Climatology of Tropical Cyclone Rainfall Magnitude at Different Landfalling Stages Using 20-yr IMERG Data

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Introduction & Motivation

1. Rainfall-induced flooding from tropical cyclones (TCs) remains a significant cause of fatalities and damages along the coasts (***Willoughby, 2012; Rapport, 2014***). Therefore, a better understanding of the precipitation patterns at different landfalling stages is an extremely important task.
2. Previous statistical studies have been mainly focusing on TC rainfall over ocean (Lonfat et al. 2004; Chen et al. 2006; Rogers et al. 2003; Ueno 2007; Cecil 2007; Wingo & Cecil 2010; Pei and Jiang 2018)
3. A few statistical studies about TC landfall rain were focused on TC rainfall asymmetries, not rainfall magnitude & raining area (Jiang et al. 2008, Xu et al. 2014, and Yu et al. 2017)
4. Recently, Touma et al. (2019) found that the highest median rainfall intensity and the largest rainfall area over land occur when major hurricanes have weakened to tropical storms, resulting in greater flood risk despite the weaker wind speeds. Niu et al. (2022) showed similar results for the Northwestern Pacific TCs. However, both studies were using daily accumulates of rain gauge measurements over the land only.

Therefore, the motivation of this study is to refine the global TC rainfall climatology at different landfalling stages, by using 20 years of NASA satellite observations, which have much higher spatial & temporal resolutions than the rain-gauge data. We'll compare TC rainfall at different stages relative to landfall with an emphasis on the post-landfall stage.

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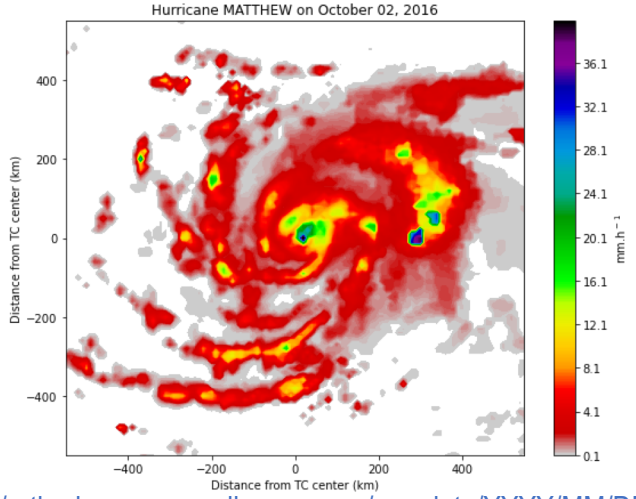
Datasets

TRMM/GPM IMERG Rainfall Estimates

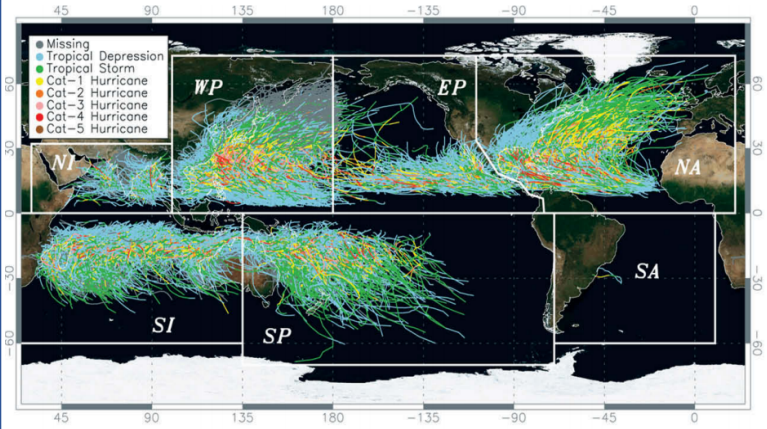


ftp://arthurhou.pps.eosdis.nasa.gov/gpmdata/YYYY/MM/DD/imerg/

NASA Integrated Multi-satellitE Retrievals for the Global Precipitation Measurement (GPM) mission: **(IMERG)** datasets (**Huffman et al. 2019, 2020**):

- 30-Minute datasets, but only 3-hourly was used.
- 0.1 x 0.1-degree, pixel size.
- WGS84 coordinate systems assumed

International Best Track Archive

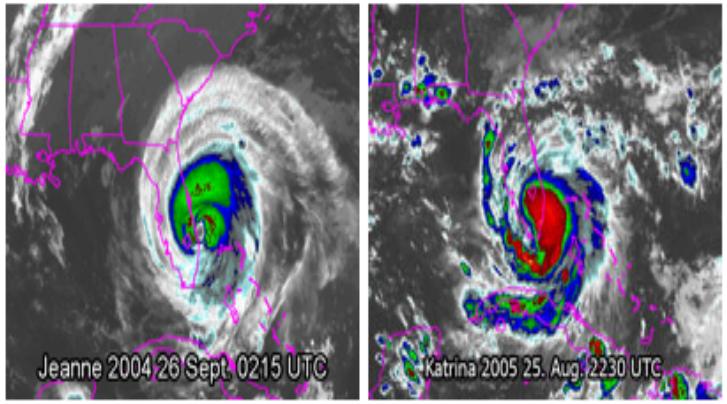


doi:10.1175/2009BAMS2755.1

International Best Track Archive for Climate Stewardship datasets (**IBTrACKS Vr.4, Knapp et al. 2010**):

- 3-Hourly.
- 27 storm attributes in seven different basins

Statistical Tropical Cyclone Intensity Forecast Technique Development



https://rammb.cira.colostate.edu/research/tropical_cyclones/ships/developmental_data.asp

SHIPS (DeMaria and Kaplan 1994, 1999, 2005; Schumacher 2013): Statistical Tropical Cyclone Intensity Forecast Technique Development.

- 6 Hourly.
- 86 to 141 parameters for each TC.
- Recently updated with all basins (Aug 2021)

Geospatial Datasets are also employed from https://international.ipums.org/international/index.shtml, and Cartopy. v0.11.2. 22-Aug-2014. Met Office. UK. https://github.com/SciTools/cartopy/archive/v0.11.2.tar.gz

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Methodology

1. **TC raining area definition:** Objectively define TC raining area from IMERG data (2000-2019) by following Jiang et al. (2011)'s TCPF method (center of rain cells are within 500-km of TC center)
2. **Definition of 7 stages relative to landfall through a new approach that combine the strengths of three previous researches (next slide)**
   - Jiang et al. (2008), Xu et al. (2014), and Yu et al. (2017)
3. **Separation of IMERG overpasses using the following criteria:**
   - By basin, by TC intensity, and by 7 landfall stages
4. **Further classification using current/point intensity -lifetime maximum intensity (LMI) scheme**
   - TD/TD, TD/TS, TD/CAT12, TD/CAT35, TS/TS, TS/CAT12, TS/CAT35, CAT12/CAT12, CAT12/CAT35, and CAT35/CAT35.
5. **TC parameters to be analyzed:**
   - Radial distribution of azimuthally averaged rainfall rate.
   - Raining area, mean rain rate, & Volumetric rain (Vr = TC rainfall average x TC area)
6. **Environmental parameters from the SHIPS developmental database**
   - **RSST**: Reynolds sea surface temperature.
   - **TPW500**: Total precipitable water up to 500 km from the TC center.
   - **SHDC**: Wind shear magnitude and direction.

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Landfall Classification: 7 stages relative to landfall

	Jiang et al. (2008)	Xu et al. (2014)	Yu et al. (2017)	This Study	
Before Landfall	**Ocean:** TC raining area >60% over ocean	**Off-shore:** TC center 400~700km away from coast	**Stage I**: 24 h prior to landfall	**Before Landfall:**	**Ocean:** TC center >700km away from coast
					Off-shore: TC center 400~700km away from coast
During Landfall	**Mixed:** TC raining area 40~60% over land	**Pre-land:** TC center 0~300/400km away from coast	**Stage II**: at the time of landfall	**During Landfall (Pre-land):** TC center 0~400km away from the coast	**Pre-land I:** TC raining area <50% over land
					Pre-land II: TC raining area ≥50% over land
After Landfall	**Land:** TC raining area >60% over land	**After-land:** TC center -200~0km away from coast	**Stage III**: 24 h after landfall	**After Landfall (After-land):** TC center is over land	**After-land I:** TC raining area <50% over land
					After-land II: TC raining area ≥50% & <100% over land
					After-land III: TC raining area 100% over land

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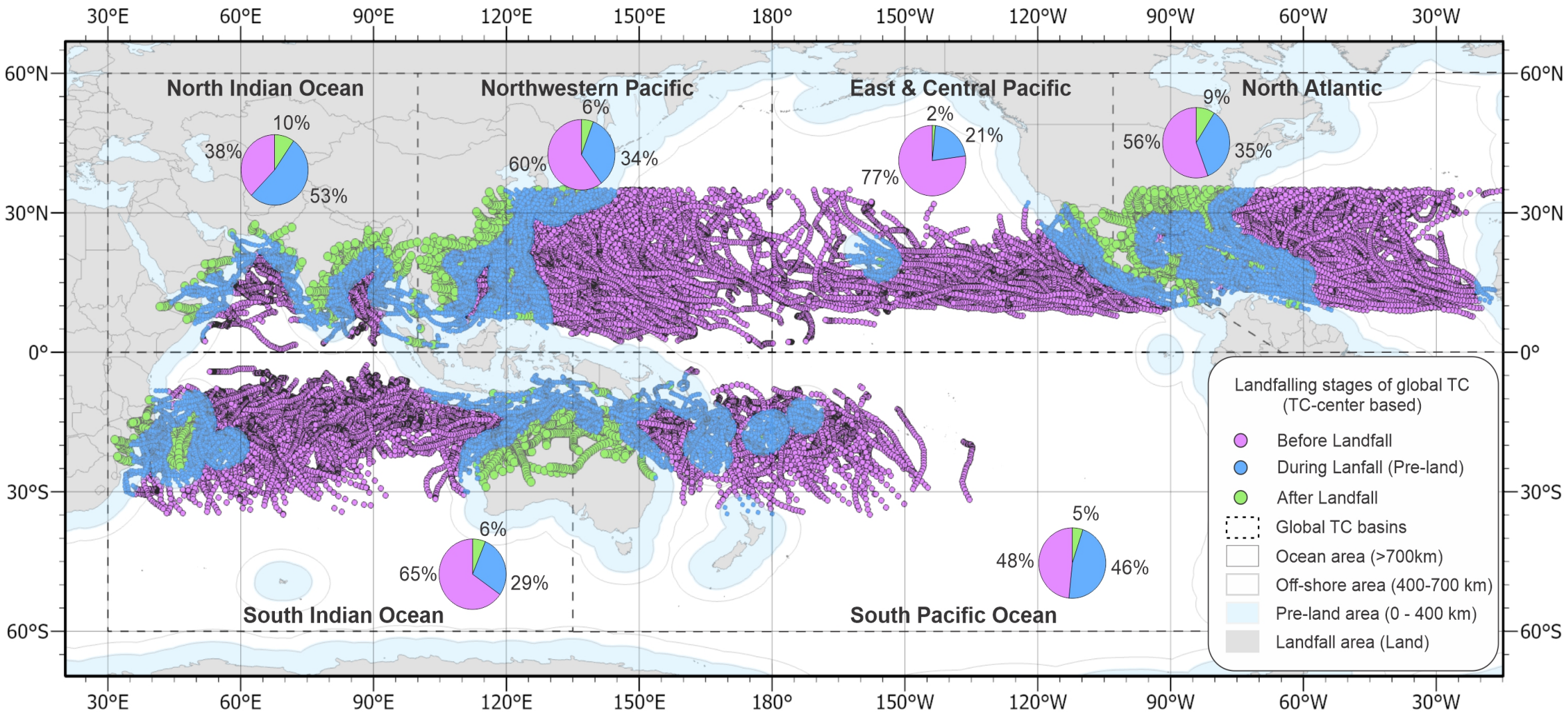
Methodology (Cont.) – Landfall Classification



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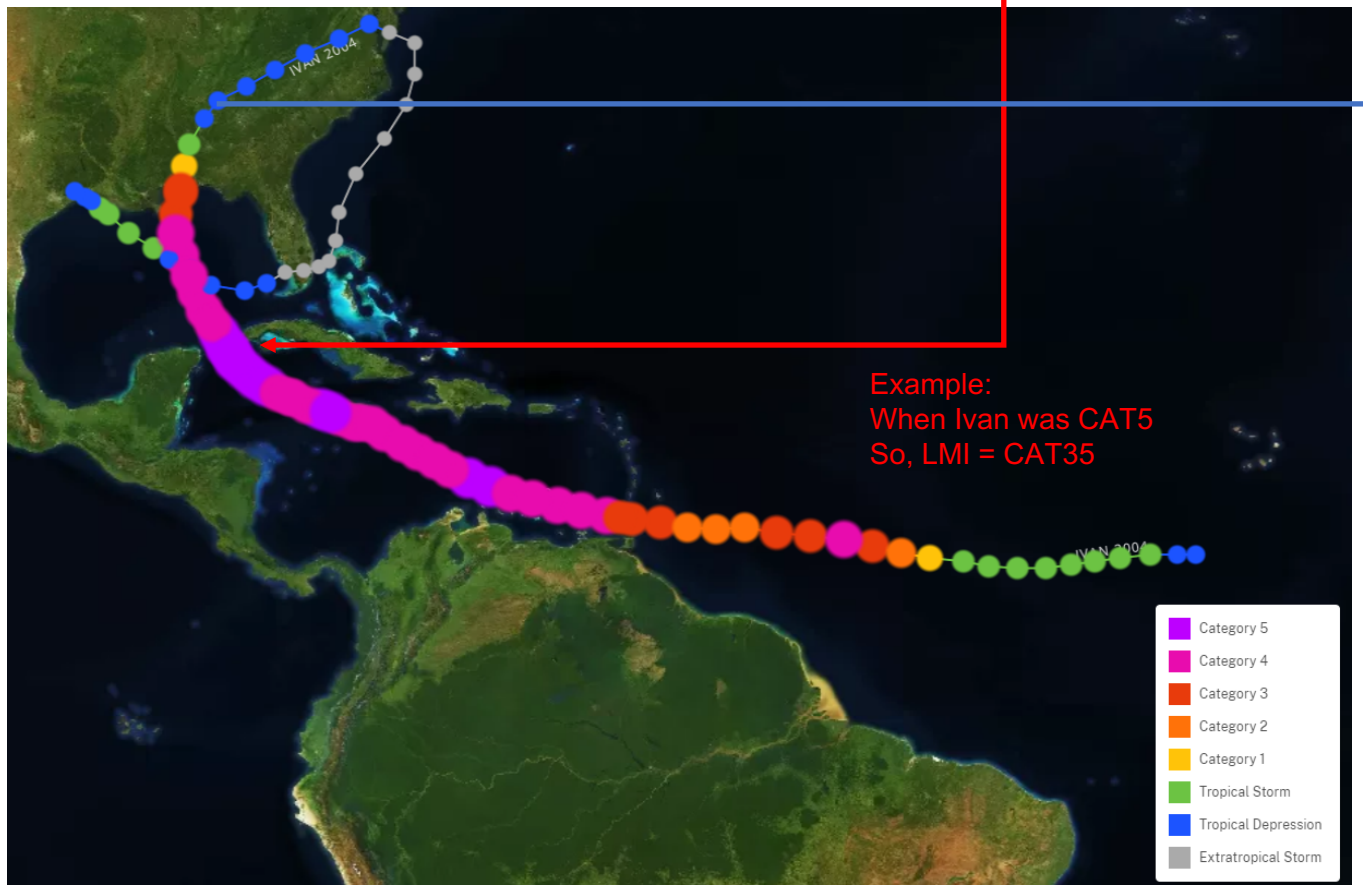
Point-LMI based classification (10 categories)

Point Intensity

Denotes the intensity category of the storm for a given point (each best-track position)

Lifetime Maximum Intensity (LMI)

Category at the maximum wind speed found along the whole lifetime of the track



By grouping the intensity scale in TD,TS, CAT12, and CAT35 ten current-LMI combinations available:

TD/TD, TD/TS, TD/CAT12, TD/CAT35, TS/TS, TS/CAT12, TS/CAT35, CAT12/CAT12, CAT12/CAT35, and CAT35/CAT35.

For instance**: TD/CAT35** indicates that the storm intensity at the current satellite observation position is a tropical depression (TD) and that storm at some moment during its lifetime reached major hurricane intensity (CAT35).

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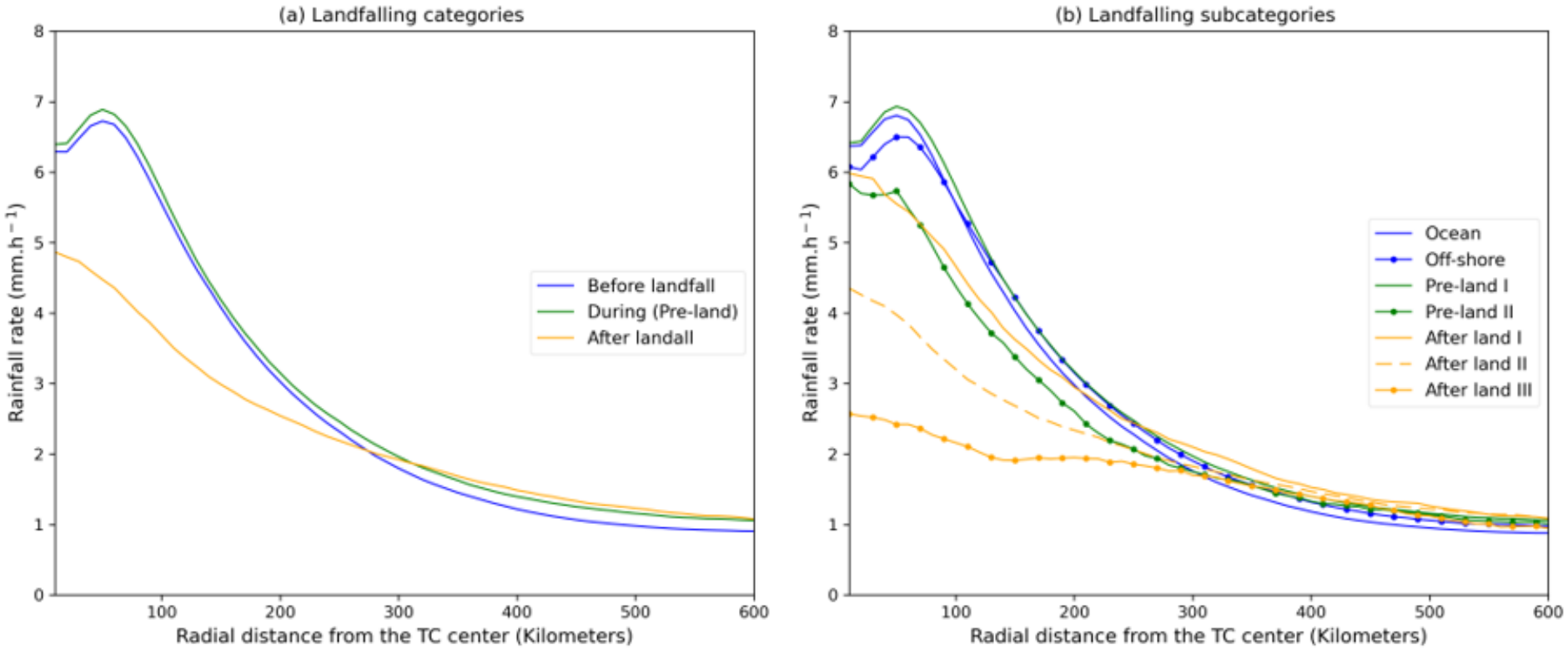
Results

Axisymmetric decomposition by landfall

Proposed for This Study

Before Landfall:	**Ocean:** TC center >700km away from coast
	Off-shore: TC center 400~700km away from coast
During Landfall (Pre-land): TC center 0~400km away from coast	**Pre-land I:** TC raining area <50% over land
	Pre-land II: TC raining area ≥50% over land
After Landfall (Aft-land): TC center is over land	**Aft-land I:** TC raining area <50% over land
	Aft-land II: TC raining area ≥50% & <100% over land
	Aft-land III: TC raining area 100% over land



Radial distribution on azimuthally averaged rainfall rate categorized by landfalling stages (a) Division as the distance from the land before, during, and after; (b) Subdivision of landfalling stages combining distance from the land and percentage of the raining area over land/ocean

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TC Precipitation life-cycle at different landfall stages

Proposed for This Study

Before Landfall:	**Ocean:** TC center >700km away from coast
	Off-shore: TC center 400~700km away from coast
During Landfall (Pre-land): TC center 0~400km away from coast	**Pre-land I:** TC raining area <50% over land
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After Landfall (Aft-land): TC center is over land	**Aft-land I:** TC raining area <50% over land
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	Aft-land III: TC raining area 100% over land

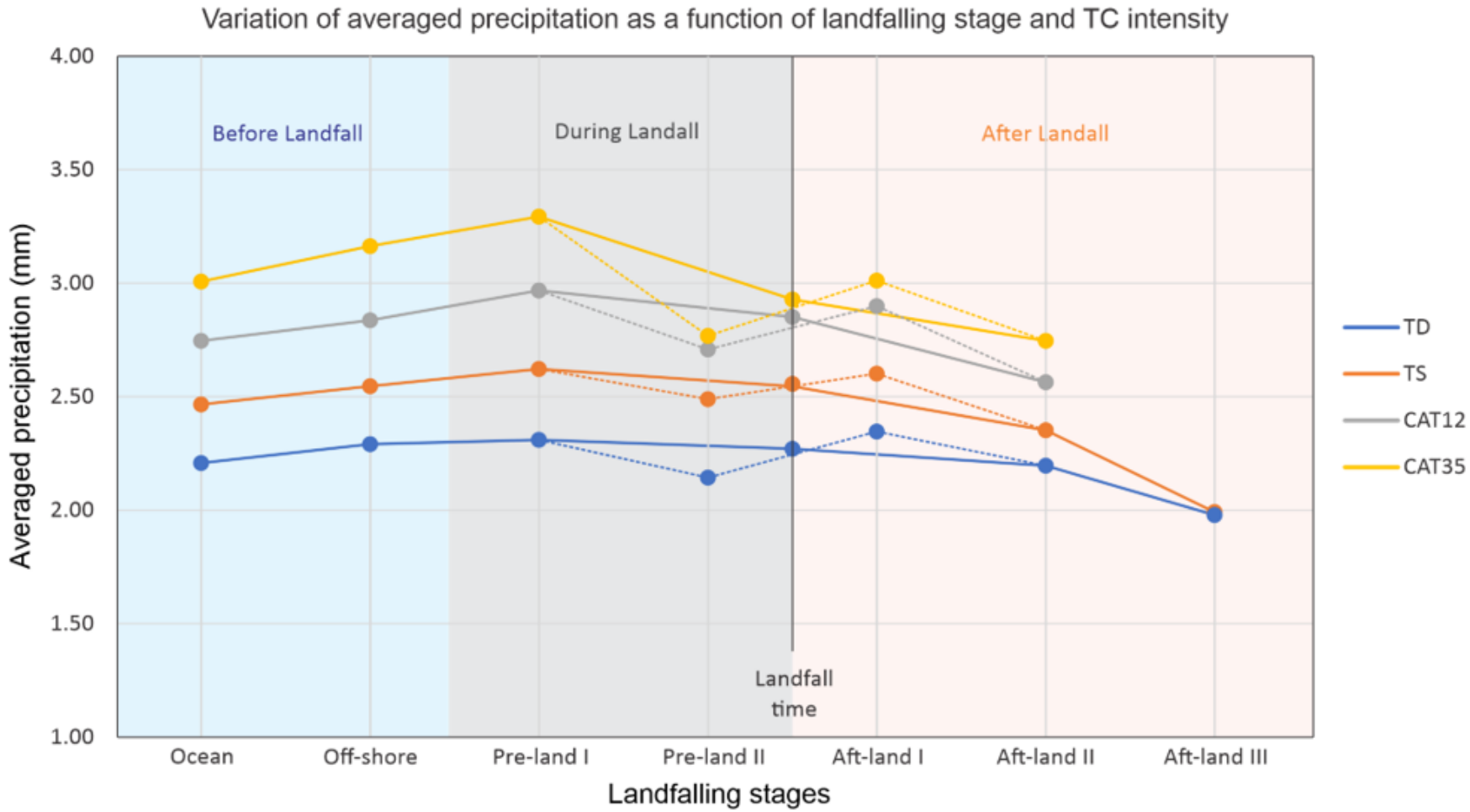
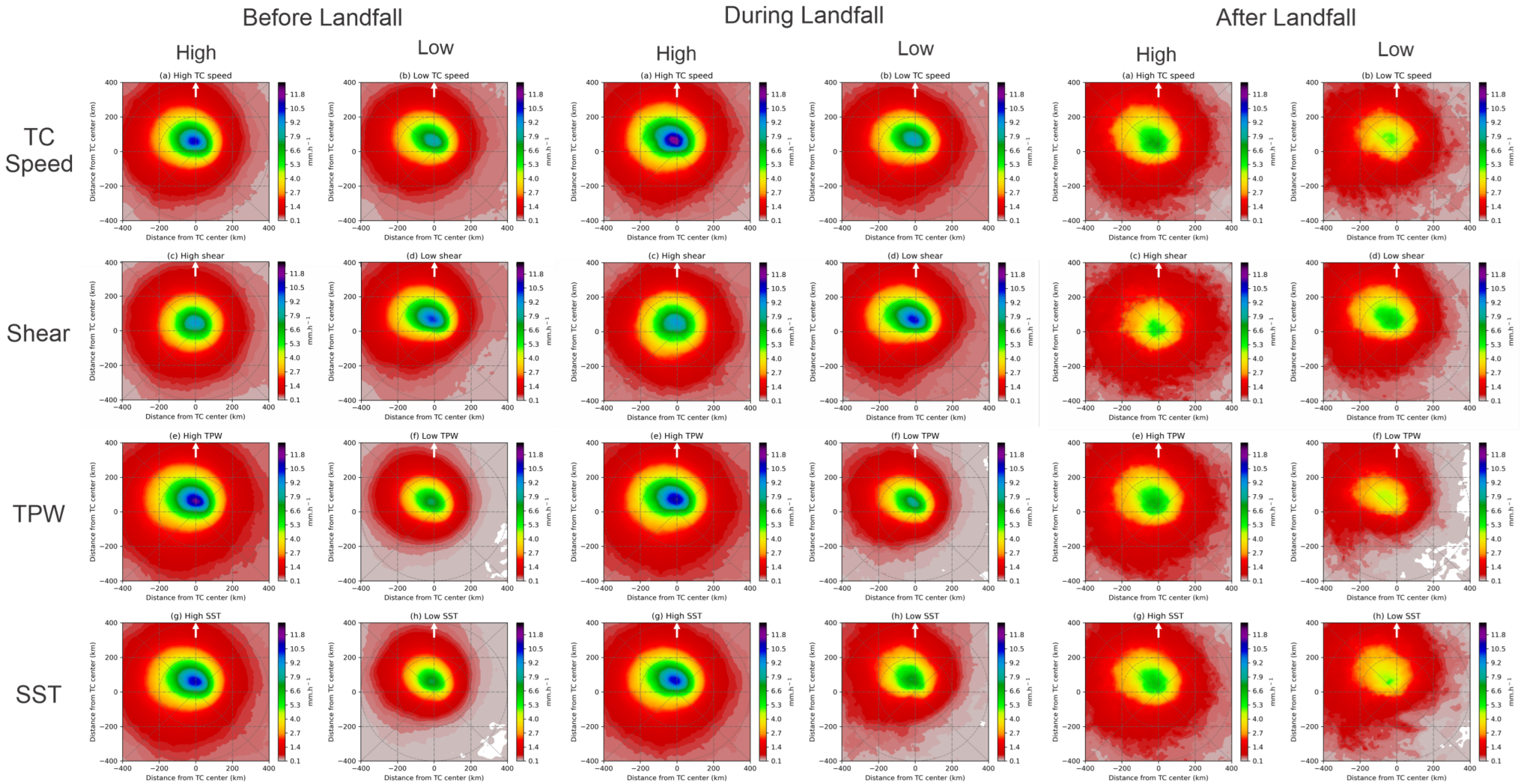


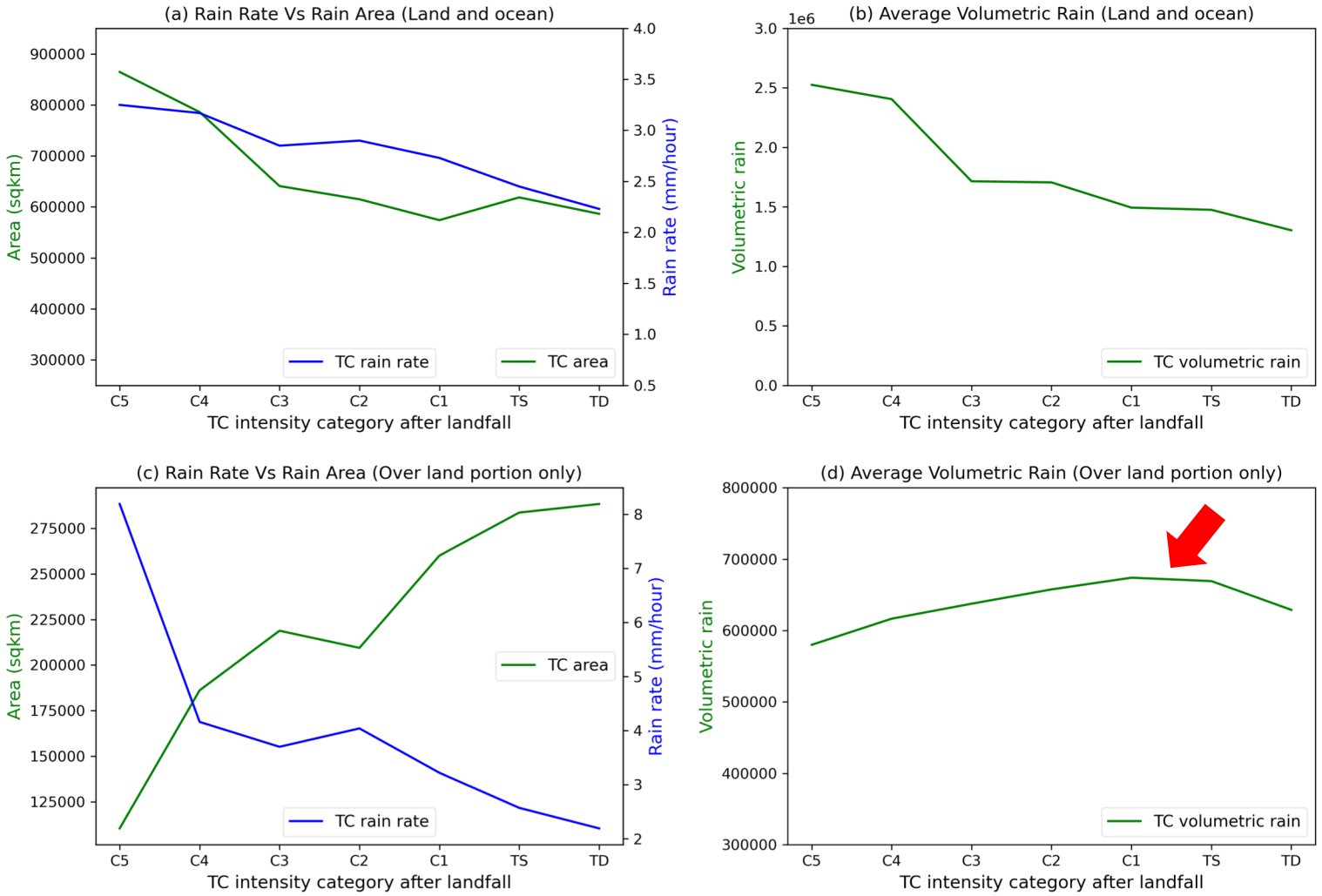
Fig. 2: Lifecycle of the tropical cyclone precipitation as a function of the landfall stage for different storm intensities. Continuous lines represent the approximated chronological order. Dotted lines in the landfall region show the averages for pre-land-II and After-land-I as influenced by the percentage of TCP area over land and the ocean in each category.

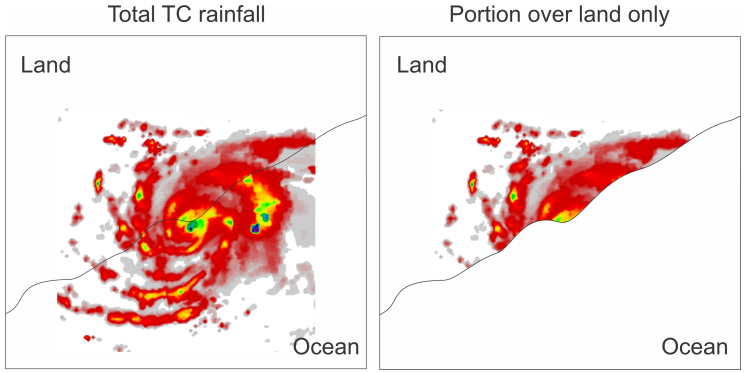
TC Precipitation life-cycle at different landfall stages (Cont.)



2D composites of shear-relative rainfall rate produced by TCs in the different landfalling stages for low/high storm motion speeds, low/high shear magnitudes, low/high TPWs, and low/high SSTs. In all the panels, the direction of environmental vertical wind shear points upward as indicated by the white arrow.

TC Precipitation life-cycle at different landfall stages (Global)





Differentiation between tropical cyclone precipitation for After-landfall stages: (a) calculation over the total storm area, and (b) calculation over the land portion only.

Global variations of tropical cyclone rain rates, area, and volumetric rain for after-landfall stages. Panels (a) and (b) represent the variation considering the **total TC extent** in the calculations. Panels (c) and (d) represent the calculations by only considering the TC extent over the **land portion**.

TC Volumetric rain: Current - Lifetime Maximum Intensity (global)

Point Intensity/ LMI	ATL	ECPA	NWP	NIO	SIO	SPA	Global
TD/TD	490,557(27)	512,688(15)	516,225(66)	240,490(2)	1,772,718(15)	233,166(21)	595,715(146)
TD/TS	495,133(326)	333,424(37)	686,394(268)	566,906(135)	704,588(217)	613,145(122)	599,036(1105)
TD/CAT12	572,565(80)	269,224(25)	674,075(122)	248,548(36)	489,416(126)	377,814(10)	524,224(399)
TD/CAT35	769,996(101)	788,967(25)	722,204(82)	522,543(21)	618,615(117)	1,030,729(41)	729,524(387)
TS/TS	463,775(154)	462,458(43)	741,719(181)	796,882(68)	549,765(105)	718,267(51)	621,434(602)
TS/CAT12	595,920(166)	410,451(24)	701,905(248)	669,440(52)	615,257(126)	362,568(16)	634,463(632)
TS/CAT35	881,308(132)	522,611(33)	777,410(250)	649,762(45)	583,934(148)	561,551(45)	718,013(653)
CAT12/CAT12	852,043(22)	439,814(14)	590,088(65)	779,141(9)	810,545(15)	417,838(4)	651,937(129)
CAT12/CAT35	631,791(76)	554,324(21)	746,759(156)	741,459(31)	754,742(104)	574,580(38)	702,966(426)
CAT35/CAT35	441,069(28)	617,749(4)	635,870(58)	759,856(10)	728,387(24)	841,561(6)	629,466(130)

Averaged tropical cyclone volumetric rain and number of samples (in parentheses) for each point-LMI category in global basins. Values are calculated over the portion of TC rain over land only.

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TC Volumetric rain: Current - Lifetime Maximum Intensity (CONUS)

Point Intensity/ LMI	Sample size	Average rain rate	Average TC area	Volumetric rain
TD/TD	12	1.73	94,023	166,750.21
TD/TS	253	2.08	250,737	518,344.65
TD/CAT12	29	2.29	286,066	646,980.80
TD/CAT35	67	2.52	409,298	1,003,133.65
TS/TS	90	2.14	215,916	473,651.21
TS/CAT12	68	2.63	273,460	689,985.93
TS/CAT35	83	2.98	409,534	1,170,270.45
CAT12/CAT12	11	2.90	298,109	621,895.43
CAT12/CAT35	37	3.54	245,279	832,431.71
CAT35/CAT35	5	3.12	300,240	919,258.69

Averaged tropical cyclone volumetric rain and samples size for each point-LMI category in the Atlantic basin. Values are calculated over the portion of TC rain over land and within the continental United States.

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Conclusions

Conclusions

- Using 20 years of TRMM/GPM satellite IMERG rainfall estimates in global TCs, A new approach that combines the TCP area and the distance from the coast is proposed to characterize the TC rain magnitude at different landfall stages.

- Our observational results show that across the Ocean, Off-shore, and Pre-land categories, TCP experience a homogeneous enhancement controlled by the portion of the TC that remains over the ocean. Once the TCP area have reached at least 50% over the land, the overall precipitations rates begin to decay and the precipitation areas over land begin to expand, following a nearly perfect inversely proportional relation. This pattern is constant for all the landfalling stages until the TC totally disappears.

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Conclusions

- Our findings demonstrate that when the combined contribution of the rainfall occurring over the land and the ocean (as a total), there is a regular decrease in rainfall rates and volumetric rain.

- However, once the rainfall occurring over the land is analyzed independently, the volumetric rainfall slightly increases as the storm's intensity decreases while making landfall, finding maxima for CAT1 and TS. (This is because the area increase)

- Further observational analysis using the concept of point-LMI categories demonstrates that TCs that at some point of their life cycle reached major hurricane strength and make landfall as TS or TD produced the highest volumetric rain over the land surface.

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Thanks!

Acknowledgments

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