TITLE: Using TRMM Measurements in a Dynamically Constrained Framework to Better Understand Tropical Cyclone Intensification

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ABSTRACT

One of the most challenging aspects in tropical cyclone (TC) research is developing an improved understanding of the processes underlying TC intensification. Recent work using airborne Doppler analyses has found a distinct difference in the location of deep convective cores, called convective bursts (CB's) here, relative to the radius of maximum wind (RMW). This result is consistent with previous theoretical work studying the importance of diabatic heating in the vorticity-rich environment inside the RMW. It provides an excellent opportunity to examine the structure and location of CB's observed by the TRMM satellite within the dynamical constraints of the RMW.

The proposal presented here intends to address this issue by performing three primary tasks: 1) Develop algorithms for plotting fields from the 13+ year Tropical Cyclone Precipitation Feature (TCPF) database in dynamical radius (i.e., normalized by the RMW); 2) Calculate statistical properties of inner-core precipitation as a function of dynamical radius for different intensity change categories using TCPF; and 3) Relate TCPF statistics to inner-core kinematic structure and TC intensity change. The work proposed here will link the observations of precipitation structure from the TCPF database (e.g., 37 and 85 GHz brightness temperatures, reflectivity profiles, lightning flashes) with kinematic and thermodynamic fields such as radial flow, vertical vorticity, inertial stability, and equivalent potential temperature from airborne Doppler data (when available) and kinematic information from flight-level data (when airborne Doppler data is not available). It will involve a combination of composite analyses using the TRMM TCPF with flight-level data and case studies using the TCPF and coincident airborne Doppler data. It will provide important insight into the role of deep convection in RI in a dynamically constrained framework.

This proposed work will use NASA satellite data to investigate the role of inner-core processes in TC intensification. Improved understanding of the processes responsible for TC intensification will translate into improved forecasting of this challenging problem. This directly addresses the NASA Strategic Sub-goal 3A (Study Earth from space to advance scientific understanding and meet societal needs) and NASA's research objectives 3A.2 (Enabling improved predictive capability for weather and extreme weather events). Specifically for this research announcement, the work proposed here satisfies NASA Goal 2.2, "Utilization of satellite/GV products for process studies and model development", addressing the sub-bullet of this PMM announcement "Analysis of TRMM and other current satellite-based precipitation information for studies of climate (global and regional variability, ENSO, etc.) and weather (tropical convection, hurricanes, midlatitude weather systems)."

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SCIENTIFIC/TECHNICAL/MANAGEMENT SECTION

1. Background and Statement of the Problem

a) Motivation

One of the most challenging aspects in tropical cyclone (TC) research is developing an improved understanding of the processes underlying TC intensification. This task is difficult because the processes important in intensification span spatial scales of many orders of magnitude, from the synoptic-scale to the microscale. While the importance of environmental fields is fairly well-established, what is not as well understood are the roles of convective-scale processes and their interaction with the vortex.

Observational and modeling studies have linked TC intensification to the occurrence of deep convection, sometimes referred to as convective bursts (CBs), within the core (e.g., Jiang 2012; Guimond et al. 2010; Rogers 2010; Reasor et al. 2009; Squires and Businger 2008; Hennon 2006; Montgomery et al. 2006; Hendricks et al. 2004; Kelley et al. 2004; Heymsfield et al. 2001; Rodgers et al. 1998; Gentry et al. 1970). Ongoing work using composites of airborne Doppler radar data from TCs has found distinct, statistically-significant differences in vortex-scale kinematic properties between TC's that are intensifying (I) and those that remain steady-state (SS). This work has also found a significant difference in the number of CBs between I and SS TC cases. Interestingly, though, there is little difference in the structure of the CBs themselves between I and SS cases. Rather, a key result from this work is that the majority of CBs in I cases occur *inside* the radius of maximum winds (RMW), in contrast to SS cases, where the majority of bursts occur *outside* the RMW. This result is consistent with theoretical work showing the importance of diabatic heating within the high-inertial stability region inside the eyewall as having a much larger impact on vortex intensification compared with heating outside the eyewall (e.g., Vigh and Schubert 2009; Pendergrass and Willoughby 2009). This suggests that any consideration on the importance of radial location of convective bursts cannot rely simply on geographic proximity to the storm center, as is often done, but must consider the location of bursts relative to the RMW.

Recent work using the TRMM Tropical Cyclone Precipitation Feature (TCPF) database has found that the chance of TC intensification increases relative to the climatological mean when one or more CBs exist in the inner-core region (Jiang 2012). However, this analysis and others (e.g., Cecil et al. 2002; Jiang 2012) have subjectively defined "inner-core" based on convective structure , such as the horizontal fields of radar reflectivity and passive microwave ice scattering. The analyses have not been done within the dynamical framework of the TC. Once the TRMM measurements are placed within the appropriate dynamical context within the TC inner core, more physically robust conclusions can be drawn, and a more comprehensive picture of the inner-core processes underlying TC intensification will be possible.

b) Science questions

With the above issues in mind, the following questions will be addressed with this work:

1. What is importance of inner-core precipitation structure in TC intensification?
2. How does inner-core precipitation structure vary when considered in dynamical radius, i.e., defined relative to the RMW?
3. How does inner-core precipitation structure relate to inner-core symmetric kinematic structure in TC intensification?

For this work, “inner core” is defined as all radii within four times the RMW, similar to that done in the Doppler composite work of Rogers et al. (2012a). “Inner core” here is thus based on an objective dynamical definition, not a geographic one or one based on a subjective determination of convective structure. Question 1 is intended to address the broad question about the importance of precipitation structure (e.g., convective vs. stratiform, intensity of convection) within the inner core on TC intensification. Question 2 focuses on the radial distribution of precipitation, including CB’s, and the role that this dynamically-based distribution plays in TC intensification. Question 3 addresses the relationship between precipitation and the inner-core kinematic structure during the intensification of TC’s.

c) Approach

The work proposed here will leverage the strengths of the TRMM dataset -- its long record (~15 years) of TC observations, measurements of precipitation and convective signatures using reflectivity profiles, ice scattering, and lightning flashes, and the ability to obtain reliable measurements up to high altitudes -- with the strengths of airborne data -- notably the ability to provide one-dimensional (flight-level) and three-dimensional (airborne Doppler) measurements of the TC kinematic field – to provide a depiction of the physical processes underlying TC intensification that is more complete than relying only on satellite-based or aircraft-based studies. Two approaches will be followed to perform this task: a composite approach combining the TCPF database described above with NOAA and Air Force aircraft flight-level measurements of the RMW, and a case-study approach combining the TCPF database with detailed kinematic and thermodynamic measurements from airborne Doppler radar, GPS dropsonde, and aircraft flight-level data.

d) Relevance to NASA’s research objectives

The proposed research uses NASA satellite data to investigate the role of inner-core processes in TC intensification. By combining measurements from the TRMM TCPF database with airborne Doppler, dropsonde, and flight-level data, the insights gained from the TRMM measurements will be put into a dynamical context that will enable a more complete depiction of the physical processes underlying TC intensification. Improved understanding of the processes responsible for TC intensification will translate into improved forecasting of this challenging problem. This directly addresses the NASA Strategic Sub-goal 3A (Study Earth from space to advance scientific understanding and meet societal needs) and NASA’s research objectives 3A.2 (Enabling improved predictive capability for weather and extreme weather events).

Specifically for this research announcement, the work proposed here satisfies NASA Goal 2.2, "Utilization of satellite/GV products for process studies and model development", addressing the sub-bullet of this PMM announcement "Analysis of TRMM and other current satellite-based precipitation information for studies of climate (global and regional variability, ENSO, etc.) and weather (tropical convection, hurricanes, midlatitude weather systems)."

e) Results from previous research fully or partially funded by NASA

1. <u>TC inner-core kinematic and convective structure and RI</u>

(i) TC inner-core structure from airborne Doppler radar composites

Composites of inner-core structure were created using tail Doppler radar data with 2-km horizontal spacing from NOAA WP-3D radial penetrations in multiple storms from 1997 to 2008 (Rogers et al. 2012a). A total of 40 radial penetrations from 14 flights in 8 different tropical cyclones, all of hurricane intensity, were included in the composites. The composites were created by scaling the radar analyses by the radius of peak axisymmetric wind at 2 km altitude (this served as a proxy for RMW). The resulting radial coordinate, r*, was defined as r/RMW. The structure of the axisymmetric vortex and the convective and turbulent-scale properties within this axisymmetric framework were shown to be consistent with many previous studies focusing on individual cases or using different airborne data sources. On the vortex scale, these structures include the primary and secondary circulations, eyewall slope, decay of the tangential wind with height, low-level inflow layer and region of enhanced outflow, radial variation of convective and stratiform reflectivity, eyewall vorticity and divergence fields, and rainband signatures in the radial wind, vertical velocity, vorticity, and divergence composite mean and variance fields. Figure 1 shows the tangential and radial winds, vertical vorticity, and reflectivity from the composites. Statistics of convective-scale fields and how they vary as a function of proximity to the RMW showed that the inner eyewall edge is associated with stronger updrafts and higher reflectivity and vorticity in the mean and have broader distributions for these fields compared with the outer radii (Fig. 2). In addition, the reflectivity shows a clear characteristic of stratiform precipitation in the outer radii and the vorticity distribution is much more positively skewed along the inner eyewall than it is in the outer radii. Composites of turbulent kinetic energy (TKE) show large values along the inner eyewall, in the hurricane boundary layer, and in a secondary region located at about 2–3 times the radius of maximum wind. This secondary peak in TKE is also consistent with a peak in divergence and in the variability of vorticity, and they suggest the presence of rainbands at this radial band.

(ii) Convective-scale structure and evolution during rapid intensification

Rogers (2010) used a 1.67-km numerical model simulation of Hurricane Dennis (2005) to investigate the role of convective-scale processes during rapid intensification (RI, generally defined as an increase in the peak 10-m winds of 15 m s^{-1} / 24 h). The structure and evolution of inner-core precipitating areas during RI, the statistical properties of precipitation during times experiencing vigorous convection (termed convective bursts here) and how they differ from nonburst times, possible differences in convective bursts associated with RI and those not associated with RI, and the impacts of precipitation morphology on the vortex-scale structure and evolution during RI were all examined. It was found that the onset of RI was linked to an increase in the areal extent of convective precipitation in the inner core, while the inner-core stratiform precipitating area remained unchanged and the intensity of the stratiform precipitation

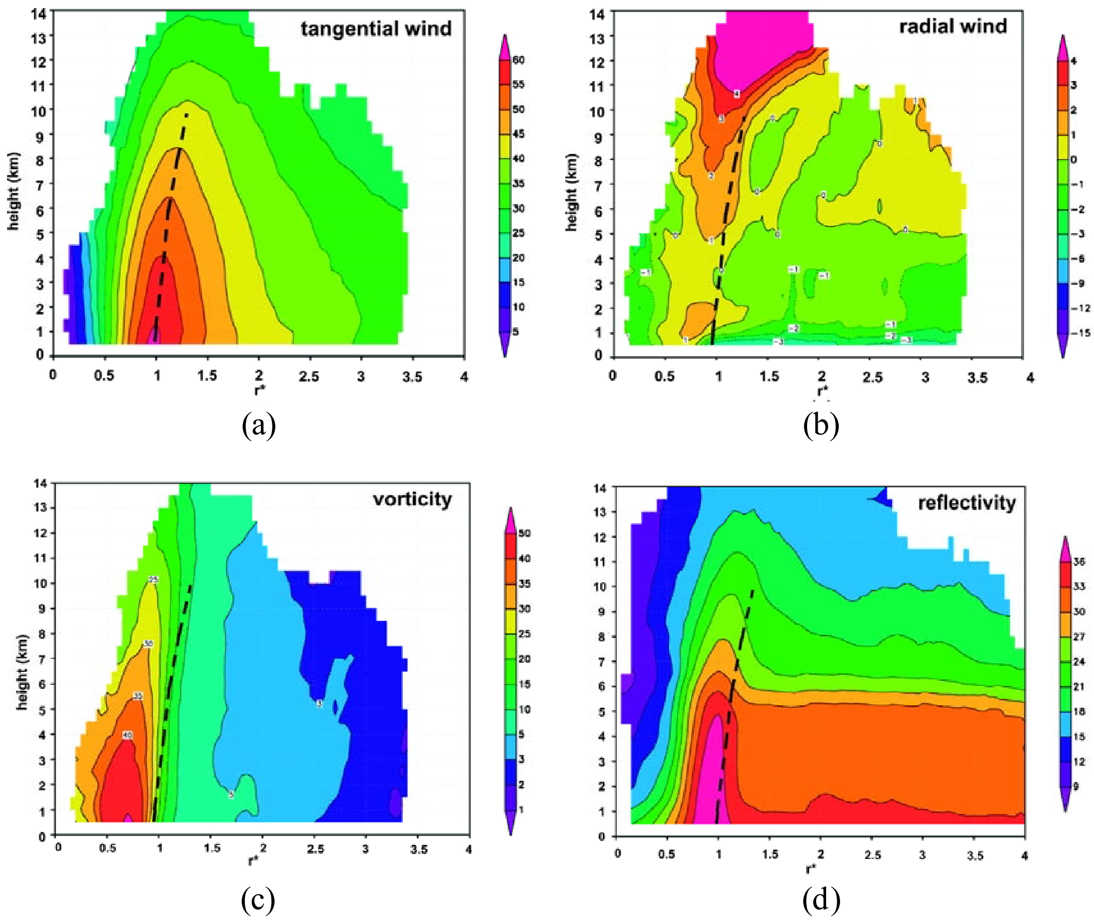


Figure 1. *Composite mean plots of axisymmetric (a) tangential wind (m s^{-1}); (b) radial wind (m s^{-1}); (c) vertical vorticity (x 10^{-4} s^{-1}); and (d) reflectivity (dBZ). All composites plotted as a function of normalized radius r* and height AGL. Data from a minimum of 20 radar analyses are required for plotting. The dashed line denotes the axis of peak axisymmetric tangential wind from 0.5- to 10-km altitude calculated from the composite in (a) (from Rogers et al. 2012a).*

increased only after RI had begun. RI was not tied to a dramatic increase in the number of convective bursts nor in the characteristics of the bursts, such as burst intensity. Rather, the immediate cause of RI was a significant increase in updraft mass flux, particularly in the lowest 1.5 km. This increase in updraft mass flux was accomplished primarily by updrafts on the order of 1–2 m s^{-1}, representing the bulk of the vertical motion distribution. However, a period of enhanced updraft mass flux in the midlevels by moderate to strong (>5 m s^{-1}) updrafts located inside the radius of maximum winds occurred 6 h prior to RI, indicating a synergistic relationship between convective bursts and the background secondary circulation prior to RI.

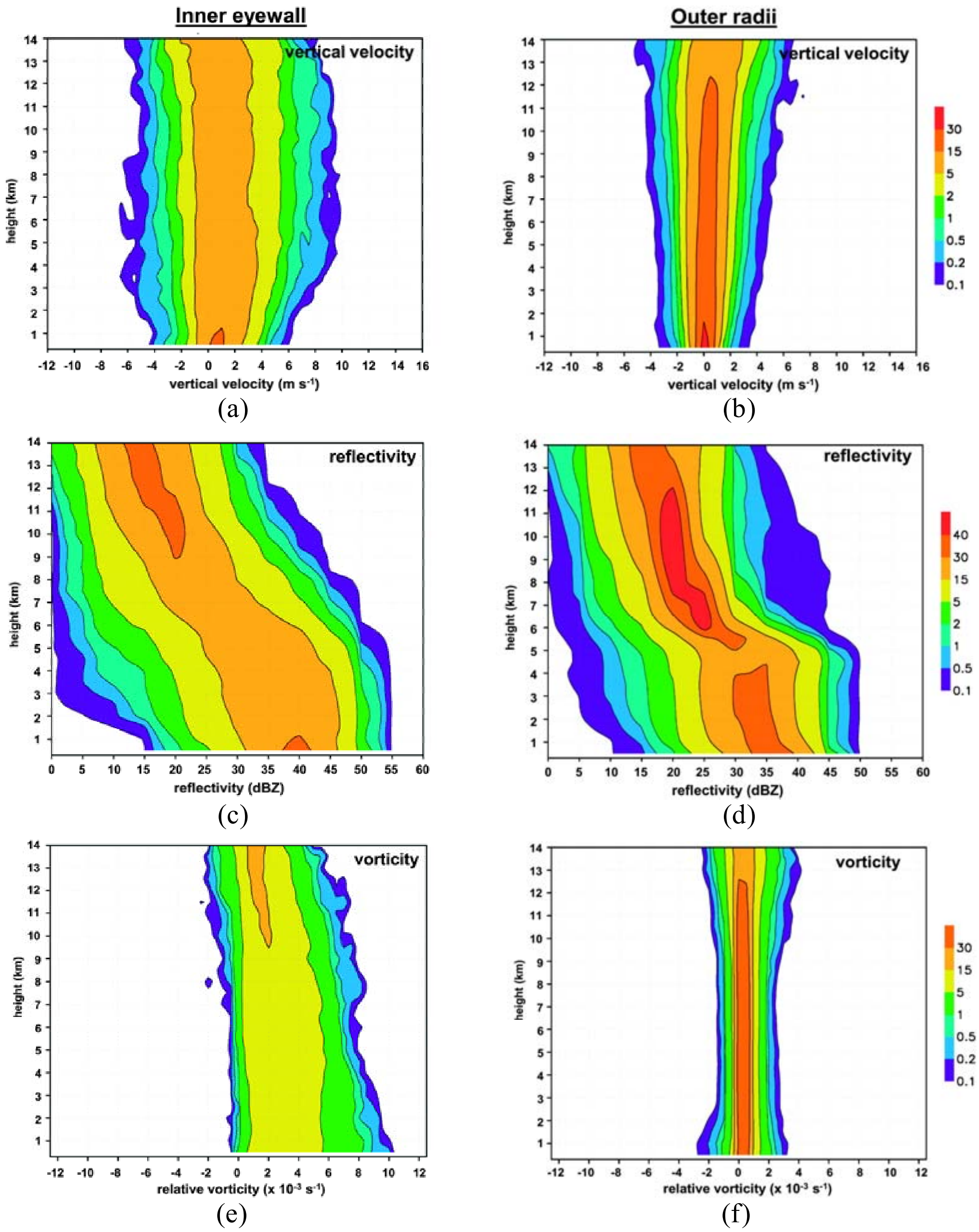


Figure 2. *(a) Contoured Frequency by Altitude Diagram (CFAD; Yuter and Houze 1995) of vertical velocity (shaded, %) for inner eyewall region; (b) As in (a), but for outer radii; (c) CFAD of reflectivity (shaded, %) for inner eyewall region; (d) As in (c), but for outer radii; (e) CFAD of vertical vorticity (shaded, %) for inner eyewall region; (f) As in (e), but for outer radii (from Rogers et al. 2012a).*

This result supports the assertion that both buoyantly driven updrafts and slantwise near-neutral ascent are important features in eyewall structure, evolution, and intensification, including RI.

2. Development and application of the TRMM Tropical Cyclone Precipitation Feature (TCPF) database

(i) Development of TCPF database

The TCPF database is based on identifying precipitation features (PFs) defined by grouping contiguous pixels based on certain criteria as observed by TRMM (Nesbitt et al. 2000, Liu et al. 2008). The TCPF database includes all PFs that are associated with TCs. Parameters in the level-1 of this database are collocated pixel-by-pixel observations and retrievals from TRMM Microwave Imager (TMI), Precipitation Radar (PR), Visible and Infrared Scanner (VIRS), and Lightning Imaging System (LIS). These include 3D radar reflectivity profiles, PR-retrieved 2A25 rain rate profiles (Iguchi et al. 2000), PR-derived 2A23 rain type and storm height (Awaka et al. 1998), 10-, 19-, 37-, and 85-GHz brightness temperatures, TMI-retrieved 2A12 surface rain rate and hydrometeor content profiles (Kummerow et al. 1996) and IR brightness temperatures. Level-2 data consist of statistics-based parameters for each identified feature, such as maximum reflectivity at each vertical level, maximum height with 15, 20, 30, 40 dBZ echo, minimum 37/85 GHz Polarization Corrected brightness Temperature (PCT, Spencer et al. 1989, Cecil et al. 2002), volumetric PR/TMI retrieved rains inside the feature, total flash counts in the feature, etc. (Liu et al. 2008). A series of storm parameters (e.g. storm center location, maximum sustained wind speed, future 12, 24, 36, and 48-h intensity change, land-ocean flag of the storm center) are calculated from the best track information. The detailed description was reported in Jiang et al. (2011). The dissemination of the database is through our web pages at http://tcpf.fiu.edu. Currently we are maintaining 13 years (1998-2010) of TRMM TC data. Yearly updates are being done each year after the TC best track data become available for all basins.

(ii) Hot towers and TC rapid intensification

The "hot tower" hypothesis assumes that there is a direct relationship between intense convection and RI. To test this hypothesis, Jiang (2012) examined the probabilities of 24-h TC intensity changes for storms with or without hot towers in the inner-core using 11 years of TRMM TCPF data. Here hot towers are defined by maximum TRMM PR 20 dBZ echo height ≥ 14.5 km following the definition of Kelley et al. (2004). Five 24-h intensity change categories are included: rapidly intensifying (RI), slowly intensifying, neutral, slowly weakening, and rapidly weakening. The thresholds used are 30 kt for RI, 10~30 kt for slowly intensifying, -10~10 kt for neutral, -30~-10 kt for slowly weakening, and -30 kt for rapidly weakening.

Probabilities in Fig. 3 are obtained by dividing the number of cases with hot towers that fall in a given intensity change category by the number of cases in the entire sample that fall in the same intensity change category. It is found that the probabilities of RI and slowly intensifying increase and those of slowly weakening and rapidly weakening decrease for samples with hot towers in the inner core. This suggests that hot towers play an active role in TC RI and could be an additional predictor in improving TC intensity change forecasts. However, the RI probability increase is not substantial, from 4.9% for samples without hot towers, to 6.3% for total sample mean (i.e., climatological probability), and to 9.6% for samples with hot towers in the inner core region (Fig. 3). There are at least 50% of non-RI cases with hot towers in the inner core. This indicates that hot towers are neither a necessary nor a sufficient condition for RI.

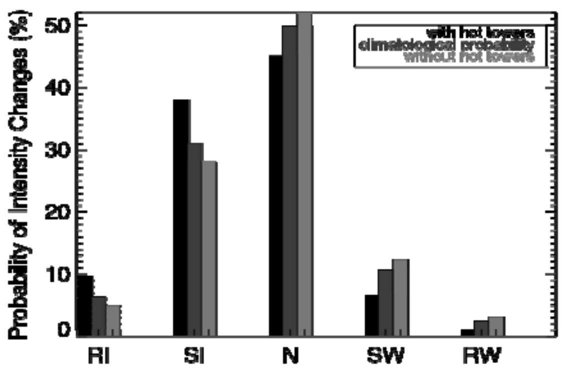


Figure 3. *Probability of rapidly intensifying, slowly intensifying(SI), neutral (N), slowly weakening (SW), and rapidly weakening (RW) for TCs with or without hot towers in the inner core region derived from TRMM Precipitation Radar (PR) observations for 1998-2008 (from Jiang 2012).*

(iii) Convective and rainfall properties in the inner core and their relation to TC intensity change

Jiang et al. (2012b) examined convective and rainfall properties in the inner core and their relation to TC intensity change. The important findings are as follows:

- The necessary conditions for RI are that the minimum 85 GHz PCT in the inner core (IC) region must be less than 235 K, the minimum 37 GHz PCT in the IC region must be less than 275 K, and the maximum 20 (30, 40) dBZ echo height in the IC region must be equal to or greater than 8 (6, 4) km. This indicates that very modest ice scattering signatures and echo top heights are necessary conditions for RI.
- At the stronger end of the convective spectrum, RI storms do not necessarily have stronger convective intensity in the IC region than those in other intensity change stages. Extremely intense convection, therefore, is not a sufficient condition for RI.
- Although IC conditional mean rain rate is not a good indicator of RI, both IC raining area and IC volumetric rain are. From both TMI 2A12 and PR 2A25 rainfall estimates, it is found that RI storms always have larger raining area and volumetric rain in the IC region than storms in other intensity change stages. This implies that the chance of RI increases when a storm's raining area in the IC region increases. In most cases, this means the storm becomes more symmetric.

f) Ongoing work

Using a methodology based on the airborne Doppler composite work shown in Rogers et al. (2012), work is underway to document differences in the inner-core structure of tropical cyclones that are intensifying compared with those that are remaining steady-state. A composite of radar analyses from TC's of hurricane strength that were intensifying (I; defined as an intensification rate corresponding to at least 20 kt over the subsequent 24 h from the Best Track at the time of the radar analysis) was constructed and compared with a composite from TC's that were remaining steady-state (SS; defined as an intensification rate of +/- 10 kt/24 h). A total of 40 eyewall passes from 14 separate WP-3D flights in 8 different TC's comprised the I composite, while a total of 53 eyewall passes from 14 WP-3D flights in 6 different TC's comprised the SS composite.

Figure 4 shows composite mean plots of axisymmetric vorticity and radial wind for each

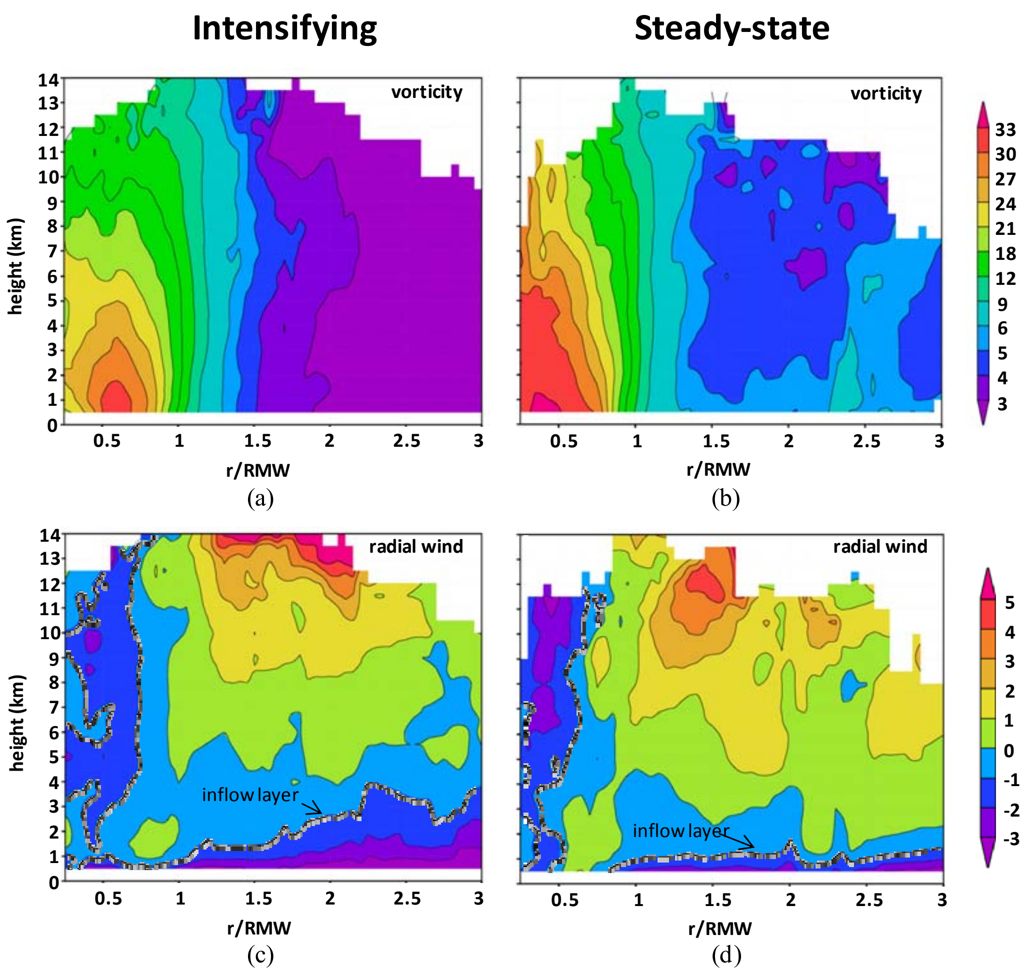
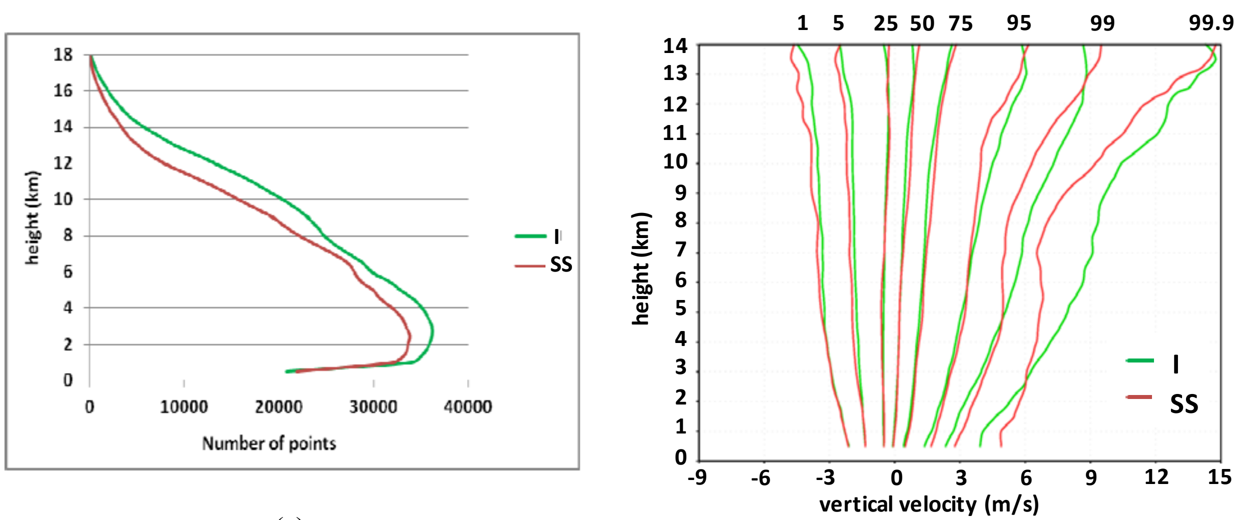


Figure 4. *Composite mean plots of axisymmetric vertical vorticity (x 10^{-4} s^{-1}) for (a) intensifying TC's; (b) steady-state TC's. Composite mean plots of radial wind (m s^{-1}) for (c) intensifying TC's; (d) steady-state TC's. All composites plotted as a function of normalized radius r* and height AGL. Data from a minimum of 7 radar analyses are required for plotting.*

of the composites. Statistically-significant differences (at the 95% confidence level) were identified for these fields. For example, intensifying storms showed a ring-like vorticity structure inside the RMW compared with steady-state storms, which showed a more monopolar structure, consistent with that shown in Kossin and Eastin (2001). Additionally, intensifying storms showed a more rapid decrease in axisymmetric vorticity with radius outside the RMW, with values in the 2-3 x RMW radial band ~50% less than that seen in the steady-state storms. For radial flow, the strength of the radial inflow outside the RMW (i.e., in the 1.5-2.5 x RMW radial band) for the intensifying TC's is about twice that for the steady-state TC's (note that, since these analyses only extend down to 500 m AGL, the true measure of the peak inflow is not capable of being sampled, as indicated in Lorsolo et al. (2010) and Zhang et al. (2011)). Additionally, the depth of the inflow layer is much larger for intensifying TC's than for steady-state TC's.

One aspect of the convective-scale structure of the two composites was investigated by examining the statistical properties of the vertical velocity distributions within the eyewall, defined as radii between 0.75 and 1.25 x RMW. While the number of points used to calculate the statistics decreased significantly above 10 km altitude (Fig. 5a), enough points were available

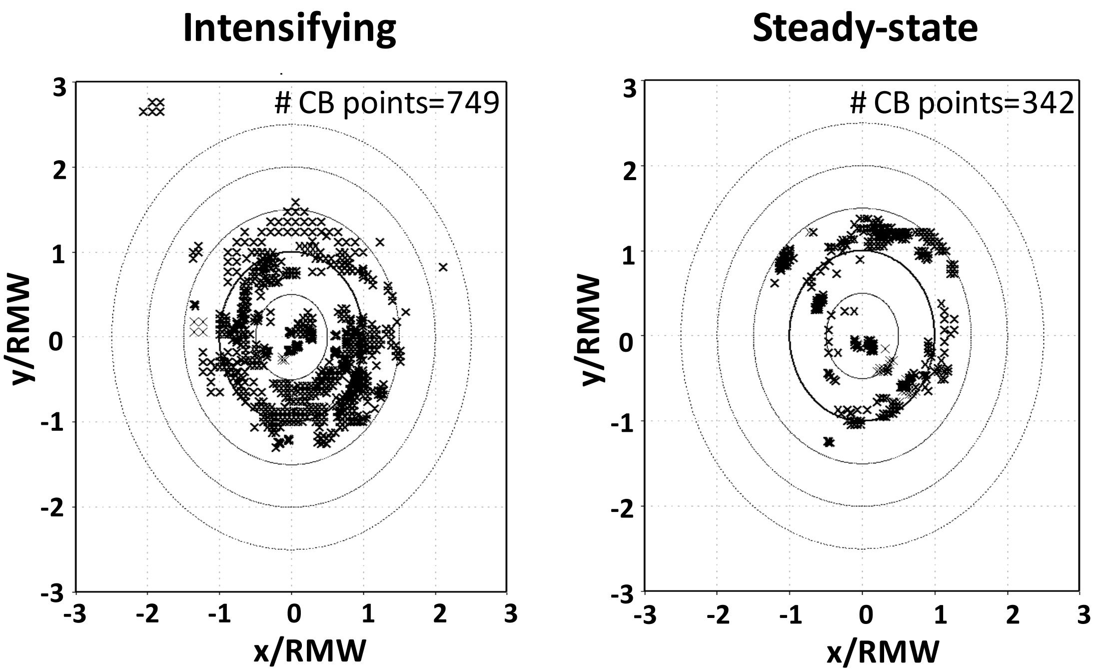


(a) (b)

Figure 5. *(a) Number of eyewall points used in calculation of statistics for intensifying (green) and steady-state (red) TC's; (b) Vertical profile of 1st, 5th, 25th, 50th, 75th, 95th, 99th, and 99.9th percentiles for eyewall points for intensifying (green) and steady-state (red) TC's.*

to calculate robust statistics up to 14 km. Figure 5b shows that there is little difference in the profiles of eyewall vertical velocity for the downdraft and weak to moderate parts of the vertical velocity spectrum (i.e., between the 1st and the 75th percentiles). It is not until the strong updraft portions of the spectrum, at the 95th percentile and above, that significant differences are noted, with intensifying TC's showing strong peak updrafts above the freezing level at ~ 5 km altitude.

The number and location of convective bursts (in normalized radius and earth-relative azimuth) for each composite are shown in Fig. 6. Convective bursts (CB's) were defined as locations where the vertical velocity at 8 km altitude exceeds 5.5 m s^{-1}, which corresponded with the top 1% of vertical velocities from a combined composite. A considerably larger number of



(a) (b)

Figure 6*. Plot of number and location (in normalized radius) of points flagged as convective bursts (CB's) identified from airborne Doppler composite for (a) intensifying TC's and (b) steady-state TC's. Each ring is plotted at 0.5 x RMW.*

CB's, distributed nearly evenly around the circulation center, is evident for the intensifying TC's. For both composites the CB's are primarily clustered between 0.5 and 1.5 x RMW. A more detailed look at the radial distribution of CB's (Fig. 7), however, shows that for intensifying TC's, the peak of the distribution (> 30% of all CB's) is located between 0.75 and 1 x RMW, whereas for the steady-state TC's, the peak of the distribution (> 35%) is between 1 and 1.25 x RMW. Overall, > 50% of all CB's are located inside the RMW for intensifying TC's, whereas < 35% of CB's are inside the RMW for steady-state TC's. The significance of this difference in the radial distribution is shown by overlaying this CB distribution on the axisymmetric vorticity field. The peak in the CB distribution for intensifying TC's is located in a region with much higher background vorticity and inertial stability than the peak for steady-state TC's. This difference has important implications for the response of the vortex to diabatic heating in the CB's (and presumably the broader distribution of precipitation), since the efficiency of the vortex response to diabatic heating is increased when heating occurs in areas of higher inertial stability, as shown in analytical and numerical model simulations (e.g., Schubert and Hack 1982; Nolan et al. 2007; Vigh and Schubert 2009, and Pendergrass and Willoughby 2009). A manuscript describing these results is currently being prepared (Rogers et al. 2012b).

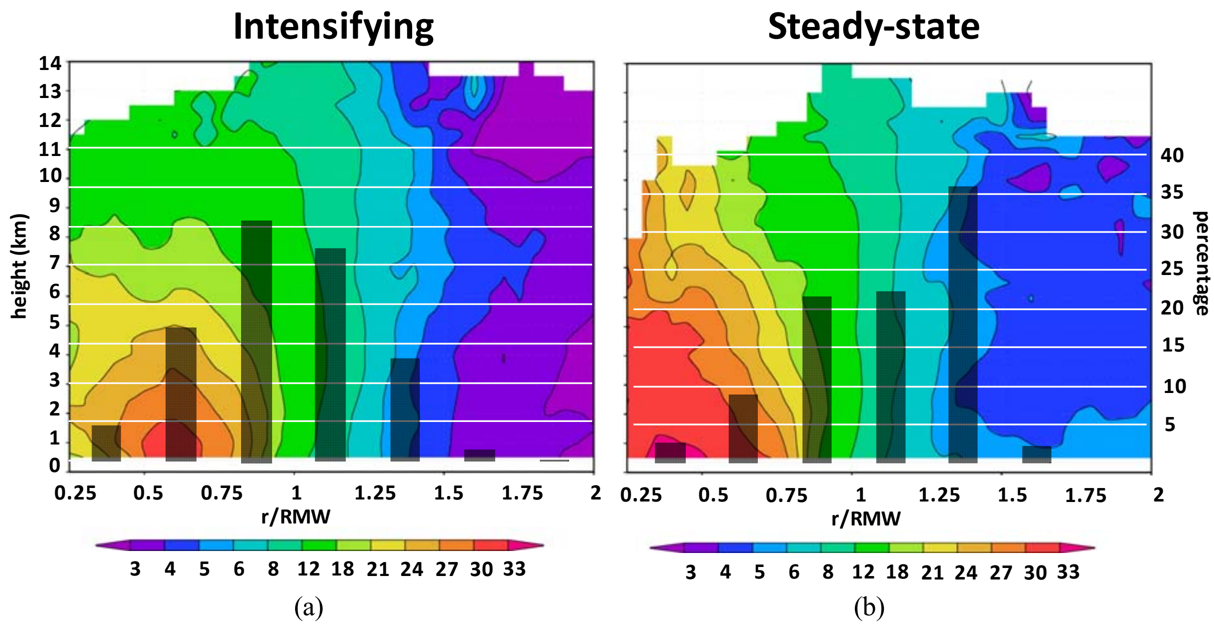


***Figure 7**. Plot of vertical vorticity (shaded, x 10^{-4} s^{-1}) for (a) intensifying TC's and (b) steady-state TC's. Percentage of CB's in 0.25 radial bins for intensifying and steady-state composites overlain as bar diagrams on vorticity plots.*

g) Publications resulting fully or in part from past three years of NASA funding

Jiang, H., 2012: The relationship between tropical cyclone intensity change and the strength of inner core convection. *Mon. Wea. Rev*., **140**, 1164-1176.

Jiang, H., and E. J. Zipser, 2010: Contribution of tropical cyclones to the global precipitation from eight seasons of TRMM data: Regional, seasonal, and interannual variations. *J. Climate*., **23**, 1526-1543.

Jiang, H., C. Liu, and E. J. Zipser, 2011: A TRMM-based Tropical Cyclone Cloud and Precipitation Feature Database. *J. Appl. Meteor. Climatol*., **50**,1255-1274.

Jiang, H., E. M. Ramirez, and D. J. Cecil, 2012a: Convective and rainfall properties of tropical cyclone inner cores and rainbands from 11 years of TRMM data. *Mon. Wea. Rev*., in minor revision.

Jiang, H., E. M. Ramirez, and D. J. Cecil, 2012b: Necessary conditions for tropical cyclone rapid intensification as derived from 11 years of TRMM data. *J. Climate*.,, to be submitted.

Jiang, H., M. Kieper, T. Yuan, E. Zipser, and J. Kaplan, 2012: An objective rapid intensification index derived from the 37 GHz microwave ring pattern around the tropical cyclone center. *J. Geophys. Res*., to be submitted.

Kieper, M., and H. Jiang, 2012: Predicting tropical cyclone rapid intensification using the 37 GHz ring pattern identified from passive microwave measurements. *Geophys. Res. Lett*., in press.

Ramirez, E. M., 2010: Convective and rainfall properties of tropical cyclone inner cores and rainbands in relation to tropical cyclone intensity changes using 12 years of TRMM data. M. S. thesis, University of Utah, Dec. 2010.

Rogers, R.F., 2010: Convective-scale structure and evolution during a high-resolution simulation of tropical cyclone rapid intensification. *J. Atmos. Sci*., **67**, 44–70.

Rogers, R.F., S. Lorsolo, P. Reasor, J. Gamache, F.D. Marks, Jr., 2012a: Multiscale analysis of tropical cyclone kinematic structure from airborne Doppler radar composites. *Mon. Wea. Rev*., **140**, 77-99.

Rogers, R.F., P.D. Reasor, S. Lorsolo, and J. Zhang, 2012b: Observations of the inner-core structure of intensifying and steady-state tropical cyclones. *Mon. Wea. Rev*., to be submitted.

2. Description of work

a) Overview of tasks and working hypotheses

The use of TRMM data to study inner-core precipitation processes complements well the use of airborne Doppler data. Measurements of ice scattering at 85 GHz, lightning flashes, and vertical profiles of reflectivity provide an indication of the structure and distribution of deep convection within the TC inner core. The ability to measure reflectivity at high altitudes will expand the database of reflectivity at those altitudes currently limited by beam spreading and attenuation for airborne Doppler radar. Sample sizes from the TRMM at altitudes above 14 km, larger than those possible from the airborne Doppler (cf. Fig. 5a), will enable robust statistics to be developed in this altitude range, which is known to contain vigorous updrafts in deep convection due to water unloading and enhanced buoyancy from the release of the latent heat of freezing (e.g., May and Rajopadhyaya 1996; Zipser 2003; Fierro et al. 2008, 2009). Finally, a long period of measurements from TRMM, nearly 15 years, will provide more samples of precipitation structure than the current airborne-derived datasets.

The tasks that will be performed consist of three primary efforts:

1. <u>Develop algorithms for plotting TCPF fields in dynamical radius</u>

   The *working hypothesis* here is that flight-level data can be used normalize radius in TCPF fields based on RMW. Flight-level measurements from NOAA and Air Force missions (flight altitudes normally between ~1 and 3.5 km altitude) will be matched with samples from the TRMM TCPF database. Both NOAA and Air Force flight-level datasets are available at HRD. A requirement that the on-station time of the flight occur within +/- 6 h of the TRMM overpass will expand the size of the database while still allowing a small enough time window to reasonably account for variations in eyewall diameter that can occur during eyewall contraction and eyewall replacement cycles.

   Once TCPF overpasses are matched with aircraft flight-level measurements of RMW, all TCPF fields (e.g., PR reflectivity profiles, TMI 85 GHz brightness temperature, LIS lightning flash counts) will be mapped onto a radial grid normalized by the RMW similar to the technique used in Rogers et al. (2012a) for airborne Doppler data. Such a mapping will permit a compositing of these parameters based on location relative to the RMW.

   An additional task that will be required is to develop an algorithm for identifying convective bursts (CB's) from the TRMM PR measurements. The algorithm shown in Figs. 6-7 employed vertical velocity, but this is not available for TRMM. A relationship between airborne Doppler-derived reflectivity and vertical velocity will be explored and adapted to the TRMM PR, alternatively, equivalent ranges of the reflectivity distributions from the airborne Doppler and TRMM PR will be used.

2. <u>Calculate statistical properties of inner-core precipitation as a function of dynamical radius for different intensity change categories using TCPF</u>
The *working hypothesis* here is that the deepest, most intense convection, as measured by parameters such as counts of CBs, height of 20 dBZ echo, 85 GHz ice scattering, and lightning flashes has a preferred radius for intensifying cases inside the RMW and outside the RMW for SS cases. This task addresses Science Questions 1 and 2, and it relies upon the compositing technique development described above. With the RMW values from each possible TCPF overpass quantified, the values of TRMM PR reflectivity, 85 GHz ice scattering, and lightning flash and CB count will be mapped onto a normalized radial grid. Normalized airctraft-matched TRMM overpasses will then be assigned to categories such as intensity change, current intensity, and proximity to land, and subgroups of TRMM overpasses corresponding to various intensity change categories will be created. The intensity change categories will replicate those used in Jiang (2012), i.e, rapidly intensifying, slowly intensifying, steady state, slowly weakening, and rapidly weakening. Composites for each of these subgroups will be calculated and the composite structure of the TCPF parameters mentioned above will be compared. Comparisons of the convective-scale structure for TC's of various intensity change categories, similar to those shown in Figs. 5-7, will be created using the TRMM TCPF database.

3. <u>Relate TCPF statistics to inner-core kinematic structure and TC intensity change</u>
The *working hypothesis* here is that there is a direct relationship between inner-core precipitation structure, inner-core kinematic structure, and TC intensity change. For intensifying cases (both slowly and rapidly), this includes more CB's, a higher altitude of 20 dBZ echoes, and more ice scattering and lightning flashes inside the RMW associated with distinct signatures such as ring-like structures in the vorticity field inside the eyewall, lower vorticity outside the eyewall, and deeper and stronger inflow layers outside the eyewall. This task addresses Science Questions 1 and 3, and it will follow a case-study approach involving near-coincidence between TRMM overpasses and WP-3D missions. Whereas the time window for considering coincidence between TRMM and WP-3D for the RMW calculation is +/- 6 h (see task 1 above), the time window for this work will be more stringent, i.e., +/- 1 h. This is because we will relate the reflectivity, ice scattering, and lightning flash counts from TRMM with the vertical velocity measurements from the WP-3D. A search of the existing TRMM TCPF and WP-3D airborne Doppler databases found two cases (one steady-state and one intensifying) that met this criterion: Hurricane Gustav (2008) had a TRMM overpass at 2143 UTC August 31 and five radial passes from the WP-3D between 2058 UTC August 31 and 0202 UTC

September 1, including one pass at 2226 UTC August 31. Hurricane Earl (2010) had a TRMM overpass at 1151 UTC September 1 and two radial passes from the WP-3D, one at 1056 UTC and the other at 1217 UTC September 1. Continued reanalysis of the Doppler database is ongoing at HRD, and as more cases are added they will be checked against the TRMM TCPF database to identify possible additional matches.

Once cases are matched, the TRMM fields will be mapped onto the normalized radial coordinate. They will also be compared with the kinematic fields derived from the airborne Doppler, similar to what was shown in Figs. 1 and 4. Vertical velocity and reflectivity statistics from the WP-3D will also be compared with reflectivity, ice scattering, and lightning flash count statistics from the TRMM TCPF, similar to what was done in Figs. 2, 5, 6, and 7. Comparisons of these fields between intensifying (slowly or rapidly) and SS cases should allow us to support or refute the hypothesis stated above.

b) Work plan

Year 1 (2012-2013):

- Examine TRMM TCPF and aircraft databases (Air Force and NOAA) to identify those cases with a sampling time difference of +/- 6 h.
- Calculate RMW of matched cases from flight-level data.
- Begin mapping fields of reflectivity, 85 GHz brightness temperature, and lightning flash counts from TRMM TCPF cases to normalized radii.
- Examine TRMM TCPF and WP-3D airborne Doppler databases and identify those cases with an overlap of +/- 1 h.
- Develop radar-based convective burst definition using Doppler radar data on cases with +/- 1 h time difference from TRMM TCPF cases.
- Continue reprocessing existing database of airborne Doppler observations.
- Include new measurements from TRMM and airborne Doppler into existing databases.

The first year will focus on identifying matching times for TRMM and aircraft measurements, acquiring the needed flight-level data, and calculating the RMW for each matched case. Drs. Rogers and Jiang will identify the matching times, and Dr. Lorsolo will acquire the flight-level data and calculate the RMW for them. Dr. Jiang and her graduate student Yongxian Pei will map the TCPF fields to the normalized radial coordinate, and they will work with Drs. Rogers and Lorsolo to develop the CB definition based on the airborne Doppler. Dr. Lorsolo will continue to reprocess the existing database of airborne Doppler observations, and she will include new airborne measurements as they become available. Dr. Jiang and her graduate student will do the same for the TCPF.

Year 2 (2013-2014):

- Apply convective burst definition to TRMM TCPF database
- Analyze statistical properties (e.g, convective burst counts, reflectivity profiles, height of 20 dBZ echo, 85 GHz scattering) of composites in normalized radial coordinate for TC's of various intensity change categories from TRMM TCPF database.
- Continue reprocessing existing database of airborne Doppler observations.
- Include new measurements from TRMM and airborne Doppler into existing databases.
- Begin writing manuscripts detailing results.

The second year will see the emphasis on constructing the composites of TRMM TCPF fields for RI and SS cases. Dr. Jiang and her graduate student will perform this composite with input from Drs. Rogers and Lorsolo. Dr. Lorsolo will continue to reprocess the existing database of airborne Doppler observations, and she will include new airborne measurements as they become available. Dr. Jiang and her graduate student will do the same for the TCPF. All will participate in writing manuscripts.

Year 3 (2014-2015):

- Analyze statistical properties (e.g, convective burst counts, reflectivity profiles, height of 20 dBZ echo, 85 GHz ice scattering) of individual cases in normalized radial coordinate for cases of various intensity change categories from TRMM TCPF database.
- Compare these fields with kinematic fields from airborne Doppler data for same cases as those used from TRMM TCPF database.
- Compare these fields with vertical velocity and reflectivity statistics from airborne Doppler analyses.
- Continue analysis of composites from TRMM TCPF database.
- Continue reprocessing existing database of airborne Doppler observations.
- Include new measurements from TRMM and airborne Doppler into existing databases.
- Finish writing manuscripts detailing results.

The third year will have an emphasis on performing the case studies for TC's of various intensity change categories whose time separation between the aircraft and satellite measurements is +/- 1 h. Dr. Jiang and her graduate student will perform the analysis of the TRMM TCPF cases in normalized radius, while Drs. Rogers and Lorsolo will perform a comparable analysis with the airborne Doppler. All will be involved with comparing vertical velocity and reflectivity statistics between the TRMM TCPF and airborne Doppler.

3. References

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4. Biographical sketches

ROBERT ROGERS

NOAA/AOML Hurricane Research Division
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PROFESSIONAL PREPARATION:

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

APPOINTMENTS:

- 2003-current: Meteorologist, NOAA/AOML Hurricane Research Division, Miami, FL
- 2000-2003: Asst. Scientist, Coop. Inst. for Marine & Atmospheric Studies, University of Miami, Miami, FL
- 1998-2000: National Research Council Postdoctoral Res. Assoc., Hurricane Research Division, Miami, FL

SELECT RECENT PUBLICATIONS:

Rogers, R.F., S. Lorsolo, P. Reasor, J. Gamache, F.D. Marks, Jr., 2012: Multiscale analysis of tropical cyclone kinematic structure from airborne Doppler radar composites. Monthly Weather Review, 140, 77-99.

Zhang, J.A., R.F. Rogers, D.S. Nolan, and F.D. Marks, Jr., 2011: On the characteristic height scales of the hurricane boundary layer. Monthly Weather Review, 139, 2523-2535.

Rogers, R.F., 2010: Convective-scale structure and evolution during a high-resolution simulation of tropical cyclone rapid intensification. Journal of the Atmospheric Sciences, 67, 44–70.

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Rogers R., and E. Uhlhorn, 2008: Observations of the structure and evolution of surface and flight-level wind asymmetries in Hurricane Rita (2005). Geophysical Research Letters, 35, L22811, doi:10.1029/2008GL034774.

Rogers, R.F., M.L. Black, S.S. Chen, and R.A. Black, 2007: An Evaluation of Microphysics Fields from Mesoscale Model Simulations of Tropical Cyclones. Part I: Comparisons with Observations. Journal of the Atmospheric Sciences, 64, 1811-1834.

Marchok, T., R. Rogers, and R. Tuleya, 2007: Validation Schemes for Tropical Cyclone Quantitative Precipitation Forecasts: Evaluation of Operational Models for U.S. Landfalling Cases. Wea. and Forecast., 22, 726-746.

Rogers, R.F., S.S. Chen, J.E. Tenerelli, and H.E. Willoughby, 2003: A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998). Monthly Weather Review, 131, 1577-1599.

SYNERGISTIC ACTIVITIES:

- Topic Chair for Structure and Intensity Change session, Seventh International Workshop on Tropical Cyclones, 2010
- Field Program Director for the Hurricane Research Division Hurricane Field Program, July 1-September 30, 2010 and 2005
- Adjunct Faculty member, Department of Meteorology and Physical Oceanography, University of Miami/RSMAS
- Associate Editor, Monthly Weather Review, 2008-present
- Associate Editor, Weather and Forecasting, 2003-present
- Member, Interdepartmental Working Group for Tropical Cyclone Research, 2008-present
- Member, NASA Hurricane Science Research Program Science Team, 2008-present
- Member, NASA Tropical Cloud Systems and Processes (TCSP) Science Team, 2005-2008
- Member, NASA CAMEX-4 Science Team, 2001-2004
- Member, NSF Hurricane Rainband and Intensity Change Experiment (RAINEX) Science Team, 2005

HAIYAN JIANG

Education
2004 Ph.D. Meteorology, University of Utah
1995 M.S. Atmospheric Remote Sensing, Chinese Academy of Meteorological Sciences (CAMS)
1992 B.S. (with honors) Atmospheric Physics, Nanjing Institute of Meteorology, China

Professional Experience
2010-present: Assistant Professor, Florida International University
2007-2009: Research Assistant Professor, University of Utah
2004-2006: Research Associate, Joint Center for Earth Systems Technology, University of Maryland Baltimore County, and NASA Goddard Space Flight Center, Greenbelt, MD
2000-2004: Research Assistant, University of Utah
2001: Summer work, NOAA Hurricane Research Division (HRD)
1998-2000: Research Associate, Research Center for Disastrous Weather, CAMS, China
1995-1998: Research Assistant, Institute of Mesoscale Meteorology, CAMS

Honors and Awards
NASA GRIP Group Achievement Award 2010
NASA New Investigator Award in Earth Science 2008-2011
NASA Earth System Science Fellowship Award 2003-2004

Graduate Student Supervised
Margaret Kieper, Ph.D student (in progress); Joseph Zagrodnik, M.S. Student (in progress); Cheng Tao, Ph.D Student (in progress); Ellen Ramirez, M.S. Student

Professional Service and Activities
Panel review for NASA 2009, 2011, 2012
Journal article reviewer for AMS and AGU journals 2003-present

Selected Journal Publications

Tao, C., and H. Jiang, 2012: Global distribution of hot towers in tropical cyclones based on 11-year TRMM data. *J. Climate*, in review.

Zagrodnik, J., and H. Jiang, 2012: Properties of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) and Microwave Imager (TMI) Rainfall Retrievals in Tropical Cyclone Inner Cores and Rainbands. *J. Geophys. Res.*, in review.

Jiang, H., E. M. Ramirez, and D. J. Cecil, 2012: Convective and rainfall properties of tropical cyclone inner cores and rainbands from 11 years of TRMM data. *Mon. Wea. Rew.*, in revision.

Kieper, M., and H. Jiang, 2012: Predicting tropical cyclone rapid intensification using the 37 GHz ring pattern identified from passive microwave measurements. *Geophys. Res. Lett.*, in press.

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Jiang, H., J. B. Halverson, J. Simpson, and E. J. Zipser, 2008: Hurricane "rainfall potential" derived from satellite observations aids overland rainfall prediction. *J. Appl. Meteor. Climatol.*, **47**, 944–959.

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Jiang, H., J. B. Halverson, and J. Simpson, 2008: On the differences in storm rainfall from Hurricanes Isidore and Lili. Part I: Satellite observations and rain potential. *Wea. Forecasting*, **23**, 29-43.

5. Current and Pending Support

Rogers

Current Support:

NASA: Hurricane Severe Storm Sentinel (HS3). December 2010 – September 2015. Total budget $347,700, 1 month/year time as co-I.

NASA: Hurricane Science Research Program. November 2010 – October 2012. Total budget $61,720, 0.5 month/year time as Science Team member.

NASA: Supplemental Education Awards, "Undergraduate Summer Education and Research Program in Hurricane Monitoring and Forecasting Using Remote Sensing Observations". September 2011 – August 2013. Total budget $13,114, 0.2 month/year time as co-Investigator.

Pending Support:
None

Jiang

Current Support:

NASA: Hurricane Science Research Program (NNH08ZDA001N-HSRP): A TRMM-based Tropical Cyclone Precipitation Feature Database and Its Usage on Intensification Study. Feb 2009 – Jan. 2013. Current year budget $95K, 2 summer month PI time.

NASA: Supplemental Education Awards, "Undergraduate Summer Education and Research Program in Hurricane Monitoring and Forecasting Using Remote Sensing Observations". September 2011 – August 2013. Current year budget $14K, 0.6 summer month/year PI time.

NOAA: FY 11 Joint Hurricane Testbed (JHT): Enhancement of SHIPS Rapid Intensification (RI) Index Using Satellite 37 GHz Microwave Ring Pattern. Sep. 2011- Aug. 2013. Current year budget $70K, 1 summer month PI time.

Pending Support:
None

Total Budget

			Budget Year 1 FY13				Budget Year 2 FY14				Budget Year 3 FY15			
			NOAA		NASA		NOAA		NASA		NOAA		NASA	
			In-kind		Requested		In-kind		Requested		In-kind		Requested	
			mm	Amount	mm	Amount	mm	Amount	mm	Amount	mm	Amount	mm	Amount
Personnel														
AOML	R. Rogers	PI	2.0	$ 18,296	0.0	$ -	2.0	$ 19,028	0.0	$ -	2.0	$ 19,789	0.0	$ -
AOML	Secretary		1.0	$ 3,933	0.0	$ -	1.0	$ 4,090	0.0	$ -	1.0	$ 4,254	0.0	$ -
CIMAS	S. Lorsolo		0.0	$ -	3.0	$ 15,354	0.0	$ -	3.0	$ 15,968	0.0	$ -	3.0	$ 16,607
CIMAS	IT Support	TBD	0.0	$ -	0.5	$ 5,115	0.0	$ -	0.5	$ 5,319	0.0	$ -	0.5	$ 5,532
Subtotal				$ 22,229		$ 20,469		$ 23,118		$ 21,287		$ 24,043		$ 22,139
Fringe Benefits		AOML		$ 7,113		$ -		$ 7,629		$ -		$ 8,175		$ -
		CIMAS		$ -		$ 7,778		$ -		$ 8,302		$ -		$ 8,855
Total Salaries and Fringe Benefits				$ 29,342		$ 28,247		$ 30,747		$ 29,589		$ 32,217		$ 30,994
Indirect Costs		AOML		$ 15,258		$ -		$ 16,296		$ -		$ 17,397		$ -
		CIMAS		$ -		$ 7,344		$ -		$ 7,693		$ -		$ 8,058
Total Labor Costs				$ 44,600		$ 35,591		$ 47,043		$ 37,282		$ 49,615		$ 39,053
Equipment						$ 3,000				$ -				$ -
Supplies						$ -				$ -				$ -
Travel	Meetings					$ 3,200				$ 3,360				$ 3,528
Publications						$ 3,000				$ 3,150				$ 3,308
Other IT hardware/software support						$ 5,000				$ 5,250				$ 5,513
Subcontract		CIMAS-FIU				$ 52,120				$ 53,684				$ 55,294
Total				$ 44,600		**$ 101,911**		$ 47,043		**$102,726**		$ 49,615		**$106,695**

Budget for FIU subcontract

Salaries	Year 1	Year 2	Year 3	Total
FIU PI Jiang (1 mo/yr, assume 3% inflation rate)	$ 9,242.03	$ 9,519.29	$ 9,804.87	$ 28,566.19
Graduate Student (12 mo/yr, assume 3% inflation rate)	$ 22,600.00	$ 23,278.00	$ 23,976.34	$ 69,854.34
Subtotal Salaries	$ 31,842.03	$ 32,797.29	$ 33,781.21	$ 98,420.53
Benefits				
Faculty/Staff @ 31.88%	$ 2,946.36	$ 3,034.75	$ 3,125.79	$ 9,106.90
Graduate Student @ 0.33%	$ 74.58	$ 76.82	$ 79.12	$ 230.52
Subtotal Benefit	$ 3,020.94	$ 3,111.57	$ 3,204.91	$ 9,337.42
Total Salaries and Benefits	**$ 34,862.97**	**$ 35,908.86**	**$ 36,986.12**	**$107,757.95**
Total Direct Costs	**$ 34,862.97**	**$ 35,908.86**	**$ 36,986.12**	**$107,757.95**
Total Direct Costs Subject to Indirect Costs	**$ 34,862.97**	**$ 35,908.86**	**$ 36,986.12**	**$107,757.95**
Indirect Cost @ 49.5%	**$ 17,257.17**	**$ 17,774.88**	**$ 18,308.13**	**$ 53,340.19**
Total Costs	**$ 52,120.14**	**$ 53,683.74**	**$ 55,294.26**	**$161,098.14**

Budget Justification:

A. Senior Personnel:

Dr. Robert Rogers, as the PI, will direct the overall effort. He will be committing 2 man-months/year, to be supported entirely by a NOAA in-kind contribution, for a total of $141,258 for the 3-year period.

B. Other Personnel:

Postdoctoral Researcher – 3 months per year of support for Dr. Sylvie Lorsolo as a postdoctoral researcher is requested from NASA. She will be responsible for doing the aircraft data analysis and coordinating with Dr. Jiang and Mr. Pei on combining the aircraft and satellite data analysis. Additional support of 0.5 months per year is requested from NASA for a computer support person to assist with computer coding and hardware maintenance. The total labor request from NASA is $111,926 for the 3-yr period.

C. Fringe Benefits:

CIMAS is currently using a fringe benefit rate of 38% for full time employees.

D. Equipment:

$3,000 is requested during year-1 for purchasing a computer for archiving and analyzing the aircraft data used for this project.

E. Travel:

A total of $3,200 per year in domestic travel is requested, which is estimated based on 2 trips of 5 days each to science team meeting and/or other national conferences TBD (for example, AMS conferences) for the PI, co-I, postdoc, and/or collaborators. This is estimated based on Airfare ($600) and Hotel+Per Diem ($200 per day).

F. Subcontract:

A subcontract of $52,120.14, $53,683.74, and $55,294.26 is requested for yr-1, yr-2, and yr-3, respectively, to support the work of Dr. Jiang and her student at FIU during the course of this project. Dr. Jiang is uniquely qualified to perform the work associated with processing and analyzing the TRMM TCPF satellite database. See budget justification for FIU included.

G. Other Direct Costs:

a. Publications/Dissemination: $3,000, $3,150, and $3,308 are requested for yr-1, yr-2, and yr-3, respectively, for journal paper publication charges.

b. IT hardware/software support: $5,000, $5,250, and $5,513 are requested for yr-1, yr-2, and yr-3, respectively to cover the IT costs associated with using AOML computers (security, hardware and software maintenance costs,etc....) for this project.

H. Total Direct Costs: $283,387.

I. Facilities and Administration Costs:

F & A costs at CIMAS are calculated at 26% of the modified total direct cost which excludes equipment, capital expenditures, charges for patient care, tuition remission, rental costs of off-site facilities, scholarships and fellowships and the portion of each subcontract and/or subgrant in excess of $25,000 regardless of the period covered.

Budget Justification for FIU subcontract:

A. **Senior Personnel:**
   Dr. Haiyan Jiang will direct the satellite analysis effort. She is requesting 1 summer month salary (or 33.3 % effort) from NASA totaling $28,566.19 for the 3-yr period.

B. **Other Personnel:**
   Graduate student, Yongxian Pei – 12 months per year of support (or 100% calendar year effort) is requested from NASA totaling $69,854.34 for the 3-yr period. He will be responsible for doing satellite data analysis and coordinating with Dr. Lorsolo on combining the satellite and aircraft data analysis.

C. **Fringe Benefits:**
   FIU is currently using a fringe benefit rate of 31.88% for full time employees and 0.33% for OPS employees.

D. **Total Direct Costs:** $107,757.95.

E. **Facilities and Administration Costs:**
   F & A costs at Florida International University are calculated at 49.5% (07/01/10-until amended) of the modified total direct cost which excludes equipment, capital expenditures, charges for patient care, tuition remission, rental costs of off-site facilities, scholarships and fellowships and the portion of each subcontract and/or subgrant in excess of $25,000 regardless of the period covered. Equipment means an article of nonexpendable tangible personal property having a useful life of more than one year, and an acquisition cost of $5000 or more per unit.