Statement of

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Introduction

I thank Chairman Inouye, Vice Chairman Stevens, and the other Members of the Committee for the opportunity to speak with you today on the importance of observations in reducing the impacts of hurricanes. My name is Greg J. Holland and I am Director of the Mesoscale and Microscale Meteorology Division in the Earth Sun Systems Laboratory at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. I commenced my career as a weather forecaster and my personal research has centered on severe weather, especially hurricanes, and has covered all aspects: basic theory; conduct of major field programs; development of new observing systems; computer modeling and direct operational applications. I have authored or co-authored more than 110 peer-reviewed scientific journal articles and book chapters. I have given several hundred invited talks worldwide, as well as many contributed presentations at national and international conferences on hurricanes and related. I have convened several national and international workshops, and I have served on several national and international science-planning efforts, including Chairmanship of the World Meteorological Organization’s Tropical Meteorology Research Program. Currently, I am serving on the National Research Council Study Committee: New Orleans Hurricane Protection and I am a Lead author on the U.S. Climate Change Science Program (CCSP) Draft Synthesis and Assessment Product 3.3: Weather and Climate Extremes in a Changing Climate.

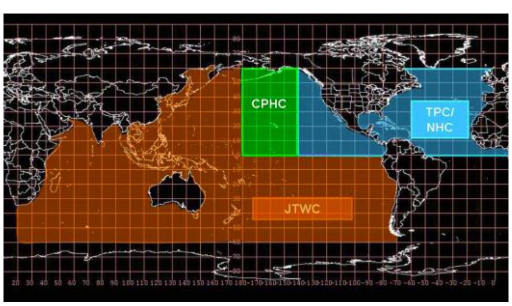
The work in my division at NCAR (www.mmm.ucar.edu/index.php) includes research on the modeling and prediction of hurricanes. We developed and are continuously improving the Advanced Weather Research and Forecasting (WRF) Model, which is in widespread use for both research and operations in over 70 countries. Our scientists have lead the development of innovative observing systems extending from specialized field instruments to the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) satellite system, an innovative and inexpensive system to obtain very accurate vertical profiles of temperature and water vapor in the global atmosphere for use in weather forecasting. And we are currently collaborating with the climate community on bringing the best of weather and climate models together into a system capable of analysis and prediction across all time and space scales.

In this testimony I address observing systems as a component of a complex hurricane forecasting and warning process. The forecast process is a delicately balanced chain, starting with the observations of many types, moving through analysis and data assimilation, computer modeling, preparation of forecasts and warnings, and dissemination to the public. It is sometimes unfortunate that debate tends towards defense of one observing instrument over another, when in reality it should be on maintaining the best possible integrated process. All parts of the complex forecast chain are critical to the outcome, which must be focused very clearly on providing the best possible forecasts and warnings to the American public.

The U.S. has never been more vulnerable to hurricanes and the scientific community is of the strong and considered view that this vulnerability will not decrease in the medium term. A warming climate also may well create more and more intense hurricanes, although this is not certain. Accurate forecasts and warnings of hurricanes are therefore a national priority. ***I urge that the Committee give the highest priority to the passage of the National Hurricane Research Initiative (NHRI), as this presents an excellent, well-considered plan for improving hurricane forecasting through the entire chain from observations to warnings and reducing the impacts of these dangerous storms.***

Background Considerations

<u>US Hurricane Responsibility Regions</u>



As shown in the accompanying figure from the Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead (ISRP), US facilities have responsibility for forecasting in all parts of the globe affected by hurricanes. The NOAA Tropical Prediction Center/National Hurricane Center (NHC) has sole responsibility for the North Atlantic and eastern North Pacific Basins. The NOAA Central Pacific Hurricane

Center (CPHC) has similar responsibilities for the central North Pacific region. The remainder of the hurricane globe is routinely monitored and warned by the DOD Joint Typhoon Warning Center (JTWC). While this is done primarily for DOD interests, JTWC forecasts are also included in the suite of advices used by other domestic forecast services, and by commercial services for both mobile and fixed assets around the world. Thus the United States has global responsibilities for forecasting hurricanes.

This global responsibility has important implications for our observational priorities in support of hurricane forecasting. Satellite observations are the foundation for our present global observing system. Certain regions, such as the eastern Pacific and North Atlantic have the additional very substantial advantage of aircraft reconnaissance. As you are well aware, the U.S. satellite system, as described by the recent National Research Council Report *Earth Science Applications from Space: National Imperatives for the Next Decade and Beyond*, "is at risk of collapse." Since accurate forecasts of hurricanes beyond a day or so depend upon global observations, this degradation of the satellite system has significant implications for the accuracy of future hurricane forecasts, at a time when the U.S. has never been so vulnerable.

Forecast System Requirements

Hurricane observing and forecast requirements are defined by the major offshore, coastal and inland impacts:

- Offshore, hurricanes impact high-seas shipping and oil and gas rigs through high winds, waves and ocean currents, including those in the deep ocean. The forecast requirements therefore focus on the future track, the intensity, the overall wind structure, and the oceanic response to its passage;
- On approaching a coast, the scale of hurricanes impacts rise sharply and now include communities and commercial facilities, local ecosystems, and port facilities. In addition to the high winds, waves and ocean currents undergo complex interactions in a variable coastline to generate storm surges that can exceed 30 ft, be accompanied by large waves and remove substantial barrier islands. Flooding and potential for landslip add to the concerns. Forecasts therefore now also must include details of the rain structure, including that occurring in outer rainbands and the amplifying effect of orography.
- As a hurricane proceeds inland its high winds diminish rapidly, but this does not completely remove the danger. Now the impacts largely arise from heavy rain and flooding, with high-winds associated with squalls and tornadoes also bringing the potential for local devastation.

The forecast lead times vary according to the time taken to effectively respond to the approaching threat. Most coastal communities require 48 hours notice of the onset of high winds (which can be many hours before the arrival of the hurricane core), some require 72 hours. Major port and offshore facilities can require up to 4-5 days to prepare for a hurricane passage. For this reason, NHC forecasts were extended to 5 days in 2001. Accurate forecasts at this extended time period are dependent on the global observing system, which again emphasizes the importance of maintaining and improving satellite observing systems.

These long lead times place great stress on the forecast system to anticipate sudden or sharp changes in hurricane characteristics, especially near vulnerable communities and facilities. The former Director of the Hurricane Center Max Mayfield was quite clear in stating that the nightmare scenario was un-forecast rapid intensification or decay on approaching the coast. Rapid intensification leaves communities poorly prepared for a major catastrophe, whereas rapid decay can lead to a false sense of security and lack of adequate response the next time a threat is forecast.

Data Usage

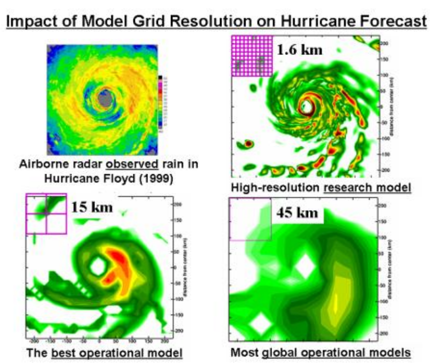
Both the global and local data that are collected are used in two major ways. A subset is passed directly to the relevant hurricane warning center, where they are used to analyze current details of the storm, such as its intensity, size, current track, etc. The warning center also produces local statistical forecasts of parameters such as track and intensity. The full data set is fed into the computer forecasting system where the relevant data are assimilated into the suite of models that produce both short and extended range hurricane forecasts.

Thus, the observing system is one component of a complex forecasting and warning process. This entire process must be taken into account when considering changes to the observing system, as changes at one end often require changes throughout the process to be fully effective. This system also best operates in a dynamic fashion, one where mobile resources (such as aircraft) can be redeployed on the fly to cover deficiencies or uncertainties that appear in the forecast model calculations.

Current Deficiencies in the Forecast System

There is no doubt that the quality of the forecast can never be better than the observations that are used to develop it. However, before focusing on the observations several deficiencies in the rest of the forecast system require consideration. Hurricane track forecasts and warnings have been improving rapidly over the past 25 years due to (1) improved global observations from satellites, especially satellite atmospheric temperature and water vapor sounders, (2) improved computer models, (3) improved methods of assimilating the many observations into the models, and (4) improved understanding of physical processes for inclusion in the models. These improvements have undoubtedly saved hundreds of thousands of lives and billions of dollars of property. However, our experience here shows that all four components need additional attention and support in order for us to arrive at the desired outcome of increasing the accuracy of forecasts and warnings. Forecasts of hurricane intensity have shown less improvement, but there are good scientific reasons for hope.

Our current approaches to assimilating the data into the forecast models are not up to international standards, especially for intensity and structure forecasts. Important data, such as land-based and aircraft radar, are not used. The assimilation occurs by collecting all data over a time period into a single snapshot rather than being incorporated at the time they are collected. This deficiency is well-recognized and is being addressed in NCAR and the Joint Center for Satellite Data Assimilation. But the national investments do not match the importance of this effort. Assimilation research and application is relatively inexpensive compared to the cost of new observing systems, and it is important that adequate and stable funding be maintained for this work. ***A good working model should be that ~15% of all observing system budgets be devoted to ensuring the data are optimally used in the forecast models by both observing system sampling strategies and improved data assimilation.***



Current operational forecast models and the computing facilities that they run on are simply not adequate for intensity and hurricane wind and rain structure forecasting, as emphasized by the report of the recent NOAA Science Board Hurricane Intensity Research Working Group (HIRWG). Research results and experimental forecast trials over the past few years have clearly demonstrated this. An example is shown in the accompanying figure (from S. Chen University of Miami). In the top left is a radar observation for hurricane Floyd (1999). The other panels (in clockwise order) are forecast precipitation patterns obtained from a high-definition (1.6 km) research model, from the typical resolution used by current hurricane models (15 km), and from current global operational models (45 km). The top right-hand corner of each panel shows the scale of the model grids relative to the hurricane. Clearly the lower resolution models are incapable of predicting critical details in the hurricane core region. The required computer power increases by 5-10 times for each halving of the grid resolution, so this requires a substantial investment in computing. But there are clever ways of reducing this. Moving to fine definition also requires an investment in applied research to further develop the manner in which air-sea interactions and the internal workings of clouds are incorporated. ***Clearly, investing in improved computer models and hardware is an investment that has to be made if we are to make substantive progress on predicting hurricane intensity and structure.***

The Observing System

A full analysis of the observing system is beyond this brief testimony, so I will concentrate on several areas of greatest need and potential return for the investment for both research and operational requirements. I will also mention promising new observing systems that are in need of research investigations for potential future use. This analysis assumes that the current suite of operational systems will be retained. In particular the geostationary satellite coverage and the aircraft reconnaissance programs are essential for maintaining the quality of analysis and short-term forecasting of hurricanes, whereas the entire satellite program including polar orbiters contributes substantially to the longer-term forecasts that are critical to planning and response.

In my opinion, the areas of greatest need and potential return are for satellite observations of:

- The full structure of the surrounding atmosphere, including winds, moisture and temperature;
- The available ocean energy for hurricane development, including the manner in which hurricanes extract this energy from the ocean;
- The surface wind structure and particularly the extent of destructive winds in hurricanes.

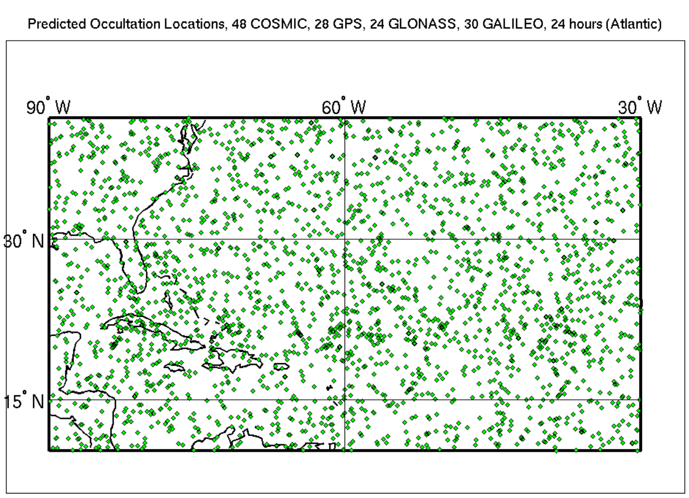
Full Structure of the Surrounding Atmosphere

Forecasts of hurricanes beyond about a day relay heavily on numerical models of the atmosphere. These models in turn are dependent upon accurate measurements of atmospheric temperatures, winds, pressure and water vapor, not only in the immediate vicinity of the hurricane, but over the much larger environment of the storms, which extends thousands of miles in all direction from the hurricane center. The only feasible way of obtaining these global observations is from satellites, although weather balloons, aircraft and surface-based observations make significant contributions. The U.S. has been the world leader in providing the satellites in both geostationary and polar orbits that contribute the vital data needed by the forecast models.

However, as has been documented by the NRC Decadal Survey and other reports and testimonies, the U.S. satellite system is in serious trouble---problems that threaten the number and quality of atmospheric and ocean data needed by the forecast models. For example, the future planned polar-orbiting NPOESS system has been reduced from six satellites to four and from three orbits to two. The NPOESS atmospheric sounding system has been degraded, and the ocean altimeter removed. In addition to this degradation of the NPOESS sounding capability, the planned Hyperspectral Environmental Sensor (HES) has been removed from the next geostationary satellite, GOES-R. Thus the Decadal Survey recommended that NOAA develop a strategy to restore the planned capability to make high temporal and vertical-resolution soundings from geosynchronous orbit.

Currently, atmospheric wind observations from satellite are obtained by measuring the movement of clouds and water vapor elements. These have been a considerable boon to forecasting in general, but they lack vertical detail and are not obtainable in areas where high cloud obscures the lower levels. ***I support the NRC Decadal Survey recommendation that NASA launch and test a lidar wind observing system from space to test the ability to provide comprehensive wind observations for the globe---such wind measurements would be expected to have a significant positive effect on hurricane forecasts.***

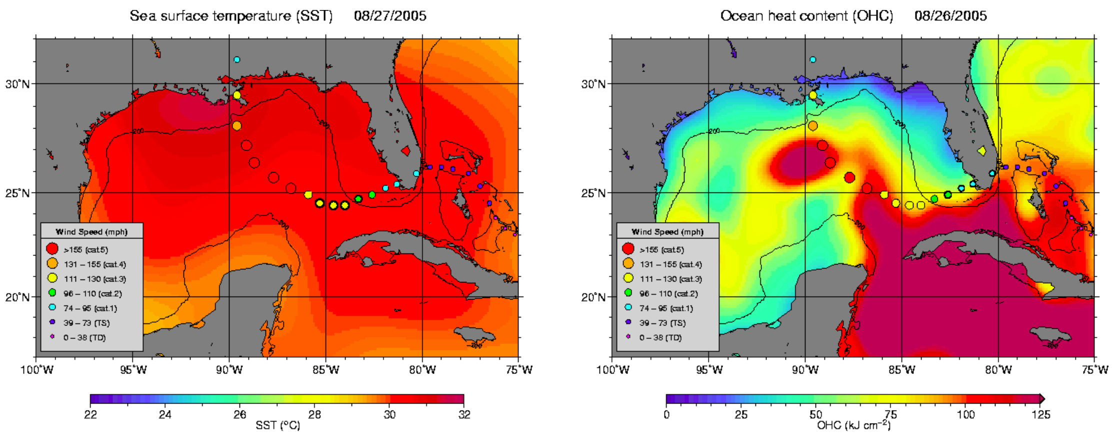
There is a new, exciting technique to make atmospheric soundings of temperature and water vapor from space at a relatively low cost of approximately $3 per sounding. The new technique called radio occultation, or RO, uses the global GPS satellite signals to obtain highly accurate vertical profiles of temperature and water vapor in both cloudy and clear regions, at a very low price compared to other observing systems. In an ongoing proof-of-operational-concept mission, COSMIC, RO data have been shown to have a positive impact on hurricane forecasting. The potential sounding coverage of a full system over the North Atlantic hurricane basin is shown in the accompanying figure. For these, and a number of other reasons, the recent NRC Decadal Survey has recommended that NOAA implement an operational constellation of RO satellites beginning towards the end of the present research COSMIC mission, in 2010 or 2011. RO data are



also very useful climate benchmark data and contribute to space weather. ***As recommended by the NRC decadal Study, NOAA should begin planning for this operational constellation immediately, while ensuring that the COSMIC mission is continued for as long as the satellites are producing good data.***

Ocean Energy

The available ocean energy dictates how intense a hurricane can become. As hurricanes move across changes in this ocean energy they can rapidly intensify or decay and this can be poorly forecast if we have

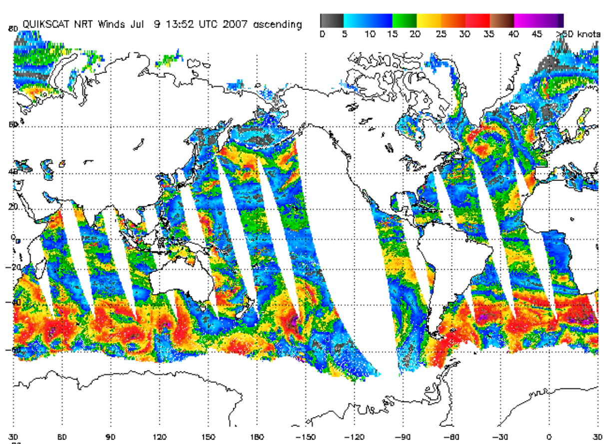


not adequately observed such changes. The observing system must be able to include subsurface conditions, as hurricanes extract energy from below the ocean surface and can mix cold-subsurface water up to the surface. A good example was provided by Hurricane Katrina, as shown in the accompanying figure (from ISRP). A deep warm pool of water associated with the Gulf Stream Loop Current (right panel) was completely hidden below generally uniform sea surface temperatures (left panel). Katrina developed rapidly on moving over this deep warm pool then weakened substantially as it moved towards the coast.

Oceanic instruments previously deployed to drift over long periods or expendable bathythermographs targeted to the expected hurricane track by hurricane aircraft provide one important means of observing this structure. But these can only be applied locally and in special circumstances and aircraft reconnaissance is only available routinely the North Atlantic and eastern North Pacific, with special missions to the Central Pacific. A much more robust and generally applicable approach is to utilize satellite radar altimetry observations. Because the warm water expands the subsurface warm pools appear as local bulges in the sea surface. Observations of these bulges can be used in ocean models to provide a definition of the subsurface structure that is sufficient for hurricane forecasting.

The loss of the NPOESS altimeter in recent cutbacks is a serious step backward for observing such an important oceanic feature. Satellite altimeter measurements are a cost-effective method obtaining critical information on the upper- ocean energy storage and location of ocean currents.

Surface Wind Structure



Surface wind observations from conventional data, such as surface ships, are patchy and often missing from the vicinity of hurricanes, due the ships staying well clear. Such surface wind data are important for several reasons: (1) Locating and identifying the initial wind swirl that indicates the development of a new hurricane; (2) Correctly identifying the extent of destructive winds, which is used to warn shipping and emergency managers of the timing of arrival of, for example, gale force winds (hese winds may occur many hours before the destructive core to substantially disrupt preparations and evacuations); (3) assimilating of the correct cyclone surface structure in forecast models impacts the forecasts of track and structure over the full forecast cycle. The only way to obtain such information over the global oceans is via satellite scatterometer observations and the Sea Winds instrument on QuickSCAT has demonstrated real skill in improving hurricane track forecasts as summarized by the IRSP. It is notable that this improvement occurs mostly 2-3 days into the forecast, which clearly indicates the importance of the global nature of the QuickSCAT observations.

Hurricane Reconnaissance

The requirements of an observing system are varied. I have already indicated the importance of global coverage by satellites, especially for the longer-range hurricane forecasts. But these global systems do not provide the depth of detail, spatial density and time resolution required in severe weather systems, such as tropical cyclones. Indeed, it would be a waste of resources to provide such coverage globally, as in many cases it is simply not needed. These data are best provided by adaptive and mobile observing systems that can go to the system of interest and take the required observations.

The U.S.A. has been fortunate to have had routine aircraft reconnaissance in the North Atlantic since soon after WWII. This reconnaissance program has produced a comprehensive long-period record of hurricane structure and intensity that enables current research in to the impacts of climate variability and climate change on future risk. It has also ensured the best possible forecast and warning service at a cost that is a fraction the direct savings. The reconnaissance system has been steadily upgraded, with addition of new platforms and instrumentation. Of particular importance are: the Doppler radar capacity, and particularly coordinated flight plans that enable dual Doppler observations of the total wind structure; GPS dropsondes that provide detailed vertical structure, especially in the poorly observed near ocean layer; and the stepped frequency microwave radar (SFMR), which provides excellent details of the core region surface winds. The addition of the G4 to the aircraft suite, together with GPS dropsondes has provided near environmental information that has demonstrably improved forecast performance. ***I recommend in the strongest possible terms that this aircraft reconnaissance strategy be retained and further upgraded.*** Initially upgrades should concentrate not on new instrumentation, but on more effective utilization of the data that are currently collected, through effective assimilation into computer models, and on the design of new sampling strategies best suited to support the evolving forecast requirement.

In recent times, adaptive approaches have evolved in research mode to a stage where the computer models are used to define where the best data can be obtained, and the aircraft are directed to obtain these data. An excellent recent example of the effectiveness of this approach in a research field experiment can be seen in the recent NSF-sponsored Hurricane Rainband Experiment (RAINEX).

The aircraft reconnaissance system is now 60 years old and based entirely on manned aircraft. Recent developments with Unmanned Aerial Vehicles (UAVs) and Underwater Autonomous Vehicles (AUVs) have raised the potential for substantial supplementation to the manned aircraft approach. Advantages offered by UAVs is the very long endurance and the capacity to take observations in areas that are too dangerous for manned aircraft and not able to be observed by remote sensing. An example is the near surface atmospheric layer. This is where the hurricane gathers its energy and is the layer that directly impacts coastal and offshore structures through high winds, waves and storm surge. Yet this is also the most under-observed part of the hurricane. There is similar capacity and need for AUVs to be targeted to areas of prime interest for oceanic observations. Such capacity would complement very nicely the operational satellites and drifting or specially deployed buoys. I do caution that care are needs to be taken here as some UAV systems cost substantially more than equivalent manned aircraft and this additional cost would need to be justified in terms of the expected forecast improvements.

I fully support the recommendations of an Interagency workshop on UASs, sponsored by NOAA, NASA, and the DOE and held in Las Vegas, Nevada, in February 2006, that an initial demonstration should be conducted for low-level observations, by a UAV in a hurricane. The objective of the demonstration should be to obtain detailed observations of the near-surface tropical cyclone boundary layer environment and to provide information on key questions of whether such observations could: supply data that will improve tropical cyclone intensity forecasts; help improve our understanding of the rarely observed tropical cyclone boundary layer environment; and provide information that successfully fills gaps in the current observing system.

Conclusion

The nation has entered a difficult and dangerous period of vulnerability to hurricane impacts arising from a combination of sustained enhanced hurricane activity and increasing development in coastal regions. We must respond and I thank the Committee for taking your valuable time to consider an important part of this required response. Satellites are a mainstay of the hurricane forecast process. But this process extends well beyond the taking of observations and other areas are also in need of serious consideration. In my testimony I considered observing systems within the overall hurricane forecasting and warning process. I have identified several areas that should be given priority attention:

- ***Data Assimilation and Sampling Strategies:*** Every new instrument should be matched with an appropriate level of support for ensuring the data enter the forecast process in an optimal manner. A good working model should be that ~15% of all observing system budgets be devoted to both observing system sampling strategies and improved data assimilation;
- ***Computer Modeling Capacity:*** Without sufficient resources to improve the resolution of hurricane forecast models and their capacity to handle cloud-scale and air-sea interaction processes, our capacity to advance the forecasting of intensity and structure will be severely limited;
- ***Satellite Observing Systems:*** I have identified three specific priority areas:
    - Lidar measurements of the complete structure of atmospheric winds;
    - Use of GPS Radio Occultation to provide comprehensive atmospheric temperature and moisture observations;
    - Radar altimetry to provide information on the ocean heat energy storage that is available for hurricane intensification;
    - Scatterometer observations of the surface winds to improve location and structure information on hurricanes and to improve longer range forecasts.
- ***Aircraft Reconnaissance:*** I have stressed the importance of this to the National warning service and have noted several instruments that have been of immense worth in improving forecasts. I also have noted the promising potential of new approaches using UAVs and AUVs to monitor hitherto unobservable components of the hurricane.

Of greatest priority in my view is for there to be a coordinated, well-funded research and system development approach focused on reducing the impacts of hurricanes on vulnerable communities. The review committees that were formed after the disastrous 2005 hurricane season have gathered views and information widely and across all components of the research, operational, engineering, social science and emergency management community. While there are differences of detail, these groups have been unanimous in their call for urgent action and in the general thrust of the actions that are required. These are embodied in the National Hurricane Research Initiative that is before you for consideration. History has shown that a full partnership between academia and operations with adequate funding will result in substantial forecast advances, including identification of critical observing needs. I urge you to give this urgent and serious attention.

Thank you for the opportunity to address the Committee on the importance of hurricane observations as part of a complete forecast and warning process – a topic that is has taken on increasing urgency as the impacts of hurricanes on our vulnerable communities is rising.