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Key Points:

- Cloud fraction (CF) of tropical cyclone (TC) high deep clouds has recently declined in the inner core while the outer-region change is much smaller
- The decline was most significant during the intensification period
- The percentage change of TC inner-core CF of high thick cloud was similar to that of TC inner-core rain rate

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
T.-K. Lai,
eric.lai@imperial.ac.uk

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Has There Been a Recent Shallowing of Tropical Cyclones?

Tsz-Kin Lai[1] and **Ralf Toumi**[1]

[1]Space and Atmospheric Physics Group, Department of Physics, Imperial College London, London, UK

Abstract Many aspects of tropical cyclone (TC) properties at the surface have been changing but any systematic vertical changes are unknown. Here, we document a recent trend of high thick clouds of TCs. The global inner-core high thick cloud fraction measured by satellite has decreased from 2002 to 2021 by about 10% per decade. The TC inner-core surface rain rate is also found to have decreased during the same period by a similar percentage. This suppression of high thick clouds and rain has been largest during the intensification phase of the strongest TCs. Hence, these two independent and consistent observations suggest that the TC inner-core convection has weakened and that TCs have become shallower recently at least. For this period, the lifetime maximum intensity of major TCs has not changed and this suggests an increased efficiency of the spin-up of TCs.

Plain Language Summary As the atmosphere is becoming warmer under the climate change, many aspects of tropical cyclone (TC) have been changing or are expected to change, for example, TC intensity and TC height. The height of stronger TCs is expected to become taller. We present the first satellite observations of TC clouds near the TC top and demonstrate that the thick clouds of the inner part of TC, which is the part with the most intense winds and rain, has actually decreased during the period between 2002 and 2021. The decrease of high thick clouds within the inner part of TC is also consistent with the observed decreased rain there. However, the lifetime maximum intensity has not changed for this period. This all suggests that the strongest convection of a TC has weakened, and become shallower. TC may also have been spinning up more efficiently converting less energy to similar maximum intensities.

1. Introduction

Tropical cyclones (TCs) may have become increasingly destructive (Emanuel, 2005; Wang & Toumi, 2022). Theory and models suggest that there will be significant increase in TC intensity (e.g., Emanuel, 1987; Hill & Lackmann, 2011; Holland, 1997; Knutson et al., 2015, 2020) in a warming climate. Most studies point to a future decrease in frequency (e.g., Knutson et al., 2020). A poleward and coastal migration of TCs has also been reported (Kossin et al., 2014; Wang & Toumi, 2021a). The TC size is correlated to TC-induced economic damages such as insured losses (Wang & Toumi, 2016; Zhai & Jiang, 2014) and its climatology has been explored (e.g., Kimball & Mulekar, 2004; Schenkel et al., 2018; Wang & Toumi, 2018) while no significant trends of TC size have been identified for the period from 1981 to 2011 (Knaff et al., 2014). Indirect methods using the sea surface temperature cold wakes (Chavas et al., 2016) also suggest no long-term change in size (Wang & Toumi, 2021b).

All of the above studies focused on the surface properties. There is a lack of evidence of any changes in the vertical characteristics. The height/depth of a TC is also an essential property (Hendricks et al., 2004; Simpson et al., 1998). Z. Wang et al. (2009) showed that pre-genesis deep convection or disturbance is conducive to genesis. The probabilities of intensification and rapid intensification increase when very tall convective towers exist in the eyewall (Jiang, 2012; Kelley et al., 2004). Schubert and McNoldy (2010) showed that stronger TC vortices have deeper secondary circulation, implying a taller convection within the eyewall. Yamada et al. (2010) demonstrated that the cloud height of simulated strong TCs will become taller under the global warming. This increase in height was associated with the warm-core structural change simulated by Knutson and Tuleya (1999). To date there have been no documented observed trends of TC cloud top height (CTH) and cloud optical depth (COD). The cloud fraction (CF) of TC deep convective cloud is of interest as a proxy for CTH and COD. It is well understood that deeper convection can yield heavier rain (e.g., Adler & Mack, 1984; Song et al., 2020). In particular the cloud depth is often inferred from infrared cloud top brightness temperatures (e.g., So & Shin, 2018); and the cloud depth is often used to estimate convective rain rate (e.g., Tapiador et al., 2019). Here we use satellite observations to show a declining trend of TC CF.

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Deep convective systems and cloud cover are linked to the associated rain rate (e.g., Adler & Mack, 1984) and we will demonstrate a correlation for TCs. TC rainfall is broadly a function of TC intensity (Lonfat et al., 2004) and available moisture. The predicted increase in TC intensity combined with ocean warming projects to a robust future increase in TC rainfall (e.g., Hill & Lackmann, 2011; Knutson et al., 2015, 2020). However, despite this expectation, there have been surprising decreases of TC inner-core rainfall rate since late 1990s (Guzman & Jiang, 2021; Lavender & McBride, 2021; Tu et al., 2021). There is some uncertainty in these trends since the Tropical Rainfall Measuring Mission (TRMM) has limitations compared to better-characterized data (Huffman, 2021). Since these studies imply a shallowing/weakening of TC inner-core deep convection, we aim to answer the question "Can we use cloud observations to test for decreases in deep convection consistent with the reported decline in inner-core rainfall rate?"

2. Methods

The global best track data of TCs are obtained for US agencies in the International Best Track Archive for Climate Stewardship (IBTrACS v.4) (Knapp et al., 2010, 2018). All the non-TC systems (e.g., extra-tropical systems, tropical waves, and tropical disturbances) are excluded. 2088 TCs with wind speeds larger than 34 knots (tropical storm or stronger) between 1998 and 2021 comprise the data set. The Supporting Information S1 provides detailed information about the case selection.

The daily CTH and COD of TCs from 2002 (4 July) to 2021 are provided by Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua Level-3 Daily Cloud Properties Product (CLDPROP) version 1.1 (Platnick et al., 2019). MODIS/Aqua, which has 36 channels ranging from 0.415 to 14.235 μm (King et al., 2003), is in sun-synchronous orbit with an equator crossing time of around 13:30 in the ascending mode. The horizontal data grid size is $1° \times 1°$, in which the image pixel count is sampled at a 5-km interval from the 1-km observation (Marchand et al., 2010). Deep convection is associated with intermediate ($3.6 \leq$ OD < 23.0) and high optical thickness (OD ≥ 23.0; Marchand, 2013). The grid box covering the TC center is regarded as the inner-core grid box which will cover ≥25% of a typical inner core. There will be a bias in occasionally loosing some inner-core information to adjacent grids in individual cases, but this is unlikely to affect the long-term trends of large samples that we are interested in here. Outer-region grid boxes are within 500 km of the TC center (excluding the inner-core grid box). Only TC cases having at least one CLDPROP record with ≥25% of spatial coverage during the averaging period are considered when calculating the corresponding average (lifetime, pre-lifetime maximum intensity [LMI], or post-LMI). Results are similar if we use a higher threshold value (e.g., 50%).

Three hourly TC precipitation data are extracted from the TRMM Project Multi-satellite Precipitation Analysis (TMPA) Rainfall Estimate L3 version 7 (3B42) (Huffman et al., 2007; Tropical Rainfall Measuring Mission (TRMM), 2011) with a spatial resolution of $0.25° \times 0.25°$. Rainfall is estimated by using microwave-only, infrared-only, and mixed microwave and infrared measurements within 500 km of the TC center at every 3-hr best-track position between 1998 and 2019 projected onto a polar coordinate centered at the TC center. We only use rain rates ≥ 0.1 mm hr^{-1} (Guzman & Jiang, 2021). The inner core for rain is defined as the region within 2× the maximum azimuthal rain rate (Guzman & Jiang, 2021). TRMM records only within 1 hr of CLDPROP are considered for calculating the ranked correlation between the TC inner-core CF of high thick clouds and TC inner-core rain rate.

We will also examine the relationship between LMI and pre-LMI rainfall. To explore the relationship, we define C as the kinetic energy of *a unit mass of air* at LMI divided by the total column latent heat released in a unit area,

$$C = \frac{mV_{max}^2}{2\int_0^t \rho_{\ell w} RL\,dt}, \quad (1)$$

where m is the mass of air, V_{max} is the maximum surface wind speed at LMI, L is the latent heat of vaporization, $\rho_{\ell w}$ is the liquid water density, R is the inner-core rain rate, and t is time to LMI from tropical storm intensity. The integrated heating between the condensation level and the cloud top is proportional to the surface rainfall and the effects of freezing and water vapor deposition are ignored (Yanai et al., 1973). C will contain some information about the efficiency of the conversion of the latent heat generated during the TC spin-up to the final kinetic energy.

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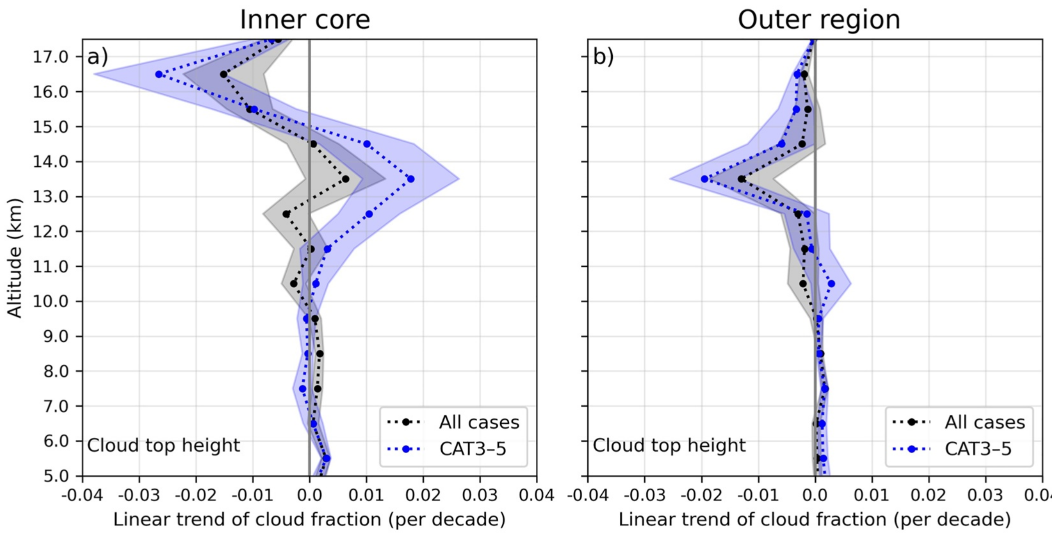

Figure 1. The linear trends (per decade) of the global annual-mean cloud fraction of tropical cyclone (TC) clouds with different cloud top height within (left) the inner cores and (right) the outer regions of TCs from July 4, 2002 to December 31, 2021. The black curves are for all available TC cases while the blue curves are for CAT 3–5 TCs. The shaded areas highlight the standard errors of the linear trends.

3. Results

Figure 1 shows the linear trends of lifetime-mean CF as a function of CTH. Globally, the amount of inner-core clouds reaching $15 \leq z \leq 17$ km has largely decreased, while the amount of those reaching lower altitudes ($12 \leq z < 15$ km) is largely increasing (Figure 1a). A similar pattern also takes place in the outer region at lower altitudes (Figure 1b). During this 20-year period, both the inner-core and outer-region CF of CTH peaks at $13 \leq z \leq 14$ km (~0.2; Figures S1a and S1b in Supporting Information S1). But the cumulative CF for CTH ≥ 13 km is much larger within the inner core (~0.6) than that in the outer region (~0.3), especially for major TCs (CAT 3–5). For inner-core COD, CF peaks at very thick clouds (COD ≥ 100) whilst the thick clouds (COD ≥ 23) have the highest cumulative CF (~0.6; Figure S1c in Supporting Information S1). Major TCs have clearly more thick clouds and less thin or intermediate clouds. For the outer region, CF peaks at thin clouds (COD < 3.6) and the cumulative CF of thick cloud is significantly smaller than that in the inner core.

The trend of inner-core COD largely declines among the very thick clouds while it increases among the thin and intermediate clouds (Figure S2a in Supporting Information S1). The pattern of outer-region COD is similar except that the CF of very thick cloud has much smaller rate of change (Figure S2b in Supporting Information S1). One can also see that the decline of TC CF of high deep clouds was larger among the major TCs. The observed changes in CF of inner-core clouds reaching $15 \leq z \leq 17$ km are −0.026 ± 0.010 (−11%) and −0.036 ± 0.016 (−12%; Figure 2a) per decade globally for all TC cases and major TCs, respectively. For the inner-core COD, the observed changes for very thick clouds are −0.020 ± 0.011 (−9%; all TCs) and −0.014 ± 0.014 (−5%; major TCs; Figure 2d).

To investigate whether the CF decline occurs during the intensification (i.e., pre-LMI) or decay (i.e., post-LMI) stages, we then further decompose the data into the pre-LMI and post-LMI periods when maximum wind speed exceeds 34 knots. For 15 ≤ CTH ≤ 17 km, there is only a global CF decline in the pre-LMI period (Figures 2b and 2c). Similarly, for COD ≥ 100, there is a significantly declining global pre-LMI trend of CF and no post-LMI global trend (Figures 2e and 2f). There is some variability between basins as expected (see the Supporting Information S1). But generally, lifetime decline in CTH and COD can be seen in many of the basins with pre-LMI decline much larger than their post-LMI trends.

To summarize, the CF of inner-core deep convective clouds of TCs has declined from 2002 to 2021 in the basins covering most TC activity. This suggests that the inner-core deep convection of TCs became shallower (and thus weaker) especially during the pre-LMI intensification stage.

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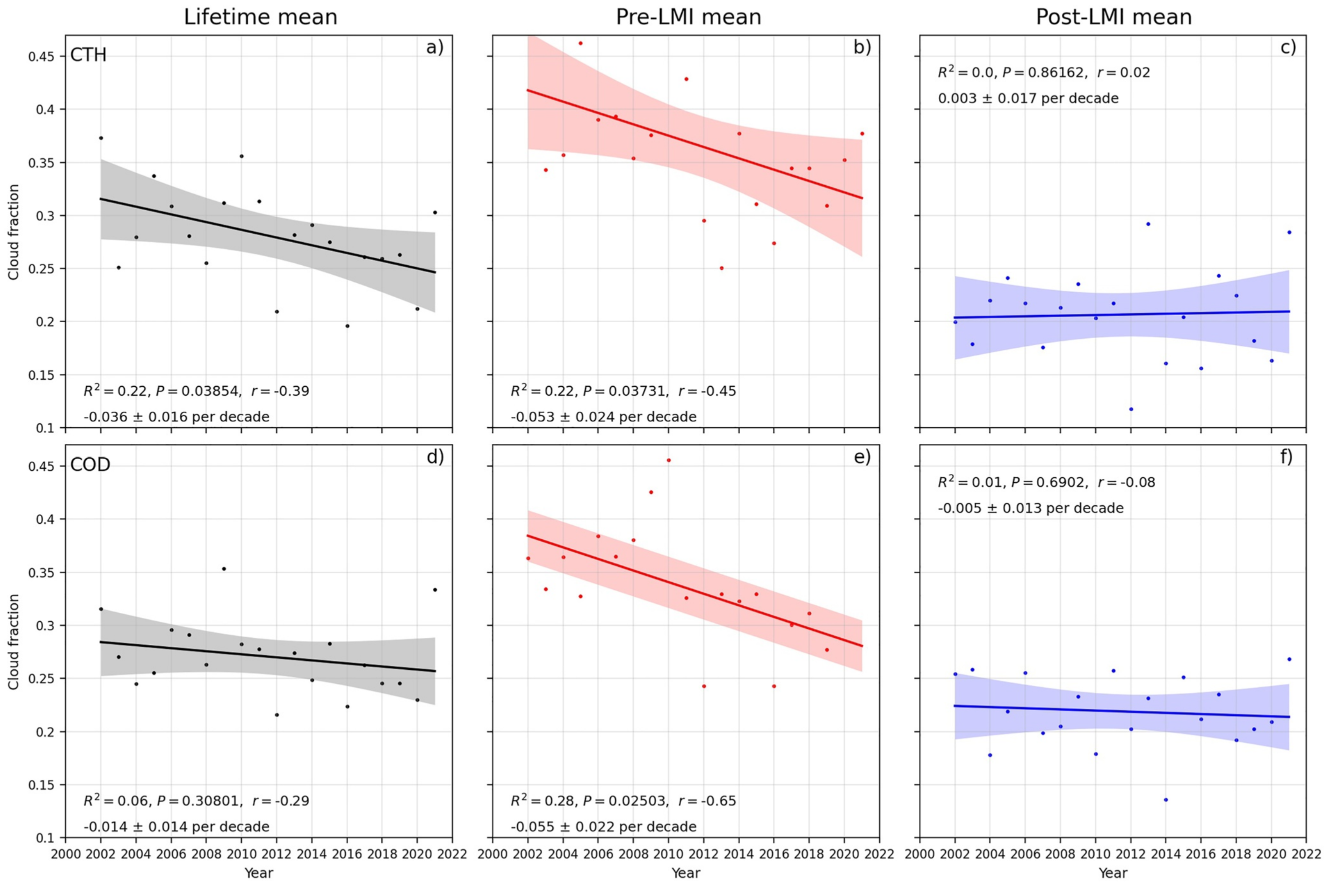

Figure 2. The time series of the global annual-mean cloud fraction of (top) tropical cyclone (TC) inner-core clouds reaching $15 \leq z \leq 17$ km or (bottom) TC inner-core clouds with high optical depth (COD ≥100) averaged over (left) the whole lifetime, (middle) the pre-lifetime maximum intensity (LMI) period, and (right) the post-LMI period from July 4, 2002 to December 31, 2021 for CAT 3–5 TCs. The shaded areas indicate the two-sided 95% confidence intervals of the linear trends with the Spearman correlation coefficient r and p value P.

One would expect an association between the inner-core rain rate and high thick CF but this has not yet been documented for TCs. Globally the ranked correlation is positive and very large ($r \geq 0.96$; Figures 3a and 3d). One can see that the post-LMI period has larger slopes of the linear fit (Figures 3b, 3c, 3e, and 3f). We note that the correlation coefficient is lower during the post-LMI period, especially for CTH (Figures 3c and 3f).

The combination of a strong positive correlation between the inner-core rain rate and the inner-core CF of clouds with high CTH or COD, and the decline of inner-core CF of high thick cloud naturally lead us to re-examine the reported decrease of inner-core rain rate. The inner-core rain rate has indeed declined substantially globally (Figure 4 and Figure S5 in Supporting Information S1) by 0.92 ± 0.12 mm hr^{-1} per decade (major TCs) or 0.52 ± 0.08 mm hr^{-1} per decade (all TCs). The outer-region rain rate increased globally only a little (not shown). The decrease in inner-core rain rate, like the CF, was larger among major TCs (comparing Figure 4 to Figure S5 in Supporting Information S1). Similar to the CF data, the rain rate is further decomposed into pre-LMI and post-LMI periods. The decrease in inner-core rain rate during the pre-LMI period is larger by 28% than the post-LMI value (e.g., Figures 4b and 4c). This is a new insight into the rain trends. This pattern of a larger rain rate decline during the pre-LMI period is similar to the pre-LMI decline of inner-core CF of cloud reaching $15 \leq z \leq 17$ km (e.g., Figures 2b and 2c).

Both inner-core rain rate and inner-core CF of high or thick cloud have declined in the past few decades (especially for major TCs). Table 1 shows the corresponding percentage changes over the whole globe and the basins. We can see that the percentage changes of lifetime-mean inner-core CF of cloud reaching $15 \leq z \leq 17$ km and inner-core rain rate are similar. This shows remarkable consistency between these independent data. The change in LMI is not significant during this time period in any basin, consistent with the relatively stable tropical SST in

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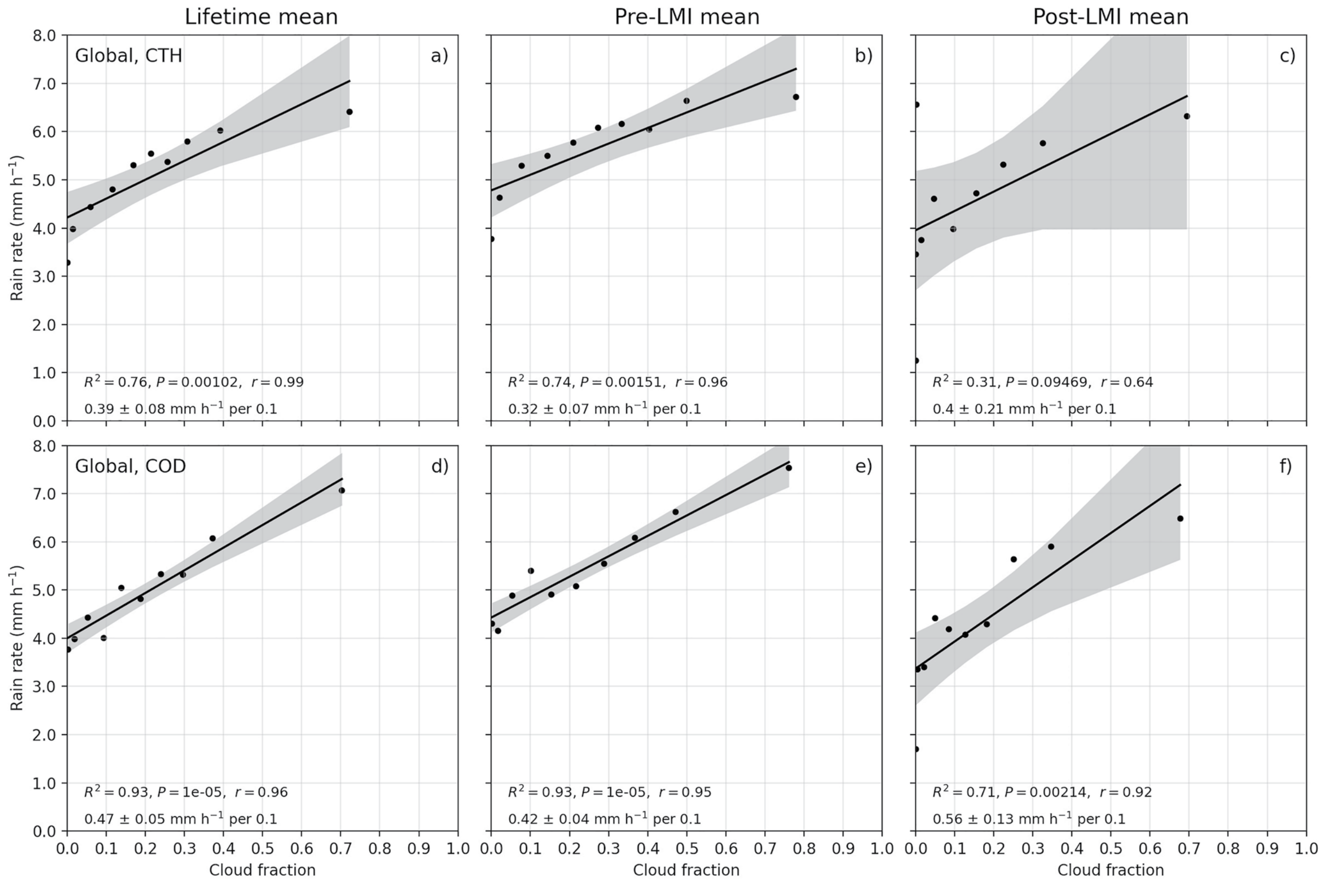

Figure 3. The correlation between the global mean tropical cyclone (TC) inner-core rain rate and cloud fraction (CF) of (top) inner-core clouds with $15 \leq \text{CTH} \leq 17$ km or (bottom) inner-core clouds with $\text{COD} \geq 100$, over (left) the whole lifetime, (middle) pre-lifetime maximum intensity (LMI), and (right) post-LMI period from July 4, 2002 to December 31, 2021. The shaded area is the two-sided 95% confidence interval of the best-fit lines with Spearman coefficient of correlation *r* and *p* value *P*. The data is binned into the mean of 10 deciles (i.e., every 10%) of the CF.

the same period (Hall et al., 2021). This lack of clear intensity changes with a declining rain rate suggests that there may have been an increase in the efficiency of the TC spin-up. There has been less column latent heat (i.e., rain) generated within the inner core during intensification but a similar ultimate LMI has been achieved. To diagnose this, we calculate a conversion ratio, C (Equation 1), as the ratio of the LMI kinetic energy to the total

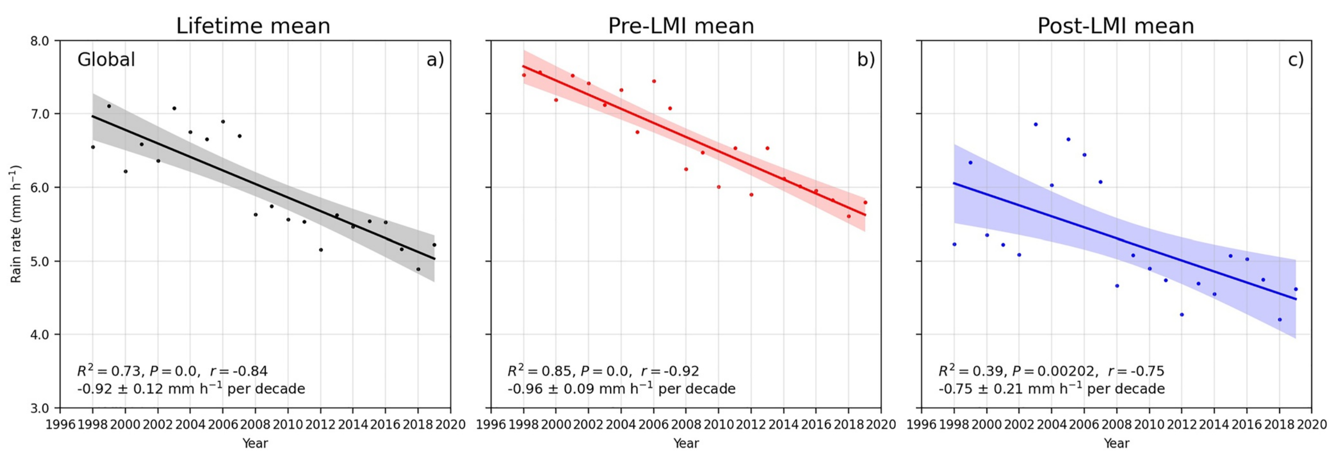

Figure 4. Same as Figure 2 but for the annual-mean tropical cyclone (TC) inner-core rain rate between January 1, 1998 and December 31, 2019 for CAT 3–5 TCs.

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Table 1
Linear Trend (% per Decade) of Lifetime-Mean Inner-Core Cloud Fraction (CF) of 15 ≤ CTH ≤ 17 km, Lifetime-Mean Inner-Core Rain Rate, LMI and the Conversion Ratio C (Equation 1) for CAT 3–5 TCs Over Different Regions During 2000–2019 (2002–2021 for CF)

Region	CF (CTH)	Rain rate	LMI	*C*
Global	−11.5 ± 5.2	−13.6 ± 1.8	+1.4 ± 1.1*	+20.7 ± 4.0
Western North Pacific	−10.5 ± 8.4*	−10.7 ± 2.1	+2.9 ± 1.9*	+18.4 ± 4.2
Eastern North Pacific	−22.1 ± 9.7	−20.7 ± 6.2	−10.3 ± 6.9*	+43.3 ± 11.2
North Atlantic	−17.7 ± 14.0*	−20.5 ± 6.2	−12.3 ± 7.1*	−1.3 ± 9.9*

Note. The asterisks denote insignificance ($P > 0.05$).

column latent heat for every major TC. This non-dimensional ratio has increased by about 21% per decade globally and in several basins (Table 1 and Figure S6 in Supporting Information S1).

4. Discussion and Conclusion

By examining MODIS/Aqua CLDPROP data, we find a decline of TC CF of inner-core clouds with high CTH or COD. Both the CF of inner-core clouds with high CTH ($15 \leq z \leq 17$ km) and that of inner-core very thick clouds with COD ≥ 100 have significantly declined globally by about 10% per decade. The corresponding changes in outer-region CF are much smaller. The height interval $15 \leq z \leq 17$ km covers the usual CTHs of the TC eyewall (e.g., Duran & Molinari, 2018; Emanuel, 2018; Houze et al., 2009). We also show that thick clouds (COD ≥ 23.0) clearly dominate the inner core while the CF of the very thick clouds is the largest and much larger than that of optically thinner clouds. Therefore, these declining trends indicate that the inner-core convection of TCs has become shallower. Our TC trend is different from other reported cloud height trends (i.e., for all weather systems). Davies et al. (2017) showed that the global cloud height in MISR did not have a significant trend during 2000–2015. For the tropics, Richardson et al. (2022) found that the height of the tropical upper-tropospheric clouds (regardless of thickness) as measured by MODIS was increasing from 2002 to 2021. Hence, the declining trend of TC inner-core CTH implied in this study is quite anomalous and remarkable. It is worthwhile to note that the pattern shift (less higher/thicker clouds with more lower/thinner clouds) shown in Figure 1 and Figure S2 in Supporting Information S1 supports the case for a shallowing of TC inner core, but not the scenario of an expansion of the TC eye (or cloud-free area) in which case we would expect a CF decline across all CTH/COD or a decline in CF of high CTH/COD without an increase in CF of low CTH/COD.

We show very strong ranked correlations between TC inner-core rain rate and CF of cloud with high CTH or COD. This is a novel but expected result based on our understanding of rain and deep convection. Based on the correlation, we also re-examined the trend of TC rain rate in the same period. We confirm and extend past studies of a declining inner-core rain rate by considering a longer-time period, showing that the decrease is much more prominent during the intensification stage and noting that this decline has occurred while the LMI has been stable suggesting increased spin-up efficiency. Since the maximum potential intensity (MPI) of a TC is sensitive to the warm core height (Holland, 1997) and the actual intensity is correlated with the MPI (Wing et al., 2007), the stable LMI indicates a stable warm core height which seems contradictory to TC shallowing. However, the average height of warm core is $p \approx 250$ hPa (Holland, 1997; Ito & Yamamoto, 2022) or $z \approx 10$ km (Munsell et al., 2018; Stern & Zhang, 2016) which is substantially lower than the range ($15 \leq z \leq 17$ km) of the decrease in inner-core CF. Hence, it is possible that the warm core height, the MPI and LMI were stable during this period.

We study the inner-core and outer-region trends of TC rain rate from 1998 to 2019 which is a bit longer than done previously by Lavender and McBride (2021) (1998–2014), Tu et al. (2021) (1999–2018), and Guzman and Jiang (2021) (1998–2016). We confirm that the lifetime mean TC inner-core rain rate has declined. Both the observed weaker inner-core CF of high deep cloud and rain rate individually suggest weaker inner-core convection. It is remarkable that the percentage changes of TC inner-core rain rate and TC inner-core CF of cloud reaching $15 \leq z \leq 17$ km were similar. These two trends observed independently using different instruments, satellite platforms and variables but of the same convective process appear quantitatively consistent. The consistency between them reinforces the credibility of the individual satellite trends.

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Finally, we find similar granularity in the trends of CF and rain rate in terms of the TC life cycle. The intensification period shows the clearest trends. All of the pre-LMI declining trends of inner-core rain rate, CF of clouds with high CTH and CF of clouds with high COD were larger than the corresponding post-LMI trends. This shows further consistency between the observations indicating that the pre-LMI weakening of inner-core deep convection was more prominent. The absolute depth of convection is not straightforwardly or universally defined. The storm height can also be defined by a reflectivity threshold which captures denser clouds and the CTH as measured by brightness temperature will typically be larger. However, both are expected to increase with more intense rain (Song et al., 2020).

There is a suggestion that during the period examined, there has been an increase in the efficiency of the TC spin-up. We find that considerably less column latent heat by inner-core rain is generated during the spin-up to achieve similar intensities for major TCs. In a future study, a deeper understanding could be achieved by examining changes in the vertical profile of the inner-core heating rate which is important for the TC dynamics.

We also reveal that the average TC lifetime-mean intensity was declining during this period, with a more significant trend for the major TCs (Figure S8 in Supporting Information S1). This would be consistent with the shallowing TC inner-core convection and weakening inner-core rain rate. Additionally, the relatively stable LMI of TCs and the lower lifetime-mean intensity together imply a higher efficiency and a faster TC spin-up as reported by S. Wang et al. (2020).

What are the implications of these findings under future global warming? CTH can be partly understood through convective proxies such as convective available potential energy (CAPE) (e.g., Sherwood et al., 2004). There is an expectation of increases of convective proxies such as CAPE generally (Lepore et al., 2021) and by extension more high thick clouds. TC intensity and rain rate are also projected to increase (Knutson et al., 2020). However, this study shows that the TC inner-core CF of clouds with high CTH or COD and inner-core rain rate have both been decreasing for an extended period of time. This confirms that the vertical cloud structure and rain do change in tandem over decades. It does not negate the expectation of increased rain and larger CTHs in a future warmer world but shows that even a 20-year-long trend can oppose a longer-term projected change. Additionally, the declines of inner-core high thick cloud and rain rate have occurred while the intensity was stable suggesting an increased efficiency of TC spin-up.

Data Availability Statement

Best track data of TCs are provided by IBTrACS version 4 (the subset "since1980"), which is freely available at https://doi.org/10.25921/82ty-9e16. The data of cloud top height and cloud optical depth are obtained from MODIS/Aqua Level-3 Continuity Daily Cloud Properties Product version 1.1 (https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/5111/CLDPROP_D3_MODIS_Aqua/; registration required for access). TC rainfall data are extracted from TRMM 3B42 version 7 (https://disc2.gesdisc.eosdis.nasa.gov/data/TRMM_L3/TRMM_3B42.7; registration required for access).

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