PROJECT SUMMARY

The genesis of tropical cyclones was described by Emanuel (2005) as one of the remaining "great mysteries of the tropical atmosphere." We believe the solution of the mystery requires a new understanding of how locally favorable regions or "sweet spots*" in the lower troposphere* are generated that are protected from hostile influences such as vertical wind shear and low column-humidity, and that favor sustained column moistening and vortex-tube stretching by deep cumulus convection. Under current NSF support the P.I. and his scientific colleagues have recently developed new hypotheses on the role of tropical waves and sub-tropical disturbances in providing a *dynamically induced* "sweet spot" and protection from hostile storm killers (shear deformation and/or dry air intrusions). They have also demonstrated using high resolution numerical simulations the existence of an upscale convective organization mechanism that operates within such regions, ultimately culminating in the construction of a cyclonic potential vorticity (PV) monolith.

The proposed PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT) is a focused observational field campaign to investigate both the structure and evolution of tropospheric wave-like disturbances in the tropics and sub-tropics and the subsynoptic- and mesoscale processes operating within the waves that contribute to the formation of tropical depressions. This new field project aims to test the following hypothesis as part of the "marsupial paradigm" of tropical cyclone formation:

H: Tropical depression formation is greatly favored in the critical-layer region of the synoptic-scale, pre-depression wave trough in the *lower troposphere.* The critical layer – distinguished by a region of the flow wherein the parent wave's phase speed equals the mean flow – provides a set of closed material contours inside of which air is repeatedly moistened by convection, protected to some degree from lateral intrusion of dry air and deformation by horizontal and vertical shear, and (thanks to its location near the critical latitude) able to keep pace with the parent wave until the proto-vortex has strengthened into a self-maintaining entity.

Four sub-hypotheses (described in the main text) are proposed also for testing. In total, these five hypotheses will be addressed using the NCAR G-V aircraft, suitable because of its ability to fly relatively high (above 40,000 ft), long duration (10 hours) and extensive range (more than 4,000 nm). With numerous instruments (in-situ, dropsondes and remote sensing), this aircraft provides a unique opportunity to sample tropical and sub-tropical waves, document their structure on multiple scales, and investigate the dynamics and thermodynamics of tropical depression formation.

Intellectual Merit: The formation of tropical cyclones remains one of the great, unsolved problems in meteorology. It inherently requires study of multiple scales of atmospheric motion from cloud particles to synoptic-scale waves. PREDICT is distinguished from previous efforts related to tropical cyclone formation by (a) new dynamical hypotheses to be tested; (b) nearly continuous aircraft observations; (c) the region of study; (d) advanced instrumentation and facilities.

Broader Impacts: While there is evidence that forecasts have improved in recent years (Brown et al. 2004), deterministic genesis prediction is still a very difficult problem. As prediction is required on longer time scales for emergency management and short-term mitigation, prediction of genesis becomes more important. Mechanisms of genesis are crucial to understand in order that processes leading to simulated genesis in weather and climate models can be adequately evaluated. PREDICT will improve our ability to anticipate genesis, by arming forecasters with conceptual tools regarding the process.

In addition, the planned involvement of NOAA's Hurricane Research Division and several universities and research institutions will offer unprecedented research and education opportunities in a variety of areas all pertaining to tropical cyclone formation: convection and mesoscale dynamics, tropical meteorology, remote sensing, cloud physics, numerical modeling and data assimilation, and theoretical studies.

D. DESCRIPTION of PREDICT

1. Science Background

a. Motivation

Recent years have seen several field campaigns aimed at understanding the dynamics of tropical cyclone formation. These include the Tropical Cloud Systems and Processes (TCSP) in 2005 (Halverson et al. 2007) and the NASA AMMA project in 2006. Adding in the results of earlier efforts such as the Tropical Experiment in Mexico (TEXMEX; Bister and Emanuel 1997, Raymond et al. 1998) and even serendipitous observations of the early intensification of hurricane Ophelia in RAINEX (Houze et al. 2006) and occasionally from reconnaissance aircraft (Reasor et al. 2005), and we have a collection of studies that have sampled pieces of a large and complex scientific puzzle. The puzzle begins with the formation of a *tropical depression*, a necessary meteorological precursor that results, in most cases, in the subsequent formation of a tropical cyclone.

Why should there be a new effort? The first answer is that the problem of tropical depression formation remains unanswered; it is one of the great remaining mysteries of the tropical atmosphere (Emanuel, 2005). The science review below outlines the complex nature of the science problem to be addressed. Perhaps the greatest shortcoming of previous campaigns is the limited sampling, both in space and in time. A second answer, therefore, is that it is difficult to piece together snapshots of tropical disturbances taken at different times. "Genesis" (the formation of a tropical depression-strength vortex at sub-synoptic scales) often occurs between sampling times, or after disturbances move out of range. Third, there are very few observations of both precursors to genesis and the ensuing tropical cyclone formation process. The limited range of previous projects has also meant a limited phenomenological scope, regarding precursors to genesis and the **multi-scale interactions** needed for TC formation. We now *know* that synoptic-scale precursors take many forms (tropical waves, monsoon troughs, upper-tropospheric PV features, etc.). We do *not know* if the genesis process itself is relatively invariant on mesoscale and sub-synoptic scales in spite of these differences in synoptic precursor patterns. Related questions arise about deep cloud populations and their associated microphysical processes, how they vary with precursor type or prevailing flow regime (as suggested by TRMM-LBA, KWAJEX and other field campaigns in the tropics.) Fourth, we have formulated several new, unifying hypotheses that must be tested in order to confront the issues raised above, hypotheses that comprise a "marsupial theory" of tropical cyclogenesis, to be articulated below. Finally, the combination of technological resources at our disposal is unprecedented.

A key ingredient in the marsupial theory is the role of *rotating deep moist convection* and how convective organization in a rotating environment differs from that of typical mesoscale convective systems in the tropics. Differences in cloud systems arising from the unique nature of the proto-vortex environment imply a different pathway of dynamical evolution than what might otherwise occur in the absence of this environment. The construction of a hurricane is a marvelous event, one that cannot be taken for granted in the current climate of Earth, nor in the perturbed climates to come. A unique cloud system structure and dynamical evolution, and a key role of precursor waves, contribute to this marvel in its early stages. The mesoscale aspects of this structure and evolution remain largely unknown.

To address limitations of previous campaigns, the PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT) will dramatically increase the spatial and temporal sampling of tropical disturbances prior to, and during, genesis. The primary research tool will be the NCAR G-V aircraft, with altitude and range advantages over previous aircraft. In addition, we propose to double-crew the aircraft for a portion of the field phase to allow sampling disturbances for as much as 16 out of 24 hours. The project will cover the majority of the Atlantic, including the Caribbean, and therefore will be poised to observe many forms of precursor disturbances and be positioned to uncover the common physical processes of genesis on the mesoscale. Finally, the project will fully integrate the plethora of satellite data and derived products now available, coordinating the aircraft missions to maximize the total data coverage.

To summarize the distinctions of PREDICT from previous efforts, PREDICT will include:

- New dynamical hypotheses comprising the marsupial theory of TC genesis
- Nearly continuous observations using double-crewing of G-V
- Expanded domain (latitude-longitude range and nearly full tropospheric observations)
- Sampling a varied phenomenology of cyclogenesis precursors
- Improved and additional instrumentation on G-V (MTP, lidar, possibly X-band radar)
- Simultaneous deployment of NOAA P-3s as part of IFEX
- Possible participation of NASA with DC-8 instrument suite similar to that of AMMA

b. Tropical Waves and other Pre-depression disturbances

The development of tropical depressions is inextricably linked to synoptic-scale disturbances that come in a variety of forms. The most common in the Atlantic basin are African easterly waves. These waves are well-studied over the eastern basin and Africa, with periods of 3-5 days and wavelengths of 2000-3000 km (e.g. Reed et al. 1977). The multi-scale nature of TC genesis within tropical waves is well-known (though not well-understood). In the schematic of Figure 1 (Gray 1998), two length scales are illustrated, with a cluster deep, moist convection confined to the trough of the synoptic-scale wave. Within these clusters are individual mesoscale convective systems (MCSs). The parent easterly waves, over Africa and the far eastern Atlantic, are relatively well studied, as in the classic GATE campaign, and more recently in NASA AMMA (2006). Sometimes a vigorous, diabatically activated wave emerging from Africa immediately generates a tropical depression, but in most instances these waves continue their westward course harmlessly over the open ocean, or blend with new waves excited in the mid-Atlantic ITCZ. In a minority of waves, the vortical anomalies contained therein become seedlings for depression formation in the central and western Atlantic and points farther west. Shapiro (1986) noted disturbances that tilt westward with height, often against the mean vertical shear. There are often tropical upper tropospheric troughs (TUTTs) present near the lower-tropospheric circulation maximum. In Bracken and Bosart (2000), a trough-ridge couplet was noted straddling the lower-tropospheric circulation maximum, such that synoptic-scale lifting was inferred at the inflection point between the trough and ridge. This paper also pointed out a markedly different structure of waves in the eastern versus western Atlantic.

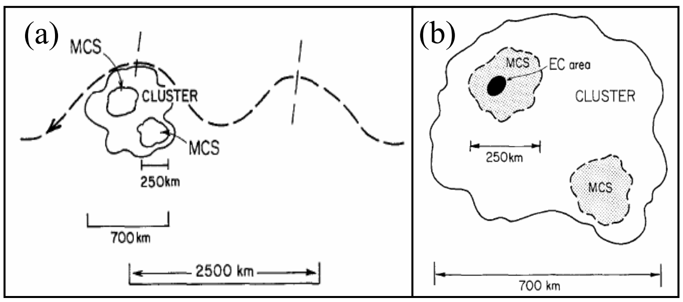

Figure 1. (a) schematic of synoptic-scale flow through an easterly waves (dashed) with an embedded cluster of convection in the wave trough. In (b) the cluster is shown to contain mesoscale convective systems (MCSs) and extreme convection (EC, black oval) within one of the MCSs. From Gray (1998).

The characteristic tracks of waves are indicated in Figure 2b. This figure clearly shows the narrowly confined wave tracks emanating from the African continent. But these tracks split in the Central Atlantic, and many of them disappear. A new cluster of tracks begins farther west. It is not clear how often these represent new features or the continuation of earlier waves. The figure shows vorticity maxima (at 600 hPa) exceeding a threshold, so it is possible that some waves weaken in the Central Atlantic and strengthen farther west. Studies by Molinari et al. (1997) and Thorncroft and Hodges (2001) suggest a

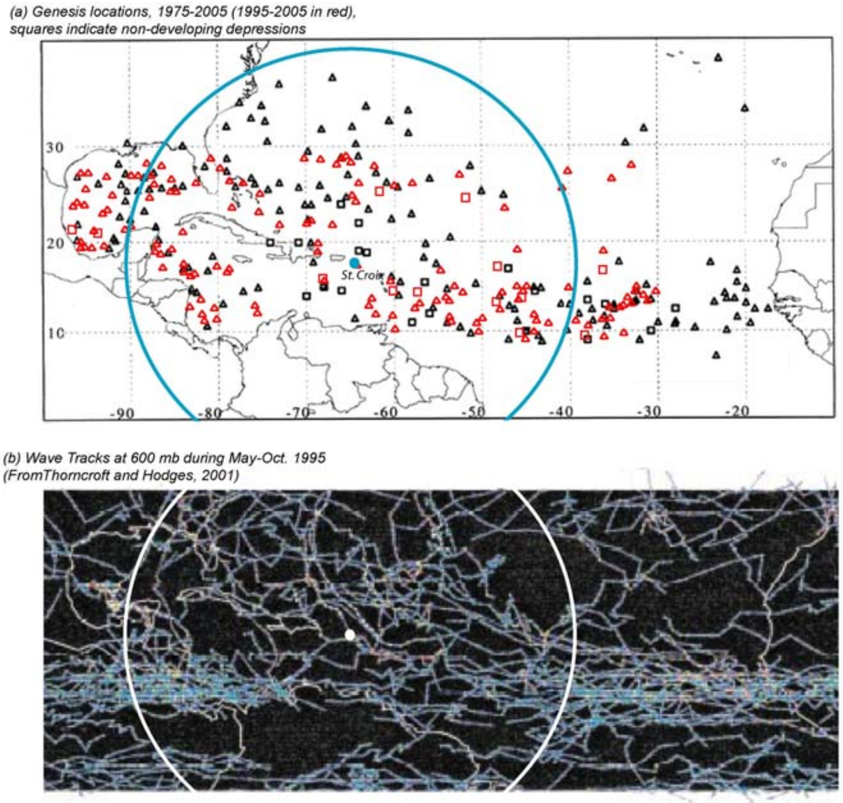

Figure 2. (a) first-detection locations of developing (triangles) and non-developing (squares) tropical depressions from 1975-2005 (1995-2005 in red), adapted from Bracken and Bosart (2000); (b) tracks of 600 hPa vorticity centers during 1995 (from Thorncroft and Hodges 2001). The blue circle in (a) and white circle in (b) denote the approximate PREDICT domain.

third grouping of wave tracks over the southern Caribbean. Many of these waves share some properties of easterly waves over the eastern Atlantic, and are responsible for cyclogenesis events at low-latitudes east (and west) of Central America. Some waves in this region may be traced back to African waves, but in other cases, the wave origin is murky.

A time-mean potential vorticity analysis by Molinari et al. (1997) shows (Figure 3) that a persistent poleward gradient of Ertel PV over the eastern Atlantic gives way to a weaker and clockwise-rotated gradient over the central Atlantic and Caribbean. A well-mixed region of PV exists south of this region, with a reversal of PV evident in the time mean. Molinari et al. suggest an instability mechanism may be operating similar to that over West Africa. Between 5 and 10 N, the PV gradient is relatively unbroken from the tropical Atlantic, across northern South America and into the eastern Pacific. With this distribution of PV, it is not surprising that the wave tracks separate in the central Atlantic with one branch moving northwestward through the Bahamas and into the Gulf of Mexico, and the other maintaining a latitude of 5-10 N. Propagation along the northern waveguide will place easterly waves in the proximity of upper-tropospheric PV streamers moving into the tropics and subtropics from higher latitudes. This may contribute to the structures observed by Bracken and Bosart (2000) in which both lower tropospheric and upper tropospheric PV anomalies are evident. However, some precursors at higher latitudes do not appear clearly connected to easterly waves. McTaggart-Cowan et al. (2008) recently categorized the evolution leading up to tropical depression formation and found six dynamically distinct, synoptic-scale precursors to

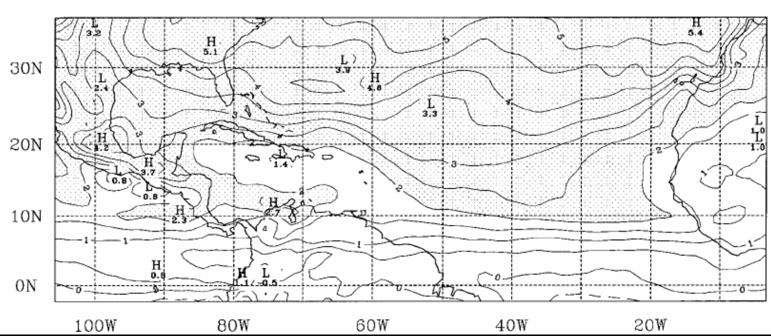

Figure 3. Seasonal mean potential vorticity for 1991 (15 June–30 September) on the 310-K isentropic surface. Units are 10^{-7} m^2 K s^{-1} kg^{-1} with an increment of 0.5×10^{-7}. Values greater than 2 $\times 10^{-7}$ are shaded. (Fig. 2 from Molinari et al. 1997)

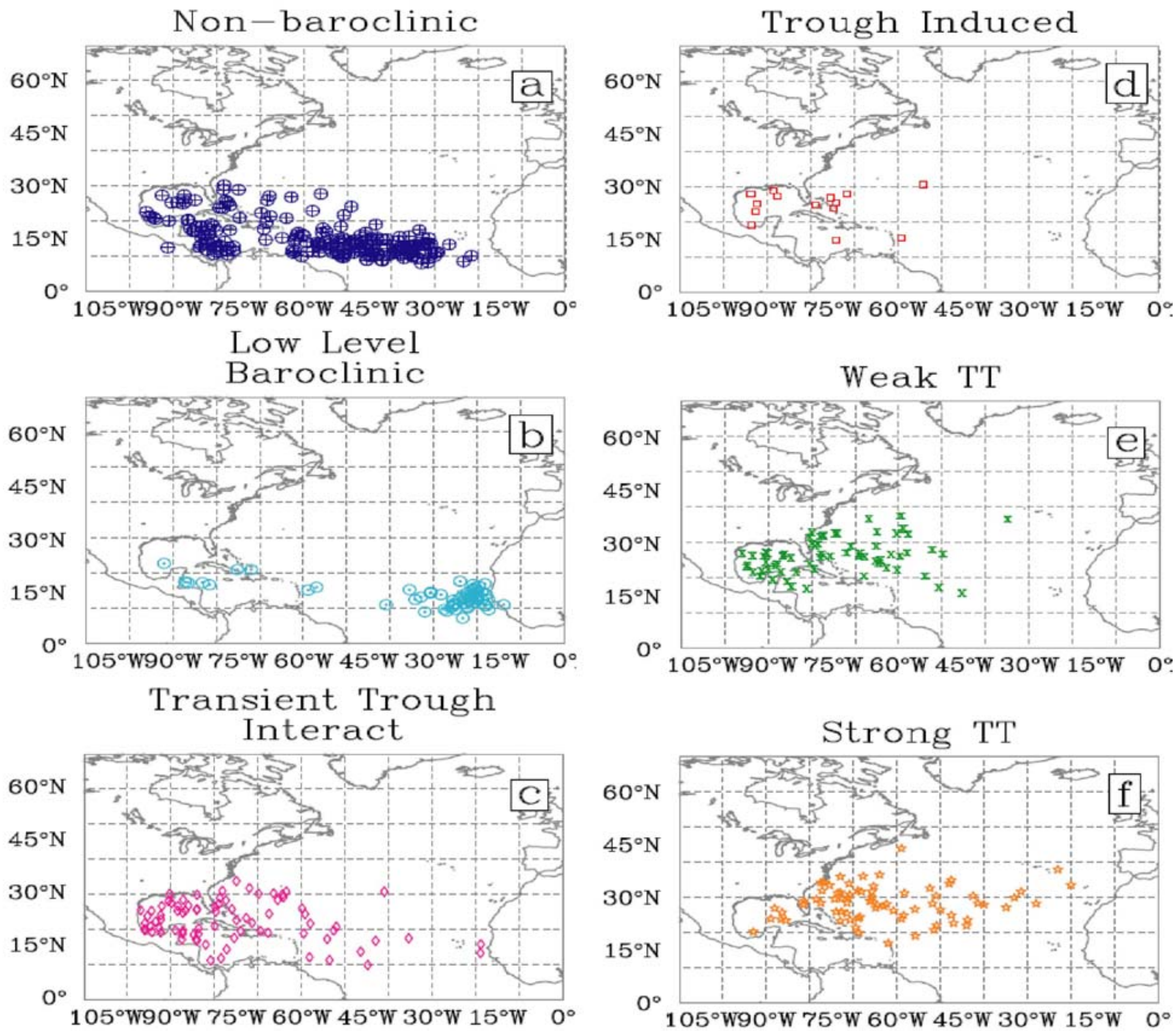

Figure 4. Spatial distribution of tropical cyclogenesis locations for all members of each category, as indicated by the title on the individual panels. Here TT=tropical transition (see Davis and Bosart 2004), Transient Trough Interact implies a trough influenced genesis, but its presence was localized in time to 24 h prior to genesis. (Fig. 10 from McTaggart-Cowan et al. 2008).

tropical cyclone formation, based on the time-dependent behavior of vertical wind shear and the quasi-geostrophic "forcing" of vertical motion, as shown in Figure 4. The most populous category comprised purely tropical disturbances (easterly waves) whose subsequent transformation to a tropical cyclone involved no baroclinic processes. In categories involving tropical transition (TT, Davis and Bosart 2004), the transformation of a cold-core to a warm-core disturbance, the convection was initially forced by a sub-tropical or extratropical cyclone, or a frontal system moving into low latitudes. Other types of systems had varying degrees of troughs or lower-tropospheric baroclinity (e.g. waves near the coast of Africa).

There is no corresponding mesoscale description of convection organization and, ultimately, dynamics of tropical cyclone formation for each category shown in Figure 4. Whereas we can assume with reasonable confidence that the synoptic-scale character of events is well captured by global analyses, the same cannot be said for the mesoscale processes within pre-depression disturbances. Are the mesoscale processes relatively universal among these different synoptic-scale precursors? In other words, is there likely a single pathway to tropical cyclogenesis that may be disguised in different forms, or are these diverse larger-scale features indicative of similarly diverse mesoscale processes?

c. Tropical depression formation

i. The crux of the problem

From Figure 2a it is apparent that there are relatively few Atlantic tropical depressions that fail to become tropical cyclones. It is also well known that most tropical waves do not become tropical depressions. This fact is supported by numerous studies (e.g., Simpson et al., 1968). Thus, the key question appears to be **which tropical waves (or other disturbances) will evolve into tropical depressions?** What is different about developing waves, and can this difference be predicted, and on what time scale? Furthermore, why do so few disturbances develop?

We believe the answer to these questions requires a new understanding into how locally favorable regions or "sweet spots*" within these disturbances* are generated in the lower troposphere: regions which, on the one hand, help protect seedling vortices from the detrimental effects of (vertical and horizontal) shearing deformation and lateral entrainment of dry air and which, on the other hand, favor sustained column moistening and low-level vorticity enhancement by vortex-tube stretching in association with deep cumulus convection.

ii. A new context for storm development: the marsupial paradigm

Recently, Montgomery (2007) has advanced the idea that such extreme environmental conditions can only result if a portion of the pre-depression synoptic-scale disturbances is dynamically isolated from the surrounding flow under a condition of locally enhanced vorticity and gradual moistening. Dynamical isolation is only possible where parcels exhibit closed trajectories, and generally this only happens in the *critical layer* of the wave where the wave translation speed equals the background flow speed in the direction of wave propagation. This "marsupial theory", named because of the analogy with the protective pouch that allows gestation of a newborn marsupial, provides a set of hypotheses (Section 2) readily testable with observations. Dynamical isolation would protect a given region from the deleterious effects of surrounding dry air. It would provide a "sweet spot" where a favorable mesoscale condition could exist for several days, dramatically increasing the chances of a tropical depression forming.

The marsupial theory subsumes many of the current ideas regarding cyclone formation. It is useful, nevertheless, to call attention to the distinctions between genesis theories to explain the formation of the surface vortex that is capable of self amplification within the favorable "pouch" of the parent disturbance. Theories on how to form a surface vortex generally fall into two categories: (i) "top-down" thinking wherein a vortex in the mid-troposphere (that presumably forms within the stratiform region of an MCS) somehow engenders a surface circulation by "building downward" and (ii) "bottom-up" thinking, in which potential vorticity anomalies are generated at low altitudes (~ 1 km) though condensation heating in relatively-downdraft-free convection. Of practical importance is the fact that mesoscale vortex formation in pathway (ii) may occur more rapidly than in pathway (i) due to the larger vertical velocities involved. Needless to say, lower tropospheric processes favorable to development provide a significant head start in the genesis sequence, relative to processes initially confined to the middle troposphere. The contrast between these two pathways is illuminated in the discussion to follow.

Once a depression forms, the prevailing paradigm for intensification is the process of wind-induced surface heat exchange process (WISHE) initially posed by Ooyama (1969) and further clarified by Rotunno and Emanuel (1987), and Emanuel (1986, 1989, 1991). The governing aspect of the WISHE theory is the rate of moist enthalpy flux across the sea surface during tropical cyclone intensification. The enthalpy flux, and the diabatic heating that follows must exceed frictional dissipation in order for a disturbance to intensify. However, the empirical evidence that most disturbances that exceed a surface wind speed of 12-15 m s^{-1} indeed become tropical cyclones places greater emphasis on the processes that produce surface winds of such strength in the first place. The latter is thus the focus of this proposed experiment.

iii. Summary of prior work on TC formation

Based on analysis of datasets obtained during a study of the genesis of eastern Pacific Hurricane Guillermo (1991) during the TEXMEX field experiment, Bister and Emanuel (1997), and Raymond et al. (1998) argued that low and midlevel mesoscale convective vortices (MCVs) associated with deep, moist convection provided a critical concentration of cyclonic relative vorticity necessary for the formation of the ambient surface vortex. Bister and Emanuel (1997) proposed that cyclonic vorticity associated with the MCVs could readily be advected downward in mesoscale downdrafts within stratiform precipitation to facilitate the development of the surface vortex once the lower and middle layers of the atmosphere achieved near-saturation (Bergeron, 1950) and once the near-surface cold pool in the rain area and the assumed surface anticyclone (meso-high) was eliminated. A conceptual problem with the Bister and Emanuel scenario is that there can be no net transport of vorticity (or potential vorticity) substance across isobaric (or isentropic) levels (Haynes and McIntyre, 1987) an axiom which seems to preclude a "top-down" influence of mid-level MCVs by downward vorticity advection. An alternative scenario of the vorticity balance advanced by Raymond et al., though not without a problem of its own, articulates a more consistent "bottom-up" pathway to tropical cyclogenesis and recognizes that the surface flow in the developing TEXMEX system (Guillermo) was cyclonic initially – as if to suggest an earlier role for near-surface organization in the genesis sequence.

An alternative version of "top-down" theory was proposed by Ritchie (1995, 2003), Ritchie and Holland (1999) and Simpson et al. (1997), who used a variety of research aircraft and conventional observations to conclude that interactions between MCVs and the larger-scale cyclonic environment were a crucial component of the genesis process. The arguments essentially invoke an increased Rossby penetration depth in addition to an accumulation of mid-tropospheric PV through the merger (or near merger) of mesoscale vortices. Although assigning a preliminary role to mid-level organization prior to surface development (and thereby acquiring the label "top-down") the theoretical argument of Ritchie and collaborators is consistent, at least, with "potential vorticity thinking" and the inverse-Laplacian nature of PV inversion: larger horizontal scales have a more extensive and deeper influence than smaller scales. Chen and Frank (1993) used a numerical simulation to show that MCVs could be important TC genesis building blocks. Zhang and Bao (1996) were the first to simulate an observed case of TC genesis from an MCV. Although this study was limited by the use of a mesoscale model with fairly coarse horizontal grid spacing (25 km) and cumulus parameterization, it suggested that organization of convection by the MCV, on the scale of the MCV, was crucial for genesis.

From the discussion thus far it is evident that field observations, though fragmentary, have inspired a variety of dynamical perspectives on tropical cyclogenesis, and that some of these ideas are more plausible than others. Considerable uncertainty remains, and to insist that any one perspective is "correct" would engender controversy. The role of numerical models in filling some of the gaps left by limited observations should be noted. Theoretical work by Montgomery and Enagonio (1998), Moller and Montgomery (2000) and Enagonio and Montgomery (2001) advanced the concept of upscale energy transfer of asymmetries through wave-mean flow interaction as a genesis and intensification mechanism for tropical cyclones. Davis and Bosart (2001) and Hendricks et al. (2004) conducted a numerical simulation of the formation of Hurricane Diana (1984), a storm noteworthy for first developing as a cold-core baroclinic system and then undergoing a tropical transition (TT) to a warm-core TC (Bosart and Bartlo 1991). In the simulations the building blocks of the TC intensification process were mesoscale vortices resulting from localized cores of deep cumulus convection that Hendricks et al. (2004) first coined "vortical hot towers" (VHTs). These VHTs were instrumental in producing large values of cyclonic vorticity on near-cloud scales beneath them via the stretching of already vorticity-rich air in the pre-hurricane environment. TC intensification was posited to be a two-stage process. In the first stage multiple VHTs, equivalent to concentrated low-level potential vorticity (PV) anomalies, were produced in conjunction with the deep convective cores while in the second stage the multiple PV anomalies underwent merger and axisymmetrization as part of the intensification of the warm-core vortex via the WISHE process as envisioned by Rotunno and Emanuel (1987). In an idealized modeling study, Montgomery et al. (2006) showed how multiple mergers can occur within a cold-core MCV embryo with enhanced CAPE and midlevel moistening to build a self-sustaining warm-core tropical cyclone. Montgomery et al. also demonstrated that a robust surface vortex could be obtained without locally enhanced surface fluxes of moist entropy from the underlying ocean.

With the exception of Raymond et al (1998) and possibly Hendricks et al. (2004) the aforementioned studies articulated a predominantly "top-down" view of tropical cyclogenesis in which mid-level vorticity aggregation and moistening play a significant role prior to surface development. In both "top-down" and "bottom-up" viewpoints, to be sure, there is new convection engendered by a mesoscale vortex. The difference is in the vertical structure of PV and whether the vortex builds downward prior to the eruption of deep convective cores (top down), or whether its manifestation at the surface occurs *because of* deep convective cores (bottom up) (Tory et al. 2007). The two pathways are not mutually exclusive (Halverson et al., 2007) and it is entirely possible that a particular pathway is more relevant in one region than in another. Owing to the morphology of easterly waves in the Atlantic MDR, and their associated critical layers in the lower troposphere, we are inclined to favor the "bottom-up" pathway in this sector. The PREDICT campaign offers a unique opportunity to test this intuitive notion with an open mind and with detailed observations.

The "bottom-up" viewpoint has some support from existing observations. Reasor et al. (2005) explored the first stage of TC intensification through an examination of the genesis of Hurricane Dolly (1996). They argued that in the first stage of TC intensification (pre-WISHE; Molinari et al. 2004) the initial seedling surface disturbance is created in conjunction with mesoscale and convective-scale diabatic heating processes. On the basis of an analysis of airborne Doppler radar observations taken in Atlantic Hurricane Dolly (1996) they found that "the early development of Dolly supports a stochastic view of tropical cyclone genesis in which multiple lower-to-middle-tropospheric mesoscale cyclonic circulations are involved in building the surface cyclonic circulation." An observational study by Sippel et al. (2006) of Tropical Cyclone Allison (2001) also found a bottom-up development, but suggested that true VHT's were smaller than previously simulated and that so-called "convective burst" vortices intermediate in scale between VHT's and the hurricane-scale vortex were crucial for the organization of the storm.

2. PREDICT Hypotheses

In the Introduction, descriptions of genesis from the synoptic-scale, mesoscale and convective-scale perspectives were presented. Genesis is believed to be inherently a multi-scale process, but it is likely that the roles of different scales can be evaluated and the following hypotheses can be tested to elucidate their relative importance in genesis over the western Atlantic, with strong implications for genesis elsewhere. The main hypothesis (H1) is the following:

H1: Tropical depression formation is greatly favored in the critical-layer region of the synoptic-scale, pre-depression wave or subtropical disturbance.

This hypothesis is the underlying tenet of the *marsupial paradigm*, or "marsupial/pouch theory" of tropical cyclogenesis. The *critical layer* of the parent wave is a region of cyclonic rotation and weak deformation that provides a set of closed material contours inside of which air is repeatedly moistened by convection, protected from lateral intrusion of dry air and deformation by horizontal or vertical shear, and (thanks to its location near the critical level) able to keep pace with the parent wave until the dominant vortex (a.k.a. proto-vortex) has strengthened into a self-maintaining entity. During this time the parent wave is maintained and possibly enhanced by diabatically amplified eddies within the wave (proto-vortices on the mesoscale), a process favored in regions of small intrinsic phase speed. In regard to wave maintenance it is important to note that we regard diabatic amplification as a key element of a feedback loop, but logically as an effect, not cause, of the parent wave. In other words, the critical layer giving birth to the proto-vortex is not simply an illusion caused by merger of such vortices that would have formed anyway, but an essential element of the incipient wave which governs the particular location(s) of proto-vortex development. Key to the marsupial paradigm is the existence of a *hybrid diabatic Rossby wave/vortex structure*; a configuration that may be uniquely instrumental in TC genesis.

As evident in H1 the critical layer helps furnish a rotating pouch that has minimal shear deformation which in turn supports progressive moistening of the tropospheric column by deep convective events. Humidification of a mesoscale region in the lower-middle troposphere (3-6 km MSL) is thought to be crucial for weakening downdrafts and divergence in the underlying tropical boundary layer. Conversely, dry air that has been drawn laterally into the pouch at these levels at the time of its formation can promote cool downdrafts that are inimical to genesis.

Hypothesis H1 naturally motivates four sub-hypotheses (H2-H5) that we also propose for testing:

H2: Despite the variety of pre-cursor disturbances, tropical cyclone formation proceeds through essentially the same mesoscale and cloud processes.

This hypothesis is related to the marsupial theory and seeks to generalize it; the goal is to test whether there are other types of disturbance or combinations of disturbances that do not depend on a *critical-layer* sweet spot for nurturing the nascent mesoscale vortex. Favorable regions might conceivably arise through wave superposition or the intrusion of extratropical anomalies into the subtropics. Thus, an important goal of PREDICT is to sample a variety of precursor disturbances, including easterly waves, remnant fronts and PV streamers in order to understand whether the underlying process of tropical depression formation is inherently the same despite the synoptic-scale variations. It will therefore be necessary to relate the mesoscale convective organization to synoptic-scale structure and induced large-scale lifting and destabilization. This, in turn, demands knowledge of the origin and morphology of the pre-depression disturbances. In the case of easterly waves, these attributes are well studied in the far eastern Atlantic. But this is not true of easterly waves in the central and western Atlantic, nor of other disturbances, such as PV filamentary structures in the upper troposphere and their role in organizing convection on the mesoscale. Based on our recent experience with diabatic Rossby wave/vortices in the subtropics it seems likely that other types of precursors besides easterly waves may also possess a "sweet spot" for tropical cyclogenesis or tropical transition, with flow kinematics in the lower to mid-troposphere similar to those of a tropical wave critical layer. Whether genesis requires an upper-level precursor (as in TT) or something at lower levels (as in pure TC genesis) it is likely that both kinds of development require elements of the marsupial paradigm.

Regarding mesoscale and cloud / cloud system processes, the null hypothesis expressed in H2 is that a successful genesis sequence can be realized through a variety of synoptic patterns yet is characterized by a typical combination of mesoscale flow organization and thermodynamic properties of deep moist convection. This is not to say that mesoscale dynamics and cloud properties are uniform across the whole tropics, nor in developing versus non-developing systems; rather, that *successful development entails a* *typical sequence of events, with similar moist thermodynamic requirements and resulting deep cloud properties*. This notion integrates tightly with the marsupial theory, insofar as the "desirable properties" may often require protection from a hostile exterior environment. We emphasize that H2 is simply a null hypothesis. At this point, little is known about mesoscale processes from in situ observations, especially at meso-β scales (20-200 km) encompassing tropical cyclones.

H3: Genesis is a bottom-up process.

This statement requires that PV is generated in the lower-troposphere as the mesoscale response to the organization of convection within a wave. Numerical models strongly suggest that these PV features are "born" warm core, and that their amalgamation produces a warm-core vortex capable of self-amplification. Furthermore, this hypothesis suggests that the mesoscale PV features maximizing 1-2 km above the surface are in essence the building blocks of the tropical depression. The vertical structure of the rotational wind and pressure perturbation around organized convection must be observed in order to address this issue. We must observe the vertical structure of vorticity and divergence, as well as thermodynamic structure, to confirm or reject this hypothesis. As in H2, cloud populations and their associated microphysical processes play a key role in determining the genesis pathway. A predominantly convective type of vertical heating profile is expected as column moistening proceeds (protected in the marsupial pouch) and the deleterious effects of cooling by stratiform anvils (in the lower troposphere) and their associated downdrafts (entering the boundary layer) are progressively eliminated.

H4: The primary effect of Saharan Air Layers is to inject dry air into the marsupial pouch of candidate tropical disturbances.

If the proto-vortex region is not insulated from the external environment in cases of Saharan Air intrusion, it reduces the chance of depression formation. It is well known that dust-laden Saharan air juxtaposes with the convecting region of tropical waves in many instances (Dunion et al. 2004). There are some potentially important effects of the dust carried in Saharan Air Layers, such as on cloud physics and stabilization of the environment of convection through radiative absorption. To address the hypothesis, these effects of dust must be quantified. It is one thing to regard dust aerosol as simply a marker of dry air, when it is principally the accompanying *moisture deficit* that is inimical to genesis on short time scales. It is another to regard the anomalous radiative absorption/scattering by aerosol as directly inimical to genesis on longer timescales (e.g., via cooling of SST or stabilization of lapse rate). Both ideas are plausible. Ideally our field experiment can differentiate between these short- and longer-term causal mechanisms and shed light on related issues, such as the role of a changing composition and climate, in the context of tropical cyclogenesis.

H5: Despite potentially significant model errors, poor initial conditions are the key factor in poor predictions of genesis.

In particular, we wish to test whether a practically useful path for increasing prediction skill is to reduce errors on the synoptic-scale, which is highly feasible from an observational and data assimilation perspective, rather than on the mesoscale or convective scale. Uncertainty of flow configuration beyond 48 hours is an acute problem over the western half of the Atlantic where, owing to a diffluent flow pattern, westward propagating disturbances may continue their motion straight west into the Caribbean or begin curving northwestward (in some cases, northward) towards coastal regions of the southeastern United States. Intrusion of extratropical anomalies further complicates the picture. Because genesis depends on precursor disturbances and how they interact with their environment, and these factors likewise are uncertain, it is important to address model errors that arise from poor initialization of resolvable motions and their consequences for TC precursors. Needless to say, this problem has significant consequences for coastal populations of U.S., and considerable improvement is needed in this region in order to differentiate between developing and non-developing systems. The West Atlantic is either a graveyard (e.g., Chris 2006) or spawning ground (e.g., Katrina 2005) of tropical depressions depending largely on whether or not the environment is favorable for genesis. In 2004, the largest errors in the NHC official 24-48 h intensity forecasts at landfall (or closest approach in the case of Alex) occurred for TT events.

3. Field measurement objectives and strategy

a. Measurement objectives

PREDICT seeks measurements of synoptic-scale and mesoscale features, emphasizing the interplay between convection and rotational structures on the mesoscale in the genesis process. Below is a list of key observational and simulation objectives, with their related hypotheses listed:

i. Map the structure of tropical waves and identify the sweet spots therein, emphasizing mesoscale variations of convection, humidity and rotational features. Determine horizontal and vertical wind shear, saturation fraction characteristics of the critical layer **(H1)**. The region to be covered corresponds approximately to the “cluster” region in Fig. 1. However, a variety of different types of possible precursor disturbances should be measured **(H2)**. These measurements are important for determining whether a critical layer exists and whether genesis is intimately related to convection in this area **(H1)**. The measurements will also be helpful in assessing the validity of estimates of vertical shear and column humidity derived from large-scale analyses.

ii. Observe the vertical structure of the temperature, pressure-gradient and wind fields in candidate pouch regions. Measure area-integrated vorticity and divergence at different altitudes around areas of deep convection. These convective regions will often be individual MCSs (scale of 200 km). There may be smaller, intense convective features (50-100 km) embedded within that would also be a target. Measurements around the circuit need to be made relatively quickly to avoid problems with evolution of the region inside. If gaps within the convecting region exist, transects would be helpful for determining whether there is cyclonic circulation within convective regions, whether a warm core exists, and whether the convection is updraft or downdraft dominated in the lower troposphere. If rotation is updraft dominated and circulation maximizes at low altitudes (1 km or so), we have evidence for “bottom up” development **(H3)**. To address H3, PREDICT measurements must be taken at multiple altitudes around and through regions containing organized convection.

iii. Measure the water vapor field at several altitudes (including mid-troposphere, lower troposphere and PBL) to assess column humidity and mesoscale variations of water vapor near convective features. These measurements will help confirm (a) whether Saharan air makes intrusions (see also *iv*) and (b) whether downdrafts would be inhibited at low altitudes **(H3)**.

iv. Examine the aerosol and thermodynamic properties of Saharan Air Layers. In particular, measure concentrations and radiative forcing within regions of dust. Document the mesoscale distribution of dry air and dust to determine if it is actually being entrained into regions of convection **(H4)**. The counterflow virtual impactor (CVI) can detect dust residuals after condensate particles sublimate in the probes’ housing and would give the composition of the aerosols/ice nuclei producing the condensate. The addition of numerous condensation nuclei will affect particle sizes. Smaller particles will be lofted, perhaps forming more extensive stratiform regions and making mesoscale downdrafts more likely. A related effect is changing the vertical profile of diabatic heating over a region, and thus changing the PV anomaly generation profile.

v. Conduct hierarchies of numerical simulations of genesis, tested with field observations, to (a) further test genesis hypotheses, and (b) deduce key limiting factors in predicting genesis, including observations

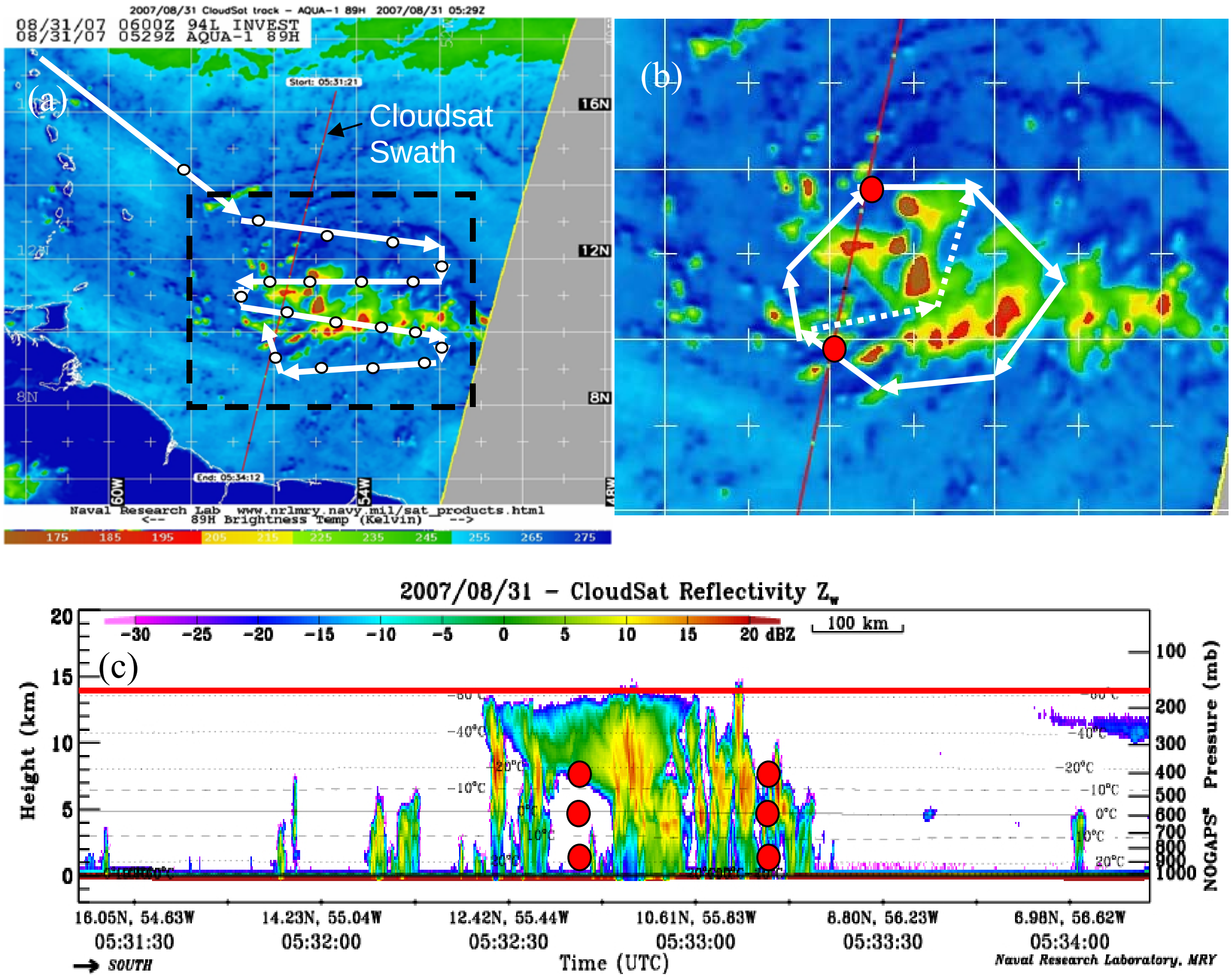

Figure 5. (a) 89 GHz brightness temperatures from AMSU on 31 August, 2007 prior to the development of the tropical depression that became hurricane Felix. Superposed are flight tracks and suggested dropsondes locations (white); (b) close-up of 89 GHz image in (a) with mesoscale flight tracks superposed; (c) CLOUDSAT image (see red track in (b)) showing reflectivity. Large red dots indicate intersections of mesoscale flight patterns in (b) with cross section, showing flight levels of 1, 5 and 14 km. Courtesy NRL.

needed to improve genesis prediction and limitations of model physical processes **(H5)**. Observations will be crucial for both initialization and verification of numerical simulations. Examine which observations bear most strongly on prediction skill for depression formation.

The targeted geographical region is the Central and Western Atlantic Ocean, including the Caribbean Sea. The project is planned for a 1.5-month period, **15 August – 30 September, 2010**. Figure 2 shows the approximate PREDICT study region. The planned base for the study is in the Virgin Islands (St. Croix), although from a scientific standpoint, a base anywhere in the eastern Caribbean Sea should suffice. Given the range of the G-V, the approximate longitudinal domain is 40ºW to 90ºW. The latitudinal domain will extend from the Equator to 35ºN. The climatology of TC genesis in the PREDICT region of study is also illustrated in Fig. 2. Within the PREDICT domain (blue circle in Fig. 2a) an average of 6-7 events occur each year. Based on best track statistics compiled by NHC (http://www.nhc.noaa.gov/pastprofile.shtml), 60% of the annual average number of named storms occur during the planned time of PREDICT (15 August to 30 September). Hence an average of four named systems could be expected within the spatial and temporal domain of PREDICT. From previous studies such as McBride and Zehr (1981) we expect the number of non-developing systems to be several times that of developing systems. From the later climatological work of Thorncroft and Hodges (2001), we estimate roughly 6-10 easterly wave events would fall within the PREDICT time and space domain. To these are added precursor disturbances originating from higher latitudes moving into the tropics or subtropics. In total, it is reasonable to expect at least 10-12 disturbances will occur that have potential to develop, but will not. Therefore, a total of 15 disturbances in 45 days would appear a reasonable expectation.

b. Use of the NCAR G-V (overview only)

PREDICT proposes to use **200 research flight hours** of the NCAR G-V, equipped with **500** Global Positioning System (GPS) dropsondes and other instruments (Table 1). Because of its range and altitude, the G-V is well suited to survey mesoscale and synoptic-scale structures accompanying candidate disturbances for genesis. The G-V will fly between 40,000 and 45,000 feet MSL, conducting a survey pattern (Figure 5a) within a synoptic-scale feature, mapping out the distribution of state variables (especially wind) at flight level, deploying dropsondes at roughly 100-150 km spacing. Following the ferry (2.5 hours or less), the pattern at high-altitude (Figure 5a) would take about 2.5 h to execute. In this particular case, there is a well-defined, east-west elongated region of deep-convective elements, the western half of which appears particularly active. While the AQUA image shown below may or may not be available in near-real time, GOES data for this case clearly indicates strong convection in this region. The tops of the mesoscale convective features (roughly 50 km in scale, yellow-red regions in Figure 5b) are around 14 km (45,000 ft; Figure 5c). After the survey pattern is completed, the mesoscale pattern will focus around the most active convection as suggested in Figure 5b. Preference will be given to the intersection of the wave critical layer with the region of convection. Note that we will not generally target individual convective features at takeoff time. The target region will be determined in real time from the high-level survey and available satellite data (including geostationary IR, WV, and microwave data from SSMI, TRMM and AMSU). We will also deduce where the critical layer of the wave intersects the wave trough in the lower troposphere (from global analyses, satellite data or dropsondes), then this will also aid in guiding the aircraft to subregions within the wave trough (or gyre). For the mesoscale pattern, a circuit around this convection will be executed at least three altitudes, 8 km, 5 km and 1 km, designed so that each circuit would be completed in an hour or less. The flight pattern can be easily scaled to encompass larger or smaller convective regions. Following a mesoscale circumnavigation of a region, if it is noted that convective features within the region are sufficiently far apart, then a traverse of the mesoscale region would be highly desirable to better observe what is happening within the region (see dashed line in Fig. 5b). In some cases, convective activity may be relatively weak in the target region during the time of sampling. But there needs to have been widespread deep convection in the recent past, coupled with the presence of a critical layer, to provide an acceptable mesoscale target. The primary measurements and flight patterns are outlined and expanded upon in the EDO. *Please refer to this document for detailed information.*

c. General deployment considerations

In general, cases with **organized convection** (persisting through the diurnal cycle with horizontal dimension more than 200 km, not tied obviously to land) **embedded within a larger-scale disturbance** (baroclinic or not) are of primary interest and would probably trigger an intensive observing period (IOP). Preference will be given to convection that is located in a region near where the critical layer of the larger-scale wave intersects the wave trough in the lower troposphere (e.g. 700 hPa). Evidence of mesoscale circulation, based on satellite loops or QUIKSCAT surface winds will not be necessary to launch aircraft. We want the opportunity to sample convection without a lower tropospheric circulation already present, at least in some cases. Satellite observations and global analyses (and short-range forecasts) will be the primary tools used to decide on a deployment. Consultation with the National

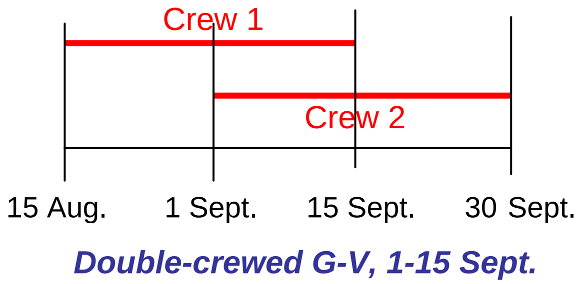

Figure 6. Schematic time-line for PREDICT.

Hurricane Center will be important for determining systems that have at least some development potential.

One of the limitations of past projects is a lack of continuous, or nearly continuous sampling of disturbances prior to depressio formation. One of the objectives of PREDICT is to have two flight crews available for a portion of the experiment (Figure 6) so that back-to-back missions may be flown. In the schematic time-line of the project, two flight crews are used each for 30 days, so that they overlap for 15 days (the first half of September) when Atlantic tropical storm formation is climatologically most likely. In a typical scenario during the double-crewed segment of the project, we would execute the flight patterns of Fig. 5 on back-to-back missions during a single 24-hour period. Each flight would last about 10 hours. It is desirable that this schedule could be maintained for at least 48 hours if a case continues to show potential to develop. Thus, we plan to use 4 flights (possibly more) on a single case.

4. Post-Field Analysis, Numerical Modeling and Data Assimilation

The objectives of post-field analysis will be to quantitatively address the hypotheses advanced in Sec. 2. The analysis can be broken into 3 categories; (a) mesoscale analysis of field data, combined with global analyses; (b) microphysical analysis (c) numerical modeling and data assimilation. We anticipate placing dropsondes data on the Global Telecommunication System (GTS) so that they may be transmitted to operational centers. It is also desirable to create analyses with and without the collected observations. This can be done through off-line data assimilation experiments that create datasets of higher resolution than available from global models.

Resulting analyses will be important for performing initial estimates of vertical structure of divergence, vorticity and temperature on both the synoptic-scale and mesoscale. The vertical structure of these quantities is particularly relevant around mesoscale convective elements. Preliminary trajectory analyses will also be constructed with global analyses, mainly for purposes of mission planning and quick-look synopses immediately after the project. Considerably more detailed trajectory analyses will be performed using simulations using mesoscale models (in particular the WRF model) constrained with field observations to fully address the marsupial hypothesis, and to better understand the origin of upper tropospheric PV features in cases where these appear important.

The vertical profiles of divergence will be converted to profiles of vertical mass flux. This can be accomplished from dropsondes analysis, employing time-space correction. Trier and Davis (2007) were able to obtain useful profiles in the lower and middle troposphere from such data. It can also be accomplished form the mesoscale flight patterns around closed circuits, although there will be a non-negligible time delay between patterns at different altitudes. Doppler radar data from the cloud-radar will also be used to the extent possible to vertical air motions. However, we do not expect to penetrate significant convective features. Still, vertical air motions (appropriately filtered) surrounding convective features are still useful for deducing how convection interacts with the temperature in the environment (Mapes and Houze 1995).

We will aggressively pursue ensemble data assimilation techniques as a method to initialize models, through which process studies, ensemble predictability studies and data denial exercises can be conducted. The ensemble Kalman filter (EnKF) has been implemented by Snyder and Zhang (2003) for the study of convective-scale phenomena. This approach involves the incorporation of both a large-scale balanced state and various types of perturbations, part of which could be meteorological observations obtained during the field campaign. It appears to make better use of sparse observations (even taken at different times) by allowing covariances to be flow dependent (see also planning letters of Majumdar, Torn and Zhang).

In addition to allowing the inclusion of experimental observations, the simulation ensembles can be the focus of lag-correlation sensitivity analysis by which the sensitivity of features at one time to conditions at a previous time can be assessed. This uses lag correlations among ensemble members. It is not dependent on linear dynamics as is the adjoint sensitivity calculation. Ideally both techniques will be used to assess sensitivity, and experiments can then be conducted by which observations are withheld from the assimilation process to see what observations have the greatest effect on simulating the formation process. PREDICT observations should allow better diagnosis of the relative roles of observational uncertainty and model physics in this sensitivity.

We will also investigate the numerical treatment of the basic physics of the genesis process by performing detailed evaluation of predictions using field observations. One of the striking elements of simulations, particularly those run at "convection permitting" grid spacings of 1-4 km, is their production of PV anomalies at a low altitude (~1 km) in regions of deep convection. These anomalies have been shown crucial for genesis in numerous studies (e.g. Davis and Bosart 2001, Hendricks et al. 2004, Montgomery et al. 2006, Davis and Bosart 2006). Such anomalies have a warm core structure from the outset. There is some tantalizing observational evidence for these structures (Reasor et al. 2005), but not enough to confirm their general validity. Measurements from PREDICT will be crucial for documenting the validity of these features and assessing the physical reasonableness of numerically simulated genesis.

Numerical simulations will also be used to construct detailed budgets of moist entropy and vorticity, including terms related to frictional dissipation. The flux form of the vorticity budget will be used (Haynes and McIntyre 1987, Raymond et al. 1998). This flux form is given by

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial x}\left[u\eta + \omega\frac{\partial v}{\partial p} - F_y\right] - \frac{\partial}{\partial y}\left[v\eta - \omega\frac{\partial u}{\partial p} + F_x\right], \tag{1}$$

where ζ is the relative vorticity (on a pressure surface), η is the absolute vorticity, ω is the vertical velocity in pressure coordinates and F is the frictional force. The form of (1) is well-suited to budget computations over regions with complex convective processes operating within that are either not fully resolved (observations) or are difficult to understand from a Lagrangian perspective. Combined model and observational studies will be used to better understand how convection is organized by various pre-depression synoptic-scale (and mesoscale) disturbances. The related modeling activities will span a hierarchy from idealized to real-data simulations.

Post-analysis of cloud microphysical data will emphasize analysis of residuals from the Counterflow Virtual Impactor (CVI) to infer whether or not Saharan dust was directly involved in convection. Trajectory analyses from models may assist in determining whether Saharan air was able to penetrate into regions of convection, but this analysis alone will not be sufficient. In addition, particle size distributions will be analyzed to suggest how the presence or absence of dust affects these, assuming that we will sample both regions affected and not affected within the same convective cluster.

Through a mixing ratio-thermodynamic analysis, the so called Q-theta Q or Paluch-type analysis (Paluch 1979, Heymsfield et al. 2005) using the CVI, particle probes and temperature and water vapor measurements, we will conduct an analysis of the origin of entrained air in the updraft regions that are successfully sampled with the G-V. From the particle probe data, we will develop relationships between the measured ice water content (IWC) or that derived from the particle probe size distributions and the radar reflectivity either measured or again from the PSD. This type of analysis will allow us to infer the amount of precipitation-size particles (water and/or ice) in the updraft regions and its change with height for water budget estimates, to deduce vertical motions from the Doppler cloud-radar data and to correct for attenuation above the melting layer.

The particle size distributions will be used to assess the performance of the microphysical packages in WRF as they apply to developing hurricane situations (e.g. Heymsfield et al. 2006). From the physics standpoint, we wish to examine whether in fact vigorous tropical convection is largely devoid of supercooled liquid water as has been found in many studies of tropical maritime convection or whether there are some conditions operative within the hypothesized marsupial pouch that are conducive to its maintenance. Provided we are able to sample some supercooled regions, the role of dust, and secondary ice production processes such as the Hallett-Mossop process on ice production and diabatic heating will be studied.

5. Collaborations

PREDICT is proposed as a self-contained project. However, there are some potential opportunities for collaboration that are currently in the planning stages. We briefly mention them here, and suggest how the collaborations could be manifested in the field to benefit both projects.

a. NOAA

The principal participation of NOAA will be with one or two NOAA P-3s as part of the Genesis Experiment (GENEX) also planned for 2010 (see attached letter of support from NOAA's Hurricane Research Division Director, Dr. Frank Marks, Jr.). Current planning is to base the P-3s in Barbados. Flight coordination with one or more NOAA P-3s is desirable primarily for (a) tail Doppler radar reflectivity and winds and (b) surface winds from the stepped-frequency microwave radiometer. The P-3 would fly at approximately 10,000 feet. The precise flight patterns will require coordination with HRD and will have to accommodate any operational requirements that may exist. Targets will be mesoscale convective features (100-200 km scale). The objective will be to enhance the wind measurements from the G-V by remotely sensing convective regions. As shown by Raymond et al. (1998) and Reasor et al. (2005), P-3 Doppler winds can be useful for obtaining divergence profiles and documenting the existence and vertical structure of mesoscale cyclonic circulations. Mapes and Houze (1995) also used P-3 Doppler radar data collected during purls (relatively tight circular flight tracks) within MCSs to compute accurate divergence profiles. Two factors may limit the extent of coordination between the G-V and NOAA aircraft. First is the likelihood of tasking the P-3s to perform operational missions elsewhere. If these missions require sampling the disturbance targeted by PREDICT, coordination is still possible. Second, there is the difference in range of the G-V and P-3s, which is about a factor of 2 for a given 9-10 hour flight. Forward deployment, or alternate-site recovery of the P-3 would help mitigate the difference in range of the two aircraft.

b. NASA

Plans for a NASA field effort in 2010 are just beginning. However, indications are that the focus will be over the Central and Western Atlantic Ocean, centered on September, using the DC-8 equipped with new remote-sensing capabilities. To the extent possible, PREDICT will coordinate with any NASA effort should it be deemed that collaboration would be mutually beneficial. It should be noted that the 1-page letters of intent include statements from NASA and NOAA scientists. There is a full intent to collaborate with these agencies in modeling activities even if full coordination of measurements across agencies proves impractical in the field phase.

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I. Facilities, Equipment and Other Resources

Platform	Function	Key Motivation	Request	Cost
G-V	a. Upper-trop surveillance b. Dropsondes c. Remote sensing d. Microphysics	a. High Altitude b. Range	200 research hours	$1.3M
Dropsondes	Tropospheric wind, temp and moisture profiles	a. Thermodynamics b. Mesoscale and synoptic-scale dynamics	500	$0.6M
EOL Field Support	Data catalogue, operations director, aircraft coordination, special products and displays			$0.4M
Table 1. Facilities requested for PREDICT.				Total $2.3M

G-V Instruments	Function	Key Motivation
Highest Priority		
Microwave Temperature Profiler	Temperature profiles along flight track	Thermodynamic structure; detecting mesoscale warm core
Differential GPS	Accurate altitude measurement	Compute geopotential height on pressure surfaces
Small Ice Detector	Size distributions and phase of aerosols and water/ice particles 1 to 60 microns	Water phase, size distributions, crystal shapes, estimates of scattering properties, quantifying the properties of aerosols >1 micron.
Counterflow Virtual Impactor	a. Measurement of condensed water content b. Residuals of cloud active aerosols	a. Water budget estimates b. To determine whether African dust and air is involved in the convection
2-D imaging probes	Size distributions and shape of cloud through precipitation particles	a. Water budget estimates b. Estimates of radiative properties of cloud particles
TDL hygrometer	Accurate humidity	Influence of Saharan air on convection

High Priority but Uncertain Availability		
Cloud radar	Differential reflectivity, vertical velocity	Distinguish particle and air motions
Not Highest Priority		
Fast ozone	Ozone concentration	Detect presence of stratospheric air in upper-level troughs

Table 2. Instruments for G-V.

J. Special Information and Supplementary Documentation

PREDICT Science Steering Committee	
Michael Montgomery	Naval Postgraduate School and NOAA HRD
Christopher Davis	NCAR
Lance Bosart	University at Albany SUNY
Andrew Heymsfield	NCAR
PREDICT Investigators	
Michael Bell	Naval Postgraduate School and NCAR
Scott Braun	NASA GSFC
Timothy Dunkerton	NorthWest Research Associates and NPS
Sharan Majumdar	University of Miami
Brian Mapes	University of Miami
Robert Rogers	NOAA HRD
Ryan Torn	NCAR (university at Albany SUNY Sept. 08)
Chris Velden	University of Wisconsin
Fuqing Zhang	Texas A&M University

To: OFAP
From: Professor M. T. Montgomery (P.I.), U.S. Naval Postgraduate School and NOAA's Hurricane Research Division
Re: Letter of intent for participation in PREDICT (page 1 of 2)

Testing the marsupial hypotheses in the Atlantic sector during PREDICT

The genesis of tropical cyclones (TCs), hurricanes and typhoons is one of the most important and still largely unsolved theoretical and practical problems in tropical and dynamical meteorology. In prior NSF research the P.I. posed the TC genesis problem as the metamorphosis of a middle-level mesoscale convective vortex (MCV) with weak cyclonic circulation at the ocean surface into a self sustaining warm-core tropical depression vortex. Cloud system model experiments suggested a plausible vortex construction process driven by vortical hot towers (VHTs) within an MCV embryo possessing a small but finite amplitude cyclonic surface circulation (Montgomery et al. 2006, *J. Atmos. Sci.*). Yet to be answered, however, is how such embryonic circulations are created in the first place, and whether they can survive and strengthen sufficiently when subject to dry air intrusions and/or vertical shear so as to complete the transition to a self-sustaining warm-core vortex.

The P.I. and his NPS team have recently advanced new dynamical and thermodynamical hypotheses concerning the creation of TC embryos and subsequent multi-scale processes that operate within and sometimes culminate in the birth of a tropical depression vortex. The P.I. has recently been awarded a new five year NSF grant to explore these hypotheses and to develop a comprehensive understanding of synoptic scale, mesoscale and cloud scale phenomena relevant to the genesis of tropical cyclones within realistic tropical wave and monsoon trough environments. The grant "**On the marsupial theory for tropical cyclogenesis within tropical wave and monsoon trough environments: A multiscale observational, modeling and theoretical study"** is a five year NSF grant that covers a time frame (at no cost) well beyond the the proposed period of PREDICT and subsequent analyses.

As part of the marsupial project the P.I. will work with his NPS team and all senior personnel and participants in PREDICT to ensure that the observational component of this research program includes all available analyses, airborne Doppler radar data (from NOAA P3s), in situ dropwindsonde data (from GV and NOAA P3), satellite products, as well as a (no-cost) collaboration with NOAA's Hurricane Research Division [as part of its annual field program for the Atlantic and Eastern Pacific region]. The P.I. plans to work closely with his colleagues Timothy Dunkerton (NWRA) and Zhuo Wang (NPS) in developing a suite of large-scale operational analysis tools to assist the team in real-time planning and execution of GV missions (see supporting EDO for details). The P.I. also plans to work with PREDICT senior personnel Chris Davis (NCAR), Lance Bosart (SUNY/Albany) and participants Rob Rogers/Frank Marks/Jason Dunion (HRD), Scott Braun (NASA), Michael Bell (NPS/NCAR) and Brian Mapes (RSMAS) in the analysis of dropwindsonde, satellite, and Doppler radar data collected during the PREDICT campaign. Such observational data of mesoscale processes in combination with large-scale analyses should provide crucial insight into the multi-scale interaction between waves and vortices that are expected result in new conceptual tools of such atmospheric events for the forecasting community.

The broader impacts and outreach from the P.I's funded research program and the PREDICT experiment are manifold. This research will advance the state of understanding of the multi-scale interaction between tropical waves and proto-vortices that do or do not become tropical storms. This work will also obtain new insight into how different environments in the current climate influence TC genesis. The military graduate students, that work with the P.I. and the PREDICT team, come at no cost to NSF. The NPS military students, post-docs, research associates and senior personnel working on this project will constitute a highly creative research team with both practical and theoretical objectives. The novel analyses and tools developed herein will be integrated into the P.I's graduate dynamic meteorology, tropical meteorology and geophysical fluid dynamics courses at the Naval Post Graduate School.

Multi-scale Aspects of Western Atlantic Tropical Cyclogenesis

Christopher A. Davis
NCAR

I will focus on the distinction of the synoptic-scale structure and mesoscale aspects of developing versus non-developing systems. One goal is to seek an underlying understanding of genesis that transcends latitude, that is, pertains to tropical transition (higher latitude) and easterly wave (or other) genesis in the tropics. I propose both numerical experiments and observational analysis of dropsondes, flight-level data, and microwave temperature profiler (MTP) data to (a) determine the influence of quasi-balanced larger-scale vertical motions on convective organization; (b) understand the mechanism for mesoscale vorticity generation within the convection; and (c) evaluate whether genesis as simulated in mesoscale models is realistic. Item (a) seeks to determine whether there are attributes of precursors that are sufficient to initiate genesis. Especially in tropical transition (TT), the transformation of cold core disturbances to warm core, there is evidence that precursors of extratropical origin exert a powerful influence on genesis. However, the precise factors that distinguish developing and non-developing cases are not known. Item (b) essentially addresses whether genesis involves a scale contraction or synoptic-scale vorticity to the mesoscale, or fundamentally relies on an upscale cascade of vorticity. Clearly, the spinup of vorticity in tropical cyclone formation requires convergence and contraction. The question is whether the contraction occurs on the mesoscale or on the convective scale. Item (c) requires the field data to perform detailed interrogations of both mesoscale and global model predictions of genesis.

I anticipate extensive collaboration with several other investigators in PREDICT, including Drs. Lance Bosart, Michael Montgomery and Fuqing Zhang. PREDICT represents a unique opportunity to understand processes that generate mesoscale circulation and how that circulation grows to tap the latent energy of the upper ocean.

I anticipate devoting 0.2 FTE of base each year to the analysis of PREDICT data, in addition to time spent developing the project, and in addition to any external funding support than can be obtained.

PREDICT Letter of Intent: 30 December 2007

Professor Lance F. Bosart
Department of Earth and Atmospheric Sciences
The University at Albany/SUNY
1400 Washington Avenue
Albany, New York 12222

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The PI has four research objectives related to tropical cyclone (TC) formation that are relevant to PREDICT. The first objective is to investigate the structure and evolution of upper-level synoptic-scale precursor disturbances that serve as precursors to tropical depression (TD) formation and to distinguish between those precursor disturbances that trigger TD formation from those that do not. The second objective is to investigate the structure and evolution of the precursor synoptic-scale disturbances that inhabit the multiple pathways that can lead to tropical cyclogenesis in the North Atlantic. Research reported in McTaggart-Cowan et al. (2008) identified six distinct TC genesis pathways in the North Atlantic: 1) non-baroclinic, 2) trough induced, 3) low-level baroclinic, 4) weak tropical transition (TT), 5) transient trough interaction, and 6) strong TT. In support of these twin research objectives it will be necessary to determine how precursor disturbances act to generate organized deep convection prior to TD formation along the different genesis pathways. At issue is how the organizing convection is related to the precursor disturbance, what role vertical wind shear associated with the precursor disturbance plays in organizing the convection and subsequent TD formation, and whether TD formation proceeds through a similar mesoscale process that is quasi independent of the genesis pathway.

The third objective is to examine the structure, evolution and interaction of multiple mesoscale and convective-scale vortices prior to and accompanying TD formation. At issue is how these vortices grow and interact, whether their development is from the top down and/or from the bottom up, and how the associated evolution of the mesoscale moisture, vorticity and potential vorticity (PV) fields determines the nature and distribution of the organizing convection and the associated vortices. The fourth objective is to participate in cooperative diagnostic and modeling investigations of TT (including null events). Cooperative research opportunities with other PIs participating in PREDICT will be pursued.

In order to accomplish these research objectives, the PI will participate in the analysis of flight-level and dropsonde observations obtained from the proposed PREDICT research aircraft (NCAR G-V). The PI is especially interested in using observations derived from the G-V to help document the evolution of the three-dimensional moisture, vorticity and PV fields on the convective scale and the mesoscale and to relate these fields to the structure of the triggering precursor synoptic-scale disturbance prior to and during TD formation.

The PI will conduct the proposed research with two graduate students (one Ph. D.; one Masters) or possibly one Ph. D. student and one postdoctoral research associate. He also plans to continue his ongoing productive cooperative research with Dr. Chris Davis of NCAR and Dr. Michael Montgomery of the Naval Postgraduate School in support of the four research objectives described above. The estimated proposal budget will be $160,000 each year for three years.

Andrew Heymsfield

NCAR

I am interested in examining phase change and the growth of hydrometeors in the critical temperature range 0 to -12C in the updrafts of maritime mesoscale convective systems. (MCS) Almost nothing is known about the ice nucleation processes operative in MCS, tropical storms, or hurricanes in this temperature range. Is much of the liquid water coalesced into raindrops that fall out of the updrafts before reaching the 0C temperature level? What faction of the cloud base mixing ratio is carried to supercooled temperatures versus falling out through the updrafts. Is liquid water almost entirely absent in the 0 to -12C temperature range, or does it freeze at supercooled temperatures and play a key role in the subsequent latent heating in the updrafts? Do secondary ice formation processes, including the so-called Hallet-Mossop effect which involves the interaction of small and large cloud droplets and ice particles, play a prominent role in the ice production and depletion processes in the updrafts. Is the precipitation at subfreezing temperatures dominated by graupel resulting from the freezing of large drops or is it the result of the accretional growth of ice particles.

A particularly interesting question will be to address the interrelationship of precipitation and updraft dynamics. If much of the condensate falls out of the updrafts at temperatures above 0C, does this unloading of the updrafts lead to updraft acceleration at subfreezing temperatures or is the acceleration, if present, the result of latent heating. Is appreciable dry air entrained into the updrafts and how is this affected by updraft acceleration. Is there significant "evaporation" ice nucleation?

Can we remotely sense the ice particle production process in maritime MCS from radar data. Can we quantify the association of lightning and supercooled liquid water, and can we ascertain the ice nucleation and precipitation production processes in the updrafts from remote sensing (radar) measurements.

Proposed research in support of PREDICT: Diagnosing the influence of observations on high-resolution numerical predictions of tropical cyclogenesis

PI: Dr Sharanya J. Majumdar
RSMAS Division of Meteorology and Physical Oceanography, Univ. Miami
4600 Rickenbacker Causeway, Miami, FL 33149.
Phone: (305) 421 4779. E-mail: smajumdar@rsmas.miami.edu

Proposed Project Duration: 3 years
Approximate Cumulative Budget: $250,000 (1 month PI salary per year, full graduate student stipend, Indirect Cost Rate 53.5%)
No additional funds are requested for fieldwork.

Our research aims to contribute towards several scientific questions proposed as part of PREDICT, with a particular focus on the following question:

"What additional observations or improvements in numerical models are most important for improving prediction of tropical depression formation?"

While tropical cyclone (TC) formation has been difficult to predict historically, the representation of important mesoscale processes in high-resolution numerical models has offered new ground for optimism. The proposed research, in collaboration with other PIs in PREDICT, will focus on identifying the dominant processes that control the predictability of developing TCs, using the hurricane Weather Research and Forecasting (WRF) model. The influence of assimilating special observations in WRF will be investigated both qualitatively (via diagnostics) and quantitatively (predictive skill).

An example of identifying the relative influence of data on *different scales* is to compare the assimilation of environmental wind fields versus inner-core variables. Does the absence of an accurate environmental wind field hurt the predictability of TC genesis more than the absence of dynamic and thermodynamic data in the incipient inner-core?

An example of identifying the important *variables* and levels for observation would be to examine the differences between assimilating wind versus temperature versus humidity data in a developing TC. Which variables are necessary to produce the optimal representation of the environment that interacts with the convective structure?

In parallel, the assimilation of aircraft-borne data (and routine rawinsonde data) collected in 'sensitive' regions identified by *adaptive observing strategies* such as the ensemble transform Kalman filter will provide insights into the efficacy of such strategies, which are heretofore unproven for prediction of TC formation.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory
Hurricane Research Division
4301 Rickenbacker Causeway Miami FL 33149

Dr. Robert Rogers
NOAA/AOML Hurricane Research Division
4301 Rickenbacker Causeway
Miami, FL 33149

January 3, 2008

Dr. Steve Nelson
National Science Foundation

Dear Dr. Nelson:

This letter is intended to state NOAA's interest in the data that will be collected as part of the proposed NSF PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT) experiment. The data that will be collected during the PREDICT experiment will serve NOAA's goals of improving tropical cyclone prediction and understanding. While forecasts of tropical cyclone track have shown significant improvements in recent years, corresponding improvements in forecasts of tropical cyclone intensity have been much slower. The lack of improvement in intensity forecasting is the result of many factors: deficiencies in the observations and the specification of the initial state of the atmosphere, deficiencies in the numerical models (e.g., resolution limitations, lateral boundary condition errors, and parameterization inadequacies), and deficiencies in our basic understanding of the physical processes involved. The forecasting problem becomes even more acute for tropical cyclogenesis. While global models have shown some skill in recent years in predicting tropical cyclogenesis, our understanding of the physical processes involved remains limited, largely because observing genesis events is a difficult task. Yet with operational hurricane forecasts now extending to five days, the forecast window frequently extends to a time period that requires the successful prediction of tropical cyclone formation. Thus improving the prediction of tropical cyclogenesis is vital.

A key aspect of the NOAA Intensity Forecasting Experiment (IFEX) is the collection of observations during all portions of a tropical cyclone's lifecycle, particularly during the early lifecycle stages that include pre-genesis events, in support of the development and testing of the Hurricane Weather Research and Forecasting (HWRF) model. The data that will be collected by PREDICT will aid NOAA by: 1) allowing for the d evelopment of improved specifications of initial conditions for incipient tropical cyclones and their environment, a particular challenge for weak or developing systems; 2) providing datasets for evaluating the ability of the models to reproduce the observed structure and evolution of developing disturbances, and 3) enabling investigations of the physical mechanisms that underlie the development (or non-development) of incipient tropical cyclones.

If you have any further questions, please feel free to contact me at 305-361-4536, or Robert.Rogers@noaa.gov.

Sincerely,

Robert Rogers

Research Intent for the PREDICT Experiment

Ryan Torn
NCAR/MMM, University at Albany, State University of New York

My interest in PREDICT is rooted in the dynamics, predictability and data assimilation research that I have performed over the past six years. Specifically, I am interested in testing the hypotheses that improved initial conditions near the precursor disturbances will lead to better forecasts of tropical cyclone (TC) genesis.

One method of improving a model's initial conditions is to assimilate additional observations in regions where small errors can rapidly amplify during the subsequent forecast. In all data assimilation schemes, the observation information is spread to model state variables based on error statistics; this is done in most operational assimilation systems via quasi-fixed error covariance matrices based on climatological error statistics. As a consequence, these statistics are not likely to correct the state in a manner consistent with the transient mesoscale systems that will be studied in this experiment. Ensemble data assimilation systems, which I use extensively, employ error statistics derived from an ensemble of short-term forecasts, which provide a flow-dependent estimate of how to adjust the model's state variables based on the observations. Such ensemble systems have been shown to be competitive or even superior to variational systems in regions of sparse observations or at the meso- and convective scale, where error statistics are unknown and can rapidly change.

Using data taken during this experiment, I would like to evaluate the impact of assimilating observations of these mesoscale systems with flow-dependent error statistics on TC precursor predictability. The analysis ensemble generated by ensemble data assimilation systems are equally-likely representations of the atmosphere, which provides multiple initial conditions that can be used to assess the predictability and error growth associated with these systems. In addition, the analyses generated by such a system also give three-dimensional gridded fields based on the observational data collected during the field campaign. At this time, I do not plan to run this data assimilation system in real-time; however, it can be done if the PIs believe it would be useful. Such a system could be used in the field phase to suggest where to take observations within the mesoscale systems.

Previous work by Greg Hakim and I has shown that the statistics from such an analysis ensemble can be used to derive dynamical relationships between model state variables. I also plan to use the ensemble analyses to statistically evaluate the dynamical hypotheses being proposed by this field campaign. For example, I would like to assess how the humidification of the mid-layers or the overall circulation contribute to the model's development of these mesoscale systems into tropical cyclones.

PREDICT Letter of Intent to Propose: 31 December 2007

Senior Research Scientist Christopher S. Velden
Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin - Madison
Email: chrisv@ssec.wisc.edu

The principle hypotheses to be tested in this proposed research project will involve an extensive observational component. In addition to the in situ resources planned for the 2010 field experiment, the needed 4D environmental analyses will benefit greatly from targeted satellite observations. The investigator and his team will bring an extensive array of satellite-based data and products to support this research effort focused on TC genesis processes, including: 1) High-density (space and time) wind vector fields derived from GOES rapid-scan imagery for detailed diagnostics such as upper-level divergence and vertical wind shear, 2) Microwave-based observations from AMSU to delineate tropospheric thermal anomalies over precursor disturbances, 3) Moisture fields derived from multi-satellite platforms, morphed temporally using the MIMIC tool to provide time-continuous evolution of TPW structures, 4) Analyses of the Saharan Air Layer (SAL) and Saharan dust based on algorithms developed at CIMSS, and 5) The highest resolution satellite imagery to map mesoscale cloud structure with aircraft radar and flight observations.

The above tools will help support the objectives outlined by other co-investigators related to TC formation that are relevant to PREDICT. My objectives are related to these, and will focus on several areas. The first objective is to investigate the upper-level mesoscale structure and evolution of disturbances that might serve as precursors to tropical depression (TD) formation, and to distinguish between those precursor disturbances that trigger TD formation from those that do not. The second objective is to better identify the role of the SAL as an inhibiting agent in the TC genesis process. Third, can specific satellite signatures of the genesis process be identified and related to key mesoscale formation processes as established by aircraft radar and flight data? If so, can these be used to extend existing satellite-based objective TC intensity estimation algorithms to the incipient TC stages of development? At issue here is if we can employ the field experiment findings to extend them practically into operational practice using satellite-based analyses. The fourth objective is to participate in cooperative diagnostic and modeling investigations with other PIs participating in PREDICT.

I will conduct the proposed research with one assistant scientist and one graduate. My estimated proposal budget will be $75K, $150K, and $150K for the three years, assuming the middle year as the field project.

PREDICTABILITY AND DATA ASSIMILATION OF TROPICAL DEPRESSION FORMATION

PIs: Fuqing Zhang (Texas A&M) and Chris Davis (NCAR)

Our primary objective is to explore the dynamics, observability and predictability of tropical cloud systems preceding the formation of tropical depressions through assimilating both simulated and field-campaign airborne lidar/radar, dropsonde and other in-flight measurements in addition to standard in-situ and remote observations that are routinely available.

Our primary approach will be using a high-resolution cloud-resolving ensemble analysis and forecast system based on WRF and ensemble Kalman filter (EnKF) developed at the Texas A&M University under a previous NSF support. The EnKF is a flexible state-estimation technique that use ensemble forecasts to estimate flow-dependent background error covariance or other probabilistic aspects of the background forecast. The effectiveness of the EnKF from convective to regional scales has been demonstrated by the PI and other research teams exclusively using both simulated and real-data observations. We will also be using the WRF-4DVAR currently under development in collaboration with Dr. Hans Huang at NCAR if it becomes available and affordable at any phase of the project.

Our working hypotheses are: (1) despite potentially significant model errors, poor initial conditions are the key factor in poor predictions of the earliest stages of tropical cyclones; (2) better forecass of these pre-depression systems may be expected with the ever-improving observing systems and the use of advanced data assimilation techniques including EnKF and 4DVAR; (3) predictability of the tropical depressions may be strongly flow-dependent, under some synoptic flow patterns, deterministic prediction of these systems may be ultimately limited by the chaotic nature of moist convection, its upscale error growth and interaction with large-scale environment; and (4) advanced ensemble analysis and prediction systems are necessary to provide flow-dependent *probabilistic* forecasts and risk assessment for tropical cyclones.

Related science questions are: What additional observations or improvements in numerical models and data assimilation methodology are most important for improving prediction of tropical depression formation? What are the key processes that limits the predictability of the pre-depression disturbances.

Our plan contributions to PREDICT: (1) The OSSE experiments with simulated observations for past events (both developed and non-developed) will be used to provide guidance to the design of flight plans and patterns during the PREDICT; (2) the WRF/EnKF cloud-resolving ensemble analysis and forecast system will be continuously running throughout the field phase of the project to provide real-time forecast guidance with the possibility of ingesting field campaign observations near real-time; (3) after the field campaign, the real-data experiments with PREDICT observations will be conducted to examine the design of future observational platform and network for monitoring and forecasting early stages of tropical cyclones. The analyses and forecasts will also be shared among PREDICT investigators to examine the structure, dynamics and predictability of pre-depression tropical cloud systems.

Estimated NSF budget request: 150K per year for 3 years supporting one month of my summer salary and a full-time postdoctoral researcher, computing and storage, field costs, travel, etc.

MESOSCALE & LARGE-SCALE ASPECTS OF TROPICAL DEPRESSION FORMATION

PI: Timothy J Dunkerton
Northwest Research Associates & Naval Postgraduate School

Estimated budget request: Two months of labor support for the PI and two months of labor support for Zhuo Wang, Assistant Research Professor at NPS, with travel support for the duration of the field experiment for two persons and additional travel support for science team meetings in each year. Period of performance: August 2010 – July 2012. Estimated cost to NSF: 67K per year for three (3) years.

Science objectives: To apply new knowledge of tropical wave dynamics, forward enstrophy cascade in the tropical wave critical layer and deep moist convection embedded therein, obtained in our ongoing research of the "marsupial theory", to the PREDICT field campaign in the central and western Atlantic. The evolution of precursor waves in the days prior to genesis, their aftermath after the proto-vortex departs the critical layer, and secondary excitation of new waves from the emerging tropical depression will occupy the large-scale component of the research. Structural changes of waves prior to genesis, owing to mean-flow shear (Orr mechanism) and other wave refraction effects, together with changes induced by diabatic activation (transition from equivalent barotropic in the lower troposphere to a deep first-baroclinic mode structure spanning the depth of the troposphere) are of interest, including subsequent effects on the UT/LS which have not been investigated previously. The forward enstrophy cascade describes the entrainment and redistribution of vorticity and moisture in the cat's eye of the tropical wave critical layer: most importantly, the formation of *mesoscale boundaries* that may be instrumental in triggering deep convection in the proto-vortex. The evolution of these boundaries is accessible from a successful field program when in situ measurements are combined with chaotic advection calculations driven by the large-scale analyses. More problematic is to obtain an understanding of the inverse energy cascade representing the self-aggregation of mesoscale convective vortices and rotating convective elements (vortical hot towers) triggered near the center of the critical-layer gyre. Circulation and moist entropy budgets around coarse-grained contours, as defined by a translating stream function within the gyre, may nevertheless capture the aggregate spinup of the meso-β vortex even when cloud-system vortices at meso-γ fall below the resolution of aircraft measurements. As a fast aircraft, the G-V provides an optimum platform for contour coverage (or execution of purls) in a reasonable time. If aircraft coverage together with vertical profiling by on-board instrumentation allows it, we may be able to obtain a vertical cross-section of mesoscale boundaries spanning the boundary layer to lower free troposphere, the most critical altitude range for convective triggering, Ekman pumping, excitation of inertia-gravity waves and density currents associated with convective outflow. Having such measurements of unbalanced motions in conjunction with vortical flow visualization obtained from the synthesis of aircraft and analysis-derived gyre finestructure (as described above) may provide, for the first time, the necessary juxtaposition of detailed vorticity and divergence fields in order to formulate an elementary understanding of TC genesis dynamics at meso-β.

Field campaign support: The PI and Zhuo Wang of NPS will provide real-time support to the PREDICT field campaign with products designed as part of our ongoing research on the marsupial theory of tropical cyclogenesis, including a depiction of gyre structure in a frame of reference moving with the wave, with satellite remote sensing products superposed (see Figures 11 & 12 of the EDO).