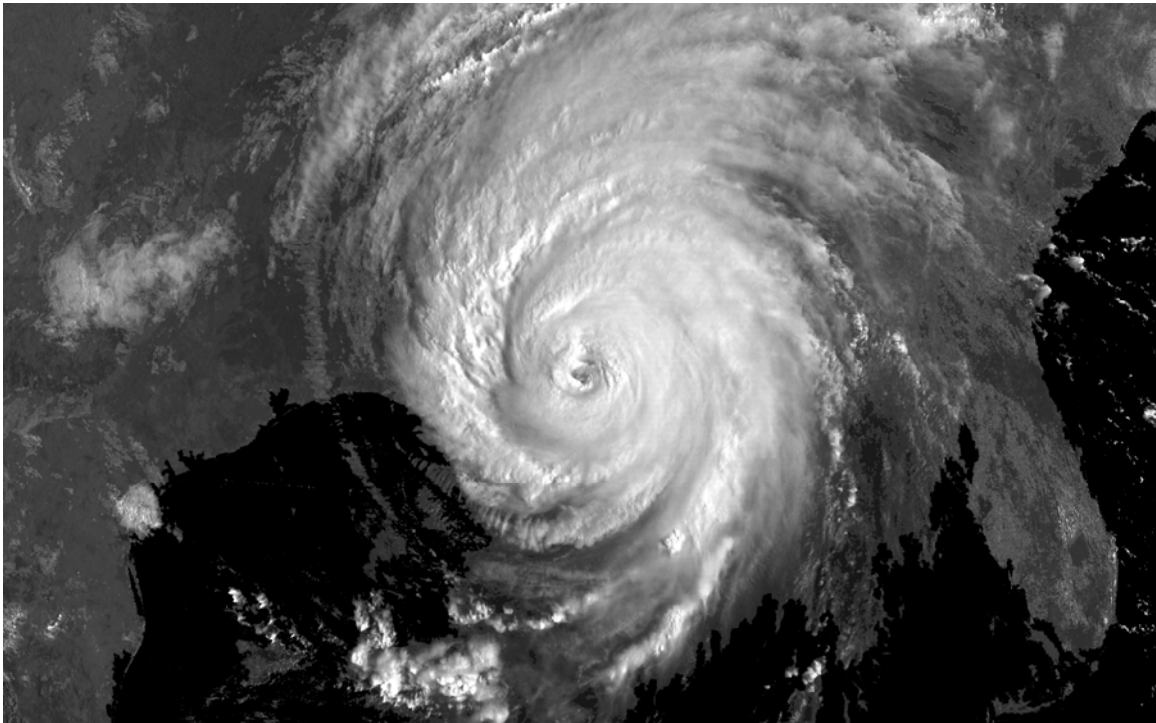


Hurricanes and the U.S. Gulf Coast: Science and Sustainable Rebuilding

June 2006



Hurricane Katrina approaching Gulf Coast, Chinese FY-1 meteorological satellite image, 29 August 2005

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<http://www.agu.org/report/hurricanes/>, published 19 June 2006

Executive Summary

The knowledge available among AGU members provides scientific expertise on nearly all of the physical environment of the dynamic Gulf Coast ecosystem complex. Intelligently rebuilding features such as fisheries, oil fields, seaports, farms, and wetlands after hurricanes Katrina and Rita will require “a well-constructed collaborative effort to maximize the role of science in decisions made about the rebuilding,” wrote Charles Groat, former director of the U.S. Geological Survey, in a news article published in *Eos* that stimulated an AGU meeting of experts.

As a step toward developing a scientific basis for safer communities along the Florida-Alabama-Mississippi-Louisiana-Texas coastline, the American Geophysical Union (AGU) convened an interdisciplinary “Conference of Experts” on 11–12 January 2006 to discuss what we, as Earth and space scientists, know about the present and projected environment in New Orleans and the Gulf Coast areas affected by the hurricanes of 2005. Twenty scientists, all experts in the fields of science relevant to the Gulf Coast, met to consider ideas for a coordinated effort to integrate science into the decision-making processes necessary for the area’s sustainable rebirth. Political, economic, and social issues were intentionally not discussed. Nevertheless, it was recognized that science and these issues are intertwined and of paramount importance. This report contains a summary of the discussion and is intended to be helpful in providing scientific understanding useful in redevelopment of the affected area.

The objectives of the meeting were to review and assess the scientific knowledge in the areas most relevant in hurricane protection, to identify gaps in knowledge that could be filled by focused research, and to propose mechanisms to link science to the most effective reconstruction of New Orleans and other coastal areas affected by the recent hurricanes. The meeting attendees considered seven topics addressing the current understanding, near-term needs, and longer-term directions for: hurricanes, storm surge and flooding, subsidence, climate change, hydrology, infrastructure, and disaster preparedness and response. The messages from the conference are as follows:

Hurricanes

While all hurricanes are detected before landfall and their trajectories known to some degree, predictions of cyclone intensity and structure still contain great uncertainty. Although there have been substantial increases in the accuracy of hurricane track prediction over the past decade, seasonal predictions have shown little skill, for example, predicting an increasing number of hurricanes when fewer actually occur. European ocean-atmosphere models, however, have demonstrated improved capability and may provide more reasonable approximations in the future. Rising sea surface temperatures, routinely observed through infrared and microwave emission satellite sensors, increase the tropical cyclone heat potential and contribute to tropical cyclone formation and their intensification. The conference participants proposed the use of improved seasonal forecasts such as those being applied in Europe.

Storm Surge and Flooding

The basic physics of storm surge is well understood. Remarkably accurate numerical models have existed for approximately 25 years in the United States and abroad for geometrically simple coastal areas. Recent developments have allowed modeling of complex regions like the Louisiana shoreline including channels, levees, and buildings. Nevertheless, better wind data, enhanced shoreline topography, and improved techniques to assess the location and range of flooding are necessary in storm surge models for simulating the range of flooding probabilities. Such modeling scenarios can be used to predict the extent of damage such as levee overtopping were such an extreme event to take place. In the longer term, advanced high-resolution data could provide even better approximations of inundation and expected damage from flooding, thus allowing cities and regional disaster mitigation agencies to prepare an appropriate response to an impending disaster.

Subsidence

Natural processes as well as human impacts have contributed to subsidence, the sinking of land over time, along the Gulf Coast. Presently, there is considerable discussion and debate among the scientific community regarding mechanisms and rates of subsidence in the Mississippi delta area. Regional faulting, forced drainage, oil and gas extraction, and groundwater withdrawal all have led to lowering of the elevation of highways and levees below their originally designed levels. As a result of subsidence, new Federal Emergency Management Agency (FEMA) Base Flood Elevations maps that will be available for the area in 2007 may not be accurate; yet those maps will form the basis for flood control and establish levels for rebuilding. In the future, levees and other flood control systems should be designed and built to account for the amount of sea level rise and predicted subsidence expected over the design life of the structure. In designing new structures, consideration should be given to likely changes over time in storm surge, subsidence, and sea level. New and improved instrumentation would allow researchers to make better predictions of geological and subsidence processes.

Climate Change

There are strong theoretical reasons to expect that warming of the oceans already has led to more intense hurricanes and will continue to affect tropical storm characteristics. Increasing ocean temperatures also cause sea level to rise due to thermal expansion and thus enhance storm surge. It is well established that a sea surface temperature of at least 26 degrees Celsius (79 degrees Fahrenheit) is required for hurricane formation. Recent analyses have found that the frequency of intense hurricanes and severe rainfall has increased in recent decades. Hurricane strength and numbers are projected to increase further with rising ocean temperatures. The hurricane climatology of the 21st century will be quite different from that of the twentieth century. Planning should take into account the strong probability of more frequent and more intense hurricanes. In the near future, prediction models will be able to provide notice of exceptionally strong hurricane seasons more in advance than is presently possible. As these advances continue and more is known about the fundamental physical basis of climate change, hurricane response plans can be continually improved.

Hydrology

Human settlement in New Orleans and throughout the Gulf Coast has greatly modified the natural conditions of the Mississippi River system. In New Orleans, for example, canals have been dredged for navigation and drainage, levees that limit flooding have been raised, tidal wetlands have been eliminated, and dams and locks have been constructed. As development projects have continued and expanded, the mechanisms that had preserved the Mississippi delta in the face of subsidence and erosion have been largely stifled. While the rebuilding of coastal communities has to account for such conditions, long-term flood protection will likely require reestablishing some natural systems such as wetlands that serve as a natural barrier adding some protection from storm surge and flooding.

Infrastructure

When floodwaters from hurricanes Katrina and Rita spilled through the Gulf Coast and breached the levee system in New Orleans, infrastructure damage ranged from unusable roads and bridges to inoperable telecommunications, electrical, and satellite observation systems. The breakdown of communications, both physical and organizational, will require extensive attention and modification. Additionally, ravaged systems such as navigation channels and coastal ports will require renovation and better protection against future damage. Improved models supported by a better understanding of the region's natural systems are needed to plan a unified system of storm protection.

Disaster Preparedness and Response

No matter how resilient the new Gulf Coast may be, preparation for future hurricanes will require development of the capability for massive and timely responses to protect resources and lives. Key to an effective response are detailed scenarios, maps, and visualizations of the affected areas. In addition, training of first responders is necessary so they can react to ever changing scientific data. Most critical is accurate information with 3–4 days notice that would provide time for evacuations, if necessary. Improved forecasts of hurricane trajectory, intensity, and structure are most vital to completing these tasks.

Future Considerations

The key objective of the conference of experts was to ensure the integration of science into the overall reconstruction efforts after the recent hurricane disasters along the Gulf Coast. Given the breadth of the Earth and space science topics within AGU's purview, the organization and member scientists are well prepared to discuss and demonstrate the relevance of sound science to decision-makers charged with rebuilding when future catastrophes strike.

Several recommendations emerged from the conference that would continue the dialogue between scientists and planners at all levels. The suggestions are as follows:

- 1) Establish a multidisciplinary steering committee to maintain an overview on reconstruction and new threats to the region from natural disasters, and charge

- that committee with monitoring the rebuilding and identifying key scientific issues and assets to address them;
- 2) Assemble a database of experts who would be available to provide scientific guidance as needed; and
 - 3) Provide periodic assessments of reconstruction and planning efforts.

Successful and sustainable reconstruction of New Orleans and the Gulf Coast and effective planning for future hurricane events must incorporate the best available science. This can only be ensured by strong continuing interaction among scientists, planners, and decision-makers at all levels.

Introduction and Background

On 11–12 January 2006, AGU convened a conference of 20 experts whose stated goals were to:

- 1) Discuss what Earth and space scientists know about the science that undergirds the present environment in New Orleans and the Gulf Coast areas affected by hurricanes in 2005,
- 2) Determine what data are presently available for use by decision-makers, and
- 3) State what the future needs are in research, development, and monitoring.

Political, economic, and social issues were explicitly not discussed.

Seven subject areas were examined: hurricanes, storm surge and flooding, subsidence, climate change, hydrology, infrastructure, and disaster preparedness and response. Results of the deliberations in each area are presented emphasizing the current knowledge base, near-term lessons and needs, and longer-term directions. This paper summarizes the discussions and recommendations of the conference. Relevant publications are included as additional readings.

It is anticipated that this white paper will help demonstrate how important science is in its supporting role of aiding decision-makers in the rebuilding of New Orleans and the Gulf Coast.

The impetus for this work came from an article written by Charles (Chip) Groat, former director of the U.S. Geological Survey, that was published in *Eos* on 20 September 2005. Groat challenged two sectors of the population. The first are those decision-makers who have treated scientific understanding as a minor ingredient but who now have an opportunity to listen more carefully to scientists and act more responsibly. The second is the scientific community, who now have an opportunity to be organized, reasonable in their expectations, effective in their communications, and persistent in engaging those responsible for the next steps in the recovery and rebuilding of New Orleans and hurricane-affected areas of the Gulf Coast.

Science and the Gulf Coast

The Gulf Coast comprises one of the most complex, dynamic, and productive environments of the United States, with an underlying geology shaped by tectonic forces and sedimentation processes, varied estuarine and coastal ecosystems, and a turbulent climate. Knowledge of this environment and its interactions with human activities is

fundamental to sustainable reconstruction. Below, some of the elements of current scientific understanding of this environment are briefly highlighted.

Hurricanes

Current Understanding

Hurricanes surely are the most visible and violent natural phenomena encountered on the Gulf Coast. A hurricane is an intense, whirling storm similar in character to other rotating storms in the atmosphere on larger (midlatitude storms) and smaller (tornados) scales. Nevertheless, while storms may produce winds and rain over a broad region and tornados generate destructive winds over a small area, hurricanes are unique in their ability to produce both devastating winds and intense rainfall for hundreds of kilometers around the storm center. Although about 85 hurricanes occur each year in all the world's tropical oceans, only a fraction in the North Atlantic pose threats to the United States. A still smaller fraction actually makes landfall, and only a subset of these affect the Gulf Coast.

Hurricanes are distinguished by their driving force—heating from an underlying warm ocean—and by their intensity. A category 1 hurricane possesses winds in excess of 74 miles per hour (33 meters per second), whereas a category 5 has winds greater than 157 miles per hour (70 meters per second). Winds in excess of 179 miles per hour (80 meters per second) have been recorded. Once formed, a hurricane will persist unless it is perturbed by internal instabilities, cold water, friction from the underlying land surface, or winds aloft that change its vertical structure. The high winds are of particular significance since they are the primary force behind much of the damage that occurs. Direct wind damage increases roughly with the cube of the wind speed. Economic losses vary with the fourth power of the wind speed. Storm surges driven by a hurricane's low pressure and destructive winds are major killers that can lead to complete destruction of low-lying coastal communities and industries. As the hurricane moves inland, heavy rain and associated flooding become the major contributors to damage and loss of life. As we have seen in New Orleans, flooding damage and inundation also can last for days and sometimes months.

Hurricanes are among the most destructive elements of nature and are the cause of the largest number of fatalities related to natural disasters in the Western Hemisphere. For this reason, great resources are expended on preparation, protection, and response to hurricanes. Specialized aircraft reconnaissance, advanced satellite systems, and enhanced coastal observing systems are utilized to provide essential data for hurricane analysis and prediction. Since the advent of satellite observations, all hurricanes are detected long before landfall.

Predictions of hurricane paths have improved markedly due to dedicated research efforts and advances in numerical forecast models, but predictions of hurricane intensity and detailed structure have made very little progress. Despite the urgency of the problems faced, there has been an alarming decay in the resources provided for hurricane research and development in the past decade. Urgent action is needed to reverse this trend and increase support for multidisciplinary approaches to ameliorating the impact of these dangerous systems.

Uncertainty in predictions requires that hurricane warnings cover long coastal stretches that could be threatened. As a result, many communities incur unnecessary costs in preparation and/or evacuation. If the forecasts of landfall and intensity are made in probabilistic form, regional and local authorities can conduct risk analyses that allow reasoned decision-making processes in which the costs of evacuation are compared with the potential cost of damage and loss of life. Thus improved probabilistic forecasts have a direct benefit in reducing the secondary economic and social impacts of hurricanes.

Role of the Ocean

The transfer of heat from the ocean to the atmosphere is the primary driver of hurricanes. Viewed as a heat engine, a hurricane extracts heat energy from the warm ocean surface and exhausts it into the upper atmosphere where excess energy is radiated to space and transported toward higher latitudes. Hurricanes require sea surface temperatures (SST) above 26 degrees Celsius (79 degrees Fahrenheit) to form. A hurricane's maximum strength is governed largely by the amount of energy it can extract from the underlying ocean. In general, the warmer the SST, the more intense the hurricane. The overall correlation between SST and intensity is relatively small (0.35). When the SST is substantially higher than the threshold temperature, then intense hurricanes can form. The reason the correlation is low is because lower-category storms also form in this high SST regime, but other factors such as vertical wind shear reduce their potential intensity.

The tropical ocean is strongly stratified with relatively warm surface waters, usually a few tens of meters thick, overlaying colder subsurface waters. As a hurricane travels over the ocean it generates a cold-water wake produced both by wind mixing the warm surface water with colder water below and by extraction of heat through evaporation that fuels the hurricane. This cold water limits the hurricane's strength by reducing its energy supply and similarly limits the intensity of succeeding hurricanes that might follow.

In some regions of tropical oceans the warm surface layer is thicker, reaching more than 100 meters (329 feet). Such a layer contains a great deal of heat energy and vertical mixing, but the mixing may not be sufficient to bring cold subsurface waters to the surface. Tropical cyclones often intensify rapidly while passing over such regions, where the ocean surface remains warm. For example, Hurricane Katrina intensified first over a warm eddy and then strengthened very rapidly from category 1 to category 5 as it passed over deep warm waters in the Gulf.

The primary ocean data required for hurricane prediction are the SST and the heat content of the warm layer, referred to specifically as the tropical cyclone heat potential. Sea surface temperature is observed routinely by satellites through infrared and microwave emission sensors. Sea surface temperature is more difficult to measure in cloudy conditions such as occur in the disturbed tropical environment. Only research satellites such as the Tropical Rainfall Measuring Mission (TRMM) currently possess this crucial capability to measure through clouds. Measurement of ocean heat content requires additional observations of temperatures within the ocean—either direct temperature measurements by expendable probes or indirect inference from satellite-measured sea surface height.

Role of the Surrounding Atmosphere

The movement, initial development, and intensification of hurricanes are in response to their near environment. The major factors are the capacity to sustain convective clouds, vertical wind shear, and the degree of midlevel moisture. Vertical wind shear has a negative effect on intensification and especially on initial development. A dry middle level can induce cool, dry downdrafts from convective systems that impair a hurricane's capacity to take up energy from the ocean surface.

In the decade since 1995, sustained changes in the broad flow over the equatorial North Atlantic have produced a distinct change in the numbers and characteristics of hurricane developments. Thirty percent of the waves entering the North Atlantic basin developed into tropical storms in 2005, compared with the normal 10 percent. Recent research has shown that the increased number resulted from variations in the tropical trade winds that flow across the North Atlantic.

In the 2005 hurricane season, there were 27 named storms in the North Atlantic. Nineteen of those formed from waves in the westward flowing tropical trade winds, principally in the eastern portion of the basin.

Current observing approaches utilize advanced satellite sensors and aircraft reconnaissance to target regions where observations are required, both within the hurricane and in its surrounding environment. These resources are under threat from budget reductions, delays in implementing new systems, and delays in replacement of existing systems currently depended on for monitoring and prediction.

Hurricane Prediction

There currently is insufficient skill in empirical predictions of the number and intensity of storms in the forthcoming hurricane season. Predictions by statistical methods that are widely distributed also show little skill, being more often wrong than right. Advanced global models are beginning to show some ability to predict seasonal characteristics. Examples include the coupled ocean-atmosphere climate models used in extended prediction by Meteo-France, the European Centre for Medium-Range Weather Forecasts (ECMWF), and the UK Meteorological Office. On 1 May 2005, the Meteo-France model predicted 22 named tropical storms and hurricanes for the 2005 hurricane season in the North Atlantic. On 1 June the ECMWF and the UK Met Office integrations were showing similar results. What was extraordinary about these forecasts was that their predictions, some months in advance of the hurricanes, were two standard deviations above the already elevated 1995–2004 mean. These models also forecast a reduced number of storms for the northwestern Pacific during the same period. In hindcast mode these three models have outperformed statistical forecasts over the previous 10-year period of elevated storm activity. Yet despite these successes and the clear promise of the techniques, no operational model within NOAA is making extended range forecasts with climate models.

Major improvements in hurricane track forecasts have been made in recent years. The 72-hour forecast is now approaching the skill of a 24-hour forecast two decades ago. Four- to five-day forecasts also are increasingly skillful. Nevertheless, there has been little improvement in the forecasting of hurricane intensity that currently relies primarily

on statistical techniques. High-resolution models such as the Advanced Research Weather (ARW) model of the National Center for Atmospheric Research (NCAR) have demonstrated that such models can yield impressive capabilities for prediction of both intensity and track. NOAA is developing an operational version of the ARW for implementation in 2007, but this will not have sufficient resolution to replicate the improvements noted in the NCAR model.

Near-Term Needs

The most immediate need is to improve the range, accuracy, and precision of real-time predictions of hurricane track, intensity, and structure. This will require continuing improvements in observations and forecast models.

The most urgent observational needs are for maintenance of the current atmospheric observing systems and further development of new capabilities.

For aircraft observations, the implementation of a Stepped Frequency Microwave Radar on U.S. Air Force Hurricane Hunter aircraft will lead to substantial improvements in observing the ocean surface and surface winds.

Unmanned aircraft systems have promise for obtaining direct observations of the near-surface wind conditions that are critical for many aspects of the overall forecast approach including surge modeling and predicting wind damage impacts.

Satellite remote sensing remains one of the most powerful tools, especially the space radars, scatterometers, and multispectral systems. Improvements in the ocean observing system are also vital.

Major improvements are needed for the assimilation of all available and relevant atmospheric and ocean data in real time into numerical predictions. At present, much data that are potentially usable for predictive models, for example, hurricane reconnaissance radar data, are not utilized operationally or inserted into the models as initial data.

Prediction models offer promising prospects for improvement through research.

Better coupling between ocean and atmosphere in numerical models is needed. There are still grave uncertainties in the magnitudes of evaporation and sensible heat exchange in high-wind environments. Most parameterizations have only been validated for wind speeds less than 45 miles per hour (20 meters per second). The Coupled Boundary Layers/Air-Sea Transfer (CBLAST) program, in which buoys were dropped into the path of a hurricane, has provided some clues as to the magnitude of these transfer coefficients, but funds have not been available for a thorough analysis of the data.

The effects of ocean waves on the transfer of heat and momentum between the atmosphere and the ocean are not well modeled. Without additional research on the interchange processes between the atmosphere and the ocean, progress in modeling and prediction will be limited.

Nested high-resolution models should be incorporated increasingly into operational practice, despite current uncertainties in some physical processes. The research community is developing advanced atmospheric and ocean models, covering

limited areas with high resolution, that are nested within the larger-scale models used for operational weather forecasting.

Atmospheric and ocean predictions should be coupled to storm surge models to improve prediction of flooding and inundation. This also would aid in planning reconstruction.

NOAA should explore the use of advanced climate simulation models for extended prediction of hurricane characteristics.

Longer-Term Directions

In the longer term, collaboration between research and operational centers should be fostered in both development and application of hurricane prediction models. It is clear that current collaborations are not optimal and are in need of sustained effort to make the best use of the substantial investment that is currently made in these areas. The Gulf Coast will continue to be affected by hurricanes for the foreseeable future. Indications are that the effects may worsen. A combination of improved research and operational applications of this research, especially through numerical models, will prove to be a prudent and productive investment in improved hurricane predictions.

Storm Surge and Flooding

Current Understanding

Although the dominant characteristic of hurricanes is their strong winds, most fatalities and a major fraction of economic losses are caused by water. In a hurricane, coastal regions may experience flooding both from high river flows induced by the storm's torrential rains and the storm surge propelled by the hurricane's winds. The storm's strong onshore winds produce a powerful stress that forces water onto the shore. A secondary effect is a rise in sea level induced by the storm's low pressure. These effects add to the normal variation in tides and are further complicated by water level setup due to waves (most significant over relatively steep continental shelves) and runoff due to precipitation. Storm surge is determined primarily by meteorological forcing (storm intensity, path, and spatial and temporal scales) and topographic parameters (width and slope of the continental shelf, geometry and character of local coastal and shelf features such as barrier islands, headlands, bays, sounds, inlets, marshes, channels, levees, and barriers). In a low-lying region such as the Gulf Coast the storm surge can extend inland for miles. During Katrina, storm surges approaching 30 feet were experienced in some areas.

The basic physics of storm surge is relatively well understood, although for complex coastal areas the governing equations are not amenable to simple solutions. Storm surge estimates in the 1950s and 1960s were obtained assuming a steady force balance between the onshore wind stress, the water surface slope, and bottom friction. These calculations were intended for use along straight coastlines with only slightly varying bathymetry. They were the basis for much of the storm surge protection infrastructure designed until the 1970s and that in many areas is still in use today.

Beginning in the 1960s, the availability of high-speed computers permitted development of numerical approximations to the governing equations using structured computational grids (often composed of squares), first in two spatial dimensions (vertically integrated) and more recently in three dimensions. This capability eliminated the need to assume a steady state force balance (which may not be appropriate for the rapidly changing winds that occur in hurricanes), allowed inclusion of the effect of mass redistribution (the balance between the net amount of water flowing into an area and the change in water level), and the representation of more realistic shorelines and bathymetries. A primary example of models of this type developed in the 1980s is NOAA's SLOSH (Sea, Lake and Overland Surges from Hurricanes) model that has been used to compute FEMA Flood Insurance Rate Maps. It still is used by the National Weather Service to forecast hurricane storm surge and is the basis for many emergency management decisions. Unfortunately, the SLOSH code is proprietary, so the lack of access to the code has tended to stifle progress, thus making the model inflexible to changing local conditions or new knowledge. Other countries, for example, Britain, Netherlands, and Denmark, also have developed national surge models that have overcome many of the deficiencies of the U.S. models.

Recently, advances have been made in a number of areas of direct relevance to storm surge modeling. Unstructured, finite element numerical techniques have been developed for storm surge models that allow the use of computational grids composed of triangles. These grids are readily configured to represent complex topographic or bathymetric features such as irregular coastlines, rivers, channels, inlets, barrier islands, causeways, levees, etc., and can therefore provide very high resolution in localized areas of interest. With accurate wind fields, these models have demonstrated accuracy of a few feet when run using data from past hurricanes. Combined storm surge and tidal models are now able to account fully for the effect of the astronomical tide on the total water level and therefore the potential flooding during a storm. Such models should be used to plan coastal protection systems. Finally, interactions between storm surge and wind wave models are being pursued to allow inclusion of the water surface setup due to gradients in the radiation stress associated with wave breaking, the influence of wave conditions on the air-water drag, and the influence of waves on bottom friction. Research is also under way to include the influence of different land covers on the air-water drag and bottom friction. The latter effects are particularly important in areas of inundation or coastal wetlands.

Near-Term Needs

Improve geographic, bathymetric, and geodetic data, and develop and apply high-resolution unstructured grid models for storm surge prediction. Accurate representation of local bathymetric and topographic features is critically important for computing storm surge elevations and flooding. These features reflect both natural processes and human actions and are complicated by subsidence and uncertainty in datums. Recently developed very high resolution geographic/geodetic/land use data products offer the potential for significant advances in this area, if they can be transferred effectively into the computation grids required by storm surge models. The representation of conveyances and obstructions to surges must be improved, particularly in developed areas. This suggests the continued development of unstructured grid models and tools to

construct the required computational grids from the continuously growing catalogue of very high resolution data products.

Develop a well-defined reference equipotential surface that is needed to connect water level variations accurately to land. The vertical datum or knowledge of the geoid and its changes (accounting for natural processes and subsidence) are usually not adequately known. There are some areas along the Gulf Coast that are particularly problematic. Gravity surveys in addition to LIDAR/InSAR/GPS mapping should provide more accurate storm surge calculations.

Improve meteorological data needed for storm surge analysis and prediction. Accurate storm surge predictions necessarily begin with accurate meteorological fields. These are required in three different contexts: historical, to provide storm surge model validation for past events; probabilistic, to provide forcing fields for use in the design of storm surge protection systems and emergency planning; and forecast, to provide forcing fields for storm surge forecasts to be used for emergency response.

Enhance the historical database needed for research to advance prediction and as the basis for storm protection design. Our knowledge of the meteorological fields associated with historical tropical cyclones has steadily improved due to the development of techniques for interpolating increasingly available observational data from satellites, aircraft, buoys, and land stations. The NOAA Hurricane Research Division's H*Wind product is composed of gridded wind fields at snapshots in time for hurricanes in the North Atlantic basin for at least the past 5 years. Storm protection system design has most often been based on idealized storms such as the "standard project hurricane" or the "maximum probable hurricane." These are based on storm parameters such as the central pressure, radius to maximum winds, and maximum wind speed that are independently determined based on the historical probability distributions of corresponding storm parameters. Resulting storm parameters are used with a parametric vortex wind model to create a corresponding wind field that is then propagated on selected tracks. Nevertheless, any probabilistic representation of tropical cyclones is quite difficult to elicit due to the relatively small numbers of storms that have occurred since the beginning of observational data collection, the significant geographical variability associated with those storms, and the indication that the storm statistics (e.g., frequency, intensity, duration) may be changing as a function of global warming. As a result, considerable uncertainty exists in current probabilistic representations of tropical cyclone meteorological fields.

Improve the detailed representation of tropical cyclones in forecast models. Tropical cyclones are not well characterized in current forecast models. Predictions are limited mostly to basic storm parameters such as central pressure, eye location, and maximum wind speed. While considerable improvement has been achieved over the past decade in track forecast skill, errors in the forecast track can still lead to substantial errors in surge forecasts due to the localized nature of storm surge. The same improvement has not been seen in the forecast skill for other tropical cyclone parameters.

Improve the coupling of wave and storm surge models and the parameterization of land types, to increase the accuracy of storm surge predictions. Even with an accurate wind field, considerable uncertainty will still remain in the calculation of surface wind

stress and frictional forces, particularly at high wind, in fetch-limited conditions, and in areas of varying land types and covers.

Incorporate into forecast models the interactions between storm surge and hydrologic runoff. Significant flooding can result from the combination of both coastal storm surge and hydrologic runoff from extreme precipitation (e.g., Hurricane Fran in 1996 and Floyd in 1999 in eastern North Carolina). While hydrological runoff often lags storm surge by hours to days, the processes may interact and these interactions should be modeled when appropriate. To date, this has been attempted only rarely.

Longer-Term Directions

Given the considerable uncertainty in tropical cyclone characteristics, probabilistic and forecast assessments of the associated storm surge are best done through ensemble modeling. While different ensembles can be constructed, the most obvious method is to make multiple model runs using the same initial conditions and surge model, but with different meteorological forcing to simulate errors in the tropical cyclone parameters or different surge model parameterizations to simulate uncertainty in these relationships. A consensus projection of the resulting storm surge would then need to be developed. This requires the development of techniques to define ensembles of tropical cyclone meteorological fields as they approach landfall to allow corresponding ensembles of storm surge model runs to be assembled.

Information currently available for assessing either the general susceptibility of an area to storm surge and flooding or the likelihood that an area will flood during a specific event is not being communicated to the public in the most effective way to affect human behavior. Better integration of the new generation of high-resolution geographic data products (to street and building scales), current 3-D computer animation technology, and storm surge model output could make such information more relevant, effective, and more readily available to the public.

High-resolution storm surge calculations, whether part of an ensemble forecasting system or part of a statistically based design process, potentially require the interfacing of multiple models (e.g., meteorological model, wave model, hydrologic model, storm surge model) and the execution of multiple model runs. These combinations will require access to significant computational resources and advanced model integration techniques.

While water levels and inundation are the primary concerns, storm surges may have additional impacts. For example, flood waters may entrain contaminants whose dispersal following the storm needs to be assessed to aid with mitigation efforts. Waves and surge can cause significant sediment erosion, transport, and deposition, causing failure of critical infrastructure or significant disturbances to ecologically significant landscapes (e.g., barrier islands, marshes, or wetlands). Storm surge also may introduce high-salinity water into ecologically sensitive areas that are not accustomed to such conditions. In each case, models will be called upon to help address issues that are far beyond the realm of traditional storm surge computations. These newer applications may require further development within the framework of current models, as well as incorporation of processes not included in traditional storm surge models, for example,

three-dimensional, baroclinic, coupled wave/current/sediment bed change, etc. These needs represent active areas of research in coastal modeling.

Subsidence

Current Understanding

The U.S. Gulf Coast from south Texas to the panhandle of Florida is slowly being drowned at varying rates by waters of the Gulf of Mexico. Whereas global sea level rise can account for only ~2 millimeters per year, the dominant factor is the sinking or subsidence of the land. Subsidence is defined as the *lowering of the surface of the Earth with respect to a datum or point of reference*.

Numerous studies have demonstrated that both natural and human-induced processes have played roles in the lowering of the land surface relative to sea level. Prior to human-induced changes in the amount of sediment carried by the Mississippi River and the construction of flood control levees, subsidence and much slower global sea level rise tended to be offset naturally by deposition of river sediments during floods and by organic sediment production in marshes. Following the great flood of 1927, local citizens wanted protection from floods and farmers and manufacturers in the Midwest wanted a stable Mississippi River in order to transport their crops and goods to market. If the U.S. Army Corps of Engineers (USACE) had not built the regional system of levees as requested by Congress, the Mississippi would have remained unreliable for commerce to and from the heartland and south Louisiana would have continued to be ravaged by floods.

An enormous volume of debris eroded from the Rocky Mountains and the Appalachians is carried by the waters of the Mississippi. Upon entering the Gulf of Mexico, the river slows to a stop and the sediments come to rest, forming the Mississippi River delta. Over time, the Gulf of Mexico basin has accumulated an aggregate thickness of sedimentary deposits of nearly 60,000 feet (more than 10 miles). This massive pile of sediments at the edge of the continent has two characteristics. First, its colossal weight has depressed and continues to depress the Earth's crust. Second, the pile of sediment is weak and unable to support itself laterally. Over time, large tracts of the unstable pile have been displaced southward along sloping faults.

Geological and geophysical investigations have shown that subsidence is widespread, extending beyond the Mississippi River delta and coast, and is occurring more rapidly than previously thought. Several natural and human-related processes are known to be causing subsidence in the Gulf Coast today. Almost all previous studies have provided qualitative insights rather than quantitative measurements of how much subsidence has occurred. Modern-era subsidence is the integrated effect of multiple processes operating at several different spatial and temporal scales.

Some of these are natural processes:

- Sediment compaction/consolidation
- Regional faulting
- Crustal downwarping
- Salt evacuation

- Water loading
- Mantle flow.

Some are human-induced processes:

- Groundwater extraction-compaction of shallow aquitards (clays) and aquifers (sands)
- Oil/gas extraction related compaction of reservoirs
- Fault motion induced by shallow groundwater withdrawal
- Drainage of wetland soils resulting in organic sediment decomposition
- Burdens placed by buildings, roads, and levees.

If major subsidence of the coast of Louisiana and surrounding states continues at rates such as those during the recent past, there will be major and likely catastrophic implications for the entire region. These could include:

- 1) Growing vulnerability to tropical systems and associated storm surges,
- 2) Destruction of the conventional vertical control network used to determine elevation for building levees, defining floodplains, and safe construction of communities, and
- 3) Poorly developed strategies for future flood protection and ecosystem restoration.

All predictions of natural future impacts generally omit how humans will react. If nothing is done and the patterns of subsidence continue, sections of the northern Gulf Coast will be destroyed or rendered too dangerous in which to live. It is not a question of if inundation of unprotected areas will occur, but when. Since there is disagreement concerning the rates of subsidence, it is difficult to ascertain a specific time. Mitigation strategies can be developed to reduce short-term (100–200 years) risks to people and infrastructure, enhance the environment, and create economic development that could transform the state and region.

Near-Term Needs

Establishment and expansion of vertical control is mandatory if levees are to be rebuilt from accurate and up-to-date benchmarks. GPS with real-time capability coupled with an accurate and precise geoid model based on up-to-date airborne/satellite gravity data is the most cost-effective system to provide accurate elevations for recovery and rebuilding of homes and infrastructure. In applications where broad-based mapping is required, for example, in flood hazard delineation, airborne LIDAR (light detection and ranging) and satellite-based RADAR (radio detection and ranging) interferometric technologies offer unprecedented accuracy and economy.

FEMA and local governments need accurate elevations in order to determine how high citizens must raise or build homes and businesses to be above the 100-year flood elevation. Lack of local benchmarks will require surveyors to begin most of their surveys in outlying areas, resulting in greatly increased costs and completion times. Technology such as GPS linked to an updated geoid model can provide a highly cost effective solution to meet those needs.

Because almost all infrastructure in coastal Mississippi and Louisiana will need rehabilitation or reconstruction, accurate elevations are critical to the construction or

repair of evacuation routes, waterways, sewerage and storm water drainage systems, communications, and other systems and services.

The height and geographical location of barriers tall enough to withstand storm surges will be guided by models such as those developed by NOAA and the Corps of Engineers. These barriers must be built high enough to account for future subsidence that will lower the land over the design life of the barrier. Future elevations can be estimated by taking today's elevations and subtracting the effects of future sinking using subsidence velocity measurements.

Future engineered solutions to protect communities and infrastructure from flooding must include thoughtful consideration of the potential negative consequences to the ecosystem of human activities. Protection and restoration of ecosystems can be both successful and mutually supportive if designed properly. The behavior of coastal wetlands and barrier islands during storm surges needs to be investigated further to gauge their potential protective contributions.

Longer-Term Directions

A landscape model that can accurately predict future integrated effects of subsidence and sediment accretion needs to be developed.

A Gulf Coast-wide subsidence and accretion observing system that could be monitored by a real-time GPS, interferometric synthetic aperture RADAR (InSAR), and LIDAR would be useful in planning and developing mitigation programs.

Long-term planning for the Gulf Coast needs to incorporate the potential effects of climate change, both oceanic and terrestrial, on the future geomorphology and on storm surge dynamics.

Improved models of fault movement, petroleum extraction, and water pumping are required to predict the future extent of subsidence processes.

Planning for the use of water and sediment to nourish and establish wetlands should include patterns and rates of subsidence.

Climate Change

Current Understanding

There is broad consensus that the global climate is changing. Instrument records indicate significant globally averaged warming over the past century that has accelerated in the past few decades. A host of phenomenological observations confirm these conclusions. Although attributed by some to natural variability, objective scientific research points to human influences. What are the implications of global climate change for tropical storms and hurricanes? What changes in their frequency, intensity, and trajectories may be anticipated? What is the relative importance of natural variability and long-term trends, a question of vital importance for long-term reconstruction planning? In the context of global climate change, what can be said about regional changes and trends, particularly of the Gulf Coast? These are questions of vital importance for long-term reconstruction planning that require urgent, careful, and objective scientific analysis.

There are strong theoretical reasons, supported by modeling, to expect that the warming of the ocean would affect tropical storm characteristics. Because a hurricane acts as a heat engine that gains its energy from the ocean surface, increases in intensity are expected and probably inevitable. Recent observational studies have indicated that these increases already may be occurring and may be larger than originally predicted by theory and modeling studies.

Analysis of global data since 1970 shows little variation in the total annual number of tropical storms and hurricanes. Each year, 80 to 90 tropical storms and hurricanes occur in the tropical oceans with only about 11 percent occurring in the North Atlantic. Nevertheless, in the North Atlantic there has been a statistically significant increase in the annual number of hurricanes since 1995. The proportion of intense (categories 4 and 5) hurricanes has increased in all basins. The length of time that hurricanes remain high-category storms also has increased, by a half day. The duration of the North Atlantic hurricane season has lengthened, beginning earlier and ending later. In particular, July and October are now seeing more storms.

These observations are consistent with the hypothesis that increasing SST is leading to increased hurricane activity, though it appears likely that a substantial component of these changes is through indirect means, where the ocean changes modify the atmospheric circulation, which in turn drives the hurricane changes. Global numerical model experiments with doubled carbon dioxide and consequent warmer oceans produced a similar shift in hurricane intensity on a worldwide scale. The observed trends in SST and hurricane intensity cannot be explained by natural variability alone. It has been shown, for example, that the North Atlantic Oscillation explains only about 10 percent of the SST changes.

There is a strong basis in both theory and observation for projecting continued longer and more severe hurricane seasons for the foreseeable future. The hurricane climatology of the past decade, with increasing numbers of more intense hurricanes, should be considered the new normal. If present predictions of future greenhouse warming are correct, hurricane intensity will stay high and even increase as long as SSTs continue to increase.

European models are showing exceptional skill in predicting storm frequency 1 to 3 months in advance. It appears possible to give 3 to 4 months notice of an exceptionally intense hurricane season. Such predictions would be of significant value to coastal communities in planning and testing protection and response measures, training, and stocking of needed supplies. This information should be provided to decision-makers.

The climatology of the twentieth century should not be taken as the basis for planning and building for the 21st century. Existing hurricane response plans and plans for post-Katrina reconstruction should be reviewed in the light of apparently changing hurricane climatology.

Near-Term Needs

Urgent attention needs to be given to improved projections of the likely impact of greenhouse warming on hurricane frequency and characteristics, particularly as they affect the North Atlantic. These projections must be coupled with and responsive to the

needs of planning and design groups responsible for construction standards both onshore and offshore.

Longer-Term Directions

Many mysteries remain in our understanding of hurricanes. For example:

- Why are there about 85 hurricanes per year, and not 10 or 200?
- Can we explain the relationships among hurricane frequency, duration, and intensity?
- What is the role of hurricanes in the general circulation?

Without a better understanding of the fundamental physical basis for hurricane behavior, we cannot hope to make greatly improved predictions. Continued and adequately funded research by aircraft and satellites will enable scientists to help describe and in time understand the details of how hurricanes behave.

Hydrology

Current Understanding

New Orleans and indeed the entire Gulf Coast lie between two water systems: the sea and the rivers emptying into it. Before European settlement, the Mississippi carried a stream of sediment-laden waters through an intricate network of channels, natural levees, marshes, lagoons, and barrier islands to the Gulf. Today, the coastal zone of Louisiana contains about a quarter of the nation's wetlands and almost half of the coastal wetlands. The interior areas of the river's delta were sheltered from storm effects, and intrusion of salt water was limited. Regular flooding over banks and through channels provided sediment flows that replenished the marshlands and expanded the delta. Meanwhile, subsidence due to lithosphere depression, compression of sediments and peat, and most recently extraction of oil and gas have worked to submerge the delta. Three components of water are present in this complex and dynamic landscape: the fluvial, steadily flowing streams, the tidal stretches with reversing flows, and the permanently subaqueous plain. This watery network has changed constantly over time as some channels have become clogged from sediment deposition and others have gained active flows.

Early settlements such as New Orleans were established on naturally elevated levees and were protected from hurricanes by the natural landscape. Flooding from the Mississippi was a greater threat than storms from the Gulf. Human activities in recent decades both in the region and in the upper Mississippi basin have caused changes in the tidal wetlands that in some areas have produced rapid deterioration. Tributary channels have been closed. Artificial levees have been constructed, and people have settled in low-lying areas under their protection. Land has been extensively developed for human uses. Canals have been dredged for navigation, oil and gas production, and transportation. Coastal hydrology has been greatly modified. Wetland loss has accelerated markedly. Finally, storm surges and wave action of great storms such as Katrina may produce large temporary or long-term losses of wetlands.

Changes in the Mississippi itself have been significant. A salt wedge now penetrates the river's deep, main channel, extending with low river flow even above New

Orleans. Currently, the river system has two major active channels: the Mississippi and the Atchafalaya. River flow and sediment discharge have changed dramatically over time. In the nineteenth century there was a large sediment transport because of upstream land changes. In the latter half of the twentieth century, sediments greatly diminished because of upstream dams and locks. Jetties in the navigational channels of the delta that have been made by man facilitate the movement of sediment away from the delta. The amount of material now available to restore wetlands is limited. Since the 1930s levees have been constructed along most of the Mississippi that have prevented sediments from replenishing the bordering wetlands. Instead, those sediments are deposited at the very edge of the continental shelf in the Gulf of Mexico. The river has been prevented from switching to a new course. The Atchafalaya's flow has been limited by control barriers; otherwise it would be the new course for the Mississippi. The mechanisms that had built and preserved the delta in the face of subsidence and erosion have been largely stifled.

Near-Term Needs

One of the simplest and thus conceptually attractive methods to provide some level of protection for New Orleans and the larger Gulf Coast area is to restore through natural processes a coastline barrier that would serve as a buffer to any incoming storm, reduce the rate of land loss, and minimize inland flooding. Given current rates of sea level rise and other difficulties in reestablishing natural processes, it is unclear at present whether such an approach is actually feasible.

The use of freshwater and sediment resources of the Mississippi and other rivers must be based on detailed predictions of discharge and sediment availability that encompass basin hydrology including land use and land cover changes.

Longer-Term Directions

In the long term, flood protection can only be secured with a combination of levees and a sustainable coastal landscape. Rebuilding the region in an environmentally and economically sustainable fashion will require integrated planning, investment, and management that recognize the forces of nature, the need to protect communities, the value of natural resources and ecosystem services, and financial constraints.

Infrastructure

Current Understanding

Louisiana and the other parts of the coastal delta face great difficulty recovering vital services lost due to hurricanes Katrina and Rita. The energy infrastructure including production facilities, pipelines, and refineries has been devastated. This caused an increase in energy costs because many of the facilities are still offline. In addition, the area is left with a staggering need for redevelopment to better protect the population from future hurricanes and tropical storms. Integration of scientific information into the reconstruction of the destroyed infrastructure is one of the greatest needs for those involved with rebuilding.

The crippling flooding associated with hurricanes Katrina and Rita proved that the flood control measures in New Orleans were incapable of providing adequate protection

to the city. Considerable evidence in the aftermath of events has noted design and construction deficiencies in the overwhelmed floodwalls and levee system, although final assessments of the cause of levee failure are yet to be released. It is known that levee failure led to massive failures in the storm protection system and damage to the physical infrastructure.

In the past, dams and flood control levees were built using I beams or inverted T beams, but the loose soils of New Orleans slipped from the barriers and left them unstable. Finding a way to ensure robust flood control levees and providing better protection of evacuation routes are glaring needs that demand immediate attention.

Several vital components of the communications infrastructure such as a key satellite receiving station along the Mississippi coast as well as scores of cellular telephone towers were downed or rendered unusable from flooding and wind damage. That damage reduced the ability to issue warnings and prevented the effective spread of information concerning the hurricanes.

Hurricane floodwaters destroyed innumerable structures and significantly damaged shipping lanes in the major deepwater port region. Evacuation routes were inundated or rendered unsafe because of the storm surge, adding further confusion and difficulty for fleeing citizens. Chemicals and contaminants from refineries along with sewerage mixing with floodwaters, fortunately, did not translate into illness among the population. In addition to people being uprooted by flooding, the fabric of the region from buildings to wetlands was disrupted. Future developments have been imperiled.

Physical infrastructure challenges include determining the best ways to prioritize reconstruction projects, rebuilding Gulf Coast seaports, and carving out new shipping lanes where the existing ones were damaged.

Near-Term Needs

Needs for reconstruction must be carefully prioritized. There are a large number of projects involved with rebuilding the Gulf Coast, many of which require immediate attention. One significant hurdle will be prioritizing the various needs throughout the region. The piecemeal development over the past half century in areas of the Gulf Coast affected by the hurricanes has been undone. A chance to rebuild an adequate infrastructure now exists.

Reconstruction must be directed toward building an integrated infrastructure that takes into account both economic/social needs and physical realities. Major elements of that infrastructure include rebuilding coastal ports and energy facilities, providing safer storm shelters, constructing more resilient observation and communications centers, protecting critical infrastructure such as hospitals and shelters, providing better planned and maintained evacuation routes, and creating more effective flood control levees. Planners, engineers, and scientists need to confront these problems together. Existing models, for example, need to consider rising sea levels and warming in the Gulf of Mexico. The underlying geology of the region must not be overlooked since it plays such a vital role in any construction.

Selected navigation channels have to be maintained.

Longer-Term Directions

Improving technology shortcomings such as computer models or satellite data interpretations that can simulate wind and water conditions more realistically is essential. In addition, there is a need for a more resilient infrastructure and improved siting for many of those components. All will require additional research. Better quality data will improve the accuracy of landfall predictions, tidal heights, and storm surges associated with large storms. Model output should provide wind speed over land from which assessments can be made of site-specific potential damage. Such systems will require significant upgrades from existing technology and the use of supercomputers.

Creation of an integrated system to determine how the storm surge will interact with ground features such as the landforms and buildings can help prevent the types of water bottlenecks that initiated the floodwall breaches in New Orleans. The Interagency Performance Evaluation Task Force (IPET) as well as several other groups already have performed such modeling. Additionally, placing restrictions on development in areas adjacent to flood control structures might be considered as a way to minimize future damage. Construction of protected satellite and ground observation stations will allow better land and sea observations to be made even under adverse conditions. Hardened communications systems are vital for protecting a vulnerable population. Ideally, scientific equipment and human systems could be coordinated and tied together seamlessly to hasten a rapid recovery after any future disaster.

Disaster Preparedness and Response

The destruction inflicted by the hurricanes of 2005 pose two closely interrelated challenges:

- 1) Reconstructing the Gulf Coast region's shattered infrastructure, economy, and society and
- 2) Ensuring that preparations are made to ensure effective responses to future storms.

These tasks will be as complex and challenging as the Gulf environment itself. To be effective and sustainable, their planning and execution must be based on the best and most complete knowledge of physical realities and processes. Science has much to contribute to these issues.

Preparedness

Hurricanes Katrina and Rita starkly revealed the vulnerability of the existing development and infrastructure. It clearly would be illogical simply to reproduce the levees and structures of the past. If anything can be predicted with near certainty, it is that hurricanes of comparable magnitude will occur. Scientific insights into the mechanisms of hurricane formation and development, the role of hurricanes in the global circulation, and the influences of climate change have direct bearing on immediate problems of preparedness. Better information also is needed on the projected effects of future hurricanes, winds, wave action, and storm surge levels. Better data on topography, the geoid, and higher-resolution models of river flow and storm surge are needed to map the areas of vulnerability and guide rational preparedness. At present, necessary levee heights

cannot be determined accurately in many locations because of imprecision in the datum for mean sea level. Science can and must provide substantial inputs to preparedness planning and execution.

Response

However resilient the new Gulf Coast may be, future hurricanes will require massive and timely responses to protect resources and lives. While potentially threatening hurricanes may be detected a week in advance of possible landfall, their final landfall may be predicted only a few days in advance. Responses can not be improvised on the spot. Plans and resources to implement these responses must be devised, tested, and put in place before the event.

The emergency response system implemented in Texas links local responders and decision-makers into disaster response districts that are in turn connected to a state operations center with a backbone communications system of dedicated high-speed lines. Real-time data from local sources, satellites, and national resources such as the NOAA Hurricane Center flow into this operations center. A common situational awareness is established among all parties. Real-time data guide local decisions on evacuation and state-level decisions on evacuation routes and destinations, as well as poststorm rescue operations. For example, helicopter rescues in New Orleans were guided by GPS and high-resolution real-time satellite images.

Such a complex response system requires meticulous preparedness, planning, training, and testing. Detailed scenarios, maps, and visualizations were used in briefings to key personnel throughout the system. Models of storm wind patterns, river flooding, and storm surge were basic inputs into these scenarios. Training at all levels employed similar data. Realistic exercises reinforced training and tested the system. Computer models are increasingly central to this effort. With such a tested system the continuity of effective government can be maintained in the face of a storm's destructive power.

While designing and planning such a system requires information on possible winds and surges, response to a specific storm depends crucially on timely and accurate forecasts, and on high-quality, real-time data. The critical period is 96 to 72 hours before landfall when many actions that determine the effectiveness of response are initiated. Responses are massive and complex. Accurate predictions of hurricane trajectory, intensity, and structure are vital. Areas for evacuation must be defined, evacuation routes activated, and resources for transportation, evacuation management, and poststorm rescue deployed. Predictive models operating in real time are becoming ever more important as are real-time environmental data of many kinds. The collection and use of geophysical data are important both in planning for and responding to storm impacts.

Conclusion: Future Integration and Decision Support

The brief survey by the group of experts revealed that while we know much about the complex environment of the Gulf Coast and the great storms that attack it, existing knowledge needs to be better linked to planning and reconstruction. The potential for acquiring better and more useful knowledge needs to be vigorously pursued. Satellite imagery and observations need to be explored further. Necessary data need to be

provided in real time to local and regional command centers. We see an immediate need for standing mechanisms to facilitate the integration of scientific knowledge into the massive reconstruction efforts currently in progress. Sound decisions should be informed by sound science. Incomplete or inaccurate information will surely lead to ineffective and wasteful measures.

As scientists, we see great needs for enhanced research. A large number of these research needs are being pursued at present. Future research is important, and it is also important to apply what we already know to the present issues and problems. This will require continuing interaction among scientists and planners at all levels. Scientists and levee-builders must be on the same team, and processes that foster an effective team must be designed and institutionalized.

The broad umbrella of AGU provides a forum and clearinghouse for virtually all of the scientific disciplines relevant to planning and executing the reconstruction of the Gulf Coast and building its defenses against future Katrinas. We propose an AGU-based framework for integrating science into reconstruction. Its elements would include the following:

- A standing interdisciplinary steering committee or focus group on post-Katrina reconstruction and environmental hazards to the Gulf Coast. This committee would review the overall reconstruction effort and continuing threats to the region, identify key scientific issues, and marshal scientific assets to address them.
- A database of experts in relevant areas, with an emphasis on experts within the affected areas. These individuals would be available to provide scientific guidance as needed or as requested by the steering committee.
- Periodic scientific assessments of the reconstruction and planning effort. Is existing science being fully utilized? What new knowledge is required?
- Educational resources must be developed to help citizens understand that the Earth is dynamic and that life-altering changes can and do occur on human timescales.

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