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Influence of environmental moisture on TRMM-derived tropical cyclone precipitation over land and ocean

Haiyan Jiang,[1] Jeffrey B. Halverson,[2] and Edward J. Zipser[1]

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[1] The rainfall climatology and persistence model (R-CLIPER) used operationally in the Atlantic Ocean basin mainly utilizes tropical cyclone (TC) intensity to predict TC rainfall. However, the rain production by TCs is also influenced by environmental parameters such as total moisture availability, horizontal moisture convergence, vertical wind shear, and sea surface temperature (SST). Previous TC case studies have used environmental moisture parameters to diagnose TC rainfall. In this study, we composite over 3000 snapshots of 3-hourly TRMM 3B42 rainfall fields for Atlantic landfalling tropical cyclones between 1998–2006 to analyze the rainfall distribution and storm total volumetric rain as a function of total precipitable water (TPW), horizontal moisture convergence (HMC), and ocean surface flux (OSF) over land and over ocean. For over ocean conditions, higher TPW, HMC, or OSF values are associated with higher azimuthally averaged rain rates. Over land, this is still the case but less obvious. Computing the linear correlation coefficients between total volumetric rain and moisture parameters shows this fact much more clearly. These coefficients are generally higher for over ocean conditions than those for over land conditions. To test if moisture parameters can provide additional information other than TC intensity to help TC rainfall forecasts, a multiple linear regression is performed between TC volumetric rain and several variables including TC maximum wind speed, TPW, HMC, and OSF. By adding moisture parameters as additional variables, TC volumetric rain will be better predicted than using TC intensity (maximum wind speed) only. The correlation coefficient between volumetric rain and maximum wind speed can increase from 0.52 (0.51) to 0.67 (0.65) for over ocean (land) conditions by adding TPW, HMC and OSF. By adding TPW only, the correlation coefficient increases to 0.59 and 0.64 for over ocean and land, respectively. **Citation:** Jiang, H., J. B. Halverson, and E. J. Zipser (2008), Influence of environmental moisture on TRMM-derived tropical cyclone precipitation over land and ocean, *Geophys. Res. Lett.*, *35*, L17806, doi:10.1029/2008GL034658.

1. Introduction

[2] The accurate forecast of precipitation in tropical cyclones (TCs) remains a critical problem in the coastal areas. The rainfall climatology and persistence model (R-CLIPER) is the major tool utilized by the National Hurricane Center (NHC) for TC rainfall forecasts. *Tuleya et al.* [2007] indicated that numerical model rainfall forecasts show very little, if any, improvement over a simple version of R-CLIPER, while *Marchok et al.* [2007] showed significant improvements over several models when other metrics are considered, including total volume, rainfall patterns, and extreme rain events. The operational R-CLIPER uses radial distributions of azimuthally averaged TC rain rates derived from the TRMM Microwave Imager [*Lonfat et al.*, 2004] to construct an instantaneous rainfall footprint as a function of storm intensity. The latest improvement of this model includes adjusting based on effects of vertical wind shear and topography [*Lonfat et al.*, 2007].

[3] Besides storm intensity, shear, and topography, TC rainfall is also influenced by environmental moisture. Early TC case studies diagnosed rainfall from moisture budget calculations [*Carr and Bosart*, 1978; *DiMego and Bosart*, 1982]. *Rodgers and Pierce* [1995] demonstrated that the SSM/I and ECMWF derived total precipitable water (TPW) fields influenced the precipitation distribution of Typhoon Bobbie (1992). *Jiang et al.* [2008a, 2008b] compared the rainfall history and detailed water vapor budget of Hurricanes Isidore and Lili (2002) and found that large horizontal moisture convergence (HMC) and TPW were crucial to initiate and maintain the heavy rainfall before and during Isidore's landfall. However, no statistics-based observational studies have documented, at least to the authors' current knowledge, on the relationship between TC rainfall and environmental moisture.

[4] When and after a TC makes landfall, its rainfall may be influenced by other factors like extratropical transition [*Atallah and Bosart*, 2003] and terrain interaction, which make the correlation between TC intensity and inner core rain rate weaker over land than over ocean [*Jiang et al.*, 2008c]. This is the first reason that our study is carried out independently for the ocean and land. The second is the difference in the underlying physics of the 3B42 algorithm over ocean and land (details in next section).

[5] In this study, we quantify the dependence of TC rainfall on environmental moisture parameters and examine how these effects differ between land and ocean using a 9-yr landfalling TC database over the Atlantic basin, which includes 48 storms that made landfall over the US coastal regions. The dataset and methodology are described in section 2. Section 3 shows the distribution of azimuthally averaged rain rates as a function of moisture parameters and correlations between total volumetric rain and these moisture parameters for both land and ocean. Conclusions and future work are discussed in section 4.

2. Data and Analysis Method

[6] The Tropical Rainfall Measurement Mission (TRMM) Multisatellite Precipitation Analysis (TMPA, also

[1]Department of Meteorology, University of Utah, Salt Lake City, Utah, USA.

[2]Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland, USA.

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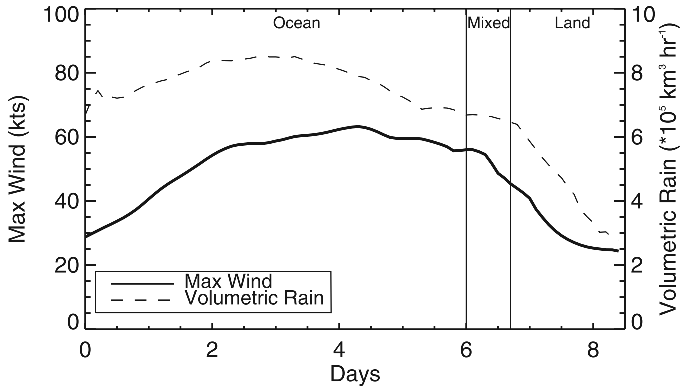

Figure 1. The time series of composites of the maximum sustained wind speed (solid line) and total volumetric rain within 5° radius of TC center (dashed line) for the 48 TCs, which are normalized with the mean length (days) of each stage. Vertical lines are plotted to separate over ocean, mixed, and overland stages.

referred as TRMM 3B42) rain rates are used. This is a combined product based on two different sets of sensors: Microwave and IR [*Huffman et al.*, 2007]. The TMPA dataset consists of gridded 3-hourly precipitation rate files with 0.25° × 0.25° longitude/latitude horizontal resolution, within the global latitude belt 50°S to 50°N. The temporal resolution is 3 hours and the files are generated on observation times (00 UTC, 03 UTC, …, 21 UTC). The major concern of TMPA is the issue of different physics in the microwave component of the retrieval over land and ocean. In the current TMPA system, passive microwave observations from TMI, AMSR-E, and SSM/I are converted to precipitation estimates with sensor-specific versions of the Goddard Profiling Algorithm (GPROF) [*Kummerow et al.*, 1996; *Olson et al.*, 1999]. For over ocean measurements, GPROF is a physically based algorithm that attempts to reconstruct the observed brightness temperatures in all channels by selecting the "best" combination of thousands of numerical model–generated microwave channel upwelling radiances. But over land, the GPROF rain retrieval uses the high frequency channel (ice scattering signature) only due to the variable emissivity of the land surface in low frequencies [*Kummerow et al.*, 2001]. The different physics over land and ocean causes different biases in the GPROF retrievals. For example, *Kummerow et al.* [2001] showed that GPROF is biased negatively by 9% over oceans and positively by 17% over land compared with rain gauge data.

[7] Best track data used in this study are provided by the National Hurricane Center (NHC). These post-analysis best tracks include positions and time of TC centers, and maximum sustained wind speed every 6 hours.

[8] In this study, 3-hourly TMPA observations for the whole lifetime of 48 US landfalling TCs over the Atlantic basin during 1998–2006 are grouped into over-ocean and over-land stages. For each TMPA snapshot within 5° radius of the TC center, if there are greater than 60% of raining pixels over ocean (land), then this observation is attributed to the over-ocean (over-land) stage. Observations that are not identified either over-land or over-ocean are attributed to mixed stage. It is possible that a case could have its center overland, but 60% of its raining pixels offshore. This case will still be attributed to "over-ocean" category. It is reasonable because (1) this study mainly concerns TC rainfall; (2) this is consistent with the 3B42 limitation for treating land and ocean observations differently. For each storm, the average lifetime is 8.5 days with 6.1 days over ocean, 1.7 days over land, and 0.7 days in mixed stage. Figure 1 shows the time series of composites of the maximum sustained wind speed from best track data and total volumetric rain within 5° radius of a TC center from the TMPA data for the 48 TCs. These composites are normalized with the mean length (days) for each stage. Total numbers of TMPA snapshots are 2349 for over ocean, 636 for over land, and 270 for mixed stage, respectively. It is found from Figure 1 that a storm generally has lower maximum wind speed and total volumetric rain over land than over ocean. Note that we only analyze over land and over ocean samples in the following section.

[9] Both radial variation and storm total volume of TC rain are analyzed. These parameters are derived in storm-relative coordinates. The azimuthal averages are calculated in 28-km-wide annuli (according to the 0.25° resolution of TMPA data) around the storm center outward to the 555-km (5°) radius. The storm total volumetric rain is integrated within 5° radius of the TC center.

[10] The environmental moisture parameters used for this study are calculated from the Navy Operational Global Atmospheric Prediction System (NOGAPS) analysis [*Goerss and Phoebus*, 1992; *Goerss and Jeffries*, 1994], which has 1° × 1° spatial resolution and 12-h temporal resolution. The moisture parameters are interpolated into 3-h temporal resolution to match TMPA data. A simple expression of the vertically integrated water vapor budget is as follows [*Braun*, 2006; *Jiang et al.*, 2008b]:

$$\mathbf{P} = Local\ Change\ of\ TPW + \mathbf{HMC} + \mathbf{OSF} - C \qquad (1)$$

where TPW is the total precipitable water (mm, equivalent to kg m^{-2}), HMC is the horizontal convergence of water vapor vertically integrated for the whole atmospheric column (mm hr^{-1}), OSF is the ocean surface moisture flux (mm hr^{-1}), P is precipitation rate (mm hr^{-1}), and C is liquid and solid water stored as cloud (cloud storage, mm hr^{-1}). Local changes of TPW and cloud storage terms are insignificant. But TPW itself is important because it is related to HMC. According to equation (1), major moisture parameters associated with precipitation are HMC, TPW, and OSF. To examine the dependence of TC rain on these parameters, the mean HMC, TPW, and OSF within 5° radius of the TC center are calculated from the NOGAPS analysis. OSF is estimated from a bulk parameterization method described by *Liu* [1988] and *Jiang et al.* [2008b]. Only over-ocean pixels have OSF values, OSF is assigned as zero for land pixels.

3. Results

3.1. Azimuthally Averaged TC Rain Rates as a Function of Moisture Parameters

[11] Figure 2 shows radial distributions of azimuthally averaged rain as a function of mean TPW, HMC, and OSF within 5° radius, as well as maximum wind speed for comparisons, for over land and over ocean conditions. Probability density functions (PDFs) of TPW, HMC, OSF, and maximum wind speed are also plotted. As expected based on water vapor budget theory, numerical case studies [*DiMego and Bosart*, 1982; *Braun*, 2006], and observational case studies [*Carr and Bosart*, 1978; *Rodgers et al.*, 1994; *Rodgers and Pierce*, 1995; *Rodgers et al.*, 1998, 2000; *Jiang et al.*, 2008b], high TPW, HMC, and OSF are favorable for precipitation in general as seen in Figures 2a–2f. As the radial distance from the TC center decreases and TPW, HMC, and OSF values increase, the rain rate increases both over land and over ocean. But the correlations are lower for over land than over ocean stages. The highest rain rates are located at the inner core region with highest TPW values both overland (Figure 2a) and over ocean (Figure 2b), and highest HMC value over oceans (Figure 2d). There are double peaks of rain rates over land in Figure 2c (HMC) and Figure 2e (OSF). The first peaks of rain rates are located at maximum or close to maximum HMC and OSF values, which are 1.85 mm/hr and 0.8 mm/hr respectively for land samples. The second peaks in Figure 2c and Figure 2e corresponding to much lower values of HMC and OSF are associated with the peak in Figure 2g because HMC and OSF are functions of the surface wind speed [*Liu*, 1988]. In Figure 2f, the peak rain rates are corresponding to OSF value of 1.8 mm/hr (the maximum OSF for ocean samples is 2.3 mm/hr) and radial distance of around 100-km, which is further away from the TC center than peaks shown in the Figures 2a–2e, 2g, and 2h. From the PDF of OSF (dashed line overplotted in Figure 2f), it is found that small percentages of total samples cause this pattern. After checking the data, we found that these are only 31 samples from two storms: Hurricanes Floyd (1999) and Isabel (2003). Relatively large eye features are shown in TMPA rainfall images of these samples. OSF is a function of surface wind speed and sea surface-air moisture difference [*Liu*, 1988]. It is reasonable to have relatively larger mean OSF values within 5° radius for larger-eye samples because the integrated surface wind speed within 5° radius for these samples is larger due to the larger radius of maximum wind. From the overlain PDFs, the peaks we discussed above contain very low percentages of samples. However, these samples are at the high end and represent the most devastating storms.

[12] For comparison, radial distributions of azimuthally averaged rain as a function of maximum wind speed over land and ocean are also presented in Figures 2g and 2h. Generally, higher maximum wind speeds correspond to higher rain rates at each radial distance as shown by *Lonfat et al.* [2004]. This is more obvious for ocean samples than for land samples. For land conditions, the peak rain rates correspond to 70 kts of maximum wind speed, which is 35 kts weaker than the strongest land samples. Only a small percentage of over land samples (12 samples) have intensities greater than 80 kt. However, these samples are from 8 devastating storms (Bonnie 1998, Georges 1998, Bret 1999, Isabel 2003, Ivan 2004, Dennis 2005, Katrina 2005, and Rita 2005). There are considerable uncertainties for retrievals from microwave observations over land, including 3B42. A comparison between 3B42 and surface radar + gauge data for two landfalling storms in Atlantic during 2002 was performed by *Jiang et al.* [2008a]. Their results show a general overestimate of 3B42 for heavier rainfall samples over land. More validation studies are needed to assess the 3B42 uncertainties, but the pattern of Figure 2g should not be affected unless the overestimate varies greatly from case to case. Heavy rain and flooding of hurricanes over land may not be well correlated with storm intensity [*Jiang et al.*, 2008a, 2008c]. This is due to (1) the difference in the precipitation structures and properties during the pre- and post-landfall stages of TC lifecycle, and (2) interactions with terrain and baroclinic weather systems.

3.2. Correlation Coefficients Between TC Volumetric Rain and Moisture Parameters

[13] To examine the relationships between TC total rainfall amount and moisture parameters, linear correlation coefficients are calculated between TC volumetric rain within 5 radius and each of the following parameters: mean TPW, HMC, OSF, and HMC+OSF (the sum of HMC and OSF) within 5° radius and maximum wind speed for overland, over ocean, and all conditions (Table 1). In general, all coefficients for overland conditions are smaller than their counterparts for over ocean and all conditions except for volumetric rain versus OSF. Coefficients for overall conditions are always greater or equal to their overwater/overland counterparts. As a single predictor, the maximum wind speed is not the best to predict TC total volumetric rain among these examined parameters. For overland conditions, correlation coefficients of the volumetric rain versus HMC (0.53) and HMC+OSF (0.60) are higher than that of volumetric rain versus maximum wind speed (0.51), while for over ocean conditions, correlation coefficients of the volumetric rain versus TPW (0.53), HMC (0.59) and HMC+OSF (0.63) are higher than that of volumetric rain versus maximum wind speed (0.52).

Figure 2. Radial distributions of azimuthally averaged rain as a function of mean (a, b) TPW, (c, d) HMC, and (e, f) OSF within 5° radius, and (g, h) maximum wind speed for overland (636 samples) and over ocean (2349 samples) conditions, respectively. Color contours represent rain rates. PDFs of TPW, HMC, OSF, and maximum wind speed for overland and over ocean samples are overplotted accordingly as dashed lines.

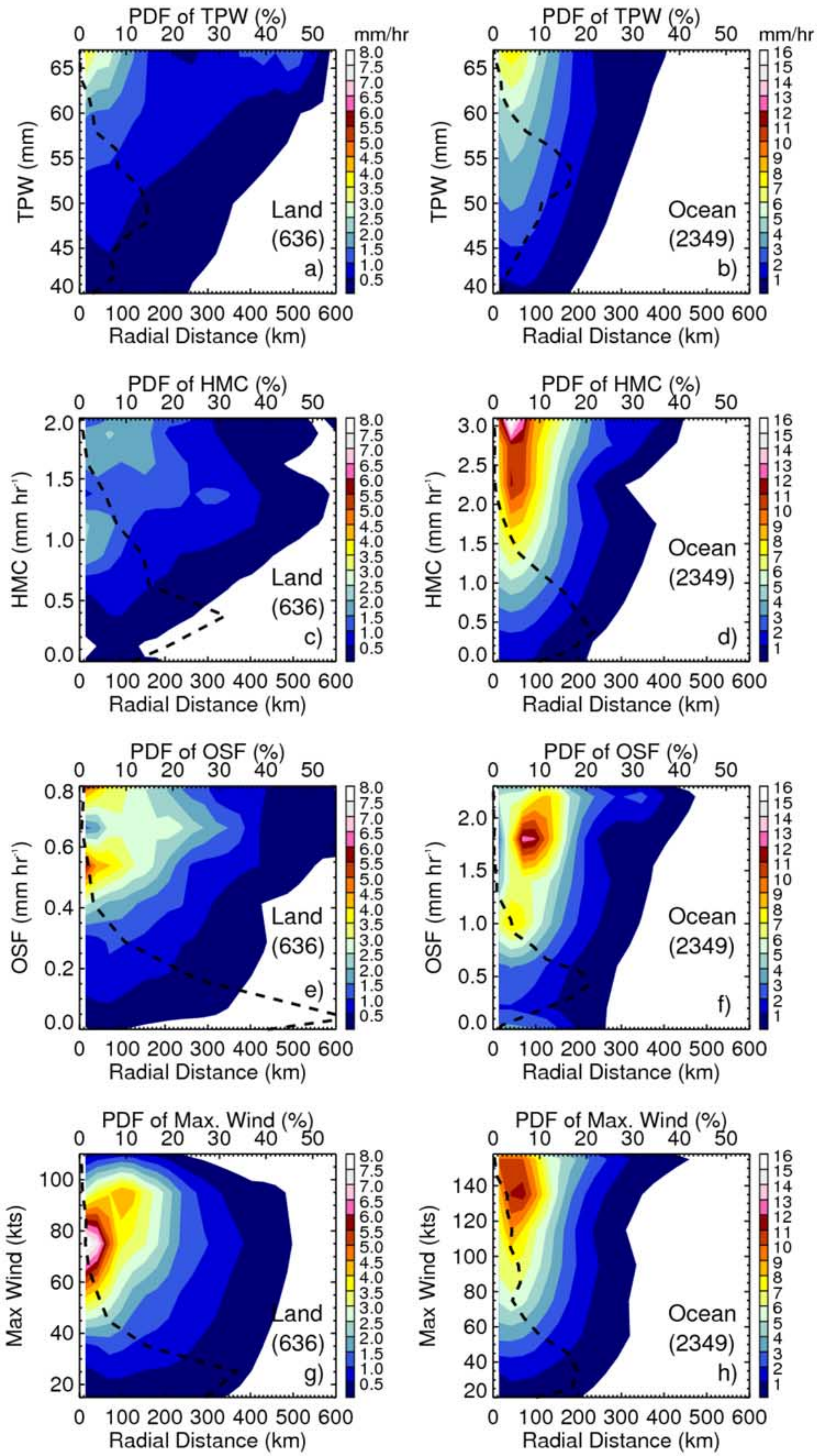
PDF of TPW (%)
TPW (mm)
Land (636)
a)
Ocean (2349)
b)
PDF of HMC (%)
HMC (mm hr⁻¹)
c)
d)
PDF of OSF (%)
OSF (mm hr⁻¹)
e)
f)
PDF of Max. Wind (%)
Max Wind (kts)
g)
h)
Radial Distance (km)
mm/hr

Figure 2

[14] To test the effects of adding moisture parameters on predicting TC volumetric rain, multiple linear correlation coefficients of storm volumetric rain versus the combination of the following parameters: maximum wind speed, and mean TPW, HMC, OSF, and HMC+OSF within 5 radius are presented in Table 2. Substantial improvement to the correlation coefficients is seen after combining moisture parameters with the maximum wind speed as independent variable. The best strategy is to utilize all four parameters of maximum wind speed, TPW, HMC, and OSF, which can boost the correlation coefficients compared to using maximum wind speed only from 0.51 (0.52, 0.56) to 0.65 (0.67, 0.70) for overland (over ocean, overall) conditions. However, it is noted that HMC and OSF are model-derived parameters and cannot be easily derived from observations. In contrast, TPW can be retrieved from satellite observations such as SSM/I and TMI. Since the improvement by adding only TPW to maximum wind speed is comparable to that by adding TPW, HMC, and OSF, this study suggests that TPW is a crucial parameter for forecasters to use in order to produce better TC rainfall predictions. For forecasting purposes, we must know the correlations with time lags. Assuming that TC intensity (maximum wind speed) can be adequately forecast itself, we further compute the multiple linear correlation coefficients among current volumetric rain, current maximum wind speed, and 12-h and 24-h previous TPWs. It is found that the 12-h time lag gives us almost same correlation coefficients (0.60, 0.64, and 0.66 for land, ocean, and all conditions, respectively) as those computed using no time lags, while the 24-h time lag gives us slightly smaller correlation coefficients (0.56, 0.60, and 0.63 for land, ocean, and all conditions, respectively), but this is still better than using the maximum wind speed parameter only. As mentioned before, R-CLIPER uses mainly TC intensity to predict TC rainfall. From Figure 2g we can see that this would cause errors for TC landfall precipitation forecasts.

4. Conclusions and Future Work

[15] Predicting TC rainfall, especially over land, is a major operational challenge. Based on water vapor budget theory, rainfall production is mainly controlled by moisture convergence and ocean surface moisture flux. This study uses multi-satellite derived rainfall to investigate the effects of environmental moisture parameters on TC rainfall for over land and over ocean. Our results reveal that the sum of HMC and OSF is highly correlated with TC rainfall for both land and ocean, although it is not as high as expected possibly due to the uncertainties in the NOGAPS analysis. This high correlation is the combined effect of wind speed and total moisture availability. The multiple correlation coefficients between volumetric rain versus the combination of maximum wind speed and TPW are around the same level as those between volumetric rain and HMC+OSF (see Tables 1 and 2). The results suggest that better TC rainfall prediction can be achieved by either adding TPW into the current forecast scheme (i.e., using TC intensity only), or using HMC+OSF instead, or using all TC intensity and moisture parameters. The former strategy is easier to implement because TPW is retrievable from satellite observations.

[16] We plan to apply the methodology to other TC basins that have at least 100 landfalling storms during the TRMM era. Satellite-derived TPW will be used to develop an operational prediction scheme for TC rainfall. Additionally, the water budget based moisture analysis could play a role in future studies investigating effects of environmental factors on TC genesis and intensity change. We also plan to test the sensitivity of our results to the use of the NOGAPS fields by doing this with other models, such as National Centers for Environmental Prediction (NCEP) reanalysis.

Table 1. Linear Correlation Coefficients of Storm Volumetric Rain Versus Each of the Following Parameters: Mean TPW, HMC, OSF, and HMC+OSF Within 5° Radius and Maximum Wind Speed

Linear Correlation Coefficients	Land	Ocean	All
Volumetric Rain vs. Max. Wind	0.51	0.52	0.56
Volumetric Rain vs. TPW	0.38	0.53	0.54
Volumetric Rain vs. HMC	0.53	0.59	0.59
Volumetric Rain vs. OSF	0.48	0.45	0.51
Volumetric Rain vs. HMC+OSF	0.60	0.63	0.66

Table 2. Multiple Linear Correlation Coefficients of Storm Volumetric Rain Versus the Combination of the Following Parameters: Mean TPW, HMC, OSF, and HMC+OSF Within 5° Radius and Maximum Wind Speed

Multiple Linear Correlation Coefficients	Land	Ocean	All
Volumetric Rain vs. Max. Wind and TPW	0.59	0.64	0.67
Volumetric Rain vs. Max. Wind, TPW, and HMC	0.63	0.65	0.68
Volumetric Rain vs. Max. Wind, TPW, HMC, and OSF	0.65	0.67	0.70
Volumetric Rain vs. Max. Wind, TPW, and HMC+OSF	0.64	0.67	0.69

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J. B. Halverson, Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, USA.

H. Jiang and E. J. Zipser, Department of Meteorology, University of Utah, 135 S 1460 E, Room 819 WBB, Salt Lake City, UT 84112, USA. (h.jiang@utah.edu)