynamic structures at the WRF model initial time. The impact of the ADR data on three hurricanes, Jeanne (2004), Katrina (2005) and Rita (2005), are examined during their rapid intensification and subsequent weakening periods before landfall.

With the ADR wind data assimilated, the three-dimensional winds in the hurricane vortex become stronger and the maximum 10-m winds agree better with independent estimates from best track data than without ADR data assimilation. Through the multivariate incremental structure in WRF 3D-Var analysis, the central sea level pressures (CSLPs) for the three hurricanes are lower in response to the stronger vortex at initialization. The size and inner core structure of each vortex are adjusted closer to observations of these attributes. Addition of reflectivity data in assimilation produces cloud water and rainwater analyses in the initial vortex. The temperature and moisture are also better represented in the hurricane initialization.

We conduct 48-h forecasts to evaluate the impact of ADR data using the Advanced-research Hurricane WRF (AHW), a derivative of the Advanced Research WRF (ARW) model. Assimilation of ADR data improves the hurricane intensity forecasts. Vortex asymmetries, size, and rain bands are also simulated better. Hurricane initialization with ADR data is quite promising towards reducing intensity forecast errors at modest computational expense.

Recent Trends in Dynamical Medium-Range Tropical Cyclone Track Prediction and the Role of Resolution Versus Physics in the ECMWF Model

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A commonly held view in the tropical cyclone (TC) modeling community is that dynamical TC track and intensity prediction requires: 1) high-resolution (order 1 km); 2) the assimilation of detailed observations in the inner core; and 3) ensembles of independent deterministic and perturbed models. However, the recent performance of the operational high-resolution run of the ECMWF global model challenges these notions and suggests that the critical and dominant factor in numerical TC prediction skill is the modeling of physical processes. In this paper we analyze how model changes, in both resolution and in the parameterization of key physical processes, impact the model forecasts of the global tropical wind field and TC tracks. Since a change in the cumulus convection scheme in November 2007, the ECMWF TC track forecasts have outperformed multi-model consensus by 20% globally in the medium-range (72 h). We compare this finding to trends in model performance vis-à-vis consensus in both the Atlantic and western North Pacific basins for the period 1992-2008 and demonstrate that this gain/improvement by the ECMWF model is unprecedented. The results will be updated to include the 2009 southern Hemisphere season to see if the trend persists and the talk will conclude with a number of opinions regarding the way forward for improved numerical hurricane forecasts.

Session 8
Tropical Cyclone Model Development and Technology Transfer, Part 3

SESSION 8

Model Development for Typhoons at the Japan Meteorological Agency

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The Japan Meteorological Agency's numerical model framework for typhoon prediction is presented. Two systems are used for typhoon forecasting; one is a high-resolution global spectral model, which became operational in November 2007; and the other is an ensemble prediction system, which was implemented in February 2008. The global model has a resolution of TL959L60 (about 20 km in the horizontal and 60 vertical levels), and runs 4 times a day with a prediction range up to 216 hours. The data assimilation system is the 4 dimensional variational system (4DVAR), which has been in operation since 2005, and a typhoon bogus technique is adopted. The Typhoon Ensemble Prediction System has a resolution of TL319L60 (about 60 km in the horizontal and 60 vertical levels), and runs 4 times a day with a prediction range of 132 hours. The ensemble size is 11 and a singular vector method is employed to create initial perturbations.

In the presentation, the verification results of the two systems in 2008 will be presented as well as the detailed system configuration. In addition, recent participation by JMA in activities such as THORPEX Pacific Asian Regional Campaign will be briefly introduced.

The Hurricane Research System: Development of a High Resolution, Non-Hydrostatic Model for Addressing the Need for the Next Generation of Improved Tropical Cyclone Intensity Prediction

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The hurricane forecast improvement project (HFIP) is a unified NOAA approach to guide and accelerate improvements in hurricane track, intensity and structure forecasts, with an emphasis on rapid intensity change. An integral component of the HFIP will be the development of improved coupled atmosphere-ocean-land surface, high-resolution non-hydrostatic regional models. The HFIP model development effort will pursue a two-stream development path: one path that builds on current operational capabilities consistent with current and future computer limitations for operations, and a second development path that will focus on research using high resolution models (grid lengths of 1-3 km) which may be necessary to properly resolve the inner-core processes that influence intensity changes. Developed from NCEP's WRF-NMM/HWRF modeling system (Gopalakrishnan et al., 2006), the Hurricane Research System (HRS) is the next generation, high-resolution hurricane modeling system designed for improving forecasts related to the rapid intensity change problem. This modeling system is currently being developed at NOAA's OAR labs (specifically at AOML and ESRL). The development of
This system will be outlined here.

A baseline configuration for the HRS was tested at the current operational moving grid resolution of 9 km for most of the hurricane season of 2008. Some results from these runs will be presented. In addition, we have produced forecasts at 3 km grid length from 69 previous hurricane forecasts from 200?-2007, selected for the challenging nature of their intensity evolution. We see significant improvements in track, intensity and structure between forecasts obtained at the operational resolution of 9 km and at the higher resolution of 3 km. The results from some of these cases will be presented. Development of the third nest valid for inner core structure prediction down to 1 km resolution is ongoing.

Reference: Gopalakrishnan, S.G., N. Surgi, R. Tuleya, and Z. Janjic, 2006 : "NCEP's Two-way-Interactive-Moving-Nest NMM-WRF modeling system for Hurricane Forecasting", 27th Conference on Hurricanes and Tropical Meteorology, 24-28 April 2006, Monterey, California

Impact of Horizontal Resolution on Rapid Intensity Change Forecasts using the Hurricane Research System

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Advances in the prediction of tropical cyclone (TC) intensity and structure have lagged behind advances in track prediction. A primary reason for this lag is the multiscale nature of the physical processes relevant for intensity and structure changes. Such processes range in spatial scale from 1000's of km to mm and in temporal scale from days to seconds. Numerical models are a key tool used to understand and predict TC structure and evolution. Only within the past several years, however, have cloud-resolving models (grid length of O(1 km)) become commonplace. Such resolution is believed to be important because it is not until that resolution is reached that the deep convective cores, which produce a large amount of the diabatic heating and mass flux within the TC core, are explicitly resolved.

Tests of the impact of horizontal resolution on the ability of numerical models to reproduce rapid intensity change are shown here. The Hurricane Research System (HRS) model, developed from NCEP's WRF-NMM/HWRF modeling system and adapted by NOAA/AOML and NOAA/ESRL, has been run at 9-km and 3-km grid lengths on 69 hurricane cases selected for the challenging nature of their intensity evolution. Results from select cases that had airborne Doppler radar coverage and demonstrated rapid intensity change will be shown. The inner-core vortex- and convective-scale structures will be compared with the radar data for these cases in an attempt to identify model skill and biases and how they vary as a function of resolution.

Impact of Sea Spray on the Balance of Turbulent Kinetic Energy in the Hurricane Surface Boundary Layer

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The feedback effects of sea-spray on the mean wind, temperature and moisture profiles in the surface boundary layer associated with tropical cyclones is investigated using a 1-D coupled sea-spray and surface boundary layer (SBL) model. This model is capable of simulating the microphysical aspects of evaporation of saline water droplets of various sizes and their dynamic and thermal interaction with the turbulence mixing that is simulated by the Mellor-Yamada 1.5-order closure scheme. The sea-spray droplet generation is described by a state-of-the-art parameterization which predicts the size spectrum of sea-spray droplets at a given surface stress (or wind speed). The results from a series of simulations reveal salient characteristics of the way in which evaporating droplets of various sizes modify the turbulence mixing near the surface, which in turn affects further droplet evaporation.

Based on these results, a bulk parameterization scheme of sea-spray mediated air-sea heat and momentum fluxes has been developed at NOAA/ESRL. Results from testing the scheme with the current operational setup of the HWRF model indicate that the scheme may be used as a way to reduce the weak intensity bias since the scheme's impact on hurricane track prediction is small enough that it can be neglected. It is found that because the very turbulence that transports momentum and heat across the air-sea interface is also responsible for the generation of sea spray, the resultant effect of sea spray on both the momentum and heat fluxes is complicated by the interaction between the sea spray, turbulence and mean flow.

Evaluation of Planetary Boundary Layer Parameterizations in Tropical Cyclones by Comparison of in-situ Observations and High-Resolution Simulations of Hurricane Isabel (2003)

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The planetary boundary layer (PBL) depicted in high resolution simulations of Hurricane Isabel (2003) is studied and evaluated by direct comparison with in-situ data obtained during CBLAST. Two schemes for parameterizing turbulence in the PBL are evaluated: the Yonsei University (YSU) scheme and the Mellor-Yamada-Janjic (MYJ) scheme. Evaluation of these schemes is useful since they both widely used and are based entirely different methods for representing the PBL. Overall, the tracks and intensities predicted by the two schemes are very similar. The peak surface wind speeds are substantially improved for both schemes when they are modified to have more accurate formulas for the roughness of the ocean surface as a function of wind speed.

The PBL schemes are also evaluated by direct comparison of boundary layer profiles of wind, temperature, and humidity to those observed from dropsondes. Overall, both schemes reproduce the boundary layer structures remarkably well, even more so when the improved formula for surface roughness is used. A consistent difference between the YSU and MYJ schemes is an excessive dissipation of low-level momentum in the MYJ scheme, leading to an excessively large radial inflow and overall secondary circulation. The relationship between the simulated instantaneous surface wind speeds and 1 minute mean wind speeds is also explored, with surprisingly different results between the two schemes.

An Integrated Tropical Cyclone Information System for Research

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In spite of recent improvements in hurricane track forecast accuracy, currently there are still many unanswered questions about the physical processes that determine hurricane genesis, intensity, track and impact on large-scale environment. Furthermore, a significant amount of work remains to be done in validating hurricane forecast models, understanding their sensitivities and improving their parameterizations. None of this can be accomplished without a comprehensive set of multiparameter observations that are relevant to both the large-scale and the storm-scale processes in the atmosphere and in the ocean.

To address this need, we and our colleagues from Marshall Space Flight Center have developed the framework for a comprehensive Integrated Tropical Cyclone Information System (iTCIS) of high-resolution satellite, airborne and in-situ observations and model outputs pertaining to: i) the thermodynamic and microphysical structure of the storms; ii) the air-sea interaction processes; iii) the larger-scale environment as depicted by the SST, ocean heat content and the aerosol loading of the environment. Our goal was to create a one-stop place to provide the researchers with an extensive set of observed hurricane data, and their graphical representation, together with convection-resolving model output, all organized in an easy way to determine when coincident observations from multiple instruments are available.

Currently the iTCIS is populated with satellite observations of all tropical cyclones observed globally during 2005. Our future plans are to extend the database both forward in time till present as well as backward to 1998. Furthermore, NASA field campaign data will be included and displayed using Goggle Earth field-campaign-specific approach that allows the creation of overlays on-demand. This innovative approach, known as the Real Time Mission Monitor (RTMM) has been developed at the Marshall Space Flight Center. It has proven very valuable during past field campaigns, both during the campaign as well as in the post-campaign analysis. The RTMM is described in a separate presentation.

We began the development of analysis tools that will communicate with the database and will allow for online investigations without the need to download large data volumes. The analysis tools will be used to compute single and multiparameter statistics and to determine spatial, temporal and multiparameter covariances that are needed to evaluate model performance, provide information for data assimilation, and characterize and compare observations from different platforms.

We envision that the developed hurricane information system will help in the validation of the hurricane models, in the systematic understanding of their sensitivities and in the improvement of the parameterizations employed by the models. Furthermore, it will help in studying the physical processes that affect hurricane development and impact on large-scale environment.

This talk will describe the structure of the satellite-based component of the iTCIS, the analysis system and the future plans. A poster will accompany the talk. It will illustrate how the iTCIS can be used to discriminate between high resolution WRF model simulations that employ different parameterizations with the goal to determine the model setup that produces most realistic simulations.

The work described here was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Session 9
Other Research to Improve the Prediction of Tropical Cyclone Intensity and Structure, Track, Precipitation, Coastal, and Inland Inundation, Part 1

Differential O2 Absorption Barometric Pressure Radar (DIAR_BAR): Improvements in Tropical Storm Forecasts

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Currently, sea surface air pressure measurements can only be observed from in situ measurements using buoy, ship and dropsonde techniques, which are sparse in spatial coverage and expensive to implement. There are no pressure remote sensing methods available even in experimental stages. This study considers use active microwave systems to obtain the differential O_2 absorption at 50-56 GHz bands to fill the observational gap. The numerical simulation results show that the rms errors of the instantaneous sea surface pressure estimates can be as low as 4 mb. With multiple radar measurements the uncertainty in radar sea surface pressure estimates would drop to about 1 mb which is similar to conventional in situ buoy measurements. A prototype system of the DIfferential O_2 Absorption Radar for Barometry (DIAR-BAR) has been developed and integrated it into an aircraft. The flight test results show the instrument performance meets or exceeds the all system requirements indicting the concept of the differential O_2 absorption for the pressure remote sensing measurements could be realized with existing radar technologies.

Motivated by the potential application of DIAR-BAR, the importance of using surface pressure distribution in three dimensional variational data assimilation system for WRF is investigated in a case study of hurricane Katrina. Hurricane Katrina crossed Florida peninsula on August 26, 2005, which provides us surface pressure data with good spatial distribution that is rarely available for other hurricanes in their developing stage over the ocean. Various patterns of surface pressure distribution are assimilated, and the bias in landfall position for 84-hour forecasting decreases from 360 km in the control run up to 38 km in assimilation runs. It demonstrates the DIAR-BAR system will have great potential for weather observations and other meteorological applications, especially for forecasts of hurricanes.

Astronomic Tides, Flows, and Hurricane Storm Surge Modeling of the Pascagoula River, Mississippi

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This study presents simulated astronomic tides, flows and storm surges for the Pascagoula River located in lower Mississippi along the Gulf of Mexico. The work is motivated by the absence of an existing model that can accurately describe storm tide propagation up the Pascagoula River and out of its banks. The research described herein directly incorporates a full accounting of the hydraulic conditions for flood/river forecasting, including representation of inundation areas. Astronomical and meteorological tides are obtained from computations performed with ADCIRC-2DDI a two-dimensional depth integrated hydrodynamic circulation code.

The full Western North Atlantic Tidal (WNAT) model domain includes the Atlantic Ocean west of the 60 degree west Meridian, the Caribbean Sea and Gulf of Mexico and is modified to incorporate the Pascagoula River and its tributaries. The domain is described with an unstructured finite element mesh of triangles that range in side length from approximately five meters within the river banks to approximately 160 kilometers in the deep ocean. Recently acquired LiDAR data is used to build the overland DEM and National Landcover Data is interpreted to characterize the bottom friction. In addition, the atmospheric wind models that provide wind input to the ADCIRC surge model produce wind speeds that assume open-ocean marine conditions; therefore, for overland and nearshore areas the wind speeds are adjusted via wind-reduction factors.

In addition, a shelf-based domain for the Pascagoula River system is developed that can produce results comparable to the large-scale domain. The simulated results show good agreement with the large scale domain approach, recorded storm data and observed high water elevations. It is revealed that the shelf-based model is capable of accurately predicting storm tides generated by hurricanes along the coastal areas provided the shelf-based model receives accurate elevation forcing at its open boundary. This work will enable the Lower Mississippi River Forecast Center in their effort to provide forecasts for this complicated riverine system.

Toward Modeling of River-Estuary-Ocean Interactions to Enhance Operational River Forecasting in the NOAA National Weather Service

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NOAA National Weather Service (NWS) uses hydrologic models and one-dimensional (1D) hydraulic routing models to forecast river flows and stages at over 4,000 locations in the United States. In coastal zones where rivers widen and flow into estuaries, 1D modeling does not sufficiently represent the two or three-dimensional (2D/3D) hydraulic conditions. Water levels near river mouths and in estuaries vary in two dimensions depending on tides, winds, freshwater inflows, and other forcing factors. A logical next step in improving the availability and accuracy of water forecasts in coastal areas is to develop the capability to robustly couple 1D river models and 2D/3D estuary/ocean operational models. To achieve the coupling, 2D/3D ocean and estuary models would receive freshwater inflows from 1D models, and 1D river models would receive stage boundary conditions from the 2D/3D models.

In this presentation, we will explain the suitability of several 2D/3D, Chesapeake Bay water forecasting models for this two way coupling. We will evaluate models based on several criteria, including but not limited to mesh size requirements, computational requirements, wetting and drying functionality, ability to ingest freshwater flows, model stability under a wide range of conditions, ease of use, and accuracy.

Sensitivity of an Asymmetric Gradient Wind Model to Sources of Tropical Cyclone Track Information and Implications for Storm Surge Prediction

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The sensitivity of an asymmetric parametric gradient surface wind model to three different sources of tropical cyclone track information is examined to ascertain the impact on predictions of storm surge. The central and background pressures, wind speed intensity and significant (34-, 50-, and 64-kt) wind radii are obtained from: (1) National Hurricane Center (NHC) forecast advisories and Automated Tropical Cyclone Forecast (ATCF) Best Track data, (2) NOAA H*Wind analyses, and (3) Colorado State University (CSU) Multiplatform Satellite Surface Wind Analyses. Employed in a real-time, event-triggered storm surge forecasting system (Mattocks and Forbes, 2008), these parametric winds are generated from NHC forecast advisories the moment they are inserted into the real-time weather data stream, maximizing the number of hours of forecast utility. The winds are directly coupled to the ADCIRC ocean model at every time step and calculated at exact finite-element mesh node locations. A directional surface roughness parameterization that modulates the wind speed at a given location based on the types of land cover encountered upwind from 72 different wind directions (5° increments) is used to smooth the transition of the winds over patchy terrain and across land-water boundaries. Although H*Wind wind radii have been found to be statistically larger than the NHC Best Track radii, both significantly underestimate the extent of the tropical storm force wind area (Moyer et al., 2007). Since the magnitude and expanse of the water surface elevations produced by storm surge prediction models strongly depend on the accuracy of the wind forecast guidance, it is imperative to quantify the response of the coastal ocean model to different sources of wind forcing information. Therefore, verifications of the simulated wind speeds and phases against their real meteorological counterparts, of ocean model elevations against actual sea surface elevations measured by NOAA tide gauges, and of simulated depth-averaged current velocities against Acoustic Doppler Current Profiler (ADCP) data were performed. The results provide insights on additional operational data that is needed to improve the accuracy of storm surge predictions during tropical storm landfall events.

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Moyer, A.C., J.L. Evans, and M.D. Powell, 2007: Comparison of observed gale radius statistics, *Meteorol. Atmos. Phys.*, **97**, 41-55.

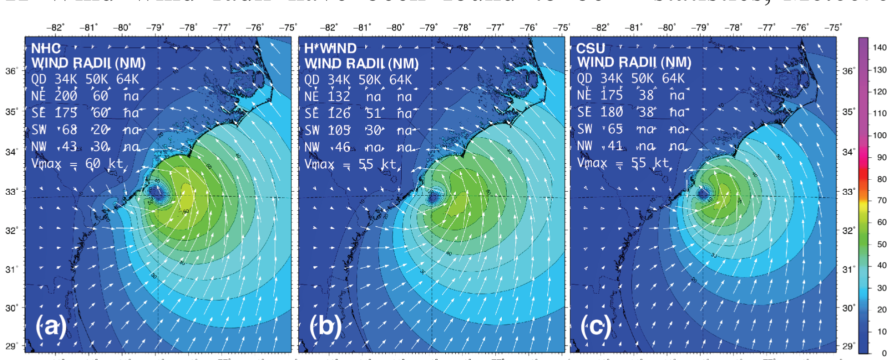

FIG 1. Comparison of TS Hanna wind fields produced by the asymmetric gradient wind model using tropical cyclone track information from (a) NHC, (b) H*Wind analysis, and (c) CSU Multiplatform Satellite Surface Wind Analysis.

Surface Windfields and Roughness Derived from Mobile Radar Winds

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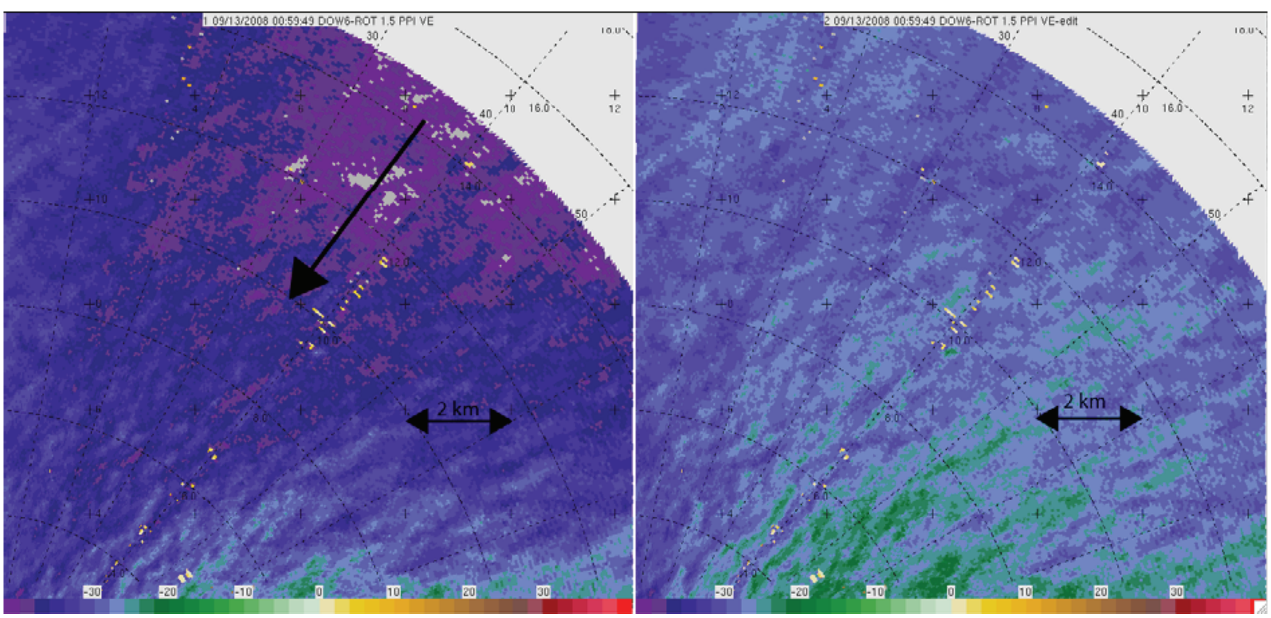
It is advantageous to obtain measurements of potentially damaging hurricane winds over a large portion of the landfall area. While an array of anemometers can provide several point measurements within this area, radar observations allow for the quantification of the two dimensional wind field over a broad area. However, radar measurements are obtained at nonstandard heights, and at large heights, are not substantially modulated by surface roughness. The purpose of this research is to demonstrate the utility of mobile radars in the mapping of a standard wind field in hurricanes, which will benefit both the engineering and meteorological communities.

Using a standard logarithmic profile, the 10-m wind speeds (U_{10}) were derived from the observed Doppler velocities. For the initial analysis, a roughness length of 0.03 m was assumed. The 10-m winds were calculated at each gate yielding a continuous two-dimensional sector. In addition, winds at 1, 2, 3.5, and 10 m measured by in situ anemometers are compared with radar derived winds and surface roughness is deduced.

This standardization procedure was applied to Hurricanes Gustav (where a DOW and several instruments were deployed near Houma, Louisiana, and Ike (2008) where a DOW and several instruments were deployed in and near Galveston, Texas. In both hurricanes, the DOW sampled onshore flow within 5 km of the coast. The10-m wind maps derived for these hurricanes are shown below (Figures). In both hurricanes, a correction factor was applied to the initial observations to correct the magnitude of the off-axis wind speeds.



Caption: Raw (left) and 10-m Zo=0.03 wind field (right) at one time in Galveston during Ike.

Performance of an Objective Model for Identifying Secondary Eyewall Formation in Hurricanes

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The formation of a second eyewall around a preexisting smaller eyewall is generally the precursor to an eyewall replacement cycle. These cycles often cause dramatic and rapid changes in intensity and are very important to recognize in a forecasting setting, particularly when a hurricane is approaching land. Additionally, the formation of a secondary eyewall occurring away from land can broaden the hurricane wind field and influence the magnitude of storm surge. An objective forecast algorithm, based on environmental and geostationary satellite features, was developed using a Bayesian approach that provides significant skill in forecasting the likelihood of secondary eyewall formation (SEF, Kossin and Sitkowski 2009). A *beta* version of the algorithm was run in real-time during the 2008 Hurricane Season and those results will be presented.

The algorithm requires the knowledge of prior SEF events (climatology) to output a probability. Over 4,500 microwave images in combination with aircraft, radar, and additional satellite data (when available) were used to identify 45 SEF cases in the North Atlantic basin from 1997-2006. Nearly one third of all hurricanes developed a secondary eyewall at least once during their lifetime. Comparatively, 70% of major hurricanes (Saffir–Simpson category 3–5) were observed to form secondary eyewalls at least once during their lifetimes. Secondary eyewalls were observed to form during each month of the hurricane season except June, while more than 60% of the total number were observed during September.

The mean intensity at the time of SEF was 109 kt. Intensity changes preceding and following SEF were varied. The limitations of using the best track to discern intensity changes associated with the SEF events, and a strategy to apply reconnaissance data to the problem, will be discussed.

Kossin, J. P., and M. Sitkowski, 2009: An objective model for identifying secondary eyewall formation in hurricanes. Mon. Wea. Rev., to appear.

Early Online Release available here:
http://ams.allenpress.com/perlserv/?request=get-abstract&doi=10.1175%2F2008MWR2701.1

Session 10
Other Research to Improve the Prediction of Tropical Cyclone Intensity and Structure, Track, Precipitation, and Inland Inundation, Part 2

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Evaluation of Hurricane Mitigation Hypotheses through an Interactive Program of Observational Analyses and Numerical Simulations

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The disastrous hurricane season of 2005 and the devastation of Hurricane Katrina have refocused attention on the hurricane threat in the United States. An Effort under the Department of Homeland Security (DHS) to Develop Concepts, Methodologies and/or to Anticipate, Prepare for and/or Mitigate the Impact of Catastrophic Geophysical Phenomena is underway. The thrust of this program is to reduce the intensity of Hurricanes before landfall.

This hurricane mitigation program will involve highly interactive hurricane observations and simulations in order to identify and evaluate viable hurricane mitigation hypotheses. Cutting-edge instruments will be employed in a hurricane environment in order to: 1) measure the variability of supercooled liquid water contents in the rainbands, 2) identify cold pools that might result from evaporation of small drops and updrafts and 3) sample the aerosols, including those acting as cloud condensation nuclei (CCN) within the hurricane. The measurements made within and around hurricanes will provide the input for the simulations and serve as the basis of assessing the validity of the results of the simulations.

Because there is no single best model, this program will involve interactions among several models. The NOAA GFDL ocean-tropical cyclone atmosphere model looks at altering sea-surface temperatures (SSTs); the Hebrew University of Jerusalem (HUJ) model incorporates explicit bin microphysics with an aerosol budget where evaporated drops return the aerosols to the atmosphere; the RAMS model uses bulk microphysics which emulates a full bin model like the HUJ. It has the advantage that its computational costs are about 1/100 that of the full bin approach yet it explicitly predicts sources of aerosol, transport and dispersion, activation in clouds, and their regeneration after droplet/ice particle evaporation.

These models are proposed to be combined in coupled atmosphere-ocean simulations that will aim at producing realistic simulations of hurricane clouds, precipitation, cold-pools, air-sea interactions, sea spray, and factors affecting tropical cyclone intensity, including the eye wall replacement process. This will be done for the dual purpose of further improving hurricane forecasts with the added and more accurate simulations of physical processes and for testing the sensitivity of the storm to the introduction of various aerosols for both microphysical and radiative effects (e.g.., ultra-fine hygroscopic and/or black carbon aerosols at various places within the storm).

This research will contribute to NOAA's excellent work on hurricane track and intensity predictions. The goal is to reduce the intensity of the winds once they do hit landfall and therefore reduce the wind caused damage as the storm crosses land. Damage will not be prevented, but the financial savings and potential to save lives will make the research extremely beneficial.

Review of NOAA Intensity Forecasting Experiment (IFEX) 2008 Accomplishments and Preliminary Plans for 2009

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A review of the 2008 hurricane season's NOAA Intensity Forecasting Experiment (IFEX) accomplishments will be presented, and plans for the upcoming 2009 season will be discussed.

The NHC Visiting Scientist Program

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During the 2008 hurricane season, NHC hosted eleven visiting scientists (researchers and outside forecasters) for up to a week's time each. The goals of the program are to: 1) facilitate better understanding by researchers/outside forecasters of the NHC hurricane forecasting process including the tools and techniques utilized by the Hurricane Specialists; and 2) open additional dialog between NHC and the research/outside forecast community that could lead to improvements in our analysis and prediction methodologies. The presentation will discuss the format of the program, who participated, what was the feedback of both participants and hosts of the program, and how the project may evolve during the upcoming 2009 season.

Using NASA's Real Time Mission Monitor to Manage and Conduct Airborne Science Missions

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The Real Time Mission Monitor (RTMM) is a visualization and information system that fuses multiple Earth science data sources, to enable real time decision-making for airborne and ground validation experiments. Developed at the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center, RTMM is a situational awareness, decision-support system that integrates satellite imagery, radar, surface and airborne instrument data sets, model output parameters, lightning location observations, aircraft navigation data, soundings, and other applicable Earth science data sets. The integration and delivery of this information is made possible using data acquisition systems, network communication links, network server resources, and visualizations through the Google Earth virtual globe application.

RTMM has proven extremely valuable for optimizing individual Earth science airborne field experiments. Flight planners, mission scientists, instrument scientists and program managers alike appreciate the contributions that RTMM makes to their flight projects. We have received positive feedback from a broad spectrum of scientists who used RTMM during field campaigns including the hurricane-focused 2006 NASA African Monsoon Multidisciplinary Analyses (NAMMA), 2007 NOAA-NASA Aerosonde Hurricane flight, 2007 Tropical Composition, Cloud, and Climate Coupling (TC4), 2008 Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) missions, and the 2008 Soil Moisture Active-Passive Validation Experiment (SMAP-VEX).

Improving and evolving RTMM is a continuous process. RTMM recently integrated the Waypoint Planning Tool, a Java-based application that enables aircraft mission scientists to easily develop a pre-mission flight plan through an interactive point-and-click interface. Individual flight legs are automatically calculated for altitude, latitude, longitude, flight leg distance, cumulative distance, flight leg time, cumulative time, and satellite overpass intersections. The resultant flight plan is then generated in KML and immediately posted to the Google Earth-based RTMM for interested scientists to view the planned flight track and subsequently compare it to the actual real time flight progress.

We are planning additional capabilities to RTMM including collaborations with the Jet Propulsion Laboratory in the joint development of a Tropical Cyclone Information System which will serve as a web portal for access to tropical cyclone data, visualizations and model output.

A description of the system architecture, components, and applications along with reviews and animations of RTMM during the field campaigns, plus planned enhancements and future opportunities will be presented. A poster will complement the talk.

Bi-Static GPS Result for Hurricane Seasons 2007 and 2008 with Implications to High Altitude UAV Operations

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The GPS ocean reflection experiment (GORE) has acquired results from the 2007 and 2008 hurricane seasons as part of an ongoing effort to assess the use of bi-static techniques in hurricane research. Previous accomplishments have included the demonstration the L-Band surface roughness does not saturate at tropical cyclone wind speeds. A preliminary wind speed calibration using COAMPS high resolution model surface wind fields has allowed the comparison with other methods used by NHC and HRD. This paper will report comparisons of the GPS surface reflection results with wind speed results from flight level, H*Wind, SFMR, dropsondes, etc., for several hurricanes such as Fay, Gustav, Ike, and Paloma in 2008 as well as Felix and Erin from 2007. A new area of research has been added in which the GPS bi-static RADAR operates in radiometer mode and some results from this work will be presented. Finally, some considerations relating to using the bi-static approach at Global Hawk UAV altitudes will be given.

Session 11
Joint Hurricane Testbed: Project Updates and Plans for the Future

S E S S I O N 11

The Joint Hurricane Testbed (JHT): 2008 Update

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Joint Hurricane Testbed

New analysis and forecasting tools and techniques, developed by the research community, were tested and evaluated during 2008 at the National Hurricane Center (NHC), in real time for the eighth consecutive hurricane season, as facilitated by the Joint Hurricane Testbed (JHT). Ten 4th round (FY07-09) projects were tested and evaluated during the 2008 hurricane season, following any necessary technique modifications or other preparations. These projects include upgrades to dynamical models and model components, enhancements to observed data and assimilation techniques, track forecasting algorithms, intensity estimation and forecasting algorithms. An announcement of Federal Funding Opportunity for new FY09 funding was released in July. Letters of Intent followed by full Proposals were submitted by Principal Investigators and evaluated by the JHT Steering Committee for a 5th round of JHT projects to begin in August 2009.

Validation and Processing Tools for the Air Force Reserve Command 53rd Weather Reconnaissance Squadron WC-130J Multi-Aircraft SFMR Systems

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The Stepped Frequency Microwave Radiometer (SFMR) has become an integral part of the operational sensor suite onboard the Air Force Reserve Command 53rd Weather Reconnaissance Squadron WC-130J and NOAA WP-3D aircraft. Our JHT project has sought to improve the operational utilization of wind and rain products from these instruments. To this end, Remote Sensing Solutions (RSS) and NOAA/NEDIS/STAR have developed and deployed a real-time and post analysis data collection, processing and visualization tool. This novel application provides hurricane specialists with the ability to visualize and interact with the SFMR and other aircraft reconnaissance observations together in multiple formats (time series, radial, GIS, storm relative GIS). This application is allowing hurricane specialists the capability to efficiently and accurately estimate wind products such as the hurricane wind radii in each quadrant of a tropical cyclone and storm intensity. In addition to this application, RSS has developed efficient algorithms that automatically assess the validity of the SFMR retrievals. RSS has also worked to quantify the effects of shallow water bathymetry and determine potential biases in the SFMR observations by working with our JHT team member, NOAA Hurricane Research Division. This presentation will report on the accomplishments in the areas discussed above, and offer an overview of the features and capabilities of the innovative tools that have been developed during this effort.

An Improved Wind Probability Program:
A Year 2 Joint Hurricane Testbed Project Update

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Under Previous JHT support a new program for estimating the probability of occurrence of 34, 50 and 64 kt winds was developed by NESDIS and CIRA. A Monte Carlo (MC) method was utilized to combine the uncertainty in the track, intensity and wind structure forecasts. The MC probability program was transitioned to NHC operations for the 2006 hurricane season. A verification program was also developed and provided to NHC. Verification results showed that the probabilities were skillful using standard metrics for probabilistic forecasts, and were relatively unbiased.

In the current project, three improvements to the MC program were proposed. First, the timeliness is being improved through code optimization. Second, the MC code is being modified to produce the NHC "wind speed probability table" product. Third, the probability estimates are being refined by making the underlying track error distributions a function of the forecast uncertainty. The current MC model uses basin-wide error statistics but recent research has shown that the spread of track forecasts from various models provides information about the expected track error. J. Goerss from NRL developed a real-time tool to quantitatively estimate the track forecast uncertainty (the Goerss Predicted Consensus Error, GPCE).GPCE input is being used by the MC model to provide additional information about the track error distributions.

The first two tasks were completed in Year 1 or early in Year 2 of the project. The optimized code resulted in a factor of six increase in speed, and the MC model-based wind speed probability table was implemented for the 2008 hurricane season. The primary emphasis of the presentation will be on the third task to make the track error distributions a function of the GPCE input. A parallel version of the code was developed utilizing the GPCE input, and was tested on 169 forecast cases from the Atlantic 2008 season where the initial storm position was within 1000 km of the U.S. coastline. Examples of the impact of the GPCE input on the MC model will be presented, along with a quantitative comparison with the operational version using the Brier Score. Results show that the GPCE input modifies the probabilities by as much as 15% and the resulting fields are qualitatively reasonable. The quantitative evaluation shows that the Brier Score is improved with the GPCE input relative to the operational version of the MC model.

Web-ATCF, User Requirements, and Intensity Consensus

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The Automated Tropical Cyclone Forecasting System (ATCF) has been in use at the NHC since 1990. Since this time, a concerted effort has been made to develop common data formats and functionality so that tropical cyclone information can be easily shared among the operational forecast centers in real-time. The ATCF has become a target platform for many NHC and JHT products. Development is coordinated between the tropical cyclone forecast agencies and developers at NRL and NHC. This particular JHT project had three main thrusts:

1) Web-ATCF: The web-ATCF adds powerful capability as a thin client software bundle that allows a variety of web proxy, web server and ATCF server configurations for use in demanding, secure IT environments. A prototype will be deployed at NHC for this season. The intended use is as a display tool for coastal forecast offices, NASA, and DoD customers.
2) User Requirements: Approximately 50 NHC requirements were addressed in the two year project. Some of the more interesting updates will be reviewed.
3) Intensity Consensus: Intensity consensus aids developed in 2007 were upgraded for the 2008 season. ICON is a four-model average (SHIPS, GFDL, LGEM and HWRF) and IVCN is a five-model average that can be computed if two or more members exist. Results from the 2008 season indicate that these intensity consensus aids performed well. Suggestions for 2009 will be discussed.

Session 12
Products, Services, and Lessons Learned during the 2008 Tropical Cyclone Season,
Part 1

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SAB 2008 Year in Review

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NOAA/NESDIS/Satellite Analysis Branch (SAB)

The Satellite Analysis Branch (SAB) derives position and intensity estimates for tropical disturbances and cyclones around the world using the internationally recognized Dvorak technique and cutting edge technologies provided by various research groups. A review of the 2008 hurricane/typhoon season from the operational perspective will be provided as well as an update of NESDIS-funded tropical cyclone initiatives through the Product System Development and Implementation (PSDI) program.

The Determination of Optimal Thresholds of Tropical Cyclone Incremental Wind Speed Probabilities to Support Expressions of Uncertainty in Text Forecasts

Pablo Santos, Mark DeMaria, Dave Sharp

As tropical cyclone events unfold, decision-makers require a meteorologist's most likely wind speed forecast, along with an accompanying expression of uncertainty. Both are necessary to effectively manage preparations for life-threatening weather events. The inherent uncertainty in tropical cyclone forecasts results in the shortcoming of deterministic-only wind speed forecasts such as those found within the current *Zone Forecast Product* and *Coastal Waters Forecast* issued by National Weather Service (NWS) Weather Forecast Offices. To address this shortcoming, the NWS offices in Miami and Melbourne have developed an experimental means to consistently and coherently incorporate uncertainty information in these products through the creative use of the National Hurricane Center's incremental wind speed probabilities. These probabilities are created upon the issuance of each official advisory for 34-, 50-, and 64-knot winds through 120 hours. The probabilities are derived using uncertainties in the official track and intensity forecast, and also from a climatology and persistence wind radii forecast model (with error statistics determined from the previous five years of forecasts). Then, the probabilities are configured locally, in gridded form, to match the traditional time increments of the textual *Zone Forecast Product* and *Coastal Waters Forecast*. Together with gridded hazard information (e.g., tropical storm/hurricane watches/warnings) and gridded deterministic wind speed information, the tropical cyclone incremental wind speed probabilities trigger enhanced wording which conveys the situational uncertainty for successive forecast periods. The logic has been encoded within tropical cyclone versions of the respective text formatters which invoke the prescribed expressions. This includes the zone-based versions which are used to generate the legacy products, and the dynamic point-n-click (point-based) versions found on Weather Forecast Office web sites. The logic depends, in part, on the exceedance of preliminary incremental wind speed probability thresholds as a function of time (e.g., forecast period) for uncertainty involving tropical storm force winds and hurricane force winds. Experimental and operational testing during the 2006 to 2008 seasons has yielded encouraging results. Yet, since the incremental wind speed probability thresholds are a critical component to the formatter logic, it is prudent to formally identify those values which tend to maximize the responsible detection of a potential event while minimizing false alarms which can lead to the overuse of enhanced expressions. Optimal thresholds were determined using Relative Operating Characteristics Diagrams and Threat Scores. Initial results were recently presented at the 2009 Annual Meeting of the American Meteorological Society for the 34 and 64 knot incremental wind speed probability thresholds for coastal points extending across the U.S. Gulf of Mexico and Atlantic coasts. This paper will recount the original validation but also present a cross validation using Peirce Scores. More so, validation results for the 50 knot thresholds will be introduced, along with the inclusion of additional validation points located away from the coast at inland locations.

Envirocast® Vision™ TouchTable:
Linking Federal Partners to Collaborate, Communicate and Visualize the Hurricane Threat to Decision Makers, Emergency Managers and the Public

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StormCenter Communications, Inc.

StormCenter Communications, inc. is leading an effort to connect NWS and FEMA through an advanced technology designed at the Northrop Grumman Futures Lab that promotes real-time collaboration and visualization of NOAA and NASA data for enhanced decision making. Currently StormCenter is working closely with NWS SR HQ, FEMA Region VI, NHC, CPHC and HRD to develop enhanced briefing capability for a more coordinated approach to Federal preparedness, response and communications. Working closely with NOAA Research, NOAA Operations, FEMA and NASA, the Envirocast® Vision™ TouchTable is providing an opportunity to address the visualization and collaboration requirements of AWIPSII and serve as a model for transition from research to operations for many applications.

Session 13
Products, Services, and Lessons Learned during the 2008 Tropical Cyclone Season,
Part 2

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The Digital Hurricane Consortium

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Our nation's ability to determine the severity of and the appropriate response to a hurricane impact is based on the accuracy and sufficiency of the information recorded and how quickly actionable information can be collected, interpreted, analyzed, and relayed from the affected areas to public and private decision makers at the local, state and national levels. Ideally, a dense network of robust direct and remote observing platforms would measure the physical quantities needed to define the event. Standardization and synthesis of real-time data would produce a short term view of the event based on the latest available information. After the event, prompt and detailed post-storm evaluation would allow a final analysis of record which can be used to define the storm impact on coastal communities and ecosystems.

Since the late 1990s, university field research programs have deployed monitoring equipment to characterize and document hurricanes at landfall. With few exceptions, these programs have operated independently or at times with ad hoc collaborations. Recently the university research programs responsible for collecting wind, storm surge, wave, precipitation and damage data convened to discuss in-field coordination and the production of real-time data streams which would serve a variety of stakeholders. The major outcome of this gathering was the formation of a new umbrella organization called the Digital Hurricane Consortium (DHC) that will provide "global" coordination at landfall while allowing individual programs to meet their research deliverables. The formation of the DHC is an important step toward producing integrated, multi-platform data sets that are standardized and quality controlled.

This presentation will provide background information on the suite of observational assets that have been deployed into hurricanes (using Hurricane Ike as an example) and define the concept of developing an adaptive, event-driven observing system which can be applied to any tropical cyclone. This adaptable network of portable weather stations, mobile Doppler radars, and wave / surge sensors would be jointly deployed to the impacted areas to bridge the information void near the coast. Dissemination of the real-time information would result in improved situational awareness and more efficient response, while detailed post-storm analysis would benefit the scientific and engineering communities by providing a more detailed evaluation of storm structure at landfall.

Application of the National Hurricane Center Tropical Cyclone Wind Speed Probability Product to Quantifying Potential Impacts of Hurricane Forecast Improvements

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The Tropical Cyclone Wind Speed Probability product became operational at the National Hurricane Center (NHC) in 2006, replacing its Strike Probability Program. Since then, several new applications of this probabilistic product have been explored. One such application involves the possible use of the product-generated probabilities to provide "first guess" objective guidance for hurricane watch and warning issuance. A preliminary scheme has been developed that uses a set of hurricane warning issuance rules based on product probability values.

The current study sought to refine the preliminary scheme by using a larger sample set, which includes 19 hurricanes making landfall along the U.S. coast from 2004-2008. The original scheme was run over this larger dataset and the probability threshold values were varied until the scheme-derived hurricane warnings correlated well with both the storm total coastal lengths (R^2 = 0.85) and storm total average durations (R^2 = 0.76) of the official hurricane warnings issued for these 19 hurricanes. The wind speed probability thresholds chosen for this new scheme are $p_{up} \geq 8.0\%$, which prompts the issuance of a hurricane warning, and $p_{down} = 0.0\%$, which prompts the removal of an existing hurricane warning.

Using this new scheme, a series of tests were conducted to investigate the potential impacts of forecasted improvements on hurricane warning length and duration. This was accomplished by artificially reducing the underlying error distributions in the wind speed probability model and then calculating the reduction in warning size and duration. Both track and intensity error reductions were considered. Preliminary results suggest that the ratio of reductions in hurricane warning duration and coastal length and prescribed improvements in track and intensity forecasts is less than one, and that the impacts of improvements in track and intensity forecasts on warnings are not additive. The relationships derived from this study, combined with socioeconomic analyses of the costs and benefits of hurricane warnings, provide a simple framework for quantifying the value that future improvements to hurricane track and intensity forecast may bring to society.

A Proposed New Storm Surge Scale

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It is now well-recognized that the original Saffir-Simpson (SS) scale's relationship of storm surge based solely with intensity is not valid. The SS scale's intention was to give an estimate of the potential flooding and damage to property based on a hurricane's sustained wind speed (Simpson 1974). However, the surge depends on intensity, storm size, bathymetry, storm speed, barometric pressure, and local topographical features. A combination of these factors results in large surge differences between hurricanes of comparable intensity, such as Category 4 Hurricane Charley's relatively minor surge inundation versus Category 3 Katrina's record surge. It has also been proposed by Powell and Reinhold (2007) that Integrated Kinetic Energy (IKE) may provide a better correlation to storm surge than intensity.

A new scale will be presented which accounts for all surge factors, as well as IKE. These results are based on many hypothetical surge simulations using the Advanced CIRCulation (ADCIRC) model. The variations include 5 different bathymetries for continental shelf slope and distance; small-, average-, and large-sized hurricanes defined by radius of tropical storm-force winds; slow-, average-, and fast-moving hurricanes; and different intensities. It is found that, if one partitions by bathymetric zones, 3 tables result for storm size categories. Storm speed turns out to be a minor component that's only relevant for intense hurricanes in shallow bathymetry, and can be used as a correction factor in these tables.

However, the tables can be further simplified if IKE is included. IKE cannot be used as a replacement for intensity because a large Category 3 hurricane and small Category 5 hurricane have the same IKE magnitude, but produce different surges since wind stress plays an important role. However, a nonlinear combination of $IKE^{0.5}$ and intensity produces a linearly increasing trend for all bathymetries. This scale varies from 0 to $7X10^6$ $kg^{0.5}$ J. It is proposed that a 0-7 metric be used to represent storm surge potential based on bathymetric zone. The general public need not know how the metric is computed, and there is precedence for using metrics in other scales. For example, users of the Richter scale do not know or care that it is a base-10 logarithmic scale obtained by calculating the logarithm of the combined horizontal amplitude of the largest displacement on a Wood–Anderson torsion seismometer. Another advantage of the proposed scale is that it is not quantized like the SS scale, where a 5-knot intensity difference can result in a unit Category change.

We will also present tables for computing the eastward displacement of 5-ft and 10-ft surge inundation. This scale could be useful for anticipating the extent of surge inundation east of a hurricane landfall. These proposed scales are a natural evolution of the SS scale, and intended to educate the general public on their regional storm surge vulnerability, not to replace storm surge model forecasts. This work was funded by the Northern Gulf Institute and by NOAA.