Coupling of Precipitation and Cloud Structures in Oceanic Extratropical Cyclones to Large-Scale Moisture Flux Convergence

SUN WONG

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

CATHERINE M. NAUD

Applied Physics and Applied Mathematics, Columbia University, New York, New York

BRIAN H. KAHN, LONGTAO WU, AND ERIC J. FETZER

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

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ABSTRACT

Precipitation (from TMPA) and cloud structures (from MODIS) in extratropical cyclones (ETCs) are modulated by phases of large-scale moisture flux convergence (from MERRA-2) in the sectors of ETCs, which are studied in a new coordinate system with directions of both surface warm fronts (WFs) and surface cold fronts (CFs) fixed. The phase of moisture flux convergence is described by moisture dynamical convergence Q_{cnvg} and moisture advection Q_{adv} . Precipitation and occurrence frequencies of deep convective clouds are sensitive to changes in Q_{cnvg} , while moisture tendency is sensitive to changes in Q_{adv} . Increasing Q_{cnvg} and Q_{adv} during the advance of the WF is associated with increasing occurrences of both deep convective and high-level stratiform clouds. A rapid decrease in Q_{adv} with a relatively steady Q_{cnvg} during the advance of the CF is associated with high-level cloud distribution weighting toward deep convective clouds. Behind the CF (cold sector or area with polar air intrusion), the moisture flux is divergent with abundant low- and midlevel clouds. From deepening to decaying stages, the pre-WF and WF sectors experience high-level clouds shifting to more convective and less stratiform because of decreasing Q_{adv} with relatively steady Q_{cnvg} , and the CF experiences shifting from high-level to midlevel clouds. Sectors of moisture flux divergence are less influenced by cyclone evolution. Surface evaporation is the largest in the cold sector and the CF during the deepening stage. Deepening cyclones are more efficient in poleward transport of water vapor.

1. Introduction

A key question related to climate sensitivity is how clouds and precipitation respond to changes in the large-scale circulation (Bony et al. 2015). A more direct and fundamental question is how clouds and precipitation respond to changes in moisture flux convergence induced by changes in the large-scale circulation. In this work, we investigate moisture balance in extratropical cyclones (ETCs) to quantify coupling of precipitation and cloud processes to the large-scale circulation not only because ETCs are dominant weather patterns responsible for extreme precipitation in the extratropics (Pfahl and Wernli 2012) but also because different sectors of ETCs have

different dynamical conditions for cloud and precipitation formation (e.g., Houze and Hobbs 1982).

Because it is still unclear how precipitation in ETCs will evolve in a changing climate (e.g., Li et al. 2014; Yettella and Kay 2017), recent studies of ETCs through composites mainly focus on unraveling the interactions between clouds, precipitation, and the underlying large-scale dynamics and/or thermodynamics (e.g., Bauer and Del Genio 2006; Chang and Song 2006; Field and Wood 2007; Naud et al. 2010, 2012, 2013, 2015; Booth et al. 2013, 2018; Pfahl and Sprenger 2016). Using combined *CloudSat* (Stephens et al. 2002) and *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIPSO; Winker et al. 2009) data, Naud et al. (2010, 2015) and Booth et al. (2013) described the cloud vertical structures across transects of either surface warm or cold fronts in ETCs and investigated their relationships

Corresponding author: Sun Wong, sun.wong@jpl.nasa.gov

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with large-scale dynamic and thermodynamic variables. Detailed investigations of warm frontal cloud structures indicated that the cloudiness in the vertical tilting of warm fronts increases with the upper-tropospheric vertical velocity ahead of the surface warm fronts and also with the background moisture content (Naud et al. 2010; Booth et al. 2013; Govekar et al. 2014), implying a relationship between cloud formation and the uplifting mechanism of warm conveyor belts (WCBs; Browning 1986; Schemm et al. 2013). These studies raise a further question of how internal variation of moisture flux convergence of ETCs influences the internal variation in cloud structures.

Precipitation averaged over the area of ETCs has been correlated to the moisture fluxes in WCBs (Field and Wood 2007; Pfahl and Sprenger 2016). Rudeva and Gulev (2011) demonstrated that deepening cyclones have larger differences in extreme values of surface turbulent fluxes and precipitation than decaying cyclones. Polly and Rossow (2016) illustrated that the extreme values (maximum vs minimum) within the ETCs largely depend on cyclone depths. Both studies suggest changes in cloud and precipitating structures within the ETCs during cyclone evolution. This paper aims at further connecting these changes to moisture flux convergence within the ETCs.

In this investigation, we focus on structural changes of clouds and precipitation among different sectors of ETCs throughout their life cycle and relate the changes to phases of large-scale moisture flux convergence in the sectors. Sectors of ETCs are defined in a new coordinate system (referred to as ETC coordinates) in which directions of both surface warm and cold fronts are fixed to facilitate composites revealing the structures of both fronts. Phases of moisture flux convergence are shown in a two-dimensional phase space introduced by Wong et al. (2016). Composites and statistics of long-term satellite records of macroscopic cloud properties and precipitation surrounding ETCs are then linked to phases of moisture flux convergence. To avoid complexity caused by topographical or coastline effects, we focus on oceanic ETCs with centers at 30° – 50° latitudes in both hemispheres for 2007–15 (including 14 087 ETCs).

2. Satellite and reanalysis data

Collection-6 level 2 retrievals of cloud-top pressure (CTP) and cloud optical depth (COD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the *Aqua* platform (King et al. 2003, 2013; Platnick et al. 2003; Ackerman et al. 2008; Frey et al. 2008; Menzel et al. 2008) are used to represent cloud macroscopic properties. We average MODIS nonzero COD from 1-km pixels to 5-km resolution and use the CTP provided at the same resolution.

FIG. 1. (a) Temporal evolution of a typical storm's depth along its track. The dashed line is at 6-hourly resolution, and the solid line is the filtered evolution by a 1-day window mean. (b) Histogram of storm deepening rates and depths of ETCs with centers at latitudes of 30° – 50° in both hemispheres for 2007–15.

Following Rossow and Schiffer (1999), we use the MODIS-retrieved CTP and COD as proxies to classify clouds into nine categories. In terms of CTP, there are high-level (CTP < 440 hPa), midlevel (440 < CTP < 680 hPa), and low-level (CTP > 680 hPa) clouds. In terms of COD, there are thin (COD < 3.6), medium-thick (3.6 < COD < 23), and thick (COD > 23) clouds (see Fig. 5a, second column). Therefore, the nine cloud types are cirrus (Ci; high, thin), cirrostratus (Cs; high, medium thick), deep convective (Cb; high, thick), altocumulus (Ac; midlevel, thin), altostratus (As; midlevel, medium thick), nimbostratus (Ns; midlevel, thick), cumulus (Cu; low, thin), stratocumulus (Sc; low, medium thick), and stratus (St; low, thick). The cases that cannot be classified are simply identified in this study as “clear,” which may include undetected thin cirrus or partially cloudy pixels for which CODs are not retrieved. We note that such representation of cloud-type combinations using passive sensors (MODIS or ISCCP) tends to mask the existence of lower-level clouds under thick high clouds (Chen and

FIG. 2. Composites in the ETC coordinate (see section 3c and the appendix for definitions) of (first column) TMPA P (mm day^{-1}), (second column) MERRA-2 PWV (mm), (third column) MERRA-2 $\partial Q/\partial t$ (mm day^{-1}), (fourth column) Q_{cnvg} (mm day^{-1}), and (fifth column) Q_{adv} (mm day^{-1}) for cyclones with (a) deepening (Acc), (b) neutral (Stn), and (c) decaying (Dec) stages (see section 3c for definitions of these cyclone development stages). Also indicated are the boundaries of nine sectors as defined in Table 1.

Del Genio 2009; Marchand et al. 2010; Wong et al. 2016; Wang et al. 2016). Therefore, this study tends to observe fewer low-level clouds behind the surface warm fronts compared to previous studies using *CloudSat*/*CALIPSO* (e.g., Naud et al. 2010).

We use the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; or TRMM 3B42, version 7; Huffman et al. 2007; Huffman and Bolvin 2009) for our precipitation composites. The TMPA product is constructed by combining microwave and infrared precipitation estimates and is available at 3-hourly intervals and $0.25^\circ \times 0.25^\circ$ spatial resolution, covering the globe from 50°S to 50°N . Compared to Global Precipitation Climatology Project daily product, TMPA has a wider rain-rate spectrum with more frequent detection of both light and extreme heavy precipitation (Wong and Behrangi 2018).

Large-scale atmospheric conditions that correspond to the MODIS retrievals are obtained from the NASA Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2; Bosilovich et al. 2015; Gelaro et al. 2017) at 0.5° latitude $\times$ 0.625° longitude horizontal resolution by matching the MERRA-2 grid cell and time that are closest to the MODIS observational location and time. Then, TMPA data within

the collocated MERRA-2 grid cells are chosen to represent the corresponding precipitation.

3. ETC coordinates and moisture flux convergence phase space

a. Identification of warm and cold fronts

ETC center locations are obtained with the NASA Modeling, Analysis, and Prediction (MAP) Climatology of Midlatitude Storminess (MCMS) algorithm (Bauer et al. 2016). The algorithm uses the 6-hourly sea level pressure output of ERA-Interim (Dee et al. 2011) to identify extratropical cyclone center locations and tracks.

Separately, surface cold and warm fronts in each ETC are identified using the MERRA-2 temperature and winds. MERRA-2 has a finer horizontal spatial resolution than ERA-Interim that allows more precise front delineation. The fronts are determined at 6-hourly temporal resolution, consistent with the MCMS dataset, using an algorithm based on two published methods: a temperature gradient method (Hewson 1998) to locate and delineate surface warm and cold fronts and a method based on wind direction changes (Simmonds et al. 2012) to determine cold fronts with weaker baroclinicity. The algorithm is described in detail by Naud

TABLE 1. Definitions of nine sectors in ETCs in the ETC coordinate system.

Sector	ETC coordinate ranges
PWS	$240 < x_{\text{ETC}} < 1500 \text{ km}$, $500 < y_{\text{ETC}} < 1500 \text{ km}$
PWF	$240 < x_{\text{ETC}} < 1500 \text{ km}$, $240 < y_{\text{ETC}} < 500 \text{ km}$
WF	$240 < x_{\text{ETC}} < 1500 \text{ km}$, $-240 < y_{\text{ETC}} < 240 \text{ km}$
WS	$240 < x_{\text{ETC}} < 1500 \text{ km}$, $-1500 < y_{\text{ETC}} < -240 \text{ km}$
CF	$0 < x_{\text{ETC}} < 240 \text{ km}$, $-1500 < y_{\text{ETC}} < -240 \text{ km}$
PCF	$-240 < x_{\text{ETC}} < 0 \text{ km}$, $-1500 < y_{\text{ETC}} < -240 \text{ km}$
CS	$-1500 < x_{\text{ETC}} < -240 \text{ km}$, $-1500 < y_{\text{ETC}} < -240 \text{ km}$
PA	$-1500 < x_{\text{ETC}} < -240 \text{ km}$, $240 < y_{\text{ETC}} < 1500 \text{ km}$
C	$-240 < x_{\text{ETC}} < 240 \text{ km}$, $-240 < y_{\text{ETC}} < 240 \text{ km}$

et al. (2010, 2016). The frontal detection method is set to distinguish between cold and warm fronts, but does not recognize systems that are undergoing occlusion. Consequently, occluded fronts are misidentified as either cold or warm fronts; preliminary tests and this study indicate that most often the occluded front is classified as a warm front. However, in the rest of this study, we use all the detected warm fronts, including those that might in fact be occluded fronts.

b. Cyclone depth and deepening rate

Following Polly and Rossow (2016), the depth of an ETC is measured by the difference between the SLP at the cyclone center and the outermost closed SLP contour. The depth of each ETC is determined for each 6-hourly time step along its track. Figure 1a shows an example of time evolution of the depth of a typical ETC. The deepening rate is defined by the time derivative of its depth smoothed by a 1-day window-mean filter (i.e., the slope of the solid line in Fig. 1a). A joint histogram of cyclone deepening rate versus its depth is shown in Fig. 1b, in which minima in the evolution curve are excluded. To find the minima, we choose segments of the curve with positive second derivatives and absolute deepening rates less than $0.24 \text{ hPa day}^{-1}$, half of the standard deviation. Cyclone snapshots close to their beginning of the genesis and end of the lysis stages are also excluded.

Given the distribution in Fig. 1b, we define deepening ETCs as the cyclones with deepening rates greater than $0.24 \text{ hPa day}^{-1}$, decaying ETCs as the cyclones with deepening rates less than $-0.24 \text{ hPa day}^{-1}$, and neutral ETCs as the cyclones with deepening rates within $\pm 0.24 \text{ hPa day}^{-1}$ and a negative second derivative (i.e., maxima in Fig. 1a). There are 28 328 snapshots from 8486 deepening ETCs, 26 431 snapshots from 8742 neutral ETCs, and 21 929 snapshots from 7164 decaying ETCs. Collocation with MODIS overpasses samples only portions of these snapshots and further reduces the sample sizes to about 1000–2000 at

FIG. 3. (a) TMAP P (mm day^{-1}) and (b) MERRA-2 $\partial Q/\partial t$ (mm day^{-1}) as functions of Q_{cnvg} (mm day^{-1}) and Q_{adv} (mm day^{-1}); see section 3d for definitions of these two variables). The dotted lines indicate where moisture flux convergence ($Q_{\text{cnvg}} + Q_{\text{adv}}$) is zero, and the solid lines indicate where $Q_{\text{cnvg}} + Q_{\text{adv}}$ is a nonzero constant (here it is 15 as an example). The labels mark the coordinates that represent the average Q_{cnvg} and Q_{adv} in each sector (see Table 1) for each development stage of ETCs, with cyclones of Acc, Stn, and Dec stages marked in red, black, and blue labels, respectively.

the center and about 200 at about 1300 km from the center. ETC composites are constructed according to these three evolution stages in the ETC coordinate system described below.

c. ETC coordinate

To reveal the structures of either surface fronts (warm or cold), composites of cloud and dynamical fields are commonly constructed by rotating the targeted surface fronts into a fixed direction (Naud et al. 2010, 2012, 2016; Booth et al. 2013). As the relative locations of warm and cold fronts vary across cases, by fixing the direction of one front when compositing, the other front becomes smoothed, and its typical structure is lost in the average. In this study, we introduce an ETC coordinate in which the warm fronts are fixed in the direction of positive abscissa (x_{ETC}), and the cold fronts in the direction

FIG. 4. Occurrence frequencies of nine cloud types as functions of Q_{cnv} (mm day^{-1}) and Q_{adv} (mm day^{-1}) for (a) high-level clouds Ci, Cs, and Cb; (b) mid-level clouds Ac, As, and Ns; and (c) low-level clouds, Cu, Sc, and St. The frequencies are counted with bin widths of 4 mm day^{-1} in both Q_{cnv} and Q_{adv} and for all data within 1300 km from the centers of all ETC snapshots. The dotted lines indicate where moisture flux convergence ($Q_{\text{cnv}} + Q_{\text{adv}}$) is zero. Cloud-type definitions are according to Rossow and Schiffer (1999; see text section 2).

of negative ordinate (y_{ETC}). In the appendix, we describe in detail how the coordinate transformation is accomplished between the longitude–latitude coordinates and the ETC coordinates.

d. Moisture flux convergence phase space

Moisture flux convergence in the water vapor budget equation is separated into two terms (Wong et al. 2016):

$$P - E + \frac{\partial Q}{\partial t} = -\nabla \cdot (Q\mathbf{V}) = -\mathbf{V} \cdot \nabla Q - Q\nabla \cdot \mathbf{V} \quad (1)$$

$$\equiv Q_{\text{adv}} + Q_{\text{cnv}},$$

with

$$Q = \int_{p_{\text{top}}}^{p_{\text{srf}}} q \frac{dp}{g} \quad \text{and} \quad \mathbf{V} = \frac{1}{Q} \int_{p_{\text{top}}}^{p_{\text{srf}}} q \mathbf{v} \frac{dp}{g},$$

where Q is the column-integrated specific humidity q , and $\mathbf{V}$ is the vertically averaged horizontal wind $\mathbf{v}$ weighted by the vertical profile of specific humidity (or column-integrated moisture flux divided by Q). Both Q and $\mathbf{V}$ are obtained from MERRA-2 hourly column-integral data at 0.5° latitude $\times$ 0.625° longitude resolution. The term of moisture advection $-\mathbf{V} \cdot \nabla Q$ (Q_{adv}) and the term of moisture dynamical convergence $-Q\nabla \cdot \mathbf{V}$ (Q_{cnv}) were used to construct a two-dimensional phase space (the Q_{cnv} Q_{adv} space) to quantify the relationship between clouds, precipitation, and the large-scale circulation (Wong et al. 2016); the coupling between phases of moisture flux convergence and transition of shallow-to-deep convection in the intraseasonal oscillation of the Indian summer monsoon (Wang et al. 2015; Wu et al. 2018); and the dependence of precipitation and surface evaporation on moisture flux convergence (Wong and Behrangi 2018). In

FIG. 5. For the PWS, histogram anomalies in (first column) Q_{adv} vs Q_{cnvg} (%), (second column) CTP vs COD (%), (third column) Q2 (%), and (fourth column) ω (%) for cyclones of (a) deepening (Acc), (b) neutral (Stn), and (c) decaying (Dec) stages. The average Q_{cnvg} and Q_{adv} are listed in parentheses in the titles of the first column, and the numbers outside the parentheses are the average moisture flux convergence ($Q_{cnvg} + Q_{adv}$). Numbers in the nine boxes in the second column are the occurrence frequency anomalies of the nine cloud types (see text for definitions). Labels of cloud types (see section 2) are included in the nine boxes in the top row of the second column for reference. The clear sky frequency anomalies are listed in the titles. The average P , surface evaporation rate, and $\partial Q/\partial t$ are listed in the third column titles, respectively. The solid lines in the third and fourth columns are the average Q2 and ω anomalies, respectively, with the horizontal dash and dash-dotted lines indicating the estimated average levels of convergence and divergence, respectively.

this study, we apply the $Q_{cnvg}Q_{adv}$ space to examine the phases of moisture flux convergence in each sector of ETCs during their life cycles. We note that Q_{cnvg} and Q_{adv} are derived from variables at the MERRA-2 horizontal resolution (referred to as “large scale” in this study) instead of fine resolution that can resolve mesoscale processes. Therefore, the connection between phases of moisture flux convergence and cloud properties, which are reported at 5-km resolution, should be interpreted as the responses of the statistical distributions of mesoscale cloud properties (or cloud-type combinations) to moisture transport properties of the large-scale circulation.

4. Characteristics of ETCs in the ETC coordinate and $Q_{cnvg}Q_{adv}$ phase space

With both warm and cold fronts collocated across cyclones in the ETC coordinate, Fig. 2 shows composites

of TMPA precipitation (P ; first column), MERRA-2 precipitable water vapor (PWV; second column), PWV tendency ($\partial Q/\partial t$; third column), Q_{cnvg} (fourth column), and Q_{adv} (fifth column) for deepening (Acc), neutral (Stn), and decaying (Dec) cyclones. Since each grid cell in the ETC coordinate may contain samples with varying geographical gridcell area, area averages are performed for the composites. Sectors of ETCs are defined as regions that show consistent characteristics in composites of phases of moisture flux convergence, CTP versus COD histograms, and vertical velocity ω profiles. We name the different sectors as pre-warm sector (PWS), pre-warm front (PWF), surface warm front (WF), warm sector (WS), surface cold front (CF), post-cold front (PCF), cold sector (CS), polar air intrusion (PA), and the center (C; see Fig. 2). Table 1 specifies the horizontal ranges of ETC coordinates for each sector definition. We acknowledge that these names can be

FIG. 6. As in Fig. 5, but for the PWF sector.

different from those conventionally used in the literature. For example, the sectors PCF, CS, and PA may be collectively named as the cold sector, and PWF and WF are not distinguished separately in other work.

During the deepening stage (Fig. 2, top row), rainbands are clearly concentrated along the WF and CF, with the WF rain distributed closer to the center than the CF. A band of maximum PWV [the atmospheric river (AR)] is located in the WS alongside the CF, consistent with the structures reported in [Cordeira et al. \(2013\)](#) and [Dacre et al. \(2015\)](#), and the driest and coldest air is in the PA. The atmosphere is moistened ($\partial Q/\partial t > 0$) in the quadrants of $x_{\text{ETC}} > 0$ and dried ($\partial Q/\partial t < 0$) in the quadrants of $x_{\text{ETC}} < 0$ (except in the CF). Positive tendencies in the upper-right quadrant (PWS) are mainly caused by moisture advection. Rain bands associated with both fronts are positioned in narrow areas with large gradients of PWV, with the WF located within the region of both maximum Q_{cnvg} and Q_{advt} , and the CF nearest to the region of maximum convective available potential energy (CAPE; not shown, but similar to the distribution of PWV).

The PWV in the WS is largest during the neutral stage (Fig. 2, middle row). Patterns of $\partial Q/\partial t$, Q_{cnvg} , and Q_{advt}

in the neutral stage are similar to those in the deepening stage, but with smaller magnitudes accompanying the lighter precipitation. The rain rate in the CF becomes much weaker than that in the WF.

During the decaying stage (Fig. 2, bottom row), precipitation within ETCs is the lightest among the evolution stages. While the WF rainband is still apparent, the CF rainband becomes indistinguishable from the WS precipitation. Moreover, the AR also becomes less distinguishable, with negative values of $\partial Q/\partial t$ and Q_{advt} beginning to appear in the WS. The decaying stage contains the most frequent occluded fronts. In such cases, the front location algorithm still detects a surface front but tends to flag it as a WF. It is likely that this results in the less distinguishable structure observed in the CF and WS during the decaying stage. Identifying occluded fronts and properly accounting for them in a transformed coordinate system warrant further investigation in future work.

Composites of P and $\partial Q/\partial t$ on the $Q_{\text{cnvg}}Q_{\text{advt}}$ space are shown in Fig. 3. Data are binned in the phase space with bin widths of 4 mm day^{-1} . Contours of constant P (Fig. 3a) align more along the Q_{advt} axis when $Q_{\text{cnvg}} > 0$, indicating that P is more sensitive to Q_{cnvg} (and the

FIG. 7. As in Fig. 5, but for the WF sector.

associated uplift) than to Q_{adv} . In contrast, $\partial Q/\partial t$ (Fig. 3b) is more sensitive to Q_{adv} than to Q_{cnvg} .

Lines of constant moisture flux convergence ($Q_{adv} + Q_{cnvg} = \text{const.}$) align parallel to the dotted line (the line of zero moisture flux convergence; $Q_{adv} + Q_{cnvg} = 0$). Along a line of constant positive value of $Q_{adv} + Q_{cnvg}$ (the solid lines in Fig. 3), larger positive Q_{adv} corresponds to larger $\partial Q/\partial t$ and smaller P , implying that the supply of moisture favors moistening the atmosphere rather than precipitation. Along the same line, larger positive Q_{cnvg} implies that the supply of moisture favors precipitation. Since changing PWV and precipitation formation are related to the cloud types in the atmosphere, there are variable combinations of cloud types along a line of constant $Q_{adv} + Q_{cnvg}$ because of the relative contributions of Q_{adv} and Q_{cnvg} .

The occurrence frequencies of each of the nine cloud types as functions of Q_{adv} and Q_{cnvg} are shown in Fig. 4. The frequencies are counted by clouds that are detected by MODIS within 1300 km from the centers of collocated ETC snapshots. The sum of all nine panels in Fig. 4 plus the clear one (not shown) is 100% for all Q_{adv} and Q_{cnvg} . Different regimes in the $Q_{cnvg}Q_{adv}$ phase space are in favor of different combinations of cloud types. For

example, Ci and Ac mainly occur in conditions with large positive Q_{adv} but relatively small positive Q_{cnvg} , while As and Sc mainly occur in conditions with negatively large Q_{adv} . Both Cs and Cb are most likely in a regime when both Q_{adv} and Q_{cnvg} are large and positive. However, the occurrence frequencies of Cb are distributed similarly to that of precipitation (Fig. 3a), sensitive to changes in Q_{cnvg} when $Q_{cnvg} > 0$, while the frequencies of Cs have sharp gradients in the Q_{cnvg} direction when Q_{cnvg} approaches 0 and in the Q_{adv} direction when Q_{adv} approaches 0. Although formation of Cu clouds need mesoscale convergence, it is linked to a regime of $Q_{cnvg} < 0$ when large-scale variables are used to compute moisture budget terms.

5. Precipitation, cloud structures, and moisture flux convergence in ETC sectors

For each stage of cyclone evolution, we construct the histogram anomalies of Q_{adv} versus Q_{cnvg} , CTP versus COD, the apparent water vapor sink (Q2) profiles, and the vertical wind speed profiles ω (as change rate of parcel pressure) for each sector of the ETCs (Figs. 5–13). Values of Q2 are computed using the MERRA-2 specific

FIG. 8. As in Fig. 5, but for the WS.

humidity and wind velocities as in Wong et al. (2011a,b), with positive (negative) values indicating a loss (gain) of water vapor through condensation (evaporation) or subgrid-scale turbulent flux divergence (convergence). The histogram anomalies are computed as the histograms sampled only in one sector and one development stage minus the histograms sampled from all sectors and stages (i.e., sampled within 1300 km from the centers of all available ETC snapshots, referred to as the climatological histograms). As composites involve ETCs of various geometrical sizes, properties of the atmosphere outside small ETCs are also included. The anomalies highlight special features in one sector and stage relative to the climatologically average ETC properties. The histogram anomalies of Q_{advT} versus Q_{cnvg} and CTP versus COD are summed to zero for the individual histograms. The histogram anomalies of Q2 and ω profiles are summed to zero on each pressure level. The climatological histograms from which the anomalies deviate are shown in the appendix (Fig. A3).

a. Pre-warm sector

The PWS is located downwind of the WF and the moisture flux convergence (Fig. 5, first column) is primarily advective, with nearly zero average Q_{cnvg}

(~ 0.4 – 1.4 mm day^{-1}) across the cyclone life cycle and a much larger positive average Q_{advT} (~ 0.8 – 3.7 mm day^{-1}). The anomalous distribution in the $Q_{cnvg}Q_{advT}$ space shows large negative anomalies (green color) for regimes of dry advection, indicating redistribution of samples toward regimes of moist advection (purple color for $Q_{advT} > 0$). Compared to the average Q_{cnvg} of all sectors ($\sim 2.9 \text{ mm day}^{-1}$ in Fig. A3), the PWS is less convergent. This is consistent with the larger proportion of descending (positive anomaly in positive ω in Fig. 5, fourth column) motions than ascending (negative ω) motions. More Ci and Cs clouds accompany low-level clouds in this sector (Fig. 5, second column). The average precipitation rate (Fig. 5, third column; 1.5 – 2 mm day^{-1}) is small compared to that of all sectors (6.2 mm day^{-1} in Fig. A3), while the atmosphere begins to store moisture (averaged $\partial Q/\partial t \sim 0$ – 5.2 mm day^{-1}) relative to the average drying of all sectors ($\sim -2 \text{ mm day}^{-1}$ in Fig. A3). This is consistent with Fig. 3 that the regime of large Q_{advT} but relatively small Q_{cnvg} has larger $\partial Q/\partial t$ than P. Positive anomalies in negative Q2 in the mid- to lower troposphere (Fig. 5, third column) indicate moistening, while positive anomalies in positive Q2 above 500 hPa indicate the loss of water vapor to maintain high-level clouds detrained from the convection in the WF. Cyclone evolution

FIG. 9. As in Fig. 5, but for the CF sector.

only slightly modulates the characteristics of moisture flux convergence and clouds in the PWS. The average Q_{adv} (Fig. 5, first column) decreases from the deepening to decaying stages with decreasing average $\partial Q/\partial t$ (Fig. 5, third column), consistent with Fig. 3b.

b. Pre-warm front

The PWF sector is located downwind of the WF where elevated ascending motion becomes evident. Both Q_{cnvg} and Q_{adv} are enhanced in the PWF (Fig. 6, first column) from the values in the PWS, resulting in a larger moisture flux convergence ($Q_{cnvg} + Q_{adv} \sim 7\text{--}15.4 \text{ mm day}^{-1}$) compared to the PWS ($\sim 1.2\text{--}5.1 \text{ mm day}^{-1}$; Fig. 5, first column). The larger Q_{cnvg} ($\sim 3.9\text{--}4.8 \text{ mm day}^{-1}$) compared to the climatological average (2.9 mm day^{-1} in Fig. A3) is associated with the more frequent ascending motions (Fig. 6, fourth column) that are elevated, with ascent above 700–800 hPa and descent below. This is consistent with the elevated ascent in the tilting portion ahead of surface warm fronts reported in Naud et al. (2010) and Booth et al. (2013). Compared to the PWS, the ascending motions are associated with more frequent occurrences of Cs to Cb clouds (Fig. 6, second column) and positive Q2 above 700–800 hPa (Fig. 6, third column). Precipitation rates ($7.3\text{--}9.5 \text{ mm day}^{-1}$)

in the PWF sector are slightly above the climatological average rate ($\sim 6.3 \text{ mm day}^{-1}$), and the average values of $\partial Q/\partial t$ are the highest among all sectors ($0.6\text{--}9 \text{ mm day}^{-1}$).

From deepening to decaying stages, the average Q_{cnvg} does not change much, but the average Q_{adv} significantly decreases by about 4 times (Fig. 6, first column). This development is shown as the labels of PWF in Fig. 3, which mark the average Q_{cnvg} and Q_{adv} as coordinates in the $Q_{cnvg}Q_{adv}$ space. From the deepening (the red PWF label) to the decaying stages (the blue PWF label), $\partial Q/\partial t$ undergoes a larger decrease than P does, consistent qualitatively with the third column of Fig. 6, in which the average P decreases from about 9 to 7 mm day^{-1} , but the average $\partial Q/\partial t$ decreases by an order of magnitude. We note that the values of P and $\partial Q/\partial t$ shown in Fig. 3 are averages of all samples regardless of sectors or development stages, while the values shown in the third columns of Figs. 5–13 are averages in particular sectors at certain development stages and are different from those in Fig. 3. We will address the relationship between these two values in section 6.

The path of the PWF labels in the $Q_{cnvg}Q_{adv}$ space indicates a tendency in Fig. 4a that the corresponding decrease in the frequency of Cs is larger than that of Cb.

FIG. 10. As in Fig. 5, but for the PCF sector.

This is reflected in the second column of Fig. 6 such that the distribution of high-level clouds is more weighted toward Cs during the deepening stage and toward Cb during the decaying stage.

c. Surface warm front

With the average Q_{cnvg} in the WF ($\sim 7\text{--}10\text{ mm day}^{-1}$; Fig. 7, first column) doubling those in the PWF, the upward motions become upright throughout the troposphere (Fig. 7, fourth column) with more frequent occurrence of Cb clouds (Fig. 7, second column) and the strongest precipitation rates ($10\text{--}16\text{ mm day}^{-1}$; Fig. 7, third column). The moisture flux convergence in the WF is the largest among all sectors ($Q_{\text{cnvg}} + Q_{\text{adv}} \sim 10\text{--}19\text{ mm day}^{-1}$; Fig. 7, first column).

The modulation by cyclone life cycle is similar to that in the PWF sector. With Q_{adv} decreasing more rapidly than Q_{cnvg} (Fig. 7, first column) from the deepening to decaying stages, $\partial Q/\partial t$ decreases by one order of magnitude, while P decreases by just about one-third (Fig. 7, third column). These changes are accompanied by a large decrease in the occurrence frequency of Cs and a steady occurrence frequency of Cb, with the high-level clouds weighted more toward Cb (Fig. 7, second column) in the decaying stage. This phenomenon was

observed in the case study of a stationary WCB by Crespo and Posselt (2016).

d. Warm sector

The WS is located upwind of the WF, with the most abundant PWV (Fig. 2, second column) being transported in the AR. Both the average Q_{cnvg} and Q_{adv} decrease in the WS (Fig. 8, first column) from the values in the WF sector (Fig. 7, first column), accompanied with smaller average P and $\partial Q/\partial t$ (Fig. 8, third column) compared to the WF sector. Upward vertical velocities (Fig. 8, fourth column) are weaker than those in the WF sector, and the occurrence frequencies of Cs and Cb (Fig. 8, second column) are reduced from the WF sector. Ci clouds are more abundant (Fig. 8, second column). Negative Q2 in the 300–700-hPa layer (Fig. 8, third column) indicates the evaporation of stratiform precipitation, and positive Q2 in the 200–300-hPa layer (about the same levels of mass divergence; dash-dotted lines in Fig. 8, fourth column) helps maintain the existence of high-level stratiform clouds.

From the deepening to decaying stages, there are larger decreases in the average Q_{adv} than decreases in the average Q_{cnvg} (Fig. 8, first column). Similar to the PWF and WF sectors, average $\partial Q/\partial t$ in the WS decreases more than

FIG. 11. As in Fig. 5, but for the CS.

the average P (Fig. 8, third column), consistent with Fig. 3. This is accompanied by a decrease in the occurrence frequencies of Cs with a fairly steady occurrence frequency of Ci (Fig. 8, second column). The path of the development of WS in the $Q_{\text{cnvg}}Q_{\text{advt}}$ space (the WS labels in Fig. 3) is in a regime of a large gradient of Cs occurrence frequency, but steady maximum of Ci occurrence frequency (Fig. 4a).

e. Surface cold front

Phases of moisture flux convergence in the CF sector exhibit a wide extent across the Q_{advt} direction in the $Q_{\text{cnvg}}Q_{\text{advt}}$ space (Fig. 9, first column). This is because of the sharp gradient of Q_{advt} across the CF, from a positive value in the WS transitioning to a negative value in the PCF. The characteristics of moisture flux convergence and cloud-type combinations in the CF are significantly modulated by cyclone life cycle (see Fig. 9).

In the deepening stage, positive average Q_{cnvg} ($\sim 10 \text{ mm day}^{-1}$; Fig. 9a, first column) is associated with more upright ascending motions (Fig. 9a, fourth column) and average precipitation ($\sim 16 \text{ mm day}^{-1}$; Fig. 9a, third column) that are as strong as those in the WF (Fig. 7a, fourth column). The water budget and the cloud-type combinations are different from those in the WF. As

the average Q_{cnvg} is about equal in the CF and WF ($\sim 10 \text{ mm day}^{-1}$), the CF is subject to a large negative average Q_{advt} ($\sim -7 \text{ mm day}^{-1}$), resulting in a much smaller average moisture flux convergence (2.7 mm day^{-1}) compared to the WF value (19.4 mm day^{-1}). To support the high average precipitation rates, the water vapor converted to precipitation comes from the AR with large negative $\partial Q/\partial t$ ($\sim -7 \text{ mm day}^{-1}$; Fig. 9a, third column) and from surface evaporation ($\sim 6.6 \text{ mm day}^{-1}$), which is twice of that in the WF (3.1 mm day^{-1}). Consequently, among sectors where the average precipitation rates are high, the CF in a deepening ETC is where strong interactions occur with the ocean surface.

Occurrence frequencies of high-level clouds in the CF of deepening ETCs are distributed with more weight toward Cb (Fig. 9a, second column), consistent with the observation of more isolated deep convective clouds in the CF (Houze and Hobbs 1982; Crespo and Posselt 2016). The mid- to low-tropospheric positive Q2 (600–1000 hPa in Fig. 9a, third column) are typically associated with Cb. The long tail in the high-level cloud frequency distribution extends across Cs and Ci regimes, accompanied by the upper-tropospheric positive Q2 (150–300 hPa in Fig. 9a, third column) and midtropospheric negative Q2 (300–700 hPa in Fig. 9a, third

FIG. 12. As in Fig. 5, but for the PA sector.

column). These are related to the maintenance of high-level stratiform clouds and evaporation of stratiform precipitation, respectively.

In the neutral stage, Cb occurrence frequency is reduced by half from the deepening stage (Figs. 9a,b, second column), accompanied by a large reduction in the mid- to low-tropospheric positive Q2 (third column). Cs frequencies are reduced slightly from the deepening stage, accompanied by slight decreases in upper-tropospheric positive Q2 and midtropospheric negative Q2. In the decaying stage, the probability distribution in $Q_{\text{cnvg}}Q_{\text{advt}}$ space is weighted more heavily below the line of zero moisture flux convergence (the dotted line in Fig. 9c, first column) and the average Q_{cnvg} is largely reduced to one-third of the value in the deepening stage, accompanied by a reduction in upward ω and the magnitudes of Q2 (Figs. 9c, fourth and third columns, respectively). Therefore, there are more abundant mid- and low-level clouds than high-level clouds.

f. Post-cold front

The PCF sector has positive probability anomalies in the $Q_{\text{cnvg}}Q_{\text{advt}}$ space below the line of zero moisture flux

convergence (Fig. 10, first column). Although the moisture flux is divergent, the low occurrence frequencies of Cb during the deepening and neutral stages (Figs. 10a,b, second column) are related to the weak positive average Q_{cnvg} (first column) and the associated weak ascending motions (fourth column). These convective features are accompanied by positive Q2 in the 600–800-hPa layer and moderate average precipitation rates ($6\text{--}8\text{ mm day}^{-1}$; Figs. 10a,b, third column). In the decaying stage (Fig. 10c), the average Q_{cnvg} is further reduced (first column), and there are more abundant midlevel thick clouds (second column) accompanied by a reversal in vertical motion to have weak descents above 800 hPa (fourth column). The reduction of high-level stratiform clouds in all stages indicates that the convection is less organized than in the WF or CF sectors.

g. Cold sector and polar air intrusion

Both the CS and PA are regions of moisture flux divergence ($Q_{\text{cnvg}} + Q_{\text{advt}} < 0$). In the $Q_{\text{cnvg}}Q_{\text{advt}}$ space, PA has a probability distribution weighted nearer to the center (Fig. 12, first column) because it is the driest among all sectors, while the CS has positive anomalies

FIG. 13. As in Fig. 5, but for the C sector.

extending toward large negative Q_{adv} (Fig. 11, first column). While both sectors are dominated by low- to midlevel clouds (Figs. 11, 12, second column; as also shown in Naud et al. 2016), the larger negative Q_{cnvg} in the CS is associated with stronger descending motion (Figs. 11, 12, fourth column) and more clear conditions. Moreover, the stronger moisture flux divergence (Figs. 11, 12, first column) in the CS is also associated with stronger negative Q2 in the boundary layer (Figs. 11, 12, third column). This is consistent with the large ventilation of water vapor from the boundary layer behind the CF reported by Boutle et al. (2011). The inferred surface evaporation rate ($\sim 5\text{--}6.7\text{ mm day}^{-1}$) in the CS is larger than those in other sectors except the CF sector during the deepening stage.

The modulation during cyclone evolution is small for both the CS and PA (Figs. 11, 12). This is also indicated by the closeness of the CS and PA labels of different stages in Fig. 3.

h. Center

The C sector has positive anomalies in the $Q_{cnvg}Q_{adv}$ space showing clear maxima situated on the Q_{cnvg} axis,

with tails extending toward the positive Q_{cnvg} direction and the negative Q_{adv} direction (Fig. 13, first column). The positive average Q_{cnvg} and the tails along the positive Q_{cnvg} axis are associated with more upright ascending motions (Fig. 13, fourth column) aligned with more abundant Cb than Cs (Fig. 13, second column). The profiles of Q2 exhibit a greater weighting in the lower troposphere compared to the upper troposphere (Fig. 13, third column), implying that the clouds are more convective than stratiform. Average P in the C sector is the largest among all sectors in ETCs, and this is largely maintained by the large Q_{cnvg} and the negative $\partial Q/\partial t$ (Fig. 13, third column). The tails along the negative Q_{adv} axis indicate midlevel medium to thick clouds in Fig. 4 (viz., As and Ns) as shown in the second column of Fig. 13.

The modulation by cyclone evolution is manifested as the shortening of both tails along the Q_{cnvg} and Q_{adv} directions, with the decaying stage exhibiting higher probability near the center (Fig. 13, first column). As the path of the label C in Fig. 3 moves closer to the center from deepening to decaying stages, the cloud frequency distributions in Fig. 4 imply a sharp decrease in Cb and an increase in As.

FIG. A1. A schematic diagram to show the mapping between the longitude–latitude coordinate system used on Earth’s surface to the ETC coordinate system used to study ETCs. The cyclone center is marked by the label C. The inner concentric circle centered at C intersects the surface warm front (red curve) at WF, and the surface cold front (blue curve) at CF. The thick black straight lines are geodesics linking WF and CF, respectively, to the center, with the angle ψ between them. A point M on Earth’s surface is mapped onto the ETC coordinates (x_{ETC} , y_{ETC}) as described in the appendix. The outer concentric circle intersects with only the cold front, and a geodesic (red dashed line) is extended from the end of the warm front to meet the circle.

precipitation than stratiform clouds. Such situation is observed in the cases of the cold front (CF) and center (C) sectors in deepening ETCs. Another equally important source of atmospheric moisture in the CF sector during the deepening state is surface evaporation, with rates comparable to those in the cold sector (CS).

The effect of changing moisture advection on modulating cloud-type combination can also be observed in the PWF and WF sectors during the ETC life cycle. From deepening to decaying stages, Q_{adv} in these sectors is significantly reduced, while Q_{cnvg} is marginally altered. The high-level cloud distribution shifts with more weighting toward thick clouds in these cases.

When Q_{cnvg} is positive while Q_{adv} is largely negative, the frequencies of Cs and Ci are largely reduced with some remnant of Cb, indicating less organized convection as observed in the PCF sector. When the moisture flux convergence ($Q_{\text{cnvg}} + Q_{\text{adv}}$) is largely negative, surface evaporation becomes important in the moisture budget with more occurrence frequencies of low-level clouds and “clear” sky as observed in the CS. A very dry condition will have the distribution in the $Q_{\text{cnvg}}Q_{\text{adv}}$ space close to the center, as in the polar air intrusion (PA) sector, where thin midlevel clouds are observed.

Water recycling processes in ETCs are summarized as loops in the $Q_{\text{cnvg}}Q_{\text{adv}}$ phase space (Fig. 3). The most rapid recycling during the deepening stage is realized as the largest loop of phase changes in the $Q_{\text{cnvg}}Q_{\text{adv}}$ space, with the largest precipitation in the WF and CF

sectors and the largest surface evaporation in the CF and CS. This is also related to the largest differences in extreme values (maximum minus minimum) of cyclone precipitation (Rudeva and Gulev 2011) and cloud radiative forcings (Polly and Rossow 2016). Since poleward transport of atmospheric moisture is mainly driven by transient eddy processes caused by ETCs, the extreme contrasts of Q_{adv} in ETCs (i.e., moist advection in the PWF minus dry advection in the PCF) measure their efficiency in poleward moisture transport. Consequently, deepening cyclones are more efficient in poleward moisture transport.

The occurrence of midlatitude extreme precipitation is related to interannual variability in ETC activity (Ma and Chang 2017). Changes in Q_{cnvg} are mainly responsible for such variability (E. Chang 2018, personal communication). Results from this study (Fig. 4) imply that more deep convective clouds are associated with these extreme events. Climate variability in ETC structures associated with extreme precipitation needs further study. It would also be interesting to investigate how distributions in the $Q_{\text{cnvg}}Q_{\text{adv}}$ space may change for ETCs in a warmer and moister future climate and how those correspond to cloud type and amount changes in ETCs.

We caution that the inability of the front detection technique to determine frontal occlusion may cause uncertainties in the properties of the WS and CF sectors, particularly in the decaying stage. How these factors

FIG. A2. An example of a deepening cyclone (left) before and (right) after the ETC coordinate transformation for (a) P (mm day^{-1}), (b) SLP (hPa), and (c) MERRA-2 PWV (mm). The cyclone center is marked with the label C, and the warm and cold fronts are indicated as diamonds and crosses, respectively, in (a). The nine sectors in the ETC coordinates are also labeled. Black areas indicate where data are missing in those particular ETC grid cells (recalling that TMPA P is only available to 50°N).

may influence the results with respect to the evolution of these two sectors also calls for further investigation. In addition, cyclone size is not considered in this study. We plan to incorporate scaling of cyclone size in the ETC coordinate transformation in the near future so that contamination of the environment surrounding the cyclones in compositing can be minimized.

Acknowledgments. The TMPA data can be downloaded from its webpage (Huffman et al. 2007; [http://](http://precip.gsfc.nasa.gov)

precip.gsfc.nasa.gov). The cyclone center database (Bauer et al. 2016; <https://gcss-dime.giss.nasa.gov/mcms>) and the frontal database (Naud et al. 2010, 2016; <https://data.giss.nasa.gov/storms/obs-etc>) are available online. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work is supported by the NASA Precipitation Measurement Mission Science Team (PMM; NNN13D497T), and the NASA Making Earth

FIG. A3. As in Fig. 5, but for climatological histograms in (a) Q_{advt} vs Q_{cnvg} (%), (b) CTP vs COD (%), (c) Q2 profiles (%), and (d) ω (%). These histograms are counted for all samples of midlatitude oceanic cyclones regardless of sectors and development stages.

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APPENDIX

ETC Coordinate Transformation and Climatological Histograms

This appendix documents the mapping from any point within 1500 km from the C of an ETC to a point in the ETC coordinate. For each ETC, concentric circles are drawn at an interval of 60 km (about the spatial resolution of MERRA-2) around C. An arbitrary point M in an ETC (Fig. A1) is mapped onto the ETC coordinate by scaling its relative angular distances from the WF and CF, while keeping its distance from C unchanged.

First, we identify the circle that passes M and its intersections with the WF and CF (Fig. A1). The angle θ between M and WF is the angle between the two geodesics connecting M and WF to C. The angle ψ is the angle between the two geodesics connecting WF and CF to C, representing the angle spanning between the two fronts for this particular circle. The point M on Earth's surface is mapped to the ETC coordinate by keeping the distance CM fixed and scaling the angle Θ between M and the x axis (the WF direction) as

$$\Theta = \theta \frac{\left(-\frac{\pi}{2}\right)}{\psi}, \quad (\text{A1})$$

where $-\pi/2$ is the angle between WF and CF in the ETC coordinates. Then the coordinates $(x_{\text{ETC}}, y_{\text{ETC}})$ are calculated as

$$x_{\text{ETC}} = CM \cos \Theta \quad \text{and} \quad y_{\text{ETC}} = CM \sin \Theta. \quad (\text{A2})$$

If the point M is outside the WS, the angle ψ between the two fronts becomes a blunt angle instead of an acute angle, and $-\pi/2$ in Eq. (A1) is replaced by $3\pi/2$.

For those circles intersecting with only one of the fronts (e.g., the CF in Fig. A1 for the outer circle), the end point of the other front (as in Fig. A1, the WF) is extended by a geodesic (the red dashed line in Fig. A1). The mapping of the points on these circles is then similar to that of M. For those circles intersecting no fronts, we do not perform the mapping and the data are discarded. In this way, all points with concentric circles passing through them intersecting at least one of the fronts are mapped one-to-one onto the ETC coordinate. Although the angular distances between any two points on a concentric circle are distorted, different sectors in ETC are efficiently defined in the ETC coordinate as shown in section 4.

Figure A2 shows an example of a deepening cyclone before and after the ETC coordinate transformation. In this example, the WF and CF do not intersect at the C. The area sandwiched between the WF and CF is transformed into the WS, and the portion of WF between the C and the intersection is transformed into the C sector. Cyclonic features of SLP and PWV are preserved after the coordinate transformation, although the orientation is rotated to fit the axes of ETC coordinate. When the occluded front is long and not all included in the C sector, the occluded front is usually identified as a WF, and the CF is extended by a geodesic to the C. The area sandwiched between the extended CF and the occluded front is identified as the WS. All area west of the extended CF and all area north (south) of the WF in the Northern (Southern) Hemisphere are identified as outside the WS. The assumption to extend CF using a geodesic may be the reason for the less distinguishable WS during the decaying stage.

For Figs. 5–13 in the text, the anomalies are calculated as deviations from the climatological histograms plotted in Fig. A3.

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