Scientific Objectives of the Fifth Convection And Moisture Experiment (CAMEX-5)

Proposed by the CAMEX-4 Science Team

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EXECUTIVE SUMMARY

The mission of the NASA Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its responses to natural and human-induced changes in order to improve the prediction of climate, weather, and natural hazards. In this role, the NASA ESE develops scientific research and measurement strategies investigating the land, ocean, and atmospheric components of the Earth system and their interactions. These investigations, which cover a broad continuum of spatial and temporal scales, focus on general research themes of climate variability and change, the water and energy cycle, weather, atmospheric composition, the Earth surface and interior, and carbon cycle, ecosystem and biogeochemistry processes. These themes encompass 23 basic questions outlined by Asrar et al. (2001) as NASA ESE research priorities needed to improve the understanding of global Earth system variability, primary forces, response mechanisms, consequences of change, and predictability of future change.

One of the NASA ESE investigations contributing to the climate, water, and weather research themes is the Convection And Moisture Experiment (CAMEX), which responds to the following subset of the 23 NASA ESE research questions. Namely,

- How are the global precipitation, evaporation, and the cycling of water changing?
- How are the variations in local weather, precipitation, and water resources related to global climate variation?
- How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?

CAMEX, which was primarily designed to validate satellite measurements of moisture and to create a better understanding of the water cycle, also places an emphasis upon studies of tropical cyclones (TC). Utilizing NASA expertise in remote sensing and spaceborne observations, the CAMEX tropical cyclone goals are to increase the overall understanding of TC behavior, identify remote sensing measurements and modeling requirements for improved hurricane predictability, and to validate the performance of NASA spaceborne sensors to accurately monitor the short-term impacts and long-term trends of tropical storms and hurricanes. These goals have lead to a strong collaborative partnership with the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory and the United States Weather Research Program (USWRP) who have similar goals to advance the understanding and predictability of hurricanes as part of their responsibility to expedite the transfer of hurricane research advancements to operational forecasting enhancements.

The centerpiece of the CAMEX effort has been a series of field research campaigns employing spaceborne, airborne, and ground-based assets with a particular emphasis on remote sensing observations. Four field campaigns have been conducted during an eight-year period between 1993-2001. The first two provided a performance test bed for new airborne or ground-based instrumentation designed to simulate or complement precipitation and moisture observations made by satellite sensors. The latter two field campaigns incorporated many of the early CAMEX sensors into a larger, more complete collection of remote sensing and *in situ* devices for a focused investigation of tropical storms, hurricanes, and convection. These latter two experiments, which were called CAMEX-3 and CAMEX-4, were based in Florida during 1998 and 2001, respectively, in order to sample tropical cyclones in the western Atlantic Ocean basin and the Gulf of Mexico while also supporting validation activities for the Tropical Rainfall Measuring Mission (TRMM). Joint aircraft missions with NOAA HRD during CAMEX-3 and CAMEX-4 successfully sampled a total of eight tropical storms and hurricanes. Many of the findings from these field campaigns have been published or are being prepared for publication in a special issue of the American Meteorological Society *Journal of Atmospheric Sciences.* These results highlight interpretations of CAMEX observations of TC convection, wind, moisture, microphysics, and temperature for improved model representations of TC intensity change, motion, rainfall potential, and landfalling impacts.

The success of the CAMEX research and the strong partnership forged between NASA, NOAA, and USWRP represents a sturdy rung of the ladder being built by many of the scientific community to reach a greater understanding and improved predictability of tropical cyclone behavior. Yet, many more rungs in the ladder still remain to be built. Improved skill in prediction of TC genesis, intensity change, and rainfall potential are just a few of these rungs requiring attention due to deficiencies in the understanding of the physical processes involved and additional deficiencies in numerical model parameterizations and data assimilation inputs. The spaceborne and suborbital observational capabilities and technological development activities of NASA put it in a unique position to assist the hurricane research community in addressing these deficiencies, while also tackling the NASA ESE mission goal to understand and predict changes to the total Earth system. In particular, the launch of several new satellites, such as Aqua, Jason-1, and CloudSat, during the 2001-2005 time frame and the prospect of using uninhabited aerial vehicles (UAV) for hurricane monitoring during the next decade offer new research tools that need to explored and validated. Thus, the timing is right to consider a new field phase of CAMEX to support the validation and utilization of new satellite products while also demonstrating the impact that higher spatial and temporal resolution airborne information from UAV platforms might contribute to forecast improvements.

The timing is also right to assess the gaps in knowledge that still exist for CAMEX. Operational requirements and NASA goals for five-day forecasts and beyond necessitate an accurate knowledge of the contributing factors to hurricane genesis and intensity change. However, previous CAMEX field operations have not adequately obtained observations related to tropical cyclone genesis due to the rare instances of these types of systems at the previous deployment locations. Airborne measurements of cloud and precipitation properties have led to improved microphysical parameterizations, but have also pointed out the need for measurements at a greater variety of atmospheric temperature levels. Numerical modeling efforts have demonstrated a requirement for higher resolution humidity information to drive the model convection, but additional observations in the tropical cyclone core and synoptic environment are needed to initialize and validate these models. New partnerships with other NASA ESE research teams are also recommended to ensure a more complete understanding of tropical cyclone behavior and water cycle variability within the context of the total Earth system.

In order to contribute to the NASA ESE mission and build upon the strengths of NASA expertise to assist the hurricane research community, the CAMEX-4 Science Team recommends that a new field experiment, called CAMEX-5, be conducted to address the understanding and prediction of tropical genesis, intensity, motion, rainfall potential, and landfall impacts by remote and *in situ* sensing of the three phases of water from spaceborne and airborne platforms. Hurricane behavior is a multi-scale problem: the hurricane vortex is hundreds of km in horizontal scale, but the eye and eyewall are tens of km (mesoscale), and the embedded convective clouds are order of km (cloud scale). In addition, hurricanes are heavily influenced by phenomena in their environment that are thousands of km wide (synoptic scale). In CAMEX-5, it is proposed to address the broader goals of CAMEX by specifically considering each scale of motion and how it interacts with other scales. A specific set of questions has been generated for each scale of interest. For the synoptic scale, these questions are as follows:

1. **What are the roles of environmental vertical wind shear in tropical cyclone genesis, intensification, track, and rainfall?**
2. **How does the amount and distribution of environmental moisture contribute to tropical cyclone genesis, intensification, track, and rainfall?**
3. **How do large-scale effects, such as interactions between easterly waves, terrain, upper-level troughs, atmospheric dust layers, and the Intertropical Convergence Zone, contribute to tropical cyclogenesis and intensity change?**
4. **What are the capabilities and limitations of using spaceborne and airborne information to improve forecasts of tropical cyclone track, intensity, and rainfall?**

For mesoscale processes, they are:

5. **How does a surface circulation develop?**
6. **What controls the timing, location, and intensity of convection and precipitation and how do these processes feedback to the vortex?**
7. **Do radiative processes and cloud-radiation interactions contribute to storm development and intensification?**
8. **How are developing and mature systems impacted by landfall?**

For cloud scale processes, they are:

9. **How can the representations of hurricane microphysics be improved through the use of *in situ* and remotely sensed microphysical quantities?**
10. **How can quantitative precipitation forecasts be improved through application or assimilation of remotely sensed microphysical quantities as well as better representations of microphysical, boundary layer, thermodynamic, and other processes?**
11. **How does the release of latent heat from microphysical processes feedback upon the updraft and downdraft characteristics of hurricanes and their evolution?**

The recommended CAMEX-5 deployment location for the NASA aircraft is Costa Rica. This site will be conducive to addressing all of the science questions raised earlier while significantly improving the opportunities for sampling tropical cyclogenesis scenarios. The eastern tropical Pacific Ocean, on average, experiences more tropical cyclones each season than the Atlantic Ocean. In contrast to the Atlantic, which can have TCs develop from the east to the west extremes of the ocean, the eastern Pacific TCs are concentrated in a limited domain centered in a region south of Mexico. The most frequent region of genesis of named storms is east of 16º N, 111º W, extending roughly east-to-west between 14º N, 97º W and 15º N, 105º W. It is generally believed that easterly waves traveling across Central America from the Caribbean are the most frequent source of the synoptic scale vorticity maximum that may (or may not) grow into a tropical depression or cyclone as it progresses westward. A Costa Rican deployment site will also be conducive for sampling more mature tropical storms and hurricanes in the western Caribbean as well.

This location offers opportunities to continue the NASA ESE partnership with the NOAA HRD plus two other proposed National Science Foundation tropical cyclogenesis and hurricane rainband studies that are expected to deploy to Acapulco, Mexico during 2005. Partnership with the NASA Tropical Composition, Cloud, and Climate Coupling (TC-4) field study that might also deploy to Costa Rica in 2005 will provide synergistic opportunities to investigate tropical humidity, cloud-radiation interactions, and the relationship of convective intensity to cloud and precipitation microphysical processes and storm evolution. All partners could greatly benefit from field observations collected during the June-August time frame of 2005 using airborne assets that include high altitude aircraft carrying remote sensing instrumentation, medium altitude aircraft carrying remote sensors and *in situ* instrumentation, and lower altitude aircraft carrying storm surveillance radar and *in situ* devices to sample boundary layer conditions and air-sea interactions. This type of collaborative study with new partners will build yet another sturdy rung on the ladder needed to reach a greater understanding and improved predictability of tropical cyclones. The lessons learned during this climb will also directly contribute to the NASA ESE mission to develop a scientific understanding of the Earth system and its responses to change in order to improve the prediction of climate, weather, and natural hazards.

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1 INTRODUCTION

1.1 Relationship of CAMEX to the NASA Earth Science Enterprise Mission

The mission of the NASA Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its responses to natural and human-induced changes in order to improve the prediction of climate, weather, and natural hazards. In this role, the NASA ESE develops scientific research and measurement strategies investigating the land, ocean, and atmospheric components of the Earth system and their interactions. These investigations, which cover a broad continuum of spatial and temporal scales, focus on general research themes of climate variability and change, the water and energy cycle, weather, atmospheric composition, the Earth surface and interior, and carbon cycle, ecosystem and biogeochemistry processes. These themes encompass 23 basic questions outlined by Asrar et al. (2001) as NASA ESE research priorities needed to improve the understanding of global Earth system variability, primary forces, response mechanisms, consequences of change, and predictability of future change.

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1.2 Description of CAMEX Field Campaigns and Early Research Results

The centerpiece of the CAMEX effort has been a series of field research campaigns employing spaceborne, airborne, and ground-based assets with a particular emphasis on remote sensing observations. Four field campaigns have been conducted during an eight-year period between 1993-2001. CAMEX-1 conducted in 1993 and CAMEX-2 conducted in 1995 provided a performance test bed for new airborne or ground-based instrumentation designed to simulate or complement precipitation and moisture observations made by satellite sensors. CAMEX-3 conducted in 1998 and CAMEX-4 conducted in 2001 incorporated many of the early CAMEX sensors into a larger, more complete collection of remote sensing and *in situ* devices for a focused investigation of tropical storms, hurricanes, and convection. These latter two experiments were based in Florida during 1998 and 2001, respectively, in order to sample tropical cyclones in the western Atlantic Ocean basin and the Gulf of Mexico while also supporting validation activities for the Tropical Rainfall Measuring Mission (TRMM).

CAMEX-3 was an early opportunity for the NASA ESE and NOAA HRD to explore the benefits of a collaborative field mission. The NASA ESE assembled a unique array of remote sensing and *in situ* aircraft instrumentation for the high altitude ER-2 and the medium altitude DC-8 aircraft along with ground-based radar, profiler, and radiosonde resources. These assets were highly complementary to the radar and *in situ* instrumentation of the NOAA P-3 aircraft. Together, the two agencies developed joint research strategies to investigate the interplay of hurricane inner core dynamics with the upper tropospheric environment, map the synoptic flow environment, identify the intensity changes of landfalling hurricanes, and sample the environment of potential hurricane genesis conditions. The NASA / NOAA aircraft missions proved to be a highly successful endeavor that provided three-dimensional sampling of hurricane conditions with the NASA aircraft focusing on the upper altitudes above 9 km and the NOAA aircraft concentrating on the lower altitudes below 9 km.

Based upon the success of CAMEX-3, the NASA Earth Science Enterprise collaborated with NOAA HRD again for CAMEX-4. An emphasis upon improving modeling techniques was added to the research objectives which focused more specifically upon observation and modeling of rapid intensification, observation and modeling of storm movement, improving remote sensing techniques for observing wind, temperature, and moisture in tropical cyclones and their environment, and enhancing the understanding of tropical convective system structure and dynamics including scale interactions between intense convection and mesoscale systems. The collaboration between NASA, NOAA, and the USWRP Hurricanes at Landfall Initiative developed into an even stronger relationship during CAMEX-4. A NOAA P-3 aircraft accompanied the NASA ER-2 and DC-8 aircraft on every priority science mission including auxiliary thunderstorm missions in the vicinity of Key West, Florida as part of the Keys Area Microphysics Project. This smaller project was a secondary CAMEX objective to study thunderstorm structure, precipitation systems, and atmospheric water vapor profiles in an effort to improve quantitative precipitation estimates.

All together, a total of eight tropical storms and hurricanes were investigated during the CAMEX field campaigns including Bonnie, Danielle, Earl, and Georges during 1998 and Chantal, Erin, Gabrielle, and Humberto during 2001. Most of these storms were sampled with aircraft over the open ocean, but Bonnie, Georges, and Gabrielle also provided opportunities to monitor landfalling impacts. A few of the storms were sampled on multiple occasions during a course of several days. Most notable of these was Hurricane Humberto, which was sampled on three consecutive days during a cycle of both increasing and decreasing intensity. Information collected for each of the eight CAMEX tropical cyclones as well the TRMM validation activities have been archived and are readily available for distribution. See http://camex.msfc.nasa.gov to access available data.

Analysis of this information has begun to successfully address the CAMEX research topics. As an example, Heymsfield et al. (2001) have thoroughly examined the eyewall structure of Hurricane Bonnie and suggest that convectively induced downdrafts may contribute as much as 3°C to a hurricane's warm core. Geerts et al. (2000) describe the intense convection that developed within the eye of Hurricane Georges due to orographic lifting during landfall in the Dominican Republic. Skofronick-Jackson et al. (2003) demonstrate how to estimate vertical content and particle size distribution of hurricane hydrometeors using CAMEX active and passive microwave airborne observations with an iterative retrieval algorithm. Kamineni et al. (2003) discuss how high resolution water vapor cross-sectional data contribute to improved hurricane intensity and track forecasts. Appendix A contains a more complete list of journal articles referencing CAMEX information. Additional research findings are also being prepared for a special issue of the American Meteorological Society *Journal of Atmospheric Sciences*.

2 NEW SCIENCE ISSUES AND MEASUREMENT STRATEGIES

The success of the CAMEX research and the strong partnership forged between NASA, NOAA, and USWRP represents a sturdy rung of the ladder being built by many of the scientific community to reach a greater understanding and improved predictability of tropical cyclone behavior. Yet, many more rungs in the ladder still remain to be built. Improved skill in prediction of TC genesis, intensity change, and rainfall potential are just a few of these rungs requiring attention due to deficiencies in the understanding of the physical processes involved and additional deficiencies in numerical model parameterizations and data assimilation inputs. The spaceborne and sub orbital observational capabilities and technological development activities of NASA put it in a unique position to assist the hurricane research community in addressing these deficiencies, while also tackling NASA ESE mission goal to understand and predict changes to the total Earth system. In particular, the launch of several new satellites during the 2001-2005 time frame and the prospect of using uninhabited aerial vehicles (UAV) for hurricane monitoring during the next decade offer new research tools that need to explored and validated. Thus, the timing is right to consider a new field phase of CAMEX to support the validation and utilization of new satellite products while also demonstrating the impact that higher spatial and temporal resolution airborne information from UAV platforms might contribute to forecast improvements.

A new field phase of CAMEX could both benefit from information collected by and contribute to the evaluation of the Aqua and Jason-1 satellites plus the SeaWinds instrument, which were launched after the 2001 CAMEX field phase. Aqua measures clouds, precipitation, atmospheric temperature and moisture content among other parameters. Jason-1 monitors global ocean circulation, El Nino conditions, and ocean eddies. SeaWinds, like its counterpart on the QuikSCAT satellite, measures sea surface wind and direction as it flies aboard the Japanese Advanced Earth Observation Satellite (ADEOS-II) spacecraft. CAMEX could assist with the validation of the CloudSat, Aura, and CALIPSO satellites scheduled for launch after 2003. CloudSat will provide radar measurements of the vertical structure of clouds and will better detect the upper-level outflow of hurricanes because it is more sensitive than previous spaceborne radars. The Aura satellite will provide measurements of the spatial and temporal variability of ozone, water vapor, and cirrus clouds in the upper troposphere and lower stratosphere. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) will provide lidar measurements of aerosol and cloud distributions as well as backscatter and extinction profiles through aerosol and thin cloud layers. New partnerships with NASA ESE research teams utilizing these new satellites ensure a more complete understanding of tropical cyclone behavior and water cycle variability within the context of the total Earth system.

The timing is also right to assess the gaps in knowledge that still exist for CAMEX. Operational requirements and NASA goals for five-day forecasts and beyond necessitate an accurate knowledge of the contributing factors to hurricane genesis and intensity change. However, previous CAMEX field operations have not adequately obtained observations related to tropical cyclone genesis due to the rare instances of these types of systems at the previous deployment locations. Airborne measurements of cloud and precipitation properties have led to improved microphysical parameterizations, but have also pointed out the need for measurements at a greater variety of atmospheric temperature levels. Numerical modeling efforts have demonstrated a requirement for higher resolution humidity information to drive the model convection, but additional observations in the tropical cyclone core and synoptic environment are needed to initialize and validate these models.

In order to contribute to the NASA ESE mission and build upon the strengths of NASA expertise to assist the hurricane research community, the CAMEX-4 Science Team recommends the next phase of CAMEX include a new field campaign called CAMEX-5. This experiment would concentrate the understanding and prediction of tropical genesis, intensity, motion, rainfall potential, and landfall impacts by remote and *in situ* sensing of the three phases of water from spaceborne and airborne platforms. Hurricane behavior is a multi-scale problem: the hurricane vortex is hundreds of kilometers in horizontal scale, but the eye and eyewall are tens of kilometers (mesoscale), and the embedded convective clouds are order of kilometers (cloud scale). In addition, hurricanes are heavily influenced by phenomena in their environment that are thousands of kilometers wide (synoptic scale). CAMEX-5 will address the broader goals of CAMEX by specifically considering each scale of motion and how it interacts with other scales. A specific set of questions (discussed below) has been generated for each scale of interest.

2.1 Synoptic Scale Influences

2.1.1 General Discussion and Science Questions

The basic environmental conditions favorable for tropical cyclone development and intensification are well known. Yet, specific processes by which the environment produces and influences a tropical cyclone are not as well understood. *In situ* environmental sampling is also extremely limited in the oceanic locations where tropical cyclones occur. Acquiring and assimilating remotely sensed data or special *in situ* observations is necessary to improve the characterization of relevant environmental conditions within a forecast model. This subsequently enables improved predictions of track, intensity, and precipitation. Better characterization of the synoptic scale environment also enables more accurate examination of the physical processes involved in tropical cyclone development. These issues may be addressed by the following key questions:

1. **What are the roles of environmental vertical wind shear in tropical cyclone genesis, intensification, track, and rainfall?**
   Strong vertical wind shear in the environment is known to have a detrimental effect on tropical cyclone development. Some storms seem more susceptible to these detrimental effects than others. This may be a function of storm intensity, size, organization; magnitude or orientation of the shear; or other characteristics of the environment. There are even indications that some shear may have a positive effect on tropical cyclogenesis, through forcing and organizing downshear convective bursts.
2. **How does the amount and distribution of environmental moisture contribute to tropical cyclone genesis, intensification, track, and rainfall?**
   Water vapor is a key element for the understanding of the processes of precipitation, evaporation, and the release of latent heat. Most numerical models have several limitations in the representation of these factors due to the lack of adequate and accurate moisture measurements with sufficient vertical and horizontal resolutions. The high-resolution moisture data sets acquired during CAMEX made a large impact on the numerical estimate of mass convergence and moisture fluxes during experimental forecasts. The forecast track and intensity estimates from the experiments show a marked improvement compared to the control experiment where such data sets were excluded.
3. **How do large-scale effects, such as interactions between easterly waves, terrain, upper-level troughs, atmospheric dust layers, and the Intertropical Convergence Zone, contribute to tropical cyclogenesis and intensity change?**
   Several mechanisms have been proposed as keys to tropical cyclogenesis. Very little is known about how a small-scale tropical depression first emerges within a larger scale disturbance, such as an easterly wave. How does the structure of an easterly wave change as it crosses from the Caribbean to the Pacific? What are key differences in the structure and environments of developing versus non-developing waves? What determines the balance

between an upper-level trough's positive momentum transports and its detrimental shear? Initial studies have shown that current forecast models do not sufficiently capture the low humidity, static stability, and strong low-level winds of suspended atmospheric dust layers and how the interaction of these features with tropical cyclones or incipient disturbances impacts TC intensification/suppression. How well can satellite measurements (e.g., moisture, aerosol profiles) improve remote characterization of atmospheric dust layers and its impact on TCs?

4. **What are the capabilities and limitations of using spaceborne and airborne information to improve forecasts of tropical cyclone track, intensity, and rainfall?**
   With the launch of new satellites and the promise of suitable UAV platforms for scientific research, new spaceborne observations and technology should be explored and evaluated. How accurate are the relevant satellite-based retrievals, and how are they affected by spatial resolution? Which remotely sensed parameters are the best indicators of intensity change? How well can TC predictions be improved by new data assimilation inputs or targeted observations? How should a flexible network of spaceborne and airborne observations be designed to utilize the best capabilities of each observation type for improved TC forecasting skill?

2.1.2 Synoptic Scale Measurement Strategy

The surveillance of the synoptic scale is important since genesis does follow from the growth of incipient disturbances. What makes some disturbances grow and not others is still not fully understood. Only a few instances of genesis may be observable during a CAMEX field phase, but observing the non-developing disturbances is equally important. It is imperative that detailed data sets of winds, temperature, moisture, pressure, cloud cover, precipitation and the sea state are obtained. Two general measurement domains are recommended.

Over a domain enclosing ~1000 km around a potentially suspected active region, a data resolution of roughly 50 km in horizontal and 500 meters in the vertical is recommended. Suitable measurements currently are possible from airborne remote sensors for cloud, precipitation, temperature, and humidity profiles. Wind profiles can be provided by dropsondes, although higher temporal resolution wind profiles such as those measured by an airborne lidar system would be also desirable. Twice daily sampling missions would be recommended if NASA could partner with other agency field campaigns for aircraft resources. Adaptive observation strategies guided by numerical models, satellite observations, and conceptual models could identify the most critical regions for sampling by medium and high altitude aircraft. Lower altitude aircraft with scanning Doppler radar are necessary to map the low-level vorticity structure.

Over a domain enclosing ~5000 km, a recommended data resolution would be 100 km in the horizontal and 1 km in the vertical. Remotely sensed satellite and other related data assimilation products would be high priority assets for this domain. The desired temporal sampling resolution would be once a day.

A surface-based measuring component is also desired in order to supplement observations of the environment and of the mesoscale structure of waves passing through the 1000 km and 5000 km domain areas. Fixed surface-based observations are needed to help delineate the environment of tropical cyclones and tropical cyclone precursor disturbances using continuous observation or at least fixed temporal sampling. Surface-based options are not mutually exclusive; each could stand-alone or complement the others. Some possible options are listed below:

- Available coastal upper air networks, ocean buoys, and ships of opportunity could provide information to augment the satellite observations of the 5000 km domain.
- Land-based profiler, Doppler radar and/or rawinsonde sites could be of considerable value because they can be located to best detect easterly waves that provide the primary precursor disturbances for tropical cyclones.
- The NOAA Research Vessel Ron Brown, sitting at a fixed position would provide an excellent site for describing wave passages. The ship is equipped with a C-band radar, rawinsonde system, and wind/precipitation profiler and could serve as a platform for many more *in situ* and remote sensors.
- Ground-based lightning observations would provide a means of sensing the location and frequency of lightning (and hence, strong convection) during tropical cyclone or easterly wave passage. These data have been shown to be of value in the early stages of tropical cyclogenesis. Existing networks could be augmented with additional sensors near the deployment location or on research vessels.

In addition to the collection of synoptic scale observations, a detailed data assimilation component will be important to the next field phase of CAMEX in order to properly exploit the dropsonde, flight level and other remote sensed profiling data. Assessing the utility of targeted airborne observations for improved forecasts should be considered. Validating satellite observations with airborne *in situ* and remotely sensed data will also be important to improving general data assimilation procedures for TC scenarios. Given a medium altitude aircraft flying between 9-12 km, a flight pattern can be mapped within +/- 45 minutes of satellite overpass that could cover an area within several satellite footprints. This flight pattern will allow a large number of independent aircraft measurements within a single satellite footprint region so that small-scale variability of parameters such as water vapor within the satellite observation region could be studied.

2.2 Mesoscale Processes

2.2.1 General Discussion and Science Questions

Tropical cyclones almost always develop within larger-scale pre-existing disturbances. In the Atlantic and eastern Pacific, the pre-existing disturbances are typically associated with easterly waves, which have a zonal scale of 2000-4000 km. Very little is known about how a small-scale tropical depression first emerges and how a depression intensifies into a tropical storm and hurricane. In the eastern Pacific, orographic influences may provide a means to intensify vorticity on the mesoscale through the production of lee vortices and low-level jets near the coastline (Farfan and Zehnder 1997). However, the frequency and extent to which orographic forcing plays a critical role is uncertain. Tropical cyclone motion is fairly well understood and predictions of storm tracks are consistently improving. However, we still have relatively little understanding of the factors associated with tropical cyclone genesis and intensity change, and predictive skill is still quite limited. With 5-day forecasts of track and intensity now being routinely issued, the importance of better understanding and predicting genesis, particularly near coastal zones, becomes paramount. The key questions are the following:

5. How does a surface circulation develop?

Mid-tropospheric cyclonic circulations are common in tropical disturbances, but no tropical cyclone can form until a circulation reaches the surface. Whether a mid-tropospheric vortex "builds down" to the surface or if a surface circulation spins up by other means is not known. Different mechanisms are likely at work from one genesis case to another, but the details of these mechanisms are not well understood. Convection is an essential ingredient, but what is the role of cumulus convection during genesis? Cumulus convection may play multiple, and sometimes opposing, roles in the development of a tropical cyclone. Typically, convection fills the planetary boundary layer with low-energy air via cold downdrafts, and thus opposes tropical cyclone development. This is one reason that tropical depression formation is so rare, even though easterly waves are common. On the other hand, convection acts to increase the vorticity locally and some hypotheses suggest that intensification proceeds as the vorticity anomalies merge, with each merger producing a progressively stronger and larger vortex, thereby aiding the development of the vortex. A central question is how convection evolves in such a way to reduce the negative impacts of downdrafts, increase the vorticity production, and thereby generate the tropical depression vortex. Mid-level moistening by convection may be important because it reduces cold downdrafts, but the details of this process remain uncertain.

6. What controls the timing, location, and intensity of convection and precipitation and how do these processes feedback to the vortex?

Many factors (on many scales) can control the timing, location, and intensity of convection and precipitation. For example, vertical shear is known to produce asymmetries, but its impact on the intensity and longevity of convection is lacking. Convective bursts are frequently observed within tropical cyclones, but are not necessarily directly correlated with changes in intensity. The causes of these bursts and the manner in which they impact the larger vortex remain unclear. Outer rainbands are sources of asymmetric heating outside of the tropical cyclone inner-core. The structure and evolution of rainbands may play an important role in vortex evolution through the generation of potential vorticity, production of low-energy air in the boundary layer via downdrafts, and the formation of secondary eyewalls leading to eyewall replacement cycles.

7. **Do radiative processes and cloud-radiation interactions contribute to storm development and intensification?**

Tropical cyclone core and outflow regions consist of ice cloud with high albedos. The bottom parts of these layers absorb heat from the ocean surface while the tops radiate heat to outer space. Numerical studies of the effects of cloud-radiation interactions suggest that radiative effects can significantly impact the rate of intensification during genesis. Radiative destabilization associated with the low-level clouds in the vicinity of the storms may play an important role in the intensification of tropical cyclones and it appears that the radiative cooling at the tops of low-level clouds may be more important than for higher level clouds. What are the magnitudes of radiative heating and cooling at cloud top? Does the contribution to cyclone intensification depend on the areal extent of cloudiness, the altitude, and/or the thickness of cloud layers?

8. **How are developing and mature systems impacted by landfall?**

Upon landfall, the cessation of surface fluxes of heat and moisture combined with increased surface friction acts to rapidly weaken the low-level tropical cyclone vortex. In some instances, such as passage over Florida, the Yucatan Peninsula, or Central America, a tropical cyclone is weakened appreciably, but upon movement back over water, re-intensification can occur. It is not clear, however, whether or not such systems reorganize in the same manner as in the genesis stage and over what time scales this process takes place. Also, quantitative precipitation forecasting for landfalling TCs is a significant issue due to the dramatic impact of inland flooding. A better understanding of warm and cold microphysical processes, environmental wind shear interactions, convection intensity and movement, dry air intrusions, and baroclinic / frontogentic processes are needed to properly address this issue.

2.2.2 Mesoscale Measurement Strategy

Measuring the characteristics of convection will be critical to answering each of the questions. Ideally, measurements would characterize the three-dimensional precipitation, velocity, and thermodynamic fields within pre-genesis and post-genesis disturbances. Practical measurements contributing toward this ideal would include:

- precipitation structures and maps derived from radar and radiometer observations
- horizontal wind flow derived from Doppler velocities acquired by scanning Doppler radar (preferably dual-Doppler)
- convective intensity and location acquired from high-resolution radar reflectivity, Doppler velocities and electric field / lightning information
- thermodynamic and kinematic fields along and beneath the aircraft flight track derived from wind, temperature, pressure, and humidity observations acquired by *in situ* aircraft and dropsonde instrumentation

- vertical profiles of humidity and temperature acquired by lidar and passive microwave profiler instrumentation

Other desirable measuring systems include airborne lidar to map the winds in clear areas where Doppler radar is ineffective and a surface-based network of Doppler radars and profilers to provide continuous measurements during passage of a wave or during landfall of a tropical cyclone.

Downward looking instruments onboard high altitude aircraft should be positioned above cloud top. This allows measurement of the entire vertical extent of the cloud and lessens safety concerns when sampling the strongest convection. Additional measurements from lower aircraft would be beneficial, as the aircraft will not remain precisely aligned with each other. Electric fields should likewise be measured from above cloud. For the required spatial coverage, dropsondes will be necessary from multiple aircraft. Dropsondes are most desirable from the highest altitudes in order to sample the entire troposphere. Successful execution of convective missions using piloted aircraft will require close coordination with low and medium altitude aircraft, as it provides real-time horizontal mapping from quantitative weather radar. Such coordination will also yield the necessary scanning Doppler wind measurements, which are critical. This may require a strong reliance on numerous dropsondes, flight level winds from a low-level aircraft, and measurements from radiometers or scatterometers. A ground-based network or shipborne radar could also contribute to characterizing the low-level winds while a disturbance passes.

2.3 Cloud Scale Processes

2.3.1 General Discussion and Science Questions

Cloud scale properties, both in the liquid and ice phases, are of significant importance to improving the representation of quantitative precipitation forecasts in hurricane models. Although CAMEX *in situ* and remote sensing measurements along with two decades of measurements by NOAA aircraft have provided a wealth of information on cloud microphysical structure and three-dimensional air motion characteristics of hurricanes, there are still important gaps in the understanding and knowledge of these properties. For example, although hurricane eyewall penetrations reported on by Black and Hallett (1986, 1999) suggest that supercooled liquid is almost nonexistent unless the updraft velocities exceed 5 m/s, the conclusions were primarily drawn from penetrations at temperatures above -10ºC. Furthermore, information on the cloud droplet and hydrometeor particle size distributions and ice/liquid water content ratios was usually unavailable, thereby limiting the ability to develop representations of these properties for use in models. The NASA DC-8 aircraft did collect hurricane eyewall microphysical data from CAMEX-3 and CAMEX-4, but the measurements have been confined to temperatures below -30ºC, and instruments needed to confirm the presence and amount of liquid water were unavailable. Lastly, *in situ* data sets needed to evaluate retrievals of cloud properties from remote sensing instruments mounted on overflying and underflying research aircraft have not been obtained in a systematic fashion. In response to lingering questions about the microphysical composition and three-dimensional wind fields of hurricanes, key questions are:

9. **How can the representations of hurricane microphysics be improved through the use of *in situ* and remotely sensed microphysical quantities?**

Representation of microphysical quantities and interactions is a considerable source of uncertainty both in cloud resolving models and in remote sensing retrievals. The interrelationships between the hydrometeor type, size, size distribution, fall velocity, height, and horizontal location in the cyclone or disturbance are not well known. These interrelationships affect particle growth, precipitation efficiency, and the spatial distribution of precipitation and latent heating/cooling due to phase changes. These microphysical properties are needed for reliable numerical models of ice phase hurricane microphysics. What roles do aerosols play in determining the cloud and precipitation structure of hurricanes and how do they impact intensity? The availability of condensation nuclei may affect droplet size distributions, with implications for precipitation efficiency, latent heating and cooling, and subsequent effects on the larger scale vortex through the absorption of infrared radiation. What are the spatial and temporal distributions of liquid water content and particle size distributions? How do they compare to values simulated by very high-resolution numerical models? Do significant amounts of supercooled liquid water exist at temperatures of -20° C in hurricanes, even at temperatures of -30ºC and below? Liquid water is a primary driving force in hurricane dynamics (Lord and Lord, 1988). The amount of liquid water available for droplet and ice particle growth is a controlling factor in the development of rain and ice phase eyewall precipitation. Quantifying and understanding this is central to representing precipitation formation in tropical cyclone forecast models.

10. **How can quantitative precipitation forecasts be improved through application or assimilation of remotely sensed microphysical quantities as well as better representations of microphysical, boundary layer, thermodynamic, and other processes?**

Precipitation forecasts have little skill in hurricanes, but rainfall has a tremendous impact. Freshwater floods are the leading cause of hurricane-related deaths. How do uncertainties in representation of cloud scale processes (question 9) scale up to uncertainties in quantitative precipitation forecasts for the hurricanes?

11. **How does the release of latent heat from microphysical processes feedback upon the updraft and downdraft characteristics of hurricanes and their evolution?**

How do particular microphysical characteristics (the numerous uncertainties mentioned in question 9) control the magnitude, timing, and spatial distribution of latent heating and cooling?

2.3.2 Cloud Scale Measurement Strategy

Progress in addressing the primary cloud scale scientific questions requires detailed measurement of hydrometeor characteristics - particle phase, ice particle type, particle (liquid and ice) size distributions and densities (especially in the melting layer), particle fall velocities, liquid and total water contents. These characteristics, and their spatial and temporal variability, depend in part on the local temperature, relative humidity, pressure, and three-dimensional wind. It is important to understand the hydrometeor characteristics - as revealed by *in situ* measurements - in terms of more readily available remote sensing measurements. Thus, the *in situ* microphysical measurements should be co-located with remotely sensed measurements such as radar reflectivity, brightness temperatures, and electric fields.

Necessary instrumentation includes a suite of cloud probes on aircraft penetrating the storms at a variety of levels, with the mixed phase region being most desirable; Doppler radars (preferably multiple wavelengths); passive microwave radiometers (10 to 183+/-7 GHz; preferably 6 to 640 GHz); airborne electric field mills and/or surface-based lightning network; flight level wind and thermodynamic instruments on the microphysics aircraft; dropsondes released from high altitude aircraft to describe the wind structure and thermodynamic environment; scanning Doppler radar to describe the three-dimensional wind field.

A medium altitude aircraft such as the DC-8 would be the most practical for obtaining *in situ* microphysical data at the middle hurricane levels (8-12 km). A high altitude aircraft should provide coincident remote sensing measurements from above cloud top. It is essential that these aircraft are closely coordinated; for optimal measurements the aircraft will be vertically stacked with each other. As in previous CAMEX field campaigns, it should be possible to measure the particle size distributions and observe particle habits from the medium altitude aircraft. The instrument complement can be expanded to include information on particle phase and condensed water content. Nadir-viewing Doppler radar data from the medium altitude aircraft and the overflying high altitude aircraft can be used to provide information on particle fallspeeds. It would also be highly desirable for the medium altitude aircraft to make microphysical measurements at temperatures as warm as possible (approximately –20º C or above) in the convection. Furthermore, medium altitude aircraft spirals, along with coordinated medium and high altitude aircraft flight patterns, would provide an optimal database, particularly for obtaining information through the melting layer. Cloud electrification measurements could be monitored from the plane to reduce the chance of a lightning strike to the aircraft. Low altitude aircraft can provide *in situ* microphysical data up to a height of about the 0º C level in the convection. It also provides scanning Doppler radar and the onboard radar display necessary for locating targets during a mission using piloted aircraft. The NASA WB-57F aircraft could also make measurements of the microphysical and radiative properties at cloud top and above using due care for flight safety.

3 DESCRIPTION OF NEW CAMEX FIELD OPERATIONS

As mentioned earlier, previous CAMEX field operations have focused on the western Atlantic Ocean basin and the Gulf of Mexico from an aircraft deployment location in Florida. For the next CAMEX field phase, the CAMEX-4 Science Team recommends a Costa Rican deployment location for the NASA aircraft. This location will be conducive to addressing all of the science questions raised earlier in this paper while significantly improving the opportunities for sampling tropical cyclone genesis scenarios. The benefits of the climatology, logistics, and potential partnerships of a Costa Rican deployment are presented below along with recommended measurement priorities for satellite, aircraft, and surface-based observations. Yet regardless of the location of the next CAMEX field phase, the most crucial aspect of field success will be joint aircraft missions conducted with high altitude aircraft carrying remote sensing instrumentation, medium altitude aircraft carrying remote sensors and *in situ* instrumentation, and lower altitude aircraft carrying storm surveillance radar and *in situ* devices to sample boundary layer conditions and air-sea interactions.

3.1 Climatology

The eastern tropical Pacific Ocean, on average, experiences more tropical cyclones each season than the Atlantic Ocean. In contrast to the Atlantic, which can have TCs develop from the east to the west extremes of the ocean, and from 10º N to 35º N, the TCs are concentrated in a limited domain centered in a region south of Mexico. The region of genesis is the most concentrated one on the planet (Frank 1987, Molinari et al. 2000). Figures 1, 2, 3, and 4 represent initial locations of tropical cyclones (depressions, storms, and hurricanes) for June, July, August, and September respectively during the years 1970-2002, according to the National Hurricane Center's best track files. These locations correspond to the completion of the tropical cyclogenesis process since the genesis process has been occurring for a period of time before the disturbances reach the plotted locations. The range rings are plotted at 400 n mi (740 km) intervals from San Jose, Costa Rica in red and from Acapulco, Mexico in blue.

While the maximum occurrence of TCs is centered at 16º N, 111º W, the most frequent region of genesis of named storms is east of that location, extending roughly east-to-west between 14º N, 97º W and 15º N, 105º W. As Molinari et al. (2000) show, the occurrence of tropical depressions increases rapidly as one proceeds westward from the longitudes of Central America, especially west of 95º W. Therefore, if the target of interest is the tropical wave -to-depression transition, this often happens between 93º-105º W, while the depression-to tropical storm transition centers somewhat farther west, say from 95º-111º W. It is generally believed that easterly waves traveling across Central America from the Caribbean are the most frequent source of the synoptic scale vorticity maximum that may (or may not) grow into a tropical depression or cyclone as it progresses westward.

3.2 Logistics

Much of the genesis area is accessible to aircraft basing in San Jose, Costa Rica (10º N, 84º W), and in Acapulco, Mexico (17º N, 100º W). The wave-to-depression transition is especially accessible to jet aircraft based in Costa Rica, while the entire cyclone area can be reached from Acapulco. Using a ferry speed of 400 kt (conservatively 6º of longitude per hour), an in-storm pattern could begin at any location east of 96ºW with a 2-hour ferry flight. Storm center locations west of 104º W (pattern start location of 102º

W) would be reachable only with a 3-hour ferry flight. Therefore, the optimum location for a target storm is between 93º-98º W, a frequent genesis location.

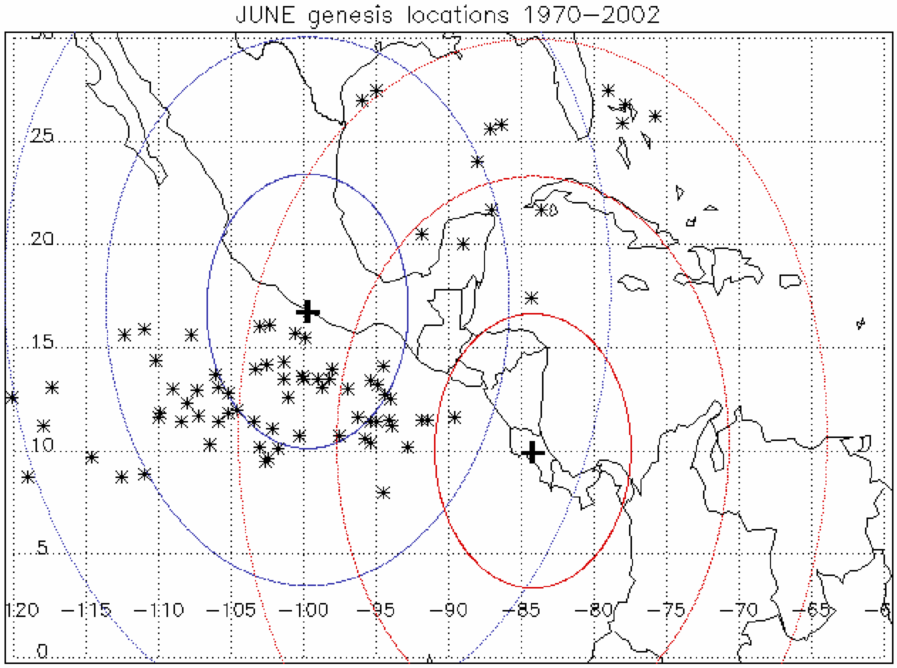

Fig. 1. Initial locations of tropical cyclones (depressions, storms, and hurricanes) for June during the years 1970-2002, according to the National Hurricane Center's best track files. These locations correspond to the completion of the genesis process. The range rings are plotted at 400 n mi (740 km) intervals from San Jose, Costa Rica in red and from Acapulco, Mexico in blue.

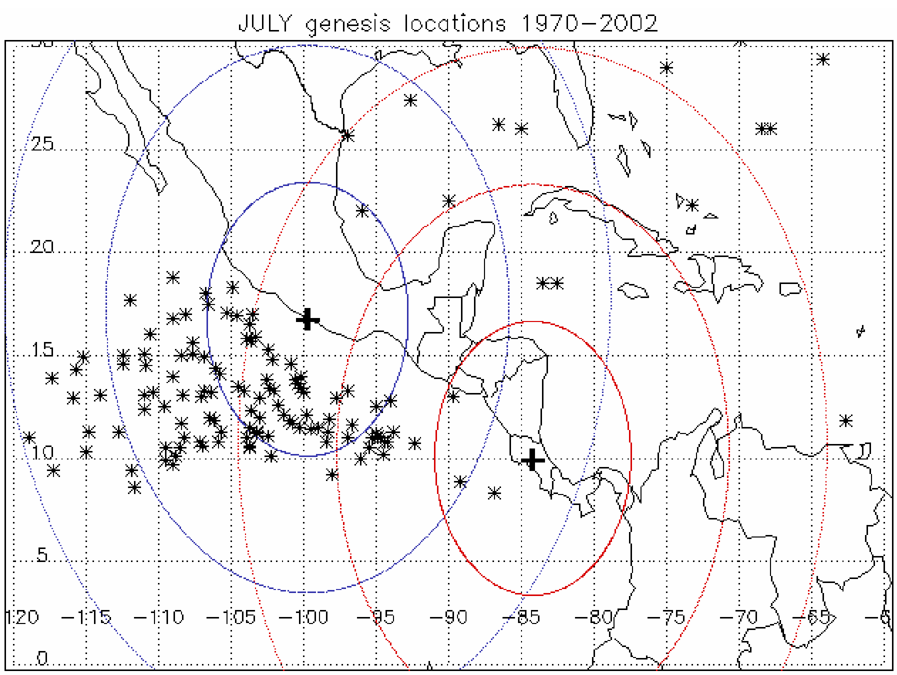

Fig. 2. Same as Fig. 1 except for July

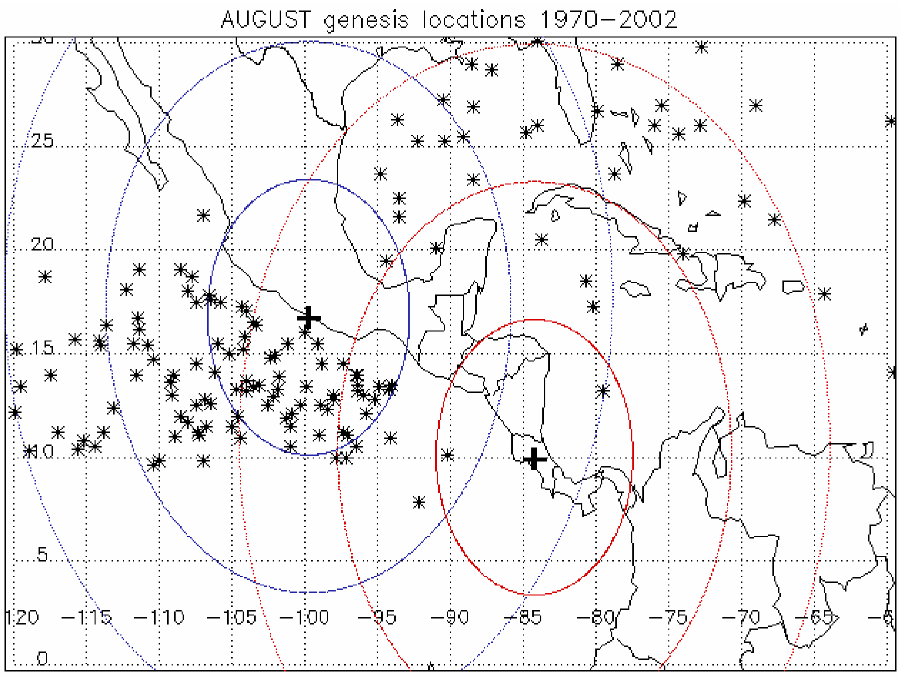

Fig. 3. Same as Fig. 1 except for August

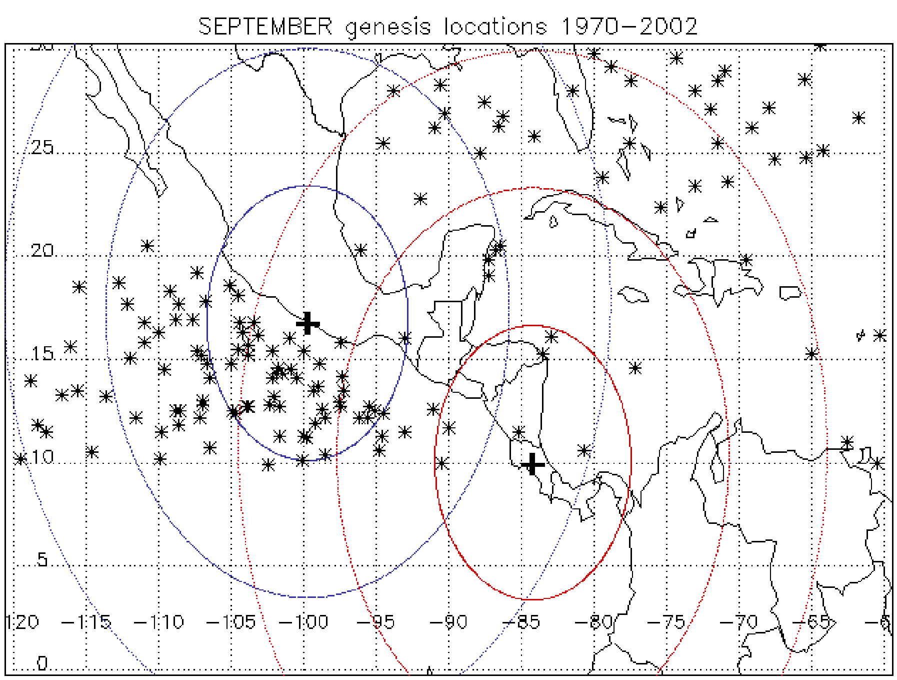

Fig. 4. Same as Fig. 1 except for September

For storm centers located west of about 100º W, the aircraft based in Costa Rica could mainly supply environmental data in the eastern semicircle, while aircraft based in Acapulco could cover the storm for several days. For storms centered in the western Caribbean, the situation is reversed, as aircraft based in Costa Rica can reach most locations, but locations east of 85º W would be far from the Acapulco base. The optimum target for joint missions from both Costa Rica and Acapulco would be a storm approaching landfall in Belize or on the Yucatan peninsula.

3.3 Potential Partnerships With NOAA, NSF, and USWRP

The previous field phases of CAMEX have benefited greatly from the joint missions with the NOAA HRD, scientifically and logistically. The practical aspects are obvious: NOAA flies low, NASA flies high; NOAA has quantitative radars for flight safety and scientific direction, NASA does not; NOAA and NASA aircraft have different but complementary remote sensing capabilities. The hurricane and its precursor disturbances extend throughout the troposphere, and together, the NOAA and NASA aircraft have proven their ability to sample the whole storm. Scientifically, the long-term interests of NOAA HRD scientists in improving the understanding of intensity change and quantitative precipitation observations and forecasting are well matched to the interests and capabilities of NASA investigators. These two issues are sufficiently challenging that they are also at the top of the priority list put forth by the USWRP Hurricanes at Landfall Initiative.

Intensity change notably includes genesis. Why so few tropical disturbances intensify into depressions and then into tropical cyclones while the majority of them remain weak is one of the most intriguing unsolved problems in the atmospheric sciences. It is also a major challenge to forecasters, which explains its high priority for NASA, NOAA, USWRP, and the National Science Foundation (NSF). The Florida deployment locations used previously for CAMEX worked well for investigating hurricanes, but most of the favored genesis areas in the Atlantic are far away from Florida. In contrast, the genesis area is highly concentrated in a location accessible from Costa Rica. The essential joint missions with the NOAA aircraft are feasible if those aircraft are also based so that they can reach the same areas, for example Acapulco. If the goal is to investigate and understand why some incipient storms intensify and some do not, the combination of NOAA basing in Mexico and NASA in Costa Rica is responsive to that goal.

In addition, there are two relevant NSF-sponsored programs proposed for 2005. These are the second Tropical Experiment in Mexico (TEXMEX II) and a hurricane rainband experiment, which require cooperation with the NOAA HRD as well as participation of the NOAA P-3s and the ELDORA radar onboard the Naval Research Laboratory P-3. The spatial resolution of the ELDORA makes it a tremendous asset for mapping the precipitation and wind in joint missions with CAMEX. Likewise, TEXMEX II is specifically designed for the genesis areas for the same reason that is proposed for CAMEX-5: that is the most concentrated genesis region on earth, and it is accessible from an Acapulco base. The hurricane rainband experiment could be done from any base that can reach mature hurricanes, including Acapulco. Given sufficient flight hour resources, therefore, the objectives of all four programs can be reached with an Acapulco base for the P-3s and a Costa Rica base for the NASA aircraft. The joint lessons learned from this type of partnership could be invaluable to the general hurricane community.

3.4 Potential Partnership With Other NASA Earth Science Teams

In addition to partnerships with other hurricane studies, the NASA ESE could also benefit from CAMEX partnerships with other NASA Earth Science research teams. One is Tropical Composition, Cloud, and Climate Coupling (TC-4), which is another NASA ESE investigation with several planned field phases. The primary goals of TC-4 are to gain a better understanding of chemical, dynamical, and physical processes occurring in the tropical upper troposphere and in the layer surrounding the tropical tropopause as well as the roles that the anvils of deep convective clouds and tropical cirrus play in humidifying the upper troposphere and lower stratosphere. These issues are relevant to studies involving global climate change, stratospheric ozone depletion, global tropospheric chemistry, and the Earth's radiation balance. The key questions TC-4 seeks to answer are:

1) What mechanisms maintain the humidity of the stratosphere? What are the relative roles of large-scale transport and convective transport and how are these processes coupled?
2) What are the physical mechanisms that control (and cause) long-term changes in the humidity of the upper troposphere in the tropics and subtropics?
3) What controls the formation and distribution of thin cirrus in the Tropical Tropopause layer, and what is the influence of thin cirrus on radiative heating and cooling rates, and on vertical transport?
4) What are the chemical fates of short-lived compounds transported from the tropical boundary layer into the Tropical Tropopause layer? (i.e., What is the chemical boundary condition for the stratosphere?)
5) What are the mechanisms that control ozone within and below the Tropical Tropopause Transition layer?
6) How do convective intensity and aerosol properties affect cirrus anvil properties?
7) How do cirrus anvils, and tropical cirrus in general, evolve over their life cycle and how do they impact the radiation budget and ultimately the circulation?
8) How can space-based measurements of geophysical parameters, particularly those known to possess strong variations on small spatial scales (e.g., H_2O, cirrus), be validated in a meaningful fashion?

In order to address these questions, the TC-4 Science Team has expressed an interest in partnering with CAMEX during a Costa Rican deployment as one of several TC-4 field campaigns planned for the next several years. The TC-4 research goals to investigate the mechanisms controlling upper tropospheric and stratospheric humidity of the tropics meshes very well with the CAMEX-5 interest in studying the details of how environmental moisture contributes to tropical cyclone behavior. Both TC-4 and

CAMEX-5 have synergistic interests in radiative processes, cloud-radiation interactions, and the relationship of convective intensity to cloud microphysical processes and storm evolution. TC-4 sampling targets will include mesoscale convective systems that are common in the genesis region that would benefit both scientifically and logistically from a partnership with P-3 aircraft equipped with storm surveillance radar. Field observations collected during the June-August time frame of 2005 would be beneficial to the goals of both CAMEX and TC-4. Sharing logistics expenses could provide a cost savings for NASA while also increasing the utility of the aircraft. During possibly inactive periods in the TC genesis region, an alternate target for the TC-4 aircraft is present almost every other day in the Gulf of Panama, which is easily reached from Costa Rica. As with the other potential CAMEX partnerships, the opportunities for synergistic discoveries between CAMEX and TC-4 could be invaluable to the scientific community.

Partnerships could also be developed with several NASA ESE satellite teams who could utilize CAMEX data for validation purposes or who could supply new satellite products benefiting the TC research of CAMEX-5. One such partnership might be with the Atmospheric Infrared Sounder (AIRS) Validation Team. The AIRS provides measurements of atmospheric temperature and humidity; land and sea surface temperatures; cloud properties; radiative energy flux from the Aqua satellite. Current validation efforts have demonstrated that the AIRS is currently able to achieve its specified retrieved temperature uncertainty of 1 K in 1 km layers under most cloud conditions. However, reducing the uncertainties for other retrieved quantities remains a challenge for a number of reasons. Future CAMEX observations could help resolve some of these sources of uncertainty in AIRS retrievals. Useful observations would be:

- Observations of cloud state, such as cloud coverage and cloud top pressure and temperature, to help diagnose the AIRS cloud clearing procedure and associated errors.
- Fine-scale observations of water vapor and temperature distributions including upper tropospheric humidity to help constrain and diagnose the AIRS water vapor retrieval errors.

3.5 CAMEX-5 Measurement Priorities by Observation Platform

Appendix B lists the measurement priorities by observation platform for the recommended CAMEX-5 observations. This table demonstrates how various measurements serve several purposes although the priorities may shift between the three different scales of study. All measurements mentioned in Section 3 have been combined, for the sake of brevity, into nine general categories. For example, aircraft radar and passive microwave observations of rainfall have been combined into high priority precipitation measurements addressing the mesoscale research questions. Dropsondes measurements are considered *in situ* aircraft observations for the purpose of this table.

4 EXPECTED SIGNIFICANCE OF CAMEX-5

The most significant aspects of a new field phase for CAMEX will be the comprehensiveness of the research and the strength of the collaborative partnerships. Addressing the CAMEX-5 synoptic scale questions will lead to a better understanding of tropical cyclone behavior within the context of the large scale environment. The CAMEX observations and measurement strategies pertaining to data assimilation and adaptive observations will identify optimal ways to characterize this large scale environment. The mesoscale questions, indeed the questions at all scales, contribute to understanding the mechanisms by which a small fraction of tropical disturbances develop into tropical cyclones that might have significant weather impacts on society. Success in addressing the cloud scale questions will result in better parameterizations of all phases of water in numerical models. Besides contributing to more accurate precipitation forecasts, these improvements have implications for the modeled storm dynamics by enhancing parameterizations of latent heating/cooling and water loading. The coupling of detailed microphysical observations together with remote sensing measurements will also lead to superior remote sensing retrievals that will in turn yield more accurate quantitative precipitation estimations.

The CAMEX-5 emphasis to address the understanding and prediction of tropical genesis, intensity, motion, rainfall potential, and landfall impacts by remote and *in situ* sensing of the three phases of water from spaceborne and airborne platforms will allow multiple aspects of the water cycle to be examined as well. Incorporating results from the tropical cyclone studies into the broader context of water cycle variability and responses to change will contribute directly to a greater knowledge of the relationships and interactions of the total Earth system. Similarly, a partnership with the TC-4 will provide synergistic opportunities relevant to broader studies of global climate change, stratospheric ozone depletion, global tropospheric chemistry and the Earth's radiation balance due to the TC-4 emphasis on studies of chemical, dynamical, and physical processes of the upper troposphere and stratosphere.

CAMEX-5 will also provide numerous opportunities to validate current NASA observational capabilities and remote sensing retrievals or to develop new retrieval applications or concepts for new technologies. For example, observational capabilities or strategies tested during CAMEX-5 could eventually be deployed on routine UAV missions of the future as part of a flexible observational network monitoring critical weather events such as hurricanes using both spaceborne and suborbital platforms. The collaborative nature of CAMEX-5 with multiple governmental and academic partners will ensure that newly developed applications or technologies are pertinent and relevant to a broad spectrum of users. Thus, CAMEX-5 will both provide and promote the use of NASA technological capabilities to assist the general hurricane research community to advance toward more accurate and dependable tropical cyclone predictions. Lessons learned from this activity will directly contribute to the NASA ESE mission to develop a scientific understanding of the total Earth system and its responses to change in order to improve the prediction of climate, weather, and natural hazards.

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APPENDIX A Journal Articles That Reference CAMEX-3 or CAMEX-4 Data

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APPENDIX B CAMEX-5 Measurement Priorities by Observation Platform

CAMEX-5	Satellite	Aircraft *In situ*	Aircraft *Remote Sensor*	Surface
SYNPOTIC SCALE				
Precipitation	high	low	high	medium
Moisture	high	high	high	high
Temperature	high	high	high	high
Pressure	low	high	low	high
Wind	high	high	high	medium
Cloud State	high	medium	medium	medium
Sea State	high	high	high	high
Cloud Physics	low	low	low	low
Electric Fields / Lightning	low	low	low	medium
MESOSCALE				
Precipitation	high	high	high	high
Moisture	high	high	high	high
Temperature	high	high	high	high
Pressure	low	high	low	high
Wind	high	high	high	high
Cloud State	high	high	high	medium
Sea State	high	high	high	high
Cloud Physics	med	high	high	medium
Electric Fields / Lightning	high	high	high	medium
CLOUD SCALE				
Precipitation	high	high	high	medium
Moisture	low	high	high	medium
Temperature	low	high	high	medium
Pressure	low	high	medium	medium
Wind	low	high	high	medium
Cloud State	high	high	high	medium
Sea State	low	low	low	low
Cloud Physics	medium	high	high	medium
Electric Fields / Lightning	high	high	high	medium