Near-storm Environmental Relationships with Tropical Oceanic Convective Structure Observed during NASA CPEX and CPEX-AW

Benjamin Rodenkirch¹ and Angela Rowe¹

¹University of Wisconsin-Madison

July 20, 2023

Abstract

Deep tropical oceanic convection (TOC) is a prevailing component of the tropical atmosphere and plays a significant role in modulating global weather and climate. Despite its importance, prediction challenges remain, partly attributed to a lack of understanding of how TOC relates to its near-storm environments. Prior studies suggest location-dependent relationships between TOC structure and associated environments, necessitating targeted regional studies. The NASA 2017 Convective Processes Experiment (CPEX) and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns collected high-resolution measurements of convective storms and their environments in the Gulf of Mexico, Caribbean, and western Atlantic basins, providing a rare opportunity to investigate near-storm environmental relationships with 3-D TOC structure where in situ non-tropical cyclone-related deep TOC research is comparatively lacking. Collocated CPEX and CPEX-AW airborne observations from the multi-wavelength Airborne Precipitation Radar, Doppler Aerosol Wind Lidar, and dropsondes revealed large near-storm environmental variability across TOC of similar convective type (i.e., isolated, organized) and within individual convective systems. However, trends still emerged amongst the large environmental variability. Two-dimensional (2-D) TOC structure was most consistently linked to planetary boundary layer (PBL) near-storm environments, with organized TOC being associated with generally greater PBL RH and vertical speed shear than isolated TOC. TOC intensity was linked to upper tropospheric (i.e., above the freezing level) near-storm environments, with isolated TOC intensity most consistently associated with upper tropospheric CAPE and organized TOC intensity associated with upper tropospheric RH. Synoptic-scale low-level convergence was also linked to greater organized TOC intensity, motivating further research using these unique datasets.
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Benjamin D. Rodenkirch¹ and Angela K. Rowe¹

¹Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, WI

Corresponding author: Benjamin Rodenkirch (brodenkirch@wisc.edu)

Key Points:

- Planetary boundary layer moisture and wind shear were generally greater for multi-core versus single-core tropical oceanic convection.
- Single-core and multi-core convective intensity were most linked to greater upper-level CAPE and moisture, respectively.
- Synoptic-scale low-level convergence likely fosters convective intensification in otherwise less favorable environmental conditions.
Abstract

Deep tropical oceanic convection (TOC) is a prevailing component of the tropical atmosphere and plays a significant role in modulating global weather and climate. Despite its importance, prediction challenges remain, partly attributed to a lack of understanding of how TOC relates to its near-storm environments. Prior studies suggest location-dependent relationships between TOC structure and associated environments, necessitating targeted regional studies. The NASA 2017 Convective Processes Experiment (CPEX) and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns collected high-resolution measurements of convective storms and their environments in the Gulf of Mexico, Caribbean, and western Atlantic basins, providing a rare opportunity to investigate near-storm environmental relationships with 3-D TOC structure where in situ non-tropical cyclone-related deep TOC research is comparatively lacking. Collocated CPEX and CPEX-AW airborne observations from the multi-wavelength Airborne Precipitation Radar, Doppler Aerosol Wind Lidar, and dropsondes revealed large near-storm environmental variability across TOC of similar convective type (i.e., isolated, organized) and within individual convective systems. However, trends still emerged amongst the large environmental variability. Two-dimensional (2-D) TOC structure was most consistently linked to planetary boundary layer (PBL) near-storm environments, with organized TOC being associated with generally greater PBL RH and vertical speed shear than isolated TOC. TOC intensity was linked to upper tropospheric (i.e., above the freezing level) near-storm environments, with isolated TOC intensity most consistently associated with upper tropospheric CAPE and organized TOC intensity associated with upper tropospheric RH. Synoptic-scale low-level convergence was also linked to greater organized TOC intensity, motivating further research using these unique datasets.
Plain Language Summary

Thunderstorms are a common occurrence in the tropics and influence Earth’s weather and climate. Predicting tropical thunderstorms remains challenging for weather and climate models, partly due to a lack of understanding of how atmospheric moisture and winds relate to tropical thunderstorm structure and strength. Prior studies suggest these environmental relationships are dependent on location in the tropics, thereby necessitating focused regional studies. This study helps address a notable regional research gap in the Gulf of Mexico, Caribbean, and western Atlantic basins, using rare, high-resolution radar and lidar measurements of tropical thunderstorms and their environments from the NASA 2017 Convective Processes Experiment (CPEX) and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns. Analysis of these uniquely collocated datasets links larger tropical thunderstorm structures to greater atmospheric moisture and wind shear near the ocean surface. Meanwhile, stronger tropical thunderstorms were most consistently associated with greater upper tropospheric buoyancy and moisture, along with stronger localized ascent of air near the ocean surface. The results of this study offer valuable insight into how tropical thunderstorms interact with the atmosphere, while also providing necessary guidance for improving the prediction and representation of tropical thunderstorms in global weather and climate models.
1 Introduction

Deep tropical oceanic convection (TOC) is a prevalent feature of the tropical atmosphere and plays a key role in driving both regional and global weather and climate, including influences on the large-scale tropical atmospheric circulation and upper ocean responses (Alexander & Young, 1992; Brown & Zhang, 1997; LeMone et al., 1998; Saxen & Rutledge, 2000; Tompkins, 2001; Cetrone & Houze, 2006; Liu & Lian, 2010), as well as radiative fluxes particularly near cloud-top levels (LeMone et al., 1998; Igel & van den Heever, 2015). TOC also frequently produces thermodynamically driven cold pools, which can trigger development of non-precipitating cumulus congestus clouds (a further radiative influencer), initiate new deep convection, alter planetary boundary layer (PBL) characteristics, and thus further modify air-sea exchange (e.g., Chandra et al., 2018; Houze, 2018; Touzé-Peiffer et al., 2021). Accurate TOC representation and parameterization is therefore critical for the success of weather and climate modeling efforts. However, despite decades of TOC research, challenges persist in modeling TOC. This challenge is partly attributed to a lack of understanding of TOC structure, initiation, and evolution, including how TOC relates to its near-storm environments throughout storm system lifecycle (Cetrone & Houze, 2006; Igel & van den Heever, 2015; Minamide & Posselt, 2022). Studying near-storm environmental relationships is challenging, as it requires frequent, high-resolution measurements to capture fundamental small-scale convective processes, features, and environments. Highly temporally and spatially resolved \textit{in situ} data collection is an ideal means of garnering such measurements.

Observational analysis from field campaigns in the western Pacific basin (e.g., TOGA-COARE, KWAJEX, EMEX, PISTON) has investigated near-storm environmental wind shear relationships
with TOC structure using in situ sonde deployments. These studies have linked greater low-tropospheric speed shear to a greater degree of spatial organization of west Pacific mesoscale convective systems (MCSs), with quasi-linear convective systems oriented perpendicular to the low-level shear vector (Alexander & Young, 1992; LeMone et al., 1998; Chudler & Rutledge, 2021). Guy and Jorgensen (2014), however, found differing results in the Indian Ocean during the DYNAMO field campaign, with quasi-linear MCSs oriented more parallel to the low-tropospheric shear. Furthermore, quasi-linear MCSs in the west Pacific have also been linked to strong deep layer vertical speed shear owing to more expansive stratiform precipitation and anvil advection (Saxen & Rutledge, 2000). The analysis of these shear-convection relationships has been extended to the greater tropics using cloud-resolving model (CRM), spaceborne remote sensing, and European Centre for Medium-Range Weather Forecasts Reanalysis-Interim (ERA-Interim) reanalysis datasets, finding similar deep layer speed shear relationships with tropical squall lines specifically (Tompkins, 2001) and tropical MCSs more generally (Igel & van den Heever, 2015).

However, Tompkins (2001) acknowledges CRM limitations (e.g., limited vertical dimension and unrealistic cyclic boundary conditions), while Igel and van den Heever (2015) acknowledges biases stemming from inherently inconsistent storm-relative CloudSat measurements. Additionally, much of the in situ research has predominately focused on (quasi-) linear convection and is largely based in the west Pacific and Indian Ocean. With TOC structure varying across the tropics, including an abundance of non-linear TOC (Houze et al., 2015), an evaluation of TOC relationships with near-storm wind shear necessitates detailed in situ studies in other tropical oceanic regions across different TOC types.
Similar to wind shear, field campaign data in the western Pacific and Indian Ocean basins, along with broader tropical oceanic CRM and ERA-Interim reanalysis data, have been used to investigate near-storm environmental moisture relationships with TOC structure. Analysis of these datasets have shown mid-tropospheric relative humidity (RH) to positively correlate with TOC precipitation area and intensity due to decreased dry air entrainment (Brown & Zhang, 1997; LeMone et al., 1998; Tompkins, 2001; Cetrone & Houze, 2006; Savarin et al., 2014; Chen et al., 2016; Chen et al., 2017; Schiro et al., 2020). However, the relationships between lower-tropospheric moisture and TOC precipitation area and intensity vary, in both strength and sign, across tropical oceanic studies, even within similar regions (Tompkins, 2001; Cetrone & Houze, 2006; Chen et al., 2017; Schiro et al., 2020). The inconsistencies may relate to data collection during differing TOC lifecycle stages, with low-level inflow shown to potentially be more important during early lifecycle stages compared to mid-level inflow for later lifecycle stages (Mechem et al., 2002).

Similarly, inconsistent relationships between environmental CAPE and TOC structure exist across prior studies of the western Pacific basin. Cetrone and Houze (2006) and Chudler and Rutledge (2021) found KWAJEX and PISTON MCSs, respectively, to be associated with lesser CAPE compared to smaller, less organized convective systems, while Kingsmill and Houze (1999) found opposing results using TOGA-COARE data. The conflicting results could stem from thermodynamic instability being asymmetrically concentrated in the lower troposphere in the KWAJEX soundings and near-surface modification by MCSs in the PISTON soundings, thereby negatively biasing CAPE measurements near the MCSs (Cetrone & Houze, 2006; Chudler & Rutledge, 2021).
Collectively, both the strength and sign of near-storm mean-layer environmental moisture, wind shear, and CAPE relationships with TOC structure are inconsistent across studies. These inconsistent findings could be attributed to a multitude of factors, like differing analysis methods and data sources. However, a lack of regional context may be a major culprit. This lack of modern, regionally diverse, and regionally distinct in situ research is an issue, because TOC structure and its relationships with near-storm environments have been shown through TRMM observations and ERA-Interim reanalysis to exhibit regional dependencies (Houze et al., 2015; Chen et al., 2017). Satellite and reanalysis datasets provide the ability to examine each tropical oceanic region separately, but their limited spatial and temporal resolutions cannot sufficiently capture essential small-scale near-storm environmental variability and convective processes. Consequently, targeted regional in situ studies, particularly in understudied areas, equipped with collocated high-resolution hydrometeor, moisture, and wind measurement capabilities are imperative to adequately analyze near-storm environmental relationships with TOC structure.

Two such targeted in situ regional studies were the 2017 NASA Convective Processes Experiment and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns based in Ft. Lauderdale, Florida and St. Croix, USVI, respectively. CPEX and CPEX-AW performed a total of 23 science flights aboard the NASA DC-8 research aircraft from 27 May 2017 – 24 June 2017 and 20 August 2021 – 4 September 2021, respectively, to study TOC processes in the Gulf of Mexico, Caribbean Sea, and western Atlantic—regions that were notably lacking recent in situ, non-tropical cyclone related deep convective research (Cui et al., 2020). The DC-8 aircraft was equipped with, amongst other instrumentation, a multi-wavelength airborne precipitation radar, a Doppler wind lidar, and
dropsondes. Together, these instruments provided rare, coincident, high-resolution profiling of three-dimensional (3-D) convective structure and near-storm winds and moisture for convective systems of different spatial scales and intensities (Turk et al., 2020; Hristova-Veleva et al., 2021). Given the uniqueness of this suite of observations, the CPEX and CPEX-AW field campaigns present an exceptional opportunity to analyze their region’s near-storm environmental relationships with tropical oceanic 3-D convective structure, which will be the focus of this study. In particular, how does 3-D TOC structure relate to near-storm environmental RH, vertical speed shear, and CAPE in different tropospheric vertical layers in the CPEX(-AW) observational domain?

To address this research question, the organization of the paper is as follows. Section 2 offers a description of the CPEX(-AW) instrumentation and data used for the analysis, while Section 3 outlines the analysis methodology. Section 4 presents the results of the analysis, and Section 5 provides a discussion of the results in the context of prior studies. Section 6 concludes the paper with main takeaways from the analysis and next steps for future research.

2 Data

2.1 CPEX and CPEX-AW Overview

The NASA DC-8 aircraft was equipped with six science instruments during CPEX (Chen & Zipser, 2017) and five during CPEX-AW (Skofronick-Jackson et al., 2021). This paper will focus on analysis of the higher spatial resolution airborne datasets from the following instrumentation: dropsondes, the Doppler Aerosol WiNd Lidar (DAWN; Kavaya et al., 2014), and the Third-Generation Airborne Precipitation Radar (APR-3; Sadowy et al., 2003). Together, these three
instruments provided coincident, detailed measurements of near-storm moisture, winds, and 3-D convective structure (e.g., Figure 1) at sufficient resolutions to analyze characteristics of distinct vertical layers. Seventeen of the 23 CPEX(-AW) science flights sampled 20 separate deep precipitating convective systems (hereafter referred to as convective cases) with this instrument payload. As such, only observational data from these 17 science flights were used for analysis for this paper.

Figure 1: APR-3 Ku-band reflectivity profiles (fill), dropsonde wind profiles (blue barbs), and DAWN wind profiles (black barbs) for an (a) isolated and (b) organized TOC system observed during CPEX.
2.2 Dropsondes

CPEX vertical profiles of pressure, temperature, horizontal wind velocity, and humidity were collected using Yankee Environmental Systems eXpendable Digital Dropsondes (CPEX Dropsonde, 2019; Black et al., 2017). The dropsondes provided accuracy and resolutions appropriate for the purposes of this study (Greco et al., 2018; Black et al., 2017): 1.5 mb (at 25°C) accuracy at 2.5 mb resolution for pressure, 0.148°C accuracy with 0.0168°C resolution for temperature, 0.5 m s\(^{-1}\) accuracy with 0.2 m s\(^{-1}\) precision for horizontal winds, and 1.8% (at 25°C) accuracy at 0.1% precision for RH. CPEX-AW released the National Center for Atmospheric Research (NCAR) dropsondes, which used the Airborne Vertical Atmospheric Profiling System (AVAPS) developed by Vaisala Inc. (AVAPS Dropsondes, 2023). These CPEX-AW dropsondes provide similarly appropriate accuracy and resolutions as the ones used from CPEX (AVAPS Dropsondes, 2023) with the largest differences seen in horizontal wind velocity (0.5 m s\(^{-1}\) accuracy at 0.01 m s\(^{-1}\) resolution) and RH (3% accuracy at 0.01% resolution). Unfortunately, RH accuracies were notably worse in actively precipitating environments from both campaigns as the dropsondes exhibited moisture biases when encountering precipitation, likely due to water ingress (Greco et al., 2018). As such, moisture data from dropsondes deployed in actively precipitating environments was excluded from analysis in this paper. All the dropsonde data was processed using the NCAR Atmospheric Sounding Processing ENvironment (ASPEN) software (Greco et al., 2018; Vömel et al., 2021; Martin & Suhr, 2021). Post-mission GPS correction was also employed (CPEX Dropsonde, 2019). Dropsonde profiles with frequent, graphically visible anomalous spikes in equivalent potential temperature were excluded from analysis, amounting to 195 usable dropsondes across the 20 convective cases.
2.3 Doppler Aerosol WiNd Lidar (DAWN)

High-resolution vertical profiles of wind near convection were collected by the DAWN instrument aboard the NASA DC-8 aircraft during CPEX(-AW). DAWN is equipped with a 2-µm, 10-Hz laser that utilizes atmospheric aerosols to measure horizontal wind components (Kavaya et al., 2014; Turk et al., 2020; Greco et al., 2020). DAWN vertical wind profiles were obtained at horizontal resolutions as fine as 3-7 km and a vertical resolution of ~33 m using the LOS wind profiles (CPEX DAWN, 2019; Greco et al., 2020). These profiles were severely attenuated when encountering opaque clouds (e.g., convective anvil cirrus), and data gaps frequently existed in the middle troposphere due to low aerosol concentrations (e.g., Bedka et al., 2021). DAWN wind speed accuracy was < 0.05 m s⁻¹ with < ~1.5 m s⁻¹ precision (Greco et al., 2020) and showed a low bias of < 0.20 m s⁻¹ compared to dropsonde winds (Greco et al., 2020). Given the scales that are being explored for comparing mean-layer wind shear (differences hypothesized to be several m s⁻¹), the DAWN wind accuracy and precision are adequate for the purposes of this study. DAWN data was processed and quality controlled via methods described in Kavaya et al. (2014), CPEX DAWN (2019), Greco et al. (2020), and Bedka et al. (2021).

2.4 Third-Generation Airborne Precipitation Radar (APR-3)

Vertical radar reflectivity profiles of 3-D convective hydrometeor structure were collected using the APR-3 instrument (Sadowy et al., 2003). APR-3 mirrors the Global Precipitation Measurement Mission Dual-Frequency Precipitation Radar (GPM-DPR) 13.4-GHz (Ku-) and 35.6 GHz (Ka-) bands, which simultaneously measure co- and cross-polarized reflectivities and vertical Doppler velocities (Durden et al., 2012; Turk et al., 2020; CPEX APR-3, 2018). Only Ku-band reflectivity profiles were used for analysis, as the Ku-band captures precipitation structure better than the Ka-
band, which is more quickly attenuated by precipitating hydrometeors. Doppler velocity datasets were corrupted for a majority of CPEX convective cases (i.e., cases prior to 16 June 2017). Therefore, Doppler velocity was not incorporated in subsequent analysis. APR-3 scans at a vertical resolution of 60 m (Sadowy et al., 2003; Durden et al., 2012). Ku-band horizontal resolution is ~730 – 800 m at 10-km altitude with a 10 dBZ sensitivity (Sadowy et al., 2003; Durden et al., 2012). APR-3 data was processed via methods described in Durden et al. (2012), with Ku-band calibration uncertainty for the CPEX and CPEX-AW campaigns estimated at 1 dB (CPEX APR-3, 2018; Turk et al., 2020).

3 Methods

3.1 Convective Case Characterization

In order to investigate near-storm environmental relationships with TOC structure, each of the 20 CPEX(-AW) convective cases was categorized as either isolated, organized, or scattered based on horizontal precipitation extent and continuity provided by archived hourly Integrated Multi-satellite Retrievals for GPM (IMERG) satellite data. Given the inherent small number of cases from the field campaigns, categorization of each convective system was manual. Isolated convective systems were defined as horizontally small, single-core precipitating regions, while organized convective systems were defined as broader, continuous, multi-core precipitating regions. Scattered convection was defined as broad, discontinuous precipitating regions. An example of each type of convection in the context of IMERG is depicted in Figure 2 using the CPEX data portal (Hristova-Veleva et al., 2020). The focus of this paper is on isolated and organized non-tropical cyclone TOC cases. As such, 12 out of the 20 total convective cases sampled during CPEX(-AW) underwent further analysis (Table 1). All but one (i.e., Case 15) of
the 12 cases was sampled during a similar time of day (i.e., between 1800 UTC and 0000 UTC),
so diurnal influences on convective structure are assumed to have been similar across cases.
Figure 2: An example of (a) isolated, (b) organized, and (c) scattered TOC sampled during CPEX, as defined by GPM IMERG precipitation area and continuity. CPEX science flight tracks are overlaid in red with hourly timestamps.
3.2 Dropsonde Characterization

Only dropsonde profiles temporally collocated with their respective convective case’s APR-3 data (i.e., within or near the anvil region) were considered for analysis, amounting to 111 dropsondes. Each dropsonde from the cases identified in Table 1 was characterized by the convective type of its respective case, along with the convective-relative environment it was deployed into. Using APR-3 plots overlaid with dropsonde and DAWN wind profiles (e.g., Figure 1), the three environmental categories were “Clear” (little to no reflectivity overlaid with the profile), “In Cloud” (deployed through a non-precipitating cloud layer(s)), and “In Precip” (deployed through an actively precipitating region). Skew-T diagrams of the dropsonde profiles (not shown) also aided in validation of the environmental categorization. The distribution of dropsondes amongst the three environmental categories for each case is shown in Table 1, along with the distribution of full and partial (i.e., sparse data coverage in certain layers due to GPS transmission issues) dropsonde profiles for each case. Due to the notable moisture biases of In Precip dropsondes, as

Table 1: CPEX and CPEX-AW convective cases used for analysis in this study. The number of associated dropsondes (full and partial) for each case is provided with dropsonde deployment environment.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Field Campaign</th>
<th>Region</th>
<th>Convective Type</th>
<th>Number of Dropsondes (Full)</th>
<th>Number of Dropsondes (Partial)</th>
<th>Clear</th>
<th>In Cloud</th>
<th>In Precip</th>
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<td>1</td>
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<td>CPEX</td>
<td>Western Atlantic</td>
<td>Isolated</td>
<td>11</td>
<td>2</td>
<td>9</td>
<td>3</td>
<td>1</td>
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<tr>
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<td>CPEX</td>
<td>Caribbean</td>
<td>Isolated</td>
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<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
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<td>Gulf of Mexico</td>
<td>Isolated</td>
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<td>0</td>
<td>3</td>
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<td>0</td>
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<td>3</td>
<td>1</td>
</tr>
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<td>19</td>
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<td>10</td>
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<td>5</td>
<td>4</td>
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</tbody>
</table>
previously mentioned in Section 2, only wind data from In Precip dropsondes was used for analysis in this paper.

All near-storm environmental analysis was performed for data from all convective lifecycles and separately excluding dropsondes deployed into weakening convective systems. Excluding the weakening lifecycle stage was tested as a means to focus on environments supporting convective development and sustainment. However, the results of the analysis excluding the weakening lifecycle stage data (figures not shown in this paper) were similar to the results of the analysis that included data from all lifecycle stages, and thus all analysis presented in later sections includes data from all lifecycle stages.

3.3 Mean-layer, Near-storm Environmental Metrics

Mean RH and vertical wind speed shear were calculated for each dropsonde profile for four distinct layers: the PBL, mid layer, upper layer, and deep layer. The base of the PBL is defined as the profile height nearest to the surface, ranging from 6.5 m to 338.5 m because of dropsonde transmission issues. Metric values were not found to correlate with near-surface height within that range. The top of the PBL is defined as the first height for which the virtual potential temperature exceeds its value nearest to the surface by 0.5 °C (e.g., Blumberg et al., 2017). The mid layer extends from the top of the PBL up to the freezing level (i.e., 0 °C), while the upper layer extends from the freezing level up to the lowest maximum height of the 111 qualifying dropsondes (7622.5 m), such that a uniform upper layer cap was achieved. The deep layer ranges from the profile height nearest to the surface up to the lowest maximum dropsonde height.
Layer RH calculations use RH data at all height levels within the specified layer thresholds to calculate profile mean-layer RHs. With the assistance of the Sounding/Hodograph Analysis and Research Program in Python (SHARPy; Blumberg et al., 2017) open-source meteorological package, vertical speed shear was calculated for the four distinct layers using the dropsonde component winds at each layer threshold height (interpolated as necessary). In addition to mean-layer RH and vertical speed shear, both most-unstable convective available potential energy (MUCAPE, using the most unstable air parcel found within the lowest 300-mb of the troposphere) and mixed-layer CAPE (MLCAPE, using a parcel with the mean temperature and moisture values from the lowest 100-mb of the troposphere) were calculated for each dropsonde for the deep layer and the upper layer (i.e., above the freezing level) using SHARPy. Upper layer CAPE supplements deep layer CAPE as an effort to avoid potential negative biasing of near-storm CAPE measurements by MCSs, as previously discussed in Chudler and Rutledge (2021). Environmental metrics for layers that were not fully sampled by partial dropsonde profiles (see Table 1) were excluded from analysis.

Similar to the dropsonde data, only DAWN profiles that were temporally collocated with their respective convective case’s APR-3 data—and thus near convection—were included in analysis. The DAWN instrument provided much denser wind profiling (both spatially and temporally) in non-anvil regions compared to the dropsondes. That being said, PBL depth and freezing level height could not be identified for each DAWN profile owing to temperature and moisture data not available from DAWN. With PBL depth in dropsonde data found to vary appreciably within short geospatial and temporal ranges, only deep layer wind shear could be confidently calculated for the DAWN profiles. The DAWN deep layer, in comparison with the dropsonde deep layer, was
similarly capped at the lowest maximum dropsonde height of 7622.5 m. However, the deep layer for the DAWN data slightly varies from the dropsonde deep layer, in that a uniform near-surface value of 500 m was employed to omit low SNR (i.e., noisy) data from DAWN shear calculations. For similar reasons, DAWN profiles, with a vertical resolution of ~33 m, were also required to contain at least 20 data points within the lowest 1 km of the atmosphere. An equivalent 500 m – 7622.5 m dropsonde deep layer shear was computed for direct comparison with DAWN deep layer shear.

3.4 Contoured Frequency by Altitude Diagrams

For collective analysis of convective intensity from reflectivity data, all APR-3 Ku-band reflectivity profiles for an individual case were binned into 2-dimensional histograms with 5-dBZ and 0.5-km intervals to create Contoured Frequency by Altitude Diagrams (CFADs) (Yuter & Houze, 1995). The reflectivity bins extend from -20 dBZ to 60 dBZ. The height bins extend from 1.5 km to 8 km, so as to omit potentially spurious near-surface data (Sadowy et al., 2003; Durden et al., 2003) and provide a uniform upper layer altitude cap to allow for case intercomparison. The heights from the reflectivity profiles, and thus in each CFAD, were not adjusted for brightband height, as brightband height across all the convective cases did not vary considerably (i.e., < ~0.5-km, or one height interval). Each CFAD was normalized by the maximum bin count in any height interval, allowing for frequency comparisons across height levels (e.g., Zagrodnik et al., 2019). Each CFAD was also separately normalized by the maximum bin count in each height interval, allowing for easier frequency comparisons at a given height level. Subsequent so-called “difference CFADs” were produced by subtracting one case’s normalized CFAD from another. These difference CFADs allow for investigation of convective intensity and storm structure
differences between cases with distinct mean-layer environmental metric differences (Yuter & Houze, 1995). Convective case intercomparisons, via difference CFADs, were only performed between cases of similar convective type (i.e., isolated vs. isolated, organized vs. organized), as comparisons across convective type would offer little value due to inherent differences in single-core vs. multi-core storm structure. Convective case intercomparisons were also only performed between cases that were observed during a similar convective lifecycle stage, such that predominantly convective elements are not compared with predominantly stratiform elements.

4 Results

4.1 Near-storm Environmental Relationships with Convective Type

To analyze potential near-storm environmental relationships with TOC type (i.e., isolated versus organized), mean-layer dropsonde metrics are presented as box-and-whisker plots (e.g., Figure 3). CAPE is first analyzed, showing that isolated convection has greater median deep layer MUCAPE (929 J kg\(^{-1}\) vs. 900 J kg\(^{-1}\), Figure 3a) and MLCAPE (570 J kg\(^{-1}\) vs. 524 J kg\(^{-1}\), Figure 3b) compared to organized convection. More distinctly, isolated convection is also observed to have greater median upper layer MUCAPE (613 J kg\(^{-1}\) vs. 549 J kg\(^{-1}\), Figure 3c) and MLCAPE (393 J kg\(^{-1}\) vs. 317 J kg\(^{-1}\), Figure 3d). Large CAPE variability exists within each convective type, however, that motivates further subdivision by case. Figure 4 reveals large CAPE variability within each case as well, even when accounting for location of the dropsonde relative to the precipitating system. This result is not surprising, as like many prior observational studies of CAPE and TOC structure (e.g., Chudler & Rutledge, 2021), CPEX(-AW) likely sampled near-storm environments where CAPE was both unrealized and separately already realized. Large intra-case variability may also partly be attributed to flight duration and spatial extent, but some cases have large metric variabilities
(e.g., Figure 4) despite convective flight legs covering small areas (e.g., Case 1 and Case 15) and/or having small observation periods (e.g., Case 15). Therefore, despite no clear general relationship between convective type and MUCAPE/MLCAPE in either layer in the CPEX(-AW) region, some cases—even of similar convective type—do have distinctly different CAPE magnitudes compared to others (e.g., isolated Cases 1 and 3 with upper layer CAPE in Figure 4d), which will be investigated more as individual case comparisons in Section 4.2 and Section 4.3.
Figure 3: Dropsonde-derived (a) deep layer MUCAPE, (b) deep layer MLCAPE, (c) upper layer MUCAPE, and (d) upper layer MLCAPE for isolated (red) and organized (blue) TOC systems sampled during CPEX and CPEX-AW (In Precip profiles excluded). Each box extends from the first quartile to the third quartile of the data, with a black line at the median. Whiskers extend from the box by up to 1.5 times the inter-quartile range, and outlier points are points beyond the whiskers.
Figure 4: Same data as Figure 3, but dropsonde observations are further sorted by convective case (In Precip profiles included as well). Markers denote the convective-relative environment the dropsonde was deployed into.
RH appears to have a slightly clearer distinction between convective types, with organized convection associated with slightly greater median RH in the PBL (88.8% vs. 85.8%, Figure 5b) and upper layer (55.6% vs. 53.0%, Figure 5d), while isolated convection is associated with a slightly greater median deep layer RH (66.1% vs. 64.5%, Figure 5a). Both isolated and organized convection have similar mid layer median RH (71.0% vs. 71.7%, Figure 5c), which regionally differs from aforementioned west Pacific studies that consistently link greater mid layer RH to more organized convection. As with CAPE, large mean-layer RH spreads exist for both convective types, particularly for organized convection (Figure 5), and within individual cases (Figure 6), especially Cases 1, 13, and 16. Organized Cases 13 and 16, in particular, record some of the lowest mean-layer RH values of any case and will be investigated further in Section 4.4. When comparing only the clear air dropsondes for each case across convective type, deep layer RH is generally greater for isolated convection (Figure 6a), while PBL RH is generally greater for organized convection (Figure 6b). Distinct mean-layer RH differences between cases of similar convective type also exist, which further motivates case comparisons in Section 4.2 and Section 4.3.
Figure 5: Same as Figure 3, except showing (a) deep layer RH, (b) PBL RH, (c) mid layer RH, and (d) upper layer RH.
Figure 6: Same data as Figure 5, but dropsonde observations are further sorted by convective case (In Precip profiles included). Markers denote the convective-relative environment the dropsonde was deployed into.
Similar to RH, the PBL is a focal point for vertical wind speed shear distinctions between convective type. Organized convection has greater median PBL speed shear (5.0 kts vs. 3.5 kts, Figure 7b) compared to isolated convection, as well as greater mid (17.7 kts vs. 8.6 kts, Figure 7c) and deep layer (22.0 kts vs. 16.0 kts, Figure 7a) speed shears. As with prior metrics, a large degree of mean-layer speed shear variability also exists within each convective type (especially for organized convection). When grouped by case (Figure 8), large speed shear spreads within cases are evident and are notably unrelated to the environment the dropsondes were deployed into (i.e., Clear, In Cloud, or In Precip). However, similar to CAPE and RH, distinct mean-layer speed shear differences do exist amongst cases of similar convective type, which further warrants comparing individual cases in Section 4.2 and Section 4.3. Ultimately though, organized convection is associated with generally greater PBL, mid, and deep layer near-storm speed shear than isolated convection (Figure 8a,b,c).
Figure 7: Same as Figure 3, except showing (a) deep layer speed shear, (b) PBL speed shear, (c) mid layer speed shear, and (d) upper layer speed shear. In Precip profiles are now included.
Figure 8: Same data as Figure 7, but dropsonde observations are further sorted by convective case. Markers denote the convective-relative environment the dropsonde was deployed into.
Incorporating the spatially and temporally denser DAWN observations provides an enhanced look into deep layer speed shear trends compared to dropsondes alone (Figure 9). The addition of the DAWN observations reveals even larger deep layer speed shear variability within each convective type (Figure 9a) and each convective case (Figure 9b) than the dropsonde observations previously showed. Notably, median deep layer speed shear is actually greater for isolated convection compared to organized convection (25.0 kts vs. 21.2 kts, Figure 9a), which the less frequent dropsonde data did not capture. When comparing all isolated case speed shear observations with the organized cases, however, the relationship between deep layer speed shear and convective type is unclear (Figure 9b).

Overall, the composite analysis of near-storm environmental relationships with convective type reveals broad near-storm environmental metric variability within each convective type. However, general mean-layer CAPE, RH, and speed shear trends do exist with regards to two-dimensional (2-D) TOC structure. Coupled with distinct metric variability between cases of similar convective type, it raises the question whether similar (or perhaps even more pronounced) near-storm environmental trends apply to vertical convective structure (i.e., convective intensity) for each convective type.
To analyze near-storm environmental relationships with isolated TOC intensity, normalized CFADs (see Section 3.4) were created for each isolated case (except Case 15, which had limited APR-3 reflectivity data). Then, cases with distinctly different mean-layer metric values (Section 4.1) had their normalized CFADs differenced to visually determine which case had more frequent greater Ku-band reflectivities throughout the vertical column (i.e., which convective system was
more intense). Subsequent comparison of convective intensities and their associated dropsonde mean-layer environmental metrics was performed. Ensuing CFAD figures were normalized by the maximum bin count in each height interval. However, similar analysis was performed with CFADs normalized by maximum bin count in any height interval, and each method produced the same conclusions. Together, the isolated case comparisons show the more intense isolated case (an example shown in Figure 10a comparing Cases 1 and 2) to consistently possess greater upper layer MUCAPE and MLCAPE and greater deep layer MLCAPE (as determined in Figure 4). This general relationship could result from greater CAPE environments promoting hydrometeor growth through enhanced thermodynamic instability (i.e., buoyancy). No other environmental metrics showed as clear of a distinction in isolated convective intensity and thus are not shown.

Figure 10: (a) Case 2 normalized CFAD subtracted from the Case 1 normalized CFAD. (b) Case 7 normalized CFAD subtracted from the Case 8 normalized CFAD. APR-3 Ku-band reflectivity data is binned into 5-dBZ and 0.5-km intervals and normalized by the maximum bin count in each height interval.
4.3 Near-storm Environmental Relationships with Convective Intensity (Organized)

Similar to the isolated case comparisons, organized TOC intensity was explored via normalized CFADs in the context of distinct mean-layer differences between cases (Section 4.1). When comparing all CPEX(-AW) organized convective cases with distinct mean-layer environmental metric differences, no consistent mean-layer speed shear, MUCAPE, nor MLCAPE relationships with convective intensity were found. However, when a notable difference in upper layer RH existed between two organized cases, the more intense convection (e.g., Figure 10b comparing Cases 7 and 8) was consistently associated with greater upper layer RH (Figure 6d). This relationship could be explained by less dry air entrainment promoting enhanced hydrometeor growth and limiting negative buoyancy introduction.

When intercomparing the isolated case comparison results with those from organized cases, it is noteworthy that there are no similar, consistent near-storm mean-layer metric trends with convective intensity. This lack of similarity between convective types points to single-core and multi-core systems interacting differently with their near-storm environments. An additional lack of consistent near-storm environmental relationships with organized TOC intensity suggests multi-core systems also variably interact with their near-storm environments. The latter finding is likely attributed to diverse vertical organizational structures of multi-core TOC (e.g., linear vs. non-linear MCSs), which were observed during CPEX(-AW) and will be explored further in the following section.
4.4 Case 13 vs. Case 16 Organized Convection Comparison

As highlighted in Section 4.1, large mean-layer RH variability existed for organized convective systems (Figure 5). Upon further examination, Cases 13 and 16 contained many of the lowest mean-layer RH values of any sampled CPEX(-AW) convective system (Figure 6), and thus were responsible for the particularly large mean-layer RH spreads of organized TOC. The relatively dry near-storm observations, coupled with the especially large RH variability, motivated further investigation into the convective environments of Case 13 and Case 16.

The convective flight legs and observations of Cases 13 and 16 each encompassed a synoptic-scale horizontal moisture gradient (Figure 11; Hristova-Veleva et al., 2020), providing a reason for large intra-case RH spreads and notably dry near-storm observations that were particularly influential on the RH results of Section 4.1. No other observed convective systems during CPEX(-AW) were located near synoptic-scale moisture gradients, making Cases 13 and 16 unique in that aspect.

From a satellite-based perspective, both cases had similar 2-D structures (Figure 11) with an intensifying sector and a matured sector identified by decreasing and increasing infrared brightness temperatures with time, respectively. Both cases’ deep precipitating regions were located on the moist side of their respective synoptic-scale moisture gradient, with each moisture gradient collocated with a similar strength (~15 m s\(^{-1}\)), along-gradient 800 – 650 mb mid-level jet (not shown but observed by the dropsondes). However, despite these similarities, the vertical structures of the organized Case 13 and Case 16 convective systems were markedly different, with Case 13 mainly composed of leading line convective elements with trailing stratiform (Figure 12a), while Case 16 was characterized by numerous embedded convective elements within predominant widespread stratiform (Figure 12b). Cases 13 and 16 therefore provided a unique opportunity to
investigate how differing organized vertical convective structures relate to near-storm moisture and speed shear in the CPEX(-AW) region.

Figure 11: (a) Case 13 TPW (bottom layer fill), GPM IMERG surface precipitation estimation (top layer fill), and DC-8 science flight track (red line). (b) Same as (a), but for Case 16.
For this case comparison, all dropsonde and DAWN observations for the Case 13 and Case 16 analysis were further contextualized as being collected within or beyond each case’s synoptic-scale moisture (TPW) gradient (Figure 13, Figure 14). The larger spread in deep layer shear (Figure 13a) accounts for including DAWN measurements (as in Section 4.1), with considerable overlap between cases. Similarly, no clear case distinction was found between mean-layer speed shear from dropsondes in similar locations relative to the moisture gradient (Figure 13). There is a hint of stronger PBL shear near the convection in Case 13, but Case 16 dropsondes within the moisture gradient were all in precipitating regions, thus highlighting inconsistencies in approaches to dropsonde targets across cases and campaigns. Therefore, no distinct differences in mean-layer shear with organized vertical convective structure is revealed from this case comparison.

Figure 12: APR-3 Ku-band reflectivity profiles (fill), dropsonde wind profiles (blue barbs), and DAWN wind profiles (black barbs) for (a) Case 13 and (b) Case 16 organized cases. Case 13 has a leading line, trailing stratiform structure, while Case 16 has many embedded convective elements amongst prevailing stratiform.
Figure 13: Dropsonde-derived (a) 0.5-km – 7.6-km deep layer speed shear (DAWN observations included as well), (b) PBL speed shear, (c) mid layer speed shear, and (d) upper layer speed shear for Case 13 and Case 16. Observations are color-coded by the location of their dropsondes relative to the synoptic-scale moisture gradient, and their markers denote the convective-relative environments their dropsondes were deployed into.
Figure 14: Same as Figure 13, except showing (a) deep layer RH, (b) PBL RH, (c) mid layer RH, and (d) upper layer RH.
Observations collected within the moisture gradient unsurprisingly tended to have greater mean-layer RH compared to observations collected beyond the moisture gradient (Figure 14). With Case 16 only having quality (i.e., not In Precip) RH observations beyond the moisture gradient, mean-layer RH comparisons were only performed amongst data collected from the impinging dry air beyond the moisture gradient associated with each convective system. The deep layer and mid layer were notably drier for Case 16 compared to Case 13 (Figure 14a,c), with the 800 – 650 mb jet layer (located entirely within the mid layer, not shown) in particular having dewpoint depressions exceeding three times those of Case 13. The distinctly differing near-storm environmental moisture of Cases 13 and 16 motivated further analysis on how the near-storm environments may have influenced convective intensity.

Reflectivity CFADs were again used to compare convective intensity between cases. Cases 13 and 16 were each subdivided into their intensifying and matured sectors for the normalized difference CFAD plots (Figure 15). Case 16’s intensifying sector, with drier mid-levels and lesser average deep layer, upper layer, and PBL speed shear, was more intense than the intensifying sector of Case 13 (Figure 15a). However, for the matured sectors of the two systems, Case 16 was more intense than Case 13 (Figure 15b) despite similar near-storm, mean-layer RH and speed shear. These results indicate that near-storm environmental relationships with convection may not only be dependent on the degree and type of organization, but also on convective lifecycle stage.
Without clear relationships between TOC structure and near-storm environments from these two cases, there are additional environmental factors to consider in controlling convection formation, evolution, and intensity. Recent work (e.g., Galarneau et al. 2023) has highlighted not just the importance of moisture, but of low-level convergence in concentrating moisture and priming conditions for MCS development over tropical oceans. In revisiting dropsonde observations from Cases 13 and 16, synoptic-scale low-level convergence is observed in the Case 16 precipitating system (Figure 16) but not in Case 13 (not shown). This broad low-level convergence could explain Case 16 being notably more intense than Case 13 (Figure 15), despite much drier impinging air (Figure 14a,c). Therefore, this case comparison suggests that sufficient large-scale low-level convergence can provide enough forcing for TOC to thrive in otherwise seemingly less favorable near-storm environmental conditions and also influence the vertical structure of organized convection (e.g., increasing the number and intensity of convective elements).

Figure 15: Same as Figure 10, but for the (a) intensifying and (b) matured sectors of Case 16 and Case 13.
Figure 16: (bottom) Dropsonde skew-T diagram and hodograph (18:34:14 UTC) from the southern half of Case 16 (center) showing near-surface southeasterly winds (black oval). (top) Dropsonde skew-T diagram and hodograph (18:01:43 UTC) from the northern half of Case 16 (center) showing near-surface northeasterly winds (black oval). For each dropsonde skew-T diagram, CAPE is shaded in light red, full lines on wind barbs represent 5 m s$^{-1}$, and half lines on wind barbs represent 2.5 m s$^{-1}$. 
5 Discussion

The analysis presented in Section 4 showed that CPEX(-AW) near-storm, mean-layer environmental metrics varied widely within a given convective type and case, but notable environmental trends with convective type and intensity emerged amongst the variability. Deep layer RH was generally lesser for organized TOC compared to isolated TOC (Section 4.1), which conflicts with the prevailing idea that a drier tropical troposphere inhibits TOC development through enhanced dry air entrainment and negative buoyancy introduction. However, when evaluating convective intensity within the context of near-storm RH and CAPE, clearer relationships were observed within the upper layers (i.e., above the freezing level). More specifically, stronger organized TOC was associated with greater upper layer RH (Section 4.3), while stronger isolated TOC was linked to greater upper layer CAPE (Section 4.2). These results align with observations in the west Pacific (Cetrone & Houze, 2006 and Kingsmill & Houze, 1999, respectively) and are more consistent with the concept of greater moisture and CAPE promoting hydrometeor growth through enhanced positive buoyancy. This logic, though, did not translate to a case comparison between two CPEX(-AW) MCSs forming on the moist side of strong synoptic-scale moisture gradients (Section 4.4), with the more intense organized system having a distinctly drier impinging synoptic airmass that logically contrasts with results from prior observational (Brown & Zhang, 1997; LeMone et al., 1998; Cetrone & Houze, 2006), CRM (Tompkins, 2001), and ERA-Interim (Chen et al., 2017; Schiro et al., 2020) studies. However, evaluating this case comparison in the context of other studies may not be appropriate, as the dropsonde observations within the synoptic-scale moisture gradients (where both CPEX(-AW) systems flourished) were not consistently reliable.
The result in Section 4.1 that PBL RH was generally greater for organized TOC compared to isolated TOC (Figure 5b, Figure 6b) is consistent with studies using CRM (Tompkins, 2001) and ERA-Interim reanalysis (Chen et al., 2017; Schiro et al., 2020) datasets, yet differs from KWAJEX observations in the west Pacific (Cetrone & Houze, 2006), highlighting potential regional variability in these relationships. Mid and upper layer RH relationships with convective type were unclear (Figure 6c,d), which also differs from more conclusive observationally based studies in the west Pacific (e.g., Brown & Zhang, 1997; LeMone et al., 1998; Cetrone & Houze, 2006). The inconsistencies with other studies may be due to legitimate regional variation, but also from incorporation of observations from different convective regions and lifecycle stages (e.g., Mechem et al., 2002). Additionally, these RH trends may signify convective evolution in other ways, such as through relationships with other environmental metrics that impact convective lifecycle. For example, studies in the Indian Ocean (Savarin et al., 2014; Chen et al., 2016; Chandra et al., 2018) related drier mid-levels to greater PBL depth (via longer PBL recovery times) owing to enhanced dry air entrainment promoting stronger cold pools that can influence TOC evolution (e.g., Tompkins 2001; Feng et al., 2015; Rowe & Houze, 2015; Grant et al., 2018) and are known to vary globally over oceans (Garg et al. 2020). While the present study does not explicitly investigate cold pools, CPEX(-AW) observations do show a similar link between mid layer dryness and PBL depth ($R_{Pearson} \approx 0.537$, Figure 17), further highlighting the complexity in generalizing environmental moisture relationships with convective system structure.
Figure 17: Dropsonde-derived PBL depth vs. mean mid layer RH (In Precip dropsondes excluded). Observations are color-coded by the convective type of the case they were associated with, and their markers denote the convective-relative environments their dropsondes were deployed into. A linear regression of the data is overlaid (black dashed line), with a corresponding regression coefficient of 1.1 mb % $^{-1}$ and a Pearson correlation coefficient of 0.537.
Consistent with previous research linking cold pools to convective lifecycle through relationships with wind shear (Yuter & Houze, 1995; Houze, 2018), vertical speed shear in the PBL was generally greater for organized TOC compared to isolated TOC (Figure 8b,c). This finding is also consistent with prior ERA-Interim reanalysis and PISTON observational studies linking more organized convection to stronger low-level wind shear (e.g., Chen et al., 2017; Chudler & Rutledge, 2021). Differing from previous studies using CRM, reanalysis, and TOGA COARE data (Tompkins, 2001; Igel & van den Heever, 2015; Saxen & Rutledge, 2000), this CPEX(-AW) analysis did not find a clear link between deep layer shear and TOC 2-D structure (Figure 9b). However, previous studies, particularly those in the west Pacific, were predominately based on observations of quasi-linear TOC and thus may not be directly comparable to the CPEX(-AW) observations that sampled few quasi-linear convective systems. One example of a leading convection-trailing stratiform archetype was Case 13, which was compared with a non-linear MCS (Case 16) with similarly intensifying and matured sectors (Section 4.4). Owing to the inconsistency in reliable dropsonde observations on either side of the synoptic-scale moisture gradient, direct comparisons between the wind shear profiles between cases were inconclusive. However, a key result of this comparison was in highlighting the likely role of synoptic-scale low-level convergence in promoting more intense convection in the non-linear MCS (Case 16) despite drier mid-level air in the vicinity of the system, pointing to a key component of future research.

6 Conclusions

Using a unique suite of collocated, high-resolution airborne observations of deep (non-tropical cyclone) TOC from the NASA 2017 CPEX and 2021 CPEX-AW field campaigns, this study presented an analysis of near-storm environmental relationships with 3-D TOC structure in the
Gulf of Mexico, Caribbean Sea, and western Atlantic region. Large variability in near-storm mean-layer CAPE, vertical speed shear, and RH was observed amongst systems of similar convective type (isolated, organized) and also within individual convective systems. Despite this large variability and the inherently small sample size of 12 convective systems (4 isolated, 8 organized), notable links emerged between near-storm environmental metrics and 3-D convective structure:

- The PBL was the layer most commonly related to 2-D TOC structure, with organized (i.e., multi-core) TOC being associated with generally greater PBL RH and speed shear compared to isolated (i.e., single-core) TOC.

- The upper layer (i.e., above the freezing level) was the layer most consistently related to vertical convective structure (i.e., TOC intensity), with more intense isolated TOC being associated with greater upper layer CAPE and more intense organized TOC being associated with greater upper layer RH.

- Synoptic-scale low-level convergence potentially fostered more intense TOC in otherwise seemingly less favorable near-storm environmental conditions, and it may influence the vertical organizational structure of multi-core TOC (e.g., by increasing the number and intensity of convective elements).

While prior studies, combined with this study, find inconsistent relationships between near-storm PBL environments and TOC, this study and others denote the importance of PBL characteristics to the organization of TOC. Therefore, accurate PBL representation in weather and climate models appears critical to improve TOC parameterization. A lack of similar environmental trends with TOC intensity across convective type suggests that single-core and multi-core TOC systems interact differently with their near-storm environments, thus necessitating distinguished process-
level research on both types of TOC. Additionally, prior studies tend to not discuss upper layer environmental influences on TOC. The results of this study contend that relationships between TOC intensity and environments above the freezing level should be given more attention.

With prior studies (e.g., Chen et al., 2017) showing TOC relationships with near-storm environments to vary regionally, this study helps address a notable regional gap in in situ analysis of relationships between TOC structure and near-storm environments. Consequently, the results of this paper are specific to the Gulf of Mexico, Caribbean Sea, and western Atlantic region and cannot be confidently translated to other tropical oceanic regions. The unique capabilities of the CPEX(-AW) remote sensing instrumentation in their ability to capture essential small-scale (both spatially and temporally) near-storm environmental features and variability are also highlighted, and they serve as an important benchmark for future TOC studies. The CPEX(-AW) instrumentation, particularly DAWN, offer a glimpse into the potential of future spaceborne remote sensing, with higher resolution measurements capable of improving modeling efforts through improved process-level knowledge of tropical convection (e.g., Turk et al., 2020; Mazza & Chen, 2021), data assimilation (e.g., Cui et al., 2020; Hristova-Veleva et al., 2021; Minamide & Posselt, 2022), and model evaluation (e.g., Cui et al., 2020; Minamide & Posselt, 2022).

Future work will extend analysis of near-storm environmental relationships with 3-D TOC structure to the eastern Atlantic region using similar airborne observations from the recent 2022 NASA CPEX – Cabo Verde (CPEX-CV) field campaign. Unlike CPEX-AW, however, CPEX-CV science flights included a focus on repeated sampling of convective systems and similar storm-relative regions, providing the opportunity to better analyze and compare specific TOC regions
that could not be adequately performed in this study. Furthermore, idealized TOC simulations using the NCAR Cloud Model 1 will also be executed, wherein input sounding moisture and winds (informed by CPEX(-AW) observations) will be altered to analyze their effects on TOC structure and organization.
Acknowledgements

This research was supported by NASA Award 80NSSC20K0894. The authors thank all NASA CPEX, CPEX-AW, and CPEX-CV leadership and participants, for which this research would not be possible without. This research especially benefited from the guidance of Simone Tanelli and Ousmane Sy at the Jet Propulsion Laboratory (JPL) on APR-3 data and that of Kristopher Bedka (NASA Langley Research Center) on DAWN data. The authors also thank Randy J. Chase for providing APR-3 coding assistance and Svetla Hristova-Veleva on the JPL Portal for important visual synthesis of datasets to support this research.
Information on the NASA CPEX 2017 campaign is available at the main project page: https://cpx.jpl.nasa.gov/cpex2017/, which includes a link to the processed data used in this analysis: https://tcis.jpl.nasa.gov/data/cpex/ (Chen & Zipser, 2017). From this link, data used in the analysis is accessed from the latest versions of the APR-3, DAWN and dropsonde folders with no registration required for access. These folders also include the README files referenced in the text. Images from the CPEX data portal can be recreated at the following link: https://cpxexportal.jpl.nasa.gov/.

For NASA CPEX-AW 2021 datasets, the main project page is found here: https://cpx.jpl.nasa.gov/cpex-aw/ with no similar direct link to the data repository (Skofronick-Jackson et al., 2021). The CPEX-AW data is freely accessible through registering at the NASA EarthData repository following this campaign-specific link: https://search.earthdata.nasa.gov/search?fpj=CPEX-AW. To access this data by instrument, see the main site for the entire CPEX-AW data collection (http://dx.doi.org/10.5067/CPEXAW/DATA101) and direct links therein for accessing APR-3 (https://dx.doi.org/10.5067/CPEXAW/APR3/DATA101), DAWN (http://dx.doi.org/10.5067/ASDC/SUBORBITAL/CPEXAW-DAWN_DC8_1), and dropsonde (http://dx.doi.org/10.5067/ASDC/SUBORBITAL/CPEXAW-Dropsondes_1) data that were used for this analysis. Images from the CPEX-AW data portal can be recreated at the following link: https://cpx-aw.jpl.nasa.gov/.
Figures were made with Matplotlib version 3.4.2 (Hunter, 2007; Caswell et al., 2021), available under the Matplotlib license at https://matplotlib.org/. Code to process and plot the publicly available datasets used in this analysis is available upon request via the first author’s GitHub page.
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Near-storm Environmental Relationships with Tropical Oceanic Convective Structure Observed during NASA CPEX and CPEX-AW

Benjamin D. Rodenkirch¹ and Angela K. Rowe¹

¹Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, WI

Corresponding author: Benjamin Rodenkirch (brodenkirch@wisc.edu)

Key Points:

- Planetary boundary layer moisture and wind shear were generally greater for multi-core versus single-core tropical oceanic convection.
- Single-core and multi-core convective intensity were most linked to greater upper-level CAPE and moisture, respectively.
- Synoptic-scale low-level convergence likely fosters convective intensification in otherwise less favorable environmental conditions.
Abstract

Deep tropical oceanic convection (TOC) is a prevailing component of the tropical atmosphere and plays a significant role in modulating global weather and climate. Despite its importance, prediction challenges remain, partly attributed to a lack of understanding of how TOC relates to its near-storm environments. Prior studies suggest location-dependent relationships between TOC structure and associated environments, necessitating targeted regional studies. The NASA 2017 Convective Processes Experiment (CPEX) and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns collected high-resolution measurements of convective storms and their environments in the Gulf of Mexico, Caribbean, and western Atlantic basins, providing a rare opportunity to investigate near-storm environmental relationships with 3-D TOC structure where in situ non-tropical cyclone-related deep TOC research is comparatively lacking. Collocated CPEX and CPEX-AW airborne observations from the multi-wavelength Airborne Precipitation Radar, Doppler Aerosol Wind Lidar, and dropsondes revealed large near-storm environmental variability across TOC of similar convective type (i.e., isolated, organized) and within individual convective systems. However, trends still emerged amongst the large environmental variability. Two-dimensional (2-D) TOC structure was most consistently linked to planetary boundary layer (PBL) near-storm environments, with organized TOC being associated with generally greater PBL RH and vertical speed shear than isolated TOC. TOC intensity was linked to upper tropospheric (i.e., above the freezing level) near-storm environments, with isolated TOC intensity most consistently associated with upper tropospheric CAPE and organized TOC intensity associated with upper tropospheric RH. Synoptic-scale low-level convergence was also linked to greater organized TOC intensity, motivating further research using these unique datasets.
Plain Language Summary

Thunderstorms are a common occurrence in the tropics and influence Earth’s weather and climate. Predicting tropical thunderstorms remains challenging for weather and climate models, partly due to a lack of understanding of how atmospheric moisture and winds relate to tropical thunderstorm structure and strength. Prior studies suggest these environmental relationships are dependent on location in the tropics, thereby necessitating focused regional studies. This study helps address a notable regional research gap in the Gulf of Mexico, Caribbean, and western Atlantic basins, using rare, high-resolution radar and lidar measurements of tropical thunderstorms and their environments from the NASA 2017 Convective Processes Experiment (CPEX) and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns. Analysis of these uniquely collocated datasets links larger tropical thunderstorm structures to greater atmospheric moisture and wind shear near the ocean surface. Meanwhile, stronger tropical thunderstorms were most consistently associated with greater upper tropospheric buoyancy and moisture, along with stronger localized ascent of air near the ocean surface. The results of this study offer valuable insight into how tropical thunderstorms interact with the atmosphere, while also providing necessary guidance for improving the prediction and representation of tropical thunderstorms in global weather and climate models.


1 Introduction

Deep tropical oceanic convection (TOC) is a prevalent feature of the tropical atmosphere and plays a key role in driving both regional and global weather and climate, including influences on the large-scale tropical atmospheric circulation and upper ocean responses (Alexander & Young, 1992; Brown & Zhang, 1997; LeMone et al., 1998; Saxen & Rutledge, 2000; Tompkins, 2001; Cetrone & Houze, 2006; Liu & Lian, 2010), as well as radiative fluxes particularly near cloud-top levels (LeMone et al., 1998; Igel & van den Heever, 2015). TOC also frequently produces thermodynamically driven cold pools, which can trigger development of non-precipitating cumulus congestus clouds (a further radiative influencer), initiate new deep convection, alter planetary boundary layer (PBL) characteristics, and thus further modify air-sea exchange (e.g., Chandra et al., 2018; Houze, 2018; Touzé-Peiffer et al., 2021). Accurate TOC representation and parameterization is therefore critical for the success of weather and climate modeling efforts. However, despite decades of TOC research, challenges persist in modeling TOC. This challenge is partly attributed to a lack of understanding of TOC structure, initiation, and evolution, including how TOC relates to its near-storm environments throughout storm system lifecycle (Cetrone & Houze, 2006; Igel & van den Heever, 2015; Minamide & Posselt, 2022). Studying near-storm environmental relationships is challenging, as it requires frequent, high-resolution measurements to capture fundamental small-scale convective processes, features, and environments. Highly temporally and spatially resolved in situ data collection is an ideal means of garnering such measurements.

Observational analysis from field campaigns in the western Pacific basin (e.g., TOGA-COARE, KWAJEX, EMEX, PISTON) has investigated near-storm environmental wind shear relationships
with TOC structure using *in situ* sonde deployments. These studies have linked greater low-tropospheric speed shear to a greater degree of spatial organization of west Pacific mesoscale convective systems (MCSs), with quasi-linear convective systems oriented perpendicular to the low-level shear vector (Alexander & Young, 1992; LeMone et al., 1998; Chudler & Rutledge, 2021). Guy and Jorgensen (2014), however, found differing results in the Indian Ocean during the DYNAMO field campaign, with quasi-linear MCSs oriented more parallel to the low-tropospheric shear. Furthermore, quasi-linear MCSs in the west Pacific have also been linked to strong deep layer vertical speed shear owing to more expansive stratiform precipitation and anvil advection (Saxen & Rutledge, 2000). The analysis of these shear-convection relationships has been extended to the greater tropics using cloud-resolving model (CRM), spaceborne remote sensing, and European Centre for Medium-Range Weather Forecasts Reanalysis-Interim (ERA-Interim) reanalysis datasets, finding similar deep layer speed shear relationships with tropical squall lines specifically (Tompkins, 2001) and tropical MCSs more generally (Igel & van den Heever, 2015). However, Tompkins (2001) acknowledges CRM limitations (e.g., limited vertical dimension and unrealistic cyclic boundary conditions), while Igel and van den Heever (2015) acknowledges biases stemming from inherently inconsistent storm-relative CloudSat measurements. Additionally, much of the *in situ* research has predominately focused on (quasi-) linear convection and is largely based in the west Pacific and Indian Ocean. With TOC structure varying across the tropics, including an abundance of non-linear TOC (Houze et al., 2015), an evaluation of TOC relationships with near-storm wind shear necessitates detailed *in situ* studies in other tropical oceanic regions across different TOC types.
Similar to wind shear, field campaign data in the western Pacific and Indian Ocean basins, along with broader tropical oceanic CRM and ERA-Interim reanalysis data, have been used to investigate near-storm environmental moisture relationships with TOC structure. Analysis of these datasets have shown mid-tropospheric relative humidity (RH) to positively correlate with TOC precipitation area and intensity due to decreased dry air entrainment (Brown & Zhang, 1997; LeMone et al., 1998; Tompkins, 2001; Cetrone & Houze, 2006; Savarin et al., 2014; Chen et al., 2016; Chen et al., 2017; Schiro et al., 2020). However, the relationships between lower-tropospheric moisture and TOC precipitation area and intensity vary, in both strength and sign, across tropical oceanic studies, even within similar regions (Tompkins, 2001; Cetrone & Houze, 2006; Chen et al., 2017; Schiro et al., 2020). The inconsistencies may relate to data collection during differing TOC lifecycle stages, with low-level inflow shown to potentially be more important during early lifecycle stages compared to mid-level inflow for later lifecycle stages (Mechem et al., 2002).

Similarly, inconsistent relationships between environmental CAPE and TOC structure exist across prior studies of the western Pacific basin. Cetrone and Houze (2006) and Chudler and Rutledge (2021) found KWAJEX and PISTON MCSs, respectively, to be associated with lesser CAPE compared to smaller, less organized convective systems, while Kingsmill and Houze (1999) found opposing results using TOGA-COARE data. The conflicting results could stem from thermodynamic instability being asymmetrically concentrated in the lower troposphere in the KWAJEX soundings and near-surface modification by MCSs in the PISTON soundings, thereby negatively biasing CAPE measurements near the MCSs (Cetrone & Houze, 2006; Chudler & Rutledge, 2021).
Collectively, both the strength and sign of near-storm mean-layer environmental moisture, wind shear, and CAPE relationships with TOC structure are inconsistent across studies. These inconsistent findings could be attributed to a multitude of factors, like differing analysis methods and data sources. However, a lack of regional context may be a major culprit. This lack of modern, regionally diverse, and regionally distinct in situ research is an issue, because TOC structure and its relationships with near-storm environments have been shown through TRMM observations and ERA-Interim reanalysis to exhibit regional dependencies (Houze et al., 2015; Chen et al., 2017).

Satellite and reanalysis datasets provide the ability to examine each tropical oceanic region separately, but their limited spatial and temporal resolutions cannot sufficiently capture essential small-scale near-storm environmental variability and convective processes. Consequently, targeted regional in situ studies, particularly in understudied areas, equipped with colocated high-resolution hydrometeor, moisture, and wind measurement capabilities are imperative to adequately analyze near-storm environmental relationships with TOC structure.

Two such targeted in situ regional studies were the 2017 NASA Convective Processes Experiment and 2021 CPEX – Aerosols & Winds (CPEX-AW) field campaigns based in Ft. Lauderdale, Florida and St. Croix, USVI, respectively. CPEX and CPEX-AW performed a total of 23 science flights aboard the NASA DC-8 research aircraft from 27 May 2017 – 24 June 2017 and 20 August 2021 – 4 September 2021, respectively, to study TOC processes in the Gulf of Mexico, Caribbean Sea, and western Atlantic—regions that were notably lacking recent in situ, non-tropical cyclone related deep convective research (Cui et al., 2020). The DC-8 aircraft was equipped with, amongst other instrumentation, a multi-wavelength airborne precipitation radar, a Doppler wind lidar, and
dropsondes. Together, these instruments provided rare, coincident, high-resolution profiling of three-dimensional (3-D) convective structure and near-storm winds and moisture for convective systems of different spatial scales and intensities (Turk et al., 2020; Hristova-Veleva et al., 2021). Given the uniqueness of this suite of observations, the CPEX and CPEX-AW field campaigns present an exceptional opportunity to analyze their region’s near-storm environmental relationships with tropical oceanic 3-D convective structure, which will be the focus of this study. In particular, how does 3-D TOC structure relate to near-storm environmental RH, vertical speed shear, and CAPE in different tropospheric vertical layers in the CPEX(-AW) observational domain?

To address this research question, the organization of the paper is as follows. Section 2 offers a description of the CPEX(-AW) instrumentation and data used for the analysis, while Section 3 outlines the analysis methodology. Section 4 presents the results of the analysis, and Section 5 provides a discussion of the results in the context of prior studies. Section 6 concludes the paper with main takeaways from the analysis and next steps for future research.

2 Data

2.1 CPEX and CPEX-AW Overview

The NASA DC-8 aircraft was equipped with six science instruments during CPEX (Chen & Zipser, 2017) and five during CPEX-AW (Skofronick-Jackson et al., 2021). This paper will focus on analysis of the higher spatial resolution airborne datasets from the following instrumentation: dropsondes, the Doppler Aerosol WiNd Lidar (DAWN; Kavaya et al., 2014), and the Third-Generation Airborne Precipitation Radar (APR-3; Sadowy et al., 2003). Together, these three
instruments provided coincident, detailed measurements of near-storm moisture, winds, and 3-D convective structure (e.g., Figure 1) at sufficient resolutions to analyze characteristics of distinct vertical layers. Seventeen of the 23 CPEX(-AW) science flights sampled 20 separate deep precipitating convective systems (hereafter referred to as convective cases) with this instrument payload. As such, only observational data from these 17 science flights were used for analysis for this paper.

Figure 1: APR-3 Ku-band reflectivity profiles (fill), dropsonde wind profiles (blue barbs), and DAWN wind profiles (black barbs) for an (a) isolated and (b) organized TOC system observed during CPEX.
2.2 Dropsondes

CPEX vertical profiles of pressure, temperature, horizontal wind velocity, and humidity were collected using Yankee Environmental Systems eXpendable Digital Dropsondes (CPEX Dropsonde, 2019; Black et al., 2017). The dropsondes provided accuracy and resolutions appropriate for the purposes of this study (Greco et al., 2018; Black et al., 2017): 1.5 mb (at 25°C) accuracy at 2.5 mb resolution for pressure, 0.148°C accuracy with 0.0168°C resolution for temperature, 0.5 m s⁻¹ accuracy with 0.2 m s⁻¹ precision for horizontal winds, and 1.8% (at 25°C) accuracy at 0.1% precision for RH. CPEX-AW released the National Center for Atmospheric Research (NCAR) dropsondes, which used the Airborne Vertical Atmospheric Profiling System (AVAPS) developed by Vaisala Inc. (AVAPS Dropsondes, 2023). These CPEX-AW dropsondes provide similarly appropriate accuracy and resolutions as the ones used from CPEX (AVAPS Dropsondes, 2023) with the largest differences seen in horizontal wind velocity (0.5 m s⁻¹ accuracy at 0.01 m s⁻¹ resolution) and RH (3% accuracy at 0.01% resolution). Unfortunately, RH accuracies were notably worse in actively precipitating environments from both campaigns as the dropsondes exhibited moisture biases when encountering precipitation, likely due to water ingress (Greco et al., 2018). As such, moisture data from dropsondes deployed in actively precipitating environments was excluded from analysis in this paper. All the dropsonde data was processed using the NCAR Atmospheric Sounding Processing ENvironment (ASPEN) software (Greco et al., 2018; Vömel et al., 2021; Martin & Suhr, 2021). Post-mission GPS correction was also employed (CPEX Dropsonde, 2019). Dropsonde profiles with frequent, graphically visible anomalous spikes in equivalent potential temperature were excluded from analysis, amounting to 195 usable dropsondes across the 20 convective cases.
2.3 Doppler Aerosol WiNd Lidar (DAWN)

High-resolution vertical profiles of wind near convection were collected by the DAWN instrument aboard the NASA DC-8 aircraft during CPEX(-AW). DAWN is equipped with a 2-μm, 10-Hz laser that utilizes atmospheric aerosols to measure horizontal wind components (Kavaya et al., 2014; Turk et al., 2020; Greco et al., 2020). DAWN vertical wind profiles were obtained at horizontal resolutions as fine as 3-7 km and a vertical resolution of ~33 m using the LOS wind profiles (CPEX DAWN, 2019; Greco et al., 2020). These profiles were severely attenuated when encountering opaque clouds (e.g., convective anvil cirrus), and data gaps frequently existed in the middle troposphere due to low aerosol concentrations (e.g., Bedka et al., 2021). DAWN wind speed accuracy was < 0.05 m s\(^{-1}\) with < ~1.5 m s\(^{-1}\) precision (Greco et al., 2020) and showed a low bias of < 0.20 m s\(^{-1}\) compared to dropsonde winds (Greco et al., 2020). Given the scales that are being explored for comparing mean-layer wind shear (differences hypothesized to be several m s\(^{-1}\)), the DAWN wind accuracy and precision are adequate for the purposes of this study. DAWN data was processed and quality controlled via methods described in Kavaya et al. (2014), CPEX DAWN (2019), Greco et al. (2020), and Bedka et al. (2021).

2.4 Third-Generation Airborne Precipitation Radar (APR-3)

Vertical radar reflectivity profiles of 3-D convective hydrometeor structure were collected using the APR-3 instrument (Sadowy et al., 2003). APR-3 mirrors the Global Precipitation Measurement Mission Dual-Frequency Precipitation Radar (GPM-DPR) 13.4-GHz (Ku-) and 35.6 GHz (Ka-) bands, which simultaneously measure co- and cross-polarized reflectivities and vertical Doppler velocities (Durden et al., 2012; Turk et al., 2020; CPEX APR-3, 2018). Only Ku-band reflectivity profiles were used for analysis, as the Ku-band captures precipitation structure better than the Ka-
band, which is more quickly attenuated by precipitating hydrometeors. Doppler velocity datasets were corrupted for a majority of CPEX convective cases (i.e., cases prior to 16 June 2017). Therefore, Doppler velocity was not incorporated in subsequent analysis. APR-3 scans at a vertical resolution of 60 m (Sadowy et al., 2003; Durden et al., 2012). Ku-band horizontal resolution is ~730 – 800 m at 10-km altitude with a 10 dBZ sensitivity (Sadowy et al., 2003; Durden et al., 2012). APR-3 data was processed via methods described in Durden et al. (2012), with Ku-band calibration uncertainty for the CPEX and CPEX-AW campaigns estimated at 1 dB (CPEX APR-3, 2018; Turk et al., 2020).

3 Methods

3.1 Convective Case Characterization

In order to investigate near-storm environmental relationships with TOC structure, each of the 20 CPEX(-AW) convective cases was categorized as either isolated, organized, or scattered based on horizontal precipitation extent and continuity provided by archived hourly Integrated Multi-satellitE Retrievals for GPM (IMERG) satellite data. Given the inherent small number of cases from the field campaigns, categorization of each convective system was manual. Isolated convective systems were defined as horizontally small, single-core precipitating regions, while organized convective systems were defined as broader, continuous, multi-core precipitating regions. Scattered convection was defined as broad, discontinuous precipitating regions. An example of each type of convection in the context of IMERG is depicted in Figure 2 using the CPEX data portal (Hristova-Veleva et al., 2020). The focus of this paper is on isolated and organized non-tropical cyclone TOC cases. As such, 12 out of the 20 total convective cases sampled during CPEX(-AW) underwent further analysis (Table 1). All but one (i.e., Case 15) of
the 12 cases was sampled during a similar time of day (i.e., between 1800 UTC and 0000 UTC), so diurnal influences on convective structure are assumed to have been similar across cases.
Figure 2: An example of (a) isolated, (b) organized, and (c) scattered TOC sampled during CPEX, as defined by GPM IMERG precipitation area and continuity. CPEX science flight tracks are overlaid in red with hourly timestamps.
3.2 Dropsonde Characterization

Only dropsonde profiles temporally collocated with their respective convective case’s APR-3 data (i.e., within or near the anvil region) were considered for analysis, amounting to 111 dropsondes. Each dropsonde from the cases identified in Table 1 was characterized by the convective type of its respective case, along with the convective-relative environment it was deployed into. Using APR-3 plots overlaid with dropsonde and DAWN wind profiles (e.g., Figure 1), the three environmental categories were “Clear” (little to no reflectivity overlaid with the profile), “In Cloud” (deployed through a non-precipitating cloud layer(s)), and “In Precip” (deployed through an actively precipitating region). Skew-T diagrams of the dropsonde profiles (not shown) also aided in validation of the environmental categorization. The distribution of dropsondes amongst the three environmental categories for each case is shown in Table 1, along with the distribution of full and partial (i.e., sparse data coverage in certain layers due to GPS transmission issues) dropsonde profiles for each case. Due to the notable moisture biases of In Precip dropsondes, as

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Field Campaign</th>
<th>Region</th>
<th>Convective Type</th>
<th>Number of Dropsondes (Full)</th>
<th>Number of Dropsondes (Partial)</th>
<th>Clear</th>
<th>In Cloud</th>
<th>In Precip</th>
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<tr>
<td>1</td>
<td>20170610</td>
<td>CPEX</td>
<td>Western Atlantic</td>
<td>Isolated</td>
<td>11</td>
<td>2</td>
<td>9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
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<td>20170624</td>
<td>CPEX</td>
<td>Caribbean</td>
<td>Isolated</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>20170624</td>
<td>CPEX</td>
<td>Gulf of Mexico</td>
<td>Isolated</td>
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<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
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<td>CPEX</td>
<td>Caribbean</td>
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<td>2</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
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<td>CPEX</td>
<td>Caribbean</td>
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<td>0</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>20170601</td>
<td>CPEX</td>
<td>Gulf of Mexico</td>
<td>Organized</td>
<td>6</td>
<td>12</td>
<td>0</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
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<td>0</td>
<td>2</td>
</tr>
<tr>
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<td>20170617</td>
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<td>Caribbean</td>
<td>Organized</td>
<td>0</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
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<td>10</td>
<td>5</td>
<td>4</td>
</tr>
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<td>1</td>
<td>0</td>
</tr>
<tr>
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<td>5</td>
<td>4</td>
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<td>5</td>
</tr>
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</table>
previously mentioned in Section 2, only wind data from In Precip dropsondes was used for analysis in this paper.

All near-storm environmental analysis was performed for data from all convective lifecycles and separately excluding dropsondes deployed into weakening convective systems. Excluding the weakening lifecycle stage was tested as a means to focus on environments supporting convective development and sustainment. However, the results of the analysis excluding the weakening lifecycle stage data (figures not shown in this paper) were similar to the results of the analysis that included data from all lifecycle stages, and thus all analysis presented in later sections includes data from all lifecycle stages.

3.3 Mean-layer, Near-storm Environmental Metrics

Mean RH and vertical wind speed shear were calculated for each dropsonde profile for four distinct layers: the PBL, mid layer, upper layer, and deep layer. The base of the PBL is defined as the profile height nearest to the surface, ranging from 6.5 m to 338.5 m because of dropsonde transmission issues. Metric values were not found to correlate with near-surface height within that range. The top of the PBL is defined as the first height for which the virtual potential temperature exceeds its value nearest to the surface by 0.5 °C (e.g., Blumberg et al., 2017). The mid layer extends from the top of the PBL up to the freezing level (i.e., 0 °C), while the upper layer extends from the freezing level up to the lowest maximum height of the 111 qualifying dropsondes (7622.5 m), such that a uniform upper layer cap was achieved. The deep layer ranges from the profile height nearest to the surface up to the lowest maximum dropsonde height.
Layer RH calculations use RH data at all height levels within the specified layer thresholds to calculate profile mean-layer RHs. With the assistance of the Sounding/Hodograph Analysis and Research Program in Python (SHARPpy; Blumberg et al., 2017) open-source meteorological package, vertical speed shear was calculated for the four distinct layers using the dropsonde component winds at each layer threshold height (interpolated as necessary). In addition to mean-layer RH and vertical speed shear, both most-unstable convective available potential energy (MUCAPE, using the most unstable air parcel found within the lowest 300-mb of the troposphere) and mixed-layer CAPE (MLCAPE, using a parcel with the mean temperature and moisture values from the lowest 100-mb of the troposphere) were calculated for each dropsonde for the deep layer and the upper layer (i.e., above the freezing level) using SHARPpy. Upper layer CAPE supplements deep layer CAPE as an effort to avoid potential negative biasing of near-storm CAPE measurements by MCSs, as previously discussed in Chudler and Rutledge (2021). Environmental metrics for layers that were not fully sampled by partial dropsonde profiles (see Table 1) were excluded from analysis.

Similar to the dropsonde data, only DAWN profiles that were temporally collocated with their respective convective case’s APR-3 data—and thus near convection—were included in analysis. The DAWN instrument provided much denser wind profiling (both spatially and temporally) in non-anvil regions compared to the dropsondes. That being said, PBL depth and freezing level height could not be identified for each DAWN profile owing to temperature and moisture data not available from DAWN. With PBL depth in dropsonde data found to vary appreciably within short geospatial and temporal ranges, only deep layer wind shear could be confidently calculated for the DAWN profiles. The DAWN deep layer, in comparison with the dropsonde deep layer, was
similarly capped at the lowest maximum dropsonde height of 7622.5 m. However, the deep layer
for the DAWN data slightly varies from the dropsonde deep layer, in that a uniform near-surface
value of 500 m was employed to omit low SNR (i.e., noisy) data from DAWN shear calculations.
For similar reasons, DAWN profiles, with a vertical resolution of ~33 m, were also required to
contain at least 20 data points within the lowest 1 km of the atmosphere. An equivalent 500 m –
7622.5 m dropsonde deep layer shear was computed for direct comparison with DAWN deep layer
shear.

3.4 Contoured Frequency by Altitude Diagrams
For collective analysis of convective intensity from reflectivity data, all APR-3 Ku-band
reflectivity profiles for an individual case were binned into 2-dimensional histograms with 5-dBZ
and 0.5-km intervals to create Contoured Frequency by Altitude Diagrams (CFADs) (Yuter &
Houze, 1995). The reflectivity bins extend from -20 dBZ to 60 dBZ. The height bins extend from
1.5 km to 8 km, so as to omit potentially spurious near-surface data (Sadowy et al., 2003; Durden
et al., 2003) and provide a uniform upper layer altitude cap to allow for case intercomparison. The
heights from the reflectivity profiles, and thus in each CFAD, were not adjusted for brightband
height, as brightband height across all the convective cases did not vary considerably (i.e., < ~0.5-
km, or one height interval). Each CFAD was normalized by the maximum bin count in any height
interval, allowing for frequency comparisons across height levels (e.g., Zagrodnik et al., 2019).
Each CFAD was also separately normalized by the maximum bin count in each height interval,
allowing for easier frequency comparisons at a given height level. Subsequent so-called
“difference CFADs” were produced by subtracting one case’s normalized CFAD from another.
These difference CFADs allow for investigation of convective intensity and storm structure
differences between cases with distinct mean-layer environmental metric differences (Yuter & Houze, 1995). Convective case intercomparisons, via difference CFADs, were only performed between cases of similar convective type (i.e., isolated vs. isolated, organized vs. organized), as comparisons across convective type would offer little value due to inherent differences in single-core vs. multi-core storm structure. Convective case intercomparisons were also only performed between cases that were observed during a similar convective lifecycle stage, such that predominantly convective elements are not compared with predominantly stratiform elements.

4 Results

4.1 Near-storm Environmental Relationships with Convective Type

To analyze potential near-storm environmental relationships with TOC type (i.e., isolated versus organized), mean-layer dropsonde metrics are presented as box-and-whisker plots (e.g., Figure 3). CAPE is first analyzed, showing that isolated convection has greater median deep layer MUCAPE (929 J kg\(^{-1}\) vs. 900 J kg\(^{-1}\), Figure 3a) and MLCAPE (570 J kg\(^{-1}\) vs. 524 J kg\(^{-1}\), Figure 3b) compared to organized convection. More distinctly, isolated convection is also observed to have greater median upper layer MUCAPE (613 J kg\(^{-1}\) vs. 549 J kg\(^{-1}\), Figure 3c) and MLCAPE (393 J kg\(^{-1}\) vs. 317 J kg\(^{-1}\), Figure 3d). Large CAPE variability exists within each convective type, however, that motivates further subdivision by case. Figure 4 reveals large CAPE variability within each case as well, even when accounting for location of the dropsonde relative to the precipitating system. This result is not surprising, as like many prior observational studies of CAPE and TOC structure (e.g., Chudler & Rutledge, 2021), CPEX(-AW) likely sampled near-storm environments where CAPE was both unrealized and separately already realized. Large intra-case variability may also partly be attributed to flight duration and spatial extent, but some cases have large metric variabilities
Despite convective flight legs covering small areas (e.g., Case 1 and Case 15) and/or having small observation periods (e.g., Case 15). Therefore, despite no clear general relationship between convective type and MUCAPE/MLCAPE in either layer in the CPEX(-AW) region, some cases—even of similar convective type—do have distinctly different CAPE magnitudes compared to others (e.g., isolated Cases 1 and 3 with upper layer CAPE in Figure 4d), which will be investigated more as individual case comparisons in Section 4.2 and Section 4.3.
Figure 3: Dropsonde-derived (a) deep layer MUCAPE, (b) deep layer MLCAPE, (c) upper layer MUCAPE, and (d) upper layer MLCAPE for isolated (red) and organized (blue) TOC systems sampled during CPEX and CPEX-AW (In Precip profiles excluded). Each box extends from the first quartile to the third quartile of the data, with a black line at the median. Whiskers extend from the box by up to 1.5 times the inter-quartile range, and outlier points are points beyond the whiskers.
Figure 4: Same data as Figure 3, but dropsonde observations are further sorted by convective case (In Precip profiles included as well). Markers denote the convective-relative environment the dropsonde was deployed into.
RH appears to have a slightly clearer distinction between convective types, with organized convection associated with slightly greater median RH in the PBL (88.8% vs. 85.8%, Figure 5b) and upper layer (55.6% vs. 53.0%, Figure 5d), while isolated convection is associated with a slightly greater median deep layer RH (66.1% vs. 64.5%, Figure 5a). Both isolated and organized convection have similar mid layer median RH (71.0% vs. 71.7%, Figure 5c), which regionally differs from aforementioned west Pacific studies that consistently link greater mid layer RH to more organized convection. As with CAPE, large mean-layer RH spreads exist for both convective types, particularly for organized convection (Figure 5), and within individual cases (Figure 6), especially Cases 1, 13, and 16. Organized Cases 13 and 16, in particular, record some of the lowest mean-layer RH values of any case and will be investigated further in Section 4.4. When comparing only the clear air dropsondes for each case across convective type, deep layer RH is generally greater for isolated convection (Figure 6a), while PBL RH is generally greater for organized convection (Figure 6b). Distinct mean-layer RH differences between cases of similar convective type also exist, which further motivates case comparisons in Section 4.2 and Section 4.3.
Figure 5: Same as Figure 3, except showing (a) deep layer RH, (b) PBL RH, (c) mid layer RH, and (d) upper layer RH.
Figure 6: Same data as Figure 5, but dropsonde observations are further sorted by convective case (In Precip profiles included). Markers denote the convective-relative environment the dropsonde was deployed into.
Similar to RH, the PBL is a focal point for vertical wind speed shear distinctions between convective type. Organized convection has greater median PBL speed shear (5.0 kts vs. 3.5 kts, Figure 7b) compared to isolated convection, as well as greater mid (17.7 kts vs. 8.6 kts, Figure 7c) and deep layer (22.0 kts vs. 16.0 kts, Figure 7a) speed shears. As with prior metrics, a large degree of mean-layer speed shear variability also exists within each convective type (especially for organized convection). When grouped by case (Figure 8), large speed shear spreads within cases are evident and are notably unrelated to the environment the dropsondes were deployed into (i.e., Clear, In Cloud, or In Precip). However, similar to CAPE and RH, distinct mean-layer speed shear differences do exist amongst cases of similar convective type, which further warrants comparing individual cases in Section 4.2 and Section 4.3. Ultimately though, organized convection is associated with generally greater PBL, mid, and deep layer near-storm speed shear than isolated convection (Figure 8a,b,c).
Figure 7: Same as Figure 3, except showing (a) deep layer speed shear, (b) PBL speed shear, (c) mid layer speed shear, and (d) upper layer speed shear. In Precip profiles are now included.
Figure 8: Same data as Figure 7, but dropsonde observations are further sorted by convective case. Markers denote the convective-relative environment the dropsonde was deployed into.
Incorporating the spatially and temporally denser DAWN observations provides an enhanced look into deep layer speed shear trends compared to dropsondes alone (Figure 9). The addition of the DAWN observations reveals even larger deep layer speed shear variability within each convective type (Figure 9a) and each convective case (Figure 9b) than the dropsonde observations previously showed. Notably, median deep layer speed shear is actually greater for isolated convection compared to organized convection (25.0 kts vs. 21.2 kts, Figure 9a), which the less frequent dropsonde data did not capture. When comparing all isolated case speed shear observations with the organized cases, however, the relationship between deep layer speed shear and convective type is unclear (Figure 9b).

Overall, the composite analysis of near-storm environmental relationships with convective type reveals broad near-storm environmental metric variability within each convective type. However, general mean-layer CAPE, RH, and speed shear trends do exist with regards to two-dimensional (2-D) TOC structure. Coupled with distinct metric variability between cases of similar convective type, it raises the question whether similar (or perhaps even more pronounced) near-storm environmental trends apply to vertical convective structure (i.e., convective intensity) for each convective type.
To analyze near-storm environmental relationships with isolated TOC intensity, normalized CFADs (see Section 3.4) were created for each isolated case (except Case 15, which had limited APR-3 reflectivity data). Then, cases with distinctly different mean-layer metric values (Section 4.1) had their normalized CFADs differenced to visually determine which case had more frequent greater Ku-band reflectivities throughout the vertical column (i.e., which convective system was
more intense). Subsequent comparison of convective intensities and their associated dropsonde mean-layer environmental metrics was performed. Ensuing CFAD figures were normalized by the maximum bin count in each height interval. However, similar analysis was performed with CFADs normalized by maximum bin count in any height interval, and each method produced the same conclusions. Together, the isolated case comparisons show the more intense isolated case (an example shown in Figure 10a comparing Cases 1 and 2) to consistently possess greater upper layer MUCAPE and MLCAPE and greater deep layer MLCAPE (as determined in Figure 4). This general relationship could result from greater CAPE environments promoting hydrometeor growth through enhanced thermodynamic instability (i.e., buoyancy). No other environmental metrics showed as clear of a distinction in isolated convective intensity and thus are not shown.

Figure 10: (a) Case 2 normalized CFAD subtracted from the Case 1 normalized CFAD. (b) Case 7 normalized CFAD subtracted from the Case 8 normalized CFAD. APR-3 Ku-band reflectivity data is binned into 5-dBZ and 0.5-km intervals and normalized by the maximum bin count in each height interval.
4.3 Near-storm Environmental Relationships with Convective Intensity (Organized)

Similar to the isolated case comparisons, organized TOC intensity was explored via normalized CFADs in the context of distinct mean-layer differences between cases (Section 4.1). When comparing all CPEX(-AW) organized convective cases with distinct mean-layer environmental metric differences, no consistent mean-layer speed shear, MUCAPE, nor MLCAPE relationships with convective intensity were found. However, when a notable difference in upper layer RH existed between two organized cases, the more intense convection (e.g., Figure 10b comparing Cases 7 and 8) was consistently associated with greater upper layer RH (Figure 6d). This relationship could be explained by less dry air entrainment promoting enhanced hydrometeor growth and limiting negative buoyancy introduction.

When intercomparing the isolated case comparison results with those from organized cases, it is noteworthy that there are no similar, consistent near-storm mean-layer metric trends with convective intensity. This lack of similarity between convective types points to single-core and multi-core systems interacting differently with their near-storm environments. An additional lack of consistent near-storm environmental relationships with organized TOC intensity suggests multi-core systems also variably interact with their near-storm environments. The latter finding is likely attributed to diverse vertical organizational structures of multi-core TOC (e.g., linear vs. non-linear MCSs), which were observed during CPEX(-AW) and will be explored further in the following section.
4.4 Case 13 vs. Case 16 Organized Convection Comparison

As highlighted in Section 4.1, large mean-layer RH variability existed for organized convective systems (Figure 5). Upon further examination, Cases 13 and 16 contained many of the lowest mean-layer RH values of any sampled CPEX(-AW) convective system (Figure 6), and thus were responsible for the particularly large mean-layer RH spreads of organized TOC. The relatively dry near-storm observations, coupled with the especially large RH variability, motivated further investigation into the convective environments of Case 13 and Case 16.

The convective flight legs and observations of Cases 13 and 16 each encompassed a synoptic-scale horizontal moisture gradient (Figure 11; Hristova-Veleva et al., 2020), providing a reason for large intra-case RH spreads and notably dry near-storm observations that were particularly influential on the RH results of Section 4.1. No other observed convective systems during CPEX(-AW) were located near synoptic-scale moisture gradients, making Cases 13 and 16 unique in that aspect.

From a satellite-based perspective, both cases had similar 2-D structures (Figure 11) with an intensifying sector and a matured sector identified by decreasing and increasing infrared brightness temperatures with time, respectively. Both cases’ deep precipitating regions were located on the moist side of their respective synoptic-scale moisture gradient, with each moisture gradient collocated with a similar strength (~15 m s⁻¹), along-gradient 800 – 650 mb mid-level jet (not shown but observed by the dropsondes). However, despite these similarities, the vertical structures of the organized Case 13 and Case 16 convective systems were markedly different, with Case 13 mainly composed of leading line convective elements with trailing stratiform (Figure 12a), while Case 16 was characterized by numerous embedded convective elements within predominant widespread stratiform (Figure 12b). Cases 13 and 16 therefore provided a unique opportunity to
investigate how differing organized vertical convective structures relate to near-storm moisture and speed shear in the CPEX(-AW) region.

Figure 11: (a) Case 13 TPW (bottom layer fill), GPM IMERG surface precipitation estimation (top layer fill), and DC-8 science flight track (red line). (b) Same as (a), but for Case 16.
For this case comparison, all dropsonde and DAWN observations for the Case 13 and Case 16 analysis were further contextualized as being collected within or beyond each case’s synoptic-scale moisture (TPW) gradient (Figure 13, Figure 14). The larger spread in deep layer shear (Figure 13a) accounts for including DAWN measurements (as in Section 4.1), with considerable overlap between cases. Similarly, no clear case distinction was found between mean-layer speed shear from dropsondes in similar locations relative to the moisture gradient (Figure 13). There is a hint of stronger PBL shear near the convection in Case 13, but Case 16 dropsondes within the moisture gradient were all in precipitating regions, thus highlighting inconsistencies in approaches to dropsonde targets across cases and campaigns. Therefore, no distinct differences in mean-layer shear with organized vertical convective structure is revealed from this case comparison.
Figure 13: Dropsonde-derived (a) 0.5-km – 7.6-km deep layer speed shear (DAWN observations included as well), (b) PBL speed shear, (c) mid layer speed shear, and (d) upper layer speed shear for Case 13 and Case 16. Observations are color-coded by the location of their dropsondes relative to the synoptic-scale moisture gradient, and their markers denote the convective-relative environments their dropsondes were deployed into.
Figure 14: Same as Figure 13, except showing (a) deep layer RH, (b) PBL RH, (c) mid layer RH, and (d) upper layer RH.
Observations collected within the moisture gradient unsurprisingly tended to have greater mean-layer RH compared to observations collected beyond the moisture gradient (Figure 14). With Case 16 only having quality (i.e., not In Precip) RH observations beyond the moisture gradient, mean-layer RH comparisons were only performed amongst data collected from the impinging dry air beyond the moisture gradient associated with each convective system. The deep layer and mid layer were notably drier for Case 16 compared to Case 13 (Figure 14a,c), with the 800 – 650 mb jet layer (located entirely within the mid layer, not shown) in particular having dewpoint depressions exceeding three times those of Case 13. The distinctly differing near-storm environmental moisture of Cases 13 and 16 motivated further analysis on how the near-storm environments may have influenced convective intensity.

Reflectivity CFADs were again used to compare convective intensity between cases. Cases 13 and 16 were each subdivided into their intensifying and matured sectors for the normalized difference CFAD plots (Figure 15). Case 16’s intensifying sector, with drier mid-levels and lesser average deep layer, upper layer, and PBL speed shear, was more intense than the intensifying sector of Case 13 (Figure 15a). However, for the matured sectors of the two systems, Case 16 was more intense than Case 13 (Figure 15b) despite similar near-storm, mean-layer RH and speed shear. These results indicate that near-storm environmental relationships with convection may not only be dependent on the degree and type of organization, but also on convective lifecycle stage.
Without clear relationships between TOC structure and near-storm environments from these two cases, there are additional environmental factors to consider in controlling convection formation, evolution, and intensity. Recent work (e.g., Galarneau et al. 2023) has highlighted not just the importance of moisture, but of low-level convergence in concentrating moisture and priming conditions for MCS development over tropical oceans. In revisiting dropsonde observations from Cases 13 and 16, synoptic-scale low-level convergence is observed in the Case 16 precipitating system (Figure 16) but not in Case 13 (not shown). This broad low-level convergence could explain Case 16 being notably more intense than Case 13 (Figure 15), despite much drier impinging air (Figure 14a,c). Therefore, this case comparison suggests that sufficient large-scale low-level convergence can provide enough forcing for TOC to thrive in otherwise seemingly less favorable near-storm environmental conditions and also influence the vertical structure of organized convection (e.g., increasing the number and intensity of convective elements).

Figure 15: Same as Figure 10, but for the (a) intensifying and (b) matured sectors of Case 16 and Case 13.
Figure 16: (bottom) Dropsonde skew-T diagram and hodograph (18:34:14 UTC) from the southern half of Case 16 (center) showing near-surface southeasterly winds (black oval). (top) Dropsonde skew-T diagram and hodograph (18:01:43 UTC) from the northern half of Case 16 (center) showing near-surface northeasterly winds (black oval). For each dropsonde skew-T diagram, CAPE is shaded in light red, full lines on wind barbs represent 5 m s⁻¹, and half lines on wind barbs represent 2.5 m s⁻¹.
5 Discussion

The analysis presented in Section 4 showed that CPEX(-AW) near-storm, mean-layer environmental metrics varied widely within a given convective type and case, but notable environmental trends with convective type and intensity emerged amongst the variability. Deep layer RH was generally lesser for organized TOC compared to isolated TOC (Section 4.1), which conflicts with the prevailing idea that a drier tropical troposphere inhibits TOC development through enhanced dry air entrainment and negative buoyancy introduction. However, when evaluating convective intensity within the context of near-storm RH and CAPE, clearer relationships were observed within the upper layers (i.e., above the freezing level). More specifically, stronger organized TOC was associated with greater upper layer RH (Section 4.3), while stronger isolated TOC was linked to greater upper layer CAPE (Section 4.2). These results align with observations in the west Pacific (Cetrone & Houze, 2006 and Kingsmill & Houze, 1999, respectively) and are more consistent with the concept of greater moisture and CAPE promoting hydrometeor growth through enhanced positive buoyancy. This logic, though, did not translate to a case comparison between two CPEX(-AW) MCSs forming on the moist side of strong synoptic-scale moisture gradients (Section 4.4), with the more intense organized system having a distinctly drier impinging synoptic airmass that logically contrasts with results from prior observational (Brown & Zhang, 1997; LeMone et al., 1998; Cetrone & Houze, 2006), CRM (Tompkins, 2001), and ERA-Interim (Chen et al., 2017; Schiro et al., 2020) studies. However, evaluating this case comparison in the context of other studies may not be appropriate, as the dropsonde observations within the synoptic-scale moisture gradients (where both CPEX(-AW) systems flourished) were not consistently reliable.
The result in Section 4.1 that PBL RH was generally greater for organized TOC compared to isolated TOC (Figure 5b, Figure 6b) is consistent with studies using CRM (Tompkins, 2001) and ERA-Interim reanalysis (Chen et al., 2017; Schiro et al., 2020) datasets, yet differs from KWJEX observations in the west Pacific (Cetrone & Houze, 2006), highlighting potential regional variability in these relationships. Mid and upper layer RH relationships with convective type were unclear (Figure 6c,d), which also differs from more conclusive observationally based studies in the west Pacific (e.g., Brown & Zhang, 1997; LeMone et al., 1998; Cetrone & Houze, 2006). The inconsistencies with other studies may be due to legitimate regional variation, but also from incorporation of observations from different convective regions and lifecycle stages (e.g., Mechem et al., 2002). Additionally, these RH trends may signify convective evolution in other ways, such as through relationships with other environmental metrics that impact convective lifecycle. For example, studies in the Indian Ocean (Savarin et al., 2014; Chen et al., 2016; Chandra et al., 2018) related drier mid-levels to greater PBL depth (via longer PBL recovery times) owing to enhanced dry air entrainment promoting stronger cold pools that can influence TOC evolution (e.g., Tompkins 2001; Feng et al., 2015; Rowe & Houze, 2015; Grant et al., 2018) and are known to vary globally over oceans (Garg et al. 2020). While the present study does not explicitly investigate cold pools, CPEX(-AW) observations do show a similar link between mid layer dryness and PBL depth ($R_{\text{Pearson}} \approx 0.537$, Figure 17), further highlighting the complexity in generalizing environmental moisture relationships with convective system structure.
Figure 17: Dropsonde-derived PBL depth vs. mean mid layer RH (In Precip dropsondes excluded). Observations are color-coded by the convective type of the case they were associated with, and their markers denote the convective-relative environments their dropsondes were deployed into. A linear regression of the data is overlaid (black dashed line), with a corresponding regression coefficient of 1.1 mb %^{-1} and a Pearson correlation coefficient of 0.537.
Consistent with previous research linking cold pools to convective lifecycle through relationships with wind shear (Yuter & Houze, 1995; Houze, 2018), vertical speed shear in the PBL was generally greater for organized TOC compared to isolated TOC (Figure 8b,c). This finding is also consistent with prior ERA-Interim reanalysis and PISTON observational studies linking more organized convection to stronger low-level wind shear (e.g., Chen et al., 2017; Chudler & Rutledge, 2021). Differing from previous studies using CRM, reanalysis, and TOGA COARE data (Tomkins, 2001; Igel & van den Heever, 2015; Saxen & Rutledge, 2000), this CPEX(-AW) analysis did not find a clear link between deep layer shear and TOC 2-D structure (Figure 9b). However, previous studies, particularly those in the west Pacific, were predominately based on observations of quasi-linear TOC and thus may not be directly comparable to the CPEX(-AW) observations that sampled few quasi-linear convective systems. One example of a leading convection-trailing stratiform archetype was Case 13, which was compared with a non-linear MCS (Case 16) with similarly intensifying and matured sectors (Section 4.4). Owing to the inconsistency in reliable dropsonde observations on either side of the synoptic-scale moisture gradient, direct comparisons between the wind shear profiles between cases were inconclusive. However, a key result of this comparison was in highlighting the likely role of synoptic-scale low-level convergence in promoting more intense convection in the non-linear MCS (Case 16) despite drier mid-level air in the vicinity of the system, pointing to a key component of future research.

6 Conclusions

Using a unique suite of collocated, high-resolution airborne observations of deep (non-tropical cyclone) TOC from the NASA 2017 CPEX and 2021 CPEX-AW field campaigns, this study presented an analysis of near-storm environmental relationships with 3-D TOC structure in the
Gulf of Mexico, Caribbean Sea, and western Atlantic region. Large variability in near-storm mean-layer CAPE, vertical speed shear, and RH was observed amongst systems of similar convective type (isolated, organized) and also within individual convective systems. Despite this large variability and the inherently small sample size of 12 convective systems (4 isolated, 8 organized), notable links emerged between near-storm environmental metrics and 3-D convective structure:

- The PBL was the layer most commonly related to 2-D TOC structure, with organized (i.e., multi-core) TOC being associated with generally greater PBL RH and speed shear compared to isolated (i.e., single-core) TOC.

- The upper layer (i.e., above the freezing level) was the layer most consistently related to vertical convective structure (i.e., TOC intensity), with more intense isolated TOC being associated with greater upper layer CAPE and more intense organized TOC being associated with greater upper layer RH.

- Synoptic-scale low-level convergence potentially fostered more intense TOC in otherwise seemingly less favorable near-storm environmental conditions, and it may influence the vertical organizational structure of multi-core TOC (e.g., by increasing the number and intensity of convective elements).

While prior studies, combined with this study, find inconsistent relationships between near-storm PBL environments and TOC, this study and others denote the importance of PBL characteristics to the organization of TOC. Therefore, accurate PBL representation in weather and climate models appears critical to improve TOC parameterization. A lack of similar environmental trends with TOC intensity across convective type suggests that single-core and multi-core TOC systems interact differently with their near-storm environments, thus necessitating distinguished process-
level research on both types of TOC. Additionally, prior studies tend to not discuss upper layer environmental influences on TOC. The results of this study contend that relationships between TOC intensity and environments above the freezing level should be given more attention.

With prior studies (e.g., Chen et al., 2017) showing TOC relationships with near-storm environments to vary regionally, this study helps address a notable regional gap in in situ analysis of relationships between TOC structure and near-storm environments. Consequently, the results of this paper are specific to the Gulf of Mexico, Caribbean Sea, and western Atlantic region and cannot be confidently translated to other tropical oceanic regions. The unique capabilities of the CPEX(-AW) remote sensing instrumentation in their ability to capture essential small-scale (both spatially and temporally) near-storm environmental features and variability are also highlighted, and they serve as an important benchmark for future TOC studies. The CPEX(-AW) instrumentation, particularly DAWN, offer a glimpse into the potential of future spaceborne remote sensing, with higher resolution measurements capable of improving modeling efforts through improved process-level knowledge of tropical convection (e.g., Turk et al., 2020; Mazza & Chen, 2021), data assimilation (e.g., Cui et al., 2020; Hristova-Veleva et al., 2021; Minamida & Posselt, 2022), and model evaluation (e.g., Cui et al., 2020; Minamida & Posselt, 2022).

Future work will extend analysis of near-storm environmental relationships with 3-D TOC structure to the eastern Atlantic region using similar airborne observations from the recent 2022 NASA CPEX – Cabo Verde (CPEX-CV) field campaign. Unlike CPEX-AW, however, CPEX-CV science flights included a focus on repeated sampling of convective systems and similar storm-relative regions, providing the opportunity to better analyze and compare specific TOC regions
that could not be adequately performed in this study. Furthermore, idealized TOC simulations using the NCAR Cloud Model 1 will also be executed, wherein input sounding moisture and winds (informed by CPEX(-AW) observations) will be altered to analyze their effects on TOC structure and organization.
Acknowledgements

This research was supported by NASA Award 80NSSC20K0894. The authors thank all NASA CPEX, CPEX-AW, and CPEX-CV leadership and participants, for which this research would not be possible without. This research especially benefited from the guidance of Simone Tanelli and Ousmane Sy at the Jet Propulsion Laboratory (JPL) on APR-3 data and that of Kristopher Bedka (NASA Langley Research Center) on DAWN data. The authors also thank Randy J. Chase for providing APR-3 coding assistance and Svetla Hristova-Veleva on the JPL Portal for important visual synthesis of datasets to support this research.
Open Research

Information on the NASA CPEX 2017 campaign is available at the main project page: https://cpez.jpl.nasa.gov/cpez2017/, which includes a link to the processed data used in this analysis: https://tcis.jpl.nasa.gov/data/cpez/ (Chen & Zipser, 2017). From this link, data used in the analysis is accessed from the latest versions of the APR-3, DAWN and dropsonde folders with no registration required for access. These folders also include the README files referenced in the text. Images from the CPEX data portal can be recreated at the following link: https://cpezportal.jpl.nasa.gov/.

For NASA CPEX-AW 2021 datasets, the main project page is found here: https://cpez.jpl.nasa.gov/cpez-aw/ with no similar direct link to the data repository (Skofronick-Jackson et al., 2021). The CPEX-AW data is freely accessible through registering at the NASA EarthData repository following this campaign-specific link: https://search.earthdata.nasa.gov/search?fpj=CPEX-AW. To access this data by instrument, see the main site for the entire CPEX-AW data collection (http://dx.doi.org/10.5067/CPEXAW/DATA101) and direct links therein for accessing APR-3 (https://dx.doi.org/10.5067/CPEXAW/APR3/DATA101), DAWN (http://dx.doi.org/10.5067/ASDC/SUBORBITAL/CPEXAW-DAWN_DC8_1), and dropsonde (http://dx.doi.org/10.5067/ASDC/SUBORBITAL/CPEXAW-Dropsondes_1) data that were used for this analysis. Images from the CPEX-AW data portal can be recreated at the following link: https://cpez-aw.jpl.nasa.gov/.
Figures were made with Matplotlib version 3.4.2 (Hunter, 2007; Caswell et al., 2021), available under the Matplotlib license at https://matplotlib.org/. Code to process and plot the publicly available datasets used in this analysis is available upon request via the first author’s GitHub page.
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