Proposal Cover Sheet

NASA Research Announcement 00-OES-06
Proposal No. _____________________ (Leave Blank for NASA Use)

Title: Evaluating Microphysical Parameterization Schemes for Use in Hurricane Environments

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Budget:
1st Year: $54,176 2nd Year: $52,093 3rd Year: $55,213 Total: $161,482

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- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications contained in this NRA [namely, (i*) Certification of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs*, *and (ii) Certifications, Disclosures, And Assurances Regarding Lobbying and Debarment & Suspension*].

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Signature: ________________________ Date: _________________

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Evaluating Microphysical Parameterization Schemes for Use In Hurricane Environments

Robert Black
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A proposal submitted in response to NASA NRA-00-OES-06

Duration: 3 years	Proposed Starting Date:	1 May 2001
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Evaluating Microphysical Parameterization Schemes for Use In Hurricane Environments

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PROJECT SUMMARY

The major objective of the work proposed here is to evaluate microphysical parameterization schemes currently available in three-dimensional primitive equation models using *in situ* and remotely-sensed data gathered by the NOAA P-3's and NASA DC-8 aircraft as a part of the CAMEX-4 field program. As a part of this evaluation, deficiencies in the parameterization schemes will be identified, and possible improvements will be developed and tested.

Current bulk ice microphysics schemes used in mesoscale numerical models consist of two, three, or four classes of ice. The current proposal seeks to investigate the assumptions underlying the development and conversions of the ice and water species predicted in these schemes by performing comparisons between high-resolution simulations of tropical cyclones using the Penn State/NCAR mesoscale model MM5 and *in situ* and remotely-sensed observations of microphysical properties from the NOAA P-3's and NASA DC-8. Specific validation techniques are proposed in an attempt to enable comparisons between the sampling provided by the probes and Doppler radar onboard the planes and the high-temporal resolution output provided by the model. Improvements in the microphysical scheme in the model will improve the specification of latent heating magnitude and distribution, which will improve forecasts of tropical cyclone intensity.

1. Background and statement of the problem

Forecasting tropical cyclone intensity remains a difficult task for the operational and research communities. Tropical cyclone intensity is dependent on many factors, such as the magnitude and direction of vertical shear within the storm core, sea surface temperature and oceanic mixed layer depth underneath the storm, and the magnitude and distribution of latent heat release within the storm circulation. High-resolution (grid length ≈ 1 km) numerical models have been used as a method for addressing these factors. Such high resolution obviates the need for the parameterization of deep convection, a traditional source of uncertainty in determining latent heating profiles. While convective parameterization is avoided using high resolution, the parameterization of microphysical processes such as hydrometeor production, conversion, and fallout, and their dependence on rainwater, ice and graupel distributions, assumes great importance in determining latent heating distributions and, ultimately, tropical cyclone intensity.

As a result of this sensitivity, the success of numerical simulations of tropical cyclones is to some extent dependent on how these microphysical processes are parameterized in the model. Such parameterizations range in complexity from a simple removal of supersaturation to spectral ice schemes that explicitly predict the size spectra of ice particles (Hall 1980; Farley and Orville 1986). Most schemes used in mesoscale and cloud-scale models today are bulk microphysical schemes that use two or three categories to describe the presence of ice. Schemes with two ice categories, called two-class ice schemes, have separate prognostic equations for cloud ice and precipitating ice, usually taken to be snow (Cotton et al. 1982; Hsie et al. 1984). More sophisticated three-class ice schemes have prognostic equations for cloud ice, snow, and a third class of ice that is formulated to be either hail (Lin et al. 1983) or graupel (Rutledge and Hobbs 1984). Recently a four-class ice scheme has been formulated (Ferrier 1994) that has separate equations for cloud ice, snow, graupel, and hail. The benefit of this scheme is that it is applicable to a wide range of environments, from midlatitude continental convection to tropical squall lines (Ferrier et al. 1995).

The sensitivity of simulations of deep convection to the type of microphysical scheme used has been shown by a number of studies. Using the three-dimensional hydrostatic mesoscale model MM4, Zhang (1989) investigated the sensitivity of simulations of a midlatitude mesoscale convective system and associated midlevel mesoscale vortex using parameterizations using no ice phase and using a two-class ice scheme. He found that freezing and deposition in the upper levels were important processes in causing the rapid development of the mid-tropospheric warm core vortex, while subcloud-layer melting weakened the concentration of cyclonic vorticity in the lower levels. McCumber et al. (1991) used a NASA three-dimensional non-hydrostatic cloud model to compare simulations using no ice scheme, a two-class ice scheme, and a three-class ice scheme. They found that three-class ice schemes produced better results than two-class ice schemes, with the optimal mix of bulk ice hydrometeors for tropical convection being cloud ice, snow, and graupel. In a simulation of an idealized tropical cyclone using an axisymmetric, nonhydrostatic model, Lord et al. (1984) found that inclusion of a three-class ice scheme produced significant differences in the structure and evolution of the simulated storm when compared with a run with no ice. The simulation with ice processes had a much slower intensification rate initially, though it eventually reached an intensity higher than the run with no ice. Further, the simulation with ice processes had much more mesoscale structure than the no-ice run, with pronounced mesoscale downdrafts forming below the melting level. These downdrafts caused low-level convergence that triggered the formation of banded features outside the eyewall.

With the advent of more computing power, high-resolution, nonhydrostatic, three-dimensional models of tropical cyclones have become practically commonplace. Researchers have conducted simulations of Hurricanes Andrew (Liu et al. 1997; Zhang et al. 2000), Bob (Braun et al. 1999), Bonnie (Rogers et al. 2000; Zhu et al. 2000), and Floyd (Tenerelli et al. 2000) using MM5, with a fair amount of success. These simulations use either two- or three-class ice microphysics schemes. A problem common to all of the simulations is that they produce reflectivities that are too large when compared against radar observations. An example of this discrepancy is shown in Figure 1, taken from the Andrew simulation presented in Liu et al. (1997) which used the Tao-Simpson (1993) microphysical parameterization scheme, a three-class ice scheme based on Lin et al. (1983). The simulation shown in Fig. 1 produced a swath of >50 dBZ echoes that was much wider and longer than that observed by the Miami WSR-57 radar. While some of this discrepancy is likely attributable to resolution issues (they used a grid length of 6 km), the widespread nature of the anomalously high reflectivities indicate that there are deficiencies in the microphysical scheme. This high reflectivity bias suggests that there are too many large graupel particles that melt as they fall into the warm air below. As a result, more cloud hydrometeors fall to the ground, thereby reducing the water loading in the atmospheric column. Such a situation would have implications on the magnitude of the eyewall updrafts, cyclone secondary circulation, and overall storm intensity. Identification of such deficiencies in the parameterization can lead to improvements in the scheme that may ultimately improve simulations of tropical cyclone intensity. The reflectivity comparison in Fig. 1 illustrates only one potential problem with the current microphysical parameterization used in these simulations. Several specific problem areas for the microphysical parmeterizations in this and other models have been identified, as discussed later.

The group at NOAA/HRD (Black and Willis) has been making microphysics measurements in hurricanes for many years (Black and Hallett 1986; Black, 1990; Willis 1998). The utility of these measurements for the development of, and comparison to, model ice parameterizations has been hampered because 1) the P-3 can only sample at relatively warm (-5°C) levels; and 2) the instrumentation sampling volume for the important large hydrometeors has been somewhat limited. What we are proposing for the CAMEX-4 campaign will alleviate these shortcomings; i.e., installation of a NASA High-Volume Particle Sampler (HVPS) on the P-3, and coordinated sampling strategies between the high level DC-8 and the NOAA P-3's. The P-3's ability to sample strong eyewall convection, with its vertical motion and vertical Doppler radar capabilities, will provide a complementary synergism with the capabilities of the DC-8 and the remote sensing capabilities of the NASA ER-2.

2. Description of work

The major objective of the work proposed here is to evaluate microphysical parameterization schemes currently available in three-dimensional primitive equation models using *in situ* data gathered by the NOAA P-3 and NASA DC-8 aircraft as a part of the CAMEX-4 field program. As a part of this evaluation, deficiencies in the parameterization schemes may

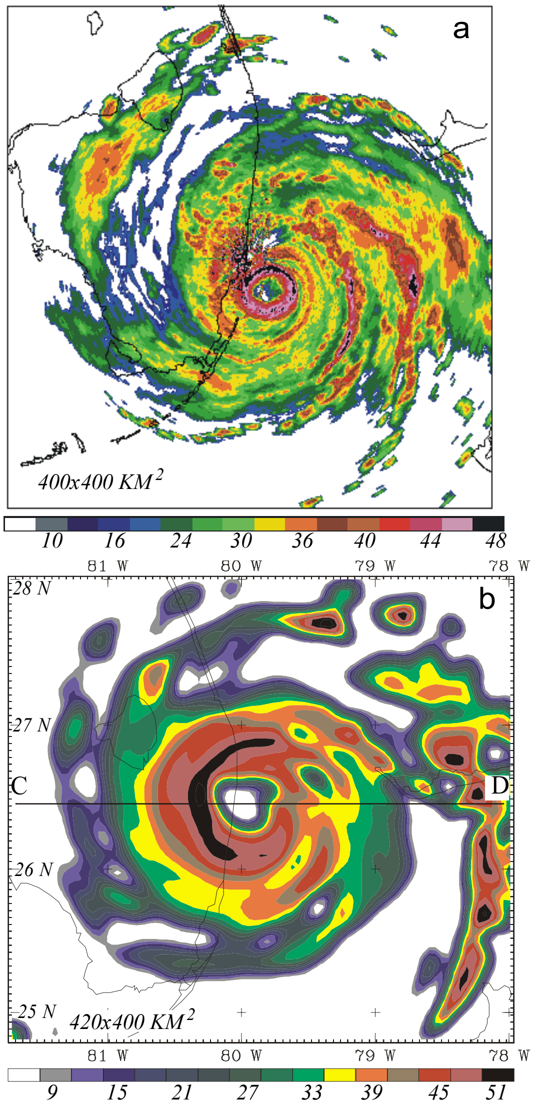

Figure 1. (a) Radar reflectivity from the Miami WSR-57 radar at 0830 UTC 24 August 1992 and (b) the simulated reflectivity that is taken from 68-h integration valid at 0800 UTC 24 August 1992. The legend given along the abscissa denotes the intensity of reflectivity in terms of dBZ. The intervals marked on the frame are mesh grids (6 km for the finest mesh, similarly in the rest of figures). (Adapted from Liu et al. 1997).

be identified, in which case possible improvements will be developed and tested. Specific storms flown by the P-3 and DC-8 during CAMEX-4 will be selected for simulation using the mesoscale model described below.

(a) Modeling component

The modeling component of the proposed research will be carried out using the Penn State/NCAR three-dimensional mesoscale model (*i.e.*, MM5, see Dudhia 1993), which has demonstrated the capability to simulate weather systems spanning a wide range of environments (see the review by Anthes 1990). Both Rogers and Zhang have obtained successful simulations of tropical cyclones using MM5, simulating Hurricanes Andrew (1992) and Bonnie (1998) (Liu et al. 1997; Zhang et al. 2000; Rogers et al. 2000). The MM5 contains a) nonhydrostatic dynamics; b) multiple-nested grid capability; c) a choice of the Anthes-Kuo, the modified Arakawa-Schubert and the Kain-Fritsch and Betts-Miller convective schemes; d) explicit calculations of cloud water/ice, rainwater/snow and graupel as predictive variables; and e) high-resolution boundary-layer schemes. A detailed description of the model can be found in Grell et al. (1995).

A two-way interactive, movable, quadruply nested-grid configuration will be employed to achieve the multiscale simulations. Table 1 describes the tentative (x, y) dimensions. A total of 28 levels in the vertical will be used, with higher resolution in the PBL. The outermost mesh A-domain is fixed and designed to simulate the large-scale environment in which the storm evolves. The size of the domain is chosen sufficiently large to minimize the influence of the lateral boundary conditions on the evolution of the storm. The intermediate mesh B-domain is used to simulate the mesoscale environment around the storm, while mesh C is designed to explicitly simulate the storm-scale flows and provide boundary conditions for the innermost mesh D. The finest mesh D-domain, with a grid size of 1.67 km, is designed to resolve explicitly the central core and spiral rainbands of the storm. Coarser meshes provide finer meshes with time-dependent lateral boundary conditions, while the finer-mesh solutions are fed back to coarser meshes every time step, thereby achieving the two-way interaction of the meshes. The outermost lateral boundary conditions (*i.e.*, for mesh A) are specified by linearly interpolating NCEP's 12-h observational analysis according to Perkey and Kreitzberg (1976). Finer meshes can be moved within coarser domains continuously at any specified rate (in a research mode) to track the movement of the cyclone center.

Table 1: The tentative model domain configuration.

Domain	Mesh A	Mesh B	Mesh C	Mesh D
Dimensions (x, y)	86 x 86	160 x 160	160 x 160	160 x 160
Grid size (km)	45	15	5	1.67

The model water cycles include the simultaneous use of the Kain-Fritsch convective parameterization and the Tao-Simpson (1993) cloud microphysics scheme for the 45- and 15-km grid meshes, but only the cloud microphysics scheme is used for the 5- and 1.67-km grid meshes. The Tao-Simpson microphysics scheme, which was modified from Lin et al. (1983), is a three-class ice scheme that contains prognostic equations for cloud water (ice), rainwater (snow) and hail/graupel, and it allows for the generation of supercooled water. This scheme includes the processes of condensation/evaporation, freezing/melting, sublimation/deposition, autoconversion (*i.e.*, aggregation) of cloud water (ice, snow) to form rainwater (snow, hail/graupel), collection by rainwater (snow), and accretion.

While tropical cyclone simulations using this scheme have been reasonably successful (see Liu et al. 1997; Rogers et al. 2000; Zhu et al. 2000), there are several potential problem areas that have been identified in this scheme that may limit the success of current simulations:

1) Autoconversion of cloud water to rain water and cloud ice to snow and graupel should be investigated. The importance of this process has been noted by other researchers (e.g., Manton and Cotton 1977; Rotstayn 1997). Traditional Kessler-type schemes have been modified to produce schemes that are capable of responding to differing air masses (e.g., Tripoli and Cotton 1980). This capability is important in tropical environments, since different CCN distributions produce different likelihoods of rain and snow formation.
2) Graupel and hail species should be separated in the scheme and should be made to be dependent on updraft magnitude and liquid water content. Mixing ratio data from the P-3's and DC-8 (as part of A. Heymsfield's proposal) will be helpful in accomplishing this task. Additionally, graupel mixing ratios as a function of vertical velocity will be investigated.
3) Parameterization for vapor deposition should include new measurements of saturation vapor pressure with respect to supercooled water (Fukuta and Gramada 2000).
4) Since graupel grows almost exclusively through the accretion of cloud water (Mason 1971), the model parameterization equations describing accretion of cloud ice and snow onto graupel are likely close to 0.
5) The freezing of rain to form graupel should be made to be dependent on the ice nucleation process. There have been some improvements in the parameterization of ice nucleation that need to be incorporated into the models. The possibility of implementing these schemes into the current microphysical parameterization scheme could be explored.
6) The aggregration of cloud ice to form snow is highly temperature dependent in current schemes – maybe too much so. The assumptions underlying the aggregation collection efficiencies can be tested and improved through the use of TRMM-measured collection efficiencies, the University of North Dakota Citation measurements (A. Heymsfield, personal communication), and P-3 and DC-8 in-cloud Lagrangian spiral descents as a part of CAMEX-4.
7) The model assumption of a monodisperse cloud ice distribution in this scheme should be investigated. The incorporation of a more realistic drop-size distribution could be explored.
8) Size distributions for cloud water should be different for maritime vs. continental environments (likely differences for other species as well). Similar to point (6), the possibility of incorporating a more realistic size distribution, such as that discussed in Feingold and Heymsfield (1992), could be explored.

These possible areas of improvement have been identified only through examining the formulation of the most sophisticated microphysical scheme available to MM5. In all likelihood other deficiencies will be identified once specific comparisons between simulations and *in situ* observations begin.

Other model physics include a choice between a modified version of the Blackadar (1979) PBL parameterization (Zhang and Anthes 1982) and the Burk-Thompson PBL scheme. Our runs will use the Blackadar scheme, which has been extensively tested in various weather conditions and whose flaws and merits are better known. Radiative effects are included in a cloud-radiation interaction scheme (Dudhia 1989; Grell et al. 1995). Sea surface temperature is held constant during the integration and friction at the sea surface is calculated with a roughness length that is dependent on surface wind speeds. The land surface temperature is predicted using surface energy budget equations in which the effects of short- and long-wave radiation and cloud radiation are included. For a more detailed description of MM5, the reader is referred to Dudhia (1993) and Grell et al. (1995). The model will be initialized using the NCEP 1.25° analyses, which is then enhanced by rawinsondes, surface observations and the Navy's SST field.

Once the simulations are conducted, detailed diagnostic fields will be computed from the model that will facilitate comparison with the probe data and other observational platforms onboard the planes and on the ground. Budgets of hydrometeor mass and conversion processes will be computed in a manner consistent with the measurements taken from the probes (see Comparison of Model Microphysics and Observations below). Since it is virtually impossible for the model to perfectly replicate the magnitude and distribution of hydrometeor concentrations, probability distribution functions will be computed and compared with observations statistically to provide a picture of the distribution of hydrometeors independent of position, intensity, and timing errors associated with the simulations. Model-derived radar reflectivity will also be computed and compared with lower-fuselage and tail-mounted Doppler radar onboard the P-3 and DC-8 and, when appropriate, ground-based Doppler radars.

Such comparisons will likely reveal deficiencies in the microphysical parameterization scheme such as assumed size distributions, calculated fall speeds, and conversion rates. Modification of these parameters will essentially amount to “tuning” the parameterization scheme to apply to a hurricane environment. While applicability to a variety of environments without the need for “tuning” is clearly the desired property for any parameterization scheme, no comparison of microphysical schemes to *in situ* observations of hydrometeor distributions in hurricane environments has been attempted by previous researchers. This work will provide a unique attempt to characterize weaknesses in the current schemes for this particular environment, and it may guide future developments of parameterization schemes that can apply to this environment. Furthermore, as more sophisticated parameterization schemes, designed to be applicable to a wide range of environments, are implemented in the model (*e.g*., the four-class ice scheme of Ferrier (1994)), the data acquired and validation techniques developed here can be used to test the new scheme in a hurricane environment. Other comparisons between the observations obtained here could be made with the scheme being developed by Dr. M.K. Yau at McGill University, who is including second-moment prognostic equations to predict hydrometeor size distributions in the parameterization scheme. We plan to collaborate with him during the later periods of the proposal, after his scheme has been developed.

(b) Observational component

The observational components of this proposal are submitted in coordination with a proposal by A. Heymsfield of NCAR entitled “Microphysical observations in support of the Convection and Moisture Experiment (CAMEX-4)”. The thrust of this effort is to do coordinated sampling between the instrument augmented P-3 and the NASA DC-8 and ER-2. This should provide a synergism that has not been available heretofore. This proposed coordinated microphysics and remote sampling will provide a data set to allow substantive parameterization development and model comparisons, in addition to remote sensing comparisons and algorithm development. The ability of the P-3 to sample strong eyewall convection with its vertical radar capabilities and *in situ* microphysical measurements, augmented with the large hydrometeor sampling capabilities of a NASA HVPS in concert with the capabilities of the NASA DC-8 and ER-2 aircraft, will provide a nonpareil sampling of the important hurricane convective and stratiform features.

We have extensive knowledge of the microphysical processes in the vicinity of the freezing level. We find graupel only in significant updrafts (10 m s^{-1}) in eyewall and rainband convection, and ice aggregates and complex-growth ice hydrometeors virtually everywhere else (Black and Hallett 1999). Ice is pervasive in the entire hurricane volume, with the possible exception of the inner eyewall updrafts. Most downdrafts have very high concentrations (100-200/liter) of aggregates and complex hydrometeors. We do not know to what elevations the graupel extends, or to what elevation the high concentrations of aggregates extend. One immediate focus of the work proposed herein is to address questions regarding the vertical extent of ice particle and condensed water substance fluxes. It is this component of the observational puzzle for which the DC-8 and ER-2 will provide the necessary key observations. But it is important that these measurements be obtained in a coordinated context.

Data collection onboard the planes will follow techniques used by Black and Willis in past missions. Specifically, raw 2-D image data tapes will be checked for start and stop, as well as for the numerous known image defects, in a timely manner. WP-3D data will be analyzed in the same way as the DC-8 data, with similar products produced. Analysis of the 2-D particle image data will include artifact rejection and partial restoration of incomplete images following the techniques presented in Black and Hallett (1986) and others. Special problems with the raw image data will be overcome as circumstances allow. The basic product is the particle size distribution, from which many derived quantities are computed. The size distributions are computed for four species of water: liquid, irregular ice, columns/needles, and rounded ice particles. Computed quantities include number concentration, ice and liquid water content, radar reflectivity, ice and water mixing ratio, radar attenuation, median volume diameter, and the parameters of a exponential fit to the size distribution in a manner similar to that done in Black (1990). If the images are in rain, rain rate is computed. Other products include particle imagery and average cross-sectional area. These products will be made available for distribution to the research community via anonymous ftp as easily readable files.

(c) Comparison of model microphysics and observations

Despite the importance of detailed comparisons between observed and model-produced microphysical properties, only a relatively cursory noting of gross similarities between model and observations has been reported in the literature. In this proposed work we will attempt to rectify this situation as follows:

1) bounds and limits comparisons

We plan to make a conventional comparison of the statistics of the microphysical output of the model, and the statistics of the microphysics observed by the aircraft (P-3's and DC-8). The observed microphysics will be sorted in the same wary as the model-produced microphysical parameters. The observations will be sorted and processed to match the model output – mixing ratios of the three (or four) ice categories. The sort will also attempt to match temperature levels, storm location, eyewall, rainband, stratiform region, etc. The data comparisons will be further sorted by updraft/downdraft magnitude interval.

2) comparison of CDF's of observed and simulated vertical air motions

One of the strengths of the P-3 data is the direct vertical air motion measurements. These measurements were also made on the DC-8 during CAMEX-3. We propose to directly compare the distributions of these measurements to the CDF's of the model produced vertical velocities on the 1.67 km scale. This will be attempted with both boxcar and moving averaging of the 1 s vertical wind measurements. In addition to these *in situ* vertical velocity measurements, the Doppler radars provide profiles of vertical velocities of an almost matching spatial scale to that of the model produced vertical velocities. The three Doppler radars will provide as extensive data set for direct comparison of the CDF's of the vertical velocities. If these CDF's match reasonably well, it lends credence to the subsequent comparisons of the model-generated microphysics that have their origin in the model-produced vertical air motions.

3) comparison of model-produced CDF's of microphysics and CDF's of observed microphysics

Historically, direct comparisons of model output and observed microphysics have not been very successful, nor productive. Convective processes are on a very small temporal and spatial scale; thus it is very difficult to have model output and observations at precisely the same spot, and at the same time, in the life cycle of any feature. The technique of comparing the statistical distributions (CDF's) does not require a precise temporal and spatial match, as is the case in direct comparisons. As long as the distributions are stable, comparisons of the two distributions yields useful results. We have used a variation of this method to derive Z-R relations between radar data and rain gage data.

In this comparison we will examine the CDF's of the model output microphysics, namely mixing ratios of multiple ice and water categories, and the CDF's of the observed microphysics parameters averaged to the same sacle of the model output. First, we will make overall comparisons at matching elevations, or temperatures. The P-3 will be sampling near the freezing level: while the DC-8 is sampling near 200 mb. Since the total sample will probably be of modest size, it is important that the sampling by the two aircraft be coordinated in time and space. The CDF's in both cases will be sorted by vertical velocity (updraft/downdraft magnitude) interval, and the comparisons will be made. Sorts by storm feature (*e.g.*, eyewall, convective and stratiform regions) will also be done and comparisons will be made. An attempt will be made to assign ice densities to the microphysical classes using the methods outlined in the A. Heymsfield proposal.

4) Doppler radar-microphysics comparisons

Vertical Doppler radar profiles (Z, w, and spectral width) will be available from the P-3 tail radar, EDOP on the ER-2, and ARMAR on the DC-8. We propose to tune relations between microphysical parameters and radar parameters. The model microphysical output fills a three dimensional grid at high time resolutions. The *in situ* microphysical sampling provides a fairly small sample of nearly instantaneous line samples. The model microphysical output can be converted to radar parameters matching the measured radar profiles. Then the CDF's of each of these can be compared, and appropriate improvements made in the model microphysical parameterizations. Conversely, the radar parameters can be converted to microphysical parameters matching the model microphysics outputs, and these CDF's compared. Both of these approaches will be explored in the proposed work. This will extend the comparisons to a data base of much larger extent. This is particularly important in the vertical, where the aircraft sampling is only at two levels, -10 to –5 °C by the P-3s, and 200 mb by the DC-8.

We will use forward and backward hydrometeor trajectory analysis to guide the microphysical analysis and comparisons. The model output will be used to calculate hydrometeor trajectories. This analysis will be used to analyze the comparisons of hydrometeor transports from convective features, *i.e.*, eyewall convection. The fluxes of water mass and hydrometeors calculated in the A. Heymsield proposal will be used in conjunction with this trajectory analysis, to strengthen model/observation comparisons.

(d) Work Plan

The proposed study will proceed in the following steps:

1) Year one (2001-2002):

- coordinate flight plans with NASA DC-8 and ER-2
- install NASA HVPS hydrometeor image instrument on P-3
- fly missions for CAMEX-4, gathering probe data in coordination with NASA
- begin analysis of data
- conduct sensitivity tests with current simulations (*e.g*., Hurricanes Andrew and Bonnie) to become proficient with parameterization code
- begin simulations of CAMEX-4 cases

The main goal of the first year is to plan the coordinated CAMEX-4 missions that will gather the microphysical data and to prepare the model for conducting simulations of the storms flown during the field program. Willis and Black will work with A. Heymsfield of NCAR and G. Heymsfield of NASA to design missions that will collect hydrometeor data simultaneously at levels just above the melting level (NOAA P-3), about 40,000 ft (NASA DC-8), and at 65,000 ft (NASA ER-2). This coordination will allow for the computation of vertical hydrometeor profiles, ice aggregation rates, and updraft magnitudes associated with the eyewall and rainband convective and stratiform regions. Paul Willis will fly on the DC-8 in support of A. Heymsfield's proposal effort and R. Black will collect HVPS data on the P-3.

The modeling component during the first year will consist of developing proficiency with the microphysical parameterization code and beginning simulations of the cases flown during CAMEX-4. Current simulations, such as the simulations of Hurricanes Andrew and Bonnie (Liu et al 1997; Rogers et al 2000; Zhu et al 2000), will be rerun by Rogers and Zhang, with sensitivity experiments and diagnostic analyses planned to identify aspects of the microphysics scheme that show significant sensitivity in determining hydrometeor distributions. Such experience will guide future tests of the CAMEX-4 cases, which will begin at the end of the first year. Additional data from the P-3 and DC-8, including GPS dropsondes, flight-level data, and AXBT ocean temperature profiles, will be used to enhance the initial fields for the CAMEX-4 cases. Also during this time period, we will working with Dr. Shuyi Chen of U. Miami, who has been funded under a USWRP grant to investigate the physical processes governing precipitation distribution in tropical cyclones. She will be investigating the sensitivity of cyclone simulations to the type of microphysical parameterization scheme used (*i.e.*, a two-class vs. three-class ice scheme).

2) Year two (2002-2003):

- continue analyses
- compute mass and conversion budgets and probability distribution functions of different species
- continue simulations of CAMEX-4 cases
- analyze simulations, computing budgets and CDF's of microphysical parameters sorted by temperature, updraft magnitude, and storm feature for comparisons with observations
- identify possible areas for improvement

The second year will see a continuation of the analyses of the probe data begun in the first year by Willis and Black. Budgets of hydrometeor mass distributions and conversion rates will be computed, as well as probability distribution functions of different species. Simulations of selected CAMEX-4 cases by Rogers and Zhang will continue. Model validation will occur using the techniques described above (section 2c – Comparison of model microphysics and observations). Diagnostic analyses computed from the simulations will include the fields described above and model-derived radar reflectivity fields to compare with the lower-fuselage and tail-mounted radars onboard the P-3 and, where appropriate, ground-based Doppler radars. Other model validation will be accomplished by comparing simulation results again Best Track data from NHC, GPS dropsondes, satellite IR and WV data, and hydrometeor vertical profiles from the TRMM satellite. Based on comparisons with the probe data and radar reflectivities, deficiencies in the parameterization scheme in this environment will likely be identified. Areas for possible improvement will be identifed, and implementation of these improvements will commence.

3) Year three (2003-2004):

- complete analyses
- write up results
- complete simulations and validation

- conduct sensitivity studies based on suggested improvements
- write up results

The final year will see the completion of the analyses of the probe data by Willis and Black. The simulations of the CAMEX-4 cases by Rogers and Zhang will also be completed during this year. Based on the improvements in the microphysical scheme identified during the end of year two and the beginning of year three, sensitivity tests will commence to evaluate the impact of these improvements on the hydrometeor distribution, radar reflectivity, and tropical cyclone intensity. While this process will essentially amount to "tuning" the parameterization scheme to apply to a hurricane environment, the comparisons using *in situ* data in the unique environment of a hurricane may guide future developments of parameterization schemes that can apply to this environment. Furthermore, as more sophisticated parameterization schemes, designed to be applicable to a wide range of environments, are implemented in the model (*e.g.*, the four-class ice scheme of Ferrier (1994)), the data acquired and validation techniques developed here can be used to test the new scheme in a hurricane environment. These results will be written up for publication in scientific journals. Also during this year we will be working with Dr. M.K. Yau of McGill University. He is currently developing a second moment scheme that explicitly predicts size distributions. The analysis obtained from the CAMEX-4 flights will be compared against his simulations to test the validity of his scheme.

(e) Prior and current work related to this proposal

The PI, Dr. Rogers, is currently funded under a NOAA USWRP grant with Dr. Shuyi Chen of University of Miami/RSMAS to study the factors controlling the structure and distribution of precipitation in hurricanes. He has conducted 5-day simulations of Hurricane Bonnie at very high resolution (1.67 km grid length for a 48-h time period; Rogers et al. 2000). The simulation reproduces reasonably well the distribution of rainfall, as measured against TRMM PR and TMI rain rates, and captures well the horizontal asymmetry in rainfall as compared against NOAA P-3 lower fuselage radar. Experiments are planned under the USWRP proposal to test the sensitivity of the simulated storm to changes in the microphysical parameterization scheme (*i.e.*, no ice vs. two-class and three-class ice schemes) and planetary boundary layer parameterization scheme.

In the past few years, Dr. Zhang has successfully conducted multi-day explicit simulations of Hurricanes Andrew (1992) and Bonnie (1998) using the multiply nested version of MM5, as described above, with finest grid sizes of 6 km for Andrew (Liu et al. 1997) and 4 km for Bonnie (Zhu et al. 2000). In all cases, NCEP analyses were used as a first guess that is then enhanced by conventional observations. As verified against various observations and the best analysis, the model captures many of the scenarios and inner-core structures of the two storms. In general, the model reproduces reasonably well the tracks, the deepening rates, the strong surface wind near the shoreline, the ring of maximum winds, the eye, eyewall, spiral rainbands and other cloud features associated with Andrew and Bonnie, although there is still significant room for further improvements. Many simulated kinematic, thermodynamic and precipitation structures in the inner-core regions also compare favorably to previous observations of hurricanes.

4. Facilities and equipment

For the simulations, Rogers will have access to a Hewlett-Packard HPC360 workstation, on which he will run the model. The Hurricane Research Division plans to acquire an upgraded HP workstation that will allow for the addition of multiple processors, an addition that will be necessary for an efficient running of the model. Therefore, funding will be sought for the purchase of these processors, as described in the budget section. Zhang has access to a DEC workstation at the University of Maryland on which he will run simulations.

Black and Willis will fly on the P-3's and DC-8 – Black on the P-3 and Willis on the DC-8. Funding will be sought for the installation and check-out of a NASA-provided High Volume Particle Sampler (HVPS) on one of the NOAA P-3's. This spectrometer will increase the sample volume to provide better sampling statistics for precipitation particles.

5. Collaborations

Dr. Andrew Heymsfield, National Center for Atmospheric Research

Dr. Shuyi Chen, RSMAS/University of Miami

Dr. M.K. Yau, McGill University

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Education

1980	M.S. in Atmospheric Science, University of Wyoming
1977	B.S. in Meteorology, The Pennsylvania State University

Experience

June 1980 to present	Research Meteorologist NOAA/AOML Hurricane Research Division 4301 Rickenbacher Cswy. Miami, FL 33149
Jan. 1980 to May 1980	Meteorologist, Intera Environmental Consultants, Ltd. 7015 Mcleod Trail S. Calgary, Alberta, T2V-1X9 CANADA

Recent publications

Atlas, David, Carlton W. Ulbrich, Frank D. Marks, Jr, Robert A. Black, Eyal Amitai, Paul T. Willis, and Christopher E. Samsury, 1999: Partitioning tropical oceanic convective and stratiform rains. Accepted, *J. Geophys. Res*.

Dou, Xiankang, J. Testud, P. Amayenec, and R. Black, 1999: The parameterization of rain for a weather radar. *J. Earth & Planetary Sciences*, 328, 577-582.

Black, R.A. and J. Hallett, 1999: The Electrification of the hurricane. *J. Atmos. Sci*., 56, 2004-2028.

Black, R.A. and J. Hallett, 1998: The mystery of cloud electrification. Amer. Sci. 86, 526-534.

Jameson, A.R., A.B. Kostinski, and R.A. Black, 1998: The texture of clouds. J. Geophys. Res. 103, 6211-6219

Haddad, Z. S., D. A. Short, S. L. Durden, E. Im, S. Hensley, M. B. Grable, and R. A. Black, 1997: A new parameterization of the rain drop size distribution. IEEE Trans. Geosci. Remote Sensing, 35, 532-539.

Black, R.A., 1997: Giant raindrops observed from large aircraft. Preprints, 22nd Conference on Hurricanes and Tropical Meteorology, Ft. Collins, CO, May 19-23. American Meteorological Society, 494-495.

Bringi, V. I., K. Knupp, A. Detwiler, L. Liu, I. J. Caylor, and R. A. Black, 1997: Evolution of a florida thunderstorm during the Convection and Precipitation Experiment: The case of 9 August 1991. Mon. Wea. Rev. 125, 2131-2160.

Black, R. A. and J. Hallett, 1995: The relationship between the evolution of the ice phase hydrometeors with altitude and the establishment of strong electric fields in Hurricane Claudette. Preprints, Conference on Cloud Physics, 15-20 January 1995, Dallas, TX. American Meteorological Society, Boston, MA.

Black, R. A. and H. Bluestein, and M. L. Black, 1994: Unusually strong vertical motions in a Caribbean Hurricane. Mon. Wea. Rev 122, 2722-2739.

Current support

Relative role of ice and coalescence microphysics in intense precipitation processes in landfalling hurricanes. A joint NOAA/NSF proposal submitted to the USWRP Hurricanes at Landfall Project, $26,000 (~25% of salary)

Synthesis of TRMM ice and liquid particle size distributions and their generalization for remote sensing applications. Proposal funded under NASA Research Announcement 99-OES-03, $2300 (< 1% of salary)

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Education

1998	Ph.D in Meteorology, The Pennsylvania State University
1995	M.S. in Meteorology, The Pennsylvania State University
1991	B.A. in Environmental Sciences, University of Virginia

Experience

Aug. 2000 to Present	Assistant Scientist, Cooperative Institute for Marine And Atmospheric Studies, University of Miami
1998 to Aug. 2000	National Research Council Postdoctoral Research Associate, Hurricane Research Division

Selected recent publications and presentations

Rogers, R.F., S. Aberson, J. Kaplan, and S. Goldenberg, 2000: A pronounced upper-tropospheric warm anomaly encountered by the NOAA G-IV aircraft in the vicinity of deep convection. Submitted to *Monthly Weather Review.*

Rogers, R.F., and J.M. Fritsch, 2000: Surface cyclogenesis from convectively-driven amplification of mid-level mesoscale convective vortices. *Mon. Wea. Rev*. In press.

Rogers, R.F., J.M. Fritsch, and W.C. Lambert, 2000: A simple technique for using radar data in the dynamic initialization of a mesoscale model. *Mon. Wea. Rev*. **128**, 2560-2574.

Rogers, R.F., S.S. Chen, J.E. Tenerelli, and M. Lonfat, 2000: A numerical study of the distribution of precipitation in Hurricane Bonnie (1998). Preprints, 24th Conference on Hurricanes and Tropical Meteorology, 29 May – 2 June 2000, Ft. Lauderdale, FL, 408-409.

Rogers, R.F., 2000: Surface-based modification of convectively-generated mesovortices and its implications for tropical cyclogenesis. Preprints, Twenty-fourth Conference on Hurricanes and Tropical Meteorology, 29 May – 2 June 2000, Ft. Lauderdale, FL, 151-152.

Tenerelli, J.E., S.S. Chen, M. Lonfat, R. Foster, and R.F. Rogers, 2000: Surface winds in Hurricane Floyd: A comparison between numerical simulations, aircraft data, and QuikScat satellite data. Preprints, Twenty-fourth Conference on Hurricanes and Tropical Meteorology, 29 May – 2 June 2000, Ft. Lauderdale, FL, 418-419.

Rogers, R.F., 1999: Amplification of warm-core vortices by convective redevelopment: A key component of tropical cyclogenesis. Preprints, 8th Conference on Mesoscale Processes, Boulder, CO, 55-60.

Bryan, G.H., R.F. Rogers, and J.M. Fritsch, 1998: Cloud-scale resolution simulations of moist absolutely unstable layers. Preprints, The Eighth PSU/NCAR Mesoscale Model User's Workshop, Boulder, CO, NCAR, 59-62.

Rogers, R.F., and J.M. Fritsch, 1996: A general framework for convective trigger functions. *Mon. Wea. Rev.*, **124**, 2438-2452.

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Education

1954-1960	Electrical Engineering, San Jose State College. BSEE 1959
1959-1960	Meteorology, Pennsylvania State University. BS 1960
1979-1980	Cloud Physics, University of Arizona

Employment

1959-62	Weather Officer, USAF, Weather support of fighter aircraft
1962-1972	Research Scientist, E. G. & G. Inc., Fog droplet aerosol measurement, tracer transport and dispersion, orographic precipitation modeling, snow physics, radar
1972-	Research Meteorologist, Cloud Physics Program Area, Hurricane Research Div., AOML, Miami, FL 33149

Field Program Experience

1972-1976	Florida Area Cumulus Experiment (Florida)
1973-1994	NOAA Hurricane Field Program - over 300 hurricane eye penetrations
1974	Global Atmospheric Research Program's Atlantic Tropical Experiment (Senegal)
1979	Australian Tropical Cyclone Research Mission
1985	Preliminary Regional Experiment for STORM (Oklahoma)
1991	Convection and Precipitation Experiment (Florida)
1993	Tropical Oceans-Global Atmospheres Coupled Ocean Atmosphere Response Experiment (Australia)
1993	Central Equatorial Pacific Experiment (Christmas Island)
1996	Florida Bay Drop Size Measurements and Radar Rainfall
1998	CAMEX III DC-8 hydrometeor Imaging
1999	INDOEX - NCAR C-130 cloud particle measurements
1999	KWAJEX DC-8 Cloud Particle Imager PI
2000	Airborne Field Mill Project - KSC, CPI data on UND Citation Aircraft

Service

Associate Editor - Journal of Atmospheric and Oceanic Technology

Selected Publications

Willis, Paul, Dodge Peter, Marks, Frank, Smith, DeWitt, and Dean Churchill, 1997: Evaluation of the Accuracy of NEXRAD Radar Rainfall Estimates in the Tropical Summer Convective Rainfall over the Everglades/Florida Bay. *Preprints, 22nd Conference on Hurricanes and Tropical Meteorology,* American Meteorological Soc. Boston, MA pp 679-680.

Marks, Frank D. Jr., Atlas, David, Ulbrich, Carlton W., Willis, Paul T.,Black, Robert A., and Christopher E. Samsury, 1998: Nature and Radar Properties of Tropical Rain, Part 1 - Drop Spectra and Z-R Relations. *JGR.*, Accepted.

Willis, Paul T., 1984: Functional Fits to Some Observed Drop Size Distributions and Parameterization of Rain. *J. Atmos. Sci.*, **41**, 1648-1661.

Jorgensen, D. P., and P. T. Willis, 1982: A Z-R Relationship for hurricanes. *J. Appl. Meteor.*, **21**, 356-366.

Willis, Paul T, and Paul Tattelman, 1989: Drop-Size Distributions Associated with Intense Rainfall. *J. Appl. Meteor.*, **28**, 3-15.

Willis, Paul T.; Heymsfield, A. J., 1988, Melting layer structure in MCC stratiform precipitation, Annalen der Meteorologie, Offenbach a./M., n.s., No 25, 1988, vol 2, p 699-701.

Willis, Paul T., and Andrew J. Heymsfield, 1989: Structure of the Melting Layer in Mesoscale Convective System Stratiform Precipitation. *J. Atmos. Sci.*, **46**, 2008-2025.

Willis, Paul T., and John Hallett, 1991: Microphysical Measurements from an Aircraft Ascending with a Growing Isolated Maritime Cumulus Tower. *J Atmos. Sci.*, **48**, 283-300.

Willis, Paul T., J. Hallett, R. A. Black, and W. Hendricks, 1993: An Aircraft Study of Rapid Precipitation Development and Electrification in a Growing Convective Cloud. *Atmospheric Research* **33** Part II, 1-24.

Marks, F. D., D. D. Atlas, and P. T. Willis, 1993: Probability-matched reflectivity-rainfall relations for a hurricane from aircraft observations. *J. Appl. Meteor.*, **32**, 1134-1141.

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Education

1985	Ph. D in Meteorology, The Pennsylvania State University
1981	M.S. in Meteorology, The Pennsylvania State University
1976	B.S. in Engineering Mechanics, University of Science & Technology of China.

Experience

Sept. 1996 to Present	Associate and Full Professor, Dept. of Meteorology, Univ. of Maryland
1989 to Sept. 1996	Assist. & Assoc. Professor, Dept. of Atmos. & Oceanic Sci., McGill Univ.
1988 to 1989	Research Associate, Department of Physics, University of Toronto
1986 to 1988	Postdoctoral Fellow, National Center for Atmospheric Research

Selected recent publications and presentations

Zhang, D.-L., Y. Liu and M.K. Yau, 2000: A multiscale numerical study of Hurricane Andrew (1992). Part III: Dynamically-induced vertical motion. *Mon. Wea. Rev*, **128**, 3772-3788.

Zhang, D.-L., Y. Liu and M.K. Yau, 2000: A multiscale numerical study of Hurricane Andrew (1992). Part IV: Unbalanced flows. *Mon. Wea. Rev.*, **128**, in press.

Zhu, T, F. Weng and D.-L. Zhang, 2000: An initialization scheme of hurricane models using the Advanced Microwave Sounding Unit data. Submitted to *Mon. Wea. Rev*.

Wang, J., and D.-L. Zhang, 2000: A case study of frontal cyclogenesis and its sensitivity to coastal initial conditions. *Acta Meteorologica Sinica*. **14**, 173-192.

Zhang, D.-L., E. N. Radeva and J. Gyakum, 1999: A family of frontal cyclones over the Western Atlantic ocean. Part I: A 60-h simulation. *Mon. Wea. Rev.*, **127**, 1725-1744.

Zhang, D.-L., E. N. Radeva and J. Gyakum, 1999: A family of frontal cyclones over the Western Atlantic ocean. Part II: Parameter studies. *Mon. Wea. Rev.*, **127**, 1745-1760.

Zhang, D.-L., and E. Altshuler, 1999: The effects of dissipative heating on hurricane intensity. *Mon. Wea. Rev.,* **127**, 3032-3038.

Zhang, D.-L., Y. Liu and M.K. Yau, 1999: Surface winds at landfall of Hurricane Andrew (1992) - A reply. *Mon. Wea. Rev.*, **127**, 1711-1721.

Carrera, M., J. R. Gyakum and D.-L. Zhang, 1999: A numerical case study of secondary marine cyclogenesis sensitivity to initial error and varying physical processes. *Mon. Wea. Rev.*, **126**, 641-660.

Huo, Z.-H., D.-L. Zhang, and J. Gyakum, 1999: The interaction of potential vorticity anomalies in extratropical cyclogenesis. Part I: Static piecewise inversion. *Mon. Wea. Rev.,* **127**, 2546-2561.

Huo, Z.-H., D.-L. Zhang, and J. Gyakum, 1999: The interaction of potential vorticity anomalies in extratropical cyclogenesis. Part II: Sensitivity to initial perturbations. *Mon. Wea. Rev.*, **127**, 2563-2575.

Liu, Y., D.-L. Zhang and M.K. Yau, 1999: A multiscale numerical study of Hurricane Andrew (1992). Part II: Kinematics and inner-core structures. *Mon. Wea. Rev.*, **127**, 2597-2616.

Huo, Z.-H., D.-L. Zhang, and J. Gyakum, 1998: An application of potential vorticity inversion to improving the numerical prediction of the March 1993 superstorm. *Mon. Wea. Rev,* **126**, 424-436.

Zhang, D.-L., and K. MacGillivray, 1997: A numerical investigation of a moderate coastal storm with intense precipitation. *Atmos.-Ocean*, **35,** 161-188.

Kuo, Y.-H., J. Bresch, M.-D. Cheng, J. Kain, D.B. Parsons, W.-K. Tao and D.-L. Zhang, 1997: Summary of a mini-workshop on cumulus parameterization for mesoscale models. *Bulletin of American Meteorological Society*, **78**, 475-491.

Liu, Y., D.-L. Zhang and M.K. Yau, 1997: A multiscale numerical study of Hurricane Andrew (1992). Part I: Explicit simulation and verification. *Mon. Wea. Rev,* **125***,* 3073-3093.

Bélair, S. and D.-L. Zhang, 1997: A numerical study of the along-line variability of a frontal squall line during PRE-STORM. *Mon. Wea. Rev.,* **125**, 2544-2561.

Budget and explanation

BUDGET SUMMARY

For period from 1 May 2001 to 30 April 2004

- Provide a complete Budget Summary for year one and separate estimated for each subsequent year.
- Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
- Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

		NASA USE ONLY	
	A	**B**	**C**
1. Direct Labor (salaries, wages, and fringe benefits)	__133,982_		
2. Other Direct Costs:			
a. Subcontracts			
b. Consultants			
c. Equipment	__15,000__		
d. Supplies	__1,500___		
e. Travel	__6,000___		
f. Other	__95,000__		
3. Facilities and Administrative Costs			
4. Other Applicable Costs:			
5. SUBTOTAL--Estimated Costs	_251,482__		
6. Less Proposed Cost Sharing (if any)	__90,000__		
7. Carryover Funds (if any) a. Anticipated amount : __________			
b. Amount used to reduce budget			
8. Total Estimated Costs	_161,482__		XXXXXXX
9. APPROVED BUDGET	XXXXXX	XXXXXXX	

	Year 1	Year 2	Year 3	Total
Direct labor costs				
Robert Black (15% of time)	11,018	11,789	12,614	35,421
Robert Rogers (20% of time)	11,000	11,770	12,594	35,364
Total direct labor	22,018	23,559	25,208	70,785
Other direct costs				
Equipment				
Computer upgrades (processors, memory, disk space)	4,000	4,000	2,000	10,000
High-Volume Particle Sampler installation on P-3	5,000	0	0	5,000
Travel				
Conferences, work meetings	2,000	2,000	2,000	6,000
Other				
Flight hours (30 hrs @ 3,000/hr)	90,000	0	0	90,000
Publication charges	1,000	1,000	3,000	5,000
Data storage tapes	500	500	500	1,500
Total other direct costs	102,500	7,500	7,500	117,500
Indirect costs				
Robert Black – NOAA 127% (includes 23.9% benefits and 66.4% overhead)	13,993	14,972	16,019	44,384
Robert Rogers – CIMAS 51.5% (includes 25.5% benefits and 26% overhead)	5,665	6,062	6,486	18,213
Total indirect costs	19,658	21,034	22,505	63,197
Subtotal – estimated costs	144,176	52,093	55,213	251,482
Less Proposed NOAA Cost Sharing				
Flight hours during Year 1	90,000	0	0	90,000
Total estimated costs	54,176	52,093	55,213	161,482

NOAA/AOML Hurricane Research Division

Black will be performing much of the analysis of the data collected during the CAMEX missions; consequently we will be asking for 10% support for his efforts. Willis is already supported under a NASA grant with A. Heymsfield, due to continue for two more years.

Assuming that the funding continues for these remaining years, Willis will not seek any salary support in this proposal. Rogers will be performing the majority of the simulations intended to test the microphysical paramterization scheme against the observations. We are asking for 20% of his salary.

We are seeking funding for the installation of the NASA-provided HVPS on one of the NOAA P-3's. In addition, we are seeking funding for additional processors for HRD's planned computer upgrade, plus money for additional disk space and storage space to accommodate the large data sets created as a result of the simulations. Finally, we are seeking funding for travel for professional conferences and publication charges.

University of Maryland

Zhang is fully funded at this point and will not seek additional salary funding through this proposal. We do seek funding for travel to professional conferences and meetings.

References cited

Anthes, R.A., 1990: Recent applications of the Penn State/NCAR mesoscale model to synoptic, mesoscale, and climate studies. *Bull. Amer. Meteor. Soc*., **71**, 1610-1629.

Black, R.A., 1990: Radar reflectivity-ice water content relationships for use above the melting level in hurricanes. *J. Appl. Meteor*., **29**, 955-961.

Black, R.A., and J. Hallett, 1999: Electrification of the hurricane. *J. Atmos. Sci*., **56**, 2004-2028.

Black, R.A., and J. Hallett, 1986: Observations of the distribution of ice in hurricanes. *J. Atmos. Sci*., **43**, 802-822.

Braun, S.A., W.-K. Tao, and B.S. Ferrier, 1999: Sensitivity of a simulation of Hurricane Bob (1991) to cloud microphysics and planetary boundary layer parameterizations. Preprints, 23rd Conference on Hurricanes and Tropical Meteorology, Dallas, TX, 497-500.

Cotton, W.R., M.S. Stephens, T. Nehrkorn, and G.J. Tripoli, 1982: The Colorado State University three-dimensional cloud-mesoscale model –1982. Part II: An ice-phase parameterization. *J. Rech. Atmos*., **16**, 295-320.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State-NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev*., **121**, 1493-1513.

Farley, R.D., and H.D. Orville, 1986: Numerical modeling of hailstorms and hailstone growh. Part I: Preliminary mdoel verification and sensitivity tests. *J. Climate Appl. Meteor*., **25**, 2014-2035.

Feingold, G., and A. Heymsfield , 1992: Parameterizations of the condensational growth of droplets for use in GCMs. *J. Atmos. Sci*., **49**, 2325-2342.

Ferrier, B.S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Part I: Description. *J. Atmos. Sci*., **51**, 249-280.

Ferrier, B.S., W.-K. Tao, and J. Simpson, 1995: A double-moment multiple-phase four-class bulk ice scheme. Part II: Simulations of convective storms in different large-scale environments and comparisons with other bulk parameterizations. *J. Atmos. Sci*., **52**, 1001-1033.

Fukuta, N., and C.M. Gramada, 2000: Vapor pressure measurement of deeply supercooled water. Preprints, 13th International Conference on Clouds and Precipitation. Reno, Nevada, 14-18 August 2000, 613-616.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1995: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note NCAR/TN-398+STR, 138 pp.

Hall, W.D., 1980: A detailed microphysical model within a two-dimensional dynamic framework: Model description and preliminary results. *J. Atmos. Sci*., **37**, 2486-2507.

Hsie, E.-Y., Anthes, R.A., and D. Keyser, 1984: Numerical simulation of frontogenesis in a moist atmosphere. J. *Atmos. Sci*., **41**, 2581-2594.

Lin, Y.-L., R.D. Farley, and H.D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor*., **22**, 1065-1092.

Liu, Y., D.-L. Zhang, and M.K. Yau, 1997: A multiscale numerical study of Hurricane Andrew (1992). Part I: Explicit simulation and verification. *Mon. Wea. Rev*., **125**, 3073-3093.

Liu, Y., D.-L. Zhang, and M.K. Yau, 1999: A multiscale numerical study of Hurricane Andrew (1992). Part II: Kinematics and inner-core structures. *Mon. Wea. Rev*., **127**, 2597-2616.

Lord, S.J., H.E. Willoughby, and J.M. Piotrowicz, 1984: Role of a parameterized ice-phase microphysics in an axisymmetric nonhydrostatic tropical cyclone model. *J. Atmos. Sci.*, **41**, 2836-2848.

Manton, M.J., and W.R. Cotton, 1977: Formulation of approximate equations for modeling moist deep convection on the mesoscale. Atmos. Sci. Pap. No. 266, Colorado State University, NSF Grant DES 7513310, 62 pp.

Mason, B.J., 1971: *The Physics of Clouds* (2nd edition). Clarendon Press, Oxford, 659 pp.

McCumber, M., W.-K. Tao, J. Simpson, R. Penc, and S.-T. Soong, 1991: Comparison of ice-phase microphysical parameterization schemes using numerical simulation of tropical convection. *J. Appl. Meteor*., **30**, 985-1004.

Meyers, M.P., P.J. DeMott, and W.R. Cotton, 1992: New primary ice-nucleation parameterizations in an explicit cloud model. *J. Appl. Meteor*., **31**, 708-721.

Perkey, D.J., and W. Kreitzberg, 1976: A time-dependent lateral boundary scheme for limited area primitive equation models. *Mon. Wea. Rev*., **104**, 744-755.

Rogers, R.F., S.S. Chen, J.E. Tenerelli, and M. Lonfat, 2000: A numerical study of the distribution of precipitation in Hurricane Bonnie (1998). Preprints, Twenty-fourth Conference on Hurricanes and Tropical Meteorology, 29 May – 2 June 2000, Ft. Lauderdale, FL, 408-409.

Rotstayn, L.D., 1997: A physically based scheme for the treatment of stratiform clouds and precipitation in large-scale models. I: Description and evaluation of the microphysical processes. *Quart. J. R. Meteor. Soc*., **123**, pp. 1227-1282.

Rutledge, S.A., and P.V. Hobbs, 1984: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. Part XII: A diagnostic modeling study of precipitation development in narrow cold-frontal rainbands. *J. Atmos. Sci*., **41**, 2949-2972.

Tao, W.-K., and J. Simpson, 1993: The Goddard cumulus ensemble model. Part I: Model description. *Terr. Atmos. Oceanic Sci*., **4**, 35-72.

Tenerelli, J.E., S.S. Chen, M. Lonfat, R. Foster, and R.F. Rogers, 2000: Surface winds in Hurricane Floyd: A comparison between numerical simulations, aircraft data, and QuikScat satellite data. Preprints, Twenty-fourth Conference on Hurricanes and Tropical Meteorology, 29 May – 2 June 2000, Ft. Lauderdale, FL, 418-419.

Tripoli, G.J., and W.R. Cotton, 1980: A numerical investigation of several factors contributing to the observed variable intensity of deep convection over South Florida. *J. Appl. Meteor.*, **19**, 1037-1063.

Zhang, D.-L. and R.A. Anthes, 1982: A high-resolution model of the planetary boundary layer - sensitivity tests and comparisons with SESAME-79 data. *J. Appl. Meteor.*, **21**, 1594-1609.

Zhang, D.-L., 1989: The effect of parameterized ice microphysics on the simulation of vortex circulation with a mesoscale hydrostatic model. *Tellus*, **41A**, 132-147.

Zhang, D.-L., Y. Liu, and M.K. Yau, 2000: A multiscale numerical study of Hurricane Andrew (1992). Part III: Dynamically-induced vertical motion. *Mon. Wea. Rev.*, **128**, 3772-3788.

Zhu, T., D.-L. Zhang, and F. Weng, 2000: Numerical simulation of Hurricane Bonnie (1998) using the advanced microwave sounding unit derived winds. Preprints, Twenty- fourth Conference on Hurricanes and Tropical Meteorology, 29 May – 2 June 2000, Ft. Lauderdale, FL, 460-461.