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U.S. WEATHER RESEARCH PROGRAM HURRICANE LANDFALL WORKSHOP REPORT

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with contributions from the Workshop Organizing Team

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

U. S. WEATHER RESEARCH PROGRAM

HURRICANE LANDFALL WORKSHOP REPORT

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May 1998

EXECUTIVE SUMMARY

The U. S. Weather Research Program (USWRP) effort on hurricane landfall is focused on what the meteorological research community can contribute to a reduction in the nation's vulnerability to dangerous and costly impacts. Because of the growth in population (4.5% per year) and industry along the coast from Texas to Miami, the U. S. has become more vulnerable to tropical cyclones (TC). In coastal communities with limited escape routes, the emergency manager community must have accurate forecasts of coastal areas that will suffer damage, when the winds will exceed gale-force (35 kt) and heavy precipitation will arrive so that all disaster preparedness activities and evacuations can be completed safely. Another key forecast challenge is to predict the inner-core wind field (including maximum surface winds, or intensity) because the most intense hurricanes (categories 4 and 5) cause 80% of all damage. The inland flooding from the storm surge and heavy precipitation, localized regions of extreme wind damage, and severe local storms including tornadoes all depend on the inner-core wind field that is rapidly changing as the hurricane makes landfall.

Because 5% of the 24-h track forecasts by the National Hurricane Center (NHC) exceed 200 n mi (370 km), much larger (4:1) coastal areas must be warned that will actually experience damaging winds. This overwarning decreases public confidence in the warnings and causes unnecessary preparations that are estimated to average $750,000 per mile. The goals of this track-related research are to provide NHC forecasters improved track guidance that will: (i) increase the preparation lead time by at least 12 h; (ii) extend the length of forecasts to 96 h with the same accuracy as the present 72-h guidance, and (iii) use new techniques that provide measures of confidence that will reduce the present 4:1 overwarning of coastal areas to a ratio of 2:1 in 90% of hurricane landfalls that are essentially perpendicular to the coastline.

The Hurricane Landfall Workshop participants prioritized research and observational opportunities to achieve these pre-landfall track forecast gains. A solid basis for prioritizing the research approaches in this topic is available from recent advances in understanding tropical cyclone motion, and many of the research objectives can be achieved with enhancements in the existing infrastructure as well as university and laboratory grants. The largest gain in track forecast accuracy may be achieved through improvements in the initial environment and vortex specification. The variational assimilation technique has great promise to improve the initial analysis in the tropics. Targeted observing strategies are being developed to make optimum use of the mobile platforms such as the new Gulfstream IV aircraft and future Unmanned Aerial Vehicles. Upgrades in the quality and quantity of environment and vortex specification are possible from other satellite-based instruments, such as those to be tested in the combined NASA CAMEX III and Hurricane Research Division (HRD) field experiments during 1998. A better understanding of the sources of forecast errors would lead to reductions in the outliers in the error distribution, which would contribute to the third goal above. Just as improvements in dynamical model guidance have contributed to recent impressive gains in track forecast accuracy, additional gains are waiting to be achieved from numerical model improvements. More details on these research opportunities are given in section 4.

Because the basic physics of wind structure change are not well known, more basic research to understand the science, and also to validate hypotheses with observations, is required. The outer wind structure is a primary factor in specifying the timing of landfall (35-kt wind crossing the coast). The goal is to increase the 35-kt wind radii forecast acuracy at 24 h to within 20% (presently errors are 30-35%). New satellite-based wind observations such as the scatterometer and high resolution cumulus cloud-drift winds plus special aircraft-deployed Global Position Satellite (GPS) dropwindsonde data sets need to be collected. An immediate goal would be to validate the NHC 35-kt wind radii that are the basis of disaster preparedness and evacuation decisions by local emergency managers. The data sets are also needed to validate the prediction model guidance available to NHC and for diagnostic studies of the physical processes of outer wind structure changes, which in turn will be the basis for theoretical studies.

The purpose of the inner-wind structure studies during the pre-landfall period is to improve the hurricane intensity prediction at the time of landfall for use by the local emergency managers in setting the size of the evacuation area. Although the average NHC 24- and 48-h intensity forecast errors are only 10 kt and 16 kt, respectively, 5% of the NHC 24- and 48-h intensity forecast errors exceed 25 kt and 40 kt, respectively. Because greater accuracy will lead to increased public safety and reduced costs, the goal is to reduce the 24- and 48-h intensity forecast errors to 10 kt and 20 kt in 95% of all forecasts. Understanding TC inner-core structure (including rapid intensity) change is a challenging scientific problem because four nonlinearly interacting physical processes are believed to be contributing (see Appendix A-4 and section 5 for a description). Thus, one approach is to collect additional comprehensive data sets in which all four physical processes are observed simultaneously. A prototype for such an experiment is the NASA CAMEX III and HRD coordinated field programs during 1998, which is expected to yield a unique data set for diagnostic studies of inner-wind structure changes. Similarly, the data set can serve as initial and verifying conditions for real-data simulations. In addition, state-of-the-art modeling techniques need to be exploited to understand the convective structure contributions to inner-wind structure change. Furthermore, additional modeling (perhaps with Large-Eddy Simulation-LES) is needed to understand the boundary layer structures and fluxes in the high winds of a hurricane. Coupled ocean-hurricane models developed by university and laboratory researchers need to be intercompared with comprehensive ocean structure and hurricane structure data sets to understand the extent to which such models will be required for real-time application in inner-wind structure prediction. Finally, theoretical studies are needed to clarify key physical mechanisms and provide conceptual models for understanding the essential elements. More detail is given in section 5.

Another challenging scientific problem with exciting opportunities for new observations is the wind structure changes during landfall, which is the critical period in which most of the damage from localized winds, tornadoes, and storm surge plus ocean surface wave run-up actually occur. This understanding is critical to the real-time assessment of damage that is necessary for organizing efficient and effective rescue and damage/economy recovery activities, and for the revision of building codes and other mitigation functions that will reduce societal vulnerability to hurricane impacts. An additional goal is to understand the physics of the additional track deflections associated with the modifications of the hurricane structure during landfall that change the precise center coastal crossing point. A major thrust in this topic is to exploit new observing technology to obtain land-based observations coordinated with off-shore observations to understand the boundary layer structure and surface flux changes as the hurricane moves from open ocean to coastal ocean to land. Examples of this new land-based technology are Doppler radars, radar wind profilers, mobile rawinsondes, and deployable mesonet surface observations. Data assimilation, high-resolution modeling and theoretical studies would complement these observational aspects. Descriptions of these science and technology efforts are given in section 6.

Only general outlooks of precipitation amounts to be expected with hurricane landfall are presently issued by the NHC. The Weather Service Forecast Offices require more specific guidance to issue accurate and timely flood warnings. Within the general context of the Quantitative Precipitation Forecasting (QPF) focus area of the USWRP, specific items more directly related to hurricane landfall precipitation have been identified. The highest priority item is an improved data assimilation system for making optimum use of existing observations, which include both space-based cloud, humidity, and wind observations and land-based radar reflectivity. New research non-hydrostatic models with high resolution, cloud-resolving physics need to be tested with real data (e.g., the CAMEX III and HRD field experiment sets). Case studies are appropriate to document the precipitation processes in observed and simulated hurricane landfall events, including both coastal and inland (perhaps topographically forced) flooding. Validation studies of the Geophysical Fluid Dynamics Laboratory model precipitation predictions are also needed to provide guidance to the NHC forecasters. Additional information is given in section 7.

A broad socio-economic impact research goal is to explore and document the potential savings that may be allowed from improved analyses and forecasts of the track, wind structure (including intensity), precipitation, and the associated effects such as storm surge, and local wind damage including tornadoes. A systematic collection of cost data from industry, commerce, and transportation sectors is required. In addition, the user community needs to be surveyed as to their needs for warnings and what they would do differently with more accurate forecasts of track, wind structure, precipitation, etc. Similarly, the needs of the emergency management community must be incorporated into the research process to best ensure that benefits of improved forecasts are realized. See section 8 for more detail.

Finally, some hindrances to progress in hurricane landfall research are listed in section 9. Some of these hindrances are related to establishing better linkages between the research community and the NCEP and original data sources. Ongoing problems such as inadequate computing resources and deficiencies in observations need to be addressed, along with assuring that all existing observations are communicated to the analysis and forecast centers.

1. Introduction

The impacts of hurricanes on the U. S. coastline from Texas to Maine are well known. Some examples of these impacts, how the National Hurricane Center is tasked to issue watches and warnings, and how the emergency management community is organized to motivate the public to make the proper disaster prevention/preparedness actions (including evacuations) are provided in

Appendix A for those who are unfamiliar with this problem. A key consideration for the emergency managers is that the disaster preparedness activities or evacuations need to be completed prior to the arrival of gale-force (35 kt) winds, or the heavy precipitation that would make such activities or evacuations hazardous. It is important to distinguish the *avoidable* hurricane impacts that can result from improved warnings, and then examine the meteorological research that can contribute to improved guidance for the National Hurricane Center (NHC) forecasters.

The key definition of hurricane landfall utilized here distinguishes between two periods (the rationale is given in Appendix A-3). *Landfall* has occurred and is continuing whenever the coastal counties are under warnings (see definitions in Appendix A-2) and inland communities of the U.S. are at risk from localized high wind damage, storm-surge inundations, and heavy rainfall that may cause urban or inland flooding from a cyclone of tropical origin. In meteorological terms, a forecast is required as the three-dimensional wind, thermal, and moisture fields in the cyclone are being modified by interaction with coastal waters and land to cause localized wind damage or other hazardous conditions including storm surge, extreme rainfall, flooding, and tornadoes. This landfall condition continues as long as hazardous winds or precipitation are possible from the storm remnants having warm core tropical characteristics, even though this may be 500 miles inland and be days after the center crossed the coast. *Pre-landfall* is the period of up to 120 h prior to landfall when the tropical cyclone is moving toward the U. S. coast. One key meteorological forecast challenge during pre-landfall is to specify the precise coastal location and time at which the 35-kt isotach will cross the coast, because all disaster preparedness activities and evacuations are to be completed by that time in that area. How large of an area should be evacuated depends on how far inland the storm surge will inundate or disastrous winds are expected, and these are tied to the intensity (maximum surface wind speed). Because of this requirement, and the psychological impact of an intense hurricane motivating the public to prepare, an accurate intensity forecast at landfall is required.

Because of the present skill in hurricane track and wind structure forecasts, the National Hurricane Center issues a watch or warning for a length of the U. S. coast that is four times longer than will actually experience the conditions. This means large numbers of people, businesses, and industries in the overwarned area may begin activities that prove to be unnecessary. The meteorological data-sparcity over the adjacent oceans, the imperfect analysis and forecast tools that the forecaster has available, and the chaotic and turbulent nature of the hurricane prevents the NHC forecaster from being able to issue watches/warnings for only the precise coastal areas that will be affected. Decreasing this overwarned area will save the U. S. public from making unnecessary preparations, and will raise public confidence in the forecasts so that the proper public response to the hurricane threat will be achieved. A much improved intensity forecast will be required to portray accurately the degree of threat in the landfall region.

Exciting new opportunities with both ground-based and satellite-based observing technology, and in scientific research advancements, now make it possible to provide improved guidance that will allow the NHC forecaster to reduce with confidence the 3:1 overwarned regions of coastal watches and warnings. New scientific insights are available that will improve understanding of the hurricane intensity change, and ultimately improve forecasts of localized wind damage and precipitation associated with hurricanes striking the U. S. coast. This research plan describes the research objectives and approaches to make substantial advancements over a five-year period.

2. Forecast measures during pre- and post-landfall

During and after the center crossing the coast (i.e., during landfall), the most important forecast measures are related to the changes in the inner-core wind structure (including intensity) and the precipitation. The three-dimensional wind distribution determines not only the localized structural damage patterns, but also is the atmospheric forcing for the storm surge prediction, and is one factor in tornado genesis and movement. In addition, this wind distribution is a primary factor in determining the distribution of convection and thus precipitation. As mentioned above, the track is also modified by the asymmetries in circulation, convective heat release, and frictional effects introduced by passage from water to land. However, the highest priority forecast measures during the landfall period are wind structure modifications and the precipitation rate, duration, and accumulation.

The most important forecast measure during the pre-landfall period is the track of the cyclone that will bring it to the *hurricane landfall point*, i.e., the location at which the 35-kt isotach first crosses the coast. Any track forecast error can result in some portion of the coast being overwarned, and/or some other portion being underwarned. Of course, the outer wind distribution (specifically the distance to the 35-kt wind radius in the cyclone quadrant adjacent to the coast) is also an important forecast measure. For the same storm track, a larger (smaller) 35-kt wind radius will result in an earlier (later) landfall. Thus, it is the combination of the track forecast and the outer wind structure forecast that determines the landfall forecast.

As the landfall point is reached, the most important forecast measures must be the same as those of the landfall period, which are inner wind structure (including intensity) and precipitation. Thus, these two forecast measures increase in importance during the later portion of the pre-landfall period. As indicated in Appendix A, an early indication of the storm intensity, especially if it is severe, appears to be a stimulus to motivate the public to respond to the emergency management instruction to start disaster prevention activities and/or evacuate the threatened areas. Whereas water management activities desire an accurate precipitation forecast perhaps 120 h in advance, the uncertainty in a 120-h track forecast is so large that a skillful precipitation distribution relative to the 120-h forecast position may not apply at the particular reservoir location. That is, the manager should not relocate the precipitation forecast of a track to the left or right by more than a few hundred kilometers and assume the precipitation distribution would still be the same over the reservoir.

Although the intent should always be to provide the most accurate guidance possible, the conclusion here is that during pre-landfall more emphasis should be placed on the track and outer wind structure to get the correct timing and location of hurricane landfall at the coast. During the later portion (perhaps 24 h) of the pre-landfall period, accurate forecasts of the intensity at the center coast-crossing time are desired. Increasingly accurate forecasts of precipitation at the coast and inland are also desired at this time, and subsequently, because the emergency managers must make decisions around that time so that disaster preparedness activities and evacuations can be completed by the time the 35-kt isotach crosses the coast (i.e., end of the pre-landfall period). The decay of the inner-core winds and the continuation of heavy precipitation continue to be critical forecast issues during the landfall period.

3. Bases for prioritizations in this plan

The Prospectus Development Team Plan (PDT)-5 report (Marks and Shay 1998) contains a complete list of scientific issues related to hurricane landfall. An excellent summary of the key scientific questions that need to be addressed is included in that report. Many exciting new observational platforms and instruments are also described, and a preliminary plan is described to exploit these new systems along with existing systems during the NOAA Hurricane Research Division (HRD) annual field experiments.

Unfortunately, the USWRP funding likely to be available for addressing the hurricane landfall problem will be inadequate to address all of the items described in the PDT-5 report. Thus, a prioritization is needed. Three aspects were considered in setting these priorities: (i) Forecast need, e.g., the above pre-landfall forecast measures considered to be most essential in helping NHC improve their hurricane watches and warnings, and thus provide emergency managers with the location and time at which 35-kt winds would first reach the coast; (ii) Socio-economic factors (i.e., where the highest benefit to the public could be achieved from an improvement in the meteorological forecast aspect); and (iii) the likely gain to be achieved in forecasting from the proposed research, given that a limit to predictability exists. During the prioritization process, it became evident that the approach to achieve some hurricane landfall forecast improvements had a more scientifically mature basis, and other forecast measures needed more basic scientific studies to resolve key issues. Some research will have obvious and immediate payoffs, while other research is more fundamental and will have payoffs further in the future.

4. Priority pre-landfall track research and observational opportunities

As indicated in section 2, the most important forecast measures during the pre-landfall period are the track of the cyclone that will bring it to the hurricane landfall point, and especially the timing of the landfall (35-kt isotach crosses the coast), which necessarily requires an outer wind structure forecast. Outer wind structure will not be addressed until section 5 even though the outer wind profile is an important contributor to the deviation of the storm motion from an environmental steering-flow (cork-in-a-stream) track, with stronger outer winds (larger storms) having larger track deviations. Although the physics of outer wind structure changes are not well known, the angular momentum changes associated with increasing Coriolis torques as the cyclone moves poleward would contribute to wind profile changes.

Two goals for this pre-landfall track aspect in the research plan are to: (i) Increase the preparation lead-time for the various public segments by at least 12 h via an improvement in forecasts of the location and timing of the hurricane landfall approach point, and by providing forecast guidance to 96 h with the same accuracy as the present 72-h guidance; and (ii) Provide more accurate forecast guidance with confidence measures that will allow NHC to reduce the present 3:1 over-warning of coastal areas to a ratio of 2:1 in 90% of the hurricane landfalls. For these two goals, the research approaches have a solid basis in recent advancements in understanding tropical cyclone motion, and build on an existing infrastructure that has recently provided better track guidance to the NHC forecasters. In each of the following research approaches, the relative investments to augment infrastructure (internal) and to incorporate external groups will be indicated. These are summarized in Table 1. Each of the five research objectives will be described in the following subsections.

Table 1. Summary of **pre-landfall track** research objective prioritizations with investment strategy via an infrastructure (internal) enhancement and university/laboratory (external) grants.

Research objective	Prioritization	Investment Strategy	
		Internal	External
Improvement in initial condition specifications: Variational assimilation; Targeted observation; Quality/quantity of observations; Unmanned aerial vehicles or other observing platforms/instruments	High	Co-lead	Co-lead
Understanding forecast errors: Reduce forecast outliers	High	Support	Lead
Improving prediction and model performance: Numerical model improvements; Statistical-dynamic technique; Remove systematic errors	High	Lead	Support
Understand and predict forecast uncertainty: Prediction of accuracy by ensemble or discriminant techniques	Medium	Lead	Support
Provision of theoretical basis: New assimilation strategies; Tropical cyclone ensemble prediction basis; Scenario-specific track predictability; Conceptual models for interpretation	Medium	Support	Lead

Improvement in initial condition specifications. The approach considered to be more likely to achieve significant improvements in the track forecast guidance is to improve the initial environmental and vortex specifications in the global and regional dynamical models. A highly promising investment would be in the three- and four-dimensional *variational assimilation* *applications* to improve specifically the initial environmental conditions in the tropics. These applications will require development of "forward models" for key observing instruments. Such assimilation research is on-going at the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) and the Naval Research Laboratory (NRL) because it is believed to be critical to improve the initial analysis throughout the globe. An internal augmentation with USWRP funds may be required (Table 1), especially to encourage direct incorporation of the GOES multispectral water vapor channel radiances for vertical profiling and wind estimation in clear air is likely to be beneficial to the tropical analysis based on encouraging studies at the University of Wisconsin CIMSS. Assimilation research by university and/or laboratories scientists has been difficult because access to operational codes, data streams, and computing resources is required (this hindrance will be addressed later). Nevertheless, an external investment may be warranted for high quality assimilation research.

Targeted observing strategies attempt to determine at what locations (horizontal and vertical) and which meteorological variables would most sensitively contribute to a better initial condition specification for dynamical models. This approach could have an immediate application for improving hurricane track prediction guidance from numerical and statistical models, because mobile observing platforms are already routinely available to be directed to the indicated areas. The new NOAA Gulfstream IV jet is a high-speed, high-altitude platform that is equipped with the new Global Positioning Satellite (GPS) dropwindsondes that are providing data of unprecedented resolution and accuracy. In conjunction with the NOAA WP3D research aircraft and the U.S. Air Force reconnaissance aircraft, an outstanding opportunity exists to demonstrate the targeted observing strategies, and improve the initial condition specification for dynamical prediction of hurricane landfall. In addition to encouraging the on-going NOAA (GFDL, EMC, and HRD) and Navy (NRL) efforts, the university community should be involved in developing targeted observing strategies appropriate to the tropics, and landfalling hurricanes in particular (Table 1).

In addition to developing analysis/assimilation techniques that will make better use of existing observations, any upgrade in the *quality and quantity of existing observations* is likely to have benefits in the data-sparse tropics. The combined NASA CAMEX-III and HRD annual field experiment during the 1998 season is expected to provide an exciting data set with which to study the hurricane landfall problem. New satellite instrument prototypes on the NASA ER-2 and DC-8, and the multi-level and wide horizontal coverage with the coordinated flight plans, should produce an unprecedented data set to study tropical cyclones. Both internal (NASA and NOAA) and external research should be funded (Table 1) to exploit this data set for improving the environmental and vortex specifications prior to hurricane landfall.

A new observing platform that has potential to improve the environmental specification is the *Unmanned Aerial Vehicles* (UAV). Developments in this area should be followed, especially as related to the tropical cyclone environment. Just two examples are the Aerosonde developed jointly in Australia and the U.S., which is to be field tested in Australia during the 1997-98 season, and the NASA ERAST program that is developing a GPS sonde capability on a UAV called Altus.

It is difficult to anticipate what *new observing platforms and instruments* might be developed during the period of this research plan. Space-based lidar wind profiles and special balloons capable of continuous profiling are but two examples. At this stage, the above examples suggest that new observing capabilities are indeed possible.

Understanding forecast errors. Improved dynamical guidance is generally credited with contributing to the recent decreases in track forecast errors by NHC (and other forecast centers). However, the dynamical guidance is not always of high quality. A high priority goal for the NHC is to *reduce the outliers in the forecast error distribution* (busts). Research studies are needed to characterize and understand the sources of these large track forecast errors. For the longer forecast intervals, the errors may evolve from the poor environmental specifications discussed above. Some examples might include an incorrect phasing between westward-moving hurricanes and eastward-moving midlatitude troughs, or multiple storm interactions. The Naval Postgraduate School has been developing conceptual synoptic models that appear to provide a basis for categorizing systematic errors and large error scenarios in the track guidance. Only a limited feasibility study has been done for Atlantic hurricanes. The kinds of error studies proposed here could easily be carried out by universities (Table 1), even with relatively limited computer resources. Hindrances to provision of the necessary model fields and data will be discussed later.

Nearly all hurricanes making landfall across warm shallow water, and then being modified by interaction with the land, have track deflections so that the center coastal crossing point departs from a projection of a smoothed offshore track. Although the direct and indirect frictional effects that change the cyclone circulation and convection distribution are a root cause, the modifications of the thermal and moisture distributions are also likely contributors. Numerical model simulations and predictions are needed to understand the relative importance of these processes in these *near-coast track deflections*. Supporting observational studies, particularly with radar and aircraft data sets are required as well. Again, USWRP investments to promote university involvement in this topic are desirable (Table 1).

Improving prediction and performance. Since dynamical model track predictions have become so important in the hurricane forecast procedure, it follows that numerical model improvements should further improve the guidance provided to NHC. First, the data assimilation efforts discussed above are intimately tied to these model improvements because the 6-h model forecast is the background field for the data quality control and the analysis/assimilation, which provides the initial conditions for the next forecast.

Many of these *numerical model improvements* are (and will be) made regardless of the impact on hurricane prediction. For example, each new computer enhancement usually is followed by an improvement in horizontal/vertical resolution, which eventually leads to an improvement in hurricane track forecasts. Any change in the convective parameterization scheme may be expected to affect hurricane tracks, either directly via the changes in the inner region convective cloud distribution, or indirectly via changes in the environmental fields that advect the hurricane. Implementation of advanced numerical techniques may also assist in the model being able to resolve more accurately features of the hurricane environment, and thus improve the guidance. Work in this area needs to be done at the NCEP/EMC, Fleet Numerical Meteorology and Oceanography Center, and national laboratories because of the need for access to computer code and resources (Table 1).

A *statistical-dynamic technique* labeled NHC-83 was the primary track guidance for NHC in the 1980's. Although the successor version (NHC-90) is still used, the accuracy has been degraded by changes in the NCEP environmental analyses. In general, each change in the analysis technique requires collecting a new data base and rederiving the statistical regression equations, which has been a well-known problem with statistical techniques. In principle, the performance of a re-derived statistical-dynamic technique should be better with recent improvements in the environmental analysis. Although a huge data base of model fields would have to be handled, a university researcher might be involved in such a task (Table 1).

A more direct utilization of the dynamical model would be to post-process the resulting hurricane tracks to *remove systematic errors.* A preliminary study is in progress at HRD, and a post-processing feasibility study at the Naval Postgraduate School to modify the Navy global model for typhoon tracks might serve as a prototype. In part because the data bases to be handled are much smaller in this approach than in the statistical-dynamic method, this is a potential research topic for university or laboratory groups (Table 1).

Understand and predict forecast uncertainty. A key reason for the 4:1 coastal over-warning is that in 5% of the cases NHC makes a 24-h track forecast error that is double the mean error. Given these outlier errors, and not knowing when such errors may occur, it is prudent to overwarn to make certain that a coastal area is not struck without warning.

What is needed is a *reliable prediction of the accuracy of the track guidance*. One research approach is the ensemble technique, in which a number of forecasts are made from perturbed initial conditions that hopefully represent the likely initial analysis error distribution. A theoretical basis for the midlatitude ensemble prediction is being developed based on baroclinic instability processes leading to rapid error growth. It is not clear that this theoretical basis applies in the tropics. At least three research groups (NOAA HRD and GFDL; Hong Kong; and Australia) are applying ensemble prediction techniques to tropical cyclone track forecasting. It would be most beneficial if the spread in the ensemble forecasts about their mean was an accurate representation of uncertainty in the track forecast. If so, the hurricane forecaster could reduce the size of the warned area whenever high confidence in the track forecast was indicated. As noted previously, reductions in the overwarned area would avoid unnecessary preparations and increase public confidence in the warnings.

A more direct way to estimate the uncertainty of a track forecast is with a *discriminant analysis* using various descriptors of the present forecast scenario. Because it is generally not possible to divide too finely the full range of forecast errors, a limited number (e.g., three: Below average, Average, Above average) of categories may be chosen. Given a dependent sample of forecasts divided into these categories, a discriminant function is derived that attempts to place correctly each case into the proper category. Given an independent forecast, the probability of the case falling into each of the categories is provided, and the category with the highest probability value is then the most likely. A contingency table of observed versus predicted categories is then a convenient display of the correct (along diagonal) and incorrect (off-diagonal) assignments. Whereas an accurate discriminant analysis of good and bad forecasts would certainly be useful to NHC in setting warnings, in practice the sets of predictors utilized thus far have not been that successful in the discrimination, and large fractions of the forecasts are miss-assigned by one or more categories. More physical insight is needed into effective predictors that discriminate among forecast errors. A cooperative program between a university researcher and the NHC may be effective (Table 1).

Provision of theoretical basis. Although a solid theoretical basis exists for many aspects of tropical cyclone motion, other aspects require further basic studies. As mentioned above, new assimilation technique applications have been identified that would make use of existing and new observation systems in the tropics. However, research to *develop new assimilation strategies* may result in further improvements in the specification of the environmental conditions that are required to improve the accuracy of the hurricane approach point on time scales of 1-3 days, and allow extension to 4 days or beyond.

It was also mentioned above that ensemble techniques have promise in specifying the confidence level of the landfall forecasts. This optimism is mainly based on midlatitude ensemble experience for which a theoretical basis is being developed. A similar *theoretical basis is needed for tropical cyclone ensemble prediction.*

Ensemble techniques may provide one method for specifying the limit of predictability of track forecasting. Although some recent estimates for overall basin-wide predictability have appeared, more *scenario-specific track predictability estimates* are required.

Advances in track prediction guidance have been achieved from sophisticated dynamical models. Interpretations of the track guidance from these complex models is difficult without conceptual ideas/models that describe the essential physical mechanisms. Thus, simpler analytical and numerical simulations that isolate physical processes may *produce conceptual models* that will assist the forecasters in interpreting dynamical track guidance.

Each of the research topics in this section are appropriate for university and laboratory research (Table 1). However, a linkage to operational data assimilation, dynamical models, and ensemble systems will be essential in the development of ideas and eventual implementation to improve forecasting.

5. Priority Pre-Landfall Wind Structure Research and Observational Opportunities.

Given the practical importance of the 35-kt wind radius for warnings, the hurricane wind structure will be defined as "inner core" and "outer wind" relative to the 35 kt wind radius. Aircraft reconnaissance data has demonstrated the inner-core wind changes are not significantly correlated with the outer wind changes. Specifically, it can not be assumed that an intensification (increase in maximum wind speed or decrease in minimum central pressure) is necessarily accompanied by an increase in outer wind strength. Thus, analysis and forecasts of these two regions in the wind structure will be considered to be separate problems. The terminology of inner-core structure will be used here in place of intensity, since the latter term does not include such important information as the radius of the maximum winds. Whereas a correct analysis and forecast of the inner-core wind structure necessarily specifies the intensity, the converse is not true. Furthermore, it is not assumed that all of the same physical processes will be involved in outer-wind structure changes.

A major distinction must be drawn between the pre-landfall track (section 4) and wind structure research and observational opportunities. Understanding of the basic physics of tropical cyclone motion is relatively advanced compared to the knowledge of wind structure changes. Furthermore, analysis and forecast guidance with considerable skill exists for the track problem, and the proposed research in section 4 was a balance of improving on existing infrastructure (internal) and investments in external groups (Table 1). Although field experiment observations are clearly advantageous, this is not such a primary requirement for track as it is for analyzing and understanding wind structure changes. Because the basic physics of wind structure change are not well known, more basic research to understand the science, and also validate hypotheses with observations, is the major difference. Fortunately, exciting new observational opportunities (both instruments and platforms) are becoming available that can be used to supplement the existing HRD field program to achieve advancements in understanding wind structure changes. Another distinction is that the payoff in terms of improvements in hurricane landfall wind structure forecasts must be regarded as a longer term goal.

Outer-wind structure. As explained in Appendix A-2 and section 4, the outer wind structure is a primary factor in specifying the timing of landfall (35-kt wind crossing the coast). Little is known about why some tropical cyclones are larger or smaller than average. The large momentum changes involved in changing the outer wind profile would seem to make it difficult for the outer structure to change rapidly. Thus, the hypothesis is that relatively slow changes in outer wind structure are controlled by the synoptic-or large-scale environment interactions with the hurricane circulation. Redistribution of momentum in the boundary layer and through convective exchanges in the vertical must also play a role. Thus, the sea-surface temperature gradients, air-sea fluxes, and the resulting boundary layer structure are likely to be necessary for forecasting.

Because reconnaissance aircraft typically have not made comprehensive observations beyond 150 miles from the center, an adequate data base to *validate the NHC radius of 35-kt wind forecasts* has not existed. Surface wind reports from ships of opportunity and cumulus cloud-drift winds from geostationary satellites are the typical data sources for NHC to specify the 35-kt wind radius. These data tend to be irregular in space and time. Potential satellite-based wind speed estimates from the Special Sensor Microwave/Imager (SSM/I) are not utilized by NHC, perhaps because these speed estimates are often contaminated by heavy rain in hurricane rainbands, and large data gaps between swaths mean the hurricane is poorly resolved or missed completely. Similarly, the surface wind speed/direction estimates from the European Research Satellite are not utilized as the reports are often time-delayed and even larger data gaps between swaths exist. Although the NASA scatterometer had improved coverage, it failed before the 1997 hurricane season.

The first task is to *build a data base of outer wind structure observations*. A concentrated effort is needed to collect cumulus cloud-drift winds, scatterometer observations, and ship reports supplemented with the dropwindsondes from reconnaissance, research, and surveillance (Gulfstream IV) aircraft. A future data source may be the autonomous Aerosonde, which might be programmed to make repeated vertical profiles at fixed locations, or to sample at large radii in different sectors. These observations should be assimilated over several days to provide initial and validating data sets for numerical models such as the Aviation and GFDL models. A working hypothesis is that these existing models have dynamical equations and adequate physical process representations to predict correctly the changes in outer wind structure -- provided the models are properly initialized. The proposed data-gathering effort should be designed to validate this hypothesis. Where significant changes in outer-wind structure are documented, *diagnostic studies* also should be completed to understand the relative contributions from various physical processes.

Theoretical models of outer wind structure and structure changes are also needed. The above data-gathering effort should provide a source for theoretical ideas and for testing. A theoretical model would be useful for filling data gaps between polar-orbiting satellite swaths that provide only partial coverage of the tropical cyclone.

This task involves both expanded HRD field experiment activities and opportunities for university researchers for diagnostic and theoretical studies (Table 2).

Inner-core structure. A conceptual framework for discussing this topic is given in Appendix A-4: *Inner-core wind structure changes are triggered by the tropical cyclone circulation interacting with the environment via baroclinic vertical wind shear processes and with potential vorticity anomalies in the upper troposphere that initiate convective cycles involving contracting rainbands during early stages or concentric eyewalls in the mature stage. Significant modulations of the convective cycles occur via boundary layer processes that determine the equivalent potential temperature under the eyewall, which includes interaction with the initial ocean thermal structure that is varying in space and time in response to the translating cyclone circulation.*

Each of the four non-linearly interacting physical processes affecting inner-core wind structure changes will be addressed separately, although the over-riding objective is to understand (and ultimately predict) the relative contribution of each process.

Table 2. Summary of **pre-landfall wind structure** research objective prioritizations with investment strategy via an infrastructure (internal) enhancement and university/laboratory (external) grants.

Research Objective	Prioritization	Investment Strategy	
		Internal	External
Outer-wind structure: Validate NHC 35-kt radii; Data base of outer wind structure observations; Validate prediction models; Diagnostic and theoretical studies of processes	High	Lead	Support
Inner-core structure: **Observational aspect:** Additional/comprehensive data sets; CAMEX III field experiment	High	Lead	Support
Diagnostic studies: Environmental effects; Convective structure; Boundary layer; Ocean response	High	Support	Lead
Modeling studies: Convective structure; Boundary layer; Coupled ocean-hurricane	Medium	Support	Lead
Theoretical studies:	Medium	Support	Lead

Observational aspect. The most pressing need is for *additional and more comprehensive data sets* that will facilitate understanding the individual physical process and for resolving the relative contributions of each process to inner-core structure changes. An excellent opportunity exists with the availability of the NOAA Gulfstream IV aircraft to obtain new upper-tropospheric observations that in combination with satellite water vapor and cloud-drift winds are necessary to resolve more accurately the interaction of the tropical cyclone with the environment. As explained in Appendix A-4, this includes: (i) upper-tropospheric stability effects on the convective structure in the inner core; (ii) vertical shear effects of the weakly baroclinic tropical atmosphere versus the strongly baroclinic midlatitude atmosphere following recurvature; (iii) vertical shear effects from a "bad" trough; and (iv) cyclonic eddy momentum fluxes from juxtaposition of a "good" trough. Another new tool is the GPS-based dropwindsondes now available on the research aircraft, which provide unprecedented vertical structure details in the boundary layer. New scatterometer data sets will provide horizontal distributions of the wind field, at least in outer regions.

The optimum situation would be to observe simultaneously all four nonlinearly interacting processes so that a resolution of the individual contributions can be achieved. Thus, aircraft Doppler radar would be required to monitor the convective redistribution at the same time as the Gulfstream aircraft is sampling the upper troposphere and all aircraft are probing the boundary layer structure with GPS sondes. An outstanding opportunity for such flights will occur when the NASA *CAMEX III field experiment* will be coordinated with the HRD annual field program. Two NASA aircraft will be equipped with various prototype instruments being tested for later space deployment. The missing link in this, and most other, field studies is coordinated ocean observations to resolve the ocean structure changes. As a minimum, extensive surveys of the SST distribution should be made to monitor the spatial and temporal distributions of this variable, which is a signature of ocean thermal response.

Data collection efforts should not await the optimum situation. Neither does the collection necessarily have to involve a landfalling cyclone, because the physical processes associated with the environmental effects should be similar for non-landfalling cyclones (special boundary layer considerations will apply in landfall cases). It is more important just to build the data base of cases even if all the desirable observations can not be made simultaneously. Considerable variability in the magnitudes of environmental effects have been found in studies. Thus, it is important to increase the data base in a variety of inner-core structure change scenarios so that statistical significance tests can be conducted. Even null or decreasing intensity cases are of interest, which provide a control to compare with the intensifying cases. The same thought applies to oceanic data collections. A case without significant environmental effects occurring simultaneously would make interpretation of the ocean contribution easier. This observational test mainly requires additional resources for expendables including air-deployable ocean current and density profilers and drifting buoys. Involvement of university researchers in the planning of the annual HRD and special field experiments and in the analyses is desirable (Table 3).

Diagnostic studies. The research tools exist to *diagnose* the *environmental effects* of vertical wind shear and eddy momentum fluxes. As indicated above, the need is for more data sets in a variety of inner-structure change scenairos to substantiate the magnitudes of these physical processes. University researchers have carried out many of these studies and should continue to play a lead role.

Convective structure analyses require special radar visualization and algorithms, which are usually in laboratories such as HRD or NCAR. Consequently, university researcher access to such facilities would be required.

University researchers have cooperated with HRD personnel for both the *boundary layer* and *ocean response studies*. Continuation of this type of cooperative studies should be encouraged (Table 3).

Modeling studies. The operational dynamical models have little or no skill in intensity forecasts. This may be partly due to inadequate horizontal resolution near the center. However, the boundary layer and cumulus parameterization schemes are also suspect. The initial SST distribution available to these models does not reflect the modifications due to the present cyclone, or large gradients or other mesoscale ocean circulation features. Thus, this discussion will be limited to research modeling studies. Another unfortunate circumstance of the deficiencies of present dynamical models for intensity prediction is that it is less likely that the adaptive observation strategies developed for track prediction will be successful. Without a relatively accurate dynamical model, the adjoint sensitivity or the ensemble model approaches to define those regions that would most likely benefit from improved observations may not be trusted.

An excellent opportunity exists to apply state-of-the-art modeling technologies to simulate *convective structures* and interactions with the boundary layer and with the upper-tropospheric stability conditions. Such a model would need to be nested, have 1 km horizontal resolution on the inner grid and ~ 200 m in vertical resolution, and yet have a horizontal domain of ~ 3000 km. A possible limiting factor for such a model with explicit moisture processes is the inadequacy of present microphysical parameterizations. Notice that similar considerations apply for the quantitative precipitation forecasts in association with landfalling hurricanes that will be discussed in section 7. Another hindrance is the computer resources to integrate, visualize, and interpret such complex models. Although existing data sets may be used to initialize and validate these models, additional data sets including microphysical quantities will eventually be required. These high-resolution model results should also be analyzed as guidance for developing improved treatments of moist processes in operational models. In most cases, the universities and laboratories have been the lead in developing these advanced numerical models, and this seems to be appropriate in the future (Table 2).

While *boundary layer processes* are an essential aspect of the convective simulations described above, other aspects also require modeling studies. One approach may be to use a Large-Eddy Simulation (LES) model. Although the LES can address the turbulent fluxes on certain scales, parameterizations of the surface fluxes are still required. As indicated in Appendix A-4, the effect of ocean spray or spume on the surface fluxes in high wind regimes needs to be understood. Numerical simulations are one approach to understand the sensitivity over a range of wind speeds, droplet size distributions, stabilities, and other boundary layer properties. Validation of such a model will likely require new observations that will be difficult to obtain. Again, the long-term goal of this task should be to develop improved flux parameterizations for the operational models. Although the universities and laboratories are again likely to be the lead for these model studies, a close coordination with the observationalists at HRD and elsewhere is essential (Table 2).

As mentioned in Appendix A-4, several universities and laboratories have developed *coupled ocean-hurricane models*. Acquisition of simultaneous atmospheric and oceanic data sets is essential to validation of these coupled models. The *in situ* observations need to be augmented by satellite-based data such as the SST from the AVHRR or the ocean surface heights from the altimeter on TOPEX. Various parameterizations in the ocean (and atmospheric boundary layer -- see above) need to be validated. Some key issues for real-time application of ocean models are: (i) criticality of pre-storm measurements (vice climatology or coarse resolution ocean model solutions) to specify the initial conditions; and (ii) a data assimilation scheme to blend real-time observations into a properly balanced initial state for the ocean model.

Whereas the HRD has provided the essential oceanic and atmospheric data sets, these coupled models have been developed at universities and laboratories (Table 2). A close collaboration between modelers and observationists is essential to continued progress.

Theoretical studies. The inherently nonlinear nature of all four of these topics (environment, convective, boundary layer, and coupled ocean-hurricane) has made numerical modeling a natural choice. However, these models are extremely complex. It is highly desirable to also promote theoretical studies that will clarify key physical mechanisms and provide conceptual models for understanding the essential elements. Because these studies are most likely to be useful if guided by observations and with realistic basic states and other initial conditions, it is desirable that the university researchers who will carry out these theoretical studies establish linkages with observationists (Table 2).

6. Priority landfall wind structure research and observational opportunities.

The research objectives in sections 4 and 5 are intended to improve understanding and the ability to observe, analyze, and forecast the pre-landfall track and wind structure, respectively. Improvements in track forecast accuracy, extensions of warnings to longer periods with the same accuracy, and developing measures of confidence so that the present overwarned areas could be significantly reduced would avoid unnecessary preparation costs and increase confidence in where landfall will occur. This aspect necessarily requires better analysis and forecasts of outer (beyond 35-kt radius)-wind structure so that the emergency managers are provided with better forecasts of *where and when* the 35-kt wind will first cross the coast, i.e., where and when the landfall occurs. However, the emergency managers must also know the scope of the threat, i.e., forecasts are needed of the inner-wind structure (including intensity) that will determine the storm surge inundations and other evacuation decisions, which are tied to the hurricane intensity category. Warning of the intensity evidently is also an important psychological factor in motivating the public to begin and complete preparedness activities appropriate to the threat. These outer- and inner-wind structure aspects are discussed separately in section 5 to emphasize their different contributions to the hurricane landfall problem, and the research strategy is not the same.

This section addresses research and observational opportunities during the actual landfall, i.e., from the time that the 35-kt winds first touch the coast (when all preparation and evacuation activities are supposed to have been completed) until the center crosses the coast and passes inland. This is the critical period in which most of the damage from localized winds, tornadoes, and storm surge plus ocean surface wave run-up (precipitation and flooding will be addressed in section 7) actually occur. Even given the contributions to improved forecasts/warnings of the pre-landfall hurricane approach conditions from sections 4 and 5, many of the special effects occur when the hurricane moves from the open ocean and crosses the coast (see Appendix A-5 for a brief description). These special effects during landfall need to be understood, particularly as they pertain to how and where the damage actually occurs as the hurricane structure is greatly modified by passing over land. In addition to adding to our scientific knowledge, this information is critical to the real-time assessment of damage that is necessary for organizing efficient and effective rescue and damage/economy recovery activities, and for the revision of building codes and other mitigation functions that will minimize future damage.

The primary meteorological variable during landfall is the four-dimensional evolution of the boundary layer wind field as it translates from the open ocean to the coastal ocean and then over land. This spatial and temporal wind field determines the localized wind damage, and in conjunction with other variables, is the primary determinant in tornado occurrence, heavy precipitation (to be discussed in section 7), and storm surge/ocean surface wave run-up that also contribute to damage (see description in Appendix A-5). Although the section title mentions only wind structure, other meteorological variables will need to be observed to understand how damage occurs from the various special effects described in Appendix A-5. An additional goal is to understand the physics of the additional track deflections associated with the modifications of the hurricane structure during landfall that change the precise center coastal crossing point.

A huge knowledge gap exists in the boundary layer structure and surface fluxes during this landfall period. Fundamental investments are needed to observe the differences in boundary layer structure between the land and the ocean in the hurricane high-wind regions. Obviously, this is a difficult task, but some new observational tools are available to make progress. The new GPS dropwindsondes that provide measurements close to the sea surface, scatterometers, and drifting buoys were mentioned in section 4. Over land, portable radar wind profilers that could be put into positions prior to landfall would provide vertical profiles every six minutes of wind speed and direction up to 3 km, and also temperature profiles to about 1.5 km if equipped with acoustic sounders (RASS). Mobile rawinsonde launchers could also provide vertical profiles of wind, temperature, and humidity. The WSR-88D (NEXRAD) network provides radial wind estimates to a radius of about 100 miles. Miniaturized Doppler radars mounted on trucks (Doppler on wheels, DOW) that were first deployed in Hurricane Fran provide very high resolution measurements of boundary layer structure. When used in coordination with a nearby NEXRAD, it should be possible to get dual-Doppler observations of these structures. Availability of rapidly deployable automatic surface observing systems (ASOS) that could be set up in a network in advance of the hurricane landfall would provide spatial continuity with high time resolution. The key observations are the vertical profiles of wind from the coast to well inland and the spatial wind structures from the coast inland. These land-based observations will be most useful if they are coordinated with the aircraft- and space-based observations just offshore that would provide the pre-landfall structure (see section 5). Whereas the Air Force WC-130 and NOAA WP-3D do not fly over land, perhaps the Aerosonde will be able to fly over land.

The concept of deploying instruments in advance of landfalling hurricanes has been demonstrated by HRD in five of the six landfalling storms during 1995-1997. A strategy is proposed in which the prototype components of such a *mobile observing system* are tested in conjunction with the HRD field programs during 1998-99 so that logistics and deployment strategies could be established. Preliminary experimental designs have been developed and these will be refined each year. If only existing systems are considered, the land-based network might include: Two DOWs; Three - four mobile radar wind profilers; Three-five mobile rawinsonde systems; and Five - ten deployable mesonet (ASOS-type) systems. Potential sources for these systems include national labs and a few universities. Funding is required for operations, travel, and logistics in test deployments and then analysis of the data (Table 3).

During this period, the *data assimilation* aspects should also be explored, both to use existing observations and the experimental data that are most promising. This research should be done at NCEP EMC, NASA Data Assimilation Office, and at universities (Table 3).

Table 3. Summary of **landfall wind structure** research objective prioritizations with investment strategy via an infrastructure (internal) enhancement and university/laboratory (external) grants.

Research objective	Prioritization	Investment	Strategy
		Internal	External
Mobile observing system tests: Doppler on wheels; Radar Wind Profiler; Mobile Rawindsondes; Deployable Mesonet	High	Co-lead	Co-lead
Data assimilation tests:	Medium	Lead	Support
Modeling and Theoretical studies: Understand near-coast track deflections	Medium	Support	Lead

As mentioned with respect to boundary layer studies over the ocean in section 4, the processes are highly nonlinear and the usual approach is with ***high resolution modeling***. Here the concentration would be on the boundary layer structure and flux changes from ocean to land. As in the boundary layer modeling over the ocean described in section 4, the Large-Eddy Simulation (LES) model is a candidate. The new observing systems described above are expected to provide excellent data sets to evaluate the performance of these models in high wind conditions of landfalling hurricanes. Because these model integrations are so complex and difficult to understand, ***theoretical studies*** are needed to assist in the interpretation of models (and observations) with the goal of developing useful conceptual models for understanding. A fruitful area of theoretical studies may be the vortex dynamics that lead to localized wind damage (see discussion in Appendix A-5). Theoretical interpretations are also needed of the special environmental conditions leading to tornadoes in landfalling hurricanes. In addition, the physical processes leading to near-coast track deflections during the landfall modification of the hurricane need to be understood.

7. Priority landfall precipitation research and observational opportunities.

Quantitative precipitation forecasting (QPF) is one of the three USWRP foci. A brief overview of the likely QPF research objectives and approaches is given in Appendix A-6. Given that context of the more general and larger scope of QPF, scientific items more directly related to hurricane landfall precipitation will be described in this section.

Just as for the general QPF problem, the highest priority item for hurricane landfall precipitation is for an *improved data assimilation system for making optimum use of existing observations* (a list of these observations is given in the paragraph on quantitative precipitation estimation in Appendix A-6). This need for obtaining the best possible moisture and wind specification and prediction of the environment is consistent with the observation that a large percent of the water vapor that is condensed and precipitated in hurricanes is evaporated from the ocean over large regions. Clearly, the final energy supplied in the high winds near the center is also important, as is how the convective clouds are organized to release this energy (see also the discussion of the contributions of the boundary layer and convective structures to the hurricane intensity in section 5). Nevertheless, it is believed that environmental conditions are the primary determinant to whether a hurricane will be "wetter" or relatively dry. Many additional complexities exist in the assimilation of the humidity field. Humidity measurements may only be representative of a small region and be contaminated by ongoing convection. The moisture profiles inferred from satellite-based instruments may only have three or four independent pieces of information. It is also important to "anchor" these satellite profiles with good surface observations. Because convection is related to vertical motion, the assimilation needs to consider the divergent component of the wind, which is not as well observed as the rotational component and has small-scale variability related to convection. Another complicating factor is that the model surface flux and boundary layer representations may have biases that make the observations appear to be incorrect, and thus cause them to be rejected.

Because the accumulation of precipitation is a function of the translation speed as well as the rain rate, the list of new observations for incorporation in the assimilation system also includes water vapor winds. These vapor winds are providing information in the cloud-free areas, and thus supplementing the cloud-drift winds to achieve a more homogeneous observation of the environment. Although the NEXRAD network is mainly limited to coastal areas, direct incorporation of reflectivity information would "fine-tune" the pre-landfall representation of the hurricane cloud field derived from the satellite-based observations.

Recall that improved assimilation of observations was the highest priority item for improved track forecasts during the pre-landfall period (section 4). That is, the environmental flow is the primary determinant of the hurricane motion. Although some of the observations to be assimilated for improved precipitation forecasts may be different, the better the track forecast, the more accurate and useful will be the predicted hurriccane landfall precipitation. Although many of the assimilation studies have to be done internally, involvement of university and laboratory researchers should be encouraged (Table 4).

As indicated in Appendix A-6, advancements in model physics are also important. The highest resolution operational hurricane prediction model is the triply nested Geophysical Fluid Dynamics Lab (GFDL) model, which has an inner grid that is 1/6 degree latitude/longitude. Consequently, the model is hydrostatic and uses a cumulus parameterization scheme. Research models have been developed with higher resolution that are non-hydrostatic and have explicit (cloud-resolving) moist physics. These *new research models need to be tested with real data* to determine the fidelity of the precipitation forecasts. Clearly the assimilation system used to provide the initial conditions for these real-data tests is critical. The observation sets obtained by the NASA CAMEX-III and HRD field experiments during 1998 should provide an excellent test bed for initializing and validating the models and the impact of various observation types on the precipitation forecast. These higher resolution models have generally been developed by universities and laboratories, so that these groups should have a leading role (Table 4).

Table 4. Summary of **landfall precipitation** research objective prioritizations with investment strategy via an infrastructure (internal) enhancement and university/laboratory (external) grants.

Research Objective	Prioritization	Investment Strategy	
		Internal	External
Improved data assimilation: Moisture observations; Divergent and rotational winds; Boundary layer considerations	High	Lead	Support
Testing research models with real data: Non-hydrostatic, cloud-resolving models; Real data cases such as CAMEX-III; Data assimilation	High	Support	Lead
Case studies of precipitation processes: NEXRAD validations; Coastal and topographical influences	Medium	Support	Lead
Validation of GFDL precipitation predictions: Provide feedback to modelers; Provide guidance to NHC forecasters	Medium	Support	Lead

The *case study approach* is also appropriate *to document* the *precipitation processes* in observed and simulated hurricane landfall events. New NEXRAD (WSR-88D) precipitation accumulations cross-validated with rain gages should greatly improve the horizontal and temporal resolution of the validation data set. Key parameters are the changes in rain rates as the hurricane crosses the coast and the changes in boundary layer and convective processes over land.

Topographically forced precipitation after the hurricane has passed inland is also of high interest because the locally enhanced precipitation over topography often leads to flooding. Comparisons between observed and simulated precipitation in these cases may be difficult if an excellent track prediction is not achieved, because only small track differences could change the topographically induced precipitation. These case studies are certainly appropriate topics for university and laboratory researchers, although collaboration with groups that have access to NEXRAD data and algorithms will be needed (Table 4).

As indicated above, the only operational model that has any hope of providing estimates of hurricane-related precipitation is the GFDL model. In some landfall events, the GFDL model predicted extremely high precipitation amounts that did not verify. *Validation studies of the GFDL model precipitation predictions are needed.* The goals should be to provide feedback to the model developers and to provide guidance to the National Hurricane Center (NHC) forecasters on how to interpret the model output. University or laboratory researchers working with NHC forecasters would be appropriate for this task (Table 4).

These specific hurricane-related precipitation studies will obviously not solve the broad QPF problems being addressed as one of the USWRP foci. However, the improved understanding and prediction capability for hurricane landfall precipitation would certainly contribute to the QPF solution, and probably be extendable to other cases of heavy precipitation from convective clouds.

8. Social-economic impact research objectives.

With the growth in population along the U.S. coast, more people and property are at risk from a hurricane landfall. Thus far, the number of deaths have decreased while the damage has increased. As indicated in Appendix A-1, the impacts of hurricane landfall on the U. S. coastal communities are varied. A recent study concludes that the annual exposure of the United States to hurricane impacts is greater than $5 billion (1995 $, direct damages). It is unclear how much these impacts might be reduced with improved forecasts. Because hurricane landfalls are relatively rare and the losses are so dependent on whether a highly concentrated population center is hit or missed, it is difficult to provide accurate estimates of the future threat. Some of the economic estimates of preparation costs are based on rather dated source materials, and have been inflated over a long period, so the estimated savings from reducing the overwarned area are not a solid as desirable. Thus, basic questions such as the value of the meteorological forecast and the preventable damage from improved hurricane landfall forecasts need to be answered with more precision and confidence.

A broad socio-economic impact research objective is to explore and document the potential savings that may be allowed from improved analyses and forecasts of the track, wind structure (including intensity), precipitation, and the associated effects such as storm surge, and local wind damage including tornadoes. These socio-economic impacts are recognized to be an important component of the overall USWRP. Clearly, progress on such a research objective requires interaction of the meteorological community with the social scientists and decision makers. Even though comparatively little research has been done on the socio-economic aspects of the hurricane landfall, the fact that it is a highly visible, discrete event with large potential for damage and for cost savings makes it an excellent target for research. Opportunities to learn from socio-economic studies in other countries should also be explored. Australia has had an extensive program to study impacts of tropical cyclones on coastal communities. The World Meteorological Organization is also expected to develop a landfalling tropical cyclone initiative that will have a socio-economic component.

Collection of reliable cost data. A systematic collection of cost data from industry, commerce, and transportation sectors is required. Some cost values from the oil industry and electric power industry have been collected at a USWRP-sponsored workshop on socio-economic impacts. However, a more comprehensive survey is needed following a number of hurricane events to provide a more reliable documentation of the potential savings. What are the lost earnings from closing down businesses and transportation? Under what perceived threat will each business close down or remain open? What is the time necessary to close down the facility and send employees home? How long after the event will the business re-open? What commercial activities may actually benefit from the hurricane landfall via sales of supplies or materials to avoid or repair damage? What are the beneficial aspects of the hurricane-associated precipitation compared to the devastating costs of flooding or other precipitation-induced damage?

The ESIG at NCAR has considerable experience in collecting cost data such as in this task. However, university or private commercial groups that have done social surveys and/or work closely with industry should also be involved in this activity (Table 5).

Identify user needs. In addition to obtaining cost information, the user community needs to be surveyed as to their needs for warnings. The National Hurricane Center (NHC) has surveyed some of the direct and indirect users of their warnings. One *direct customer* of the NHC warnings is the National Weather Service Forecast Offices (NWSFO) that tailor these warnings to the local emergency managers and the public. This set of customers is probably the easiest to contact and would be most qualified to answer meteorology-related questions.

In addition, the same cost data collection efforts described above should include a *user needs aspect* as well. A number of inputs should be sought for correlation with the cost data base. Does the hurricane threat to each sector arise from the wind, precipitation, or storm surge? What improvements in forecasts of track, wind structure (including intensity), precipitation, etc. would be most useful to each business, industry, or other public sector? What would they do differently if forecasts were more accurate? Is timeliness a more important factor? How much additional value would an extra 12 h or 24 h for preparation provide for each customer? How can more accurate and timely storm surge and wind damage accessments be translated into more effective rescue and more rapid economy recovery efforts? What is needed to advance wind-loss estimation models that can be used by insurance companies or in the infrastructure recovery efforts?

Although the survey of the direct (NWSFO) user needs is an internal NWS concern, a university researcher who is familiar with operations might be involved in distributing and synthesizing the survey (Table 5). The collection of user needs at the same time as the cost survey described above would involve those same groups, with assistance from the NHC is formulating the survey questions. The USWRP Science Steering Committee has endorsed the formation of a User Group with representatives from many industries and public sectors. This User Group will be able to provide basic information and help guide the collection of a more comprehensive user needs data base.

Table 5. Summary of socio-economic research objective prioritizations with investment strategy via an infrastructure (internal) enhancement and university/private commercial (external) grants.

Research objective	Prioritization	Investment Strategy	
		Internal	External
Collection of reliable cost data:	High	Co-lead	Co-lead
Identify user needs: Direct (NWSFO) customers; Indirect (non-NWSFO) customers	Medium	Lead	Support
Improved warning preparation/ dissemination: Needs/benefits emergency managers; Sociological study of motivation	Medium	Co-lead	Co-lead

Improved warning preparation and dissemination. As indicated above, both the NHC and NWSFO coordinate directly with the local emergency management officials to disseminate the warnings with the goal of eliciting those preparations and evacuations appropriate to the hurricane threat. This group and the media are essential links in the overall warning systems. Thus, the *needs for, and benefits from,* improved hurricane forecasts by the *emergency managers* should be documented. Although the NHC and local NWSFO do this coordination each season, a systematic collection and documentation would be useful, which could involve a university researcher (Table 5).

As described in Appendix A-2, the key timing issue for the emergency managers is when the winds will exceed 35 kt, since all preparedness activities and evacuations are to be completed by that time. Since this timing involves uncertainties in both the track and outer wind structure forecasts, procedures by which the emergency manager can deal with these uncertainties would be useful. Would the ensemble hurricane forecasts proposed in section 4 provide the basis for addressing the uncertainty in timing for completing preparations? How do the emergency managers deal with the present 3:1 overwarning? How would they change in response to improved forecasts that would reduce the overwarned area to say 2.5:1 or even 2:1?

One outcome of the prioritization process during the Workshop was a need for intensity forecasts well before landfall (defined here as the time at which 35-kt winds are first observed at the coast). The justification offered was that the public would have been more motivated to prepare for Andrew if it had been known that the storm would continue to intensify before crossing the South Florida coast. However, the emergency managers typically have storm surge inundation maps and evacuation plans that are only discretized to the nearest Simpson-Saffir intensity category. Considering that tropical cyclone intensity prediction skill is presently limited, and it is possible that the predictability may be limited to 24 h or so, it is important to document the intensity forecast needs. A benefit to cost calculation for intensity forecast improvements will not be possible until such a documentation is completed. A study is needed as to how the intensity forecast is used (or not used) by decision makers in various public and private sectors to begin and complete preparedness activities. A number of university or private commercial groups could be involved (Table 5).

In closing, the goal of these socio-economic impact studies is to document the *potential* savings to be gained from improved hurricane forecasts. Consideration of the gap between these user needs for forecast accuracy and present skill will indicate where more or better observations and guidance is most needed. Documentation of actual costs and damages in relation to forecast deficiencies will allow meaningful benefit to cost estimates. In addition to guiding selection of USWRP research projects that will have the greatest potential payoff, a documentation that meteorological research benefits the nation will be evident.

9. Hindrances to Research Objectives.

As outlined in the previous sections, significant progress in hurricane landfall research and prediction can be achieved via funding enhancements within the existing infrastructure and laboratories or university grants. However, a number of hindrances to progress need to be addressed, as summarized below.

All hurricane landfall research objectives are hindered by *research community limited access to archives*. In the case of the NCEP model analyses and forecasts, an multi-agency effort fostered by the USWRP will soon allow easy access to these fields. Although this will not solve the access problem for prior cases, it should be possible for external users to collect fields in future cases once the procedures are established. The Hurricane Research Division (HRD) is forming an archive of NCEP fields during hurricane events. Satellite imagery access is another problem that needs attention. Whereas a few centers such as the University of Wisconsin have home pages that display satellite imagery and products in real-time, collecting past images is inconvenient and expensive. Again, HRD is building an archive of satellite imagery during hurricanes via their CIRA system. Radar imagery is even more difficult to acquire -- in part because of the enormous volume and the uncertainty as to when and where data will be required to study hurricanes. A convenient archive system via CDROM technology is a task that has been proposed to UNIDATA.

A number of the research objectives that are related to improved hurricane landfall prediction are also impeded by *research community limited access to operational NCEP models*. A program administered by UCAR promotes extended visits by researchers to NCEP. In addition, some universities have sent researchers to NCEP to learn a model which they then integrate on their own computing systems. However, data assimilation systems are particularly difficult to transport to universities as the entire data ingest, quality control, and associated prediction model that provides the background fields must also be acquired. It is also important to realize that each such university/lab liaison with NCEP requires infrastructure support. That is, someone must be assigned to work with the external group for instruction in the NCEP system, and then to address the inevitable questions/problems as the group attempts to implement the system on their own computer. Although NCEP/EMC has proposed an establishment of a Model Test Facility for some years, insufficient staff have been available to implement the proposal. As the USWRP achieves its research objectives, any result that requires implementation on the NCEP system will require such personnel at NCEP, or the benefit of the research will not be realized.

A related infrastructure problem at NCEP has been *inadequate computing resources* to integrate a high-resolution prediction model with an advanced data assimilation system, plus an ensemble prediction system, while also supporting research and development. Although a new computer system acquisition is in progress, the new system will have capability that significantly lags the ECMWF system and several national meteorological services. The Science Steering committee of the USWRP has recognized this on-going problem and urged that a program of regular review and more timely upgrades be established to recoup the lost capability. Again, a deficient computing capability at NCEP, at FNMOC, and in the national labs will hinder the hurricane landfall research results from being developed and implemented in a timely manner.

Deficiencies in observations over the tropical cyclones hinders operational forecasting, dynamical model prediction, and also a number of research objectives. New data assimilation approaches will make better use of existing observations, especially from space-based remote sensors. New observations from the Gulfstream IV are expected to improve the data coverage in the environment of hurricanes approaching landfall. Research aircraft observations and field experiments such as CAMEX III provide special data sets. One benefit from these field experiments may be validation of the targeted observation strategies, so that the use of mobile platforms such as manned or unmanned aircraft is optimized. However, realizing the benefits of these research data sets for day-to-day forecasting will require new observations.

Another hindrance to optimum use of present aircraft observations into the initial conditions of operational models (Item 1 in Table 1) has been *inadequate bandwidth for communicating aircraft observations*. Although improvements have been made, the capability of modern assimilation systems to accept non-conventional data makes the communication of fields such as aircraft radar images and Doppler winds even more necessary.

10. Expected benefits.

Whereas all aspects of this research plan have as an ultimate goal to improve hurricane landfall forecasts, some components are expected to yield benefits relatively soon and other components address important science issues that need to be resolved before becoming forecast tools. This research plan also exploits new observational opportunities both for their immediate application and in support of science objectives. On a parallel path, the potential socio-economic benefits of hurricane landfall will also be documented. Highlights from the various components of the research plan will be briefly summarized here.

Three goals for the pre-landfall track forecast problem are to provide NHC forecasters with the guidance materials that will: (i) Increase the preparation lead-time for the various public segments by at least 12 h via an improvement in forecasts of the location and timing of the hurricane landfall point; (ii) provide forecast guidance to 96 h with the same accuracy as the present 72-h guidance; and (iii) Provide more accurate forecast guidance with confidence measures that will allow NHC to reduce the present 4:1 over-warning of coastal areas to a ratio of 2:1 in 90% of the hurricane landfalls that are essentially perpendicular to the coastline. The approach is to improve the initial condition specifications via investments in variational assimilation and improved quality and quantity of observations, including targeted observation strategies. Understanding the causes of track forecast outliers and improving the numerical model guidance will also contribute. Provision of the confidence measures will be from ensemble or discriminant techniques, understanding of track predictability, and conceptual models for interpretation of the track guidance.

Advancements in predicting the outer wind structure needed to better specify the timing of the hurricane landfall are expected to come from an observational program to provide the needed data base. That is, it is believed that the present dynamical models represent the physical processes involved in outer wind structure changes, provided that better observations are provided. This assumption needs to be verified and theoretical understanding provided.

Basic understanding of the inner-core wind structure (including intensity) changes is the first goal because it involved four non-linearly interacting physical processes. An important approach is to obtain additional and more comprehensive data sets to resolve the relative contributions of each process to inner-core structure changes. New observational platforms such as the Gulfstream IV (and possibly UAVs), GPS dropwindsondes, and satellite-based scatterometers will provide atmospheric over-water data, and ocean current, temperature, and salinity probes will document ocean responses. Whereas diagnostic tools are already available, extensive modeling of the boundary-layer, convective structures, and environmental influences are required. Similarly, sensitivity tests and validation of coupled ocean-hurricane models are needed. On a longer term, these studies should lead to design of an observation, analysis, and forecast system for inner-core wind structure (including intensity) forecasting.

Advances in basic understanding of the complex physical changes in the wind structure during landfall is also a high priority goal. The primary approach is again observational as new land-based observational tools are available: portable radar wind profilers with acoustic sounders; mobile rawinsonde launchers; Doppler radars mounted on trucks used separately or in conjunction with the WSR-88D network; and rapidly deployable surface mesonets. These new systems should be tested in conjunction with the HRD field programs and implemented as available to gain new data sets for understanding how localized wind damage occurs, tornado formation conditions, storm surge and ocean surface wave runup, and precipitation processes. A data assimilation and modeling approach is also needed for progress in this area, which should lead to better rescue and economic recovery procedures following hurricane landfall.

A short-term improvement of hurricane landfall precipitation is possible from a data assimilation system that would make optimum use of existing observations. Prior to landfall, satellite-based humidity and wind observations need to be incorporated. During landfall, radar reflectivity and radial winds are available. New research models need real-data sets for validation of precipitation forecasts, and case studies for diagnosis and understanding that will assist the NHC forecaster in predicting coastal and inland flooding. These advances in quantitative precipitation forecasting in hurricanes will thus contribute to a second focus of the overall USWRP.

The broad socio-economic impact research objective is to explore and document the potential savings that may be allowed from improved analyses and forecasts of the track, wind structure (including intensity), precipitation, and the associated effects such as storm surge, and local wind damage including tornadoes. Even though comparatively little research has been done on the socio-economic aspects of the hurricane landfall, the large potential for damage and for cost savings makes it an excellent target for such research. We will then be able to direct research to the most beneficial meteorological observing and forecasting systems and better document the benefit to the nation that this five-year research plan can achieve.

APPENDIX

A-1. Impacts of hurricane landfall

The public perceptions of hurricanes making landfall have been formed in part by the television reports of the aftermath. Events such as Hurricane Andrew striking southern Florida and then the Gulf Coast raise the public consciousness. Damage estimates of $30 billion from this single event make hurricane landfall a critical economic issue for the region and for the nation.

It can be clearly documented that the population at risk from hurricane landfall along the U. S. mainland coast from Texas to Maine has been increasing. In just these 17 states, a total of 168 counties are on the coast, and more than 1000 counties may be considered at risk for hurricane damage. With the population and industry shift to these coastal regions, the insured property values have increased dramatically. Multiple loss events such as Andrew threaten the integrity of the insurance industry in this country.

Given that a hurricane landfall occurs, a certain fraction of the losses are not avoidable. Closing down commerce and industry, and disruptions in transportation, incurs costs that can not be avoided. Evacuating people and mobile assets such as ships and aircraft from high-risk coastal areas to safe havens is a necessary expense. As the number of people living at the coast or on barrier islands has increased, the clearance time has increased because the number of evacuation routes is limited. The clearance time is also increased if people who really do not need to evacuate feel at risk and add to the traffic burden. Evacuations from the oil drilling rigs, particularly along the Gulf of Mexico, and closing down the petrochemical industry are expensive in terms of direct costs as well as lost revenue to the industry and lost tax income to the government. In the optimum case, only those industry closing and public evacuations that were actually necessary would be carried out. In practice, the uncertainties in the observations and understanding of the hurricane, and the inaccuracy of the forecasts, make it prudent to warn a larger area than will be affected. On average, the cost of preparations along the 300 miles of coast typically put in warning is approximately $300 million. To the extent that reductions in the overwarned area are possible through better observations, understandings, and forecasts of hurricane landfall, the nation will benefit.

Meteorological considerations are not the only factor in damage. Improvements in building codes, and enforcement of those codes by adequate inspections, could save billions of dollars. The Andrew event has caused a re-examination of the wind-induced losses during hurricane landfall because the damages were larger than would have been expected from the pre-landfall intensity estimates. Research that would contribute to a better understanding of the threat from local wind damage would have a benefit in terms of improved mitigation efforts such as building codes or structure safety standards.

Prior to Andrew, much of the hurricane landfall damage was expected to occur from storm surge, which is the rise in the ocean surface as the hurricane winds and low pressure drive water onto the coastal shelf. The sea level may rise 10-20 feet, cross the coast, and flood barrier islands and penetrate low-lying coastal regions. Given the elevation of coastal barriers and levees, much of this water damage may be unavoidable for a stronger than expected storm surge event.

Accurate assessments of damage from storm surge or wind may also reduce the hurricane landfall impact. Getting rescue and repair crews with the necessary supplies and equipment to the areas of most severe damage may save lives and will hasten the restoration of power, transportation, commerce, etc. Simply having the proper cover over damaged houses following Andrew would have prevented the additional water damage from a subsequent heavy rain event. The Federal Emergency Management Agency (FEMA) is attempting to be more proactive (rather than reactive) in moving teams and emergency supplies into hurricane landfall zones.

An excellent meteorological forecast will not necessarily result in minimal damage. That forecast has to be translated into warnings that communicate to the public the actual threat. Not a lot of information is available as to what motivates the public to take the proper actions to prepare or to evacuate. A hindsight comment following Andrew was that a better perception of the actual intensity would have prompted more appropriate precautions or evacuations. However, the whole psychological aspect of public response to warnings, what is the actual experience level with hurricanes, what percentage of the people will take actions in each situation, what impact information from different media may have, etc., and how these social factors might contribute to the avoidable damage, is uncertain. Clearly, a high level of puplic confidence in the hurricane landfall warning system must be a goal.

A-2. Key aspects of the hurricane landfall forecast problem

The National Hurricane Center (NHC) is tasked to issue a Tropical Storm (TS - maximum sustained one-minute wind speed $\geq$ 34 kt or 17 m s^{-1}) or Hurricane (maximum wind speed $\geq$ 64 kt or 32 m s^{-1}) *watch* when the center is forecast to cross the U.S. coast within 36 h. More importantly, a TS or Hurricane *warning* is issued when the center is forecast to cross the coast within 24 h. The objective is to provide the public at least 12 h of daylight to complete preparedness activities. In addition to preparing buildings or closing down businesses, this may include evacuation of an area that is expected to be inundated by a storm surge across the coast, or expected to experience severe wind damage. An important consideration in determining the size of an evacuation area is the storm intensity, because the storm surge inundation area will generally be much larger for a Category 5 hurricane than for a Category 1 hurricane. As more and more people have moved into the U. S. coastal areas, the time it takes to complete an evacuation from a threatened area has also increased. Considerable reductions in structural and other property damage could be achieved by an improvement in landfall timing forecasts that would allow two daytime periods for preparations.

The function of the local emergency managers is to motivate the public to undertake disaster preparedness activities that are appropriate to the threat represented in the national Hurricane Center watches and warnings. Whereas the 36-h watches and 24-h warnings issued by NHC are relative to the center coastal-crossing time, the key consideration for the emergency managers is that the disaster preparedness activities or evacuations need to be *completed prior to the arrival of gale-force (35 kt) winds*, or the heavy precipitation that would make such activities or evacuations hazardous. Because of the forecast track errors and the uncertainty in the radius of the gale-force winds, the length of coast that is placed under a watch, or in a warning, is longer than the length that will actually experience those winds. A typical ratio of *overwarning* is 4:1. Being aware of this overwarning, the emergency manager may delay issuing the call for preparedness activities or evacuations until more solid evidence of the threat is available. However, such a delay raises the risk that the activities or evacuations will not be completed safely, especially if the hurricane suddenly accelerates toward the coast.

Even though the watches/warnings are related to center coastal crossing times and the emergency management considerations are related to the arrival of 35-kt winds at the coast, psychological factors evidently link these different considerations. That is, some emergency managers do not believe the public can be motivated to initiate preparedness activities or evacuations unless the NHC has placed the coastal area under at least a warning. Presumably, the public are more likely to initiate preparedness activities or evacuations if the warning is for a severe hurricane than for a tropical storm. Consequently, an accurate intensity forecast at about 36 h prior to center coastal crossing time (when first watch is issued) is a requirement to motivate public action appropriate to the threat.

To minimize overwarning, and thus the perception that the NHC and emergency management community have "cried Wolf" too frequently, the accuracy of the track forecast to the *hurricane approach point*, which is defined here to be when the 35 kt winds have first reached the coast, must be improved. Since the outer wind structure (specifically the 35-kt wind radius, or other damage-threshold wind) is a factor in the timing of the emergency management activities, this is another important hurricane characteristic to be analyzed and forecast.

The inner-core wind structure is also critical for the storm surge prediction and estimating the ocean surface wave runup at the coast. Because the uncertainty in the 24-h track prediction is greater than the horizontal scale of the storm surge, a deterministic storm surge prediction is not done. In addition, the imperfect knowledge of the inner-core wind structure prediction would also prevent an accurate calculation of the storm surge in real time. Thus, the approach used at the NHC is to utilize a Maximum Envelope of Water (MEOW), which is an atlas of maximum surge elevations for an ensemble of storms of different intensities approaching the coast from a variety of directions. The NHC forecaster attempts to match the forecast characteristics of the present hurricane with one of the storm surge atlas solutions, which is a kind of a worst-case elevation along the coast. However, this does not give the distribution of the surge elevations along the coast if the track or inner-core wind structure deviates significantly from the forecast. This surge distribution is important for post-storm damage assessment if inundation has occurred, because the need/locations for focussed relief efforts will be a function of what areas were under water and for how long.

Another important consideration in the coastal and inland regions is the rate, duration, and total amount of precipitation that will be associated with the hurricane landfall. This precipitation determines the threat of urban or inland flooding, and many water management activities (e. g., releasing water to lower reservoirs or protection of levees) depend on accurate precipitation assessments. Even though the winds may decrease below gale-force shortly after the hurricane center has crossed the coast, the precipitation can still cause flooding, especially in a slow-moving storm. Indeed, the remnants of the hurricane circulation may persist while traveling 500 miles inland and then interact with a midlatitude front and continue to cause heavy precipitation. Upslope motion against topography can greatly enhance precipitation and embedded mesoscale convective systems may trigger extreme precipitation events. For these reasons, the precipitation associated with a landfalling hurricane may be spread over large inland areas and yet have highly localized maximum amounts.

Post-hurricane damage surveys have often indicated that the wind fields may include highly localized regions that cause extreme destruction just across the street from similar structures with relatively little damage. Where these differences are not due to shoddy construction practices or poor enforcement of building codes, the extreme damage is attributed to tornadoes, or to straight-line winds that are greater than would be normally associated with that hurricane intensity. Hypotheses as to the trigger mechanism and wind speeds to be expected in these straight-line events have recently been posed. Although some characteristics of tornadoes associated with hurricane landfall are known, their occurrence is a difficult forecast problem because of the small horizontal scales and generally short durations. It is anticipated that the network of Doppler radars recently installed along the U. S. coast will assist in detection of the tornado events.

The research plan to improve understanding and forecasts of hurricane landfall will be limited to events along the continental coastline from Texas to Maine. This excludes the Caribbean Islands, Hawaii, and the southwestern U.S., which may experience precipitation from remnants of hurricanes in the eastern North Pacific. Events that have changed from warm-core tropical cyclones to cold-core extratropical cyclones will also be excluded.

A-3. Specific landfall definition

As suggested by the PDT-5 report (Marks and Shay 1998), three periods related to hurricane landfall were first considered -- pre-landfall, landfall, and post-landfall. After considerable discussion of the definitions of these terms, and the forecast measures most important in each period, only two periods will be defined here. In consideration of the emergency management requirement to complete all disaster preparedness activities, *landfall* at either the tropical storm or hurricane stage *will be defined to have occurred if the 35-kt isotach crosses the coast.* That is, the public should be prepared even if the center only passes near the coast. This situation may occur along the east coast of the U. S. in which landfall damage may occur without a center coastal crossing. This landfall definition differs from the PDT-5 report, which defined landfall as ± 6 h after the center coastal crossing time. The new definition of *pre-landfall* is prior to the time at which the 35-kt isotach first crossed the coast.

In addition to taking into account the critical emergency management requirement, a solid scientific basis exists for making this landfall definition. The passing of 35-kt and higher winds over the shallow coastal waters and then over the land results in important modifications of the cyclone structure via frictional, thermodynamic, and dynamical processes. The resulting convection and circulation asymmetries begin to modify the wind structure and intensity, and modify the track to change the center crossing point by tens of miles. Such late track shifts may determine whether a population center takes the full brunt of highest winds and storm surge.

No forecast measure or scientific basis seems to exist between the PDT-5 landfall and post-landfall (+ 6h) definitions. That is, the inner-core (within 35-kt isotach) wind structure (including intensity) changes, the modification of the convection and precipitation due to passage over land, and their associated track deflections continue until the cyclone dissipates or loses its warm-core structure. As these changes occur continuously, the same forecast measures apply throughout this period, and the same scientific approaches are appropriate, no distinction for the 6 h after center coastal crossing and later periods appears to be necessary in this research plan.

Another change from the definitions in the PDT-5 report was made to extend the beginning of the pre-landfall period to 4-5 days, rather than 48 h. This extension was done on the basis of need and given some preliminary indication that longer period track forecast may become feasible during the period of this research plan. An example of the need for the potential landfall at 120 h, the decision process and preparations to return the NASA Space Shuttle from the launch pad to safe storage and complete other safety precautions requires about 72 h. Each Shuttle is valued at $2 billion and the facility is about $8 billion. Each hurricane threat to southern Florida raises the risk of Lake Okechobee overflowing, so that the decision process as to whether to release precious water must begin early as lowering the water level requires days. The U. S. Navy must consider whether to evacuate ships from several bases along the coast in time to allow then to sail out of harm's way. Other maritime interests, including the offshore oil industry, also need outlooks beyond 72 h to begin the decision process. By properly taking into account the greater uncertainty owing to larger track errors, such 120-h outlooks would have benefits. The evidence that 120-h track forecasts may be feasible is that global models at several numerical weather prediction centers already produce tracks over these intervals that have proportionally larger errors as at 72 h. Granted that the models may lose the cyclone circulation at longer intervals, and it must be demonstrated that early stages of the tropical cyclone are predicted, this provided a basis for extending the pre-landfall period to 120 h.

A-4. Conceptual framework for inner-core wind structure changes

Some background will be provided here to serve as a framework for the discussion of inner-core wind structure (including intensity) changes described in section 5. First, this is a topic with considerable on-going efforts and is controversial. The PDT-5 report (Marks and Shay 1998) provides an excellent background as to the science issues/questions in this topic. A symposium on tropical cyclone intensity has been organized at the American Meteorological Society (AMS) meeting in Phoenix during January 1998. Readers are encouraged to read the PDT-5 report and the AMS symposium preprints for more detailed discussion and references. The objective of this short discussion is only to provide a context for discussion of research objectives and observational opportunities related to the four nonlinearly interacting processes that are believed to control the inner-core wind structure (including intensity) changes in section 5.

Two theoretical paradigms are used to provide the framework for this discussion. The first is the evolution of the wind structure proposed by H. Willoughby and colleagues in association with contracting concentric eyewalls in the mature stage or contracting rainbands in the immature stage. This model provides a coherent sequence of physical processes that lead to an inner-core wind profile evolution. The key focus is then on the convective structure, although clearly the interaction with the boundary layer is an essential physical process. What triggers these convective cycles is not fully established. Possible candidates include an inherent internal vortex instability, an internal instability related to mesoscale convective systems, or an external forcing by environmental interactions or by boundary layer interactions with land.

A second theoretical paradigm is related to the maximum potential intensity (MPI) that a tropical cyclone is expected to be able to achieve. Because four competing models by Emanuel, Holland, Willoughby, and Gray are in various stages of publication, this topic is controversial.

Whereas some common elements such as the importance of the sea-surface temperature are evident, important issues remain as to details of the boundary layer processes, the static stability considerations related to the upper-tropospheric temperature, the nature of the convection in the eyewall, and the importance (or non-importance) of eye thermodynamic processes. Clearly, key measurements are needed to resolve differences among the competing theories.

From a practical viewpoint, few tropical cyclones ever reach their MPI. The reasons may simply be related to the time required for the physical processes of convective cycles to develop and advance the inner core wind structure toward the MPI value -- i.e., the cyclone is always "in progress" toward the MPI and has not had time to achieve that value. An alternative is that the environment provides favorable or inhibiting influences that either contribute to or prevent achieving the MPI. The favorable environmental interaction with the cyclone is often related to an upper- tropospheric potential vorticity anomaly (so-called good trough) that introduces a cyclonic eddy momentum flux. This flux at a large radius is able to influence the inner-core wind structure (intensity) because of the low inertial stability of cyclone outflow layer. An alternate explanation may be that the interaction with the adjacent synoptic circulation triggers a Willoughby-type convective cycle. The inhibiting influence of the environment is typically considered to be vertical wind shear that disperses the heat so that the warm-core structure maintenance or amplification is prevented. This vertical wind shear may be associated with the weakly baroclinic tropical environment, or with the juxtaposition of an upper-tropospheric trough (so-called bad trough) that introduces additional speed or directional vertical wind shear above the cyclone.

Regardless of how the inner-core convective structure is triggered or is modified by vertical shear or the upper-tropospheric stability effects, a key control on the convection is in the boundary layer structure and fluxes. The critical thermodynamic properties of temperature and humidity determine the equivalent potential temperature of the convective updraft. A controversial aspect of the boundary layer is the effects of sea spray or spume in regions of high winds. Few measurements have been made in such difficult and hazardous conditions. Some research ship and buoy observations indicate the sea-air temperature difference in high wind regions are much larger (~ 5°C) than have traditionally been assumed (~2°C). Recent Global Positioning Satellite (GPS) dropwindsondes indicate complex vertical structures in the boundary layer under the eyewall. Thus, the role of the boundary layer in the inner-core wind structure changes needs additional research.

The ultimate energy source for the tropical cyclone is the warm tropical ocean. Thus, how the heat and moisture are transferred to the free atmosphere via the air-sea and boundary layer fluxes is a critical factor, so the sea-surface temperature (SST) distribution must be specified. However, the SST distribution is simply the surface signature of the upper-ocean thermal structure that is being modified by the presence of the tropical cyclone circulation. In addition to the surface sensible and latent heat flux distributions directly modifying the ocean thermal structure, the ocean currents induced by the hurricane stress distribution advect the thermal structure, cause turbulent mixing via vertical shearing, and have divergence/ convergence that lead to modifications via upwelling and downwelling. It is well known that the hurricane induces a cold wake with SST decreases that have a maximum in the right-rear quadrant. The magnitude of these SST decreases is primarily determined by the initial ocean thermal structure, and the translation speed and intensity of the tropical cyclone.

The key issue related to inner-core wind structure is the extent to which the cold wake limits the intensity of the storm. If the reductions in surface air-sea fluxes over the relatively small (compared to total area of the cyclone) cold wake area do not significantly feedback to the eyewall equivalent potential temperature, then only the initial SST distribution has to be specified. If time-dependent ocean thermal structure changes significantly modify the negative feedback process that limits the eyewall equivalent potential temperature, then a coupled hurricane-ocean model is necessary. This requirement would introduce a number of new issues. First, observations of the initial ocean temperature, currents, and (probably) salinity distributions would be required. Second, an ocean data assimilation technique to blend the complex spatial and temporally varying ocean properties under a hurricane would be needed. Third, a high resolution, three-dimensional ocean model would have to be coupled to the atmospheric prediction model. Uncertainties in the coupling mechanisms and empirical turbulence processes in the ocean model would need to be addressed. Coupled ocean-hurricane models have been developed by several research groups, with somewhat different magnitudes of the predicted effects on hurricane intensity. These models need to be validated with good data sets in both the atmosphere and ocean.

The above discussion provides the basis for a tentative framework for addressing the overall science questions involved in inner-core wind structure changes. Specific hypotheses related to each of the four nonlinearly changing physical processes incorporated in the overall framework will have to be formulated. Research objectives and observational opportunities described in section 5 will be in the context of this tentative framework: *Inner-core wind structure changes are triggered by the tropical cyclone circulation interacting with the environment via baroclinic vertical wind shear processes and with potential vorticity anomalies in the upper troposphere that initiate convective cycles involving contracting rainbands during early stages or concentric eyewalls in the mature stage. Significant modulations of the convective cycles occur via boundary layer processes that determine the equivalent potential temperature under the eyewall, which includes interaction with the initial ocean thermal structure that is varying in space and time in response to the translating cyclone circulation.*

A-5. Special effects during landfall

The key distinction made in this research plan is between the pre-landfall and landfall periods, which are defined to be before and after the 35-kt wind first crosses the coast. This distinction has been made for practical considerations of forecasts and warnings. That is, all preparations and evacuations are to have been completed at this time of landfall so that the high winds and heavy precipitation do not prevent their successful completion. Thus, the pre-landfall forecast problem is to pinpoint the precise hurricane landfall point, which involves both the track prediction and the outer wind structure prediction, so that ideally only those areas along the coastline that are actually going to be struck have been warned. Because of the track forecast and outer wind structure uncertainties, an overwarning is necessary so that considerably larger coastal regions prepare unnecessarily (this is only known after-the-fact).

A second forecast task during the later portions of the pre-landfall period is to specify the hurricane inner-core structure, including the maximum wind speed (intensity). The reasons for this second forecast task are that the scope of the disaster preparedness activities is scaled to the storm intensity category at landfall, and (evidently) the psychology of motivating the public to begin and complete preparations or evacuations in a timely manner depends on the perceived intensity. An example of the first reason is that the inundation area from a storm surge, and thus the evacuation area, is larger for a Category 5 hurricane than for a Category 4 hurricane, etc. In addition, the planning for the disaster and economic recovery activities is different for a more intense hurricane. Thus, the local emergency managers in the warned area need a forecast of the intensity category while the hurricane is still approaching.

An idealized conceptual model of the hurricane during the pre-landfall period is that it is a relatively well balanced wind field around a nearly circular low pressure center that is translating in a relatively steady direction and speed. Although the spiral rainbands introduce asymmetries in the precipitation, the conceptual model includes a concentrated, relatively circular precipitation maximum near the center. The exceptions or potential disruptions to this pre-landfall conceptual model are many: (i) Interactions with an adjacent synoptic circulation or a changing outer wind structure may be causing a changing environmental steering, and thus track direction and speed changes on times scales of 1-2 days; (ii) This environmental interaction may also cause changes in vertical wind shear and/or eddy momentum fluxes that affect the inner-core wind structure and cause intensity variability; (iii) Triggered by this environmental interaction, or some form of vortex instability, an eyewall replacement cycle may cause changes in the intensity on time scales of 1-2 days; or (iv) Crossing a zone of large sea-surface temperature (SST) or over a warm oceanic eddy introduces important non-homogeneous surface fluxes of energy and momentum and associated convective asymmetries that are inconsistent with an idealized conceptual model of relatively symmetric conditions. In a sense, the track and intensity forecast problems may be regarded as predicting how asymmetries in the environmental forcing (including the ocean surface forcing) cause asymmetries in the hurricane that change the motion and intensity on time scales of 1-2 days.

Consider now the special effects during landfall, i.e., as the central region with winds exceeding 35 kt encounters the warm ocean on the continental shelf and then over solid land with greatly increased roughness and marked reductions in the energy source. Even if the approaching hurricane was the idealized nearly symmetric vortex in a uniform environment steering, dramatic changes in all aspects of the hurricane occur due to the changing surface conditions during landfall. In general, these changes occur on time scales less than one day because of the smaller space scales introduced by crossing from ocean to land. For a typical translation speed of 10 kt and a radius of 35-kt winds of 150 n mi, the time from beginning of landfall to eye coastal crossing is 15 hours. For a small, rapidly moving hurricane such as Andrew, the time scale may be only 8-10 h!

The primary meteorological variable during the landfall is the boundary layer wind field. The discontinuous increase in surface roughness over the land will modify the vertical profile of winds. Increased cross-angle flows toward low pressure will enhance the low-level convergence and vertical motion, which will modify the cloud formation and distribution. Increased convection and associated latent heat release and warming aloft near the shore may rapidly decrease the surface pressure, so that the low pressure center may suddenly shift toward the coast. What may have been relatively balanced wind and pressure fields in the pre-landfall period will become unbalanced in response to these frictional changes and surface pressure changes. The (inertial) time scale over which these imbalances might be eliminated is too long relative to the time scale of the disruptive influences occurring as the central region of high winds approaches and crosses the coast. Thus, the low-level winds will be strongly turbulent and highly unbalanced over land-ocean boundary.

One proposed explanation for the greater localized wind damage in Andrew than might have been expected for the pre-landfall intensity is the highly unbalanced flow on the inside of the radius of maximum wind where extremely large pressure gradients existed (recall that Andrew was a small, compact hurricane). One hypothesis is that the imbalance created as the maximum wind crossed the coast triggered an instability that amplified as a vortex sheet. Given the inward deflection of parcels down the steep pressure gradient, large increases in kinetic energy may occur over short times, which may account for the localized wind damage that appears to be associated with straight-line winds rather than tornadoes.

Tornadoes do occur in many (but not all) landfalling hurricanes. These tornadoes are found predominantly in advance and to the right side as the rainbands cross the coast, where a number of environmental conditions favorable for tornadoes occur. In addition to the high equivalent potential temperature air moving onshore, large upward motion (vertical stretching of the column) in the rainband cloud, cyclonic rotation across the rainband, and the large turning of the wind in the lower troposphere owing to the sudden increases in roughness and stability as the air crosses the land, creates tornadogenesis conditions. Considering the short time scales of these tornadoes, the strategy is one of monitoring (rather than predicting) the suspect areas with the new Doppler radars along the coast.

Another major contributor to hurricane landfall damage is the storm surge. It may be assumed that the initial advection of this water mass onto the continental shelf and its advection toward the coast on the right side of the hurricane occurs before the inner winds have been significantly modified by the presence of land. Similarly, the inverted barometer effect of lifting off the ocean surface in response to the concentrated low pressure center also occurs before the central pressure has been significantly modified. However, extreme changes in bottom friction occur as the depth decreases to the shore and the surface wind stress on the top of the water column is highly modified near the coast. Thus, predicting the detailed currents in the storm surge is a highly nonlinear problem with small space and time scales.

Many similar considerations apply to the ocean surface wave run-up that adds to the storm surge water elevation. Since some fetch length is required to grow these waves, their initial growth occurs offshore before the surface wind field is significantly modified by the presence of land. However, the final surface wave run-up near the shore is in a complex, rapidly-changing surface wind field that has short time scales.

The precipitation distribution is also disrupted over land, especially if topography is present such that enough uplift occurs to induce convection. Even the convective cells that are triggered at the coastline may be carried some distance downstream while rotating cyclonically. Meanwhile, the offshore flow to the left side of the track may be drier and unable to sustain deep convection.

In summary, many special effects are introduced during hurricane landfall. That is, at the most critical and damaging period, the hurricane is also being modified most strongly. Localized winds may cause heavy damage separate from tornadoes. Storm surges are created in narrow zones on the right side, while the left side has low water elevations. Heavy precipitation in concentrated regions may cause flooding, especially along the sloping orography. Although the central core of convection is not sustained after the eyewall is over land, the remnants of the circulation can cause heavy precipitation hundreds of miles inland.

A-6. Hurricane landfall precipitation in overall QPF context

Quantitative precipitation forecasting (QPF) is one of the three USWRP foci, which reflects its importance to human activities ranging from destructive floods, disruption of transportation/commerce, and recreation activities. Although each of these human activities is impacted by the precipitation in landfalling hurricanes, the QPF problem is much larger and more general than that associated with the approximately two hurricane landfall events per year. The intent of this discussion is to provide a larger context of the QPF research objectives and approaches likely to be undertaken under the USWRP focus. Given that context, the objective is to identify in section 7 those specific QPF items that are most directly related to precipitation during the hurricane landfall.

The varied nature of precipitation makes the QPF topic very complex. Convection may be forced by many sources: dynamical, local thermal effects or density currents, topography, and radiative effects. Although much of the significant precipitation occurs in conjunction with these convective clouds, stratiform clouds may also account for precipitation accumulations over extended intervals. So-called slantwise convection may also be involved, and this requires special treatment in numerical models.

Opportunities to improve QPF seem particularly promising because of improved understanding from observational studies and numerical simulations of isolated convective clouds and mesoscale convection systems, in conjunction with the improvements in horizontal resolution of operational models so that moist processes, which occur on small scales, may be represented better. For example, non-hydrostatic models on the mesoscale are replacing the hydrostatic models. Issues such as use of cumulus parameterization (required for coarse-resolution numerical models) versus cloud-resolving models have been addressed. Better horizontal and vertical resolution should also assist in the representation of boundary layer processes that are intimately linked to convective processes. On the negative side, a number of science issues are becoming critical to progress in QPF. Perhaps the most important for modeling is the microphysical parameterizations, which were developed in the 1970's and are relatively crude. More observations of ice and liquid microphysics are needed to improve these parameterizations. Sensitivity tests have demonstrated that use of a different parameterization may change the mesoscale convective system structure because increased fall speed of gaupel relative to ice crystals changes the generation of potential vorticity in the system. Such issues are critical to severe local storm formation (and perhaps also tropical cyclone formation) and thus QPF.

Advances are also being made in quantitative precipitation estimation (QPE). Improvements have been made in radars and the algorithms for estimating rain rates from the radar reflectivity. Other parameters such as ice characteristics and hail may be derived from the new radars. *In situ* observations of rain from gages in mesoscale networks, disdrometers, etc. may be combined with radar estimates to improve QPE. Lightning networks indicate the areas of deep convection and heavy precipitation over much of the continental U.S. area. Satellite-based instruments that provide observations related to QPE and QPF have also been improved, e.g., humidity profiles and precipitable water, cloud distribution and type discrimination, water vapor and cloud-track winds, and direct estimates of rain rates from microwave instruments (SSMI/TRMM). In special experiments, aircraft *in situ* microphysics observations and radar reflectivity may be available.

Given new or improved observations and better numerical models, the highest priority for QPF is development of an optimal assimilation scheme to incorporate all of these observations. In existing optimal interpolation schemes, the observational error characteristics must be known. The new variational schemes require a "forward model" for each observation type that describes in terms of model variables what should be observed by each instrument at specific locations and times. This forward model requires detailed knowledge of instrument characteristics and of the numerical model code, and thus requires specialized knowledge and is time-consuming and expensive to develop. However, it is believed that such techniques offer the best opportunities for improved QPF by more fully exploiting existing observations.

A number of data-impact studies are possible with the data assimilation technique. The impact of specific observations can be assessed by data-denial studies, or new observation impacts by use of observing system simulation experiments (OSSEs). The need for additional observations and the testing of targeted observation strategies may also be carried out. Although some national weather services employ synthetic observations for moisture profiles based on cloud-top temperatures and other characteristics, this possibility has not been exploited much in this country.

More effective use of the model QPFs may result from collaborations between weather forecasters and hydrologists that lead to more tailored model products. For example, animated or digital display products may convey better the nature and distribution of the predicted precipitation. The COMET program may be an appropriate vehicle to explore collaboration with hydrologists. An end-to-end system of coupling hydrological basin models to atmospheric prediction models would directly predict storm runoff, flooding, and other consequences of precipitation (e.g., soil moisture accumulation or variability).

Case studies of precipitation events are useful in evaluating the quality of model predictions and in understanding the physical processes. Statistics of model-predicted and observed precipitation are needed in a variety of situations both to assess skill and as a measure of improvement. Such model validations are not easy because of the short space and time scales of many heavy rainfall events and the inhomogeneous network of stations. Diagnostic studies are also useful for isolating the physical processes leading to the precipitation event.

Each of the above research objectives applies to the general QPF focus of the USWRP. Specific items related to the hurricane landfall precipitation forecast are described in section 7.