The PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT)

Experimental Design Overview

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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. The formation of tropical depressions: science issues

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 farther west. From Figure 2, 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? The development of extreme convection,

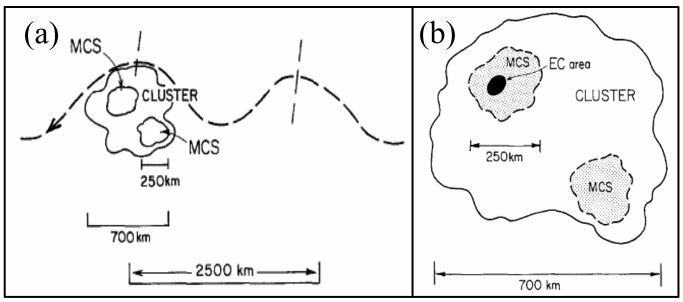

Figure 1. (a) schematic of synoptic-scale flow through an easterly waves (dashed) with an embedded cluster of convection in the wave trough. In (b) the cluster is shown to contain mesoscale convective systems (MCSs) and extreme convection (EC, black oval) within one of the MCSs. From Gray (1998).

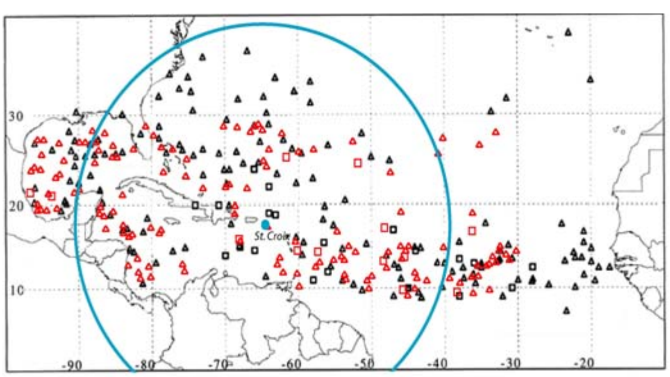

Figure 2. First-detection locations of developing (triangles) and non-developing (squares) tropical depressions from 1975-2005 (1995-2005 in red), adapted from Bracken and Bosart (2000). The blue circle denotes the approximate PREDICT domain.

which is strongly associated with genesis and may be closely related to the concept of vortical hot towers (Hendricks et al. 2004), clearly requires special circumstances in the "environment". What might those circumstances be?

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.

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.

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 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 midlevel 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.

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 theory and 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 mid-level 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. Satellite imagery and theoretical considerations suggest a limited number of mesoscale mechanisms involving Ekman pumping, convective excitation of inertia-gravity waves and triggering of nearby convection by gust-front boundaries. These mechanisms are not confirmed by direct observations but are inferred, e.g., from the radial dependence and azimuthal *symmetry* of deep convection (suggesting an emerging role for Ekman dynamics in the proto-storm) which may be contrasted with an initial *asymmetry* of convective bursts about the proto-center, accompanied by propagating cloud bands or arcs, in the earlier phase of genesis, suggesting a role for IGWs and density currents. Geostationary imagery provides qualitative guidance while numerical simulations provide quantitative information, subject to the imperfections of these models. It is important to note that all such mechanisms may play a role in the genesis sequence but at different stages. The local environment for deep convection is thought to contain abundant moisture (perhaps with measurable CIN and/or CAPE) such that heating in convective cores is intense and explosive, while the deleterious effects of cooling in the surrounding stratiform anvils is either absent or becomes progressively so during the genesis sequence. Liquid water content in precipitating cells can be exceptionally high; we have found examples in CloudSAT scans during the genesis phase where complete beam attenuation occurs prior to reaching the surface, as commonly seen in mature hurricanes and intense thunderstorms.

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.

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 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**. The primary measurements and flight patterns are outlined below and expanded upon in the EDO. 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 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.

The interannual variation of tropical cyclones in the Atlantic is large. Within the PREDICT time and spatial domains, the minimum recorded in the last two decades is one (1997) and the maximum is eight (2005). However, the number of waves is far more constant. The main distinguishing characteristic between active and inactive hurricane years is the amplitude in the lower troposphere (Thorncroft and Hodges 2001). These authors showed that 1994 and 1995, two sharply contrasting years of Atlantic hurricane activity, had nearly the same number of waves detected at 600 hPa. Because PREDICT is as interested in non-developing disturbances as in developing cyclones, a relatively small number of tropical cyclones has little bearing on the success of the project. Furthermore, PREDICT is interested in a variety of pre-depression disturbances, not just easterly waves. Hence, a year in which easterly waves are weaker or fewer in the central Atlantic is also not a major concern. Such years often favor more troughs moving into the subtropics and tropics, but these are also of interest to the extent that they organize convection.

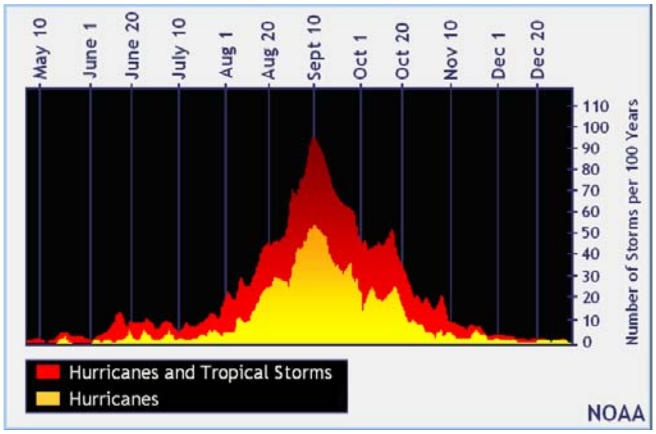

Figure 3. Number of tropical cyclones in the Atlantic per 100 years by calendar date. Courtesy of NOAA NHC

The Atlantic tropical cyclone season features a sharp peak near 10 September (Figure 3). The PREDICT time span is chosen essentially centered on this maximum, except that it is offset a few days earlier because it is more focused on pre-cursors to tropical depressions and the process of cyclone formation. Mature storms are not the focus of PREDICT. If necessary, the time frame could be shifted one to two weeks later, but not more. The length of the project, 45 days, is chosen to provide a long-enough time period that we may encounter a substantial number of disturbances, but short enough that two flight crews can overlap in their respective 30-day field deployments. We assume that a 30-day field deployment per flight crew. This will provide a 15-day overlap, beginning 1 September, when two flight crews are available (Figure 4). This is perhaps the most important aspect of the PREDICT observing strategy.

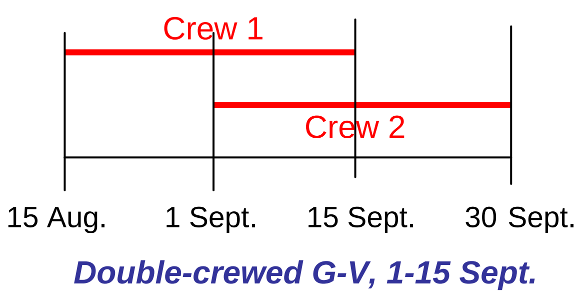

Figure 4. Schematic time-line for PREDICT.

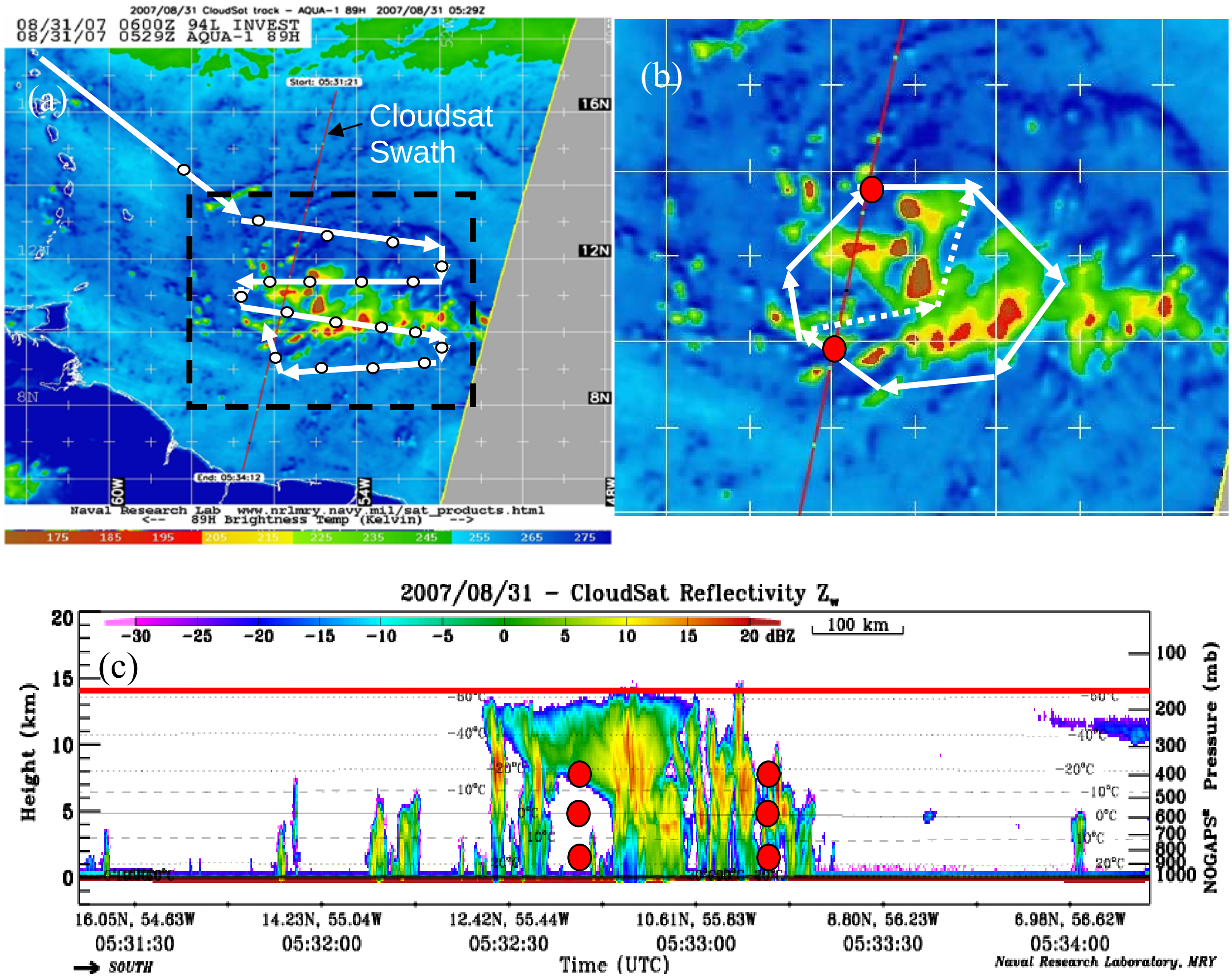

Figure 5. (a) 89 GHz brightness temperatures from AMSU on 31 August, 2007 prior to the development of the tropical depression that became hurricane Felix. Superposed are flight tracks and suggested dropsondes locations (white); (b) close-up of 89 GHz image in (a) with mesoscale flight tracks superposed; (c) CLOUDSAT image (see red track in (a)) showing reflectivity. Large red dots indicate intersections of mesoscale flight patterns in (b) with cross section, showing flight levels of 1, 5 and 8 km.

There is a clear tradeoff between lengthening the project to potentially sample more cases and reducing the overlap between crews. Our feeling is that a 45-day deployment with 15-day period when the G-V is double-crewed is the best option.

An alternative solution is to add a third flight crew, so that the double-crewed portion of the project is extended to 30 days, and there is no longer a tradeoff between length of project and period of double crewing (up to a project length of 60 days). Regardless of the solution, *we emphasize that one of the highest priorities for PREDICT is the double-crewing of the G-V to allow back-to-back missions that follow a given cloud cluster and maximize the time continuity of measurements and the chances of capturing the genesis process in action.* In a typical scenario during the double-crewed segment of the project, we would execute the flight patterns discussed below 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.

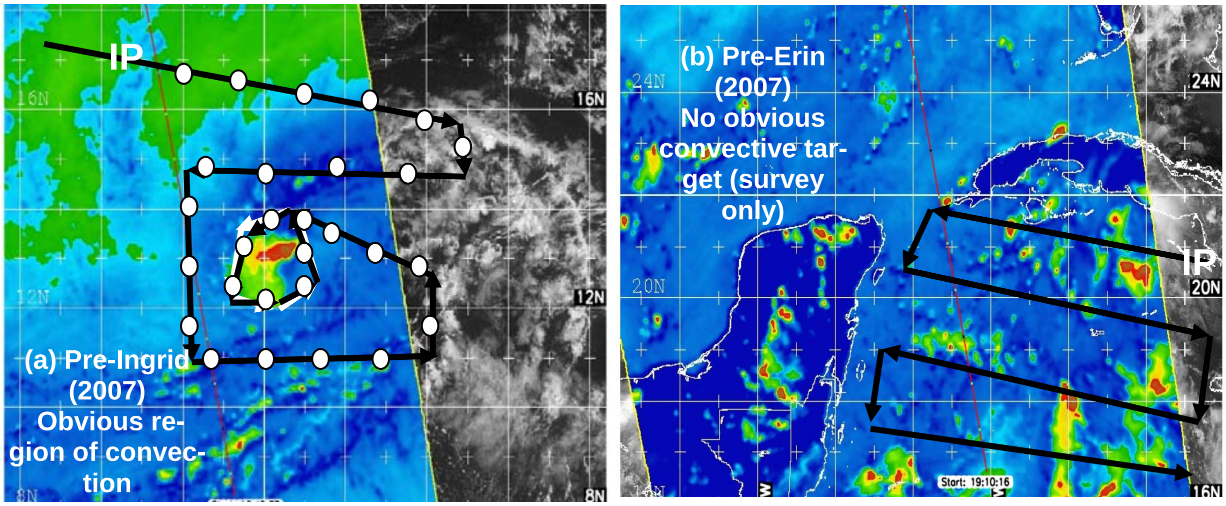

Figure 6. (a) possible G-V surveillance pattern for case with one area of focused convection; (b) pattern for region of active convection with no clear focus (dropsondes locations not shown).

b. Use of the NCAR G-V

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. The G-V will be equipped with one 4-channel dropsonde system, and most drops will start at 40,000-45,000 feet MSL. A typical time between drops will be 10 minutes. On occasion, such as when interrogating a mesoscale feature, it will be advantageous to drop four sondes every 5 minutes or so (Figure 6).

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). The maximum possible altitude is desired during this portion of the mission. This allows the G-V to fly over the extensive anvil in many places, and easily avoid the deep convective towers (for example, the tower that extends to 16 km in Figure 5c). A higher altitude also maximizes the depth of dropsonde coverage.

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). In most cases, we do not expect a well-defined lower-tropospheric cyclonic circulation to be present, so it will be the convective organization that will guide the mesoscale sampling. Because the tracks of the satellites with microwaves instruments are known several days in advance, we can choose sampling times to best correspond to times when satellite data are collected. This will be highly advantageous for post-field analysis, and rapid dissemination of the data can help for real-time planning. Extensive use of these data for targeting field operations is planned for the T-PARC experiment in the Pacific in 2008. The collaborations between Naval Postgraduate School (though PI Montgomery), Naval Research Laboratory and the university of Wisconsin will allow us to maximize the availability and use of various satellite observations.

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. We expect smaller areas, perhaps encompassing a single mesoscale convective feature, will evolve more quickly than larger areas, and the time to complete a circuit will scale linearly with the size of the convecting region. Relative to the life cycle of the convection circumnavigated, we can expect roughly the same amount of evolution regardless of size. A measure of the evolution can be constructed by comparing the dropsondes (most of which are dispersed around the convection prior to the mesoscale pattern) with the in situ and remotely sensed data (see below) from the mesoscale flight pattern. If a region containing multiple convective features is circumnavigated, and the convective features 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 Figure 5b). Of course, any such flight track must first consider safety and be acceptable to the pilots and EOL RAF. We expect to fly in cloud and precipitation part of the time, but will clearly avoid deep convection or probable turbulent areas directly associated with it.

If the dropsonde data suggest that a cyclonic circulation is present in the lower or middle troposphere, we will consider executing a Figure-4 pattern. This would be contingent on an acceptable arrangement of deep convective features and would probably be executed only at the highest altitude with dropsondes deployed.

In addition to dropsondes, the G-V will be equipped with a microwave temperature profiler (MTP), mapping a layer several kilometers deep ahead of the aircraft, and trace constituent measurements (water vapor and ozone) for determining the topology of the tropopause in cases where tropopause-based cutoffs are identified. State parameter measurements at flight level will help map the wind distribution, indicating troughs or shear lines. An additional, potentially crucial measurement for mesoscale studies is the differential GPS capability. This can derive the aircraft altitude within a few tens of centimeters. Combined with an accurate pressure sensor, it will allow us to map out the geopotential height on a pressure surface. Transects at different altitudes between convective elements in a convectively active region will allow a direct measurement of the geopotential height anomaly within a convecting region. The MTP will retrieve profiles of temperature, indicating whether or not a mesoscale warm core has begun to form. This can be supported by computing the geopotential height thickness anomaly of different pressure layers. In particular, we should have height measurements near 900 hPa, 500-600 hPa and 400 hPa.

Other remote sensing instruments will include the high-spectral-resolution lidar. This will be operated throughout the flight, and will be most useful for quantifying the concentration of dust in Saharan Air Layers that could be proximate to the convective clusters. By encircling and traversing mesoscale regions where convection is present, we will assess whether the aerosols have indeed influenced the inflow to convection. The full analysis will require detailed trajectories combined with the observations, and will be done after the project. Nonetheless, some initial progress will be obtained directly from the field data.

PREDICT will also request the G-V cloud radar, which is scheduled to be available in late 2009. The initial implementation will be a W-band (95 GHz) radar, mounted on a wing pod, and with the ability to scan across the flight track. Not all aspects of the radar are known at this time, but general properties of Doppler radar at this frequency are well known based on existing implementations (Fig. 5c, and Halverson et al. 2007). The radar beam width will be 1 degree, and the sensitivity -20 dB at 1 km distance, unattenuated. Attenuation by liquid water is severe at this frequency, but differential attenuation can be used for the detection of liquid water. One scanning option would be to scan up and down about the horizontal. In this case, the hydrometeor fall speed is less of an issue. In the limit that the angle reaches +/- 90 degrees from the horizontal, the upward and downward looking dwells can be used to distinguish particle fall speeds from vertical velocity. Purl maneuvers (circles of 10-50 km diameter) can be used to obtain excellent profiles of divergence (Mapes and Houze 1995). This would work best in stratiform regions of light precipitation, especially if liquid water is relatively absent. A different strategy would be to scan about nadir, using the cloud microphysics information to correct for particle vertical motion. For sufficiently wide scans, horizontal motion across the flight track can also be estimated. Finally, if multiple altitudes are flown, more of a volume can be sampled even with attenuation by liquid water. Since documenting the mesoscale structure is the primary objective, time evolution of features should be tolerable, or at least can be evaluated by flying at the same altitude at two different times.

The mesoscale pattern at 7-8 km will be well above the melting level. Cloud processes, particularly mixed phase microphysics and their relation to cold downdrafts, are relatively unobserved in pre-tropical-cyclone convection, especially in the crucial temperature range -5º to -20ºC. There are also few data to support the representation of ice microphysics in numerical simulations and forecasts of genesis. Observations in mature hurricanes have indicated only small supercooled liquid water contents (Willoughby et al, 1985; Black and Hallett 1986, 1999), but it is not known if this characterizes the early development stages of hurricanes where updrafts are likely stronger. The rate of conversion of supercooled cloud liquid water to ice in cloud clusters and the production of graupel may significantly affect their dynamical and precipitation structures.

Cloud physics instruments on the G-V will allow measurement of the total condensed water content (counterflow virtual impactor, CVI), water vapor content and relative humidity (TDL hygrometer), liquid water content (King Probe and Rosemount Icing Detector, calibrated for LWC measurement), and mixed phase cloud droplet and ice size distributions (small ice detector probe, SID-2; 2D-C (cloud), 2D-S (stereo), and 2D-P (precipitation) probes). These measurements are all important for quantifying the dominant precipitation processes and to understand how aerosols (dust) may be affecting cloud physics. Measurements of ice and supercooled liquid in different regions of the cloud cluster will be related to variations in dust. The CVI has the unique opportunity to sample the cloud-active nuclei and to assess their role in the condensation and ice production processes. The full list of aircraft instrumentation, measurement, purpose and rela-

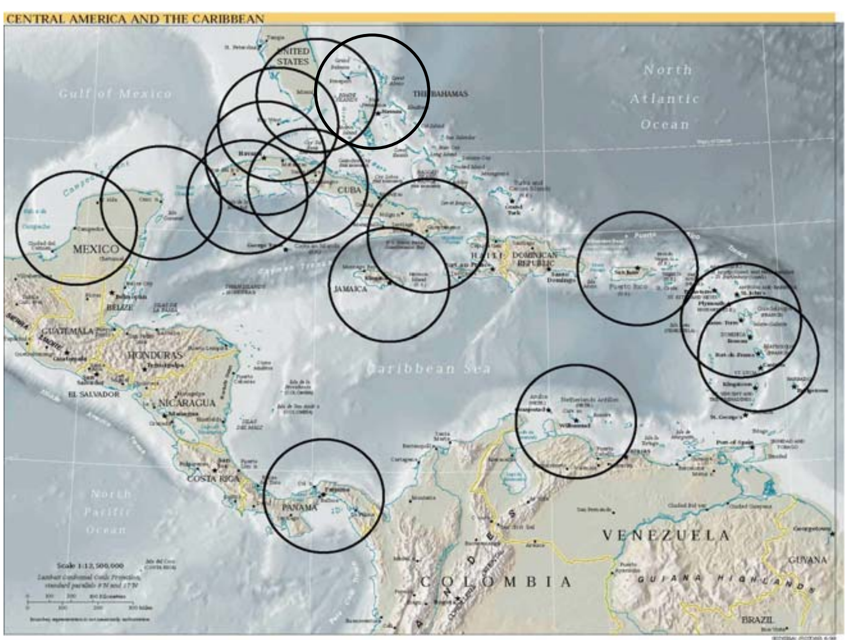

Figure 7. 250-km range rings centered on Caribbean radar locations. Sources for these data are http://weather.org/radar.htm and http://www.hwn.org/home/radarsites.html.

tion to the PREDICT hypotheses is presented in Table 2.

c. Other data sources

PREDICT will take full advantage of numerous types of remotely sensed observations to augment those collected by the G-V. These include satellite observations from GOES, and the various microwave platforms (TRMM, SSMI, AMSRE), MODIS and the newer instruments such as CLOUDSAT and QUIKSCAT.

Other important data are the weather radars in the Caribbean. These are operated by different countries and are generally not coordinated. But it will be important for PREDICT to have access to radar images in real time for mission direction, and to have Doppler radar datasets after the project for analysis and synthesis with G-V observations. Figure 7 shows the locations and approximate coverage of the Doppler radars in the Caribbean region that would be useful to PREDICT.

4. Mission selection and operation timeline

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 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 Hurricane Center will be important for determining systems that have at least some development potential. In 2007 an graphical experimental product was launched by NHC to depict regions of interest. An example of this is shown in Figure 8. In the example shown, there are multiple potential cloud systems of interest within the PREDICT domain. The daily task would therefore be to assess which one had the greatest potential for development. It is the non-developing cases that appear to have a greater likelihood for development that are most significant.

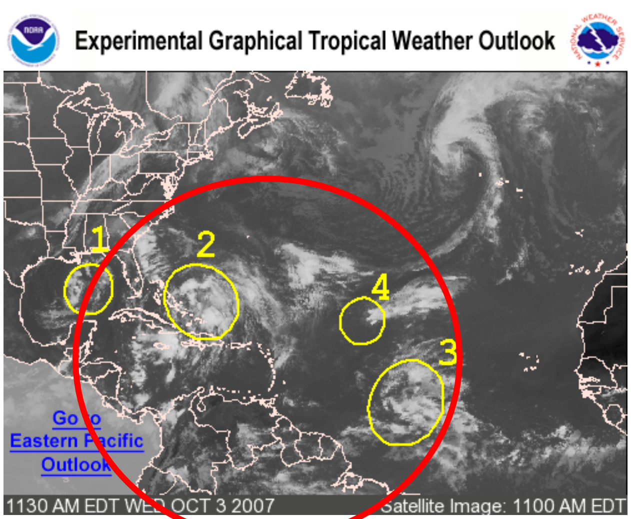

Figure 8. NHC Experimental Graphical Tropical Weather Outlook (TWO). Regions of interest indicated by yellow circles. The red circle indicates the approximate PREDICT domain.

System selection would take place 24 h prior to takeoff time. If more than one system of potential interest is identified within the PREDICT domain, systems will be prioritized. Flight plans for the two highest-priority systems will be developed. Because a 24-h forecast would be required, it is possible that one of the target systems would either develop into a tropical cyclone, or dissipate to the point where little deep convection is occurring. In order to target a particular system, there needs to be mesoscale convective activity within a relatively well defined region of several hundred kilometers. Further, a system that has already developed is of less interest because most hypotheses of PREDICT pertain to the pre-genesis state.

Mesoscale targets (200 km or less in scale) will typically be defined en route. This decision will be made based on temporal behavior of convection seen in GOES images, or the instantaneous structure revealed by possing microwave-instrumented satellites. Efforts will be made to minimize the time of data transfer of microwave images to the operations center. In general, the target region will be one where deep convection has been quasi-persistent and is where the critical layer of the wave intersects the lower-troposphere (e.g. about 700 hPa).

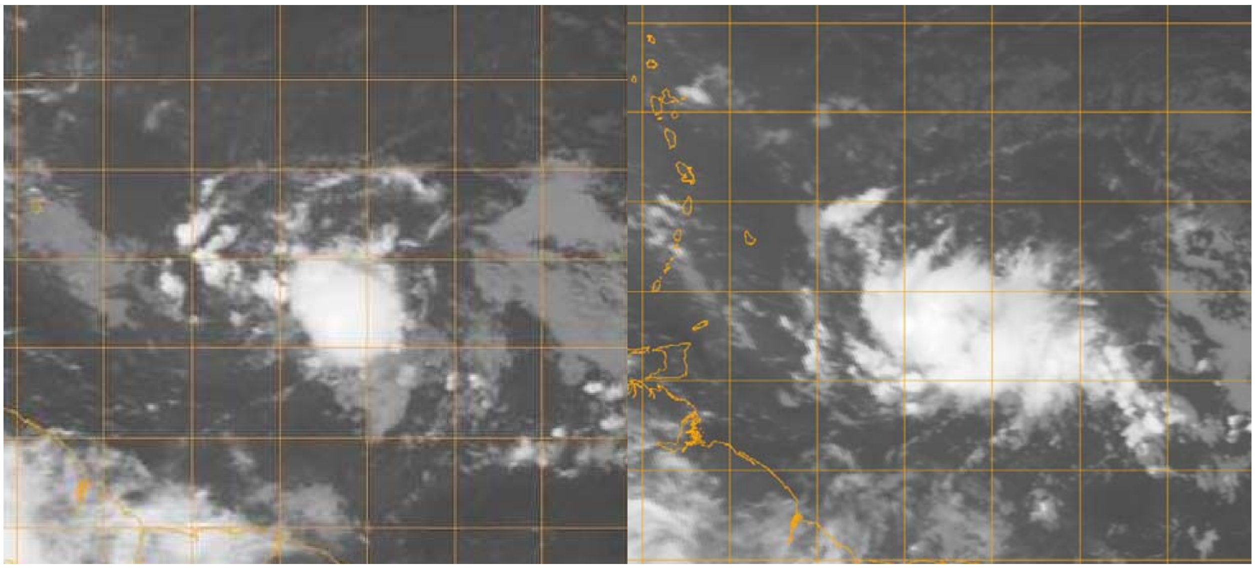

Figure 9. IR satellite images of the precursor to hurricane Felix at (a) 00 UTC 31 August and (b) 06 UTC 31 August. The time in (b) is very close to that of the Aqua image in Fig. 5a. Lat/lon lines are spaced every 2 degrees. Courtesy of NRL.

Examples of the type of information that will typically be available to make decisions are contained in Figures 9-10. Images in the figures are at 6 hourly intervals. Six hours is roughly the time from final flight planning to the mid-point of the mission. As can be seen in this example from prior to hurricane Felix, persistent convection is found within a mesoscale region that moves steadily westward. Therefore, this general area can be targeted prior to takeoff. The mesoscale convective elements have characteristic time scales shorter than six hours, hence the need to decide on targets in real time while the G-V is ferrying or while it is executing the survey pattern.

Analyses and forecasts from global models will be important tools to aid in mission planning. These are typically adequate for positioning wave troughs out to two days, and experience suggests they are able to predict the migration of troughs and fronts into the tropics on similar time scales. There is also some skill at predicting genesis, but it is unclear at present how much utility such forecasts would have for planning. Near-real-time diagnostics are being developed currently that combine global analyses and satellite information, and these can be added to the extensive suite of products produced by the Space Sciences Engineering Center at the University of Wisconsin (see letter from C. Velden) and by the Naval Research Laboratory (in collaboration with PI Montgomery at NPS). A specific example is provided in Figures 11-12, representing a novel overlay of ECMWF operational analyses and TRMM convective precipitation developed at the Naval Postgraduate School (see letter from T. Dunkerton). Here, the

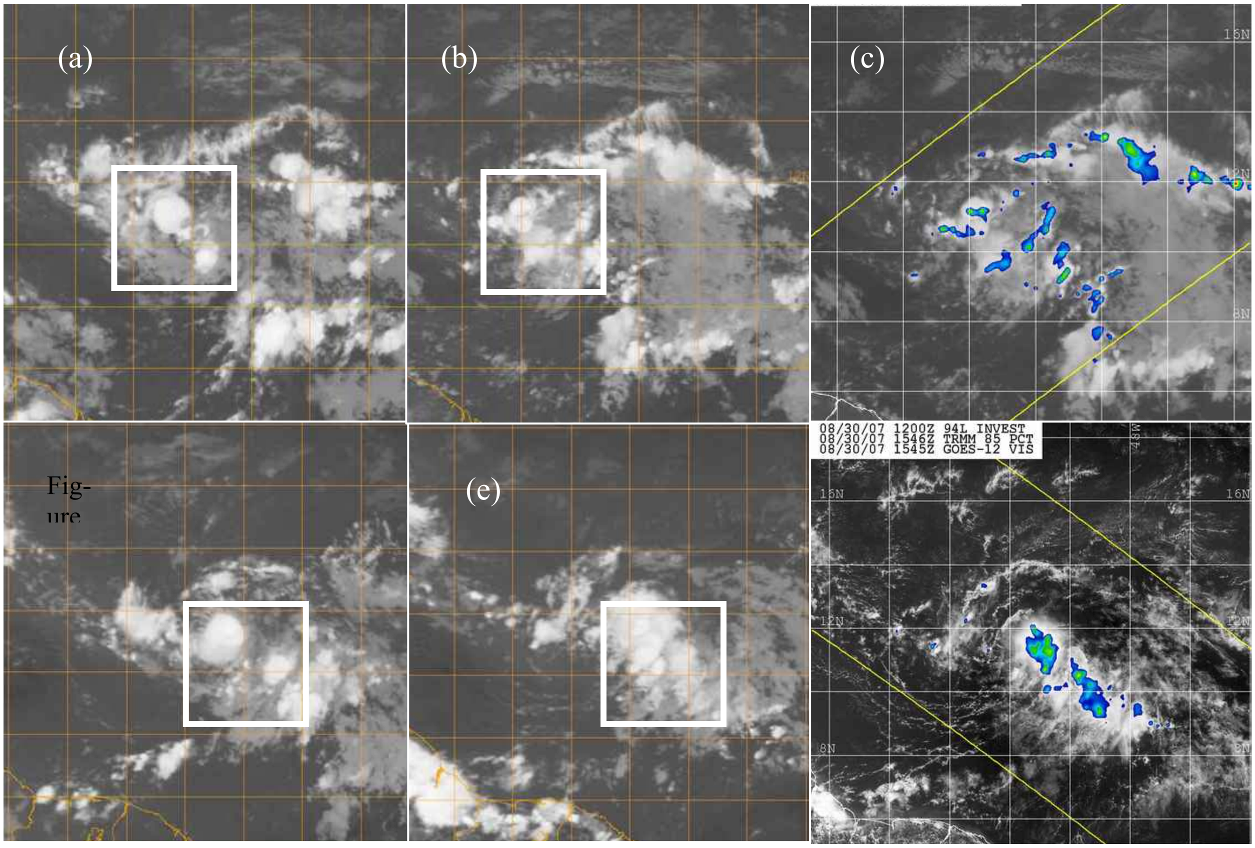

Figure 10. Infra-red images (a) 00 UTC 30 August, 2007; (b) 06 UTC 30 August; (d) 12 UTC 30 August; (e) 18 UTC 30 August. Panels (e) and (f) show 85 GHz polarized-corrected TRMM data from (c) 12 UTC and (f) 1546 UTC 30 August. White squares in (a), (b), (d) and (e) denote region of persistent deep convection moving westward at about 8 knots.

development of Felix (2007) occurs where the critical line (red) and trough axis (blue) intersect organized convection (color shading). A closed gyre is evident in a frame of reference moving westward with the precursor wave (Figure 12, approximating actual trajectories) whereas the resting frame (Figure 11) erroneously suggests an open wave. Recirculation in the lower troposphere is an indicator of possible genesis and is resolvable in global analyses with horizontal resolution of 1 degree or less in most cases. Flow visualization in the moving frame (Figure 12) provides a significant advantage over conventional products used by forecasters at NHC/TPC and elsewhere. This tool will be available for PREDICT at a web site currently under construction at NPS.

The timeline of mission planning is summarized in Figure 13. There will be a daily planning meeting during facility status and 3-day weather forecasts will be presented. An outlook, mainly based on global models and consultation with NHC, will be issued each day for the period out to a minimum of 72 h. The main purpose of the outlook will be to plan down days or maintenance. Potential targets will be identified at a two-day lead time, however, no firm decisions will be made. One day in advance, the most likely target (or two if there is ambiguity) will be identified. The takeoff time will be set for the following day, nominally giving 24 h notice. We do not anticipate delays of takeoff times based on forecasts. Once a decision to launch is made at the daily planning meeting, a mission can be called off the following morning, but there should be no reason for delay unless local weather conditions warrant a delay or mechanical problems occur. This means that crew duty cycles can operate on a set 24 h schedule (i.e., there is enough

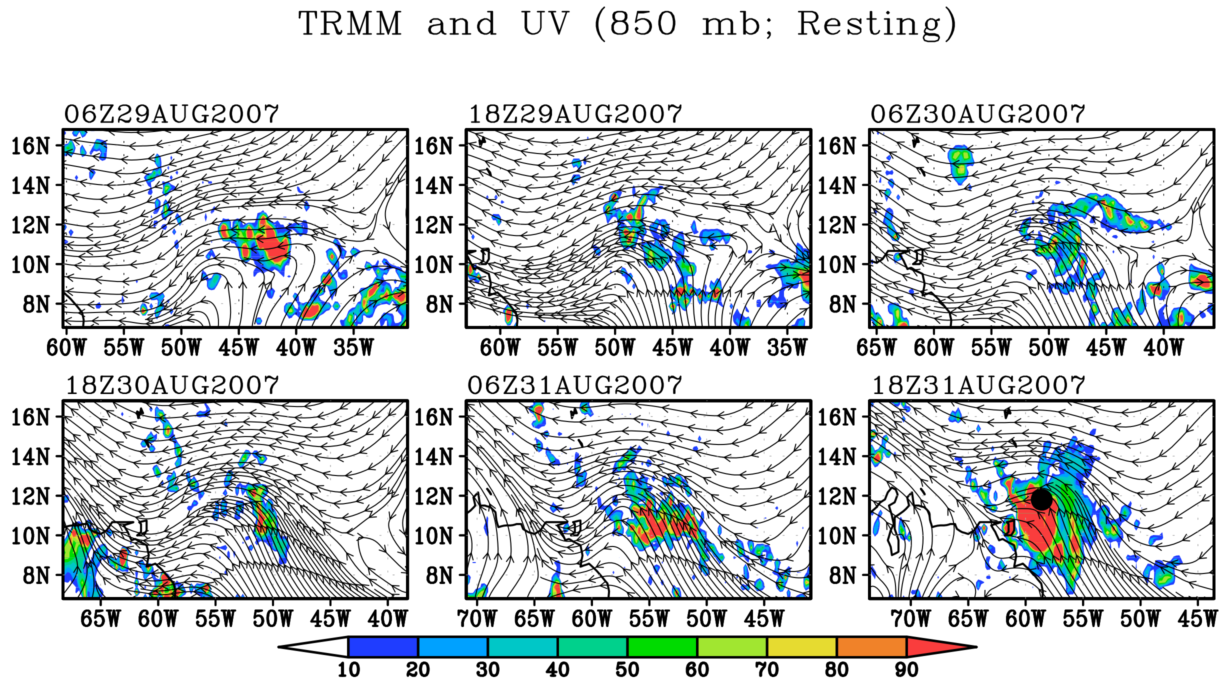

Figure 11. 850 mb streamlines (2.5-day low-passed filtered wind field) in the resting frame of reference and convection as identified by TRMM precipitation radar 60, 48, 36, 24, 12 and 0 h before the genesis of Felix between 06Z 29 August and 18Z 31 August 2007. Precipitation is represented by shading (mm/day). The closed black dot in the last panel represents the genesis location of Felix.

time to fly and obtain crew rest within 24 h). Typical requirements are for not more than three days of consecutive flying, but this will not be an issue in most systems. Systems will develop into tropical storms, dissipate, or move out of the domain within 3 days in most cases.

There tends to be a maximum of oceanic convective activity during the late evening or early morning. If there are no restrictions on operations at night, we might anticipate more night flying during the portion of the project where one flight crew is available. However, early morning takeoffs can be a good compromise if flight crews need daylight to operate near convective systems. When two flight crews are available, it is most desirable to separate takeoff times by 12 h. In this case, there will still be one daily planning meeting, but an update would be necessary to review both weather conditions within the target disturbance and adjust flight plans as necessary based on earlier flights into a given disturbance. The operations center would have to be double-staffed during the 15-day period when back-to-back missions are flown.

The Virgin Islands are sometimes in the path of mature tropical cyclones during the period slated for PREDICT. In cases where a tropical cyclone may approach the PREDICT base of operations where the G-V is housed, alternative locations for the aircraft will be sought. Every effort will be made to conduct scientific missions from an alternate base. As long as the operations center is functioning and communications are good, we anticipate that the field observations will continue. During the planning for PREDICT, alternate locations for the G-V will be selected. A backup operations center location will also be selected, in the unlikely event that a major hurricane forces an evacuation of personnel.

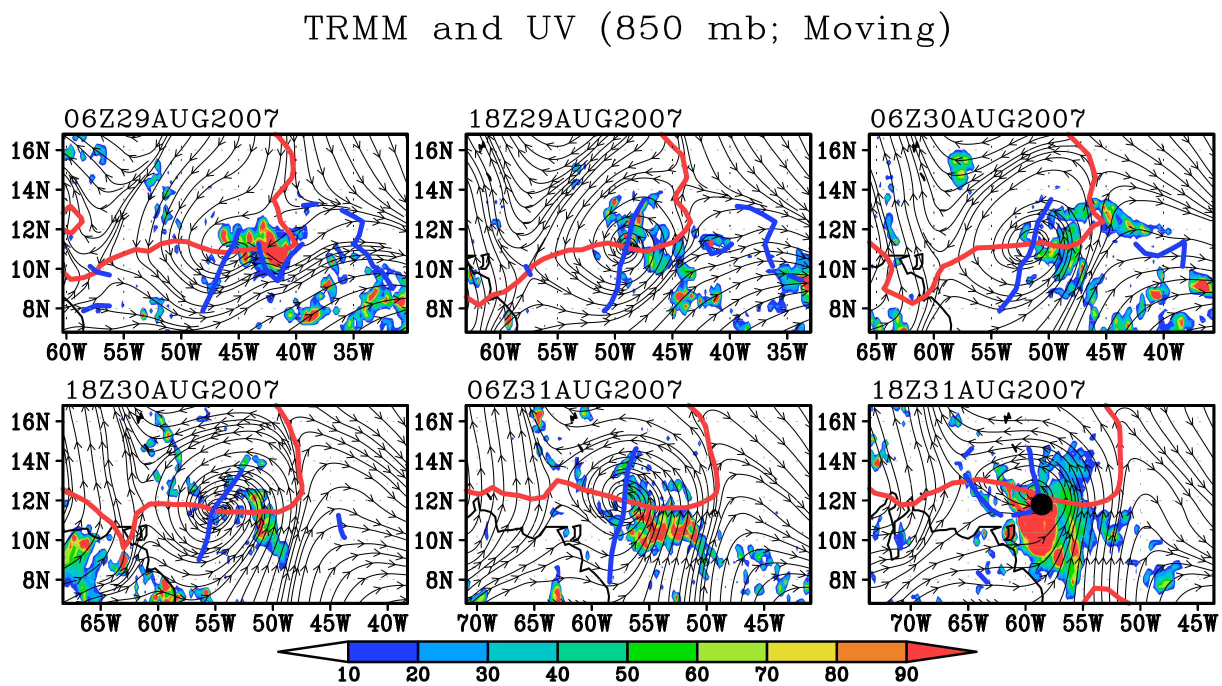

Figure 12 . 850 mb streamlines (2.5-day low-passed filtered wind field) in the frame of reference moving with the tropical wave and convection as identified by TRMM precipitation radar 60, 48, 36, 24, 12 and 0 h before the genesis of Felix between 06Z 29 August and 18Z 31 August 2007. Precipitation is represented by shading (mm/day). The blue solid curve represents the trough axis (with cyclonic relative vorticity and zero meridional wind). The red solid curve represents the local critical latitude where the zonal velocity of the time-filtered flow in the moving frame of reference is zero. The closed black dot in the last panel represents the genesis location of Felix.

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 science objectives on the NSF side and missions of other agencies.

a. NOAA

The principal participation of NOAA will be with one or two NOAA P-3s as part of the Hurricane Field Program Intensity Forecasting EXperiment (IFEX) that occurs every year but is being planned for a genesis (early lifecycle) focus in 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. If these missions require sampling the disturbance targeted by PREDICT, coordination is still possible. However, in some cases, the operational objective may be to observe an entirely different system (i.e. a more mature tropical cyclone elsewhere). 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.

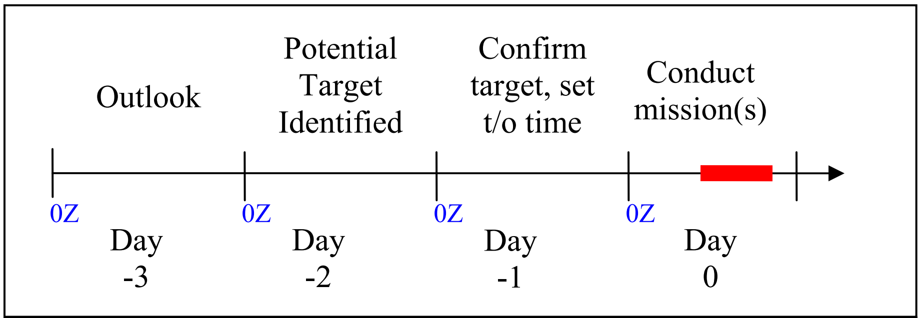

Figure 13. Timeline of activities leading up to a possible mission on Day 0. Red bar indicates mission occurrence.

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.

6. Field Project Support and Management

a. Project Planning and Coordination

Scientific oversight of PREDICT will be provided by the PREDICT science steering committee (Sec. J of SPO). Coordination with NOAA will be handled by PI Montgomery (who has a 25% appointment with HRD). Coordination with NASA is less certain but will involve steering committee member A. Heymsfield, and Participant S. Braun (NASA GSFC). The PREDICT steering committee plans to organize meetings between the key representatives of NOAA and NASA in the late winter and spring of 2008 to explore opportunities for collaboration.

PREDICT will request the NCAR Earth Observing Laboratory (EOL) to provide assistance and advice in the development of project support strategies. This includes coordination of science mission objectives with FAA requirements (or requirements of other nations). The project will ask EOL to participate in planning discussions and meetings as required and assist with the preparation of the PREDICT Operations and Data Management Plans. Critical tasks in this period before the field deployment will include the refinement of aircraft deployment strategies, development of a mission planning process (e.g. daily schedule, daily planning meeting form and content, facility schedules and flight planning deadlines, coordination with other groups).

b. Field Coordination and Support

EOL will be requested to help organize a PREDICT field operations center, tentatively based in St. Croix. It is important to co-locate the operations center and aircraft facility for the project. Other considerations for the site of the operations center include high speed Internet access and safety for facilities and staff in the height of the Atlantic hurricane season. There will be a desire to coordinate G-V flight patterns with either NOAA P-3s or NASA aircraft should they be involved. The best coordination opportunities will occur for mesoscale convective targets that are within a 2 h ferry of the NOAA P-3 (800 km). Safety considerations of NOAA P-3s require direct communication between aircraft to ensure that dropsondes and lidar operations adhere to requirements for aircraft separation, etc. To assist with coordination from a dispersed suite of airborne instrumentation and facilities and participate in the field deployment and real time coordination of PREDICT assets.

Operations Center activities will include:

- Facilitation of daily project planning and operations support activities through the conduct of a daily planning meeting and the dissemination of critical project planning information;
- Preparation and implementation of a PREDICT Field Catalog to provide a record of daily plans and activities and selected data and products used for operational planning and decision making;
- Communications and display capabilities such as the EOL Real-time Display and Coordination Center (RDCC) and Internet chat-room tools successfully utilized in projects like RICO and RAINEX.
- Coordination of aircraft operations with regional FAA centers, ground based research facilities and mobile systems to maximize flexibility in sampling location and strategies

Even though PREDICT flights will be over the open ocean, EOL and other aircraft facilities will be requested to contact FAA centers responsible for the oceanic areas of interest to make sure proper alerting and updating procedures are followed. The project will rely on the experience of the facility pilots to assist in this advanced coordination and the mission planning during field operations.

It is proposed that the PREDICT Operations Center will coordinate all project flight planning contacts with all air traffic centers during the field season. This single point of contact approach should minimize confusion and maximize the opportunity to accomplish PREDICT science objectives. The operations center intends to have real time display of aircraft position, radar and other important data needed to assure safe flight operations. Updated information will be relayed to/from project aircraft using satellite communications for chat, data, images and voice contact. The operations center will also keep aircraft informed of changing conditions at the facility operations airport as well as at alternates during rapidly changing conditions.

PREDICT will require a reliable and advanced communications system to meet the requirements outlined above. *It will be very important to have moderate bandwidth (e.g. ~ 64Kbps) satellite communications to allow transmission and receipt of data, voice and text products.* The ability to direct aircraft in and around developed hurricanes was shown to be possible and quite valuable during RAINEX. The PREDICT operations strategy will require the G-V to send position and selected flight level data to the operations center in near real-time (~10 s or less update rate) so that they can be composited, overlaid on satellite imagery and/or radar imagery (if available) and sent back to all project aircraft approximately every 5 minutes. This will allow updated information to be provided to the aircraft to tune flight strategies and maximize data collection to meet the project science objectives.

Another key to aircraft coordination will be the availability of numerous satellite products, including those from TRMM, SSMI, GOES (visible, IR, water vapor and cloud-drift winds), MODIS, AMSRE and

QUIKSCAT. These will also be valuable as research products, and will be archived in the Field Catalogue (Sec. d). It will be important to schedule missions to coincide with overpasses of the non-geosynchronous as many of the above satellites as possible.

c. Personnel

PREDICT will require one coordinator for each G-V mission, thus, two full time positions will be needed during the double-crewed segment of the project. There may be required a point of contact for communicating with NASA and NOAA aircraft, which, in turn, will have their own coordinators. There will be a science director (one of the steering committee members) for each mission on a rotating schedule. Decisions for mission planning will be made by the science director in consultation with the PREDICT steering committee and other key PIs. There will be an operations director who will be in frequent communication with the science director. With one aircraft to consider, it may be possible to combine the operations and aircraft coordinator position. If NOAA and NASA are involved in a close collaboration, the aircraft coordinator would become a full-time position. There will also be a logistics coordinator, assigned to handle transportation, lodging and other issues.

Forecasters will be a critical part of the planning process for PREDICT. It is anticipated that at least two forecasting positions will be required during intensive observation periods (IOPs), one charged with prediction of 1-3 days, and the other charged with nowcasting or forecasts within 6 h, including terminal area forecasts. These forecasters will primarily be students of university participants. Such an arrangement was highly successful in RAINEX.

d. General Data Management Support

The development and maintenance of a comprehensive and accurate data archive is a critical step in meeting the science objectives of PREDICT. The primary objective being to make as complete a dataset as possible available to the participating scientists and larger science community as soon as possible following the field phase. The PREDICT Project will request support from EOL to assist in the planning and implementation of a comprehensive data management strategy by contributing to the development of data policies and protocol consistent with NSF and other agency guidelines; collaboration in implementing a process for PREDICT data submission and archival; providing specialized data collection and processing support; and participating in a distributed archive architecture using the EOL data management system to meet project needs. A similar open data policy as used in the IHOP_2002 campaign is envisioned. (See http://www.joss.ucar.edu/ihop/dm/IHOP_datapolicy.html). All participating groups shall get access to all data collected during PREDICT. Data sharing will be simplified by the web based data archives at EOL with links as appropriate to other PREDICT archive sites.

PREDICT proposes a data management strategy that will include: [1] utilization of questionnaires and the preparation, prior to the field phase, of a Data Management Plan that defines data requirements and provides a comprehensive data management support strategy; [2] the collection of special high resolution datasets in real-time and post field phase (e.g. GOES and other satellite data, NWS soundings and WSR-88D radar); [3] set-up and support of a project data management website and distributed long-term PREDICT data archive and; [4] quality control and post processing of operational and research data necessary to the development of a dropsonde common format dataset. PREDICT proposes that the project website and archive be located at EOL. This centralized archive site will allow investigators to archive data and metadata at a single location or provide links to alternate archive sites.

e. PREDICT Field Catalog

The project will request that EOL design and implement a PREDICT Field Catalog customized to meet project needs for in-field documentation. The catalog will provide a record of daily plans and activities, and selected data and products used for operational planning. The catalog will help the project document activities in near real time, provide a single point for status updating and provide a repository for preliminary in-field research data products. Project participants will work with EOL to prepare and test web-based forms that will form the basis of in-field documentation. These include the daily operations summary, facility and expendable resources status reports and the daily weather forecast.

PREDICT will request assistance from EOL to acquire, display and archive satellite data and products needed for real time decision making and post analysis. NCAR operates a ground station in Boulder that routinely collects the full direct broadcast stream from both Geostationary GOES satellites. From these data, sectors can be custom made and imagery produced that is tailored to the PREDICT campaign. The complete 5-channel GOES-GVAR imager data are also archived on a routine basis and can made available to researchers in several different data formats including HDF, netCDF and TDF as well as in image form. PREDICT will ask EOL to assure that imagery from all the various sources is collected and sorted into the PREDICT Project Field Catalog and the project archive as it comes in and is available to project researchers both during and after the field campaign.

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I. Facilities, Equipment and Other Resources (from SPO)

Platform	Function	Key Motivation	Re-quest	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 (from SPO)

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
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Robert Rogers	NOAA HRD
Ryan Torn	NCAR (university at Albany SUNY Sept. 08)
Chris Velden	University of Wisconsin
Fuqing Zhang	Texas A&M University