A TRMM-based Tropical Cyclone Cloud and Precipitation Feature Database

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ABSTRACT

A Tropical Cyclone Precipitation, cloud, and convective cell Feature (TCPF) database has been developed by using the observations of the Tropical Rainfall Measurement Mission (TRMM) precipitation radar (PR), Microwave Imager (TMI), Visible and Infrared Scanner (VIRS), Lightning Imaging System (LIS), and the TRMM 3B42 rainfall product. First, 12 years (1998-2009) of tropical cyclone (TC) best track data are collected for storms that reached at least tropical storm intensity level. 1022 such storms are identified and separated for six TC-prone basins: Atlantic (ATL), East+Central Pacific (EPA), Northwest Pacific (NWP), North Indian Ocean (NIO), South Indian Ocean (SIO), and South Pacific (SPA). Then from the University of Utah (UU) TRMM precipitation, cloud, and convective cell feature database, TC related features are selected for those whose center is within 500 km distance from the TC center. TC best track related parameters, including TC translation speed, storm motion direction, and future 12, 24, 36, 48-h intensity and intensity change, are interpolated into the TRMM observation time for each TC feature. The statistical characteristics of measurements from different TRMM sensors inside each feature are taken from the UU TRMM level-2 data. 3B42 precipitation features are generated separately. TC and non-TC features are separated. Climatological descriptions of many TRMM-derived properties of TC and non-TC features are generated. A web application of the database is established. Using the TRMM TCPF database, regional variations of TC convection and diurnal variations of TC rainfall are examined. In terms of absolute number, the NWP basin has the deepest and most intense TCPFs according to IR, radar, and 85-GHz microwave measurements. However, ATL TCPFs appear to have the highest lightning production. The cumulative frequency distributions of convective intensity in mesoscale convective systems (MCSs) in TCs are very similar for all basins, except that NIO systems are slightly stronger. Globally, TC rainfall has a maximum at 4:30-7:30 local solar time (LST) and a minimum around 19:30-22:30 LST. However, after separating ocean from land, a distinct difference is seen. Over land, the diurnal variation of TC rainfall
shows double peaks, one around 1:30-7:30 LST and the other at 16:30-19:30 LST. The minimum is at 10:30-13:30 LST.
1. Introduction

Tropical cyclones (TCs) are important producers of both cloud cover and precipitation in the tropics and subtropics. They rank with flash floods as the most lethal and expensive natural catastrophes. In TC research, there are two equally important areas that need more efforts: 1) one is how to improve the prediction of TC intensification; 2) the other is how to improve the TC rainfall forecast. For TC intensification, especially rapid intensification (RI), one of the critical questions is what the necessary and sufficient conditions are. Favorable large-scale environmental conditions that are near-universally agreed to be necessary include: warm sea surface temperature (SST), high low- to mid-level moisture, and low vertical wind shear (Gray 1968). Other factors such as high ocean heat content (Shay et al. 2000), enhanced heat and moisture flux (Bosart et al. 2000), and whether a TC is well below its maximum potential intensity (Kaplan and DeMaria 2003) were also found to be related to RI. Defining sufficient conditions is still controversial, especially the possible role of intense convective events. Early studies suggested that hot towers (Simpson et al. 1998) and convective bursts (Steranka et al. 1986) near the eye are related to TC intensity change. Cecil and Zipser (1999) presented evidence that a relationship exists between intense convection and TC intensity using the 85 GHz ice-scattering signature observed by Special Sensor Microwave/Imager (SSM/I), but that the total rain in the inner core has a better relationship, as did Kerns and Zipser (2009). Recent observational studies also found that the chance of TC intensification increases when one or more hot towers exist in the eyewall using a limited subset of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data (Kelley et al. 2004) and WSR-88D radar data (Kelley et al. 2005). Yet uncertainties remain and additional quantification with a larger database is highly desirable.

In recent decades, fresh water flooding has become one of the main threats to human life when a TC makes landfall (Rappaport 2000). The rainfall climatology and persistence model (R-CLIPER, Tuleya et al. 2007) is one of the major tools used by the National Hurricane Center (NHC) for TC
rainfall forecasts. The operational R-CLIPER uses radial distributions of azimuthally averaged TC rain rates derived from satellite to construct an instantaneous rainfall footprint as a function of storm intensity (Lonfat et al. 2007). The improvement of the statistical rainfall prediction technique highly relies on satellite-based rainfall estimations and the regional climatology of TC rainfall.

TRMM (Kummerow et al., 1998) marks the first time that TCs in all ocean basins can be viewed by high resolution down-looking precipitation radar. After 12 years of successful operation, TRMM measurements, along with numerical model-based reanalysis, have provided invaluable sources of TC data for the study of TC intensification, rainfall, and environment. On the TRMM satellite, the PR can provide detailed vertical distribution of radar reflectivity. The TRMM Microwave Imager (TMI) can provide some information on vertically integrated ice and water path. The Visible and Infrared Scanner (VIRS) can provide information on cloud-top temperature and reflectance. At the same time, the Lightning Imaging Sensor (LIS) estimates lightning-flash counts and rates. With several instruments observing the same target, how to analyze and efficiently utilize all this information is a scientific challenge.

The University of Utah (UU) TRMM Precipitation Feature (PF) database (http://trmm.chpc.utah.edu/) provides an excellent solution by using an event-based method to define PFs (Nesbitt et al. 2000). This method groups the spatially-adjacent pixels with near-surface PR reflectivity >=20 dBZ or ice-scattering signature defined by TMI 85-GHz polarization corrected temperature (PCT; Spencer et al. 1989) <=250K. Liu et al. (2008) improved the database by using multiple definitions of cloud and precipitation features to increase its applicability to wider research areas. Besides a series of cloud and precipitation feature definitions summarized in Liu et al. (2008), convective cell features are recently added into version 6.2 of the database.

This paper introduces a TC subset of the UU TRMM PF database based on the collaboration between Florida International University (FIU) and UU. This FIU/UU TRMM TC Precipitation, cloud,
and convective cell Feature (TCPF) database is constructed with TC features identified from 12 years of TRMM observations by using TC best track data (Landsea et al. 2004, 2008). The TRMM-based multi-satellite 3B42 rainfall product (Huffman et al. 2007) provides a higher temporal resolution (3-hourly) and larger spatial coverage (50°S to 50°N) for precipitation estimates than TRMM-only observations. Here we also construct TRMM 3B42 TCPFs and non-TCPFs as a parallel product of the database. Then the populations and sizes of TCPFs, regional climatology of TC convection as derived from the PR vertical reflectivity structure and other TRMM sensors, and the diurnal cycle of TC rainfall are studied using the database.

2. Data and methods

The construction flow chart of the TRMM TCPF database with three levels of TRMM data processing is shown in Fig. 1. First, the global TC best track data are collected and interpolated into TRMM observations times. Then TCPFs are identified if the distance between TC center and the TRMM PF center is less than 500 km. TCPFs and non-TCPFs are saved separately. Using the characteristics of identified features, global climatological descriptions of precipitation, cloud, and convective cell feature populations, occurrences, and other statistics are generated. 3B42 TCPFs are generated in a similar way. This section introduces the methods used in generating three levels of TRMM and 3B42 TCPFs data.

2.1 Best Track Data

Positions and maximum sustained surface winds of TCs are reported every six hours as part of the ‘best track’ data sets. Six TC-prone basins are considered in this study: Atlantic (ATL), East+Central Pacific (EPA), Northwest Pacific (NWP), North Indian Ocean (NIO), South Indian Ocean (SIO), and South Pacific (SPA). The best track data of ATL and EPA basins are obtained from NHC. For the other
four basins, these data are from the US Navy’s Joint Typhoon Warning Center (JTWC). A total of 1022 storms that reached tropical storm intensity level or above are identified globally during 1998-2009 (Fig. 2). TC names weren’t provided in the JTWC best track data. We added this information by looking at the TC annual report from JTWC. In the best track data, landfalling TCs were not formally recorded. For example, NHC data only record US hit cases, while JTWC best track data have no information about whether a TC makes landfall or not. We carefully checked TC annual reports along with best track images for all these storms and added a landfall flag in the best track data. All landfalls including both mainland and small island landfalls are included. Numbers of TCs and landfalling TCs for each year and each basin are listed in table 1. During the 12-yr period, globally 458 out of 1022 TCs made landfall. The highest fraction of landfalling TCs is seen in NIO, 41 out of 61, about 77%. The second and third highest fractions are in ATL and NWP, 64% and 61%, respectively.

2.2 Generating TRMM TCPF level-1 and level-2 from the UU TRMM PF database

To find TRMM PFs that are related to TCs, first best track data are linearly interpolated into TRMM observation time of each feature with at least four PR pixels (one TMI pixel) for PR (TMI) swath features. If the distance between PF center and TC center at the time of TRMM observation is less than 500 km, this PF is defined as a TCPF. At the same time, a series of storm parameters are calculated from the best track information. These parameters include: land/ocean flag of TC center at the time of TRMM observation and 12 and 24-h future, storm 12, 24, 36, and 48-h future intensity changes, storm direction and speed of motion. These storm parameters, along with the statistical parameters from measurements and retrievals from PR, TMI, VIRS, and LIS in the UU TRMM PF level-2 data, are saved into the level-2 of TCPF data.

According to information obtained in the level-2 TCPF data, 13,677 individual TRMM TC overpasses are identified during 1998-2009 (Fig. 3). From Fig. 3, we can see that there are more than
half of these TC orbits with a good view of the TC by the TMI swath (760 km before the TRMM orbit boost during August 2001 and 878 km after the boost). That is, the distance between TC center and TRMM swath center is less than 300 km. However, only 2,315 of 13,677 overpasses have a good view of the TC by the PR swath (215 km before boost and 247 km after boost); i.e., the distance between the TC center and PR swath center is less than 100 km. TRMM measurements from different instruments have been collocated and saved into level-1 (pixel-level) of the UU TRMM PF data (see Liu et al. 2008 for the detailed collocation method, and Liu 2007 for a list of parameters saved in level-1). The collocated TRMM datasets include version-6 VIRS radiances (1B01), TMI brightness temperatures (1B11), rainfall retrievals from TMI (2A12; Kummerow et al. 2001), stratiform and convective rainfall categorizations (2A23; Steiner et al. 1995; Awaka et al. 1998), rainfall retrieval from PR (2A25; Iguchi et al. 2000), and LIS flashes (http://daac.gsfc.nasa.gov/data/datapool/TRMM/). Here we generate the TC subset of level-1 data by cutting a 20° longitude x 20° latitude TC centered box, which is typically large enough to observe the various sizes of TCs and their immediate environments.

Besides storm parameters, TRMM parameters in level-2 data structures are essentially as same as those in the UU TRMM PF level-2 as described in Liu et al. (2008), but with some new convective cell feature definitions added into the version 6.2 of TRMM PF database reprocessing. Table 2 lists the definitions and criteria of 13 types of features included in the TRMM TCPF database. There are 5 precipitation feature definitions including radar precipitation feature (RPF) defined by contiguous 2A25 near-surface raining pixels, TMI precipitation feature in the PR (TPF) and TMI (TTPF) swath defined by contiguous 2A12 surface raining pixels, Radar/TMI precipitation feature (RTPF) introduced by contiguous 2A25 near-surface or 2A12 surface raining pixels, and radar projection precipitation feature (RPPF) introduced by grouping the area of ground projection of radar reflectivity greater than 20 dBZ, which includes thick anvil aloft. There are two cold PCT feature definitions (TPCTF and T200F), which are defined by pixels with 85-GHz PCT <= 250 K and 200 K, respectively, in the TMI
swath. Two types of cold cloud features are defined by using VIRS 10.8-μm brightness temperature \((T_{B11}) \leq 210\) K (C210F), and 235 K (C235F). Convective cell feature definitions are introduced in order to better study the individual cells embedded in a large precipitation feature. Four types of cell features are defined by using 2A23 convective pixels (CLCONVF), radar projection reflectivity \( \geq 40\) dBZ (CL40PF), PR 6-km reflectivity \( \geq 30\) dBZ (CL6KM30F), and PR 12-km reflectivity \( \geq 20\) dBZ (CL12KM20F).

Major parameters stored in level-2 data include those from PR algorithms 2A25 and 2A23, TMI algorithms 1B11 and 2A12, VIRS algorithm 1B01, LIS flash observations, and NCEP reanalysis. Besides those parameters listed in Liu et al. (2008) and Liu (2007), the vertical profiles of 25, 30, 35, 40, 45, and 50-dBZ area with 1-km vertical resolution, and areas of 37-GHz PCT<275, 250, 225, 200, and 175 K are also saved.

An example of feature definitions for Typhoon Mitag (2007) in the NWP basin and some parameters in the defined RPPF are shown in Fig. 4. In this case, the inside PR swath definitions (Fig. 4a, b, e, f, g, h) capture the strong convective core of the eyewall, but miss a large raining region in the northwest quadrant. In contrast, inside TMI swath definitions (Fig. 4c, d) capture almost the whole TC feature with minimal swath truncation effect in the 2A12 rain (Fig. 4c). Also there were large areas of thick anvil and cold clouds (Fig. 4e) in the southwest quadrant of the storm without a strong ice-scattering signal (Fig. 4d) and hardly any surface rain (Fig. 4a, c). Only cold cloud features defined by C210F and C235F can describe anvil clouds. The detailed vertical distributions of maximum reflectivity and 20-dBZ and 40-dBZ area can be summarized in RPPFs (Fig 4b, i) and CL40PFs (Fig. 4b). The statistics of convective cells can be summarized in CLCONVF (Fig. 4f), CL40PFs (Fig. 4b), CL6KM30Fs (Fig. 4g), and CL12KM20Fs (Fig. 4h). The TC system can be described comprehensively with these multiple feature definitions. For example, several small convective cells are identified by cell feature definitions, and the contribution of these cells to total rain can be easily derived; the
differences between 2A25 and 2A12 volumetric rain may be used to validate the performance of rain retrieval algorithms in TCs, and so on.

2.3 Generating 3B42 TCPF level-1 and level-2

Although in lower spatial resolution (0.25° by 0.25°), the benefit of using the TRMM-based 3-hourly multi-satellite rainfall product 3B42 are two-fold: 1) higher temporal resolution and 2) larger spatial coverage (50°S to 50°N) to cover the whole life time of any TC. A TC subset of 3B42 rainfall data is constructed to supplement the TRMM TCPF data. The construction flow chart of the 3B42 TCPF database is shown in Fig. 5. Similar to the TRMM TCPF database, three levels of data are generated. However, unlike TRMM processing in which features are grouped first and then TCPFs are defined according to the distance from TC center, the first step is that all 3B42 raining pixels within 500-km radius of TC center are attributed to TC-related pixels and saved in level-1 TCPF data files. Other raining pixels are saved into level-1 non-TCPF data files. Then raining pixels are grouped for TC pixels and non-TC pixels separately. Storm best track parameters as listed in section 2.2 and 3B42 rainfall parameters such as total volumetric rain, raining area, greater than 5 mm/hr volumetric rain, and greater than 5 mm/hr raining area are saved in level-2 files. TC pixels are identified before grouping is to ensure that only TC-related raining pixels are included in the 3B42 TCPF data. Jiang and Zipser (2010) used two definitions of 3B42 TCPFs: one is as same as the one used here, the other is to group raining pixels first and then attribute those PFs with center within 500-km radius of TC center as TCPFs. They found out that the latter definition overestimates TC monthly rain by 1.5-3 times comparing with the former 3B42 definition and 2A25 and 2A12 estimates. This is because without the pixel-level 500-km restriction, sometime a 3B42 TCPF could become very large and connected with other non-TC features. The reasons are: 1) 3B42 features are relatively large in size due to the lower spatial resolution of the gridded 3B42 product; 2) 3B42 sometime slightly overestimates rain rate from
no rain regions due to the combination of its low spatial resolution induced by microwave data and overestimation of rain in cold cloud regions induced by IR observations. By applying the pixel-level 500-km restriction first, it is guaranteed that only TC-related rainfall is included.

Fig. 6 shows an example of the 3B42 TCPF definition and level-2 parameters for Hurricane Bonnie (1998, the same case showed in Jiang and Zipser (2010)’s Fig. 4). Fig. 6a presents how the TC raining area is connected with another feature due to the inability of 3B42 to identify non-raining regions between them. Using the 500-km pixel-level restriction eliminates the contamination. The lifetime rain accumulation of Bonnie (Fig. 6b) is derived from the level-1 3B42 TCPF data. Volumetric rain and raining area for all raining regions and heavy rain regions only (rain rate greater than 5 mm/hr) can be summarized in level-2 (Fig. 6c,d). Some level-2 parameters of the 3B42 TCPF defined in Fig. 6a and the lifetime averages of these parameters for Bonnie are listed in Table 3. It is useful to evaluate the contribution of heavy rain regions to the total TC rain. From both Table 3 and Fig. 6c,d, we can see that the heavy rain regions only contribute to about 10-20% of total raining area, but contribute more than 50-60% of total volumetric rain.

2.4 Generating TRMM and 3B42 TCPF level-3

To conveniently study the climatological characteristics of TCs, level-3 data are generated by summarizing statistics of feature properties onto a 1° x 1° grid. Because TRMM observations and 3B42 product include diurnal variations of properties of cloud and precipitation systems, they are categorized into eight local time periods.

Fig. 7 demonstrates the mean TC monthly rain from level-3 of RPF, TTPF, and 3B42 TCPF data from 1998 to 2009. Climatological differences of TC rainfall for different basins can be examined from level-3 data. Also the differences among 2A25, 2A12, and 3B42 rain estimates for TC can be compared in a long-term basis. As noted by Liu et al. (2008), when we accumulate the volumetric rain from
features onto grids, volumetric rain and raining area inside each feature are assigned to the grid where the mass-weighted centroid of that feature is located. This could be problematic when we assign volumetric rain and raining area from large cloud and precipitation features to a small grid (edge effect). To evaluate this problem for TCPFs, the TC monthly rainfall by counting the raining pixels inside the 3B42 grids (Fig. 7d) are shown to be compared with that by accumulating rain volume of PFs centered inside the grids (Fig. 7c). The general pattern of them is very close, which demonstrates that the problem is minimized by the large sample size we have. However, since the size of 3B42 TCPFs is usually larger than that of TRMM-based TCPFs, the edge effect from TRMM TCPFs should be even smaller.

TCPFs and non-TCPFs are processed into separate level-3 data files. The parameters in level-3 include: 1) 2A25, 2A12, and 3B42 rain volume and raining area, total 2A25 convective and stratiform raining area and rain volume, 3B42 rain volume and raining area for heavy rain regions (> 5 mm/hr), rain volume and raining area during eight local times, total number of PR, TMI, or 3B42 observations; 2) a population of features, including total flash counts, total area of $T_{B11} < 210$, and 235 K, total area of 85-GHz PCT < 250, 200, 150, and 100 K and 37-GHz PCT < 275, 250, 225, 200, and 175 K during eight local times, and total 20, 25, 30, 40, 45, 50-dBZ area at different altitudes; and 3) maximum 20-, 30-, and 40-dBZ echo tops, maximum flash counts, maximum reflectivity at different altitudes, minimum $T_{B11}$ and minimum 37- and 85-GHz PCT inside a feature during eight local time periods (0–3, 3–6, 6–9, . . .). Level-3 products are processed for monthly, yearly, TC seasonal only (see Jiang and Zipser 2010 for details), and 12-yr (1998–2009) periods.

3. Applications

Four applications of the 12-yr (1998-2009) TRMM TCPF database are introduced in this section.
3.1 Web application

One of the TRMM’s goals is to view TCs globally. After 12 years of functioning, the TRMM TC database has greatly benefited the TC research community. For both TC scientists and the general public, how to quickly search past storms observed by TRMM and get the data is an issue. Along with this study, we offer a web application for users to easily find TRMM observations for each TC from Dec. 1997 to Dec. 2009 (http://trmm.chpc.utah.edu/cyclone). Currently the webpage is located in the UU TRMM data web server domain, but will be migrated to FIU soon. Numbers of storms and TRMM orbits are listed in a table by each year and each basin. A series of top-down web pages allow users to click the year and basin of interest, then a storm of interest in the year and the basin. For each storm, the 3B42 rainfall accumulation image overlaid with best track and a list of TRMM orbits of the storm are accessible. After clicking the orbit of interest, users will be able to view the 9-panel TRMM image including PR near surface reflectivity, PR maximum reflectivity projection, 2A25 near surface rain, 85-GHz PCT, 37-GHz PCT, 2A12 surface rain, VIRS Tb11, 2A23 rain types, and 2A23 storm height parameters plotted from the collocated level-1 data. TRMM TCPF level-1 data for each orbit and best track data for each TC are downloadable. The TC center location, its distance to TRMM swath center, and best track maximum wind for each orbit are provided. Another interesting feature adapted from the UU TRMM data web application is that the TRMM orbital data can be viewed and manipulated from a Google Earth background to produce both horizontal images and PR vertical cross sections. For storms missed by TRMM (only 9 out of 1013 TCs during the period), only 3B42 rainfall accumulation images overlaid with best tracks are provided.

3.2 Global distribution of TC convection

One important application of the TRMM TCPF database is to study the global distribution of TC convection. Cloud-top brightness temperatures from TRMM VIRS can be used to show how deep the
convection is and how cold the cloud tops are (Mapes and Houze 1993, Gettelman et al. 2002). To estimate the convective intensity, we adopt proxies that can be measured by the TRMM PR, TMI, and LIS (Mohr and Zipser 1996; Cecil and Zipser 2002; Zipser et al. 2006). Here three such parameters are used: minimum 85 GHz PCT measured by TMI, maximum 20 dBZ echo height measured by PR, and total flash count measured by LIS. To demonstrate the size of deep and/or intense convection, area of minimum Tb11 <= 210 K, area of minimum 85 GHz PCT < 250 K, and area of 20 dBZ reaching 6 km are examined. Locations and rareness of TCPFs according to these parameters are shown in Fig. 8 for TC RPPFs from 1998 to 2009. For example, of the ~153 thousand TCPFs, only about 10% have 20 dBZ echo higher than 8.5 km and 1% higher than 15.25 km, and only about 1~2% have lightning flash count greater than 1 and 0.1% greater than 40, etc. The deepest and most intense convection in TCs is distributed differently as defined by each proxy. The coldest IR cloud top events (Fig. 8a) and tallest radar 20 dBZ echoes (Fig. 8b) are found mainly in the NWP, SIO, SPA, and NIO basins, while the most intense ice scattering signature events indicated by minimum 85 GHz PCT (Fig. 8c) and extreme lightning events (Fig. 8d) are found more frequently in the NWP, ATL, and SIO than in NIO, SPA, and EPA. As for area of deep/intense convection, largest area events are concentrated over NWP. It is not surprising that the coldest, most intense, and largest TC convection events are located in the Western Pacific warm pool region. Previous studies using IR as primary data source often find that the tropical west Pacific Ocean has the greatest concentration of cold, high clouds (Gettelman et al. 2002). Although studies using TRMM PR and TMI often find that convective intensity is much stronger over land than over ocean (Zipser et al. 2006; Liu and Zipser 2007), for TCs that mainly occur over ocean, NWP is more favorable than other basins. The large scale environmental factors in NWP that are favorable for TC and convection development include high SST, low wind shear (Gray 1968), high CAPE, and high neutral buoyancy level (Liu et al. 2007).

An interesting result demonstrated in Fig. 8 is the distinct contrast of concentration and lack of
deepest and most intense TC convection in NWP and EPA, respectively, as seen for all parameters being examined here. This seems paradoxical because the highest TC number density regions are in both NWP and EPA as shown in Jiang and Zipser (2010)’s Fig. 8. However, the highest TC number density doesn’t necessarily mean the strongest TC convection. Also the west Pacific warm pool in the NWP is more favorable for deep convection than open ocean regions in EPA.

There is a strong preference for extreme TC lightning events to be located over land or coastal regions, such as south east coast of Asia, east coast of Mexico and United States, Caribbean Islands, western coast of Australia, Baja California coast, and Madagascar (Fig. 8d). The distinct difference between land and ocean for lightning occurrence has been found in previous studies for general convection (not limited to TCs) in the globe (Orville and Henderson 1986) and Tropics (Zipser et al. 1994, Petersen and Rutledge 2001, Zipser et al. 2006) and for thunder clouds in Asian monsoon (Xu et al. 2010).

Another interesting result from Fig. 8 is that the ATL basin has a high concentration of most intense convection as defined by microwave ice scattering signature (minimum 85 GHz PCT) and lightning, but a rather low concentration of coldest and tallest convection as seen from minimum Tb11 and maximum 20 dBZ echo height. Both the number of TC RPPFs with lightning and the total flash counts in TC RPPFs are the higher in ATL than all other basins (table 4), with NWP the second highest. However, NWP has more total number of TC RPPFs, which makes NWP the third according the population percentage of TC RPPFs with lightning, following ATL and NIO. After normalizing the flash counts by sample size (total 2A25 raining area) of each basin (the fourth column of table 4), lightning production in ATL is the highest, and SPA is the lowest. However, in all basins, TC lightning production is rather low, 1-4 flashes per 10^4 km^2 raining area. Black and Hallett (1986, 1999) note that it is rare to find updrafts in hurricanes that are strong enough to produce significant supercooled water and large graupel, and therefore significant charge separation (Takahashi 1978). Using 1-yr
TRMM LIS observations, Cecil et al. (2002) found that tropical cyclones produce much less lightning than tropical continental precipitation systems. Because only fairly intense convection makes a significant contribution to lightning production, additional parameters for normalizing the flash counts are presented in Table 4. The last three columns in Table 4 make use of parameters to isolate more intense portions of TC convection. The convective certain area is defined by the total area of data points classified as “convective certain” by the TRMM PR 2A23 algorithm. 225 K of TMI measured 85 GHz PCT was used by many previous studies (Mohr and Zipser 1996, Nesbitt and Zipser 2003) as a convection criterion in mesoscale convective systems (MCSs). Xu et al. (2010) found that 35 dBZ area at 8-9 km is best correlated with lightning production. Lightning production of TCs is 2 to 4 times greater in ATL than SPA, and about 50% greater than the other four basins. Notice that the ATL basin domain includes many islands, which might be the contributor for higher lightning production. It is also possible that updrafts in TC convection in ATL are more intense, but the level of neutral buoyancy and the height of the tropopause are climatologically lower in ATL, which limits the maximum height that clouds can reach. A further study is needed to verify this.

Because small PFs are so numerous compared with large PFs, it is misleading to include the entire PF database for many important parameters. Therefore, only those features that meet the MCS definition as follows are included in Fig. 9. TC RPPFs with area $\geq 1000 \text{ km}^2$ and containing at least one convective pixel (85 GHz PCT $< 225 \text{ K}$) are defined to be MCSs. In the cumulative frequency distributions of minimum TB11 and maximum 20 dBZ height (Fig. 9a and b), the ATL TC RPPFs appear to produce low cloud top more often than TC RPPFs in other basins, consistent with what is seen in Fig. 8a-b. TC RPPFs in SPA, NWP, and NIO have higher percentage of features with colder/taller cloud top, while those in EPA are somewhere in between. The NIO TC RPPFs are found to produce moderate to intense convection (maximum 20 dBZ height between 10 and 16 km, minimum 85 GHz PCT between 190 and 100 K, Fig. 9b and c) more often than those in other basins. This is mainly
due to the relative lack of small features with high minimum brightness temperatures and low maximum 20 dBZ echo height. Laing and Fritsch (1997) noted that there is a concentration of mesoscale convective complexes (MCCs) over the Indian subcontinent due to elevated terrain and prevailing mid-level flow. This special environment makes NIO a unique TC-prone basin. Although the number of TCs is the lowest in this basin, convection associated with TCs in NIO seems stronger than that in other basins. The cumulative distributions of sizes of TC convection are shown in Fig. 9d-f. NWP (ATL) TC RPPFs appear to produce large convective features more (less) often than other basins, however, the differences among 6 basins are not big in all the cumulative distributions shown in Fig. 9.

3.3 Regional variations of vertical structure of radar echoes

Another application of the TRMM TCPF database is to study the regional variations of vertical structures of TCPFs. Fig. 10 shows the 20 dBZ echo occurrence calculated by dividing the 20 dBZ area inside TC RPPFs at selected heights by the total PR sampled area during 1998-2009. In general, there are not many changes in the preference of locations of 20 dBZ echo at different altitudes. At 2 and 4 km (Fig. 10 a-b), 20 dBZ echoes occur more frequently over NWP and EPA than other basins. At 7 and 10 km (Fig. 10 c-d), 20 dBZ echoes over NWP dominate.

The 95th percentiles and median profiles of maximum radar reflectivity, 20 dBZ area, and 35 dBZ area are compared in Fig. 11 for six basins. The maximum radar reflectivity profiles are very similar in different basins (Fig. 11 a-b). No difference is seen for the near surface reflectivity. Above the freezing level, NIO TC RPPFs reach slightly higher altitudes, while ATL TC RPPFs have slightly higher reflectivity at mid-level (8-12 km), which helps explain why ATL TCs have a higher lightning production. ATL TC RPPFs have smaller 20 dBZ area and reach lower altitudes than those in other basins. NWP and SPA TC RPPFs have larger 35 dBZ area than those in other basins. Overall, the differences of these profiles in different basins are rather subtle, and the similarities dominate. This
result confirms the previous studies showing that convective systems over tropical oceans including TCs generally produce weaker vertical motions and have weaker convective intensity than their continental counterparts (LeMone and Zipser 1980, Lucas et al. 1994).

3.4 Diurnal variations of TC rainfall

Most studies of the diurnal variations of TCs used IR measurements (Browner et al. 1977, Muramatus 1983, Steranka et al. 1984, Kossin 2002) and TC best track winds (Cerveny and Balling 2005). By using IR data, the metrics are limited to the area covered by cirrus whose IR cloud top temperature is less than a certain threshold, and the average Tb values with a certain distance from the storm center. Browner et al. (1977) found an afternoon peak (1700) and early morning minimum (0300) for the area of cloudiness in eight Atlantic TCs by using temperature thresholds ranging from 253 K to 233 K. This is similar to Steranka et al. (1984)’s result for the outer rainband regions for 23 TCs in ATL. But for the inner core region with very cold Tb’s (where deep convection exists), an early morning maximum is found by Steranka et al. (1984). On the other hand, a semidiurnal oscillation is found by Kossin (2002) for ATL hurricanes by using IR cloud top temperature measurements of 21 ATL storms in 1999. No diurnal variations of TC rainfall have been documented using satellite data. An important application of the TRMM TCPF database is to study the diurnal variations of TC rainfall using TRMM rainfall products. Three hourly 3B42 rainfall maps for 1998 – 2009 global TCs are shown in Fig. 12. Globally, TC rainfall peaks at 4:30-7:30 local solar time (LST), then decreases to a minimum at 19:30-22:30 LST. Since rainfall is more related to deep convection than cirrus canopy area, it is expected that the phase of the TC rainfall diurnal oscillation is not consistent with Browner et al. (1977)’s results using warmer Tb thresholds. On the other hand, our result is similar to those derived from coldest IR Tb thresholds (Muramatsu 1983, Lajoie and Butterworth 1984) which are more associated with deep convection. Mean values of global 3B42 TC monthly rain for different local times
are presented in Table 5. We define the amplitude of the diurnal oscillation as (maximum - minimum) / mean. The global TC rainfall diurnal variation amplitude is about 20% as seen from Table 5. Similar diurnal variations are found by using PR 2A25 rainfall estimates for TCs (not shown here).

A strong land/ocean contrast is found for diurnal variations of precipitation systems (Nesbitt and Zipser 2003, Liu and Zipser 2008). To investigate the land and ocean difference for TCs, time series of 3B42 volumetric rain are compared for land and ocean in Fig. 13a-b. Consistent with past studies for general tropical precipitation (Yang and Slingo 2001, Nesbitt and Zipser 2003, Liu and Zipser 2008), an early morning (4:30-7:30 LST; 3B42 averaged rainfall 3-hourly, so 4:30-7:30 LST is labeled as 6 LST in Fig. 13) peak is obvious for TC precipitation over oceans (Fig. 13a), but with less amplitude. The minimum is at 19:30-22:30 LST. However, although a late afternoon maximum has been confirmed by past studies (Nesbitt and Zipser 2003, Liu and Zipser 2008) for general overland precipitation and convection systems, the TC rainfall over land has double peaks (Fig. 13b), one around 1:30-7:30 LST and one at 16:30-19:30 LST. The minimum is at 10:30-13:30 LST. The second peak can be explained by the diurnal heating of the land that enhances convection. The first peak might be associated with the oceanic characteristics of the TC systems even after making landfall.

To investigate the diurnal variation of heavy rain regions in TCs, Fig. 13 c-d presents the time series of TC volumetric rain for regions with rain rate greater than 5 mm/hr. Over land (Fig. 13d), the phase of diurnal cycle in heavy rain regions is similar to all TC rain regions (Fig. 13b), but the amplitude (about 40-50%) is much higher. Over oceans (Fig. 13c), the maximum is at 4:30-7:30 LST, but the minimum is at 13:30-16:30 LST. Contributions from different storm intensity categories, e.g. hurricane (HUR), tropical storm (TS), and tropical depression (TD), are shown in different colors in Fig. 13. No big difference of diurnal variations is seen from different storm intensities.

4. Summary
This paper introduces the construction and applications of a TRMM-based TCPF database. This database is built upon the existing UU TRMM precipitation feature database. Over 1000 TCs are included for six global TC-prone basins from 1998 to 2009. TRMM measurements of radar, visible and infrared sensors, passive microwave radiometers, and lightning sensors for TCs are collocated and integrated with TC best track and NCEP re-analysis parameters. The TRMM 3B42 rainfall product is also used to build a parallel TCPF dataset. Three levels of TRMM TCPF product are constructed following the same construction concept as in UU TRMM PF database. New convective cell feature definitions are added as a result of the recent update of the parental TRMM database.

The web application of the database provides a search engine for users to easily find TC overpasses by TRMM, as well as download the level-1 data and best track data and corresponding images. The “Google Earth” function adapted from the UU TRMM database web application is very powerful and enable users to create cross sections of PR reflectivity for any TC TRMM orbits of interest.

Besides the web application, three applications of examining regional and diurnal variations of TC convection and rainfall are explored by using the TCPF database. Future studies include separating TCPFs into eyewall, innerband, and outerband regions and studying the relationship between TC convective and precipitation characteristics and TC intensity and intensity changes, and validating rainfall algorithms from PR and TMI for different rain regions in TCs. It is also a future work direction to add QuikScat sea surface wind and TMI and SSM/I sea surface temperature data into the database.

Acknowledgments

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Ramirez helped on identifying landfalling TCs from 1998 to 2004. Michael Peterson has been very helpful on adapting the “Google Earth” web feature to the TCPF database.
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Zipser, E. J., D. Cecil, C. Liu, S. Nesbitt, and D. Yorty, 2006: Where are the most intense thunderstorms
FIGURE CAPTIONS

Figure 1. FIU/UU TRMM TCPF database construction flow chart.

Figure 2. Global TC best tracks in six basins during 1998-2009.

Figure 3. Geographic distribution of TC observations from 1998 to 2009 in the FIU/UU TRMM TCPF database. Distance between TC center and the TRMM swath center are indicated in color.

Figure 4. Demonstration of the TCPF feature types using the case of Typhoon Mitag (2007). (a) 2A25 near-surface rain rate. RPF is defined by the area with rain shown by black contour. (b) The PR maximum-reflectivity ground projection. RPPF (CL40PF) is defined by area with 20 dBZ (40 dBZ) shown by black contours. (c) 2A12 surface rainfall rate. TTPF (TPF) is defined by area with rain sown by black contour in TMI (PR) swath. Red triangles are the location of flashes detected by LIS (Note that there are two flashes in the same location, also see table 2). (d) TMI 85-GHz PCT. TPCTF (T200F) is shown by 250-K (200-K) contour line. (e) VIRS Tb11 C210F and C235F are defined by area with Tb11<210 and 235 shown by black contours. (f) 2A23 rain types. CLCONVF is defined by area with spatially-adjacent convective pixels shown by black contours. (g) The PR 6-km reflectivity. CL6KM30F is defined by the area with 30 dBZ at 6-km as shown by black contour. (h) The PR 12-km reflectivity. CL12KM20F is defined by the area with 20 dBZ at 12-km as shown by black contour. (i) Vertical profiles of 20, 30, & 40dBZ area (black solid, dot, & dash lines) and the maximum reflectivity (red line) of the large RPPF defined in (b). The cross on the center of (a)-(h) is the Typhoon center location. The dash line in (a)-(h) is the edge of the PR swath. Note that there could be a truncation effect due to the narrow swath in defining large features (Nesbitt et al. 2006).
Figure 5. FIU/UU TRMM 3B42 TCPF database construction flow chart.

Figure 6. Demonstration of 3B42 TCPF feature and parameters using the case of Hurricane Bonnie (1998). (a) 3B42 rain rate of Hurricane Bonnie (1998) at 12:00 UTC Aug. 26, 1998. 3B42 TCPF feature is defined by the area with both rain>0 (black contour) and within the 500-km radius circle around the hurricane center. (b) Life time total rain accumulation of Bonnie from 3B42. (c) Time series of 3B42 TCPF volumetric rain for all rain regions and heavy rain regions (rain rate greater than 5 mm/hr) for Bonnie. (d) Time series of 3B42 TCPF raining area for all rain regions and heavy rain regions (rain rate greater than 5 mm/hr) for Bonnie. 500-km radius circle around the storm center is indicated in (a). Bonnie’s best track is indicated in (b). The time series of Bonnie’s maximum surface wind speed is indicated in (c) and (d).

Figure 7. (a) Mean 2A25 TC monthly rain from RPFs from 1998 to 2009. (b) Mean 2A12 TC monthly rain from TTPFs from 1998 to 2009. (c) Mean 3B42 TC monthly rain from 3B42 TCPFs from 1998 to 2009. (d) Mean 3B42 TC monthly rain from 3B42 TCPF level-1 raining pixels from 1998 to 2009.

Figure 8. Locations of deep convection events in TCs categorized by (a) minimum TB11, (b) maximum height of 20 dBZ echo, (c) minimum 85 GHz PCT, (d) flash count, (e) area of Tb11<=210, (f) area of 85 GHz PCT < 250 K, and (g) area of 20 dBZ reaching 6 km. Rarity of the events are represented with green (~top 2% for flash count and ~top 10% for all other parameters), orange (~top 1 %), red (~top 0.1%), and black (~top 0.01%) symbols from TC RPPFs from 1998 to 2009.

Figure 9. CDFs of convective intensity inferred from (a) minimum Tb11, (b) maximum height of 20
dBZ echo, and (c) minimum 85-GHz PCT and CDFs of convective area inferred from (d) area of Tb11 < =210 K, (e) area of minimum 85 GHz PCT < 225 K, and (f) area of 20 dBZ reaching 6 km over six basins for TC MCSs (derived from RPPFs, see text for details) from 1998 to 2009. TC MCS sample size of each basin is indicated.

Figure 10. Occurrence of PR radar reflectivity above 20 dBZ (%) at (a) 2, (b) 4, (c) 7, and (d) 10 km derived from TC RPPFs in 1998-2009. Note that the scales are different for (a) – (d).

Figure 11. 95th percentile and median of vertical profiles of (a), (b) maximum radar reflectivity, (c), (d) 20 dBZ area, and (e), (f) 35 dBZ area of TC MCSs from 1998 to 2009 over six basins. Note that scales are different for (a)-(f).

Figure 12. 3B42 TC monthly rain from 1998 to 2009 at different local times: (a) 22:30-1:30, (b) 1:30-4:30, (c) 4:30-7:30, (d) 7:30-10:30, (e) 10:30-13:30, (f) 13:30-16:30, (g) 16:30-19:30, and (h) 19:30-22:30 hours.

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Table 1: Numbers of TCs and landfalling TCs for each year and each basin.

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<th># of TCs</th>
<th># of landfall TCs</th>
<th># of TCs</th>
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Table 2: Definition of precipitation, cloud, and convective cell features from 1998-2009 in the UU TRMM version 6.2 database. The features are all defined in PR swath if not indicated otherwise. The population of total TRMM features and TC features are also listed.

<table>
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<tr>
<th>Acronyms</th>
<th>Definitions</th>
<th>Criteria</th>
<th>Total population</th>
<th>TCPF population</th>
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</tr>
<tr>
<td>CL12KM20</td>
<td>Convective cell feature with 12-km greater than 20 dBZ</td>
<td>Pixels with 12-km reflectivity &gt;= 20 dBZ</td>
<td>352,581</td>
<td>6,437</td>
</tr>
</tbody>
</table>
Table 3: Some parameters of the 3B42 TCPF defined in Fig. 6a and the lifetime averages of these parameters for Bonnie.

<table>
<thead>
<tr>
<th></th>
<th>Raining area (km^2)</th>
<th>Heavy raining area (for rain rate &gt; 5 mm/hr) (km^2)</th>
<th>Fraction of heavy raining area (%)</th>
<th>Rain volume (mm/hr km^2)</th>
<th>Heavy rain volume (for rain rate &gt; 5 mm/hr (mm/hr km^2)</th>
<th>Fraction of heavy rain volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCPF in Fig. 6a Lifetime Average for Bonnie</td>
<td>256,929</td>
<td>54,380</td>
<td>21</td>
<td>861,575</td>
<td>558,079</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>401,266</td>
<td>47,586</td>
<td>12</td>
<td>938,202</td>
<td>467,634</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 4: Number and percentage of TC RPPFs with lightning and lightning flash counts for each basin and ratios of flash count to various aspects of sample size

<table>
<thead>
<tr>
<th>Basin</th>
<th># of TC RPPFs with lightning</th>
<th>Population percentage of TC RPPFs with lightning (%)</th>
<th>Flash count</th>
<th>Flash count per 2A25 raining area (#/10^4 km^2)</th>
<th>Flash count per 2A23 convective certain area (#/10 ^4 km^2)</th>
<th>Flash count per 85 GHz PCT &lt; 225 K area (#/10 ^4 km^2)</th>
<th>Flash count per 8-km 35 dBZ area (#/10 ^4 km^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATL</td>
<td>1,148</td>
<td>3.25</td>
<td>10,855</td>
<td>4.5</td>
<td>23.5</td>
<td>36.6</td>
<td>5966</td>
</tr>
<tr>
<td>EPA</td>
<td>246</td>
<td>1.48</td>
<td>1,794</td>
<td>3.0</td>
<td>17.7</td>
<td>24.9</td>
<td>4454</td>
</tr>
<tr>
<td>NWP</td>
<td>966</td>
<td>2.07</td>
<td>9,491</td>
<td>2.5</td>
<td>15.3</td>
<td>22.5</td>
<td>4269</td>
</tr>
<tr>
<td>NIO</td>
<td>182</td>
<td>2.83</td>
<td>1,723</td>
<td>2.5</td>
<td>14.9</td>
<td>20.2</td>
<td>4115</td>
</tr>
<tr>
<td>SIO</td>
<td>470</td>
<td>1.44</td>
<td>3,709</td>
<td>2.4</td>
<td>14.8</td>
<td>17.5</td>
<td>2981</td>
</tr>
<tr>
<td>SPA</td>
<td>161</td>
<td>1.31</td>
<td>881</td>
<td>1.2</td>
<td>8.1</td>
<td>11.1</td>
<td>3202</td>
</tr>
</tbody>
</table>

Table 5: Mean values of TC 3B42 rain in Fig. 12

<table>
<thead>
<tr>
<th>Local Solar Time</th>
<th>22:30-1:30</th>
<th>1:30-4:30</th>
<th>4:30-7:30</th>
<th>7:30-10:30</th>
<th>10:30-13:30</th>
<th>13:30-16:30</th>
<th>16:30-19:30</th>
<th>19:30-22:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean TC monthly rain (mm/mo)</td>
<td>2.07</td>
<td>2.24</td>
<td>2.34</td>
<td>2.21</td>
<td>2.09</td>
<td>2.06</td>
<td>2.01</td>
<td>2.97</td>
</tr>
</tbody>
</table>