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NUMERICAL MODELING FOR TROPICAL CYCLONE INTENSITY AND PRECIPITATION – A WORKSHOP REPORT

Russell L. Elsberry
Science Coordinator
USWRP Hurricane Landfall

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EXECUTIVE SUMMARY

The U S Weather Research Program (USWRP) Hurricane Landfall research goals related to improved tropical cyclone intensity change and precipitation prediction guidance are considered to require advanced numerical models. Thus, a Workshop on Numerical Modeling for Tropical Cyclone Intensity and Precipitation Prediction was held in San Diego, California during 3-4 May 2002. The primary objectives of the Workshop were to design the highly desirable research model and minimally-acceptable operational model to meet proposed intensity and precipitation targets. For example, the target is to achieve a 20% improvement in intensity forecast accuracy relative to the National Hurricane Center performance for all Atlantic forecasts during the 2001 season. A highly desirable rain target is set as a heavy rain event (> 10 cm/h) detection rate of 80% with a false alarm rate of less than 20% at 6, 12, 18, 24, and 36 h. The minimally-acceptable storm-total rain prediction is tentatively set as an absolute error of 1 inch (25 mm).

The approach at the Workshop was to first define certain physical processes known to affect tropical cyclone wind structure (intensity) change and precipitation and what these processes imply for numerical model characteristics. A list of observations that are available or will be required to represent these physical processes was also prepared. Six overview talks and breakout sessions were organized around the topics: (i) Environmental forcing and vertical shear effects; (ii) Convective scale processes; (iii) Inner-core vortex adjustments; (iv) Interface conditions; (v) Ocean heat content effects; and (vi) Inland winds and rainfall from landfalling hurricanes. Brief summaries of key physical processes for each of the six topics and the implications for numerical modeling will be presented in the following paragraphs.

(1) The numerical model must represent the environmental forcing associated with “good troughs” and “bad troughs” that enhance or inhibit tropical cyclone intensity, respectively. That is, positive eddy momentum flux convergence or an adjacent jet streak that contributes to a larger outflow from the tropical cyclone may contribute to a spin-up of the vortex. A bad trough effect is usually related to vertical wind shear that may ventilate the warm core or cause asymmetry in the cloud/precipitation distribution that is not favorable for intensification or maintenance of the tropical cyclone. The wind structure change in response to such external environmental forcing depends on the existing vortex structure in terms of inertial stability, static stability, and baroclinity. The first important implication from these environmental forcing conditions is that the numerical model domain must be quite large for a 72 h (or 120 h in the near-future) forecast. Given the requirement for an accurate initial and predicted vortex structure to get the correct response to forcing, a high-resolution, nested, moving, two-way interactive numerical model is required. Additional research studies are necessary to understand and to demonstrate that the numerical models are capable of accurately representing vertical wind shear and other physical processes accompanying good and bad troughs. For example, how, when and where these environmental effects may trigger concentric eyewall events would contribute to improved predictions of short-term, intensity variations in mature tropical cyclones.

(2) New insights into the characteristics and role of convective processes in tropical cyclone intensity and precipitation have been gained from airborne radars and satellite-deployed microwave instruments. Although active convective areas occupy only about 10% of the whole rain areas, this convection is crucial for intensity change and energy conversion. The implications from these observations is that the model must have high resolution to be able to predict the scales and amplitudes of these updrafts and downdrafts. Whereas the highly desirable horizontal resolution of the innermost grid is 1 km, the immediate grids in the nested grid may fall in the "no-man's land" for cumulus convection parameterizatiion versus an explicit moisture process representation. Some research is required to avoid double-counting if some portions of the convection is being resolved by grid-scale vertical motion and is also being parameterized. High vertical grid resolution is required to resolve the vertically-tilted eyewall. The microphysical processes having to do with ice particles are important for correctly predicting the approximately 50% of the precipitation from the stratiform rain areas of tropical cyclones. Additional *in situ* observations of microphysics are required for validation of the models in critical locations and life cycle stages of the tropical cyclone.

(3) Recent advancements in the understanding of inner-core vortex dynamical adjustments suggest a feedback loop exists with the convection and the larger scale environment. For example, vortex Rossby waves that propagate outward and vertically from the inner core then trigger convection and cause adjustments in the near-environment wind structure. One working hypothesis is that the inner-core wind structure (intensity) evolution may be described as a balancing between generation and breakdown by eyewall mixing events. An alternate working hypothesis views the eyewall as a frontogenetic region in which diabatic processes are being balanced by mixing events and diffusion that prevent a collapse to a discontinuity. The implications for numerical modeling are that high horizontal and vertical resolution will be required for treating these mixing processes and the vortex Rossby waves that complete the feedback loop with the convection and the environment, and higher order advective schemes must be adopted to achieve accurate representations.

(4) It is well-known that the ultimate energy source for the tropical cyclone is the ocean and thus knowledge of the heat and moisture fluxes through the air-ocean interface are critical for modeling. The exchange coefficients for heat, moisture, and momentum are not known for the high wind and wave conditions of a tropical cyclone. Fortunately, the Office of Naval Research is sponsoring a Coupled Boundary Layer Air-Sea Transfer (CBLAST) program that addresses the fundamental problems of the interface physical processes and the associated vertical fluxes in both the atmosphere and ocean boundary layers. Because a key physical process is the wind-wave coupling, which includes the sea spray generation from breaking ocean surface waves, the research numerical model for tropical cyclone intensity and precipitation prediction needs to be coupled with an ocean surface wave model. In addition to testing and evaluations of the surface wave models in the high wind conditions, the wave models must be extended into the range of higher frequencies (shorter wavelengths of order 10 m) that are involved in wave breaking and sea-spray generation. Another fundamental modeling problem is a "no-man's land for frictional process representations" when a 1 km horizontal resolution

model only partially resolves the large eddy circulations that are accomplishing the vertical transports of heat, moisture, and momentum in the atmosphere.

(5) It is well-known that the surface enthalpy flux and turbulent mixing in the ocean mixed layer caused by the tropical cyclone leads to a decrease in sea-surface temperature (SST) under and in a wake behind the storm, and the magnitude of the SST decrease is larger for a more intense, slowly-moving cyclone over a shallow ocean mixed layer. Thus, the research model system needs to include a coupled ocean model to represent the potential negative feedback mechanisms of the self-induced SST decrease reducing the energy supply to the tropical cyclone. Just as uncertainty exists in the model representation of vertical mixing processes in the atmosphere, additional research is required for representing vertical mixing in the ocean model. The ocean heat content (OHC) defined relative to 26°C is a more useful parameter than just the SST because is accounts for the depth of the warm water that is available as an energy source for the tropical cyclone. A recent breakthrough in estimating the OHC from satellite-based radar altimeters needs to be assimilated in ocean circulation models to provide more accurate and timely ocean thermal structure representations, and especially in the warm and cold eddies and high gradient regions. Although the CBLAST program funded by ONR will address a number of the challenging ocean-related research issues, the ocean observation base, data assimilation, and modeling needs for operational use requires special attention.

(6) In addition to the storm surge inundation at the coast, the greatest societal impacts are associated from the damaging winds and flooding associated with the heavy rain. Although climatological studies indicate a exponential decrease in wind as the storm moves inland, the detailed horizontal distribution of high winds needs to be modeled, which is intimately tied to the frictional boundary layer processes since a strong vortex continues to exist above the boundary layer. Similarly, the decaying tropical cyclone may continue to produce large rainfall well inland, especially in conjunction with orographic lifting, and produce flooding in small river basins. The wind and precipitation structure changes as the tropical cyclone decays and a transition to an extratropical cyclone occurs needs to be predicted since a high potential for damage continues. Prediction of the inland wind structure evolution and the precipitation distribution requires a coupled land surface model, which is a complex modeling challenge for the high winds and precipitation of a landfalling tropical cyclone. Since a primary USWRP goal is to improve forecasts of flooding events that are a leading cause of death in U. S. landfalling hurricanes, the hurricane model needs to be coupled with a hydrological model of the affected river basin.

The physical processes described above that affect tropical cyclone wind structure (intensity) changes and precipitation distributions require a set of model characteristics that will be a major numerical modeling challenge. The proposed research modeling system must include a coupled ocean surface wave model, a coupled ocean circulation model, a sophisticated land surface model, and this system will need to be tied to a hydrological model. Each of these coupled system components adds new issues as well as complexity to the overall system. In all cases, the key issue is how well the individual model components will perform in the high wind conditions of a tropical cyclone.

Because the physical processes are interacting, the proposed approach is to construct the complete research modeling system and then explore the essential interacting processes. Given the requirement for such a complex, nonlinear modeling system with multiple components that are inter-dependent, questions of predictability naturally arise. Challenges such as these are also opportunities to advance the science and modeling – indeed, the proposed modeling will require advances in scientific understanding, and an advanced model can be a contribution in combined observational-numerical studies.

The desirable USWRP research model that is proposed to be used for case study simulations of wind structure change and precipitation is characterized in Table l (see section 3 of text) relative to a number of existing research models. Whereas some of these existing models have some of the desirable characteristics, no model has all of the desirable characteristics, and none of the models has been integrated with a large number of cases. Some of the desirable characteristics for the research models will be summarized here and the reader is referred to section 3 and Table 1 for details. To achieve desirable balance and accuracy characteristics, either an Arakawa B or C grid arrangement with high-order advection is required. Because of this highly complex modeling system, a number of efficient time differencing schemes (e.g., semi-Lagrangian) must be tested to allow the numbers of integrations that will be required to develop and test the research model. The proposed horizontal grid is a moveable, four-nest with grid spacings of 27 km, 9 km, 3 km, and 1 km. To minimize the effect of the 9 km grid being in the "no-man's land for cumulus parameterization," the domain of the 3 km grid would have to be sufficiently large to include all of the major convective precipitation region. Given the fine horizontal resolution required near the core, and to resolve the tilted eyewall cloud processes, about 60 levels in the vertical will be required, which is twice as many as in present research models. Perhaps 15-20 of these levels will be put in the boundary layer to resolve the large gradients in properties and vertical transports. To include all of the potential environmental effects, the outer grid should be in a 75° long. by 75° lat. domain. Even with a four-nest grid, such a large domain will require a large increase in computing resources to integrate the research model for the 120 h periods that are desired.

The initial environmental fields and lateral boundary conditions for the research model are expected to be provided by the Aviation (AVN) model. As indicated above, the inner grids must have two-way interaction and move with the storm, which only a few of the present models now have. Whereas most research models now use a bogus vortex to specify the initial conditions, real-data case studies for intensity and precipitation will require a data assimilation system. At least a three-dimensional variational (3DVAR) technique is required and perhaps a 4DVAR may be attempted in some tests. Consideration of the data assimilation technique is especially important for the operational model, which will be discussed below.

As indicated in items (4) and (5) above, the research model must be coupled with a wind-wave model that has been extended to the higher frequency, shorter wavelengths involved in wave breaking. This modeling effort will be a formidable challenge. Similarly, a coupled ocean model is required. Whereas the coupled GFDL-University of

Rhode Island ocean model is one example, a moveable ocean model with horizontal resolution comparable to the atmospheric model will need to be developed and tested. Over the land areas, a sophisticated land surface model is required to predict the inland wind decay and precipitation distribution. Such land surface models are complex, and the application in hurricane conditions is expected to require considerable testing.

The ultimate success of the hurricane landfall research model for intensity and precipitation will depend on how well the physical processes of the boundary layer and convection are predicted. Multiple options exist for the boundary layer, cumulus convection parameterization, and explicit moisture representations of water and ice microphysics. All of these physical processes are inter-related so large numbers of integrations will be required to determine the combination that best represents the atmospheric conditions and evolution. Particularly the microphysical distributions will require additional *in situ* observations in tropical cyclones for evaluation of the model.

Whereas the research model system can be designed for completeness with less concern for limitations of computer resources or timeliness, these are critical issues in the design of the minimally-acceptable operational model. That is, the operational system must acquire the observation, perform a quality control and prepare the initial conditions via a data assimilation system, and integrate the numerical model(s) to 72 h (or 120 h) on a tight schedule so that the prediction guidance is provided to the forecaster while it is still timely. Given limited computer resources, some compromises and tradeoffs must be made. One objective of the research model described above will be to determine the essential physical process representations and guide intelligent decisions regarding the tradeoffs for the operational model.

The development of the Weather and Research Forecast (WRF) model as a hurricane model was the topic of a second USWRP Workshop on 29-30 May and the reader is referred to that workshop report for a detailed description. At the San Diego Workshop, the design characteristics of an operational model were discussed in a more generic sense. These design characteristics are given in Table 2 (see section 4 in text) and compared with a number of operational models from around the world.

Whereas several of these operational models are hydrostatic, the proposed USWRP model must be non-hydrostatic. This model is expected to use the Arakawa C grid arrangement. Various time differencing options will be tested to optimize efficiency for operational implementation. As in the research model, a moveable, nested grid with two-way interaction will be required to attain at least a 4 km horizontal resolution. A triple-nest (36 km, 12 km, and 4 km) arrangement with an outer domain of at least 50° lat. by 50° long. is proposed. As in the research model, 60 levels in the vertical with high resolution in the boundary layer is needed, but some reduction may be required given the computer resources available to complete a 72 h (or 120 h) integration in the permissible time.

As in the research model, the initial and lateral boundary conditions will be provided by the AVN model. The observations and data assimilation considerations for the hurricane WRF model were the special focus of the second USWRP workshop. Both the environmental and inner-core vortex data sources will have to be maximized to achieve the target intensity and precipitation prediction goals. Specification of the inner-core vortex will be limited unless the NOAA WP-3D aircraft are used as reconnaissance aircraft, or the Gulfstream IV is equipped with a meteorological radar and is able to overfly the center. Considerable effort will be necessary to incorporate these aircraft observations in a data assimilation system.

Whereas none of the present operational models have a wind-wave model, a leading candidate for the USWRP operational model is the Wavewatch III model. A version of this ocean-wave model that would move with the hurricane is expected to receive a high priority. The GFDL-URI model is the only operational coupled hurricane-ocean model. This and other ocean models need to be tested with the high-resolution hurricane model. Whereas present operational models have simple representations of the land surface, a more sophisticated land surface model will be required to predict the inland wind decay and precipitation distribution. The experience being gained in coupling the GFDL hurricane model with a land surface model called NOAH is expected to guide the tradeoffs that might be possible for the operational model.

Many combinations of boundary layer, cumulus parameterizations, explicit moisture treatments, and ice microphysics representations must be tested to develop an optimum combination. The results from the research model physics tests should provide guidance and limit the number of options that need to be tested. The additional requirement for computational efficiency in the operational model may dictate the tradeoffs that will be necessary. Since the physics representations will play so crucial a role in the accuracy of the predicted intensity and precipitation distribution, this aspect of the operational model development should have a high priority.

Although not extensively discussed at the Workshop, the alternate strategy of an ensemble prediction system may be appropriate for obtaining probabilistic forecasts of intensity and precipitation. Operational constraints of limited computer resources and the need for timeliness will be the primary determinants of any ensemble system. If the horizontal grid size is degraded by a factor of three or four to allow the number of ensemble model integrations that might be necessary, the question is how useful are these individual integrations? Because of the great expense in integrating all the ensemble members, the economical alternative of the “poor man’s ensemble” of combining the best model from a number of forecast centers should also be explored.

The forecasters at the Workshop prioritized the guidance they would most desire from the operational model. The first priority was guidance products that would allow them to issue probabilistic forecasts and thus achieve NWS strategic goals. Another key issue for the forecaster is a communication system to receive high-resolution model outputs and then have a “forecaster-friendly” display capability. The forecasters also listed the difficult forecast scenarios that should be considered in the verifications: Trough-tropical cyclone interactions; landfall intensity changes; precipitation in slowly moving cyclones after landfall; concentric eyewall cycles; rapid intensification; and rapid decay.

Finally, the Workshop attendees were polled to determine the “showstoppers” or most difficult tasks that should be given the highest priorities. The research model topic receiving the largest priority is related to knowledge of the frictional boundary layer and ocean surface wave processes in the high wind conditions of hurricanes. A related research need is a better understanding of the generation, size droplet distribution, and effects of sea spray in the vertical fluxes of moisture, heat, and momentum in high wind and wave conditions. Insufficient knowledge of ice microphysics and convective processes and how they contribute to the precipitation distribution and dynamics was also rated as a difficult research model problem. A strong concern of the participants was that inadequate observations may be available to define the initial conditions for the 4 km horizontal resolution operational model. Another potential showstopper is a data assimilation technique to incorporate existing and future atmospheric observations. Finally, some felt that inadequate computer resources will be available in the next 3-5 years to develop the minimally-acceptable operational model.

It is clear from the Workshop that this tropical cyclone intensity and precipitation problem is complex with multiple physical processes that are contributing. Advances in science and modeling must be integrated, and observational studies will be necessary to test the operational model. The problem is too big for any group, and a collaborative effort under the USWRP Hurricane Landfall program is required to meet the challenge.

1. Introduction

a. Background

The U. S. Weather Research Program (USWRP) has established its Hurricane Landfall (HL) program following a matching of societal needs for improved forecasts and research opportunities ("low-hanging fruit"). The USWRP research goals may be generally mapped into National Weather Service forecast goals and performance measures (specific advancements in accuracy to be achieved in a set period). In the case of the establishment by the USWRP of the Joint Hurricane Testbed (JHT) during 2001, this mapping is quite evident as mature research or observational achievements were matched to the Tropical Prediction Center/National Hurricane Center (TPC/NHC) needs. The objective of this JHT is to move rapidly (usually within two years) and efficiently move these research or observational advances into analysis or forecast products.

Two of the USWRP/HL research goals are somewhat farther from being ready for consideration as an operational product: (*i*) Reduction in tropical cyclone intensity forecast errors by 20%; and (*ii*) Extend quantitative precipitation forecasts to 3 days and improve skill of day-3 forecasts to improve inland flooding forecasts. These goals are quite difficult and are considered to require considerable research before a transition to operations may be appropriate.

A session on tropical cyclone quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF) was organized at the American Meteorological Society national meeting during January 2001. A meeting summary (Elsberry 2002, *Bull. Amer. Meteor. Soc.*) has been prepared that describes the "stage-setting" overviews, approximately 35 posters, and the final wrap-up session that looked to future needs and approaches. One outcome of that session was that the USWRP/HL precipitation forecasting goal would only be achieved by a numerical model, and some required model characteristics were described.

The research community has continued to attack the tropical cyclone intensity forecasting problem from a number of approaches. A considerable fraction of the USWRP/HL effort is devoted to improved observations, analysis, and forecasting of tropical cyclone intensity. As progress has been slow, a concentrated effort needs to be organized to increase the rate of advancement toward the goal. Since that goal requires improved numerical model guidance, some preliminary discussions indicated similar model characteristics as for the tropical cyclone precipitation problem. This realization was motivation for organizing the *Workshop on Numerical Modeling for Tropical Cyclone Intensity and Precipitation Prediction* (hereafter the Workshop) in San Diego, California, during 3-4 May 2002.

b. Purposes of the Workshop

The primary objectives of the Workshop were to design the highly desirable research model and minimally-acceptable operational model for intensity and precipitation prediction. It is recognized that two kinds of modeling studies for research are being considered. First, idealized simulations of tropical cyclone inner-core structure (intensity) change and precipitation are needed to understand the role or contributions of the various physical processes as a basis for designing a proper prediction model. In this approach, a hierarchy of models of increasing complexity may be employed to achieve simulations that have realistic tropical cyclone structures, structure (intensity) changes, or precipitation distributions. Sensitivity studies or other approaches are then used to achieve basic understanding of the various physical processes. In the second approach, the focus is on the use of case studies with the objective of demonstrating the capability of an analysis, assimilation, and prediction system for tropical cyclone intensity change or precipitation distribution. This approach may include data or model sensitivity tests of various physical processes that contribute to a successful prediction. Although this approach uses real (versus idealized) data for initial conditions and for evaluation, meeting operational constraints such as timeliness and computer resource limitations are not a primary concern so much as demonstrating the system components required to achieve a capability or skill level.

It would of course be helpful if the two types of research studies had already been accomplished so that we had a complete understanding of the physical processes and their relative contributions to intensity change and precipitation. In lieu of such complete understanding, it is still appropriate to attempt a design of a minimally-acceptable operational model based on our present understanding. Here, the adjective minimally-acceptable indicates that some target will be established that does not achieve all of the desired predictability goal, but will be operationally useful vice present forecast capability. It is inevitable that the design of the minimally-acceptable operational model will involve tradeoffs to meet operational timeliness and computer resource limitations. The objective here is to do the model design based on our best understanding of the physical processes involved, as well as observational capabilities/limitations.

c. Proposed intensity and precipitation targets

A survey form was first circulated to obtain inputs as to the intensity and precipitation accuracies that could serve as targets for designing the highly desirable research model and the minimally-acceptable operational model. The preliminary responses from participants suggested intensity accuracies of 5 m s^{-1}, 6-10 m s^{-1}, and 7-15 m s^{-1} at 24, 48, and 72 h. B. Frank of Penn State University suggested it may not be feasible to do a deterministic forecast of the eyewall structure for more than a few hours. H. Willoughby of the Hurricane Research Division proposed a probabilistic approach of the cyclone intensity exceeding the five Saffir-Simpson categories at each 12-h forecast interval. Given that the NHC is the primary forecast center that is to benefit from the USWRP/HL research, the NHC highly desirable goals of 3, 4, and 5 m s^{-1} at 24, 48, and 72 h are accepted here.

Because the minimally-acceptable intensity goals from the NHC (3.5, 4.8, and 6.2 m s^{-1}) are viewed as being too challenging to achieve in 3-5 years, the target values have been set to achieve a 20% improvement in intensity forecast accuracy relative to the NHC performance for all Atlantic forecasts during the 2001 season. Thus, the minimally-acceptable intensity targets for designing the future operational are set at 5.5 m s^{-1}, 8 m s^{-1}, and 10 m s^{-1}, at 24, 48, and 72 h, respectively. Another forecast need at the NHC is for better predictions of rapid intensification events (15 m s^{-1} in 24 h). Thus, some standard needs to be set (e.g., event detection rate of 80% with a false alarm rate of less than 20%). Until guidance is received from the NHC, no rapid intensification target has been set.

The inputs on precipitation accuracy goals ranged widely. The NHC usually issues maximum storm-total precipitation outlooks based primarily on storm translation speed (larger amounts for slowly moving storms) and whether the storm is "wet" or "dry." Responsibility for precipitation amount and distribution forecasts over the U. S. lies with the Hydrometeorological Prediction Center (HPC) in Washington, DC. Preliminary minimally-acceptable precipitation accuracy requirements received from HPC were 0.1 in/h over a 1000 km^2 area at 24, 48, and 72 h, which were considered to be too stringent for tropical cyclones. Likewise, the highly desired storm-total accuracy of 0.25 in was not viewed as achievable in view of observed storm-total amounts of 10-40 in. Until more definitive guidance is received, a proposed highly desirable rain rate is set as a heavy rain (> 10 cm/h) event detection rate of 80% with a false alarm rate of less than 20% at 6, 12, 18, 24, 30, and 36 h. The minimally-acceptable storm-total rain prediction is tentatively set as an absolute error of 1 in (25 mm).

d. Desired outcomes

As indicated in the Workshop agenda in Appendix A, the first objective is to explore the level of our understanding of tropical cyclone wind structure (intensity) change and precipitation as a basis for designing a numerical model for forecaster guidance. Then, the model characteristics that are highly desirable for research, and that minimally-acceptable for operational prediction, are to be specified.

Recommendations are to be formulated as to the research requirements to support the model development and the pathways to gain the needed knowledge. Another desired outcome is to establish collaborations among the modeling groups and between research, modeling, and operational forecasters to achieve the objectives. These collaborations might involve common model testing or the sharing of code, initial analyses, or validation data sets to help in the development of the highly desirable research model and the minimally-acceptable operational model.

2. Physical processes that must be modeled

One of the basic premises of the Workshop is that certain physical processes are known to affect tropical cyclone wind structure (intensity) change and precipitation. Thus, the Workshop began with six overview talks (see Agenda in Appendix A) that "set the stage" for designing the highly desirable research and minimally acceptable models to predict tropical cyclone wind structure and precipitation. The first breakout sessions (see Appendix A) were also organized around the six topics: (*i*) Environmental forcing and vertical shear affects (J. Molinari); (*ii*) Convective scale processes (F. Marks); (*iii*) Inner core vortex adjustments (M. Montgomery); (*iv*) Interface conditions (K. Emanuel); (*v*) Ocean heat content effects (N. Shay); and (*vi*) Inland winds and rainfall from landfalling hurricanes (M. DeMaria). One of the objectives was to complete a summary of these key physical processes, and their implications for designing appropriate numerical models. A second objective was to develop a list of observations that are available or will be required to represent the physical processes. This information then sets the basic numerical model characteristics for the highly desirable research and minimally accepted operational model.

As additional source materials, those papers in the extended abstracts of the *25th Tropical Meteorology and Tropical Cyclones Conference* of the American Meteorological Society related to the Workshop topics were summarized. Whereas most of these extended abstracts are associated with one of the Workshop participants, a few extended abstracts are included that are not attached to Workshop participants. Just the large numbers of these abstracts indicates the activity in tropical cyclone intensity (especially) and precipitation. The objective of this section is to indicate how the studies of physical processes set the requirements that numerical models for research and for operational forecast guidance must address.

a. Environmental forcing and vertical shear effects

It is well known that favorable environmental conditions (including minimum vertical wind shear) are required for tropical cyclone formation. Emanuel and Holland have developed separate relationships between the maximum potential intensity (MPI) and the sea-surface temperature (SST) and the environmental conditions, which includes the static stability, upper-tropospheric conditions, and relative humidity. The wind structure (intensity) changes from formation to maximum intensity (the actual intensity versus MPI) and the decay depend on a balance between favorable and inhibiting environmental conditions. Thus, the numerical model must properly represent these environmental forcings. The SST conditions, and the associated ocean subsurface changes, will be addressed later.

In addition to SST values exceeding a minimum threshold and high specific humidity values over the tropical oceans, the static stability must be such that the latent heat release in convection occurs through a deep layer of the troposphere to warm the column and decrease the central sea-level pressure (SLP). Thus, the upper troposphere cannot be too warm for a given SST, and this factor is included in both the Emanuel and Holland MPI values.

(1) Favorable environmental forcing. A favorable factor for intensification of a tropical cyclone has been characterized as a "good trough" interaction. In this scenario, an upper-troposphere trough becomes juxtaposed with the warm outflow from the tropical cyclone to cause: (*i*) a positive eddy momentum flux convergence that contributes to a cyclonic spinup of the inner vortex; and/or (*ii*) an enhancement of the jet

streak that contributes to a larger outflow from the tropical cyclone, and consequently a spinup of the vortex.

In the case of (*i*), the adjacent cold trough and warm outflow are arranged such that the outflow (inflow) through a cylinder of radius *r* centered on the storm transports anticyclonic (cyclonic) wind components, so that the eddy momentum flux convergence is positive. A key factor in this eddy flux convergence remote (perhaps 400-800 km radius) forcing mechanism is an upper-tropospheric wind structure with small inertial stability so that the response to the forcing is experienced in the inner vortex. Such an intervening region of small inertial stability is most likely during the mature tropical cyclone stage when anticyclonic curvature and shear in the outflow reduces the absolute vorticity to near-zero values.

In the jet streak scenario of (*ii*) above, the cold trough approaches (but does not cross) the warm tropical cyclone outflow such that the horizontal temperature gradient is enhanced, which accelerates the intervening jet streak. This amplifying jet streak may move outward toward the trough in the enhanced baroclinity between the cold trough and warm outflow, and air parcels are accelerated as they are deflected toward lower pressure heights in the trough. The net effect is a more favorable outflow channel from the tropical cyclone. Again, with favorable small inertial stability conditions aloft, this additional outflow will contribute to low-level convergence and spinup of the tropical cyclone vortex.

(2) <u>Unfavorable environmental forcing</u>. In the contrasting "bad trough" scenario, the strong winds on the leading side of an approaching trough cause: (*i*) "ventilation" of the warm core of the tropical cyclone; or (*ii*) an asymmetry in the cloud/precipitation distribution that is less favorable for intensification or maintenance of the tropical cyclone than is a symmetric cloud/precipitation distribution. Recent observational and numerical modeling studies have demonstrated that the favored ascent region is shifted to the downshear left quadrant of the tropical cyclone. Clearing of the deep convection and formation of a dry slot occurs on the upshear side in response to forced subsidence. Whereas a symmetric vortex would in principal spinup to its MPI given sufficient time in quiescient favorable conditions, the asymmetric cloud distribution leads to a vortex structure that does not spinup to its MPI.

In the strong-shear ventilation scenario (*i*), the numerical models demonstrate that the advection downstream of the warm core occurs first at the top of the storm, which is where the inertial stability (resistance to radial motion) is a minimum. As the warm core aloft is reduced, the SLP begins to rise, the cyclonic flow aloft is reduced, which also reduces the inertial stability. Consequently, the vortex becomes more susceptible to the vertical shear and more of the warm core is advected downstream. This negative feedback cycle will lead to continued erosion of the deep convection and upper-tropospheric warm core, and thus a dissipation of the tropical cyclone. Such a weakening in response to an unexpected encounter with an enhanced vertical wind shear region can cause over-forecasts of intensity. The mid-and lower-tropospheric warm core may be sustained by the forced subsidence, so the rate of dissipation of the tropical cyclone may not be rapid as might have been expected. Indeed, a weaker, inertially stable, warm core cyclone may be sustained for some time if the frictional coupling with the surface is reduced.

Another wind/cloud structure change that may contribute to short-term intensity forecast errors is an eyewall contraction event in a mature tropical cyclone. A second (outer) concentric eyewall (or nearly complete spiral band) contracts and interferes with, or modulates, the inner eyewall convection. The associated weakening of the inner core vortex leads to a temporary decrease in intensity. However, a re-intensification may then occur as the outer rainband and its associated wind maximum contracts to the same radius. Although this event may also be considered in the following section on convection, it is included here because the triggering of the outer rainband maybe considered to be environmentally forced (by mechanisms not known).

(3) <u>Some implications for numerical modeling</u>. The first important implication from these environmental conditions is that the numerical domain must be quite large if a tropical cyclone is to be forecast for 72 h (or 120 h in the near-future). Since a tropical cyclone may move westward some distance and interact with an eastward-moving midlatitude trough (or tropical upper-troposphere trough) during such a forecast interval, the east-west dimension of the domain must be large enough to include both systems. Given that the tropical cyclone must be resolved with a smaller grid interval than the midlatitude trough circulation, a nested, moving, two-way interaction model is dictated.

As suggested in subsections (1) and (2), an intimate relationship exists between the existing tropical cyclone structure characteristics (e.g. present intensity, inertial and static stability) and the intensity change in response to environmental forcing. Given the same eddy momentum flux convergence or vertical wind shear, the secondary circulation of radial and vertical motion that is induced depends on the existing wind and thermal structure of the vortex. The important implication for numerical modeling is that the wind and thermal (and humidity) distribution must be accurately known at the initial time, and correctly predicted. Prediction errors may then arise from an incorrect initial vortex specification, incorrect prediction of the environmental forcing, or some combination of both factors. Since the environmental forcing depends on the relative positions or orientations of the tropical cyclone and the midlatitude (or adjacent tropical) circulation, a correct track forecast is essential. These same requirements for accurate vortex initialization, and especially the low-level wind structure, will apply in later sections that consider the interface conditions over the ocean and over land. By contrast with the requirements for predicting the tropical cyclone track (which is not so dependent on the inner core vortex structure), the initial condition specification and numerical model characteristics for tropical cyclone intensity and precipitation prediction are much more stringent.

Based on the premise that the environmental forcing will generate a response in the eyewall convection, the optimum model would have an inner region structure on the order of 1 km horizontal resolution. This breakout group suggests a 3-4 km horizontal resolution for a minimally-acceptable operational model. Since the initial vortex structure must also be accurately specified, observations on the scale of 5 km must be sought from manned aircraft Doppler radar, unmanned aircraft *in situ* observations, high resolution satellite soundings (microwave or future GIFTS). Highest priority is for winds for the tropical cyclone and its environment, but moisture values are also critical.

As will be discussed later, data assimilation techniques to prepare the initial conditions for the tropical cyclone vortex on such small horizontal scales will be a severe challenge. At least in an axisymmetric circulation sense, the tropical cyclone vortex is "balanced," which may be exploited to infer some variables from observations of other variables (e.g., good winds). However, the tropical cyclone has important asymmetries in wind, clouds, precipitation, etc. Furthermore, the vortex structure changes depend on the departures from balanced conditions as arise from the changing environmental conditions described in this section. This makes predicting tropical cyclone intensity and precipitation a very challenging task.

b. Convective scale processes

New insights into the characteristics and role of convective processes in tropical cyclone intensity and precipitation have been gained from airborne radars and satellite-deployed microwave instruments. While the eyewall and convective bands are the most obvious feature in radar images, and the largest rain rates occur in the convection, about 50% of the precipitation is from the stratiform rain areas, which represent 90% of the total rain area. Here, a convective (stratiform) region is defined to have an updraft of greater (less than) 1 m s^{-1}. Although active convective areas occupy a small (~ 10%) portion of the whole rain area, this convection is crucial for intensity change and energy conversion. As had been known from satellite imagery interpretation, it is not the total amount of cloud that is important – rather it is the location (relative to vortex center) and the organization of the convective bands.

(1) <u>Aircraft observations</u>. A key paper by Black *et al*. (1996, JAS, 1887-1909) summarizes a large number of vertical motion observations from aircraft penetrations in tropical cyclones. Although the maximum updraft/downdraft magnitudes in a tropical cyclone are of the order of 12 m s^{-1}, a few storms have updrafts of order of 25 m s^{-1} and downdrafts of 20 m s^{-1}. Most of the updrafts (downdrafts) have radial widths of 3-4 km (2-3 km). The radar signatures are surprisingly short-lived with only 10% lasting > 8 min. On a typical penetration of an eyewall or rainband, the number of updrafts may be a factor of 10 greater than the downdrafts. In general, the number of updrafts in the eyewall and rainbands decreases rapidly with elevation above the freezing level (~ 5 km).

Another noteworthy paper by Willoughby *et al*. (2002) describes the convection organization in tropical cyclone Olivia following the onset of large vertical wind shear. Differences in radar reflectivity and vertical motion in tilted structure are documented by aircraft Doppler radar along upshear and downshear radial penetrations. The observed downshear-left ascent regions and suppressed cloud regions appear to validate a number of numerical model simulations of the effect of vertical wind shear. Notice that the vertical wind shear introduces wavenumber one asymmetries in vertical motion and reflectivity that reduce the symmetric mean. The asymmetries around the eyewall may be as large as those between the eyewall and the rainbands. As indicated in section 2a (1), these asymmetries are important for the wind structure (intensity). Contrasting hypotheses exist for the relative roles of the outer convective bands. Whereas F. Marks believes convection outside of the eyewall is not that important in a mature storm, E. Zipser hypothesizes that the rainband convection is a major inhibitor to intensification of the storm to its MPI.

(2) Satellite observations. Examination of more than 300 radial distributions of rain rates (R) from the Tropical Rainfall Measurement Mission (TRMM) microwave instrument (TMI) have allowed a storm-intensity stratification of R with radius. The R distribution is of course scale dependent, so the breadth of the heavy rain rates is sensitive to the scale. For the TMI distributions, the top 10% of the rain rates is two orders of magnitude greater than the bottom 10%, and nearly an order of magnitude larger than the median rain rate. Values of $R > 20$ mm h^{-1} were found to occur only with radii < 75 km. Outside a radius of 150 km, the R distribution has about the same radial distribution with values increasing from 0.1 mm h^{-1} to 30 mm h^{-1} irrespective of storm intensity. As storms get more intense, the R distribution in the core becomes narrower, and the peak values get larger. For example, the TMI peak rain rates increase from 3 mm h^{-1} to 7 mm h^{-1} from the tropical depression/tropical storm stages to the Saffir-Simpson Category 1 or 2 stage, and to 13 mm h^{-1} for the Category 3 to 5 stage. Likewise, the 50% of area coverage also increases with storm intensity, but the total rain flux does not.

(3) Microphysical properties. Since about 50% of the precipitation is from the stratiform rain area, the mechanisms that create the stratiform rain are important. Thus, the microphysical processes having to do with ice particles are important in tropical cyclones. If the percentages of snow, ice, and gaupel are not correctly predicted, too much of the rain will be in convection, and the rain rate distribution will be shifted to the larger convective rain rates. Notice that ice falls very slowly (~ 1 m s^{-1}) and therefore may descent through the stratiform rain area while having circumnavigated the center several times. Thus, the origin of particles in the stratiform rain area may have primarily been in the eyewall (versus in the rainbands). By comparison, gaupel falls more rapidly. Conversion rates between the ice species in the stratiform rain area then become important in predicting the radial location of the various rain rates.

The radiative processes of the ice species are not well known. At least during the early storm life cycle, the radiative cooling differences between deep convection areas and the cloud-free environment may play a crucial role. Observational studies suggest the outer regions of tropical cyclones do have a distinct diurnal variation.

(4) Implications for numerical modeling. Beginning from the formation of the tropical cyclone, convective processes are critical to the wind structure and precipitation distribution. By definition, observations of the humidity and stability structure are essential to specify initial conditions for a numerical model of the tropical cyclone. Because the surface flux of moisture (and heat and momentum) are dependent on the wind structure, the initial wind structure (intensity) must be correct to get a good intensity and precipitation prediction. A critical stage in the numerical modeling of tropical cyclone intensification is when the inner grid boxes become saturated and the explicit

convection is triggered, because the rain rates then dramatically increases and the SLPs begin to fall rapidly. Thus, the timing of tropical storm onset is dependent on the initial moisture distribution and sources. Whether these initial conditions will be sufficient for model guidance on rapid intensification events remains to be determined.

Both the maximum intensity and rain rates in the inner core are limited by the horizontal resolution in the model. For example, the model will not predict rain rates > 50 mm/h with a horizontal resolution of 4 km. Thus, the highly desirable horizontal resolution in the model is 1 km. A "no man's land" has been defined between grid sizes of 5-15 km in which it is inappropriate to have both parameterized and explicitly resolved moist processes. If the horizontal resolution is within this range, some portion of the convection is being resolved by the grid-scale vertical motion and is also being parameterized, which may lead to double counting. If only explicitly resolved moist processes are allowed on these scales, the vertical motion will likely be too small, saturation will be delayed, and precipitation will be underpredicted. For a resolution of 5 km and less, the convection is explicitly resolved and should not be parameterized. Thus, it is best to avoid a horizontal resolution of 5-15 km, which means that finer resolution at greater computing cost must be the choice.

The outward tilting of the eyewall imposes a requirement for the vertical resolution in the model. Since the tilt is nearly one-to-one, the vertical spacing must be less than 500 m to resolve the vertical motion and rain droplet production, melting, and other stratiform processes. In addition to high vertical resolution across the freezing level, small vertical increments may be required at the outflow layer to handle the interaction with adjacent circulations.

The vertical shear effect discussed in section 2a is dependent on the strength of the convection and its outflow. In addition to getting the frictional and thermodynamic coupling with the boundary layer fluxes correct, the vertical transport of momentum by the convection must be accurately predicted to portray the resistance to vertical wind shear.

The optimistic hypothesis is that as the tropical cyclone circulation strengthens the convection will be increasingly dynamically forced to a limited range, and thus be more predictable than isolated convection. If the ice species in the stratiform rain area are primarily determined by the eyewall convection, this stratiform contribution to precipitation may become more predictable as well. Uncertainty in the ice microphysical conversion rates may affect the radial distribution of the lighter stratiform rain. However, the swath of heavy precipitation relative to the tropical cyclone track may be useful, if the track is well predicted.

One recommended method of evaluating the fidelity of the model predictions is to compare with the probability density functions (PDF) of vertical motion and rain rates from the aircraft radar and satellite microwave observations described in subsection (1) and (2) above. The CAMEX-3 and HL 2001 field experiments have provided microphysical observations that should be exploited. Direct comparison with the satellite microwave retrievals is not straight-forward because the retrieval algorithm is based on a model-generated microphysical profile. Thus, a discrepancy between the high-resolution, three-dimensional model microphysics and the satellite retrieval may be due to the use of a retrieval model that does not apply in a tropical cyclone environment.

The observational requirements for the convection aspect include three-dimensional wind, humidity, temperature, and pressure. Here the radial and vertical gradients are critical. These requirements will task the capability of aircraft Doppler radar and dropsondes. Perhaps the most difficult observational requirement will be the cloud water, rain water, and ice microphysical species that need to be specified in the initial conditions. The moist processes also need to be consistent with the initial vertical motion distribution if a precipitation spinup period of many hours is to be avoided.

c. Inner core vortex adjustment

(1) Dynamics-convection-environment loop. The recent advancements in the understanding of inner core vortex dynamical adjustments suggest an interpretation as a feedback loop with the convection and the larger scale environment that have been discussed above. For example, the triggering of eyewall cycles was first introduced as a result of a possible environmental forcing. The fundamental changes in outer band convection and eyewall during the contraction, changes the thermodynamical structure, which then causes an adjustment in the dynamics of the inner core vortex. Theoretical confirmation of vortex Rossby waves in high-resolution numerical models has been followed by a confirmation in aircraft observations in a HRD study of Hurricane Olivia. These vortex Rossby waves propagating outward from the inner vortex with their associated fluxes complete the feedback loop to the environment, and to the convection via serving as a triggering mechanism. Questions remain as to the mechanisms that may initiate the eyewall cycles and the timing of the progression of the eyewall cycles. It remains to be demonstrated with real-data case studies that the formation of the outer spiral band and its associated wind maximum can be predicted with a correct evolution of the precipitation in the outer and inner region, and with the correct timing and magnitude of the intensity changes.

A similar feedback loop is postulated with the onset of environmental wind shear. The shift in the preferred regions of ascent and descent leads to asymmetric convection and precipitation. The associated thermodynamical changes lead to adjustments in the dynamics of the inner core vortex, which then feedback to the environment and convection via vortex Rossby waves. Given a good representation of the environmental vertical wind shear and the tropical cyclone track so that the timing is predicted well, these adjustments should in principle be predicted by a high-resolution numerical model. While the response to vertical shear simulated in numerical models with idealized conditions appears to be generally supported by aircraft radar and ground-based lightning studies, real-data simulations of the precipitation and structure changes are required to understand the capabilities and limitations.

(2) Eyewall mixing events. Considerable interest has been generated by the theoretical studies of the eyewall convection and wind breakdown and mixing events. Rapid wind structure changes are simulated on time scales of say 3-6 h. Some satellite imagery suggesting intrusions of eyewall convection into the eye tend to support the occurrence of such mixing events, although the extent of the wind adjustments needs to be established with *in situ* measurements. Similarly, the polygonal eye structures observed in satellite imagery appear to support theoretical studies of the breakdown of a symmetric eye into polygonal shapes. The pooling of the vorticity in these simulated polygonal eye structures has been proposed to account for the eyewall mesovortices that have been encountered during some aircraft eyewall penetrations. The high winds and horizontal shears in these mesovortices may account for the localized wind damage areas in hurricane landfall cases such as Hurricane Andrew. The challenges for prediction are that they occur on small space and time scales, and they are a result of an instability mechanism that is less predictable than a forced phenomenon.

One working hypothesis is that the inner core-wind structure evolution may be described as a balancing between generation and breakdown by mixing events. The latent heat release in the eyewall convection and compensating subsidence on the inside of the eyewall act to tighten the radial pressure gradient in the inner core and generate a more steep radial gradient of tangential wind than solid-body rotation. As the U-shaped radial profile of tangential wind becomes barotropically unstable, a horizontal mixing event will be triggered to reduce the radial gradient. In the unforced theoretical model, the mixing event causes dramatic wind structure changes and extreme pressure adjustments. Presumably, the continual forcing by the eyewall convective latent heat release (which does not break down so completely in nature) sustains the inner wind structure against such dramatic wind structure changes as in the unforced models. Nevertheless, the eyewall mixing process is a physical process that must be accounted for in the numerical model, and it is some consequence for intensity change prediction whether the process is continual or occurs in discrete events whenever some stability threshold is surpassed.

An alternate (but related) working hypothesis views the eyewall region as a frontogenetic region and diffusion is the physical process that limits the horizontal scale of the frontal region. The diabatic processes in the eyewall drive the secondary circulation with forced descent and warming inside the eye, with perhaps some cooling contribution from evaporation of rain radially outward due to the tilt of the eyewall. Horizontal convergence in the lower troposphere to compensate for the increasing vertical motion with elevation in the eyewall region also contributes in a frontogenetic sense to enhancing the horizontal temperature gradient across the eyewall region.

This horizontal convergence is a maximum in the atmospheric boundary layer as the frictionally induced inflow from larger radii meets outflow (or at least much smaller frictional inflow) at the bottom of the eye. The location and magnitude of this convergence is critical because it is the main source of vertical mass flow into the eyewall cloud. A conceptual model of the eye region based on observations by H. Willoughby and various numerical models suggests the frictional inflow down the sharp pressure gradient under the eyewall overshoots the equilibrium value so that the horizontal convergence induces an ascent that bends outward immediately above the inflow.

The equivalent potential temperature of this air ascending from the boundary layer is crucial in determining the buoyancy of the eyewall convection. Early empirical studies by Riehl and Simpson have related the tropical cyclone intensity to the magnitude of the eyewall Θ_E increase relative to the environmental value. Thus, the correct modeling of how this region of the boundary layer contributes to the Θ_E increase is critical for intensity prediction. Further consideration of the physical processes and fluxes in the atmospheric boundary layer will be presented in section 2d.

The role of horizontal diffusion in this frontogenetical hypothesis may be viewed as a limiting factor that prevents a collapse to a discontinuity, which might occur in the inviscid limit. As the diffusion is proportional to the second derivative of the property (in this case, the tangential wind), the maximum diffusion limit would be a linear variation, which could be interpreted to be solid-body rotation inside the radius of maximum wind. All numerical models need some diffusion to prevent accumulation of energy on small scales. However, the eyewall breakdown and subsequent horizontal mixing process described above would be a real physical process that could limit the build-up of extreme wind gradients.

Mike Montgomery and John Persing hypothesize another mixing process on the inner edge of the eyewall that will contribute to an increase in Θ_E in the ascending air in the eyewall, and thus lead to a greater intensity. Based on a high resolution, axisymmetric numerical model, the intense radial gradient of tangential wind on the inner edge of the eyewall results in a Kelvin-Helmholtz breakdown into a vortex sheet. Whereas this mixing process will reduce the wind radial gradient, the associated mixing is hypothesized to bring higher Θ_E air into the eyewall updraft. In the Willoughby conceptual model of the eye region, recycling of the air occurs at the bottom of the eye under an inversion that separates cooler, moist air below from the warm, dry, subsiding air at higher levels. Montgomery and Persing suggest that when the recycling air below this inversion is in contact with the ocean, heat and moisture fluxes from the ocean can increase the Θ_E values. Although the wind speeds are decreasing toward zero near the center of the eye, so the surface fluxes are not large, the net increase in Θ_E can be large because the surface pressure is so low. If this Θ_E inside the eye is larger than in the eyewall, the Kelvin-Helmholtz induced mixing process could inject moist air with higher Θ_E values into the updraft. According to the Montgomery and Persing hypothesis, the Θ_E values will increase upward due to this process, and thus increase the intensity above the MPI value for the given sea-surface temperature. By contrast, mixing of the extremely dry air above the eye region inversion into the eyewall would be an inhibiting process as the evaporation of cloud water into the dry air would cool the air and decrease buoyancy in the updraft.

(3). Implications for numerical modeling. Given the interpretation of a feedback loop among environmental effects, convection, and the dynamical adjustments of the inner core vortex via vortex Rossby waves, a convergence of views on the required horizontal resolution for the highly desirable and minimally-acceptable operational models occurred among these breakout groups. That is, horizontal resolutions of 1 km and 4 km, respectively, are suggested. Nesting strategies or adaptive grid approaches are required to achieve this resolution in a region around the tropical cyclone. Whereas it would clearly be desirable (but impractical) to have uniform high resolution over the entire domain, the metric is that the nested model (or adaptive grid model) should be constructed that the interfaces between nested grids (or variable grid spacing) do not introduce significant distortion or noise relative to the solution on the uniform grid. This metric may be achievable because the tropical cyclone tends to be an isolated circulation that has relatively little vertical tilt, and the adjacent circulations generally do not have small horizontal scales as in the tropical cyclone, and thus can be resolved with a coarser grid. The exception is the case of two tropical cyclones, which would require dual nested grids.

As in the convection breakout group recommendations, more than 50 vertical levels are required. As indicated in the eyewall mixing subsection above, a proper treatment of the boundary layer processes contributing to the eyewall processes will require 7-8 levels in the boundary layer.

Also as in the convection recommendations, the eyewall processes require an explicit treatment of the moist processes that include the ice microphysics. Considerable discussion was devoted to how the outer grid processes in the operational model may be affected by the parameterization scheme chosen. Each scheme has some special characteristics that determine the timing of the onset of convection and the eventual saturation of the grid box, which triggers rapid adjustments in the vertical profile, and thus affects the dynamics. Since the cost of running an operational model is related to the sizes of the inner domain with explicit moist physics and the outer domain with parameterized moist physics, the cost-benefit ratio may be a function of the parameterization technique. Thus, some experimentation with different combinations of domain sizes and parameterizations is advisable in the development of the minimally-acceptable operational model.

An accurate treatment of the horizontal mixing processes associated with vortex Rossby waves or eyewall breakdown is clearly important for the feedback loop to the convection and to the environment. The horizontal and vertical propagation of the vortex Rossby waves should be resolved on the 1 km/60 level model. Depending on the radial gradients of wind, temperature and humidity across the inner edge of the eyewall, a 1 km horizontal spacing may be adequate, but a 4 km grid may be marginal for the eyewall mixing events. Either explicit horizontal diffusion or implicit computational diffusion inherent in second-order treatment of advective terms are additional considerations on how the model will predict the formation of the high gradient regions and the resulting mixing process.

Many of the observational considerations for the eyewall dynamics are similar to those for the convection in section 2c. The difficulty is in providing accurate initial conditions in the extreme radial gradients near the eyewall. *In situ* measurements of wind, temperature, and humidity are highly desirable. If smoothed initial conditions are provided, a vortex spinup will introduce a delay or incorrect timing/magnitude of the triggering of vortex Rossby waves or eyewall mixing events. Providing initial conditions at 7-8 levels in the atmospheric boundary layer will be difficult because manned aircraft can not be safely operated in the highly turbulent boundary layer in such high wind conditions. Knowing the flight-level winds and with remotely sensed (scatterometer, stepped frequency microwave radiometer, or lidar) near-surface winds with a few GPS dropwindsondes for the vertical profile may provide a reasonable basis for specifying the boundary layer along the flight path.

d. Interface conditions and the atmospheric boundary layer

(1). <u>Exchange coefficients</u>. Since the ultimate energy source for the tropical cyclone is the ocean, the heat and moisture fluxes through the interface and into the atmospheric boundary layer are critical requirements. However, the exchange coefficients, for heat, moisture and momentum are not well known for the high wind speed and ocean surface wave conditions in hurricanes. Dramatically different storm intensities will be simulated in the models for different specifications of the interface flux conditions. K. Emanuel presented a specific example comparing model simulations with transfer coefficients similar to Large and Pond (drag coefficient increasing linearly to 5 x 10^{-3} for U_{10} of 70 m s^{-1}, enthalpy coefficient constant between 10 m s^{-1}, and 70 m s^{-1}) and with the drag and enthalpy coefficients equal. Whereas the Emanuel model simulation with the equal coefficients produced a realistic representation of the intensification (and decay) of Hurricane Gert during 1999, the simulation with coefficients similar to Large and Pond failed to predict an intensification. The missing ingredient is hypothesized to be the absence of sea spray effects for high winds, and especially above 35 m s^{-1}. At these wind speeds, it is difficult to define an air-ocean interface given the spray droplets in the air and the air bubbles in the ocean surface layer.

The effect of the sea spray on the heat and moisture fluxes depends on the size distribution because of the atmospheric transit time from the generation of the spray droplet to its return to the ocean, and the different heat and moisture equilibration rates for different size droplets during the atmospheric transit. Because different representations of the spray conditions in models produce markedly different simulations of tropical cyclone intensity, a high priority for field program measurements is the spray size distribution at various elevations above the surface, and an estimate of the source function.

Sea spray is also believed to be important for the momentum fluxes at high wind speeds. A drag on the air is exerted as the spray droplet is ripped off the top of the breaking ocean surface wave and accelerated to some fraction of the wind speed while it is in the air. The spray droplet may then re-enter the ocean and deposit its acquired momentum to the ocean. Thus, the spray is hypothesized to have a dominant role in the wind/wave coupling process at high wind speeds, and affects the drag coefficient as well as the enthalpy exchange coefficient.

Given the importance of the interface fluxes for tropical cyclone intensity (and as a moisture source for precipitation), a critical need exists for measurements of the drag and enthalpy flux coefficients in high wind speeds. This need has been recognized by the Office of Naval Research, which has begun a five-year program called Coupled Boundary Layer Air-Sea Transfer (CBLAST) to address this need. K. Emanuel also provided preliminary estimates of the dependence of the drag coefficient on wind speed based on a new wind-wave tank at the Massachusetts Institute of Technology.

Many of the modeling studies have been carried out with horizontally uniform sea-surface temperatures (SST). However, the passage of the tropical cyclone over a warm-core eddy, across the Gulfstream, or coastal waters introduces inhomogeneities in SST and the subsurface conditions. Research is required to better understand how the surface fluxes will be changed in these conditions, and how the vertical structure of the boundary layer is modified during passage over warmer or colder water. More discussion of the ocean effects will be presented in section 2e.

Passage of the tropical cyclone over the land will also have dramatic effects on the surface fluxes and boundary layer structures. Loss of the moisture source over the land (or reduction over a swamp) is known to be an important factor in the decay of the winds in a hurricane following landfall. However, the cyclone may produce copious amounts of rain even days after landfall, especially when topography is present. How the interface fluxes and boundary layer structure affects the inland decay and precipitation will be discussed in section 2f.

(2). Wind-wave coupling. Given the importance of the spray generation from breaking ocean surface waves, and the spray effects on the momentum and enthalpy fluxes, it is mandatory that the research numerical model for tropical cyclone intensity and precipitation prediction include a coupling with an ocean surface wave model. This requirement introduces difficulties both in terms of a suitably accurate wind wave model in high wind conditions, and in acquiring the observations that will be necessary for initial conditions (and for validation). Ocean surface waves may be “fetched-limited” in those areas in which the wind direction is changing rapidly as the hurricane passes a point. However, a region to the right of the storm path may experience phenomenal surface wave heights if the storm translation speed matches the gravity wave speed so that strong forcing persists for some time. Since the different wavelengths propagate at different phase speeds, a complex wave field may be encountered. A hypothesis by P. Black and colleagues proposes that the crossing of the wind and wave directions in the rear quadrant of the hurricane causes steeper wave slopes that are more effective in generating turbulent mixing in the ocean, and thus more rapidly changes the sea-surface temperature (SST) under the hurricane.

The status of ocean surface wave modeling in high winds is controversial, with quite different predictions from the various models. A key factor is how the wave-wave interaction is parameterized in the model. Inadequate data have been available to resolve the differences. It is also emphasized that the present models do not resolve the higher frequency waves (less than 10 m wavelengths) that are involved in wave breaking, and thus in the sea spray generation discussed above.

The Scanning Radar Altimeter wave measurements by E. Walsh in several hurricanes provide wave heights and propagation directions only for longer wavelengths. In particular, the shorter sea waves are not resolved. Thus, observations in only some portions of the wave spectra are available for evaluating the capability of the wave models. It is unclear whether the non-observed higher frequency portion of the spectrum would be accurate even if the model correctly predicted the lower frequency portion that is observed.

In summary, wind-wave coupling is know to be a critical component for the modeling system, but we need a better understanding of the wind-wave structure at high wind speeds. Unfortunately, we do not know in what wind speed range the details of the wind-wave coupling become important. Clearly, this is a topic for additional research investigation. The CBLAST program is addressing this topic from both an observational and modeling approach.

(3). Adequacy of friction parameterizations. Just as a "no-man's land" has been proposed between explicitly and parameterized treatments of convection (see section 2b), a no-man's land for frictional process representations has been proposed by J. Wyngaard and colleagues of Penn State University. Given that horizontal resolutions of the order of 1 km are being proposed for tropical cyclones, such a model will be partially resolving the large eddy circulations that are accomplishing the vertical transports of the heat, moisture, and momentum. These vertical transports are being parameterized in terms of the grid-scale predicted variables with various boundary layer models, which thus may lead to double-counting of the turbulent fluxes. However, the representation of turbulence even in a 1 km model is going to be too smooth because a significant fraction of the turbulence occurs on scales that are smaller than 1 km, so the real vertical transport will be under-estimated. Thus, a 1 km model may be considered to be in the no-man's land for frictional processes, as it under-estimates the true vertical fluxes without the parameterized fluxes, and it over-estimates the fluxes if both resolved and parameterized fluxes are included.

(4). Implications for numerical modeling. As in the previous topics, the highly desirable research model horizontal resolution is of the order of 1 km, which is required to resolve the boundary layer effects associated with the eyewall and rainband structures. However, this grid spacing is in the "no-man's land" for frictional processes representation (see section 2.d (3) above), which indicates research will be necessary to formulate a strategy to avoid detrimental effects. The required vertical resolution is presently uncertain because of the lack of understanding of the surface and boundary parameterizations and especially how valid they may be at higher horizontal resolution. Vertical resolution may be a problem when trying to resolve the eddy structures that are still under-resolved at 1 km horizontal scales. Again, both model sensitivity studies and observations are required to better understand this problem in modeling frictional processes.

Particular attention must be paid to ensuring mass continuity and energetic consistency in the model in regions of high winds such as the eyewall region. Recent studies have indicated that the heat addition associated with frictional dissipation in the strong winds of a tropical cyclone must be included in the numerical model. Given the turbulent kinetic energy calculation for dissipation, the associated heating term is added to the thermodynamic equation, which makes the boundary layer more buoyant than it would be without including the frictional dissipation effect.

As discussed in section 2.d (1), the model sensitivity to the interface exchange coefficients must be addressed. A difficult problem is the handling of the sea spray effects in view of our uncertainty in the spray size spectrum. Hopefully, the CBLAST field experiment will provide guidance for the modeling community. Likewise, new laboratory wind-wave tank estimates of the exchange coefficient will also put bounds on the exchange coefficient. A capability to intercompare models with identical initial conditions and good validation sets is highly desirable.

Whereas it is suggested that future models must be coupled to an ocean surface wave model, it is not clear which wave model should be used. As indicated in section 2.d (2), considerable uncertainty exists as to the capabilities of the wave models in high wind speeds. Parameterizations of the wave-wave interactions are uncertain. In the first step, case studies of wave heights and propagation in the frequency bands observed by the SRA need to be simulated with various numerical models. Present models do not treat the waves at 10 m and smaller wavelengths (highest frequencies) that are involved in wave breaking. Observational studies of breaking waves such as planned for CBLAST are needed as guidance for the coupled wind-wave model development.

Clearly many of the frictional boundary layer processes will not be adequately resolved with a 4 km horizontal resolution that was proposed above for the minimally-acceptable operational model. Whereas parameterization of the frictional processes is more appropriate at 4 km than at 1 km, it is not clear how appropriate the existing parameterizations are for high winds at this horizontal scale. The suggested approach is to systematically vary the horizontal resolution over the range of possibilities and compare with the 1 km resolution model to determine the impacts on the boundary layer structure and processes. Similarly, sensitivity tests are required to determine the effects if a smaller number of vertical levels than 50-60 must be used in the operational model.

As indicated in section 2.c (3), providing the observations to specify the initial conditions at many levels in the boundary layer may only be possible along aircraft flight tracks with remote sensors for estimating the near-surface winds and with dropwindsondes to define the vertical profile. Although it will not be possible to provide the initial sea spray distribution, the model needs to be provided with appropriate drag and exchange coefficients. Some measure of the breaking wave distribution will be required, and this should be consistent with the remainder of the wave spectra. Whereas the local sea state (high frequency waves) may be nearly in balance with the wind, the lower frequency waves and swell will not be, so some initialization is required.

e. Ocean heat content and upper ocean processes

(1) Ocean heat content. New understandings have been achieved regarding the role of the upper ocean heat content (defined as heat content above the 26°C or 20°C isotherm) in tropical cyclone intensity change, especially from several studies of the rapid intensification and decay of Hurricane Opal during 1995. Most tropical cyclone models have assumed a fixed (and often horizontally uniform) SST. However, it is well known that the surface enthalpy flux and turbulent mixing in the ocean mixed layer caused by the hurricane leads to a decrease in SST under and in a wake behind the storm. The magnitude of the SST decrease is larger for a more intense, slowly-moving cyclone over a shallow ocean mixed layer, which may lead to 4°C - 6°C decreases in SST. For a marginal hurricane moving faster than 5 m s^{-1} over ocean mixed layer depths exceeding 30 m, the SST decrease is typically 1°C - 2°C, and the storm is moving away from the lowest SST region in the right-rear quadrant. In special cases of nearly coincident tracks such as Hurricanes Bonnie and Danielle during 1998, the energy supply to the second storm is reduced while it is over the wake of the first storm. Since the typical width of the wake (defined as SST decreases > 0.5°C) is only a few hundred kilometers, the paths must be quite close for this effect to be observed.

The normal negative feedback mechanisms of the self-induced SST decrease reducing the energy supply to the tropical cyclone becomes much smaller if the cyclone center passes over an oceanic warm core ring. Because the SST is higher and the mixed layer depth is typically more than 100 m, the upward enthalpy flux and entrainment mixing at the base of the mixed layer cause only a small (< 0.5°C) SST decrease. The reduction in the negative feedback mechanism over a warm core ring (such as in the Hurricane Opal case) or over the Gulfstream can contribute to a more intense storm than if the storm was over its normal cool wake.

The ocean heat content (OHC) defined relative to 26°C is a more useful parameter than just the SST because it accounts for the depth of the warm water that is available as an energy source for the tropical cyclone. Because only a few ocean temperature profiles are available in any 24 h period, the climatological analyses have been used as a first-order measure of OHC. The three-dimensional distribution of OHC can be changed by surface enthalpy fluxes (including incoming solar flux), entrainment mixing though the 26°C isotherm level, and horizontal advection. The advective contribution is large in the regions with faster currents such as the Gulfstream, the Loop Current entering the Gulf of Mexico through the Yucatan Strait, or in association with the drift of the warm core rings. Thus, the OHC in any period may vary from its climatological value.

A recent breakthrough in estimating the OHC has come from satellite-based radar altimeters that are capable of detecting the upward (downward) deflection of the sea-surface elevation over a warm (cold) core feature. Even though the expansion (contraction) of the upper ocean column thickness for warm (cold) regions is only of the order of 10s of centimeters, suitable averaging of the radar altimeter signal allows detection of OHC gradients across ocean fronts, warm and cold rings, and major currents such as the Gulfstream. A recent paper by M. Mainelli and colleagues demonstrated that the satellite-derived monthly OHC distributions provided an additional predictor for the Statistical Hurricane Intensity Prediction System (SHIPS) technique that improved the predictions by 3-5%. As these altimeter-based detections are assimilated into ocean circulation models, it should be possible to provide ocean thermal structure representations that are considerably more timely and accurate than the present analyses, and with smaller scale and larger horizontal gradients in OHC.

(2). <u>Upper-ocean processes</u>. Changes in the upper-ocean temperature and salinity structure may be separated into those due to the forcing associated with the tropical cyclone, which is transmitted through the interface, and the internal adjustments in the ocean in response to that forcing. Except for the momentum and enthalpy that is stored or advected away in the surface wave field, the momentum and enthalpy flux on the atmospheric side of the interface must be equal and opposite that on the oceanic side (the density differences must be taken into account and no net mass exchange across the interface is assumed). The sensible heat flux and the latent heat flux via evaporation that supply energy to the atmosphere cause a cooling of the upper ocean that accounts for about 10-20% of the SST decreases. The momentum loss from the atmosphere via frictional processes builds waves and drives upper-ocean currents. In Hurricane Gilbert, near-inertial currents of 1.2 m s^{-1} were generated. The thermally-generated turbulence caused by cooling of the upper ocean and the mechanically-generated turbulence primarily arising from current shear instability across the base of the mixed layer cause entrainment mixing at the base. Downward heat flux associated with the entrainment mixing accounted for about 65% of the upper ocean cooling (SST decrease) in Hurricane Gilbert. The remaining 15% of the SST decrease was attributed to horizontal advection.

Since these interface fluxes forcing the ocean response are intimately tied to the ocean surface wave generation and breaking, the same issues discussed in section 2d (2) are relevant to the ocean. Interaction of these waves with the ocean currents near the coast, the Gulfstream, or ocean frontal regions is an added concern for the ocean response. Divergence and convergence associated with the inertially rotating currents under and behind the storm cause alternating upwelling and downwelling in the wake. Where the upwelling (downwelling) causes mixed layer shallowing (deepening), the entrainment mixing is more (less) vigorous and its effects on the upper ocean properties such as temperature, salinity, momentum are larger (smaller) because they are spread over a smaller (larger) column depth. Thus, the ocean responds to tropical cyclone forcing in a complex, nonlinear manner with a strong inertial variation in the wake of the storm.

How the forcing at the surface is transferred vertically to the base of the ocean mixed layer is a problem analogous to the upward/downward transports in the atmospheric boundary layer. Recent float deployments in the path of a hurricane indicate rapid vertical excursions from the surface to the base of the mixed layer, which suggest Langmuir cells in which the upward and downward velocities are concentrated in narrow zones. If indeed the vertical transports are primarily occurring in such narrow zones, the horizontal resolution of the ocean model must be quite fine to resolve these fluxes – or they must be parameterized in terms of grid-scale variables. Given the paucity of such observations in the upper ocean in high wind and large heat flux conditions, developing such a parameterization will be a research challenge. Hopefully, the ocean probes to be deployed during the CBLAST-Hurricane field program will provide the necessary flux measurements within the context of the atmospheric forcing parameters.

A well-tested parameterization of the entrainment mixing for the use in the ocean model is not available. Sensitivity tests with four such parameterization techniques in the University of Miami model indicated some large differences in mixed layer temperatures and current predictions. Both variables (plus salinity if observations are available) must be a part of the validation because it is possible to tune the parameterization to match well one variable with unsatisfactory errors in the other variable.

Very few complete ocean measurements with the corresponding hurricane forcing are available to make these evaluations. More such data sets will hopefully be acquired in the CBLAST field experiments. The surface wind and wave fields are to be measured with the Stepped Frequency Microwave Radiometer and Scanning Radar Altimeter, respectively, mounted on the NOAA WP3D, which will also deploy dropwindsondes to observe the atmospheric boundary layer structure between the aircraft flight level and the surface. The ocean structure will be measured with aircraft-deployed current, temperature, and salinity probes. Floats and autonomous underwater vehicles will provide *in situ* observations. Flights will be coordinated with overpasses of polar-orbiter satellites that include radar infrared and microwave radiometers for SST estimation so that the OHC field can be mapped. The combination of measurements in both the ocean and the atmosphere are planned to close the budgets in such a way as to develop accurate flux parameterization techniques in hurricane wind conditions.

(3). <u>Implications for numerical modeling</u>. Given the horizontal scales of these physical processes and circulation features in the ocean, the model must have a horizontal grid spacing comparable to the atmospheric model. At least 1 km horizontal resolution may be needed if Langmuir cells are the dominant vertical flux mechanism in the mixed layer. Oceanic fronts and boundary currents also require fine horizontal resolution. A movable, nested model following a feature such as the tropical cyclone is a relatively novel approach in the ocean modeling community. If the coastal ocean is also to be predicted, some finite-element approach may be necessary to account for the coastal shape and the shallowing bottom topography. The vertical resolution is a problem because the entrainment mixing processes at the base of the mixed layer need to be well resolved, but this layer base may be anywhere from near the surface to more than 100 m. Some layer base-following coordinate system would be a more economical solution since the levels between the surface and the mixed layer base are nearly uniform and thus are not independent.

If only the near-inertial variations were important, a relatively long time step could be used in the ocean model. However, the float observations that suggest

Langmuir cells are a primary transport mechanism exhibit variability on the order of a hour, so a relatively small time step is required.

As indicated above, the entrainment mixing parameterizations need to be tested and refined with sensitivity studies and comparisons with good, complete ocean measurements. The coupling of the ocean surface waves and the ocean current predictions in hurricane conditions also requires considerable testing.

Whereas the CBLAST observing system mentioned in section 2.e (2) is available for only limited experimental periods, the normal ocean observing system is extremely sparse. Ocean data assimilation development also lags the atmospheric systems. In many cases, the assimilation involves vertically spreading information observed at the surface only. Examples of such observations are radar altimeters and SST fields. The large-scale data assimilation must be operating well in advance of the tropical cyclone to provide a stable, background field. On-going assimilation of radar altimeter data, buoys, ship reports, and palace floats will provide an improvement over the climatological OHC if the regular SST analyses can be used as an upper boundary control to keep the solution from drifting to a model climatology that is different from reality. Near the shore some high frequency radars will provide surface currents, waves, and winds on a fine horizontal scale, but in limited areas. Clearly the sparse ocean observation base and the data assimilation will be a difficult challenge to provide the initial conditions prior to the tropical cyclone. Then *in situ* observations prior to and during the cyclone passage are needed to refine the initial conditions for the ocean-tropical cyclone model.

Because of the small horizontal scales of the ocean features and mixing processes by Langmuir cells, a 4 km or larger horizontal grid spacing in the operational model will not be capable of directly resolving these processes. Thus, a parameterization of the vertical fluxes is required, which needs to be developed by comparison with good ocean data sets.

One concern expressed at the Workshop was the fraction of time that could be devoted to the ocean model in an operational system, and thus whether the option of one-dimensional mixing models with no horizontal advection should be considered vice a full physics, three-dimensional model. According to information provided by Morris Bender, the ocean model coupled to the GFDL hurricane model has been running on only 1 CPU compared to 43 CPUs for the atmospheric model. With the new two-nest, higher resolution atmospheric model implemented in 2002, more than 70 CPUs will be required, but the ocean model will still run on a single CPU. Thus, the ocean model requires a relatively small fraction of the total computer resource and a full physics ocean model can be considered for future applications.

In summary, the ocean component of the system raises a number of challenging issues to be studied. Fortunately, the five-year CBLAST program funded by ONR will address a number of key research issues. The ocean observation base, data assimilation, and modeling needs for operational use requires special attention.

f. Inland winds and rainfall from landfalling hurricanes

This section draws special attention to the wind structure changes and precipitation as the hurricane makes landfall and moves inland. Except for ships at sea (which should have diverted around the storm) or fixed marine activities such as oil drilling platforms, this is the period when the most people will be affected. The region of highest winds near the center are of greatest interest, both for the potential wind damage and because of direct relationship between maximum storm surge elevation and intensity. That is, the inundation areas expected from the storm surge are tied to the Saffir-Simpson intensity category, which is used to warn people in those coastal areas who need to evacuate or make other arrangements for rising water of a specified amount. Because of the success in educating the public and good warnings of the storm surge threat, the United States has experienced almost no loss of lives due to storm surge, which is the major cause of deaths in other areas of the globe. Rather, a majority of the hurricane-related deaths in the United States is from precipitation-related flooding, which is a threat that may continue for days after landfall when media attention has diminished.

(1). <u>Inland wind structure changes</u>. The central core of highest winds in hurricanes and strong tropical storms decays rapidly after landfall. In the mean, the wind decay rate is approximately exponential with an e-folding time of 10 h. For example a storm with maximum surface winds of 120 kt, 80 kt, or 45 kt at the coast might be expected to decay to 55 kt, 45 kt, or 35 kt, respectively, after only 9 h. Complex wind structure changes occur as the strong winds cross coastal waters and strike land. Whereas the surface wind drag increases over land, the surface latent heat fluxes are reduced because the land is not as an effective moisture source as the ocean. In addition, the heat capacity and conductivity of land are much less than for water. Therefore, the adiabatic expansion cooling of the air flowing toward lower pressure is not offset by surface sensible heat flux. Thus, the surface temperature decreases after landfall, which contributes to an increase in low-level static stability. The post-storm damage study following Hurricane Andrew has two extreme damage areas. The first area occurred in association with the strongest winds in the eyewall on the right (north) side of the path. However, a second damage area occurred where the winds reversed from northwesterlies before landfall to southeasterlies after the storm moved inland. One hypothesis is that frictional convergence at the coast in the highest winds on the north side triggered convection that intensified as it rotated around the eyewall and caused the damage when the severe convection brought the high winds to the surface in the rear quadrant.

Although the mean surface winds decay rapidly, the middle- and upper-level circulation spins down more slowly. Thus, circulation systems above the boundary layer may be maintained long after landfall. Outbreaks of convection in the rainbands or triggered by daytime heating over land then can bring damaging winds to the surface well inland.

In summary, the prediction of the landfall and post-landfall wind structure changes is intimately tied to the frictional boundary layer processes, both in contributing to the decay processes and to the subsequent surface damage events. Thus, the boundary layer model must be capable of representing the response of the wind field to changing surface conditions from water to land surfaces of many types (e.g., from urban areas to swamp land). This dependency also implies that an accurate land surface model will be required. Recent evidence from portable Doppler radar data collections in landfalling hurricanes suggests roll-like boundary layer structures with extreme horizontal shears over small distances, which may account for the localized wind damage reports on the scale of city blocks.

(2). Inland precipitation. The exponential decay of rain rates with radius from the center from satellite and radar measurements was described in the convection section 2b. The asymmetric distribution of precipitation in association with vertical wind shear was described in section 2a (2). A recent climatology based on rain gages indicates that the inner-core rain rate decays rapidly after landfall. However, the rainfall associated with the outer circulation beyond 150 km does not decay significantly as the intensity decreases from category 3-5 to category 1-2, or even to tropical storm. Thus, large amounts of precipitation may occur with slowly moving tropical storms long after landfall if the outer source of moisture is sustained. A recent example is Tropical Storm Allison that remained nearly stationary and caused heavy flooding over Houston shortly after landfall, but then continued to produce large rainfall as it moved parallel to the Gulf Coast and along the east coast of the United States.

An optimistic hypothesis is that the heavy rains in hurricanes offshore may be more predictable than isolated precipitation events because of the dynamical control of the convection by the strong wind circulation and associated frictional forcing of convection. The post-landfall rain is not as closely tied to the storm center as over the water. Outbreaks of intense convection in mesoscale convective systems can produce 10 cm of rain in a few hours and may be triggered by diurnal forcing. Orography may also play a crucial role in triggering heavy precipitation. Consequently, prediction of even the storm-total rainfall is not very accurate. It was suggested in the introduction (section 1c) that a reasonable target would be to reduce the maximum storm-total rainfall absolute magnitude from 3 in to 1 in. In extreme cases such as a storm-total rainfall of 43 in near Mobile, Alabama during Hurricane Danny, this target may not be attainable.

Recent research on the extratropical transitions in various ocean basins substantiates that the maximum precipitation shifts from being near the center and just to the right of the track during the mature tropical stage to being to the left of the track during the extratropical transition. Since considerable pre-storm rainfall typically occurs in advance of a tropical cyclone that is interacting with a midlatitude trough and its associated frontal system, a future track over the same area can lead to flooding from the tropical cyclone precipitation. Such a scenario accounted for the extreme flooding in eastern North Carolina during Hurricane Floyd where the soil was already saturated from the earlier Tropical Storm Dennis and the pre-storm rainfall associated with the coastal front.

A common technique for evaluating precipitation forecasts is the Threat Score, which is a measure of the overlap in observed and forecast areas for various precipitation thresholds. It is well-known that the Threat Scores for warm season precipitation exceeding 1 in over 24 h are much smaller than for cold season precipitation. However, the model guidance and the Hydrometeorological Prediction Center forecasters have Threat Scores during hurricanes that are well above the typical warm-season values for precipitation exceeding 1 in. The maximum forecast values are generally smaller than the observed maximum, and the accuracy depends very much on the correctness of the track prediction.

A measure of the skill of the storm-relative precipitation rain is the recently developed Rain-Climatology and Persistence (R-CLIPER) based on the TRMM microwave estimates (see section 2b). Comparison of historical hurricane-rain forecasts and model guidance with the reconstructed R-CLIPER values for those cases will give a skill standard for measuring improvements in model guidance and the value added by the forecasters. Whereas the accuracy in a geographic reference depends on the correctness of the storm translation speed and direction forecast, it is useful to first do the storm-relative R-CLIPER evaluation. The second evaluation is whether the models and forecasters are able to predict the asymmetric component of the precipitation distribution relative to the center and how this evolves during landfall and during interactions with adjacent weather systems.

(3). <u>Implications for numerical modeling</u>. As indicated in section 2f (1), one key factor in the inland wind structure prediction is the adequacy of the boundary layer representation to predict the exponential decay of the surface winds. The horizontal scale of the boundary layer rolls will be a controlling factor since they must be either resolved with small grid intervals or parameterized at larger grid spacings. As emphasized in section 2d (4), the proposed horizontal resolution of order 1 km for the highly desirable research model is in the "no-man's land" for frictional processes. Thus, considerable testing will be necessary to determine the accuracy of the boundary layer structure and the slower spindown of the vortex above the boundary layer. Subsequent downward mixing of damaging winds via vertical turbulent processes in rainbands also needs to be demonstrated.

Both the inland wind structure evolution and the precipitation distribution also depend on the land surface model, which is a complex modeling challenge. First, the surface roughness must be properly characterized as a function of terrain, land use, and canopy height. Just as the drag and enthalpy exchange coefficients over the ocean need to be established, the adequacy of these coefficients for momentum and evaporation transfer over different land surfaces must be confirmed for high wind conditions. Issues such as the most appropriate vertical coordinate systems must be resolved, especially when significant topography is present. Because the flow from ocean to the land can create additional convergence, the details of the coast must be resolved. Since the heating of the land or terrain slopes varies with the sun angle, the convection can be triggered at different times of the day.

The surface energy budget is closely tied to the soil moisture, which will especially affect any evaporative moisture source for inland precipitation. Since the coastal areas often have wetlands, the land surface model must be able to predict the evaporation from such a mixed terrain of shallow water and land. The effects of the pre-storm precipitation on the soil moisture must also be included in the surface energy budget. The coastal areas also have a variety of vegetation types that will affect the evapo-transpiration. Diurnal and seasonal variations must also be included in the model to correctly model the soil moisture effects.

Similar considerations apply for predicting the surface temperature via the land surface model. In addition to the important soil moisture, all of the radiative effects of short-wave, long-wave, albedo, and cloud-radiation effects need to be included. Diurnal effects are particularly important in determining the sensible heat flux to the atmosphere that may trigger the convection, especially when that convection may bring high, damaging winds downward from the still strong vortex aloft. How many soil levels, and how to initialize the soil model, are relevant modeling questions that need to be addressed.

Since the primary moisture source for continued precipitation in the landfalling hurricane is from the adjacent ocean areas, the requirement for accurate moisture observations may be a critical limitation to the forecast capability. Whereas the advection of dry air slots from the better-observed land areas may be predicted, the key requirement is for the depth and magnitude of the high moisture content air from the ocean areas. Predicting precisely where the moisture convergence will occur and result in significant convection and precipitation within the landfalling hurricane and its immediate environment will be a difficult challenge.

Since a primary goal is to improve forecasts of flooding events that cause loss of lives and damage during landfalling hurricanes, the hurricane model needs to be coupled with a hydrological model of the affected river basins. Pre-existing soil moisture conditions and streamflows and the detailed precipitation distribution in space and time are required inputs. Except for flash floods in small river basins, the rise of the river level and broaching of the banks occurs with a time delay, so that a 12 h or longer warning of flooding may be possible.

Additional observations are required for the land surface model and hydrological models. High resolution observations of the vegetation, land use, soil moisture and temperature, and streamflow are required. Cloud types and distributions and the cloud microphysics properties must be specified and predicted for calculation of albedo and cloud-radiative effects. In many places the *in-situ* observations will be limited. Various satellite platforms and instruments must be exploited including geostationary and polar-orbiting (e.g., LandSat) infrared, microwave, and synthetic aperture radars. Since a number of groups are addressing these issues of providing observations and initial condition specifications for land surface and hydrological models, collaborations are desirable to exploit their experience. The challenge is to get these measurements in real time and in high resolution of the proposed models, and then test the veracity of the entire system during the extreme conditions of a hurricane landfall.

g. Concluding remarks

These physical processes that affect tropical cyclone wind structure (intensity) changes and precipitation distributions require a set of model characteristics that will be a major numerical modeling challenge, both for the highly desirable research model (to be described in section 3) and the minimally-acceptable operational model (to be described in section 4). First, the environmental forcing considerations require a large domain. Second, the response to that environmental forcing ultimately involves convection on small horizontal scales in the inner core. Third, the thermodynamical and then dynamical adjustments to the environmental forcing and convective response occurs with vortex Rossby waves that propagate azimuthally and radially and feedback to the environment and also trigger a convective response. Resolving this environment-vortex-convection feedback in the numerical model then requires fine horizontal resolution, at least in some inner region of the vortex. This horizontal resolution requires a nested or an adaptive grid approach since a small horizontal grid increment cannot be applied throughout such a large domain. By comparison, the numerical model characteristics for tropical cyclone motion are much less stringent as it does not require the resolving of inner-core convection and dynamical vortex adjustment.

Most of this discussion of physical processes has concentrated on the mature vortex stage. This is natural because the cyclone is most damaging at this stage and the destruction potential increases rapidly with intensity, and the maximum rain rate increases with more intense storms. The consideration of vortex stage is also important because the feedback processes in the environment-vortex-convection loop are vortex-dependent. Consequently, the feedback loop will be different during the formation stage and the decay stage, and these are also important forecasting problems. Again by comparison with the numerical model requirements for tropical cyclone motion, which is not quite so vortex-stage dependent, this problem of inner wind structure change and prediction is far more challenging.

Another major modeling challenge dictated by these physical process considerations is that the proposed modeling system must include a coupled ocean surface wave model, a coupled ocean circulation model, and a sophisticated land surface model – none of these additional coupled models have been required for tropical cyclone motion forecasting guidance. Each of these coupled system components adds new issues as well as complexity to the overall system. In all cases, the key issue is how the individual model components perform in the high wind conditions of a hurricane. Critical issues arise in specifying the vertical fluxes through three interfaces: between the atmospheric boundary layer and the convection above; at the interface between the atmosphere and the ocean; and between the ocean boundary layer and the seasonal thermocline and deeper ocean. The vertical transports through each of these interfaces determine the vertical flux convergence that is the primary factor in the time tendency of the properties within the layers. Thus, it is critical that these interface fluxes be correctly predicted. Whereas the knowledge of these vertical fluxes is fairly well advanced for light to moderate wind conditions as are found in the outer region of a tropical cyclone, this is not true for the high wind and wave conditions in the inner core.

Since the vertical flux convergences must be accurately predicted, stringent model requirements are indicated for the number of vertical levels in the model system. Both the atmosphere and ocean boundary layers must be well-resolved in the vertical, and each layer has significant depth variations from the outside of the tropical cyclone to the inner-core region.

Although idealized models can address some questions without encountering the data-sparcity issue, the prediction application requires specification of initial conditions. Whereas the environment, vortex, and atmospheric boundary layer have to be specified to a certain level for tropical cyclone motion prediction, the fine horizontal and vertical resolutions described above make the initial condition specification requirements much more difficult for the intensity change and precipitation prediction. Furthermore, the more complex moisture representation in the proposed model that includes microphysical processes with multiple ice species raises challenges for initial condition specifications. Each of coupled systems (ocean surface wave, ocean circulation, and land surface) requires an initial condition specification – and all have to be internally consistent, especially for fluxes at the interfaces mentioned above. These requirements for observations and data assimilation will be a significant challenge for creating a minimally-acceptable operational model.

Given the requirement for such a complex, nonlinear modeling system with multiple components that are inter-dependent, questions of predictability naturally arise. Challenges such as these are also opportunities to advance the science and modeling. It is in this sense that the designs of the highly desirable research model and minimally-acceptable operational model are proposed in sections 3 and 4, respectively.

3. Research model characteristics and research requirements

a. Research model characteristics

The discussion of physical processes in section 2 guides the specification of the highly desirable research model characteristics. To provide a perspective, a number of research groups supplied descriptions of the models they are now using for tropical cyclone research (Table 1a-d). The desirable USWRP model that might be used for case study simulations of wind structure change and precipitation is characterized in similar categories (Table 1, bottom) to indicate where advancements are necessary. Whereas individual models may have some of these characteristics, no model has all of the desired characteristics, and none of the models has been integrated with a large number of case studies.

It is emphasized that idealized research simulations are also highly desirable, and these are likely to involve a hierarchy of models that are less stringent than the requirements in Table 1. One advantage in the idealized simulations for understanding contributions of physical processes is that they do not require a data assimilation system for these mesoscale circulations with strong winds and heavy precipitation conditions.

Development of such a capable data assimilation is a formidable task and is expected to require several years of effort (see section 4).

Table 1a. Summary of some basic model descriptions for various research numerical models being applied for tropical cyclone wind structure (intensity) change and precipitation prediction, and the proposed USWRP research model (see text for explanation of the various entries).

Organization	**Name**	**Region**	**Grid-type**	**Time Differencing**
NASA/GSFC	MM5 (3.4)	Atlantic	Arakawa B	Leap-frog
AOML/HRD	MM5 (3.0)	Atlantic	Arakawa B	Time-splitting
US Alabama	MM5 (3.0)	Atlantic	Arakawa B	Leap-frog
NPS	MM5 (3.0)	NWPAC	Arakawa B	Leap-frog
Japan MRI	MRI/NPD	NWPAC	Arakawa C	Semi-implicit
U Miami	MM5	Atlantic	Arakawa B	Time-splitting
U Hawaii	TCM3	Idealized	Arakawa A	Leap-frog
CSIRO-1	DARLAM	Australia	Arakawa C	Semi-Lagrangian
CSIRO-2	CCAM	Australia	Reversible	Semi-Lagrangian
USWRP	Case study research	Atlantic	Arakawa B/C High-order adv	TBD

As indicated in Table 1a, a number of the research groups have used the Penn State-NCAR MM5, which is useful for intercomparisons. However, the NCEP does not have the MM5 as an operational model. One of the motivations for the USWRP to promote the development of the Weather and Research Forecast (WRF) model is to have the research community and operational center using the same model. Having a research community model facilitates intercomparison of results, and advancements in research can then be more easily transferred to the operational model. The status of the WRF model is that a moveable, nested version is not available, as would be required for the tropical cyclone (see below). Thus, the research must continue for the present with various models, and it will be a significant step when an appropriate WRF model is ready for hurricanes (see section 4).

The models in Table 1a have been applied in a number of regions (column 3). One of the desires of the USWRP is to establish collaborations and make use of the knowledge and experience gained from research groups around the world, which was one of the reasons for holding the Workshop immediately after the AMS Conference when many of these international and national research groups could attend. Although the USWRP Hurricane Landfall program is primarily focused on improving forecasts for the Atlantic region, the same physical processes and numerical model characteristics are expected to apply for tropical cyclones in other regions.

Only one of the models (University of Hawaii) in Table 1a uses the Arakawa A grid arrangement, whereas other models (mainly MM5) employ the Arakawa B or Arakawa C arrangement. Preliminary indications are that the WRF model may adopt the Arakawa C (staggered) grid. Thus, the entry in column 4 in Table 1a for the USWRP is for either an Arakawa B or an Arakawa C grid. High-order advection will be a requirement to ensure mass and energy conservation in the prediction.

Whereas the MM5 models in Table 1a employ simple leap-frog time differencing, more sophisticated schemes may be appropriate to gain efficiency. A dynamical core being proposed by NCEP for WRF has a semi-Lagrangian time differencing that allows a much longer time step, and thus is more efficient. Only the two CSIRO models have used the semi-Lagrangian technique. However, it remains to be determined whether the solutions along trajectories in the strongly curved, high wind region of the eyewall will still allow the longer time steps. Because of the need to maintain accuracy and conservation properties, the USWRP entry in column 5 of Table 1a is to be determined (TBD).

One of the primary constraints on the highly desirable research model from consideration of the physical processes in section 2 is the requirements for small horizontal and vertical grid sizes. As listed in Table 1b, these small grid spacings are achieved by nesting with each interior grid haviang a factor of three smaller grid interval. Consequently, a number of research models have been integrated with an inner grid interval of 9 km to 1.7 km (Table 1b), which gets close to the highly desirable 1 km resolution that could be achieved with a four-nest grid of 27 km, 9 km, 3 km, and 1 km. The disadvantage of this four-nest selection is that the 9 km grid interval is squarely in the middle of the "no-man's land for cumulus parameterization," which is generally taken to be between 5-15 km. To minimize this effect, the domain of the 3 km grid would have to be sufficiently large to include all of the major convective precipitation region of the hurricane, so that the region of the 9 km grid contains mainly stratiform precipitation with little convection. The AOML/HRD and University of Miami groups have avoided the no-man's land by their choice of 45, 15, 5, and 1.7 grid sizes. If the 1.7 km resolution is shown to adequately resolve the inner-core physical processes, this will be a good alternative. A fifth grid of 0.55 km would be prohibitively expensive as this would increase computer requirements by a factor of 27. A third alternative of a 5-1 mesh refinement ratio (say 1, 5 and 25 km) is unlikely to be successful because the large radial mass and energy transports near the hurricane core region would not be handled well across such a large jump in grid sizes. Consequently, reflection and noise would be generated as internally generated radial flows and fluxes would not be able to cross that interface.

As described in section 2a, the outer domain has to be quite large to allow the environmental effects to be contained within that domain. With the extension of the hurricane forecasts to 120 h, the outer domain must be large so that the tropical cyclone does not approach the boundary. Having such a large domain also reduces the potential for degrading effects of the lateral boundary values from the global model affecting the central region of most interest. Experience with the GFDL operational model suggests that a 75° long by 75° lat. domain should be adequate for 120 h forecasts (Table 1b).

Table 1b. As in Table 1a except for space and time characteristics of research models.

Organizations	**Horizontal Grids**	**Domain (x, y) Outer nest**	**Vertical Levels**	**Boundary Layer resolution**	**Time Interval**
NASA/GSFC	4 nests to 2 km	30° x 30°	27	~ 6 levels	24 – 72 h
AOML/HRD	45 x 15 x 5 x 1.7 km	3870 km square	23	9 layers in lowest 100 mb	72 h -120 h
US Alabama	9 x 3 km	1413 x 900 km	23	5-6 layers	36 h
NPS	81 x 27 x 9 km	8829x5589 km	27	8 layers	60 h – 72 h
Japan MRI	1-5 km inner	TBD	38		78 h
U Miami	45 x 15 x 5 1.7 km		28		120 h
U Hawaii	45 x 15 x 5		21→36		192 h
CSIRO-1	50 x 20 km		18		72 h
CSIRO-2	50 x 20 km		18		120 h
USWRP	27 x 9 x 3 x 1 km	75° long. 75° lat.	60	15-20	120 h

As described in section 2b, many levels are required in the atmospheric boundary layer, the outflow layer, and around the freezing/melting layer. Whereas most of the research models in Table 1b have about 25 layers, the highly desirable USWRP research model requires about 60 layers to ensure adequate resolution of the physical processes described in section 2. Perhaps 15-20 of these layers may be in the boundary layer.

Most of the research models have been integrated to 72 h or to 120 h. The exceptions are the short-range (36 h), small-domain integrations at the University of South Alabama, and idealized integrations at the University of Hawaii to 192 h with near-zero environmental flow so that the cyclone does not approach the boundaries. Thus, it is reasonable to require the highly desirable USWRP research model be integrated to 120 h given the large domain described above (Table 1b).

The research models have been provided the environmental fields from a variety of global model analyses, the GFDL analysis in the case of the University of South Alabama, or idealized fields for the University of Hawaii (Table 1c). In the USWRP research case studies contemplated here for the Atlantic, it is anticipated that the environmental fields will be provided from the Aviation (AVN) model that is used for the operational GFDL model.

To better define the initial conditions near the tropical cyclone, some form of bogus vortex is usually added in the research models (Table 1c). A simple method of nudging may be used to blend the finer scale observations into the environmental fields, or a highly sophisticated four-dimensional variational assimilation may be used at the Japan Meteorological Research Institute (MRI). Development of an appropriate data assimilation technique for operational hurricane prediction is a high priority (section 4), and will be used for research studies when it becomes available. The first version is likely to be a three-dimensional variational method, as it is only in a few research studies that the time-consuming four-dimensional variational assimilation can be considered (Table 1c).

Since these are regional models, the lateral boundary conditions must be provided by a larger scale model, which may be from an interpolation between analyses or from an integration of the larger scale model (Table 1c). These boundary conditions would be extracted from the same model that provided the initial conditions as discussed above. The University of Hawaii idealized simulations can use cyclic boundary conditions in the zonal direction to avoid specifying lateral boundary conditions. In the proposed USWRP research model, the AVN model analyses or integrations will naturally be used to be consistent with the initial conditions. As the AVN model will be integrated on a T254 (~ 55 km) grid following 15 July 2002, the horizontal resolution of the global model will be only about a factor of two larger than that of the outer nest, and thus will not be expected to cause problems near the boundaries.

Many of the MM5 models in Table 1c provide the boundary conditions around the nested inner grids by relaxation of the values provided by the next larger grid model integration as a one-way influence (Table 1c). A more efficient communication between the nested grids is provided by two-way interaction, because this method allows energy, momentum, and heat generated by the tropical cyclone on the inner-most grid to pass outward to the next grid. Consequently, the nested grid interfaces can be closer than in the one-way influence approach in which the boundary value from the outer grid integration is not consistent with the stronger inner grid representation of the tropical cyclone. With one-way influence, the grid interfaces must be removed far from the cyclone. With two-way interaction, the fine grid domains can be smaller and this saves computer resources. Consequently, the proposed USWRP research model should incorporate the two-way interaction approach for all of the inner nested grids. These inner grids should be programmed to move with the tropical cyclone to keep the inner-core circulation well within the finest scale inner grid. The two-way interaction MM5 models at the University of Miami, AOML/HRD, and NPS have an automatic, multiple-grid moving capability (Table 1c).

Table 1c. As in Table 1a, except for provision of initial conditions and boundary conditions, and possible atmosphere-wave-ocean coupled models.

Organizational	**Initial Field**	**Regional Analysis**	**Lateral External**	**b.c. Nested**	**Wind Wave?**	**Coupled Ocean ?**
NASA/GSFC	ECMWF	Bogus vortex	ECMWF	Two-way	No	Fixed SST
AOML/HRD	AVN	Bogus vortex	AVN	Two-way	No	Fixed SST
US Alabama	GFDL	Bogus vortex	ECMWF	Two-way	No	Fixed SST
NPS	NOGAPS	Nudging	NOGAPS	Two-way	No	Fixed SST

Japan MRI	JMA Global	4D VAR	Global	Two-way	Planned MRI III	Planned
U Miami	AVN		AVN	Two-way	Wavewatch III	HYCOM
U Hawaii	Idealized	Idealized	Cyclic-x	Two-way	No	Fixed SST
CSIRO-1	AVN JMA	Bogus vortex	AVN JMA	Relaxation	No	Fixed SST
CSIRO-2	AVN JMA	Bogus vortex	AVN JMA	Two-way	No	Fixed SST
USWRP	AVN	3D VAR 4D VAR	AVN	Two-way	Yes TBD	Yes TBD

A conclusion from the discussion of wind-wave coupling in sections 2d-2e is that the proposed USWRP research model needs to include a coupled ocean surface wave model. Only the University of Miami model has such a coupled wave model, which is the Wavewatch 3 model developed by H. Tolman at NCEP. Preliminary tests at the University of Miami with the coupled Wavewatch 3 model in two hurricanes suggests satisfactory agreement with the wave amplitudes in those frequencies that can be observed by the Scanning Radar Altimeter. Consequently, it is reasonable to expect that the Wavewatch 3 is a viable candidate for the highly desirable USWRP research model (Table 1c). Tolman has indicated it is possible to develop a version of the ocean wave model that would move with the hurricane, which would be more efficient because it then solves for the waves at high horizontal resolution only under the hurricanes, and perhaps near islands. The propagation of the longer waves (swell) ahead of the hurricane would still be adequately resolved on a more coarse grid away from the hurricane. As indicated in section 2d, this wave model has to be extended to higher frequencies to address the shorter waves that are most influential for the interface fluxes.

The requirement for a coupled ocean model was described in section 2e. None of the research models in Table 1c are presently coupled to an ocean current model, although the University of Miami hurricane model will soon be coupled with their HYCOM and the Japan MRI will also soon be coupled to an ocean model. Other options for ocean models are the version of the Princeton Ocean Model (POM) adapted by the University of Rhode Island for coupling with the GFDL Hurricane model, the GFDL MOM, and the NCEP ocean model under development. Whichever of these ocean models is adopted, a moveable, fine resolution model of the same horizontal scale as for the hurricane model should be embedded when a hurricane exists. As indicated in section 2e, much development, testing, and evaluation of the ocean model is required for such high wind and wave conditions. For example, the parameterization of the entrainment mixing at the base of the mixed layer must be accurately predicted if the correct SST distribution is to be provided to the hurricane model.

Each of the tropical cyclone research models in Table 1d includes a horizontal diffusion to suppress computational noise, but will also prevent frontogenetic regions such as the eyewall from shrinking to an infinitesimal scale. As described in section 2c, real physical mechanisms such as the eyewall mixing events also limit the extreme radial shear of the tangential winds near the eyewall. However, the inclusion of the fourth-order horizontal diffusion in the proposed USWRP research model is primarily intended to suppress computationally generated noise.

As mentioned in section 2b, considerable discussion occurred at the Workshop about the desirability of cumulus convection parameterization in such high-resolution models. Clearly, the 1 km and 3 km grids should have explicit moisture treatments. The greatest uncertainty is whether the 9 km grid should also have explicit moisture, or whether it is acceptable to have cumulus parameterization. The Kain-Fritsch parameterization that several of the research models in Table 1d utilize was not intended to be used for horizontal resolutions below 20 km, and this is probably true of the other parameterizations, so some new form may be required. For the 27 km outer grid in the nested model, cumulus parameterization would seem to be appropriate. However, which scheme is most appropriate for the USWRP research model remains to be determined.

Various types of explicit moisture treatments have been used in the research models in Table 1d. Within these schemes, the number of water and ice species is also quite variable. Thus, we are far from a consensus on the most appropriate explicit moisture treatment. As indicated in section 2b, this is an active area of research and high quality *in situ* and remotely-sensed microphysical data sets in hurricanes are needed for calibration of these models. Thus, the explicit moisture treatment for the USWRP research model is still to be determined; likewise, the number of ice species must be determined by comparisons with *in situ* microphysical observations from the CAMEX and HRD data sets.

Table 1d. As in Table 1a, except for various aspects of the physics representations in the research models.

Organization	Horizontal Diffusion	Cumulus Convection	Explicit Moisture Type	Ice Microphysics	PBL	Land Surface
NASA/GSFC	Temp perturb	Betts-Miller or Grell	Goddard	Three ice species	Blackadar (others)	Multiple layers
AOML/HRD	4^{th} order	Kain-Fritsch	Dudhia Goddard	3 species; No supercooled water	Blackadar	Slab Force-restore
U S Alabama	Temp perturb	None	Reisner	Graupel	Blackadar	5-layer
NPS	Temp perturb	Betts-Miller	Dudhia	No supercooled	MRF	Multiple layer
JMA	4^{th} order	Arakawa-Schubert	Ikawa	Ice, snow, graupel	Deardorf Level 2.5	4-layer
U Miami	Temp Perturb	Kain-Fritsch	Dudhia Goddard	No Supercooled Graupel	Blackadar	Slab Force-restore
U Hawaii	4^{th} order	Betts-Miller	Wang	Mixed-ice	Detering	BATS

					Etling	
CSIRO-1	Smagor-insky	Arakawa-Gordon	No	No	Louis + non-local	6-layer
CSIRO-2	Smagor-insky	Arakawa-McGregor	No	No	Louis + non-local	6-layer
USWRP	4^{th} order	To Be Determined	TBD	Number of ice species ?	TBD	TBD

The atmospheric or planetary boundary layer (PBL) is a critical region within the hurricane as the energy, moisture, and heat fluxes pass through the boundary layer (see sections 2b, 2c, and 2d). Since most of the research models in Table 1d are a version of the MM5, the most common PBL model is the Blackadar scheme developed at Penn State. Since the PBL treatment is intimately linked to the convection, these aspects need to be considered together. As described in section 2d, a 1 km horizontal resolution model lies within the no-man's land for frictional processes, and a special treatment of the PBL parameterization is going to be needed. Thus, the entry in Table 1d for the USWRP research model PBL is listed as to be determined.

A final model characteristic is the coupling to the land surface model described in section 2f. Most of the research models in Table 1d have relatively simple representations of the land surface. A considerably more complex system is proposed in section 2f to properly predict the inland wind structure decay and precipitation. The tradeoff between land surface model complexity and benefit remains to be determined for the USWRP research model.

b. Research requirements

The research model characteristics described in section 3a arise from consideration of the present science understandings discussed in sections 2a – 2f. Advance of the science of course has its own merit. The consideration here is that the research modeling effort for tropical cyclone intensity and precipitation needs to be tightly integrated with these science understanding advancements. The idealized modeling efforts to understand the sensitivity to various physical processes should be guided by the range of uncertainty in the science. The idealized research models will help in the understanding of how the various physical processes are coupled as they contribute to intensity changes and precipitation amounts and distribution. One example is the understanding and treatment of the "no-man's land" for moist processes or frictional representations. Some basic modeling issues such as the required horizontal/vertical resolution, nesting approach suitability or limitations, etc. can also be addressed with the idealized models.

The other type of research modeling is the case study approach. Because of the complexity of this problem involving interactions among the physical processes described in section 2, the research strategy to achieve full understanding requires a fully coupled air/ocean/land surface model that addresses all physical processes with the required horizontal/vertical/time resolution. In this approach, the objective is to begin with as complete a data set as possible (in atmosphere and ocean and over land) and to verify against real data. Only by doing the complete model and doing a rigorous comparison with real data will the full understanding of the interacting physical processes be achieved. When only part of the problem is addressed, one can never be sure that the untreated part did not contribute to the observed change.

This case study research approach is very challenging as it must be integrated with science understanding efforts and tied to real data. Only with field experiment data sets can the required observations be sought to provide the initial conditions and verifying observations. Some of the difficult observations are the microphysical properties in clouds, sea spray distributions in the vertical and horizontal, and vertical mixing processes in the atmosphere and ocean. Since all of these observations will not be acquired at all spatial points and times, a combined observation and modeling approach is required. That is, the modeling results should be utilized to determine what variables and what locations are most contributing to the intensity changes or precipitation distribution, and thus are most important to be measured in the field experiment. Advances are achieved if these targeted observations confirm the expected variations, or if the observations indicate the model sensitivity is not verified and adjustments in the model characteristics or physical processes are required. Clearly, this is an iterative process that involves collaboration between the modelers and the observationalists.

Another collaboration required is among the modelers to share initial and validation data sets so that model sensitivity issues can be isolated. As described in section 3a, the research model characteristics are yet to be resolved. Even the dynamical core of the model that will eventually become the operational model (to be described in section 4) is not decided. Thus, the research modeling effort must necessarily proceed with multiple models in Table 1. Achieving maximum benefit from such research requires some intercomparisons among the modeling groups. Coordinated subcomponent testing should be achieved by the model team.

Another collaboration might involve the tropical cyclone forecasters. As described in section 2 (see especially section 2g), the physical processes are different for the formation, mature, and decaying stages. Some scenarios are more difficult to forecast than others, and these should be the focus of research. The forecasters can be involved in the designation of these cases and in evaluating the reality of the case study research results.

In summary, the research model strategy should involve integration with the science community, the observational community, and forecasters. This problem is complex with multiple physical processes that might be contributing to tropical cyclone intensity change or precipitation distribution. Thus, a collaborative effort will be required to meet the challenge.

4. Design considerations for minimally-acceptable operational model

Whereas the highly desirable research model system in section 3 can be designed for completeness with less concern for limitations of computer resources or timeliness, these are critical issues in the design of the minimally-acceptable operational model. That is, the operational system must receive the observations, perform the analysis and data assimilation, and then integrate the numerical model(s) to 72 h (or soon to 120 h) – all on a tight schedule so that the prediction guidance is provided to the forecaster while it is still timely. In general, the dynamical model guidance cannot be provided within the synoptic times plus the 1.5 – 2.0 h time slot in which the forecaster must make his/her assessment and issue the warning at synoptic time plus 2.5 h or 3.0 h. Thus, the dynamical model guidance that is used for the 00 UTC warning is from the model forecast generated from the 18 UTC analysis, and that forecast is then interpolated to the observed tropical cyclone position and conditions at 00 UTC. In this sequence, the model guidance is more than six hours beyond its actual starting time when it is used by the forecaster to make a decision, even though it has been interpolated to more recent position and intensity. This schedule applies to a regional model or global model that is integrated each 6 h. For a global model that is only integrated at 00 UTC and 12 UTC, the guidance is about 6 h old for the 06 UTC and 18 UTC tropical cyclone forecasts, but is about 12 h old for the 00 UTC and 12 UTC forecasts. This requirement for timeliness is why the proposed USWRP operational model must be integrated four times a day. Because the data assimilation systems are designed to be dependent on the rawinsondes for vertical consistency, the four times continue to be 00 UTC, 06 UTC, 12 UTC, and 18 UTC.

Since the proposed USWRP model is regional, it has to be embedded in a global model in either a nested grid arrangement in which the global model prediction provides the lateral boundary values, or in an adaptive grid model with high resolution focused on the tropical cyclone but with the remainder of the globe having much coarser resolution. A significant issue arises when more than one tropical cyclone exists. Should the regional model have a domain that is large enough to contain two (or more) cyclones simultaneously, or should the nested grid model be integrated two (or more) times focusing on each cyclone in turn? The operational GFDL hurricane model is run separately for each cyclone. If the two cyclones are close enough that they are interacting (which is rare in the Atlantic region), it would be better to have both cyclones well-resolved in a single, simultaneous integration of the model.

a. Operational model characteristics

In the discussions at the Workshop, which involved groups from several nations, the design of the minimally-acceptable model evolved from a comparison with the highly desirable research model described in section 3. That is, it was realized that the computer resources (and research needs and observational requirements) would not be available within five years to integrate operationally the highly desirable research model. The approach was thus to make compromises relative to that model to consider what operational model characteristics might be possible in 3-5 years that would provide guidance to achieve the targets for intensity and precipitation prediction. Similar to section 3, the characteristics of a number of operational models will be given in Table 2 to provide a perspective relative to the proposed USWRP operational model.

It is noted that a separate Workshop was held on 29-30 May 2002 to consider specifically the implementation of the Hurricane version of the Weather and Research Forecast (WRF) model as an operational model at NCEP. The Hurricane WRF is being planned as the replacement for the GFDL Hurricane model in the 2006-2008 timeframe. The reader is referred to that Workshop report for the planning processes and key issues that are related to tying the operational model development to a specific model (WRF) and at a specific center (NCEP). One such consideration at an operational center is to have a "unified model" infrastructure in which similar dynamical cores, moisture and frictional representations, and other model components are used for ease of maintenance and support. By contrast, the discussion at the San Diego Workshop was more generic in the sense that no specific model framework or specific operational center was presumed. This seems appropriate at this time since alternate dynamical cores for WRF are still being considered, even a stationary nested version of WRF is not available, and a moveable nested WRF may not be available for more than a year. Thus, advancements toward a generic USWRP operational model will need to proceed with the available models as in Tables 1 and 2 until the Hurricane version of WRF is more mature.

Table 2a. Summary of basic characteristics of existing operational or quasi-operational models for tropical cyclone wind structure (intensity) and precipitation prediction, and the proposed USWRP minimally-acceptable operational model (see text for explanation of the various entries).

Organization	**Name**	**Hydrostatic?**	**Grid Type**	**Time Differencing**
NRL	COAMPS	No	Arakawa-C	Leap-frog/Split
CWB-1	TFS	Yes	Arakawa-C	Leap-frog
CWB-2	NFS	No	Arakawa-C	Split-explicit
GFDL	GFDL 2002	Yes	Arakawa A	Euler backward
AFWA	MM5	Yes	Arakawa-B	Leap-frog
JMA	TYM	Yes	Spectral	Semi-implicit
Penn State	MM5 (3.0)	No	Arakawa-B	Leap-frog
BMRC	TC-LAPS	No	Arakawa-A	Explicit (2 level)
USWRP	Operational	No	Arakawa-C	TBD

Table 2a is similar to Table 1a in describing some basic model characteristics based on information provided by various operational centers. The exception is Penn State University, which is not an operational center but integrates the MM5 model for Atlantic hurricanes in near-real time. The Air Force Weather Agency (AFWA) does operationally run the MM5. The forerunner GFDL model has been run operationally at NCEP for Atlantic and eastern/central North Pacific cyclones since 1995, and a version of this model is integrated at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for tropical cyclones in the other regions. The Naval Research Lab (NRL) has implemented tropical cyclone initial conditions in the various Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) regional applications integrated at FNMOC. Table 2 also contains information on two models at the Central Weather Bureau (CWB) in Taiwan, the Typhoon Model (TYM) at the Japan Meteorological Agency (JMA), and the TC-Limited Area Prediction System (TC-LAPS) at the Australia Bureau of Meteorology. The latter models are for western North Pacific tropical cyclones or Australia (Table 2b), but the commonality of conditions for operational prediction makes this information useful.

One distinction from the non-hydrostatic research models in Table 1 is that the current operational models in Table 2a are mostly hydrostatic. The exceptions are the COAMPS, the Non-hydrostatic Forecast System (NFS) labeled CWB-2, and the Penn State MM5. As the USWRP minimally-acceptable operational model will have a horizontal resolution of 4 km (Table 2b), it is inappropriate for the model to be hydrostatic.

Three grid arrangements (Arakawa A, B, and C) have been utilized for the operational models in Table 2a. Whereas it is likely that the WRF model will have an Arakawa C grid arrangement, this is the grid type listed for the USWRP operational model in Table 2a. Whatever the grid arrangement, it is important that high-order advection be included to ensure mass and energy conservation in the prediction.

Although the MM5 models in Table 2a use simple leap-frog time differencing, the other operational models tend to have more accurate and/or efficient time differencing schemes. A dynamical core for WRF has a semi-Lagrangian time differencing that allows a much longer time step, and thus is more efficient. As the semi-Lagrangian technique has not been applied to hurricanes, it remains to be demonstrated whether the solutions along trajectories in the strongly curved, high-wind region of the eyewall will still allow the longer time steps. Because of the need to maintain accuracy and conservation properties, the USWRP entry in column 5 of Table 2a is to be determined (TBD).

As described in section 2, the physical processes involved in tropical cyclone wind structure (intensity) change and precipitation require at least a 4 km horizontal resolution in the USWRP minimally-acceptable operational model (Table 2b). This inner-region horizontal resolution is proposed to be achieved by a triply-nested grid of 36 km, 12 km, and 4 km in which at least the inner two grids move with the storm. The CWB-2 and Penn State models are already close to this horizontal resolution. The GFDL model inner grid has a resolution of 0.17° lat. by 0.17° long. Although tests are being made at GFDL to decrease the grid size by a factor of two, this would approach the limit at which the model should be non-hydrostatic as in the COAMPS, CWB-2, and Penn State models (see Table 2a).

As described in section 2a, the outer domain has to be quite large to allow the environmental effects to be contained within that domain, and allow hurricane forecasts to be extended to 120 h without the system approaching the lateral boundary. Experience with the GFDL model suggests that a 75° long. by 75° lat. domain should be adequate for 120 h forecasts (Table 2b). The CWB-1 model has a relatively coarse inner grid but quite a large outer domain. Other models have smaller domains for reasons of computer resources or efficiency. These same considerations led to the specification of a minimum size outer domain of 50° long. by 50° lat. for the proposed USWRP operational model. Considering that the horizontal resolution of the global model that will be providing the lateral boundary conditions (see Table 2c) is only a factor of two larger (the AVN model resolution after 15 July 2002 will be T254 or ~55 km), the outer domain does not have to be so large if it is moveable within the global model.

Table 2b. As in Table 2a, except for space and time characteristics of operational models.

Organization	Regions	Horizontal Grids	Domain (x, y) Outer nest	Vertical Levels	Time Interval
NRL	Various	81x 27x9 km	Various	30	48 h-72 h
CWB-1	NWPAC	45 x 15 km	10305x8145 km	30	72 h
CWB-2	NWPAC	45x15x5 km	8595 x 5715 km	30	72 h
GFDL	Various	55 x 16 km	75° x 75°	18	120 h
AFWA	Various	45 x 15 x 5 km	Various	41 or 31	72 h
JMA	NWPAC	24 km	7504 km square	25	84 h
Penn State	Atlantic	45x15x5 km		Varies	72 h
BMRC	Various	180x180x15 km	120°, 82°	19	72 h
USWRP	Atlantic	36x12x4 km	50°, 50°	60	120 h

Another stringent requirement based on the convective and frictional processes in the tropical cyclone (see sections 2b and 2d) is to have many levels in the vertical. The GFDL model only has 18 levels and other operational models have up to 30 levels. The requirement to resolve well the atmospheric boundary layer, the outflow layer, and around the freezing/melting layer suggests that the proposed USWRP operational model should have 60 levels (Table 2b). However, relaxing this vertical resolution requirement may be one of the trade-offs that might be necessary for given operational computer resources and time constraints.

Most of the operational models in Table 2b are integrated to 72 h. The exception is the GFDL model, which has recently been extended to 120 h. As indicated above, this 120-h integration is possible given a large outer domain. Since the NHC and other forecast centers are planning for 120-h forecasts, this is the requirement for the proposed USWRP operational model (Table 2b).

Each of the operational models in Table 2c is tied to a global model for the initial environmental conditions. This linkage is appropriate when the most complete data assimilation system is the global system that incorporates all data types and especially the satellite data streams. Since the primary focus of the proposed USWRP operational model is for Atlantic tropical cyclones, it is anticipated that the environmental fields will be provided from the Aviation (AVN) model that is used now for the operational GFDL model.

One problem with the global data assimilation techniques is that the initial conditions near the tropical cyclone do not incorporate well the hurricane reconnaissance observations that will be included in the proposed USWRP operational model on a horizontal scale of 4 km and at 60 levels in the vertical. Thus, special development of a data assimilation system appropriate to the hurricane must be pursued (see below). The strategy for providing the initial conditions near the tropical cyclone is either a regional update cycle (usually an optimum interpolation – OI) or a nudging toward the observed vortex structure at the warning position. The exception is the GFDL model that has used an axisymmetric spinup vortex and asymmetries from a prior integration. At this stage, it is likely that the proposed USWRP operational mode will have a three-dimensional variational (3DVAR) assimilation system (Table 2c).

As these are regional forecast models, the lateral boundary conditions must be provided from interpolating in space and time the values on the boundaries from an integration of the larger scale model (Table 2c). For consistency, these boundary conditions are extracted from the same model that provides the initial environmental conditions (see above). In the proposed USWRP operational model for hurricanes, the AVN predictions will naturally be used.

Nearly all of the operational models in Table 2c supply the boundary conditions around the nested grids by relaxation or some form of blending of the values derived from the next larger grid model integration in what may be described as a one-way influence. A more efficient communication between the nested grids is provided by two-way interaction, because this method allows energy, momentum, and heat generated by the tropical cyclone on the inner-most grid to pass outward to the next grid. Consequently, the nested grid interfaces can be closer than in the one-way influence approach in which the boundary value from the outer grid integration is not consistent with the stronger inner grid representation of the tropical cyclone. To avoid this inconsistency with one-way influence, the grid interfaces must be removed far from the cyclone. With two-way interaction, the fine grid domains can be smaller, which saves computer resources since a large fraction of computing is on the fine grid. This two-way interaction capability is a prime reason that the GFDL model has been able to run with high resolution near the tropical cyclone and yet have a large outer domain. Consequently, the proposed USWRP operational model should incorporate the two-way interaction approach for all of the inner nested grids. These inner grids should be programmed to move with the tropical cyclone to keep the inner-core circulation well within the finest scale inner grid.

Table 2c. As in Table 2a, except for provision of initial conditions and boundary conditions, and possible wind-wave and ocean coupled models.

Organization	Initial Field	Regional Analysis	Lateral External	b. c. Nested	Wind Wave ?	Coupled Ocean ?
COAMPS	COAMPS	Update OI	NOGAPS	One-way	No	Fixed SST
CWB-1	Global	OI	Global	One-way	No	Fixed SST
CWB-2	Global	OI	Global	One-way	No	Fixed SST
GFDL	AVN	Spin-up	AVN	Two-way	No	URI (POM)
AFWA	AVN	OI	AVN	One-way	No	Fixed SST
JMA	Global	Bogus	Global	One-way	No	Not yet
PSU	AVN NOGAPS	Nudging	AVN NOGAPS	One-way	No	Fixed SST
BMRC	LAPS	Nudging	LAPS	One-way	No	Fixed SST
USWRP	AVN	3D VAR	AVN	Two-way	TBD	TBD

A conclusion from the discussion of wind-wave coupling in sections 2d – 2e is that the proposed USWRP model needs to include a coupled ocean surface wave model. None of the operational models in Table 2c have such a coupled wave model, although the GFDL winds are used to drive the NCEP Wavewatch III wave model off-line. Since additional research validations at the University of Miami (see section 3) of the Wavewatch III model appear favorable, it is reasonable to expect that Wavewatch III is a viable candidate for the proposed USWRP operational model (Table 2c). The developer of Wavewatch III (Hendrik Tolman) has indicated it is possible to develop a version of the ocean wave model that would move with the hurricane, which would be more efficient because it then solves for the waves at high resolution only under the hurricane, and perhaps near the islands. The propagation of the longer waves (swell) ahead of the hurricane would still be adequately resolved on a more coarse grid away from the hurricane. It is expected that further research studies with this wave model will extend its applicability to higher frequencies to address the shorter waves that are most influential for the interface fluxes.

The requirement for a coupled ocean model was described in section 2e. Only the operational GFDL model presently is coupled to a ocean model, which is the Princeton Ocean Model (POM) adapted for this application by the University of Rhode Island (Table 2c). The remainder of the operational models in Table 2c use a fixed SST field during the integration, so that the presence of a cold wake under and trailing the hurricane is not included. As a minimum, a loosely coupled ocean model could be used in an off-line cycle of analysis and a forecast with forcing from the known hurricane conditions during the 12 h prior to the initial time, and then using this representation of the SST distribution fixed in time during the hurricane model integration. In addition to the fully three-dimensional version of the POM, other ocean models that might be considered include the GFDL MOM, the University of Miami HYCOM, and the NCEP ocean model under development. A moveable, high-resolution ocean model on the same horizontal scale as the hurricane model should be embedded in the large-scale ocean model whenever a hurricane exists. The parameterization of the entrainment mixing at the base of the mixed layer is crucial if the correct SST distribution is to be provided the hurricane model.

Given the ocean interface fluxes of moisture, heat and momentum, the most critical aspects of the hurricane model are likely to be the physics representations of how those properties are then re-distributed, and these are the focus of Table 2d. Each of the operational models has horizontal diffusion to suppress computational noise, but this diffusion will also prevent frontogenetic regions such as the eyewall from shrinking to an infinitesimal scale. As described in section 2c, real physical mechanisms such as the eyewall mixing events also limit the extreme radial shear of the tangential winds near the eyewall. Since these mixing processes are assumed to be on the resolvable scales, the inclusion of the fourth-order horizontal diffusion in the proposed USWRP operational model in Table 2d is primarily intended to suppress computationally generated noise.

Table 2d. As in Table 2a, except for various aspects of the physics representations in the operational models.

Organization	Horizontal Diffusion	Cumulus Convection	Explicit Moisture Type	Ice Micro-Physics	PBL	Land Surface
COAMPS	4^{th} order.	Kain-Fritsch (> 10 km)	Rutledge-Hobbs	Ice only	Mellor-Yamada TKE	Single layer
CWB--1	4^{th} order	Kuo	None	None	TKE-ε	Bucket
CWB-2	4^{th} order	Arakawa-Schubert	Zhao	Simple ice	1.5 TKE-ε	Single layer
GFDL	Smagorinsky	Convective adjustment	None	None	Mellor TKE	Single layer
AFWA		Grell (> 5 km)	None	None	MRF	5 layer
JMA	4^{th} order	Arakawa-Schubert	None	None	2.0 level Mellor	4 layer
Penn State	?	Kain-Fritsch (> 5 km)	Goddard	Ice	MRF	?
BMRC	2^{nd} order	TiedtkeEC mass flux	None	None	ECMWF	4 layer
USWRP	4^{th} order	TBD	TBD	TBD	TBD	TBD

As mentioned in section 2b, considerable discussion occurred at the Workshop about the desirability of cumulus convection parameterization in such high-resolution models. Clearly, the 4 km inner grid should have an explicit moisture treatment. It is less certain that the 12 km grid should also have explicit moisture, or whether it is acceptable to have cumulus parameterization. The common experience is that the precipitation spinup period at the beginning of an integration is dominated by the convective parameterization until the grid box becomes saturated. Subsequent precipitation at that grid box tends to be dominated by the explicit moisture treatment with little or no convective precipitation. This transition to saturated ascent tends to rapidly increase the precipitation and net latent heat release in the column, and thus lower of the surface pressure. Whether such a discrete transformation in precipitation type occurs in nature, and perhaps contributes to rapid deepening as in the model, is unclear.

The original application of the cumulus parameterization schemes in the operational models in Table 2d was not intended for grid scales of 20 km or less. Some new treatment of the parameterization technique for the 12 km grid may be required. It is uncertain which parameterization technique might be best on this grid, or even on the 36 km grid where parameterization is more appropriate, so the entry for the proposed USWRP operational model is to be determined.

Most of the operational models in Table 2d do not have an explicit moisture treatment as the horizontal grid sizes are too large. Likewise, only two of the models include ice microphysics. Little guidance is available from the research models in Table 1d as to the most appropriate explicit moisture treatment or the number of water and ice species that must be included. Such decisions will affect how much of the rain will be convective and how much will be stratiform. Another physical process that may be important during the course of the 120-h integration is cloud-radiation feedbacks, in which the number and distribution of various ice crystals is an important factor. While this is not likely to be an important physical process in the inner core of a mature tropical cyclone, it may be important during the formation stage. Until further guidance is gained from studies from the research models described in Table 1d, the appropriate entries for the explicit moisture treatment and ice microphysics columns in Table 2d are to be determined.

The atmospheric or planetary boundary layer (PBL) is a critical region within the tropical cyclone as the heat, moisture, and momentum fluxes pass through the boundary layer (see sections 2b, 2c, and 2d). A variety of PBL schemes have been used in the operational models in Table 2d. Model sensitivity tests to the PBL schemes such as by S. Braun of NASA indicate large differences in the predictions. This is not surprising as the convective schemes are intimately tied to the PBL schemes, so these aspects need to be considered together. One advantage of the 4 km operational model versus the 1 km research model is that a horizontal grid size of 4 km does not resolve the eddies that transport heat, moisture, and momentum in the PBL. Thus, such a model is not in the "no-man's land for frictional processes." Various frictional parameterizations developed for larger scales should be extendable into the range of 4 km, whereas the 1 km research model will require a new formulation. However, the PBL entry for the proposed USWRP operational model in Table 2d is still to be determined by intercomparison of the various schemes.

A final model characteristic is the coupling to the land surface model described in section 2f. The operational models in Table 2d have simple representations of the land surface. A land surface model called NOAH that has been developed by a consortium of government and academic groups is being tested for possible inclusion in the GFDL hurricane model. These tests may provide more guidance on how complex of a land surface model is needed to properly predict the inland wind structure decay and precipitation. A tradeoff between land surface model complexity and improved model performance remains to be determined for the proposed USWRP operational model.

b. Some data assimilation considerations

An operational model must have a data assimilation system to provide the initial conditions that is consistent with the background model structure and error characteristics, fits the observations, and has appropriate dynamical balances. In the complete system described in section 4a, a data assimilation technique would be required for both the atmosphere and the ocean model components. At the Workshop, it was assumed that the ocean surface wave model would quickly adjust to the wind field, so the specification of the initial surface wave distribution was assumed to be an adjustment of the distribution from the short-range forecast. Similarly, the initial land surface model initial conditions would be from the conditions after a short-range forecast since few new observations would be available for a true data assimilation approach.

Whereas the development of a data assimilation system for the ocean was recognized as an issue, experts in that topic were not present, so that components of the data assimilation will not be discussed here. One of the ocean modeling and data assimilation issues is the special considerations that will be required in coastal areas during hurricane landfall. The hurricane model needs to be provided accurate SST distributions from the ocean model in this region where the wind structure (intensity) is changing rapidly. This coastal margin is difficult to model. One advantage for the ocean data assimilation is that some areas have coastal radars that will provide dense ocean surface current measurements, albeit over a limited domain. A general problem to be considered when the ocean model is coupled to the hurricane model is that the data assimilations must also be coupled to avoid mismatches in the SST distribution that is important to both model forecasts.

The primary focus then was some general considerations on the data assimilation for the hurricane core region. As was indicated in Table 2c and the associated text, the initial conditions for this vortex region in the operational models have been provided with a regional update approach that blends in whatever rawinsondes or dropwindsondes that might be available along with the satellite water-vapor and cloud-drift winds. However, the primary source of information on the vortex structure and location is usually synthetic observations in the form of pseudo-rawinsondes that are generated from the tropical cyclone forecast center warnings. These synthetic soundings are usually just for the winds and the corresponding mass and temperature fields are either balanced or allowed to develop during the course of the integration. The specified vortex is usually symmetric with the only asymmetry being generated when an estimate of the environmental flow is added, which may include an adjustment to ensure a near-agreement with the recent storm motion. In the case of the operational GFDL, the symmetric part of the vortex is spun-up from a two-dimensional version of the prediction model while the wind structure from the warning message is being held fixed. The asymmetric part of the flow is extracted from the previous integration and placed relative to the new storm location. This procedure uses little information from aircraft flight-level data, dropwindsondes, or radar information except as might be implied in the warning message wind structure.

While these procedures have been helpful in improving tropical cyclone track prediction guidance, they are inadequate for wind structure (intensity) change and precipitation prediction to meet the targets established for the USWRP operational model. What is required is an advanced mesoscale data assimilation to provide the initial conditions in the inner core region. This means observations (with their error characteristics) must be provided, the background model forecasts (and its error characteristics) must be available, and some appropriate form of balance must be specified. It is noted that no data assimilation system is presently available for the WRF model. Thus, this aspect was a crucial item for the Hurricane WRF Workshop, and the reader is referred to that Workshop report for more information on data assimilation.

The primary focus at this Workshop was on the observations that are required, and what might be available in the inner core. In order of importance, the required observations are of wind, moisture, temperature, and pressure. On the environmental scale, remotely sensed fields from satellites will continue to be the primary data source. The Quikscat provides important surface wind structure, although it is uncertain to what wind speed these estimates are accurate. The microwave sensors (e.g., the Advanced Microwave Sounder Unit) provide new temperature and humidity information, and will possibly provide microphysical properties. For each of these sensors, a forward model must be derived that converts the model variables to an equivalent sensor-measured parameter (e.g., radiance or brightness temperature), and this can require one to two work-years each.

On the vortex scale, the *in situ* observations will be critical if the specification of the initial conditions is to be improved over the synthetic observation approach described above. A distinction is made between the three types of aircraft that will provide these *in situ* observations. First, the U. S. Air Force reconnaissance aircraft provide flight-level observations and dropwindsondes, but do not have meteorological radars. Second, the NOAA Gulfstream 4 is presently a surveillance aircraft that only provides flight-level observations and dropwindsondes in the environment of the hurricane. However, plans are made for the Gulfstream 4 to be able to fly over the inner core and provide dropwindsonde coverage. In addition, mounting a meteorological radar on the Gulfstream 4 would provide new information (see Hurricane WRF Workshop report for these plans). Third, the only aircraft that can presently provide radar reflectivity and Doppler radial winds along the flight tracks are the two NOAA WP-3D aircraft. The satellite data communication capability of these planes is being improved so more of these radar reflectivity data will be able to be transmitted. However, these are research aircraft rather than reconnaissance aircraft. Thus, an implicit assumption in this discussion is that the WP-3D aircraft are going to be tasked (and funded) to provide real-time fields, but this is likely to occur only during eminent hurricane landfall events. For other times, the only *in* *situ* observations are likely to be the Air Force and Gulfstream 4 flight-level and dropwindsondes. Far from land, even these aircraft data will not be available, which is the typical situation for the rest of the tropical cyclone regions other than the Atlantic (and occasionally the central North Pacific around Hawaii).

The WP-3D Doppler radar radial wind profiles will be easier than the radar reflectivity to assimilate in the model. Although the radial winds will have to be put in a storm-relative moving coordinate, and even though it takes some time for the aircraft to map out the storm structure in all quadrants, the winds are a model variable so constructing an appropriate forward model will be relatively straight-forward. The radar reflectivity will require a more complex forward model, and the need to be in the storm-relative coordinates with uncertainty in the storm translation will add complications. The Scanning Radar Altimeter onboard the WP-3D will provide some rain rate estimates (up to a saturation rate) that will supplement the radar precipitation estimates. The WP-3D also have microphysical measurements and both a scatterometer and stepped frequency microwave radiometer (SFMR) for detecting surface wind fields. Again, forward models will have to be derived to incorporate these measurements in the data assimilation process.

In summary, the observations necessary to specify the inner-core vortex structure are limited unless the WP-3D data are available, or the Gulfstream 4 is able to overfly the center and is equipped with a meteorological radar and an adequate broadband communication system. Considerable effort will be necessary to incorporate these aircraft observations in a data assimilation system.

c. An alternate strategy for probabilistic forecasts

Nearly all of the discussion above has been focused on a deterministic approach to forecasting the intensity and precipitation. Considerable uncertainty exists as to the length of time that these variables can be deterministically predicted. It was noted in section 1c that an alternate approach might be to make probabilistic forecasts that the intensity will exceed certain thresholds, or be in each of the Saffir-Simpson categories. Likewise, probabilities of the storm-total rain exceeding specified threshold values over a river basin could be a useful product for flood forecasting guidance. Indeed, the National Weather Service has a strategic goal to be issuing their forecasts in terms of probabilities.

An alternate strategy then might be to develop an ensemble prediction system specifically designed for tropical cyclone wind structure (intensity) change and precipitation prediction. Because this topic was not discussed extensively at the Workshop, only a few considerations will be presented here.

A common ensemble prediction approach for midlatitude synoptic forecasting is to assume the model is quite accurate and the major source of uncertainty is in the initial conditions, so that ensemble members are created by adding positive and negative perturbations to the initial analysis. Such a "perfect model" assumption has not been shown to apply for tropical cyclone intensity and precipitation predictions; indeed, the existing models have significant biases that would invalidate the common assumption in ensemble prediction that the model errors are randomly distributed around a zero mean.

A second useful approach for ensemble prediction is to also perturb the model physics by using different physics parameterizations. Thus, a combination of different model variations and perturbed initial conditions is used to form the ensemble system, and this approach is generally superior to only perturbing the initial conditions. This approach would seem to be quite appropriate for the tropical cyclone models considering the uncertainties in the physics representations discussed in sections 3 and 4.

Thus, one could envision an ensemble prediction system that would consist of an initial condition perturbation generation to represent the analysis uncertainty and also multiple variations of the model physics. The practical issues include: (i) How to generate the perturbed initial conditions appropriate for tropical conditions so that a good representation of error growth in unstable regions is predicted; (ii) How many members must be included to adequately represent the probability density function of the initial condition uncertainty? (iii) What physics representations should be perturbed, and how should they be perturbed? and (iv) How to post-process the model integrations to minimize the impacts of systematic under-prediction of intensity or precipitation?

The operational constraints of limited computer resources and the need for timeliness will be the primary determinants of the proposed ensemble system. If the ensemble is to be available in a timely period, the prediction model must be degraded relative to the single highest resolution, most sophisticated physics, deterministic model run at the forecast center. The more ensemble members to be included, and the more model physics representation variations that are to be included, the more compromises in horizontal (and perhaps vertical) resolution must be made if the ensemble prediction is to be available in time to still be useful to the forecaster. As an example, consider that an increase in horizontal grid size by a factor of two with the same domains would allow eight such degraded models to be integrated in the same time period as the deterministic model. However, an ensemble of only eight members is not adequate for representing the initial condition uncertainty, let alone the model physics variations that will be required for this problem. If then the horizontal grid size is degraded by a factor of three or four to allow the number of ensemble model integrations that might be necessary, the question is then how useful are these individual ensemble model integrations? Given that the 4 km horizontal resolution model and various physics have been considered here to be minimally acceptable, will a considerably degraded horizontal model still be useful? If the deterministic model does not contain fully adequate physics to represent the precipitation processes, would an even more degraded model have a useful precipitation distribution for ensemble prediction?

The answers to these questions probably depends on the extent to which the environmental conditions determine the intensity or precipitation. Whereas the environmental forcing may trigger circulation changes that ultimately result in intensity changes, the timing and magnitude of these changes may well be determined by mesoscale dynamics that will not be predicted well by lower resolution ensemble members. Recall from section 2b that the outer circulation contributions to precipitation appear to be similar for a variety of storm intensities, and only the inner region precipitation maximum varies strongly with intensity. Thus, well-designed ensemble members may provide useful probability of precipitation information even from relatively low-resolution model integrations. Some type of post-processing that would enhance the magnitudes near the center may provide a partial solution. Ultimately, the benefit to be gained from such an ensemble mean plus spread needs to be measured against the cost of a limited number of ensemble model integrations of varying resolutions.

Because of the great expense in integrating all the ensemble models, the economical alternative is the so-called “poor man’s ensemble.” In this approach, the predictions of the best model from a number of forecast centers are collected. A consensus of these model predictions is then formed either objectively or subjectively, and the agreement or spread among the predictions is used as a measure of the likely uncertainty. This approach presumes a number of skillful forecasts run for the same storm, and that these forecasts will be shared in a timely manner. In the same sense that each forecast center prepares a slightly different initial analysis from essentially the same observation base, and a different model is being integrated, this consensus approach has some characteristics of an ensemble prediction system with perturbed initial conditions and multiple models. Of course, the number of consensus members is much smaller than in an ensemble prediction system. However, the sophistication of the best deterministic model from each center is likely to be greater than in degraded models that are typically used in ensemble systems. The biggest advantage of this approach is that the only cost is the communication system for acquiring the predictions, which is a reason it is referred to as a “poor man’s ensemble.” Given the number and variety among the models in Tables 1 and 2, this approach could be explored. Such an approach also requires an alternate strategy to putting all one’s efforts into developing a single analysis/forecast system, and suggests an approach featuring diversity and cooperation among centers.

d. Forecaster requirements and guidance to modelers

The primary target for improved tropical wind structure (intensity) guidance for the Atlantic is the National Hurricane Center (NHC), which is tasked to prepare warnings that are then also used as guidance for the Department of Defense and many other agencies. In the case of precipitation over the U.S., the Hydrometeorological Prediction Center (HPC) becomes the primary customer and they work with the River Forecast Centers (RFC) and the affected local National Weather Service offices. Only forecasters from NHC and the Joint Typhoon Warning Center were represented at the Workshop. If HPC and RFC forecasters had been present, more discussion of the need to couple with hydrometeorological models might have occurred.

These forecasters were asked to prioritize what guidance they would most desire from the proposed USWRP operational model. Perhaps not surprising in terms of the NWS strategic goal mentioned in section 4c above, the first priority was guidance products that would allow them to issue probabilistic forecasts to five days. That is, guidance is needed on the expected range of maximum wind speeds and rainfall totals in the tropical cyclone. As mentioned in section 4c, the guidance could be the probabilities of exceeding intensity or rain thresholds at specified times. If the ensemble approach described in section 4c is to become the guidance for generating probabilistic forecasts, the forecaster needs to be provided with an assessment of the capabilities and limitations of the ensemble approach, whether one prediction model or several models is to be utilized. How much reliance can be placed in the outliers in the ensemble in projecting the "worst-case scenario?"

Key issues for the forecaster will be the communications to receive the high-resolution model outputs, and how this information can be visualized and comprehended by the forecaster in the limited time available for evaluation and decision. A "forecaster-friendly" display capability will be required to extract specific fine-mesh graphics or subsets of the full grid. Some examples include time series of the maximum wind and its location, vertical cross-section displays at selected times, etc. This guidance would be most useful if it is provided in a format compatible with the existing operational display system.

A third requirement is the facility to view the inner core structure from the model prediction, and especially wind structure changes during rapid intensification or rapid decay events that are particularly difficult to forecast. These cases usually involve environmental wind shear that is either favorable or unfavorable and the key issue is if (and when) the inner core wind and precipitation will be affected. The forecasters need more observations of the storm inner core during such events and knowledge about the accuracy of the model in predicting the changes (and timing). The vertical cross-section capability mentioned above would be one tool that the forecaster might be able to detect the vertical tilt of the vortex during decay scenarios.

It is emphasized that a "learning period" is involved when a new model is introduced, or when significant model upgrades are made prior to the beginning of the season. A well-designed series of model tests with a variety of important forecast scenarios can help the forecaster understand more quickly the expected performance (and limitations) of the model. This request for guidance on when the model prediction will be good or not good is referred to by the NHC forecasters as "guidance on guidance."

The model wind forecasts should be evaluated relative to an operational analysis (or a prototype product such as the HWind fields generated by the Hurricane Research Division). Carefully constructed, post-storm verification data sets with dropwindsondes, satellite winds, and precipitation distributions should be made available to the modelers. The verifications should be for a number of difficult forecast scenarios: (i) Trough-tropical cyclone interactions; (ii) Intensity changes near landfall; (iii) Inland heavy precipitation events associated with slowly moving cyclones after landfall; (iv) Concentric eyewall cycles; (v) Rapid intensification; and (vi) Rapid decay. The forecasters are prepared to assist in case study selection for each of these scenarios (e.g., Debby in 2001, Allison in 2001, Mitch in 1999, and Floyd in 1999 immediately come to mind).

Research model cases that are both successful and unsuccessful relative to operational model or statistical guidance are of interest to help the forecaster understand and better utilize the new model. Reliability, both in consistent performance in each scenario and in availability for all forecast cycles, is an important consideration for the forecaster. In general, recent cases should be included in the verifications so that the latest data sources (e.g., microwave satellite observations, the Global Positioning System dropwindsondes, etc.) are utilized. Historical cases may be less relevant in helping the forecaster to understand and utilize the model guidance in today's conditions.

5. Prioritization – Showstoppers and most difficult tasks

The Workshop attendees were polled as to what they felt would be "showstoppers" (i.e., an item or task that if not done well, the project would fail) and those most difficult tasks that will require special attention. While such a survey may be criticized as to sampling limitations, summaries of the responses are given in Tables 3 and 4 that might provide guidance as to prioritize the future program. Because these were free-form responses, the items have been grouped into similar categories. The research tasks are separated from those necessary to create an operational model capable of meeting the minimally-acceptable targets for tropical cyclone intensity and precipitation prediction.

a. *Research*

The research topic receiving the largest priority is that related to knowledge of the frictional boundary layer and ocean surface wave processes in the high wind conditions of hurricanes. These high winds occur on a scale of 5-10 km and thus require models with horizontal grid spacings of 1-2 km, which puts the models in the "no-man's land" relative to resolving the vertical fluxes of moisture, heat and momentum in the boundary layer. A paradigm shift is required from the treatment of the frictional processes via turbulence parameterizations for models with horizontal grid spacing of greater than about 5 km. On horizontal scales of 1-2 km, the model is partially resolving explicitly the large eddy circulations that are accomplishing the vertical transport that is being parameterized in the larger scale models. However, the representation of turbulence in even a 1 km model is going to be too smooth (not as random and chaotic as the real turbulent eddies), and thus the real vertical transport will be under-estimated. Including a turbulent mixing parameterization derived from Large-Eddy Simulations (LES) for the subgrid scale is one approach. However, then a double-counting of the turbulent vertical transports may occur as the 1 km grid is directly resolving some of the transport. This appears to be a fundamental problem and may indeed be a showstopper, as represented by the counts in Table 3a.

A related research need is a better understanding of the generation, size droplet distribution, and effects of sea spray in the vertical fluxes of moisture, heat and momentum in high wind and wave conditions. Because of the complexity of competing physical processes of heat and moisture exchange between spray droplets and the air, and the lack of observations, this is also a fundamental problem. Generation of sea spray is intimately tied to breaking surface waves, so an understanding of wave generation and breaking in high winds is needed. Fortunately, the Office of Naval Research has sponsored the Coupled Boundary Layer Air-Sea Transfer (CBLAST) program to address these questions.

Table 3. Combined summary of the research-related "showstopper" and "most difficult tasks" (first and second numbers in parentheses) based on groupings of survey responses from Workshop participants.

a. (8 + 7) Insufficient knowledge of the frictional and ocean surface wave processes in the high wind regions, which includes properly handling the vertical transports on horizontal scales of 1-2 km, and lack of knowledge of sea spray and its effects.
b. (0 + 6) Insufficient knowledge of ice microphysical processes and how this contributes to the precipitation distribution and dynamics.
c. (5+0) Inadequate knowledge of the convective processes, which includes how outer convective rainbands are triggered and the effects of horizontal mixing processes between the eye and eyewall affect the dynamics.
d. (2 + 0) Inadequate understanding of vertical wind shear and other environmental effects that modify the convection and dynamics, and especially during rapid intensity change events.
e. (1 + 0) Insufficient knowledge of ocean mixing processes in strongly forced conditions.
f. (1 + 0) Inadequate knowledge of predictability for tropical cyclone intensity and precipitation.
g. (0 + 1) Restricted data availability for the research community at large to address the problems.

The second highest research priority (Table 3b) is the need for a better knowledge of the ice microphysical processes in the hurricane cloud system. This task is not considered to be a showstopper, perhaps because the problem has been recognized and model sensitivity tests are in progress. *In situ* observations have been collected in the CAMEX-3 and HL 2001 field experiments and these are being compared with the model distributions. Nevertheless, the treatment of ice microphysics is considered to be an essential aspect in prediction of precipitation from both the convective and stratiform regions of the tropical cyclone.

Various aspects of the convection (Table 3c) have been rated as potential showstoppers. First, the rainband convection and its associated downdraft modulate the properties of the inflow layer. Second, we know that contracting rainbands and concentric eyewalls modulate the wind structure, but we do not know what triggers these contraction events and the timing or rate of progression of the events. Third, horizontal mixing between the eyewall convection and the eye is hypothesized to fundamentally modulate the convective heat release and the dynamics of the maximum wind region. This mixing aspect depends on the air-sea fluxes in the eye and inflow layer (Table 3a) and on the triggering of vortex Rossby waves that redistributes the momentum and heat. Thus these highly nonlinear processes may be the fundamental factor in limiting the tropical cyclone intensity and precipitation predictability, and thus is definitely a potential showstopper.

A topic with intermediate priority is the understanding of how vertical wind shear and other environmental effects modify the tropical cyclone wind and cloud structure.

Perhaps this factor is not rated higher because some significant advances in understanding have recently been achieved. However, the sensitivity of the cyclone to the vertical wind shear is a function of the existing cyclone wind and cloud structure, which is a function of the atmospheric and oceanic boundary layer processes. Because of the nonlinearities involved, this could be a fundamental limitation or showstopper, and continued research is required.

The remaining items *e-g* in Table 3 are included for completeness. Item *e* on ocean mixing processes is related to item *a* because the oceanic response and feedback to the atmospheric boundary layer via the interface fluxes depends on an accurate knowledge of the upper ocean mixing processes. Item *f* on limits of predictability for intensity and precipitation have been mentioned above in connection with items *c* and *d*. However, this predictability question is related to items *a* and *b* as well. Indeed, we must advance understanding of all aspects of this complex, highly nonlinear phenomenon if we are to gain a better understanding of the limits of predictability. Finally, one participant felt that restricted data availability, perhaps limited only to those participating in a field experiment or other data collection effort, is a significant impediment to getting a wider involvement by the research community (Table 3g). Whereas the problem may also involve limited funding for research with these data sets, it is an impediment that the leadership should remove.

b. *Development of a minimally-acceptable operational model*

Table 4 is a similar summary of potential showstoppers and difficult tasks if a minimally-acceptable model for tropical cyclone intensity and precipitation prediction is to be developed. For many of these items it is assumed that advances in research understandings (Table 3) will be achieved that will provide a solid basis for model development.

A strong consensus of the participants felt that inadequate observations may be available to define the initial conditions even for the 4 km horizontal resolution, minimally-acceptable model (Table 4a). Specifically, an accurate definition of the horizontal and vertical structure of the eyewall region and the rainbands is a severe problem.

Whereas airborne Doppler radars are available on two NOAA research aircraft, such radars are not available on the U. S. Air Force reconnaissance aircraft. Limitations in aircraft communication bandwidth will be a limiting factor in utilizing the radar observations. The central dense overcast over the tropical cyclone prevents visible and infrared soundings from the geostationary satellites. Microwave sensors on the polar-orbiting satellites probe through the clouds, but these have inadequate horizontal and vertical resolution to initialize a 4-km horizontal and 60-level vertical resolution model. More importantly, the polar orbiter may only provide one or two overpasses per day.

A special initial data problem arises with a cloud-resolving model that has explicit moisture treatment with multiple water phases and ice species. Variables such as cloud water, rain water, snow, or ice in various forms require a specification of their three-dimensional distributions at the initial time, and these variables are not measured on a regular station network – let alone over the tropical oceans where tropical cyclones form. Even the few water vapor observations may be only representative of the immediate vicinity of the sounding. If indeed the model output is only as good as its inputs, the inadequate observations to provide accurate initial conditions may severely limit the intensity and precipitation guidance to be achieved.

Table 4. Combined summary of the "showstopper" and "most difficult tasks" (first and second numbers in parentheses) related to development of a minimally-acceptable operational model based on groupings of survey responses from Workshop participants.

a. (9 + 10) Inadequate observations to define the initial conditions, especially for mesoscale features on the eyewall and rainbands including the microphysical species, and also including accurate and representative humidity measurements, and then the communication bandwidth for transmitting aircraft and satellite remotely sensed observations to the operational centers.

b. (7 + 1) Inadequate data assimilation techniques to incorporate the existing and future atmospheric observations on the mesoscale, also data assimilation for the ocean surface wave and subsurface in response to hurricane forcing, and inadequate linkages and researchers to work with the operational centers in data assimilation.

c. (5 + 0) Inadequate computer resources at the operational centers within the next 3-5 years to develop even the minimally acceptable model.

d. (2 + 2) Inadequate transition of numerical model results to viable and sufficiently accurate tropical cyclone intensity and precipitation guidance products to achieve forecast accuracy goals, especially considering track accuracy deficiencies, or a means to account for uncertainties in track, wind structure, and precipitation via a probabilistic approach.

e. (0 + 3) Inadequate coastal ocean and land surface modeling capability to account for modifications of wind structure and precipitation during and following hurricane landfall.

Another daunting task (note seven participants indicated a potential showstopper for Table 4b) is the data assimilation technique necessary to incorporate existing and future atmospheric observations in the 4-km horizontal and 60-level vertical resolution model. Whereas data assimilation techniques for the environmental flow specification are being improved, special problems arise in the near-environment of tropical cyclones (e.g., treatment of rain flagged and high wind speeds, but with possibly incorrect directions, from Quikscat). How to utilize aircraft radar reflectivity and Doppler wind estimates in the hurricane inner core is a challenging problem. The problems of getting more data assimilation teams involved with operational center tools and data streams have been discussed in many fora. The problem may be more acute for the Hurricane Landfall program as hurricanes are rare and mobile aircraft radars must be treated.

Similar difficulties are forseen for the required ocean surface wave and subsurface data assimilation technique. While the local wave generation is a rapid response to the wind forcing, the interaction with the swell that was generated earlier is also a part of the ocean wave prediction problem. Because the subsurface ocean soundings are so rare, indirect estimates from satellite-based radar altimeters must be assimilated to keep the ocean circulation in the model from drifting away from reality.

Considerable skepticism arose among the Workshop participants when a preliminary estimate was generated of the computer resources necessary to integrate the minimally-acceptable operational model (Table 4c) – at least 64 times the present Geophysical Fluid Dynamics Laboratory model. This led to tradeoffs in the model design, but it remains a great challenge to acquire the computer resources to develop such a model, and then to run it operationally four times a day for each hurricane. As indicated in Table 4c, five participants saw this as a potential showstopper.

Only a few forecasters from the National Hurricane Center and the Joint Typhoon Warning Center attended the Workshop. While they would welcome numerical guidance for tropical cyclone intensity and precipitation prediction, this guidance must be timely and in a forecaster-friendly format. Consider a situation in which the wind structure and precipitation distribution is perfectly predicted, but the track is incorrect as to the landfall point. The inaccuracy introduced if the storm-relative wind and precipitation distributions are shifted is a serious concern of the forecasters. Guidance must be provided to the forecasters as to the accuracy, robustness, and reliability of the model in different scenarios. Since the NOAA/NWS has a goal to issue probabilistic forecasts by 2005, guidance in the form of probabilities is needed. Will ensemble prediction systems be available on this timeframe for tropical cyclone intensity and precipitation prediction? This item (Table 4d) is viewed as a potential showstopper or at least a difficult task.

Another difficult task is the provision of an ocean model that is accurate in coastal waters for hurricane landfall prediction. Similarly, the land surface model must provide an accurate representation of the surface fluxes of heat, momentum, and moisture as the hurricane comes ashore. The inland decay rate and the potential precipitation distribution depend on these surface fluxes. As some preliminary studies of improved land surface representations have been completed, this task is viewed as difficult (in part due to inadequate data to initialize the land surface model variables) rather than a potential showstopper.

APPENDIX A

WORKSHOP on NUMERICAL MODELING for TROPICAL CYCLONE INTENSITY and PRECIPITATION PREDICTION

AGENDA

Friday, May 3, 2002

1315 Opening – R. L. Elsberry
  Purposes
  Introductions

1330 Physical processes that must be addressed
J. Molinari – Environmental forcing and vertical shear effects
F. Marks – Convective scale processes for intensity and precipitation
M. Montgomery – Inner core vortex adjustments
K. Emanuel – Interface conditions including ocean surface waves, sea spray, etc.
N. Shay – Ocean heat content effects and subsurface ocean structure changes
M. DeMaria – Inland decay and precipitation.

1515 Break

1530 First breakout session to consider Environment, convective, dynamics, ABL, Ocean BL, Land-surface processes questions

Saturday, May 4, 2002

0830 Second breakout session with cross-fertilization with complementary topics

1000 Plenary session reports and discussion

1200 Lunch

1300 Third breakout sessions to design research and operational model configurations, required observations, data assimilation and initialization issues

1500 Fourth breakout session or plenary session