Nonlinear Zonal Propagation of Organized Convection in the Tropics

JOAQUIN E. BLANCO, DAVID S. NOLAN, AND BRIAN E. MAPES

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

(Manuscript received 3 April 2019, in final form 19 June 2019)

ABSTRACT

A wide range of the observed variability in the ITCZ is frequently explained in terms of equatorially trapped modes arising from Matsuno's linear shallow-water model. Here, a series of zonally constant, meridionally symmetric aquachannel WRF simulations are used to study the propagation of tropical cloud clusters (CCs; patches of deep cloudiness and precipitation) in association with eastward-moving super cloud clusters (SCCs), also called convectively coupled Kelvin waves (CCKWs). Two independent but complementary methods are used: the first, from a local approach, involves a CC-tracking algorithm, while the second uses Lagrangian trajectories in a nonlocal framework. We show that the large-scale flow in low to midlevels advects the CCs either eastward or westward depending on model climatology, proximity to the CCKW axis, and latitude. Moreover, for most analyzed cases, sequences of CCs oscillate, describing qualitatively sinusoidal-like paths in longitude–time space, although with sharp transitions from westward to eastward motion due to westerly wind burst activity associated with the CCKWs. We also find that the discrete precipitation elements (CCs) are embedded in continuous tracks of positive moisture anomalies, which are parallel to the Lagrangian trajectories themselves. A conceptual model of the nonlinear SCC–CC interaction is presented.

1. Introduction

Zonally propagating convective activity represents a significant component of the total variability along the ITCZ. The super cloud clusters (SCCs) are envelopes of enhanced convection with zonal scales of 3000–7000 km that propagate eastward in a range of velocities that is typically between 10 and 22 m s^{-1} (Nakazawa 1988). Wheeler and Kiladis (1999) showed that the full equatorial wave family predicted by the linear theory of Matsuno (1966) can be seen in normalized power spectra of satellite data such as outgoing longwave radiation (OLR). The overlapping of these spectral peaks onto the Matsuno curves yielded the concept of convectively coupled equatorial waves (CCEWs; Kiladis et al. 2009). Since then, the convectively coupled Kelvin wave (CCKW) and SCC terms have been used interchangeably, despite the wave-versus-object dualism. Nevertheless, Blanco et al. (2016b, hereinafter B16B) found evidence of *decoupling* of CCKWs in aquaplanet-like simulations and proposed a separation of the SCC–CCKW equivalence.

The “cloud cluster” (CC) concept dates back to the early studies of tropical convection based on satellite imagery (Martin and Karst 1969; Frank 1970). The structures and propagation characteristics of observed CCs embedded in the eastward-moving SCCs were first addressed by Nakazawa (1988), followed by others such as Yano and Nishi (1989), Lau et al. (1989, 1991), Mapes and Houze (1993), and Chen et al. (1996). The use of aquaplanet simulations as in Nasuno et al. (2007), and even the simpler two-dimensional (x – z) simulations, such as in Chao and Lin (1994), Oouchi (1999), Numaguti and Hayashi (2000), Peng et al. (2001), and Tulich and Mapes (2008) permitted an in-depth view of the CC–SCC organization. A systematic result in most of these studies was the eastward propagation of the SCC, and the westward propagation of short-lived CCs.

The phase speed magnitude of the westward-moving CCs is sometimes associated with the velocity of the low-level flow (Nasuno et al. 2007; Grabowski and Moncrieff 2001). However, Numaguti and Hayashi (2000) have proposed that a more general east–west asymmetry should be the reason. They conducted experiments isolating different effects: not only did their uniform and sheared mean-flow cases in a nonrotating environment reproduce the SCC–CC typical structure

Corresponding author: Joaquin E. Blanco, jblanco@rsmas.miami.edu

and propagation characteristics, but also these were found in two other simulations with the beta effect but without background flow.¹ Some discrepancies arise though, when considering other 2D model results, such as in [Liu and Moncrieff \(2004\)](#). In turn, [Tulich et al. \(2007\)](#) found that even in absence of rotation and background-flow effects (no east–west asymmetries), there was still organization of convection in CCs and SCCs, with preferred opposite directions of propagation for both, but whether the CCs move rightward and SCC leftward or vice versa was a matter of chance. The analytical studies with linear and nonlinear 2D models from [Stechmann and Majda \(2009\)](#) included a great variety of background flows to demonstrate that they have a significant impact on the interaction between gravity waves and convection, which was evaluated via east-versus-west asymmetries with respect to a heat source. Furthermore, for studies based on full-physics models and observations, the speed of CCs is at best qualitatively compared to that of the low-level flow, without specifying the vertical level or layer of highest correlation, or the effects of low-level shear or mean vertically integrated flow.

The “CC” term in the observed tropical atmosphere is often applied to one particular type of CCEWs, that is, the 2-day waves or convectively coupled westward inertia–gravity (WIG) waves; this implicitly suggests that no particular mechanisms will drive these CCs other than the intrinsic dynamics of the tropics. [Tulich and Kiladis \(2012\)](#) bridged the separate worlds of observations and idealized simulations; they performed several 45-day simulations with a doubly nested aquapatch and concluded that the low-level vertical shear is what really drives the CCs.

Hence, there is certainly a notorious divergence of results regarding the “CC universe,” among different sets of observations, theoretical studies, and numerical simulations. An important cause for such discrepancy arises from the multiple definitions themselves of a *cloud cluster*, in terms of zonal extent, lifespan, phase speed, and frequency of occurrence. On the other hand, a given threshold of cloud-top temperature (CTT) or OLR has traditionally been the most usual parameter to define a CC in combination with a size constraint, but there is robust evidence establishing that cloud-top-defined tropical entities do not uniquely

determine the organization or the underlying precipitation. In particular, precipitation and cloud tops do not necessarily travel at the same speed, nor even in the same direction.

In such a panorama of ambiguities in terminology, we will continue to use the framework adopted in [B16B](#), which considers the following classification (hierarchy) of convective scales in the atmosphere: individual cells, mesoclusters, cloud clusters, and super cloud clusters. The corresponding acronyms and spatial and temporal scales are C [$O(1)$ km, $O(1)$ h], MC [$O(10)$ km, $O(10)$ h], CC [$O(100)$ km, $O(1)$ day], and SCC [$O(1000)$ km, $O(10)$ days], respectively. This categorization is particularly useful for idealized simulations due to their simpler ITCZ structure and variability and requires no further specification of additional properties. Precipitation will be the adopted variable to track tropical CCs, instead of OLR or CTT, while other methodological aspects regarding identification of CCs will be provided in the following sections.

The evolving spatial structure of SCCs has been described in [B16B](#) in term of smaller-scale components. Sometimes the discretization of CC elements within an SCC is not straightforward, due to the continuous nature of the organization of convection. The study of [B16B](#) was carried out with averages between 15°S and 15°N , which proved to be the best for SCC identification and tracking ([Fig. 1a](#)) when compared to using narrower tropical bands ([Fig. 1b](#)). But this may be less effective for the analysis of CC structure and evolution, with the added particularity that these “hybrid CCs” have been meridionally averaged over a 3300-km distance. The horizontal structure of an SCC and zonal flow, as studied in [B16B](#), are shown in [Fig. 2](#) for an 18-day period in 3-day intervals. A careful inspection of x – t plots of precipitation, rather than OLR, yields cyclic, cosine-like oscillations that appear as S signatures (S shapes; [Figs. 1c,d](#)): CCs move westward until they rapidly slow their speed, and subsequently travel to the east. Eventually, away from SCCs, CC motion is again westward. Therefore, these recognizable particular patterns of propagation cannot be circumscribed to the generally accepted idea of westward-moving CCs within eastward-moving SCCs. These features are also discernible in OLR longitude–time diagrams when narrower bands along the ITCZ, or individual latitudes are used ([Fig. 1b](#)). The clear S-shape signals in OLR and precipitation are also found in meridional velocity fields ([Fig. 3c](#)). A qualitative analysis suggests that the zonal flow is strongly influencing the speed of the zonal propagation of CCs. When westerly flow is present, CCs tend to slow their westward propagation,

¹ The separate consideration of external parameters and their relative strengths, such as different values for f and $u(z)$, represents an advantage of the simple 2D models: even when $f = 0$ at the equator, it is Earth’s rotation that supports equatorial easterly zonal-mean flow.

FIG. 1. Time-longitude diagrams of surface pressure contours (pink) overlapped with (a),(b) OLR and (bottom) precipitation contours (black) for days 270–315 of the OBS aquachannel simulation, averaged between (c),(d) 2°S and 2°N and (left) 15°S and 15°N. The absolute range for each variable (for the full simulation length) was divided in 16 intervals, $[\min:(\max - \min)/16:\max]$, and that is used to define the 17 contour levels. For pressure, only the smallest 9 values are plotted; for OLR, the smallest 12 values, and for precipitation, the largest 15 values.

FIG. 2. Time evolution of the CCKW structure for the OBS aquachannel simulation, in the 15°S – 15°N band, for an 18-day period. Zonal wind at 10 m is shaded, and four OLR contours are overlapped in black (120, 150, 180 and 210 W m^{-2}). Also, to facilitate the identification of SCCs rather than strong CCs, the OLR field was smoothed 50 times, and three envelopes are shown in magenta, brown, and green contours, for levels of 180, 210, and 240 W m^{-2} , respectively.

FIG. 3. Hovmöller diagrams of variables averaged between 2°S and 2°N for the OBS aquachannel simulation: (a) zonal wind at 10 m; (b) positive zonal wind areas (light-blue shaded), surface pressure (pink contours), and rain (black contours); and (c) meridional wind at 10 m.

which is followed by a steady state, and subsequent eastward motion (Figs. 3a,b).

Interestingly Figs. 5, 8, and 9 of Nasuno et al. (2007) show similar patterns for their cloud-resolving aquaplanet simulation, although these are simply referred to as “synoptic-scale signals” around the SCC; another clear example is provided by Figs. 1 and 2 of Lane and Zhang (2011), obtained with a 2D simulation. But neither of these two recent works have accounted for the eastward low-level anomaly associated with CCKW dynamics that modulates such oscillations. Another aquaplanet model was used by Yamasaki (2011), who described the slow propagation of individual CCs within the SCCs as westward-propagating modes (WPM) and eastward-propagating modes (EPM), with phase speeds of about $1\text{--}2\text{ m s}^{-1}$, but again, a physical interpretation was not made (other than suggesting that WPM and EPM modulate pressure, zonal wind, and precipitation fields), and velocity fluctuations in the propagation of precipitation were not mentioned.

The aim of this study is to advance on the analysis of the 1-yr “control SST” (CTRL) and “observed SST”

(OBS) aquachannel simulations with the WRF Model used in Blanco et al. (2016a, hereinafter B16A) and B16B, but now focusing on the mesoscale aspects of the zonal propagation of organized convection. Here we carry out an objective, quantitative study of CC propagation in association with SCCs; that is, we analyze kinematically as well as dynamically the S shapes. The use of idealized simulations permits the isolation of the primary forcing of the tropical atmosphere, while discarding “modulating” factors such as seasonality and topography. It will be shown that zonal CC propagation is determined by low- to midlevel wind, and that the oscillations of such zonal wind, linked to CCKW dynamics, have specific characteristics: the westward to eastward transitions in CC motion occurs quite fast, in a front-like manner.

Two distinct but complementary approaches are applied. The first, an objective CC-tracking algorithm in the time–longitude space, permits the quantification of CC motion based on precipitation thresholds, and for the whole population, rather than for a subset or case study. The second involves the use of Lagrangian

trajectories, which provide a large-scale perspective of the modulation of CC motion by SCCs.

The remainder of this work is organized as follows. Section 2 describes the aquachannel experiments conducted with the WRF Model; sections 3 and 4 address the local and nonlocal approaches, respectively, for the study of zonal propagation of tropical CCs. Finally, a brief discussion, followed by the summary and conclusions are presented in section 5.

2. The aquachannel and aquapatch simulations

Most of the WRF simulations used for the present analysis are the same as those used in B16A and B16B and will be briefly described here. The simulations are performed in an equatorial β -plane domain with no topography and no seasonality. The grid extends from 60°S to 60°N ($L_y \sim 13\,200$ km) with free-slip walls at the north and south boundaries and has periodic boundary conditions in the zonal direction (see Fig. 1 in B16A). Vertical spacing is variable in the range of 100–450 m, with 50 model levels extending to about 26 km.

In terms of longitudinal extent and resolution, the following configurations are used:

- 1) The low-resolution (LR) aquachannel (for brevity, simply “aquachannel”): An oceanic surface with longitudinal extent equal to the equator ($L_x \sim 40\,000$ km) and a resolution of 139 km (288×96 points, $360^\circ \times 120^\circ$).
- 2) The high-resolution (HR) aquachannel: Same dimensions as its corresponding LR version, but grid spacing of 46.35 km (864×288 points).
- 3) The HR aquapatch: Same resolution as the HR aquachannel but zonal extent equal to 1/3 of the aquachannel (square domain, 288×288 points, $120^\circ \times 120^\circ$).
- 4) The nested aquapatch: Nesting is applied twice along the equator to obtain two finer grids: 15.45-km spacing from 20° S to 20° N (864×288 points) and 5.15-km spacing from 13.33° S to 13.33° N (2592×576 points). Within the latter grid convection is solved explicitly (the cumulus scheme is turned off).

Two types of prescribed SST profiles (model forcing) are used: the CTRL and OBS profiles from the Aquaplanet Experiment project (Blackburn and Hoskins 2013; Blackburn et al. 2013; Williamson et al. 2012). These profiles (Fig. 1c in B16A) are given by the formulas

$$\text{CTRL SST} = 27 \left[1 - \sin^2 \left(\frac{90}{60} \varphi \right) \right], \quad (1a)$$

FIG. 4. Time-zonal mean of precipitation for the set of simulations. The ITCZ profiles for the new HR aquachannel simulations are separately shown below. Notice the nearly complete overlap between the solid blue and solid gray curves and also between the solid black and dashed gray curves: for these two pairs there are subtle differences at the equator.

$$\text{OBS SST} = \frac{27}{2} \left\{ \left[1 - \sin^2 \left(\frac{90}{60} \varphi \right) \right] + \left[1 - \sin^4 \left(\frac{90}{60} \varphi \right) \right] \right\}, \quad (1b)$$

where φ is latitude ranging between -60° and 60° .

Combining the different domains and SST profiles, a total of 8 experiments are considered. For the OBS nested channel experiment, the inner domains' boundaries are extended meridionally due to the typical broader ITCZ structure with this SST profile: the innermost grid is expanded to $\pm 20^\circ$, and the coarser grid to $\pm 30^\circ$ (Fig. 1 in B16A).

All computations in this study were performed with model outputs every 6 h, although for the performance evaluation of the CC-tracking algorithm, the HR aquachannel simulations were reassessed with precipitation data every 3 h. In turn, the data were stored in the original spatial resolution, with the exception of the nested aquapatches, in which only the data from the $\Delta = 46.35$ km domain were saved at 6-h intervals.

Figure 4 depicts the mean ITCZ precipitation profiles for the eight-member ensemble: solid (dashed) curves represent CTRL (OBS) SST simulations. Interestingly, the double-ITCZ feature in the OBS HR aquapatch (dashed-blue curve) becomes a coherent single ITCZ on its aquachannel counterpart (dashed-gray curve). The differences between these rain distributions generated either with moderate resolution and cumulus parameterization or with high resolution without cumulus parameterization, were described in detail in Nolan et al. (2016).

FIG. 5. Time-zonal mean of $u(z)$ at latitudes (a) 0° and (b) 7.5° .

Figure 5 shows the mean background flow under which CCs and SCCs develop, for the whole set of simulations, at the equator and at 7.5° . In general, the wind profiles follow the same pattern (except for the OBS HR aquapatch, associated with the double ITCZ): easterlies in the boundary layer decreasing in magnitude toward midlevels, and becoming strong westerlies near the tropopause.² The vertical wind shear is more pronounced at the latitude of 7.5° than at the equator. Of particular interest to this study is the flow in low- to midlevels: while at the equator it is easterly in all simulations below 4000 km, the wind transitions from easterlies to westerlies in six of the eight cases at 7.5° within the same layer.

The organization of convection in time-longitude space at a given latitude is shown for some of the simulations, for 45-day periods. Precipitation contours for each plot in Figs. 6, 7, and 8a are shown above a threshold of intensity defined as the top 6.25% of the distribution. The reason for this choice is the inspection and subsequent computation of propagating CCs in the $x-t$ space, and regardless of precipitation intensity, for different latitudes. Plots for the HR CTRL aquachannel simulation at the 0° , 3.75° , and 7.5° are shown in Figs. 6a–c. At the equator, precipitation extremes appear much more scattered when compared with the

same field at 7.5° latitude. Even when in the latter case these CCs do not represent deep convection (the precipitation threshold is below 1 mm day^{-1}), their consideration is still useful for the objective analysis of zonal propagation. Traces of the S shapes in precipitation are clearly distinguishable, particularly surrounding the CCKW axis, for two main reasons: enhanced convection, and change from easterly to westerly regime. Far from the CCKW regions, the number of CCs is significantly reduced. The WWB effects added to the zonal mean winds produce a prevalence of westerlies at 7.5° generating CCs that tend to travel more eastward than westward (net eastward drift of the S shape; Fig. 6d).

The OBS HR aquapatch case (Fig. 7e) stands out from the set of WRF simulations. As mentioned above, its double ITCZ is also associated with weak to nonexistent CCKW activity. Easterlies dominate across the entire tropical region, so these time-longitude diagrams generally lack the fluctuations in CC tracks that can be identified in all other cases. On occasion, some CCs are stationary or moving eastward slowly under isolated pockets of westerly anomalies. Yet, the overall absence of transient westerlies will help with the correlation analysis between CC propagation and background zonal wind. The remainder of the aquapatch simulations show significant CCKW activity that generates robust WWBs. In particular, Fig. 7f shows that for the OBS nested aquapatch simulation, enhanced CC activity at the equator takes place almost exclusively under westerly anomalies at low levels.

It is important to point out that a mesoscale CC, which has a spatial scale on the order of $100 \text{ km} \times 100 \text{ km}$

² Superrotation is not necessarily generated by the aquaplanet-like configurations: a background flow more in agreement with Earth's climatology was generated by some members of the Aquaplanet experiment. The “superrotation problem” in the WRF simulations used here has been addressed in Nolan et al. (2016) and B16A.

FIG. 6. Hovmöller diagrams of the strongest (6.25%) precipitation (contours) at (a) 0° , (b) 3.75° , and (c) 7.5° , and zonal wind (shaded) at the indicated altitude for the CTRL HR aquachannel simulation. (d) As in (c), but for the CTRL aquachannel simulation. Notice the different precipitation and wind scales.

FIG. 7. As in Fig. 6, but for the CTRL aquapatch simulation at (a) 0°, (b) 3.75°, and (c) 7.5° and for the (d) CTRL nested, (e) OBS, and (f) OBS nested aquapatches.

FIG. 8. Example of the applied methodology, for a 45-day period of the OBS aquachannel simulation, at the equator. (a) Precipitation greater than 86 mm day^{-1} (contours) and zonal wind at $\sim 1000 \text{ m}$ (shading). Yellow ellipses depict examples of CCs with sharp changes in zonal propagation. (b) Mean CC phase speeds are indicated with arrows, and zonal wind is shaded only for all PPs composing the CCs. (c) Mean phase speed and mean zonal wind for all CCs. The phase speed is depicted as in (b), i.e., major axis of the object. To facilitate comparisons, the zonal wind vector has unit length, and its origin coincides with the origin of the phase speed vector. (d) Categorization of all pixels in the x - t domain regarding location of the CCKW axis, computed from surface pressure anomalies and their tendencies in the 15°S - 15°N band. Red (blue) shading corresponds to CCKW-exit (CCKW-entrance) regions. Overlapped are contours of precipitation greater than 86 mm day^{-1} at the equator, as in (a).

according to the adopted scale categorization, is composed of a small group of precipitation pixels, given the resolution of our WRF simulations (a few or even a single one, if $\Delta = 139$ km). However, since the focus of this study is the analysis of zonal propagation, the meridional scale of the CC will not be considered, as was the case in the above paragraphs, as well as for the remainder of this study. In particular, when objectively quantifying CCs, these will be redefined as the smallest precipitation elements that appear *connected in time* for a given threshold of precipitation intensity. Details of the computation of these “time clusters” are provided next.

3. A local approach: The CC-tracking algorithm

A wide range of object-based methods have been previously applied in atmospheric sciences, for various phenomena such as midlatitude mesoscale convective complexes, hurricanes, and also in the classification of tropical convective structures such as SCCs and CCs (Mapes 1993; Mapes and Houze 1993; Chen et al. 1996), and CCEWs in general (Dias et al. 2012). Adopting this framework, a simple algorithm was designed for tracking the zonal propagation of tropical CCs on two-dimensional time–longitude diagrams, using precipitation outputs from the WRF Model.

Precipitation fields as function of time and longitude are only evaluated for a fixed latitude y_o . The following five latitudes were initially considered: 0° , 3.75° , 7.5° , 11.25° , and 15° . A transition to extratropical behavior was found toward the higher latitudes, particularly at 15° , where the CC propagation was strongly modulated by midlatitude synoptic-scale systems (not shown). But more importantly, after inspection of the mean ITCZ profiles (Fig. 4), the sharp precipitation decay centered at 7.5° in many of our simulations determined this as the outer limit for the analysis of tropical CC propagation.

The other important parameter regarding our algorithm is the precipitation intensity threshold. A histogram of rain rate for the x – t domain (total number of points is $n_t \times n_x \sim 420\,000$ for an aquachannel with grid spacing of 139 km) indicates a lognormal distribution. The peak of the distribution using log-spaced bins for the OBS aquachannel simulation at latitude 3.75° corresponds to a rainfall intensity of ~ 8 mm day $^{-1}$. A sensitivity analysis for the use of precipitation thresholds was carried out and the methodology adopted here consists of taking thresholds relative to the absolute peak in the entire simulation at the given latitude. More specifically, the CC identification will be performed for the upper 6.25% of values of precipitation.

All pixels above the threshold are considered precipitation pixels (PPs), while the remaining set is referred to

as nonprecipitating pixels (NPs). This means that for the subsequent identification, filtering, and classification of CCs, the precipitation intensity is not considered further. Details of the CC-tracking algorithm (including CC identification and CC properties) and its performance can be found in Blanco (2018). The approach is similar to that used by Wielicki and Welch (1986), Williams and Houze (1987), and Dias et al. (2012), although here the tracking is on time–longitude space.

Since this work focuses on the propagation velocity of CCs in relation to the background flow, special attention was placed on the algorithm performance regarding how accurately it can capture this relationship. Sometimes, the merger of several CCs into a larger object can generate an unrealistic phase speed (determined from its major axis in x – t space), and this is considered a “false detection” (for instance, westward-moving CCs under westerly flow).

a. Methodology

The full methodology of analysis using the CC-tracking algorithm is summarized in Fig. 8. Precipitation contours above the 93.75th percentile and low-level zonal wind are shown in Fig. 8a, for a 45-day period of the OBS aquachannel simulation, at the equator. Figure 8b shows CC propagation speeds after the algorithm has been applied (i.e., after filtering all non-CCs); in this case the superimposed zonal wind is shown only for the pixels within CCs. Zonal wind at a specified level is averaged over all PPs composing each CC to obtain a single value that can be compared with the CC’s phase speed: this is depicted in Fig. 8c, now with vectors for both phase speed and mean zonal wind for every CC. This one-to-one comparison allows us to produce scatterplots and linear regression between u and c_x .

From our hypothesis in the introduction, CC motion will be determined by low-level flow, which in turn is dominated by two mechanisms: general circulation dynamics (predominantly easterlies) and CCKW dynamics (westerly anomalies). Since WWBs are mainly generated to the rear side of CCKWs while easterlies exist ahead, CC propagation can be categorized not only by the sign of the background flow, but also in terms of location respect to the CCKWs. The advantage of surface pressure as a proxy for CCKW activity was discussed in B16B. A simple computation using only surface pressure averaged in the 15°S – 15°N band permits the objective determination of the CCKW region (either CCKW entrance, CCKW exit, or a transition zone) for the entire x – t domain automatically, since ahead of (behind) the passing of a CCKW, negative (positive) pressure anomalies tend to occur. The transition from entrance to exit regions is abrupt,

FIG. 9. Profiles of $u(z)$ for the OBS aquapatch simulation at latitudes (a) 0° and (b) 7.5° . Averages were computed over precipitation pixels (PPs; dashed lines) as well as over cloud cluster pixels (CCs; solid lines). Also the time–zonal mean is represented in dashed–dotted lines for comparison.

both in pressure and in wind. The propagation of individual CCs across the front-like passage of the CCKW is at times seen locally as a sideways V signature on Hovmöller precipitation diagrams (yellow ellipses in Fig. 8a), where the small-scale vertex on the “<” corresponds to this sharp transition. But far away from the center of strongest convection, the passage from westerlies to easterlies is gentle, and a large-scale S signature better represents this slow transition of CCs from “exit” to “entrance” region. Since the pressure anomaly does not perfectly correlate with east- versus west-moving CCs in this broader region, pressure tendency is also used. Surface pressure is smoothed with a 1–2–1 filter in both directions 80 times to reduce noise, and then their anomalies are taken. Pressure tendency (difference between consecutive times) is computed from these anomalies, and the field is subsequently smoothed 120 times with the same low-pass filter. The CCKW-exit region is assigned to all pixels that satisfy anomalies greater than 0.125 hPa as well as tendencies greater than -0.025 hPa . The entrance region is determined for all pixels that satisfy anomalies smaller than -0.5 hPa . All pixels that do not fall on either category are considered part of the “transition zones.” Figure 8d provides an example of the determination of CCKW-exit (red) and CCKW-entrance (blue) regions for the entire domain. The exit-to-entrance transition region is much broader (longer blank area from red to blue regions, moving forward in time) than the entrance-to-exit transition region (narrow white strip) associated with the passage of the CCKW axis. Although the precise location of the

CCKW transition zone can be locally slightly misplaced (see, e.g., the location of the 3 aforementioned “<” signatures in terms of these three areas) this does not affect the overall results. Finally, this pixel categorization for the entire domain is applied to the detected CCs.

b. CCs under easterly flow

Figure 9 shows the vertical variation of u , temporally averaged, for the OBS aquapatch case, which as noted above has only easterly flow along the tropics. Along with the time–zonal mean, the average flow over all PPs and over all CCs have also been computed. At the equator the three profiles are nearly identical, but at 7.5° the easterlies computed over CCs (or PPs) are about 2 m s^{-1} stronger than the time–zonal mean. In addition, the flow is sheared in lower levels: the magnitude of the easterlies first increases upward, and above 500 m it steadily increases until 2-km height (both in the time–zonal mean and in the PP or CC mean). The more vertically varying easterly wind in low levels at 7.5° (this latitude corresponds to that of strongest precipitation activity in the tropics for this simulation) offers a more meaningful correlation analysis between CC motion and background zonal flow, in order to determine level of highest correlation.

Scatterplots of c_x versus u are shown in Fig. 10, for vertical levels 4, 12, and 19 (altitudes of about 300, 1500, and 4500 m, respectively). In agreement with the previous qualitative analysis, nearly all CCs propagate westward. Nevertheless, the algorithm computes eastward propagation for a notable portion of all tracked clusters.

FIG. 10. Scatterplot and linear correlation of c_x vs u for the OBS aquapatch simulation at latitude 7.5° at three different vertical levels.

This misrepresentation for many CC velocities is inherent to the algorithm used, and such points in the scatterplot constitute false detections. Also, it can be seen that many scatterplot points fall along the same horizontal lines; this is simply due to the fact that CCs composed of very few PPs will accordingly have smaller number of major axis orientation (phase speed) possibilities.

The scatter distribution in the successive diagrams shifts from left to right with increasing height, indicating weaker easterly winds the farther from the surface, consistently with profile shown in Fig. 9. In addition, points are more tightly grouped for level 12 while they are relatively more scattered in the remaining cases. A linear regression is computed for these three vertical levels, as well as those in between.³ Several properties are overlapped on each plot as indicative of the goodness of the correlation. There is no significant change in the value of correlation coefficient. If the CCs are in fact advected by the wind in a given level (or layer), closeness to values of 1 for slope and 0 for y intercept of the linear fit will determine this level (or layer). The minimum difference between the mean or median phase velocity over all CCs and mean wind would also suggest an optimal result. From all these considerations, level 16 (~ 3000 m) provides the best correlation between u and c_x ; the y intercept of the linear correlation is the closest to 0, and the slope of the line is the closest to 1, while the mean and median values for $c_x - u$ are the second smallest.

c. CCs under oscillating easterly–westerly regimes

The dynamical response to organized large-scale convection is evidenced by the WWBs. To account for this effect, averages of $u(z)$ were computed over separated regions respect to the CCKW axis, as indicated in the methodology, namely: CCKW-entrance, CCKW-transition, and CCKW-exit regions. This is shown in Figs. 11a and 11b for latitudes 0° and 7.5° of the CTRL aquachannel simulation. Both exit and entrance regions have vertical profiles of zonal wind significantly different from the time–zonal mean: low-level easterlies intensify ahead of the CCKW axis but weaken and may even become westerlies behind. The indicated percentage values on each plot represents the number of the participating pixels with respect to the total ($n_x \times n_t$) for computing such average. To focus more in depth on the

³ The linear fits in Fig. 10 as well as in the upcoming figures assume no error in c_x or in u . Resolution errors in the computation of c_x increase as the number of PPs composing a given CC decreases. Errors in u are due to the averaging of zonal wind over all PPs to get a single value for each CC.

FIG. 11. Analysis of c_x vs u for the CTRL aquachannel simulation at latitudes of (a),(c),(e) 0° and (b),(d),(f) 7.5° . (top) Profiles of $u(z)$: time-zonal mean and mean computed over CCKW-exit and CCKW-entrance regions. (middle) As in the top row, but for averages computed over CCs only. (bottom) Scatterplot and linear correlation of c_x vs u for the level of highest correlation. In the scatterplots, CCs are further categorized in terms of CCKW-entrance and CCKW-exit regions.

CCs tracked by the algorithm, $u(z)$ profiles were computed by averaging in the same regions, but this time only over pixels composing detected CCs (Figs. 11b,c). It can be seen that for low to midlevels, and in a mean sense, the flow in areas of strong precipitation is similar to that of the flow in the surrounding environment.

The next step is to test whether CCs are actually advected by wind, and if so, to determine with the largest possible accuracy the vertical level or layer below 5-km height that effectively steers this organized mesoscale convection in the tropics. We confirm this hypothesis after applying the correlation method. Scatterplots of c_x versus u are shown Figs. 11e and 11f, for the level of highest correlation of each case (about 2200 m at the equator and 2600 m at 7.5°), although this is relative since the goodness of the various metrics is considered, and they all not necessarily coincide for the same level. Yet, it can be stated that the steering layer for tropical CCs is between 1800 and 3000 m, and this can be further generalized to all our WRF experiments (not shown). Particularly at 7.5° in some of the simulations, a more accurate determination of the steering layer (2600–3000 m) responds to the more sheared vertical profiles of zonal wind at this latitude.

Each CC on the scatterplots of Fig. 11 is further categorized into one of the three groups regarding CCKW activity, using blue (red) dots for entrance (exit) region. This confirms what had been estimated by simple inspection of precipitation and zonal wind Hovmöller diagrams: ahead (behind) the CCKW axis, the CCs move westward (eastward) under background low-level easterlies (westerlies).

Figure 12 depicts the results for the CTRL HR aquachannel simulation, also at 0° and 7.5°. For this case, in addition to the reduction of Δx (from 139 to 45 km), the temporal spacing was decreased from 6- to 3-hourly data, and this results in a dramatic increase in total CC detection by the algorithm. Due to the much greater density of the resulting scatterplots, CCs in the CCKW-exit and CCKW-entrance regions are shown separately. Again, the two groups of westward- versus eastward-moving CCs are well correlated with easterlies and westerlies, and their preferred origin areas are ahead and behind the CCKW axis, respectively. Also, the layer of best correlation at 7.5° (considering y intercept of the linear regression) can be narrowed to 1800–2000 m due to the large vertical shear in the troposphere (Fig. 12b).

Figure 12b gives another important finding. The low- to midlevel shear in the CCKW-entrance and CCKW-exit regions is strikingly similar: the only apparent difference is a shift toward easterlies (westerlies) for the entrance (exit) region. This contradicts

the assertion in Tulich and Kiladis (2012) that tropical CCs are driven by the vertical wind shear.

In summary, the correlation analysis applied systematically for all vertical levels supports the initial hypothesis that CCs are advected by low-level flow, either easterlies or westerlies. Despite the significant scatter in the c_x versus u diagrams due mostly to false detections, the method proved useful, as this pattern is systematic for all vertical levels. Biases (either under- or overestimations) in the overall c_x versus u correlation could then be easily determined for each level, yielding to the finding that the steering level for tropical CC motion is about 1800 to 3000 m. One disadvantage of the method, however, is that it cannot really measure the “S shapes”: the CC tracking only provides a “local” approach, as if considering separately segments of these S shapes. When the algorithm is used in conjunction with the regression method, this local perspective is addressed in an average sense: propagating characteristics of CCs are analyzed altogether without considering connections among themselves. For a robust study of zonal CC propagation along the tropics, a different approach needs to be incorporated, in which the oscillatory nature of the CCs in the time–longitude space can be quantified. The nonlocal, Lagrangian trajectory perspective provides the complementary tool for the objective study of the S shapes and is the subject of the next section.

4. A nonlocal perspective: The S shapes

The CC–SCC interaction is reassessed in this section in terms of imaginary trajectories over which CCs are embedded. These trajectories are continuous paths over which real CCs (no longer discretized) originate, live, and dissipate. In other words, if CCs can be imagined as perpetual entities, they would describe continuous oscillatory tracks, seen as *S shapes* on time–longitude diagrams. One of the advantages of this approach is that the full cycles of the CC oscillatory behavior can be studied, and not just areas surrounding the SCC axis where convection is enhanced. Other benefits of the nonlocal, S-shape perspective will be demonstrated later.

A very simple parameterization of CC motion is given by the equation

$$X_n(t) = A_1 \text{abs}[\cos(\omega t + \varphi)] - A_2 t + x_n, \quad (2)$$

where X_n represents a single CC trajectory on a time–longitude plot, while A_1 and A_2 are constants associated with the magnitudes of the easterly and westerly winds, respectively. The parameters ω and φ are the frequency

FIG. 12. Analysis of c_x vs u for the CTRL HR aquachannel simulation with $\Delta t = 3$ h at latitudes of (a), (c), (e) 0° and (b), (d), (f) 7.5° . (top) Profiles of $u(z)$: time-zonal mean and averages computed over CCKW-exit and CCKW-entrance regions for the CCs only. (middle), (bottom) Scatterplots c_x vs u for the level of highest correlation for the (middle) CCKW-exit and (bottom) CCKW-entrance regions. Centroid for each distribution is also indicated.

and phase of the oscillation, respectively, and x_n is a reference location for the n th trajectory.

Examples of this idealized representation of CC trajectories interacting with an SCC are presented in Fig. 13, for different sets of values for A_1 , A_2 . To facilitate comparisons, the same SCC structure has been kept, resembling a frequent pattern in the aquachannel Hovmöller diagrams shown before, namely, a zonal wavenumber-1 case with 2.5 periods within a given 45-day window (i.e., SCC phase speed of about 25 m s^{-1}). The frequency ω and phase ϕ are adjusted for each pair of values A_1 , A_2 so that the sharp velocity change of the CCs matches the passage of the CCKW axis.

This idealized model highlights

- 1) the periodicity of the S shapes described by the CCs, in association with successive passages of SCCs and
- 2) the “front-like” passage of the SCC, determined by the absolute value of the cosine oscillation rather than pure cosine, implying an abrupt transition from westward to eastward CC motion.

Also, this model is compatible with the three possible regimes: The first of these (Figs. 13a,b) represents a zero net drift of CC trajectories (pure oscillations around x_n), in close agreement with several of the aquachannel simulations used in this study, in which typically there is a similar number of CCs moving westward and eastward. The second (Figs. 13c,d) is associated with a stronger easterly flow, partially counterbalanced by the WWB: the S shapes appear negatively slanted (net westward drift): evidence of this behavior can be seen in the Hovmöller diagram for the OBS aquapatch (Fig. 7e). Finally, the last possible case is that of westerlies dominating over easterlies (A_2 with negative value); the resulting S shapes are positively slanted (net eastward drift). Net eastward drifts were repeatedly found at latitude 7.5° (clear cases are shown in Figs. 6d and 7c).

Another family of periodic trajectories on two-dimensional space, the trochoids, have similar characteristics. For the two-dimensional X – t space, a trochoid is parametrically defined as

$$t(\theta) = at - b \sin(\theta), \quad (3a)$$

$$X(\theta) = a - b \cos(\theta). \quad (3b)$$

For a very high ratio $\lambda = a/b$, the trochoid converges to a sinusoidal function, while for relatively small values greater than 1 such as $\lambda = 1.5$, 2, or 2.5 the trajectory resembles that of the abs (cosine) shown in Eq. (2), except for a reduced sharpness in the decrease-to-increase transition (Fig. 14). The importance of trochoids relies

on the fact that these trajectories arise as mathematical solutions to physical phenomena in fluid dynamics, for both the ocean (such as in Gerstner’s waves; see Henry 2008) and the atmosphere (parcel trajectories subject to total acceleration, and constant Coriolis and pressure gradient force; see Kao and Neiburger 1959). In these cases, advection plays a fundamental role in the resulting motion. This effect, neglected by the original Matsuno *linear* shallow water model for equatorially trapped modes, was addressed by Kao and Neiburger by the use of a Lagrangian framework. A similar approach is applied here to the problem of zonal propagation of organized convection.

a. Lagrangian trajectories for S shapes

A Lagrangian trajectory model solves the kinematic equations of motion:

$$d\mathbf{X}/dt = \mathbf{V}(\mathbf{X}, t); \quad \mathbf{X}(0) = \mathbf{X}_0, \quad (4)$$

where $\mathbf{X}(t)$ is the three-dimensional position of a hypothetical massless air particle as a function of time t , $\mathbf{V}(\mathbf{X}, t)$ is the velocity as a function of position and time, and $\mathbf{X}_0$ is the initial position of the particle. The solution to Eq. (4) is the path of the air particle through the atmosphere. As in the local CC-tracking method, trajectories here are computed only in the zonal coordinate, and for a given altitude and latitude: hence, these are strictly one-dimensional Lagrangian trajectories. However, the S-shape phenomenon is two-dimensional by definition, and implies the visualization of these trajectories in the x – t space. Therefore, plots of S shapes on Hovmöller diagrams generated by these hypothetical particles constitute pseudo-Lagrangian trajectories, in which time acts as a virtual spatial coordinate. For brevity, the S shapes produced by this method will be simply referred to as Lagrangian trajectories.

The Heun (second-order, two-step Runge–Kutta) method is used to compute the trajectories, and is given by

$$x_{\text{traj}}^{\&} = x_{\text{traj}}(t) + u_{\text{traj}}(x_{\text{traj}}, t)\Delta t, \quad (5a)$$

$$x_{\text{traj}}(t + \Delta t) = x_{\text{traj}}(t) + \frac{u_{\text{traj}}(x_{\text{traj}}, t) + u_{\text{traj}}(x_{\text{traj}}^{\&}, t + \Delta t)}{2}\Delta t, \quad (5b)$$

where u_{traj} is the zonal wind that will transport the particle to the new position, x_{traj} at the next time step ($t + \Delta t$). Figure 15 shows Lagrangian trajectories applied to the OBS HR aquachannel simulation, for latitude -7.5° and vertical level 16 (as can be seen,

FIG. 13. Conceptual model of CC trajectories with (a),(b) zero net drift and (c),(d) net westward drift. The oscillations in (b) and (d) have smaller amplitudes than those in (a) and (c). Values of model parameters are (a) $A_1 = 0.4, A_2 = 0$; (b) $A_1 = 0.2, A_2 = 0$; (c) $A_1 = 0.35, A_2 = 0.2$; and (d) $A_1 = 0.2, A_2 = 0.1$. Red dashed line indicates propagation of the SCC axis.

FIG. 14. Comparison among trochoids for five different values of $\lambda = a/b$ as well as cosine and $\text{abs}(\text{cosine})$ functions.

sensitivity to the integration method used for the trajectory is generally negligible). Eight trajectories are computed throughout the entire year, being initially equidistant from one another (i.e., a 5000-km separation). The precipitation (contours) and zonal wind (shadings) are superimposed on the sequence, to assess the performance of the method to track precipitation features. Qualitatively, the CCs and the trajectories exhibit very similar behaviors, in terms of eastward (westward) propagation under westerlies (easterlies). The S shape exhibited by one of these curves, centered at $x \sim 15\,000$ km and between days 200 and 230 is perhaps one of the best examples, not only for its almost “ideal” S pattern, but also, because there is coincidentally abundant precipitation over and surrounding such path: the CCs run mostly parallel to the trajectory, and they do so while veering either eastward or westward at different times (particularly between days 208 and 212, on the easterly-to-westerly transition).

Overall, it is remarkable how well the CCs follow the trajectories (regardless of the exactitude of the overlap, since this can be adjusted by simply modifying the starting points $[x_0, t_0]$ of the trajectories): not only does this indicate advection as the primary mechanism driving the CCs, but also, the fact that new CCs are frequently triggered ahead (in time, following the trajectory) of old ones, suggesting the role of moisture (or mse) anomalies, cold pools, or similar convection-related processes. In turn, this is confirmed by overlapping Lagrangian trajectories to variables such as meridional wind (Fig. 16b), horizontal vorticity (Fig. 16c), or total water content (Fig. 16d). The dominant pattern in all these Hovmöller diagrams is that of *continuous* S shapes of the respective variables (unlike the *discrete* CCs, superimposed in black contours)

running nearly parallel to the Lagrangian trajectories, while the Kelvin mode arises as a second feature.⁴ In contrast, for zonal wind, the Kelvin structure visually appears first (Fig. 16a).

Figure 17 shows additional examples of Lagrangian trajectories over a 45-day period for other simulations and latitudes; as in the Fig. 15 case, eight trajectories are also initially equidistant at day 1 (only three trajectories are used for the shorter aquapatch domain). It can be seen that the properties of the S shapes, such as amplitude, frequency, and net drift, vary significantly. At latitude 7.5° , for both the CTRL HR aquachannel (Fig. 17b) and CTRL nested aquapatch (Fig. 17e), the trajectories oscillate slightly on their overall eastward motion. The OBS aquapatch (Fig. 17c), presents again trajectories that consistently propagate westward due to the weak CCKW activity. And trajectories on the CTRL nested aquapatch (Fig. 17d) exhibit a high-frequency oscillatory behavior: this is due to the coherent $k = 1$ CCKW passage, whose period is relatively short (~ 7 – 8 days) compared to that of the aquachannel, due to the much shorter extent of the domain.

Nearly all simulations and analyzed latitudes show recurrent mergers between neighboring Lagrangian trajectories. For example, from the eight starting trajectories in Fig. 15, only two are distinguishable by day 360. These unions are produced by ample and frequent regions of zonal wind convergence along the CCKW axis. Figure 17 provide additional examples of this merging behavior, wherever the number or trajectories is smaller than the initial number.

⁴ Since precipitation is the most relevant variable in tropical climate analyses, the “S shape” concept will be mainly associated with zonal propagation of precipitation (i.e., discrete CCs).

FIG. 15. Lagrangian trajectories for the OBS HR aquachannel case, at latitude -7.5° and model level 16, for days 180–360. At $t = 0$ (not shown) eight trajectories are equally spaced in the 40 000-km domain. Sensitivity to computation method is also shown. Zonal wind and precipitation are overlapped.

FIG. 16. Lagrangian trajectories overlapped to cloud clusters and (a) zonal wind, (b) meridional wind, (c) horizontal vorticity, and (d) total water content. The selected 45-day window corresponds to the OBS aquachannel simulation at the equator and for model level 16.

FIG. 17. As in Fig. 15, but for 45-day periods of selected cases (notice different wind scales).

TABLE 1. Metrics for quantification of the properties of the S shapes.

Parameter	Name (units)	Interpretation
ND	Net drift (km)	Difference between final and initial location of a given trajectory over a given period of time. For a full circumnavigation around the tropics, $ND = (-) + 40\,000$ km, if the particle traveled to the (west) east.
TD	Traveled distance (km)	Sum of the absolute values of all zonal displacement (for each time interval) over a given period of time.
EW	Eastward/westward ratio (%)	Measure of persistency of the easterly (negative ratio) or westerly (positive ratio) wind. Computed as $EW = (nE - nW)/nt$ where $nt = nE + nW = 1460$ for 1-yr simulations, and nE (nW) is the number of times the trajectory has traveled to the east (west).
A	Amplitude (km)	Amplitude as in a sinusoidal function; averaged over a given period of time.
T	Period (days)	Periods as in a sinusoidal function; averaged over a given period of time.

Lagrangian trajectories are strongly dependent on which vertical level is used for the input velocity field; however, for adjacent vertical levels changes are relatively small as long as the wind shear is not a significant (not shown). By a visual inspection it was verified that from the vertical layer of highest correlation obtained from the nonlocal method, one of these levels provides the best match between S shapes and CC tracks, for a given simulation and latitude.

b. Measuring the S shapes

Another of the advantages provided by the nonlocal approach via Lagrangian trajectories is that a series of features of the S shape can be quantified by the use of metrics. Five indices are used in this study and are summarized in Table 1. These metrics are computed for 8 (or 3 for an aquapatch) initially equidistant trajectories (as shown in Fig. 15), and then averaged.

Results for the whole set of simulations and latitudes are shown in Table 2. The OBS aquapatch (double-ITCZ simulation) is once again a particular case, consistent with the findings of section 3. It represents the largest westward drift ($ND/L_x < -200\%$), due to the almost permanent easterlies ($EW < -75\%$). The finite value of the oscillatory period ($T > 17$ days) actually indicates an occasional interruption of this steady flow by some transient fluctuation.

The smallest period of the oscillation (6.9 days) corresponds to the CTRL nested aquapatch: this is qualitatively verified by the 45-day sequence shown in Fig. 17d, in which there is a robust $k = 1$ CCKW, which completes two full cycles at $x = 0$ between days 100 and 113 (i.e., $T \sim 6.5$ days). The period of the oscillations is precisely the most significant difference between the aquapatch and aquachannel configurations: the period of the former (latter) range around 6.9–10.8 (9.3–12.9) days. This is simply due to the fact that the same envelope of convection propagating at the same speed would require 3 times longer to complete a cycle, but in this case, the factor of increase is much smaller (CCKW structure and

phase speed are affected by the shortening of the model domain, as studied in B16A).

The most striking difference appears when comparing latitudes: this is not surprising, since the $u(z)$ mean states vary in a similar manner (Fig. 5). It was mentioned earlier that at 7.5° , drifts are pronouncedly eastward, contrasting with westward drifts at latitudes 3.75° and 0° . For three of the aquachannel simulations at 7.5° , $ND > 40\,000$ km, and particularly, for the two CTRL aquachannel cases, $ND > 80\,000$ km. In the remaining case, the OBS HR aquachannel, the nearly zero net drift at 7.5° still contrasts with the net westward drift at the two other latitudes ($ND < -40\,000$ km). This meridional difference is also very significant for the two CTRL aquapatch simulations.

It is worth remarking that the aforementioned “ideal” S shape centered at $x \sim 15\,000$ km and between days 200 and 230 in Fig. 15 has roughly a period of 17–20 days, and an amplitude of about 1500–2000 km, substantially larger than the computed average values of $T = 10.7$ days and $A = 555.7$ km. The reason for these smaller values is mainly due to the averaging over weak or temporarily nonexistent CCKW events, and occasional $k = 2$ CCKWs, and to lesser degree, strong localized fluctuations in wind speed both in the westerly and easterly regions (even accompanying mature $k = 1$ CCKWs). In other words, the computed T and A values are rarely representative of the actual period and amplitude of a *clean* S shape; this was generally found in all simulations and latitudes.

c. The CC–SCC interaction

The average properties over many Lagrangian trajectories for the different simulations can be used to fit the S shapes parameterization given by Eq. (2). Instead, we apply a more practical approach that consists in using Lagrangian trajectories over a simplified wind field, based on parameters taken from the simulated winds. Average values of U_{mean} and $U_{\text{amplitude}}$ are computed for a given simulation and latitude, as well as

TABLE 2. Average indices for net drift (ND), total traveled distance (TD), persistence (EW), amplitude A , and period T computed over initially equidistant Lagrangian trajectories, using model level 16. The number of trajectories is 8 (3) for the aquachannel (aquapatch) simulations. A value of $L_x = 40\,000$ km, Earth's circumference at the equator, is used as normalization parameter in all cases. For the half year, nested aquapatch simulations, the ND and TD values are additionally doubled to ease intercomparisons, i.e., 1-yr projections (half-year values in parentheses). Δx refers to the grid spacing of the outputs.

Simulation	Δx (km)	Lat ($^\circ$)	ND/ L_x (%)	TD/ L_x (%)	ND/TD (%)	EW (%)	A (km)	T (days)
Aquapatch HR OBS	46	0	−184	208.1	−88.4	−75.1	99.8	19
		3.75	−203.5	228.2	−89.2	−75.9	161.4	17.5
		7.5	−214.8	239.6	−89.7	−76.2	111.5	18.7
Aquapatch HR CTRL	46	0	−120.6	248.7	−48.5	−38.5	292.4	7.3
		3.75	−88.1	242.6	−36.3	−25.3	314	7.7
		7.5	191.7	301.9	63.5	46.3	243.1	9.1
Aquapatch nested OBS	46	0	(4.1)	(136)	3	−14.9	749.1	9.2
			8.2	272				
		3.75	(−44.1)	(119.7)	−36.9	−32.1	549.1	10.6
			−88.2	239.4				
		7.5	(−68.4)	(107.3)	−63.7	−47.1	228.6	10.8
Aquapatch nested CTRL	46	0	(−7.1)	(130)	−5.4	−5.4	547.9	6.9
			14.2	260				
		3.75	(−13.7)	(133.5)	−10.3	−6.7	535.2	7.4
			27.4	267				
		7.5	(83.2)	(151.2)	55	31.9	333.1	8.4
Aquachannel OBS	139	0	−93.5	243.4	−38.4	−23.8	562.3	12.2
		3.75	−93.9	240.1	−39.1	−25.6	471.5	12.6
		7.5	105.5	254.2	41.5	26.3	500.9	12
Aquachannel CTRL	139	0	−41.7	281.9	−14.8	−9.9	742.8	9.4
		3.75	20	299.4	6.7	0.1	1025.2	9.6
		7.5	283.7	368.9	76.9	57.6	343.9	12.5
Aquachannel HR OBS	46	0	−108.3	246.8	−43.9	−29	434.5	12.9
		3.75	−121.8	239.6	−50.8	−36.7	346.3	12.6
		7.5	−9.1	226.3	−4	−5.3	555.7	10.7
Aquachannel HR CTRL	46	0	−77.5	316.1	−24.5	−15.3	670.4	10
		3.75	−56.7	297.5	−19	−11.7	717.1	9.3
		7.5	217.1	332.6	65.3	44.5	327.6	10.5

the definition of a type of profile of $u(x, t)$ linked to a type of CCKW structure. Table 3 shows the U_{mean} and $U_{\text{amplitude}}$ values for all analyzed cases, while Figs. 18a–c illustrate how the values were calculated. The three examples corresponding to different simulations were chosen since they highlight the abrupt transition from easterly to westerly winds, associated with the passage of a CCKW axis.

Figures 18a–c help identifying a pattern of the time evolution of the zonal wind, associated with an ideal zonal wavenumber-1 CCKW. A periodic triangular pulse represents an adequate fit for the sudden easterly-to-westerly transition within an oscillation (Fig. 18d). In addition, the skewness of the triangle is a parameter that permits the tuning of such transition (i.e., controls its sharpness). The mean and amplitude values of this standard prototype (0 and 1, respectively) are replaced by some representative U_{mean} and $U_{\text{amplitude}}$ values of a given simulation. From this base, a two-dimensional zonal wind can be built, in

which the zonal wavenumber and phase speed of the CCKWs need to be set as well. We choose again the structure given by $k = 1$, $T = 18$ days (and hence, $c_x \sim 25 \text{ m s}^{-1}$). Finally, S shapes can be computed using this idealized $u(x, t)$ profile and the Lagrangian trajectory method.

Results of this combined procedure are depicted in Fig. 19, for three sets of mean background flow: $U_{\text{mean}} = 0 \text{ m s}^{-1}$ (Figs. 19a,b), $U_{\text{mean}} = -5 \text{ m s}^{-1}$ (Fig. 19c), and $U_{\text{mean}} = -12 \text{ m s}^{-1}$ (Fig. 19d), using for all cases the same amplitude in zonal wind oscillation, $U_{\text{amplitude}} = 9 \text{ m s}^{-1}$. While this last value is representative for most of the computed amplitudes in Table 3, the resulting Lagrangian trajectories exhibit a greater amplitude in their oscillations when compared with those from Figs. 15 and 17. This is because now the emphasis is not put on *average* S shapes but on *ideal* ones, in agreement with the calculation method of $U_{\text{amplitude}}$. The west-to-east transition in direction of propagation at the CCKW axis is well represented: there is no

TABLE 3. Values of U_{mean} and $U_{\text{amplitude}}$ for model level 16.

Simulation	Δx (km)	Lat ($^{\circ}$)	U_{mean}	$U_{\text{amplitude}}$
Aquapatch HR OBS	46	0	-2.47	5.24
		3.75	-2.60	5.32
		7.5	-2.9	5.58
Aquapatch HR CTRL	46	0	-2.25	8.00
		3.75	-1.33	8.42
		7.5	2.79	8.92
Aquapatch nested OBS	46	0	-1.41	7.98
		3.75	-2.26	7.77
		7.5	-2.43	7.00
Aquapatch nested CTRL	46	0	-1.30	8.81
		3.75	-1.06	8.57
		7.5	1.54	8.79
Aquachannel OBS	139	0	-1.56	8.63
		3.75	-1.32	8.85
		7.5	1.58	9.44
Aquachannel CTRL	139	0	-1.06	9.92
		3.75	-0.25	10.90
		7.5	3.66	11.59
Aquachannel HR OBS	46	0	-1.67	8.80
		3.75	-1.81	8.57
		7.5	0.31	9.15
Aquachannel HR CTRL	46	0	-1.83	11.04
		3.75	-0.93	11.33
		7.5	2.98	11.77

discontinuity in velocity (omitting the discrete 6-h intervals of the data) compared to the singularity arising from the absolute value of a sinusoidal function [Eq. (2)], or similarly edged trochoid curves. In this sense, the transition across the CCKW axis in Fig. 19 resembles that of some of the trochoid trajectories with no edges (Fig. 14). A significant feature that arises when using these idealized zonal wind structures is the absolute symmetry between two consecutive full cycles, and hence, the subsequent Lagrangian trajectories converge and diverge but never merge to one another.

The idealized S shapes of Fig. 19a reasonably characterize the CC propagation shown in Fig. 17a. Similarly, S-shape patterns could be constructed to fit results from a given simulation and latitude bin. To represent a wide range of possibilities of CC propagation in the tropics and its associated dynamics, a conceptual model was built: Fig. 20 qualitatively depicts eight S shapes, arising from different background zonal winds, for the same prototype of robust, coherent CCKW previously used ($k = 1$, $T = 18$ days, $c_x \sim 25 \text{ m s}^{-1}$). For simplicity the type of $u(x, t)$ structure has been kept the same in all cases (triangular pulse case with skew = 0.75 and $U_{\text{amplitude}} = 9 \text{ m s}^{-1}$), except for variations of U_{mean} parameter: from -10 to $+7.5 \text{ m s}^{-1}$ in 2.5 m s^{-1} increments. By the use of a relatively large amplitude, pronounced S shapes are obtained, to highlight the effect

of the dynamic mechanisms. Regardless of the relative magnitude of the easterly and westerly anomalies, which can produce either net westward, near zero, or positive drifts, one feature stands out as a common denominator: the abrupt change in direction of the trajectory across the CCKW axis, which can be redefined now from a mesoscale perspective as a *CCKW front* or *SCC front*.

Figure 20 is meant to illustrate as many potential cases as possible into the same conceptual model; this includes easterly or westerly flow at all times, shown by the pair of trajectories located left and right of the ensemble. For example, westerly anomalies ($u^* > 0$) right behind the CCKW front cause a sharp reduction on the speed of the westward trajectory under a strong easterly flow ($u < 0$ at all times in the $x-t$ domain), as can be seen for the leftmost Lagrangian trajectory in the ensemble. On the other hand, for the rightmost member, ahead of the SCC front there is a region of $u^* < 0$ that slows down the particle to nearly to zero velocity, this under a strong westerly background flow. Therefore, the applicability of this framework extends beyond the particular climatological features of the aquachannel and aquapatch experiments used in this work.

The depiction of the SCC front as a relatively wide area in Fig. 20, highlights that it is a transition region, rather than strictly a “line”; this qualification also applies to synoptic-scale cold and warm fronts in mid-latitudes. As in these classical fronts, not only is the SCC front a region of cloudiness and precipitation, but it is also a zone of considerable horizontal wind convergence. Moreover, this representation is consistent with the categorization of CCKW-entrance, CCKW-transition, and CCKW-exit regions used in section 3: the thinner of the two transition regions in Fig. 8d is equivalent to the SCC front region.⁵ For these considerations, the present conceptual model is seemingly more appropriate than the one shown in Fig. 13.

It is worth mentioning that sharp fluctuations occur quite frequently along Lagrangian trajectories due to high-frequency changes (noise) in the zonal wind, and not exclusively across the CCKW axis, as several examples from Figs. 15 and 17 indicate. Some of these tracks even exhibit sudden shifts in the opposite direction (i.e., eastward to westward). However, there is a very important reason for introducing the proposed terminology of the *SCC front*. Lagrangian trajectories

⁵ The CCKW-transition region in section 3 was computed in terms of pressure anomalies and tendencies, so it will not coincide exactly with an SCC front determined from zonal wind convergence.

FIG. 19. Lagrangian trajectories computed from idealized zonal wind profiles using a prototype for CCKW structure and speed for $U_{\text{mean}} =$ (a),(b) 0, (c) -5 , and (d) -12 m s^{-1} . In all cases $U_{\text{amplitude}} = 9 \text{ m s}^{-1}$. Periodic triangular pulse for $u(t)$ is used in all cases with a skewness parameter of (a),(d) 0.5 and (b),(c) 0.75. See details in text.

FIG. 20. Conceptual model of the SCC-CC interaction. The SCC front (heavy black line) is a finite region that strongly modulates CC propagation via significant westerly anomalies. The ensemble of eight Lagrangian trajectories (green contours) starting at the same time and longitude were computed from a wide range background flows, from dominant easterly wind to dominant westerly wind. Blue (red) arrows represent westerly (easterly) zonal wind anomalies ahead of (behind) the SCC front, that is, in the SCC-entrance (SCC exit) region. See details in text.

simply “assist” in the visualization (and measuring) of *actual* S shapes, those determined by real CCs; on the other hand, the SCC is by definition, an eastward-moving region of enhanced CC activity. Hence, an SCC front is a phenomenon that explains the shift in zonal propagation of strong convective elements, which might exist elsewhere only scatteredly and in small number, at least if relatively high thresholds of precipitation are used. In this regard, the precipitation intensity cutoff, in absolute terms, should be carefully considered. The latitude where strongest convection occurs for most aquaplanet-like simulations is the equator (Fig. 4); for example, precipitation greater than 85 mm day^{-1} is shown at this latitude in Fig. 8a for one of the aquachannel simulations, and clearly the sharp changes in phase speed of these CCs occurs exclusively along the SCC fronts (day 47 at $x \sim 26000 \text{ km}$; day 56 at $x \sim 5000 \text{ km}$; day 76 at $x \sim 0$). Furthermore, SCC fronts also appear (although significantly

smoothed) when meridional averages across the ITCZ are taken (Figs. 1b,c), while other similar but isolated features in the x - t space are filtered out.

5. Discussion, summary, and conclusions

A diversity of organized convective forms has been regarded under the umbrella of “cloud cluster,” although for most studies this concept is applied to 2-day waves, and it represents a different phenomenon than the one treated here. For symmetric (no seasonality), full-physics, aquaplanet-like simulations, spectral peaks associated with the fast WIG or eastward inertia-gravity (EIG) modes are usually negligible, while the Kelvin wave is the sole or dominant mode of large-scale organization of tropical convection (Frierson 2007; Nasuno et al. 2008; Blackburn et al. 2013). The CCs generated by these idealized simulations have unique propagation characteristics that take them out of the CCEW family of tropical waves, especially the 2-day waves. It is an unfortunate coincidence that the CC concept has been widely used for the observed, fast 2-day waves [as used by Nakazawa (1988); later, Takayabu (1994) linked the 2-day waves to the linear WIG mode] and at the same time for the simulated, slow-moving small-scale clusters in idealized simulations. Yamasaki (2011) has remarked that the CCs produced in his idealized simulations are different than the convectively coupled WIG waves, but this distinction in the ambiguous terminology has not yet been widely addressed in literature. This work has identified the high correspondence between winds and phase speeds of tropical CCs, to a direct cause-effect relation (i.e., zonal advection of CCs by background low- to midlevel flow). Since the nonlinear CC propagation treated here is significantly distinct from that of all other Matsuno’s linear modes, it would be worthwhile to determine the signal of the S shapes in the wavenumber-frequency space. This topic will be addressed in a future paper.

In this study we used WRF aquachannel and aquapatch simulations to comprehensively study the kinematics and dynamics of tropical CCs in association with SCCs: this interaction takes the form of “S” signatures on time-longitude plots. This model setting generates tropical easterlies regularly perturbed by CCKW-produced WWBs, permitting the study of advection of CCs by flow resulting at all times from the internal ITCZ dynamics and variability. In addition, the framework is optimal due to the fact that CCKWs are the dominant mode of variability in the tropics under this simplified configuration. In other words, the idealized model set-up inhibits many other modes of variability present not only in reality (monsoons, ENSO) but also in asymmetric aquaplanet

configurations (other CCEWs, MJO), thus permitting a clear analysis of mesoscale CC oscillations in time–longitude diagrams.

Two independent methods have been applied to study this oscillatory CC behavior for various latitudes. The first involves a CC-tracking algorithm, which permits an objective analysis of all CCs in an automated manner, after establishing a precipitation threshold. The major axis of each detected CC on x – t coordinates determines its phase speed, which is then correlated with the zonal wind within the same CC for different vertical levels. On the other hand, the algorithm has a clear disadvantage: the “false detection problem” arises when two or more CCs with a clear westward propagation merge and appear as having a spurious eastward propagation, which often occurs within the SCC when the precipitation threshold is not sufficiently high. Alternatively, the “no detection problem” occurs when many CCs pass unnoticed in other parts of the domain if the precipitation threshold is not sufficiently low. Nevertheless, these issues are not exclusive to the algorithm used for this work: different algorithms or parameter values for the same algorithm produce different CC climatologies in terms of number, location, and even phase speeds (see Fig. 23 of [Mapes and Houze 1993](#)). A second caveat of this objective methodology is that the individual CCs are tracked locally; that means, ignoring the broader picture in which CCs veer in time producing the S shapes.

The second method is independent from the first, as well as complementary to it, since it provides a nonlocal, integral approach of the S shapes. It is based on Lagrangian trajectories in the time–longitude space (for a given altitude and latitude), which are determined as particles are advected at each time step by the background flow. Indices were defined to objectively quantify different characteristics of the S shapes produced by these trajectories. One weakness of the method used here is that the comparison between actual CCs and Lagrangian S shapes was performed subjectively. However, it was shown that the same trajectories reproduced strikingly well the S shapes generated by other continuous variables such as vorticity, meridional wind, or total water content. This nonlocal method uses the vertical levels obtained from the local method to compute the trajectories.

The major findings combining the two methods are as follows:

- 1) Climatological easterlies are insufficient to properly characterize CC propagation in the tropics, unless there is weak or no large-scale organized convection in the form of SCCs/CCKWs.
- 2) The low- to midlevel mean flow advects CCs, specifically, in the layer of 1800–3000 m. This steering layer can be thought of analogous to that for the baroclinic waves or tropical cyclones.
- 3) While it can be true that generally CCs propagate westward, this does not always occur. Even if it does, there can be significant fluctuations in speed, as in the OBS aquapatch simulation but also in other aquaplanet-like models with robust CCKW activity but lacking superrotation.
- 4) Tropical westerly flow can occur due to the mean background flow (moderate to strong superrotation), convection-generated wind anomalies [westerly wind bursts (WWBs)], or a contribution from both. When the two effects are present westerlies can dominate over easterlies, and if so, CCs will exhibit a net eastward drift.
- 5) If the model supports CCKW activity, then there is an oscillation in CC direction of propagation and speed, with period equal to the time between successive SCCs traveling eastward. Transition into (out of) the SCC determine the transition of westward-to-eastward (eastward to westward) moving CCs, therefore shaping the overall characteristic S signature, usually with a sharp change by the passage of the SCC axis. The latter can be regarded as an SCC *front*, implying similar characteristics as synoptic-scale fronts in midlatitudes. An *ideal* S shape is not a pure sinusoidal oscillation, but a trochoid-like one.

The mechanisms analyzed here are new to the theory of tropical dynamics: to the authors' knowledge no previous discussion of them can be found in literature. Why would the S patterns not be reproduced in some idealized simulations, or pass unnoticed in most cases? The answer involves two different aspects: the model itself, and the methodology. Regarding the model, the absence of SCCs and/or the absence of superrotation may be the reasons: eastward-propagating CCs require westerly flow that come from anomalies and sometimes also from the time-mean flow. The reasons from the second group include broad ITCZ averages (the typically used -15° to 15° band), the use of OLR rather than precipitation rates, and also the imposition of relatively high thresholds that can mask out the often weaker eastward-propagating CCs behind the SCC axis. A combination of these is quite typical, when the focus is placed on the synoptic-scale features of the ITCZ, rather than on the mesoscale aspects.

The present study can provide a starting point for future studies of tropical convection. Could probabilistic precipitation forecasts be improved in tropical oceanic regions from moisture anomalies and low- to midlevel

flow? Alternatively, the role of advection in connection with other scales and modes of variability can be further explored. Nasuno et al. (2007) focused on the multiscale organization of tropical convection, addressing the smaller-scale features (MCs) embedded in the CCs. However, the roles of subsidence, cold pools, moistening, triggering of gravity waves and their respective zonal velocities or phase speeds, were all investigated exclusively in the leading region of the CCKW where CCs propagate westward. How would all the multiscale interactions change for eastward-moving CCs under predominantly westerly flow in the CCKW-exit region?

Finally, since results presented here were obtained from a set of idealized symmetric, yet, full-physics simulations, a quest for observational evidence of this mechanism is demanded. It is possible though, that in terms of the observed ITCZ variability, its contribution is very small, perhaps negligible, considering the wide variety of tropical phenomena, such as ENSO, monsoons, MJO, CCEWs, and tropical cyclones. Notwithstanding, a preliminary, qualitative analysis over a full year of TRMM precipitation data combined with MERRA2 zonal wind fields yielded some interesting examples of rapid change in westward-to-eastward propagation of CCs within a CCKW region. The documentation of these findings will be the topic of a forthcoming paper.

Acknowledgments. The authors are thankful to Chidong Zhang, Benjamin Kirtman, Zhiming Kuang, and one anonymous reviewer for their constructive and helpful comments. This work is based on J. Blanco's Ph.D. thesis at the University of Miami and was partially supported by the National Science Foundation through Grant AGS-1146701. The simulations used in this study were produced on the high-performance computers of the Center of Computational Sciences at the University of Miami.

REFERENCES

- Blackburn, M., and B. J. Hoskins, 2013: Context and aims of the Aqua-Planet Experiment. *J. Meteor. Soc. Japan*, **91A**, 1–15, <https://doi.org/10.2151/jmsj.2013-A01>.
- , and Coauthors, 2013: The Aqua-Planet Experiment (APE): Control SST simulation. *J. Meteor. Soc. Japan*, **91A**, 17–56, <https://doi.org/10.2151/jmsj.2013-A02>.
- Blanco, J. E., 2018: Modulation of cloud cluster propagation by super cloud clusters. Ph.D. thesis, University of Miami, 221 pp.
- , D. S. Nolan, and S. Tulich, 2016a: Convectively coupled Kelvin waves in aquachannel simulations. Part I: Propagation speeds, composite structures and comparison with aquaplanets. *J. Geophys. Res. Atmos.*, **121**, 11 287–11 318, <https://doi.org/10.1002/2016JD025004>.
- , —, and B. E. Mapes, 2016b: Convectively coupled Kelvin waves in aquachannel simulations. Part II: Life cycle and dynamical-convective coupling. *J. Geophys. Res. Atmos.*, **121**, 11 319–11 347, <https://doi.org/10.1002/2016JD025022>.
- Chao, W. C., and S.-J. Lin, 1994: Tropical intraseasonal oscillation, super cloud clusters, and cumulus convection schemes. *J. Atmos. Sci.*, **51**, 1282–1297, [https://doi.org/10.1175/1520-0469\(1994\)051<1282:TIOSCC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<1282:TIOSCC>2.0.CO;2).
- Chen, S. S., R. A. Houze Jr., and B. E. Mapes, 1996: Multiscale variability of deep convection in relation to large-scale circulation in TOGA COARE. *J. Atmos. Sci.*, **53**, 1380–1409, [https://doi.org/10.1175/1520-0469\(1996\)053<1380:MVODCI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1996)053<1380:MVODCI>2.0.CO;2).
- Dias, J., S. N. Tulich, and G. N. Kiladis, 2012: An object-based approach to assessing the organization of tropical convection. *J. Atmos. Sci.*, **69**, 2488–2504, <https://doi.org/10.1175/JAS-D-11-0293.1>.
- Frank, N. L., 1970: Atlantic tropical systems of 1969. *Mon. Wea. Rev.*, **98**, 307–314, [https://doi.org/10.1175/1520-0493\(1970\)098<0307:ATSO>2.3.CO;2](https://doi.org/10.1175/1520-0493(1970)098<0307:ATSO>2.3.CO;2).
- Frierson, D. M. W., 2007: Convectively coupled Kelvin waves in an idealized moist general circulation model. *J. Atmos. Sci.*, **64**, 2076–2090, <https://doi.org/10.1175/JAS3945.1>.
- Grabowski, W. W., and M. W. Moncrieff, 2001: Large-scale organization of tropical convection in two-dimensional explicit numerical simulations. *Quart. J. Roy. Meteor. Soc.*, **127**, 445–468, <https://doi.org/10.1002/qj.49712757211>.
- Henry, D., 2008: On Gerstner's water wave. *J. Nonlinear Math. Phys.*, **15** (Suppl.), 87–95, <https://doi.org/10.2991/jnmp.2008.15.S2.7>.
- Kao, S.-K., and M. Neiburger, 1959: Oscillations and trajectories of air particles in some pressure systems. *J. Geophys. Res.*, **64**, 1283–1291, <https://doi.org/10.1029/JZ064i009p01283>.
- Kiladis, G. N., M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy, 2009: Convectively coupled equatorial waves. *Rev. Geophys.*, **47**, RG2003, <https://doi.org/10.1029/2008RG000266>.
- Lane, T. P., and F. Zhang, 2011: Coupling between gravity waves and tropical convection at mesoscales. *J. Atmos. Sci.*, **68**, 2582–2598, <https://doi.org/10.1175/2011JAS3577.1>.
- Lau, K. M., P. Li, C. H. Sui, and T. Nakazawa, 1989: Dynamics of super cloud clusters, westerly wind bursts, 30–60 day oscillations and ENSO: An unified view. *J. Meteor. Soc. Japan*, **67**, 205–219, https://doi.org/10.2151/jmsj1965.67.2_205.
- , T. Nakazawa, and C.-H. Sui, 1991: Observations of cloud cluster hierarchies over the tropical western Pacific. *J. Geophys. Res.*, **96**, 3197–3208, <https://doi.org/10.1029/90JD01830>.
- Liu, C., and M. W. Moncrieff, 2004: Effects of convectively generated gravity waves and rotation on the organization of convection. *J. Atmos. Sci.*, **61**, 2218–2227, [https://doi.org/10.1175/1520-0469\(2004\)061<2218:EOCGGW>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<2218:EOCGGW>2.0.CO;2).
- Mapes, B. E., 1993: Gregarious tropical convection. *J. Atmos. Sci.*, **50**, 2026–2037, [https://doi.org/10.1175/1520-0469\(1993\)050<2026:GTC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<2026:GTC>2.0.CO;2).
- , and R. A. Houze Jr., 1993: Cloud clusters and superclusters over the oceanic warm pool. *Mon. Wea. Rev.*, **121**, 1398–1415, [https://doi.org/10.1175/1520-0493\(1993\)121<1398:CCASOT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1993)121<1398:CCASOT>2.0.CO;2).
- Martin, D. W., and O. Karst, 1969: A census of cloud systems over the tropical Pacific. Studies in atmospheric energetics based on aerospace probings, University of Wisconsin–Madison Space Science and Engineering Center Rep., 37–50.
- Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–43, https://doi.org/10.2151/jmsj1965.44.1_25.
- Nakazawa, T., 1988: Tropical super clusters within intraseasonal variations over the western Pacific. *J. Meteor. Soc. Japan*, **66**, 823–839, https://doi.org/10.2151/jmsj1965.66.6_823.
- Nasuno, T., H. Tomita, S. Iga, H. Miura, and M. Satoh, 2007: Multiscale organization of convection simulated with explicit

- cloud processes on an aquaplanet. *J. Atmos. Sci.*, **64**, 1902–1921, <https://doi.org/10.1175/JAS3948.1>.
- , —, —, —, and —, 2008: Convectively coupled equatorial waves simulated on an aquaplanet in a global nonhydrostatic experiment. *J. Atmos. Sci.*, **65**, 1246–1265, <https://doi.org/10.1175/2007JAS2395.1>.
- Nolan, D. S., S. N. Tulich, and J. E. Blanco, 2016: ITCZ structure as determined by parameterized versus explicit convection in aquachannel and aquapatch simulations. *J. Adv. Model. Earth Syst.*, **8**, 425–452, <https://doi.org/10.1002/2015MS000560>.
- Numaguti, A., and Y. Hayashi, 2000: Gravity-wave dynamics of the hierarchical structure of super cloud clusters. *J. Meteor. Soc. Japan*, **78**, 301–331, https://doi.org/10.2151/jmsj1965.78.4_301.
- Oouchi, K., 1999: Hierarchical organization of super cloud cluster caused by WISHE, convectively induced gravity waves and cold pool. *J. Meteor. Soc. Japan*, **77**, 907–927, https://doi.org/10.2151/jmsj1965.77.4_907.
- Peng, L., C.-H. Sui, K.-M. Lau, and W.-K. Tao, 2001: Genesis and evolution of hierarchical cloud clusters in a two-dimensional cumulus-resolving model. *J. Atmos. Sci.*, **58**, 877–895, [https://doi.org/10.1175/1520-0469\(2001\)058<0877:GAEOHC>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<0877:GAEOHC>2.0.CO;2).
- Stechmann, S. N., and A. J. Majda, 2009: Gravity waves in shear and implications for organized convection. *J. Atmos. Sci.*, **66**, 2579–2599, <https://doi.org/10.1175/2009JAS2976.1>.
- Takayabu, Y. N., 1994: Large-scale cloud disturbances associated with equatorial waves. Part II: Westward-propagating inertio-gravity waves. *J. Meteor. Soc. Japan*, **72**, 451–465, https://doi.org/10.2151/jmsj1965.72.3_451.
- Tulich, S. N., and B. E. Mapes, 2008: Multiscale convective wave disturbances in the tropics: Insights from a two-dimensional cloud-resolving model. *J. Atmos. Sci.*, **65**, 140–155, <https://doi.org/10.1175/2007JAS2353.1>.
- , and G. N. Kiladis, 2012: Squall lines and convectively coupled gravity waves in the tropics: Why do most cloud systems propagate westward? *J. Atmos. Sci.*, **69**, 2995–3012, <https://doi.org/10.1175/JAS-D-11-0297.1>.
- , D. A. Randall, and B. E. Mapes, 2007: Vertical-mode and cloud decomposition of large-scale convectively coupled gravity waves in a two-dimensional cloud-resolving model. *J. Atmos. Sci.*, **64**, 1210–1229, <https://doi.org/10.1175/JAS3884.1>.
- Wheeler, M., and G. N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of cloud and temperature in the wavenumber–frequency domain. *J. Atmos. Sci.*, **56**, 374–399, [https://doi.org/10.1175/1520-0469\(1999\)056<0374:CCEWAO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2).
- Wielicki, B. A., and R. M. Welch, 1986: Cumulus cloud properties derived using Landsat satellite data. *J. Climate Appl. Meteor.*, **25**, 261–276, [https://doi.org/10.1175/1520-0450\(1986\)025<0261:CCPDUL>2.0.CO;2](https://doi.org/10.1175/1520-0450(1986)025<0261:CCPDUL>2.0.CO;2).
- Williams, M., and R. A. Houze Jr., 1987: Satellite-observed characteristics of winter monsoon cloud clusters. *Mon. Wea. Rev.*, **115**, 505–519, [https://doi.org/10.1175/1520-0493\(1987\)115<0505:SOCOWM>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<0505:SOCOWM>2.0.CO;2).
- Williamson, D. L., and Coauthors, 2012: The APE atlas. NCAR Tech. Note NCAR/TN-484+STR, 508 pp., <http://www.met.reading.ac.uk/~mike/APE/atlas.html>.
- Yamasaki, M., 2011: Toward an understanding of the Madden-Julian oscillation: With a mesoscale-convection-resolving model of 0.2 degree grid. *Adv. Meteor.*, **2011**, 296914, <https://doi.org/10.1155/2011/296914>.
- Yano, J.-I., and N. Nishi, 1989: The hierarchy and self-affinity of the time variability within the tropical atmosphere inferred from the NOAA OLR data. *J. Meteor. Soc. Japan*, **67**, 771–788, https://doi.org/10.2151/jmsj1965.67.5_771.