Assessing Tropical Cyclone Contribution to Annual Global Rainfall

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ABSTRACT

Any change in tropical cyclone (TC) rainfall could positively and/or adversely impact the well-being of humans worldwide. This first global 10-year Rainfall Climatology and Persistence (R-CLIPER) model TC rainfall study seeks to enhance the basic understanding of TC contribution to annual global rainfall. The Tropical Rainfall Measuring Mission (TRMM) satellite data provided accurate rainfall rates that were incorporated in R-CLIPER and were used in conjunction with rain gauge data by the TRMM global rainfall algorithm (3B-43) to make monthly mean global precipitation amount best estimates between 50° N and 50° S. R-CLIPER integrated the TRMM-derived climatological rainfall distribution at every 10-minute time step over the lifetime of each TC to estimate the individual TC rainfall. Annual TC and global rainfall estimates were integrated on 0.25° × 0.25° latitude/longitude grids for the years between 1998 and 2007. The annual TC rainfall totals were compared to annual global rainfall totals to assess TC rainfall percent contribution to global rainfall. The results suggest TCs contributed between ~2-3% of the annual global rainfall during the 10-year period with regionally higher percentages reaching 10-15% in the subtropics and as high as 25-40% in certain local areas. The results of this study could be useful to risk and water management agencies for identifying which regions around the world depend upon TC rainfall for agriculture and other uses and have added value considering that TC rainfall contributions may fluctuate as a result of climate change.
1. Introduction

Tropical cyclones (TCs) are associated with copious precipitation both in coastal and inland regions. The abundant rainfall transported by TCs can wreak havoc through flooding while simultaneously providing essential water to affected regions around the world. Moreover, the latent heat of condensation released by tropical precipitation is a principal driver of general atmospheric circulations (Kummerow et al., 2000). Due to their sheer size and complexity, TCs can release more latent heat compared to the more numerous tropical convective systems such as those located in the Intertropical Convergence Zone (ITCZ) (Rodgers et al., 2000). In addition to evidence that suggests general atmospheric circulations are already changing, an increase of TC rainfall is plausible given a warmer and moister climate (Anthes et al., 2006). Therefore, based on the aforementioned considerations, we inquire into the impact TCs have on the general atmospheric circulation or, more specifically, annual global rainfall.

TCs are low-pressure systems that usually develop within 20° of the equator over the world’s tropical and subtropical oceans. Favorable environmental factors for TC development include the following: sea surface temperatures greater than 26°C, nonzero Earth vorticity (not satisfied within 3° N or S of the Equator), low vertical shear of horizontal wind (not greater than 16 m/s), potentially unstable atmosphere (instability greater than 10 K), and sufficient tropospheric humidity in the low to mid atmospheric levels (relative humidity of 50 to 60% between 700 to 500 hPa) (Marks, 2003). Remnants of frontal systems, convergences associated with westward propagating African easterly waves, or even northeasterly and southeasterly trade wind convergences near the ITCZ can all function as lifting mechanisms for initial TC formation (Lynch and Cassano, 2006). Well-defined axisymmetric rain bands, an eye wall, and strong cyclonic surface winds are often easily recognizable TC characteristics. Major tropical cyclone regions include the western North Pacific, eastern North Pacific, Southwest Indian Ocean, Australia/Southwest Pacific, and North Atlantic (Marks, 2003). Tropical cyclones are also known by different names depending on geographic locality—in the Western Hemisphere a strong TC is called a ‘hurricane’; in the Western Pacific Ocean, ‘typhoon’; and in the Indian and Southern Pacific Oceans, ‘cyclones’. In concurrence with Lonfat et al. (2004), the current study will categorize TCs based on wind speed. TCs characterized by wind speeds between 18 to 33 ms⁻¹ are called tropical storm (TSs), TCs with wind speeds from 34 to 48 ms⁻¹ are known as category 1-2 (CAT12) storms, and category 3-5 (CAT35) storms are TCs with winds exceeding 49 ms⁻¹.

Earlier research has examined the impact TCs have on total rainfall in specific basins such as the North Pacific and Atlantic Oceans. Rodgers et al. (2000) focused on investigating TC contribution to total rainfall in the North Pacific (including both land and ocean within the region bounded by 0°-45°N × 100°E-80°W) during the months of June to November from 1987-89 and 1991-98. Special Sensor Microwave Imager (SSM/I) instruments positioned on Defense Meteorological Satellite Program (DMSP) satellites collected monthly rainfall data over the North Pacific. The results show during the tropical cyclone season TCs contributed 7% of total rainfall in the entire North Pacific, 30% of rainfall in the Philippine northern islands, and lesser percentages in central Vietnam, China, Taiwan, and southern Japan during the TC season. Rodgers et al. (2000) acknowledged that the study underestimates TC rainfall because the chosen method does not account for either tropical depressions or landfallen dissipating TCs without
best track reports. Rodgers et al. (2000) concluded TC rainfall largely supplements seasonal rainfall during the growing season in select areas of the North Pacific and serves as an agricultural water source among additional purposes.

In 2001, Rodgers et al. expanded the North Pacific TC rainfall study to cover the North Atlantic (0°-35°N by 0°-100°W). In both the North Pacific (Rodgers et al., 2000) and North Atlantic domains (Rodgers et al., 2001) the maximum zonally averaged TC rainfall is located poleward of the maximum zonally averaged non-TC rainfall which effectively highlights the important role TCs play in the poleward heat transport. Between June and November, TCs contributed 4% of the total rainfall in the North Atlantic. Specifically, TCs contributed more than 30% of rainfall to dry regions northeast of Puerto Rico, in the middle subtropical North Atlantic, and west of Africa. TCs provided up to 10% of the total rainfall in parts of the southeastern United States, Yucatan Peninsula, and Central America. Rodgers et al. (2000, 2001) stressed the underestimation of TC rainfall contribution in the studies and highlighted the potential that the microwave technique employed by the satellites may miss or underestimate shallow orographic rainfall (such as in Taiwan, Philippine Islands, and Japan) confined below the freezing level as rainfall associated with TCs moves over a landmass.

Simo (2003) extended the scope of the Rodgers et al. (2000, 2001) studies by examining the contribution of all TCs to annual global rainfall. Passive microwave satellite observations from the Tropical Rainfall Measuring Mission (TRMM) provided annual global rainfall data. TC total rainfall estimates calculated by the satellite-based Rainfall Climatology and Persistence (R-CLIPER) model (Tuleya et al., 2007) were used to evaluate the global impact of TCs on rainfall between 1998 and 2002. R-CLIPER was run for every TC in the world in a given year using the TC track position and intensity. The study found TCs contributed between 2.3-3.0% of the annual global rainfall during the period from 1998 to 2002.

Lewis (2005) used both the TRMM and R-CLIPER model to extend the Simo (2003) study for three additional years from 1998 to 2005. The results of the Lewis (2005) study show TCs contributed approximately 2-3% of annual global rainfall, and TCs contributed 10-15% and 5-10% of the annual global rainfall in latitudinal bands between 10°-30°N and 10°-30°S, respectively, which is sensible since more TCs exist in the Northern Hemisphere than in the Southern Hemisphere (Marks, 2003).

Tuleya et al. (2007) explains how the R-CLIPER model integrates a climatological rainfall rate along a TC track to determine the total rainfall during the lifetime of a TC. Only TC track and intensity data are needed in order to run R-CLIPER. Marks et al. (2002) further explains how R-CLIPER uses the TC track and intensity data in conjunction with the climatological rainfall rate partitioned by TC intensity (Lonfat et al., 2004) to produce a mean rain rate distribution out to a 500 km radius from the TC center. R-CLIPER incorporates both weakening TC intensity due to land effects and higher mean rain rates for more intense TCs (Lonfat et al., 2004). However, R-CLIPER does not take into consideration factors such as vertical wind shear that cause azimuthal asymmetries in TC rain distribution since these factors can vary for individual TC synoptic environments (Lonfat et al., 2004; Tuleya et al., 2007). Rather than depending on detailed azimuthal distributions of TC rainfall, the approach of the current study relies upon rainfall totals integrated over the lifetime of TCs.
The current study will extend the previous work of Simo (2003) and Lewis (2005) to assess worldwide TC contribution to annual global rainfall during the past 10-year period from 1998 to 2007. Improving the current understanding of the role TCs play is vital since the Intergovernmental Panel on Climate Change (IPCC) predicts a future warmer climate will lead to an increased risk of intermittent yet intense precipitation and flooding events followed by lengthy dry periods that will also increase the risk of drought (Meehl et al., 2007). As a result, any change in TC rainfall impact could positively and/or adversely impact the well-being of many humans worldwide. As the first global 10-year TRMM and R-CLIPER TC rainfall study, the current study seeks to enhance the basic understanding of the contribution of TCs to global annual rainfall or, similarly, the impact of TCs on the general atmospheric circulation.

2. Dataset and Methods

Assessing the impact of TC rainfall on annual global rainfall requires in large part measuring precipitation over oceans in the Tropics. Space is the only platform where adequate measurements of precipitation over the ocean in the Tropics are plausible (Kummerow et al., 1998). TRMM, a joint effort between the United States’ National Aeronautics and Space Administration and Japan’s National Space Development Agency, strives to measure rainfall and energy exchange of Earth’s tropical and subtropical regions. Launched in November 1997, the TRMM satellite orbits Earth inclined at 35° and at an initial altitude of 350 km and later at an altitude of 402 km to extend the lifetime of the mission (Lonfat et al., 2004). The three primary instruments onboard the TRMM satellite are the TRMM Microwave Imager (TMI), the Precipitation Radar (PR), and the Visible and Infrared Radiometer System (VIRS). Additional TRMM details are provided in Kummerow et al. (1998).

Of the three instruments onboard the TRMM satellite, the TMI is unique in providing valuable quantitative rainfall data along a wide surface swath (878 kilometers). TMI builds upon the design of the Special Sensor Microwave/Imager (SSM/I), in service since 1987 on Defense Meteorological Satellites. The TMI quantifies atmospheric water vapor, cloud water, and rainfall intensity by measuring small microwave energy emissions from Earth and the atmosphere. Specifically, TMI employs five distinct frequencies—10.7, 19.4, 21.3, 37, and 85.5 GHz—to measure radiation intensity. The relatively low-Earth altitude (402 kilometers) of TRMM allows for improved ground resolution compared to the 860-kilometer altitude of SSM/I. In addition, PR information helps to improve algorithms (NASA, cited 2008a). Rainfall rates measured by the TMI over land are less accurate than those obtained over oceans (NASA, cited 2008b). The TMI was instrumental in providing rain estimates used by Lonfat et al. (2004) for constructing a global TMI rainfall climatology (Marks et al., 2002). The TMI rainfall climatology consists of 482 storms between January 1998 and December 2002, which collectively yields 3979 instantaneous observations where 65% of the observations are TSs, 24% are CAT12s, and 11% are CAT3-5s.

The Rainfall Climatology Parametric (R-CLIPER) model, built by Marks and DeMaria in 2001, employs the TMI rainfall climatology in conjunction with TC storm track (duration) and intensity (wind speed) to produce TC rainfall totals on a latitude/longitude grid at a 0.25° × 0.25° resolution. The version of R-CLIPER used in the current study assumes storms are symmetric with respect to spatial rainfall distribution and only accounts for landmass effects on TCs.
through weakening of the storm intensity. Topography is not taken into account by R-CLIPER. However, the current study is interested in the total TC rainfall, which R-CLIPER accurately calculates, instead of more detailed TC rainfall distribution asymmetries due to factors such as vertical shear and topography (Lonfat et al., 2007).

Prior to running R-CLIPER, a text file containing 6-hour interpolated latitude, longitude, and peak wind (knots) of every TC during each year was created using uncorrected best track data accessible via http://www.solar.ifas.hawaii.edu/Tropical/. These particular tracks were chosen for their completeness and easy accessibility. The following resources were used to edit or replace the uncorrected best tracks when incongruous or considerable variations existed between the uncorrected best tracks, which are derived from forecast advisories, and best tracks (i.e. National Hurricane Center (NHC) best tracks): NHC Tropical Cyclone Reports, Joint Typhoon Warning Center Annual Tropical Cyclone Reports, and the Naval Research Laboratory Monterey Marine Meteorology Division (Code 7500) Tropical Cyclone Page (Ver.4.28.00).

R-CLIPER requires at least three 6-hr time steps to run. TCs with only one or two 6-hour time steps were excluded from the R-CLIPER rainfall analysis. The text files for TCs that met the time step qualification requirement were individually input into the R-CLIPER model. R-CLIPER uses the TMI rainfall climatology created by Lonfat et al. (2004) to produce storm-centered 500 km radius TC mean rain rate ($R$) distributions as a function of radius ($r$) (Marks et al., 2002; Tuleya et al., 2007):

$$ R(r) = \begin{cases} R_0 + (R_m - R_0) \left( \frac{r}{r_m} \right) & r < r_m \\ R_m \exp\left[-\frac{(r-r_m)}{r_e}\right] & r \geq r_m \end{cases} $$

where $r_m$ is the radial extent of the inner-core rain rate, $r_e$ is a measure of the radial extent of the tropical system rainfall, $R_0$ is the rain rate at $r = 0$, and $R_m$ is the maximum rain rate at $r = r_m$. A linear relationship exists between $r = 0$ and $r = r_m$ after which an exponential decay exists for $r \geq r_m$ from $R_m$. The four parameters, $R_0$, $R_m$, $r_m$, $r_e$, in Eq. (1) are linear functions of storm intensity as shown in Eq. (2) (Marks et al., 2002; Tuleya et al., 2007). The values for the coefficients in Eq. (2) are shown in Table 1.

$$ R_0 = a_1 + b_1 U $$
$$ R_m = a_2 + b_2 U $$
$$ r_m = a_3 + b_3 U $$
$$ r_e = a_4 + b_4 U $$

where $U$ is the normalized maximum wind represented by

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Constants from fit of TRMM rainfall rates as a function of radius and maximum wind for the R-CLIPER model (Tuleya et al., 2007).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intercepts</strong></td>
<td><strong>Slopes</strong></td>
</tr>
<tr>
<td>$a_1 = -1.10$ in. day-1</td>
<td>$b_1 = 3.96$ in day-1</td>
</tr>
<tr>
<td>$a_2 = -1.60$ in. day-1</td>
<td>$b_2 = 4.80$ in day-1</td>
</tr>
<tr>
<td>$a_3 = 64.5$ km</td>
<td>$b_3 = -13.0$ km</td>
</tr>
<tr>
<td>$a_4 = 150$ km</td>
<td>$b_4 = -16.0$ km</td>
</tr>
</tbody>
</table>
\[ U = 1 + \frac{(V_m - 35 \text{ knots})}{33 \text{ knots}} \]

and \( V_m \) is the maximum wind speed (knots). R-CLIPER integrates the rainfall distribution at each time step over the lifetime of the TC to determine the total rainfall along the storm track of each TC on a \( 0.25^\circ \times 0.25^\circ \) grid. An Interactive Data Language (IDL) program sums the R-CLIPER integrated rainfall distribution for each TC during one year to determine total TC rainfall for the particular year under investigation.

Annual global rainfall was determined in a similar manner as annual TC rainfall. The TRMM global rainfall algorithm (3B-43) provided monthly best-estimate precipitation rate and root-mean-square (RMS) precipitation-error estimates. 3B-43 is a product of TRMM 3-hourly merged high quality (HQ)/infrared (IR) precipitation and RMS precipitation-error estimates (3B-42) that are adjusted over land using rain gauge data and combined with the monthly Climate Assessment and Monitoring System (CAMS) or Global Precipitation Climatology Centre (GPCC) rain gauge analysis (3A-45) (NASA, cited 2008b; NASA, cited 2008c). The global monthly rainfall was integrated and graphed on a \( 0.25^\circ \times 0.25^\circ \) resolution latitude/longitude grid from \( 50^\circ \text{N} \) to \( 50^\circ \text{S} \).

TC percent contribution to annual global rainfall was determined to help assess the significance of TC rainfall in annual global rainfall (Eq. 3).

\[
TC\% = \frac{\text{TC rainfall (cm)}}{\text{Global rainfall (cm)}} \times 100\% \quad (3)
\]

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3. Results and Discussion

Three factors affected the amount of TC rainfall from year-to-year: number of TCs, TC duration (defined as the number of days TCs existed starting from the tropical depression stage), and TC intensity (wind speed). Of these three factors, annual variations in TC duration had the highest correlation ($R = 0.95$) to annual variations in TC rainfall (Table 2). The strong correlation between TC duration and TC rainfall indicates the annual duration of TCs was more important than the annual number of TCs in determining annual TC rainfall totals during the 10-year period. For example, during 2004 there were 4 less TCs than the maximum number of TCs (104 TCs in 2005) in the 10-year period, and TC duration (522.25 days) in 2004 was the maximum TC duration during the 10-year period while in 2005 the TC duration was 489.75 days. The maximum annual TC rainfall total occurred in 2004 and not 2005. The correlation coefficient for TC rainfall and number of TCs is 0.78; TC rainfall and TC intensity, 0.79. The latter two correlation coefficients suggest the number of TCs and TC intensity were still important factors in determining TC rainfall since variations between the respective variables do correlate.

Table 2 Correlation analysis results for TC rainfall (TC rain) and the three factors [number of TCs (# TCs), TC duration, and TC intensity] that affect TC rainfall.

<table>
<thead>
<tr>
<th></th>
<th>TC Rain</th>
<th># TCs</th>
<th>TC Intensity</th>
<th>TC Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC Rain</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># TCs</td>
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<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC Intensity</td>
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<td>1.00</td>
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<tr>
<td>TC Duration</td>
<td>0.95</td>
<td>0.72</td>
<td>0.63</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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Fig. 1 shows the annual TC duration from 1998 to 2007 (10-year period). The longest TC duration occurred in 2004 when TCs existed for 522.25 days while 2007 experienced the shortest TC duration at 349 days.

Individual TC duration is significant particularly over landmasses because the effects of prolonged rain events can lead to devastating flooding such as occurred in Southeast and East Texas from Tropical Storm Allison in 2001 (Stewart, 2001). In order to determine the individual TC duration, the annual TC duration was divided by the annual number of TCs. The number of TCs globally changed very little during the 10-year period (Fig. 2). The maximum number of TCs was 104 TCs in 2005 while the minimum number of TCs was 91 TCs, in both 1999 and 2006. Using the results for TC duration and number of TCs, an individual TC existed for 4.80 days on average during the 10-year period (Fig. 3).
Figure 2 Global TC frequency (number of TCs) during the 10-year period. The number of hurricanes (wind ≥ 33 m/s) is shown in blue and tropical storms and depressions (17.5 m/s ≤ wind ≤ 32.5 m/s and wind ≤ 17 m/s, respectively) in red.

Figure 3 Mean individual TC duration (days) during the 10-year period.
The number of more intense TCs with wind speeds > 33 m/s was approximately one-half of the annual number of TCs (Fig. 4). Referring to Fig. 2, the years 2003 and 2005 were the most active years for hurricanes as each year recorded 52 hurricanes whereas 1999 recorded the fewest with only 38 hurricanes.

Figure 4 Annual percent of hurricanes (%) compared to the total number of TCs.
The magnitude of annual TC rainfall is on the order of $10^6$ cm during the 10-year period (Fig. 5). TC rainfall totals were highest in 2004 (1.44E+06 cm), 2003 (1.36E+06 cm), and 2005 (1.36E+06 cm) and lowest in 2007 (9.16E+05 cm), 1999 (1.02E+06 cm), and 2002 (1.17E+06 cm). The largest annual difference in TC rainfall occurred between the years of 1998 and 1999 when TC rainfall decreased 22.70% from the earlier year.

**Figure 5** Total TC rainfall (cm) during the 10-year period.
A noticeable difference exists between the TC rainfall total in the Northern Hemisphere (NH) and Southern Hemisphere (SH) (Fig. 6). For instance, the 10-year period average TC rainfall in the SH was 33.91% of the average TC rainfall in the NH. This disparity in TC rainfall between the two hemispheres results from the absence of TCs in one-half of the SH (the region roughly extending from 150° W to 30° E). The largest TC hemispheric rainfall total difference occurred in 2005 when the SH received 79.22% less rainfall than in the NH.

Figure 6 Total TC rainfall (cm) in the Northern Hemisphere (blue) and Southern Hemisphere (magenta) during the 10-year period.
The magnitude of annual global rainfall during 1998 to 2007 is on the order of $10^7 \text{ cm}$, which highlights the lopsided magnitude of TC and global rainfall with global rainfall having the greater rainfall magnitude (Fig. 7). The years of 2004 ($5.07 \times 10^7 \text{ cm}$), 2003 ($5.15 \times 10^7 \text{ cm}$), and 2006 ($5.15 \times 10^7 \text{ cm}$) all witnessed the lowest global rainfall totals during the 10-year period whereas 1998 ($5.59 \times 10^7 \text{ cm}$), 1999 ($5.55 \times 10^7 \text{ cm}$), and 2000 ($5.46 \times 10^7 \text{ cm}$) saw the highest global rainfall totals. In 2007, the global rainfall total shows a markedly visible increase following the span of years from 2003 to 2006, which showcased the lowest global rainfall totals.

![Figure 7](image-url) Global rainfall (cm) during the 10-year period.
Focusing on the smaller hemispheric magnitude indicates slightly higher rainfall totals in the Northern Hemisphere (NH) than the Southern Hemisphere (SH) each year during the 10-year period (Fig. 8). This observation could be a reflection of the changing position of the Intertropical Convergence Zone (ITCZ), the band of convergence of northeasterly and southeasterly trade winds associated with enhanced thunderstorm and convective activity. As with global rainfall, the magnitude of rainfall in the two hemispheres was also greater than the magnitude of TC rainfall in the NH and SH, which suggests TC contribution to total rainfall in the two hemispheres should be relatively small. The difference in global rainfall between the two hemispheres was smallest in 1998 (5.70E+05 cm) and largest in 2006 (3.70E+06 cm). Recall that the 10-year period average TC rainfall in the SH was 33.91% of the average TC rainfall in the NH. However, the difference between hemispheres with respect to global rainfall is much smaller. For example, the average global rainfall in the SH was 90.21% of the NH average global rainfall.

![Figure 8](image.png)

*Figure 8* Rainfall (cm) in the Northern Hemisphere (blue) and Southern Hemisphere (magenta) during the 10-year period.
Evaluating TC percent contributions to global rainfall during the 10-year period shows TCs are annually responsible for ~2-3% of the global rainfall (Fig. 9). The years 2004, 2003, and 2005 had the highest TC percent contribution (2.84%, 2.65%, and 2.64%, respectively) to global rainfall whereas 2007, 1999, and both 2002 and 2006 had the lowest TC percent contribution (1.71%, 1.84%, and 2.20%, respectively) to global rainfall. These results agree with the finding that annual global rainfall was much greater than annual TC rainfall during the 10-year period.

![Figure 9 Annual TC percent contribution (%) to global rainfall during the 10-year period.](image)
Similar to the relationship between global and TC rainfall totals in the NH and SH, TC percent contribution to total rainfall was also higher in the NH (mean TC percent contribution was 3.27%) than in the SH (mean TC percent contribution was 1.22%), but both still comprise relatively small TC percent contributions to the total rainfall in the two hemispheres (Fig. 10).

Figure 10 Annual TC percent contribution to rainfall in the Northern Hemisphere (blue) and Southern Hemisphere (magenta) during the 10-year period.
The annual global rainfall plots derived from 3B-43 further illustrate global rainfall characteristics during the 10-year period. The highest rainfall totals were consistently found in the Tropics (Fig. 11). In particular, the narrow band of high rainfall totals (shaded in red) to near 0° identifies the location of the ITCZ during each year. Large variations in global rainfall were not usually observed, which is evidenced by the similar annual rainfall distribution among the geographical locations during the 10-year period. A noticeable exception to the small variations occurred in 1998 when the zonal band of high rainfall totals associated with the ITCZ just north of 0° decreased in spatial coverage while an increase in high rainfall spatial coverage was visible in the SH, which was associated with the strong El Nino event from 1997-1998.

Figure 11 Global rainfall (cm) during the 10-year period illustrated on latitude and longitude grids with 0.25° × 0.25° resolution extending from 50° N to 50° S.
The spatial distribution of TC rainfall was temporally more variable than the distribution of global rainfall (Fig. 12). Particularly, TC rainfall in the North Indian, South Indian, and South Pacific basins had greater variations in spatial coverage compared to the remaining basins. The region between 150° W and 30° E as well as near 0° was repeatedly devoid of TC rainfall, which can be attributed to the non-favorable environment for TC development and vitality in these regions.

Figure 12 TC rainfall (cm) during the 10-year period illustrated on latitude and longitude grids with 0.25° × 0.25° resolution extending from 50° N to 50° S.
The TC percent contribution to global rainfall had both annual consistent and inconsistent features during the 10-year period. The region left of lower Baja California in the East Pacific basin consistently received more than 30% of global rainfall from TCs and was overwhelmingly the largest geographical region where TC contribution to global rainfall was the highest (Fig. 13). This TC percent contribution to global rainfall result in the East Pacific supports the TC percent contribution found in the same region by the Rodgers et al. (2000) study since the current study covers an annual time period whereas the Rodgers et al. (2000) study limited the time period to only encompass the tropical season. Although the West Pacific had 31% of the total mean number of TCs during the 10-year period the large contribution (≥ 30%) from TCs to global rainfall in the West Pacific was not as spatially expansive as in the East Pacific, which was due to the West Pacific receiving more global rainfall than the East Pacific. The tracks of the TCs were clearly a determining factor in how much TC rainfall geographical regions received each year during the 10-year period. For instance, the southeastern United States had higher TC percent contributions to global rainfall during 2001 and 2004 than during 2000 and 2006 even though during the latter two years there were high TC percent contributions to global rainfall farther east over the North Atlantic Ocean. Since 2004, a general increase in the spatial coverage of ≥ 30% TC contribution to global rainfall in northwestern Australia was observed in the results, which could be particularly important to the drought-prone continent. Despite the North Indian basin having the lowest mean TC frequency during the 10-year period, the TCs that affected the area west of India often contributed a high percentage (≥ 30%) of the local annual rainfall because any TC rainfall in the generally dry area contributed greatly to the annual rainfall. Likewise, several of the other regions and latitudes receiving TC rainfall are also associated with deserts and arid landmass, which means these areas are strongly dependent upon TC rainfall each year.
Figure 13 TC percent contribution (%) to global rainfall during the 10-year period illustrated on latitude and longitude grids with 0.25° × 0.25° resolution extending from 50° N to 50° S.
Latitudinal Variations

Latitudinal representations of global and TC rainfall add more rainfall details to the results from the 10-year period. Global rainfall had double peaks—one between 5°-10° N and S and the second peak is near 40° N and S—while global rainfall was lowest in both the NH and SH near 20°-25° (Fig. 14). The tropics, bounded by 23.4° N and 23.4° S, received the bulk of global rainfall. In 1998, the global rainfall peak in the SH was higher than the analogous NH peak, which is opposite of the rainfall patterns established during the remaining nine years. Moreover, the SH rainfall total in 1998 far exceeds rainfall totals in the SH during the ensuing time period. These observations could be the side effects of the strong El Nino event that occurred during 1997-1998 as Wu and Lau (1992) have noted that the dynamical and thermodynamical variations in association with ENSO considerably impact tropical storm activity. During an El Nino event, sea surface temperatures increase and pressure falls in the central and eastern Pacific Ocean, which lead to an anomalous increase in rainfall activity over the same region.

Figure 14 Latitudinal representation of global rainfall (cm) during 10-year period.
TC rainfall in the SH during 1998 resembled the SH global rainfall trend in 1998 (Fig. 15). Both TC and global rainfall during 1998 were more symmetric about the equator than TC and global rainfall in the following years. TC rainfall was close to 0 cm between 10° S and 10° N, which is sensible given that the equatorial region is not favorable for TC development and existence because the Coriolis force diminishes to 0 N as it approaches the Equator (0°). TC rainfall sharply increased at 10° S and 10° N before achieving the highest TC rainfall peaks near 15° S and 15° N. In 2005, the NH rainfall peak was flattened and not as pointed compared to the rainfall peak for other years during the 10-year period. The 2005 NH flattened rainfall peak seemed to compensate for the flattened peak by the shift of the rainfall curve to the right, which means NH higher latitudes received more TC rainfall during 2005 than in the other years during the 10-year period. Although a similar pattern was repeated during 2001 and 2004 the TC rainfall peak in these years was more pointed and the rainfall curve was not shifted as far to the right as in 2005. TC rainfall increases with higher latitudes whereas global rainfall quickly decreases at higher latitudes. The majority of TC rainfall during the 10-year period was located at latitudes where global rainfall was a minimum, which increases the relative importance of TC rainfall at these latitudes as indicated by the TC percent contributions to annual global rainfall. Notice the large difference between the scales of global rainfall (cm) in Fig. 14 and TC rainfall (cm) in Fig. 15, which means the contribution TCs made to annual global rainfall by latitude should also be relatively small.

**Figure 15** Latitudinal representation of TC rainfall (cm) during the 10-year period.
Annual variations occurred in the latitudinal TC percent contribution to global rainfall during the 10-year period (Fig. 16). During the 10-year period, the NH experienced the lowest peak TC percent contribution (9.20%) to global rainfall in 1999, which was approximately equal to the highest peak TC percent contribution (9.46%) to global rainfall in 1998 in the SH. This disproportionate rainfall contribution from TCs to rainfall in the two hemispheres reflects the increased TC frequency and rainfall in the NH compared to the SH. The contribution TCs made to global rainfall was small at most of the latitudes. The TC percent contributions to global rainfall were close to 0% between 5° S and 5° N, highest from 15° to 20° in both the SH (9.46% in 1998) and NH (17.04% in 2003), and close to 0% again poleward from 35° S and 45° N.

**Figure 16** Latitudinal representation of TC percent contribution (%) to global rainfall during the 10-year period.
Analysis of the 10-year TC mean frequency distribution via basins confirms the statement by Marks (2003) that most TCs exist in the NH (Fig. 17). TCs most frequently occurred in the Western Pacific (31%) basin followed by both the North Atlantic and Eastern Pacific (18%) basins. The South Pacific (14%) and South Indian (13%) basins were in next-to-last place. The North Indian (6%) basin had the fewest number of TCs during the 10-year period. Adding the frequency percentages for the NH basins yields 73% and doing the same for the basins in the SH, 27%, which means more TCs existed in the NH compared to the SH. This 2.7:1 ratio of the frequency of TCs in the NH and SH, respectively, helps to explain why more TC rainfall was observed in the NH than in the SH.

![Figure 17 Mean 10-year TC frequency (%) distribution by basin.](image)

### 4. Conclusions

During the 10-year period, TC contribution to annual global rainfall was not significant on either a global or hemispheric scale. However, TCs made considerable contributions to annual rainfall in specific regions such as near the lower Baja California coast in the East Pacific basin, Philippine Islands in the West Pacific basin, and northwestern Australia. The band of latitudes spanning from 15° to 30° in the NH received between 7 - 17% of global rainfall from TCs. The latitudes receiving TC rainfall are often associated with deserts and arid landmass, which means lack of TC rainfall in these regions could adversely impact the local inhabitants, economy, and ecosystem.

### 5. Future Research

This study unveiled many important questions related to TC rainfall and its contribution to global rainfall. For example, what regulates the annual global number of total TCs and hurricanes so that only small variations occur from year-to-year? Also, does the mean number of TCs (94 TCs) during the 10-year period accurately describe the number of TCs necessary to aide in balancing the Earth’s heat budget by transporting latent heat poleward? Is the role of TCs in the SH complementary to or independent of the role of TCs in the NH? Since the global rainfall in the NH and SH was approximately equal unlike TC rainfall in the two hemispheres, what
mechanism does the SH employ to compensate for the lack of TC rainfall and, thereby, inherent poleward transport of latent heat?

Future studies could investigate TC percent contribution to global rainfall during the tropical cyclone season only and specifically in the major TC basins to compare results with the results of Rodgers et al. (2000, 2001). Evaluating TC percent contribution to global rainfall during a longer time period or the societal impacts in different regions could enhance the current understanding of the field. Assessment of the effect TCs have in the southeastern United States during drought years could also be studied.

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7. References


